AirLoop

Wearable Air Curtain for Respiratory Protection from Aerosols and Particulates

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Executive summary

Context and Aim
Industrial workers, particularly painters, face significant health risks due to prolonged exposure to airborne dust and fine particulates. While personal protective equipment (PPE) such as respirators exists, adoption remains low due to discomfort, restricted mobility, and usability challenges. This project aims to develop a wearable air curtain system designed to reduce dust exposure while ensuring seamless integration into daily tasks without interfering with workflow or comfort.

Approach
The research employs a multi-method approach to ensure both technical efficiency and user acceptance. Computational Fluid Dynamics (CFD) simulations are used to optimize nozzle airflow distribution, ensuring maximum dust protection. Power efficiency analysis is conducted to minimize energy consumption while maintaining effective performance. Iterative prototyping and lab testing refine the system's functionality, weight distribution, and ergonomics to enhance wearability. To evaluate usability, user studies with industrial painters are conducted, incorporating observations, interviews, and wearability trials to assess comfort and practicality in real-world settings. Additionally, the design is guided by and evaluated with PPE safety regulations, including CE standards, to ensure alignment with industry safety benchmarks.

Results
Findings from CFD simulations and real-world testing will inform nozzle geometry improvements, while user feedback will drive ergonomic refinements. By integrating technical validation with human-centered design, this project aims to create a practical, market-ready air curtain PPE solution that enhances worker safety, comfort, and adoption, ultimately improving protection against hazardous dust in industrial environments.

Keywords: Wearable, Air Curtains, Dust Protection PPE, Particulate, Air Nozzle, Computational Fluid Dynamics (CFD), Power Efficiency, Ergonomic Integration of PPE, Airflow Distribution, Industrial Painters and Dust Exposure, Prototyping, Airflow Visualization, Portable Air Curtain

Abbreviation Guide

CFD – Computational Fluid Dynamics
CFR – Code of Federal Regulations
CoCoPop Framework – Etiology research method with Context-Condition-Population structure
CE – Conformité Européenne (European safety certification)
EPA – U.S. Environmental Protection Agency
EPQ – U.S. Environmental Protection Agency (Note: did you mean EPA? Let me know if EPQ refers to something else.)
FFP – Filtering Facepiece (as in FFP1, FFP2, FFP3 mask classifications)
FFR – Filtering Facepiece Respirator
ISO – International Organization for Standardization
OSHA – Occupational Safety and Health Administration
PELs – Permissible Exposure Limits
PM – Particulate Matter
PM2.5 – Particulate Matter ≤ 2.5 microns in diameter
PPE – Personal Protective Equipment
RPE – Respiratory Protective Equipment
SEM – Structural Equation Modeling
TAM – Technology Acceptance Model
TRL – Technology Readiness Level
VOC – Volatile Organic Compound)

Acknowledgements

This research has been a challenging yet deeply fulfilling journey, and I am incredibly grateful to everyone who has supported me along the way.

Navigating the search for a graduation project was not a straightforward process, as I pursued a path different from both my bachelor's and master's programs. Unlike a conventional academic path where students follow a structured curriculum aligned with a clear career trajectory, I deliberately chose to explore a field that would develop specific technical and design skills beyond the scope of my formal education. This decision was driven by a deep interest in product development, and technology integration, rather than the pursuit of a particular job title or diploma. At the start of this journey, Maarten Haans played a significant role in helping me navigate this transition. His advice and mentorship provided me with the clarity and confidence to define my research direction and explore opportunities that aligned with my values and skill development goals. His willingness to listen and provide thoughtful feedback allowed me the time and space to reflect on what truly mattered to me in this project.

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This project officially began in the second phase of research, and I was fortunate to collaborate with the Studio Lab at TuDelft, Muzus, and Human-Robot Interaction Lab members espespecially Fleur, Staffs at PMB lab especially Don, Their openness in sharing resources, providing technical support, and offering constructive feedback made a significant impact on the direction of my work. The lab's multidisciplinary environment and willingness to discuss challenges and brainstorm solutions greatly enhanced my ability to refine various aspects of the project.
A special acknowledgment to SUSAG, whose cooperation extended beyond providing networks and industry connections. They played a crucial role in offering real-world insights and constructive feedback, helping me refine the project's practicality, functionality, and compliance with industry standards. Their involvement helped ensure that my research remained grounded in actual workplace needs, making it not just a theoretical exploration but a solution with tangible applications. I am also deeply appreciative of the painters who participated in the study. Their contributions went beyond mere data collection—they engaged with the research process thoughtfully and generously, sharing their experiences and challenges.

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Summary

Project Brief

This research, conducted in collaboration with Stichting Uitvoeringsregelingen Schilders-, Afwerkings- & Glaszetbedrijf (SUSAG), the TU Delft Human-Robot Interaction Lab, and Muzus, aims to improve safety and comfort for painters in residential or community environments. Building on previous research by collaboration parties, the project addresses painters' low adherence to personal protective equipment (PPE), particularly face masks, which are often perceived as uncomfortable, unnecessary, or restrictive by painters.The study investigates the feasibility and desirability of a wearable air curtain system as an alternative to traditional respiratory PPE. By integrating airflow technology with ergonomic design, the goal is to enhance dust protection while maintaining safety and comfort. Through prototyping, user testing, and technical validation, the research evaluates the system's effectiveness, adoption potential, and impact on workflow efficiency.

Research Methodology

The project applied a mixed-methods design process that combined literature review, regulatory analysis, user research, and technical validation. Relevant standards and guidelines (OSHA, NIOSH, ISO, EN norms) were reviewed to ensure alignment with occupational safety requirements.
User insights were gathered through interviews, field observations, co-design sessions, and an online survey involving painters and stakeholders. These activities revealed behavioral patterns, comfort issues, and practical barriers that influence PPE use in day-to-day work.
To assess technical feasibility, CFD simulations were used to study airflow behavior, nozzle geometry, and jet stability. Low-fidelity prototyping and 3D-printed models enabled rapid testing of wearability and functional integration. A functional prototype was evaluated with painters to understand comfort, usability, and perceived protection in realistic conditions.
By combining user insights with iterative engineering development, the study examined whether a wearable air-curtain system can reduce dust exposure while improving comfort and workflow compatibility.

Target Challenges and Solutions

Users resist wearing PPE due to ingrained habits and traditional practices in residential setting.
Through user-centered research, this study identified behavioral patterns and designed targeted solutions to promote behavior change while increasing the desirability of PPE. The proposed solutions aim to enhance user experience by incorporating features such as temperature and humidity control to create a positive sensory experience. Additionally, the design encourages low-maintenance usage by integrating an external, long-lasting filter equipped with built-in. To further improve workflow efficiency, the design consolidates multiple PPE functionalities into a single, integrated product, addressing both convenience and user preferences.

The power consumption can be too high to sustain pressurised airflow with sufficient strength for an entire work shift.
Potential solutions include optimizing airflow pathways, employing modular or replaceable battery systems, using larger backpack-style batteries for extended shifts, integrating external batteries for flexibility, and establishing convenient charging stations for continuous operation. Additionally, the product's modular design enables compatibility with readily available blowers.

Users are often reluctant to wear protective equipment due to discomfort
The proposed solution creates a repellent air stream that deflects contaminants away from the user's breathing zone, reducing the likelihood of inhaling aerosols and particulates. The nozzle is integrated into a wearable device, with the functional unit carried as a backpack. A vest secures the device and tubing to prevent entanglement and to support tool carrying. The prototype has been evaluated with painters to assess comfort, usability, and overall desirability.

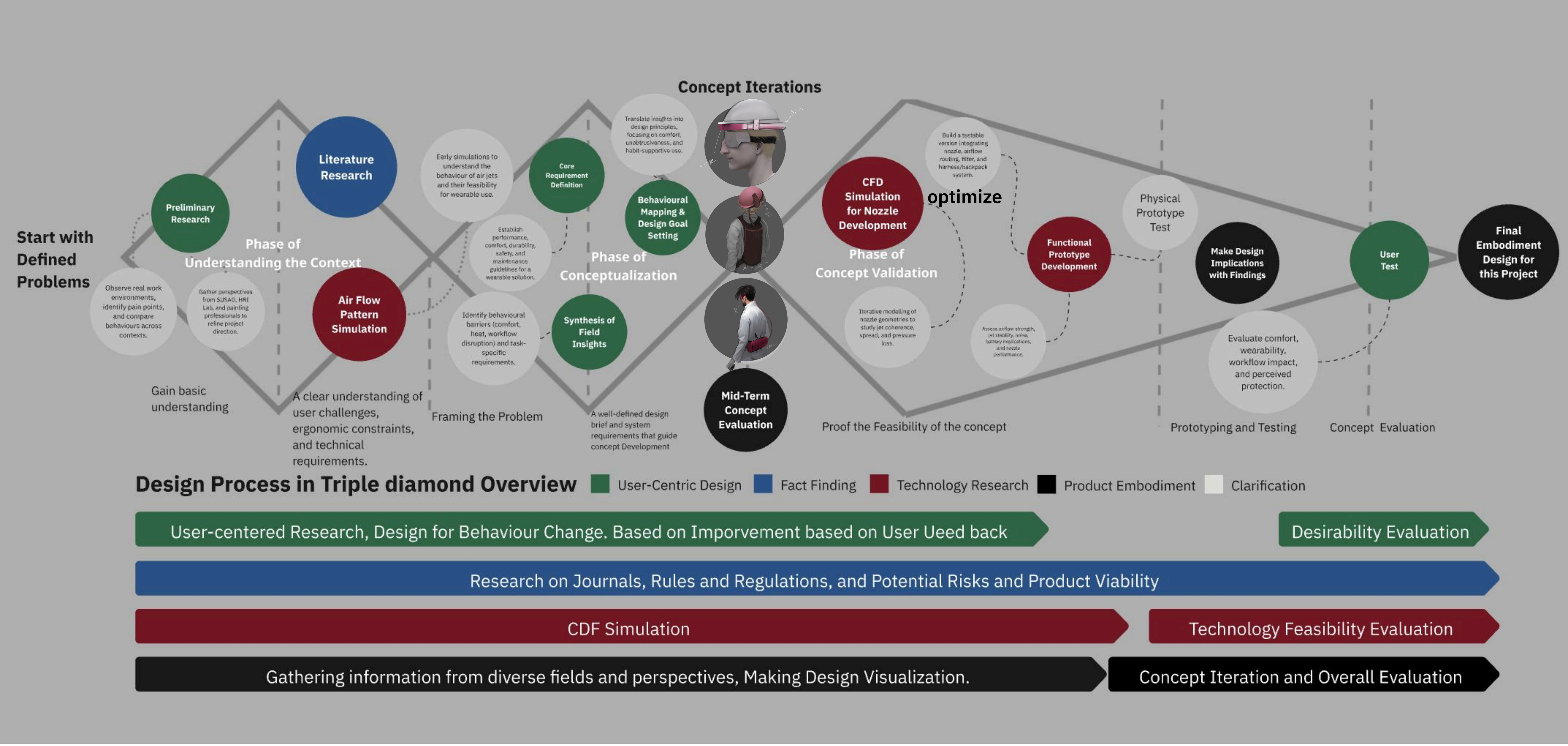
The airflow should remain separate from particulates within the breathing zone
The proposed solution involves designing the nozzle using CFD simulation to ensure laminar flow characteristics. Additionally, a physical barrier is incorporated around the user's face to enhance protection and guide the airflow precisely.

Future Steps

Future steps include handing over the design for airflow refinement and compliance testing according to CE and other relevant standards. If regulatory compliance is not achieved, the design concept or opportunities may require adjustments. Modifications might also be needed for mass production, as the current focus is on desirability and feasibility. Ultimately, the goal is to enhance respiratory protection effectively, ensuring minimal user intrusion without being limited to provide protection by only a particular airflow type.

Conclusion

In conclusion, this study explores the technological feasibility of airflow design, the desirability of integrating an air curtain into a wearable functional unit, and the viability of creating a durable, affordable, and easily maintainable product. The design prioritizes safety and aims to enhance workers' workflow. However, further evaluation and potential redesign are necessary to fully realize these objectives. The next section demonstration an overview of design activities involved in this project.



Project Timeline

The project follows a structured, iterative design process that integrates research, design, simulation, testing, and refinement to develop a compliant and user-centric product. It begins with a comprehensive literature review to understand existing knowledge on air quality and protective equipment, complemented by regulatory checks and risk assessments to ensure adherence to industry standards and safety guidelines. Preliminary research, including stakeholder interviews, field observations, and surveys, informs user needs and pain points. This data is processed to identify design implications, serving as the foundation for concept development and refinement.

The design phase incorporates airflow simulations and ergonomic testing to optimize functionality while ensuring desirability. The integration of electronic components aims to achieve a high level of technical readiness (TRL), with the product undergoing rigorous compliance testing to meet safety and functionality standards. The process culminates in the product embodiment, where all key aspects—desirability, feasibility, and viability—are consolidated into a cohesive and market-ready solution.

Introduction

1.1 Background

Figure 1. Concept by Job Nuijen

Over the past year, Marco Rozendaal, Nazli Cila, and Jordan Boyle from the TU Delft Human-Robot Interaction Lab have collaborated with the SUSAG Foundation to innovate the painting industry by exploring the use of smart agents such as robots, exoskeletons, and intelligent equipment. In partnership with MUZUS and IDE students, they have conducted research, developed innovative concepts, and created a comprehensive roadmap for the future of the industry. **The goal of this collaboration is to ensure that painters experience job satisfaction throughout their careers**.

Key considerations include the acceptability and practical deployment of smart agents, focusing on factors such as capabilities, appearance, workplace integration, and social-ethical concerns like trust and privacy. This research has been conducted in close collaboration with target users to ensure practical and ethical design solutions. Various researchers contribute to different aspects of smart agent development.

Phase 1 of the air curtain for painters was carried out within the 2024 Advanced Concept Design (ACD) course. Led by Job Nuijen and supervised by Gonny Hoekstra, this phase focused on a conceptual proposal for an air curtain system designed to block dust during sanding (see figure 1) . Phase 1 generated critical insights into ergonomic requirements, product performance requirement, noise level acceptance, and the cultural dynamics influencing PPE adoption, especially through the contributions of MUZUS.

Phase 2, the current project, builds directly on the foundational insights from Phase 1 but shifts its focus toward making the air curtain system technically feasible and ready for real-world application. Unlike the conceptual emphasis of the first phase, this stage investigates the system's actual performance—exploring airflow behavior, outlet geometry, and filtration effectiveness through iterative prototyping and testing. Significant attention was given to optimizing design geometry for flow efficiency and documenting design decisions to support potential future development.

The desirability research during the current phase also utilized the co-design approach: working closely with painters and other stakeholders to explore not only what is desirable but also what is realistically feasible. Instead of evaluating idealized concepts (see figure 2 for example), users tested functionally grounded prototypes. While residential and freelance painters remain the primary user group, early implications for broader occupational use—such as in welding, healthcare, or industrial contexts—are also considered.

In addition, Phase 2 critically examines real-life constraints such as regulatory compliance, environmental variability, and workplace integration together with the stakeholders , linking technical implementation with behavioral adoption. The project spans 100 working days and will conclude with a comprehensive handover package to the Human-Robot Interaction Lab, facilitating future development of a effective

Figure 2. Initial ideation session between the HRI Lab and SUSAG during the first collaborative meeting for project phase 2.

Work freely, Breathe Safely

-The Starting Point

Phase 2 builds on the groundwork laid by Muzus and the ACD Phase 1 project led by Job Nuijen. Together, these sources shaped early requirements and desire direction for a wearable air curtain system.

From Muzus, several user-centered priorities emerged:

- **Health Protection:** The system must effectively filter fine dust and aerosols to safeguard respiratory health.
- **Workflow Compatibility:** The design should be minimally intrusive to allow full range of motion and craftsmanship.
- **Environmental Adaptability:** It must function reliably in unpredictable environments such as those with mold, wood rot, or humidity.
- **Cultural Alignment:** Adoption must align with workplace habits, aiming to evolve them through comfort and ease of use.

The ACD Phase 1, conducted by Job Nuijen, contributed a conceptual prototype and key recommendations:

- **Filtration Performance:** Air quality needed further optimization, as PM2.5 levels exceeded safe thresholds.
- **Airflow Velocity:** Further testing was needed to understand how flow speed affects protection.
- **Component Design:** Suggestions included developing custom fans, filters, diffusers, and electronics for improved integration.
- **Fit and Comfort:** Size variability and ergonomic testing with actual painters were seen as essential for broader adoption.
- **Battery and Noise:** Future versions should prioritize compact battery integration and low-noise operation (<30 dB).

Phase 2 critically reviewed the findings above, refining design decisions based on technical feasibility and current limitations and emphasized realistic embodiment and preparation for real-life implementation.

1.2 Stakeholder Introduction

This project identifies key stakeholders across four domains: sector representatives, workplace operations, end users, and regulatory bodies, and Research and Developement parties. Their involvement is critical to developing a solution that is effective, acceptable, and ready for practical deployment. Sector bodies like SUSAG and OnderhoudNL ensure alignment with industry goals for safe and fair practices. Workplace actors—employers, safety officers, and maintenance staff—provide input on daily usability, integration, and enforcement. Painters and related professionals shape the design through their practical needs and behaviors, while regulatory and development parties like TU Delft, RIVM, and CE Notified Bodies ensure scientific validity, usability, and legal compliance.

Sector Representatives

Sector Representatives, SUSAG, which is the client of this project, and OnderhoudNL support businesses in this sector by promoting fair working conditions, economic sustainability, and compliance with regulations, in this air curtain project, these stakeholders plays a central role in connecting various sectors in the painting industry towards goals around safer and fairer practices.

Stichting Uitvoeringsregelingen SAG
Schilders-, Afwerkings- & Glaszetbedrijf

SUSAG

SUSAG stands for Stichting Uitvoeringsregelingen SAVG, which translates to the Foundation for Implementation Regulations SAVG. It is a Dutch foundation that supports companies and workers in the painting, finishing, property maintenance, and glazing sectors by ensuring fair, safe, and sustainable working conditions. The client of this project would support the implementation of an air curtain if it is as effective as or more effective than masks in protecting workers from dust exposure, complies with occupational health guidelines and CE safety regulations, enhances worker compliance by being comfortable and practical, and is economically viable for employers in the painting industry.

ONDERHOUD NL

OnderhoudNL

OnderhoudNL is the Dutch national trade association representing companies in the painting, maintenance, and finishing industry. Its primary role is to support businesses in this sector by promoting fair working conditions, economic sustainability, and compliance with regulations.

Workplace Compliance & Operations Team

The Workplace Compliance and Operations Team, consisting of employers, health and safety officers, and maintenance staff, is responsible for integrating safety tools like the air curtain into daily operations. Their feedback ensures that the product is practical, maintainable, and suitable for enforcement.

Employer

Employers prioritize cost-effectiveness, productivity, and worker compliance. They seek a solution that enhances safety and efficiency without increasing costs, training time, or disrupting workflows.

Maintenance Staff

Maintenance staff value durability, ease of cleaning, ease of replacing filters, and cost-effectiveness for long-term usability and minimal downtime.

Health and Safety Officer

Safety officers focus on regulatory compliance, effectiveness, and worker adherence. They prioritize proven dust protection, comfort, and compliance with OSHA, NIOSH, and CE standards to ensure legal alignment and consistent use. The air curtain must not introducing new risks.

End Users

End users, primarily painters, are the ultimate decision-makers in terms of adoption. Their needs for comfort, usability, and reliable protection drive the design. The user group may also extend to other professionals, DIY customers, or adjacent industries.

Secondary Professional Users

Professionals such as woodworkers, construction workers, and auto body technicians require PPE that is effective, safe, and seamlessly integrated into their workflow. The design must be non-intrusive, adaptable, and ensure reliable dust protection

Non-Professional Users (DIY / Hobbyists)

Consumers seek dust protection that is functional, aesthetically appealing, and compatible with existing equipment. The product must be visually appealing, easy to use, and marketable to hobbyists and DIY users.

Primary Users: Painters

For residential and community painters, the design must be unobtrusive, breathable, and easy to maintain, reducing heat, moisture buildup, and breathing resistance comparing to traditional respiratory protections. It should allow free movement, quick battery changes, and minimal adjustments while ensuring consistent dust protection and lightweight comfort for long work sessions.

Research and Development Parties

Research and development Parties, including TU Delft's Medisign program and the Human-Robot Interaction Lab, ensure the air curtain is developed with a focus on usability, technological feasibility, and ethical research practices.

Human-Robot Interaction Lab (HRI)

The Human-Robot Interaction (HRI) Lab focuses on developing smart agent that co-exist, cooperate with people in a safe, natural, and effective manner, aiming to enhance human life rather than replace workers. The design concept builds on previous research, with findings shared to contribute to ongoing development. This project aims to investigate desirability and technological feasibility, providing well-documented research and insights to ensure that future researchers can effectively build upon its progress.

medis+gn
TUDelft

Medisign at TUDelft

The researcher is pursuing the Medisign specialization at TU Delft. A Medisign graduation project requires careful consideration of its contribution to societal health and must adhere to ethical research practices, including compliance with Human Research Ethics Committee (HREC) protocols. Additionally, the project must demonstrate functionality, user-centered design, and practical implementation.

MUZUS

Muzus is a Dutch design research agency specializing in user-centered methods. Although not directly involved in this project, their prior research and insights—shared with the TU Delft Human-Robot Interaction Lab—provided valuable guidance on user needs and PPE-related behavior, helping shape the project's early direction.

Regulators

Regulators, including and not limited to DECOS, RIVM, EU-OSHA, and Notified Bodies—define health and safety standards and ensure legal compliance. They shape the conditions under which any PPE solution can be approved, adopted, and distributed.

The DECOS (Dutch Expert Committee on Occupational Safety) and National Institute for Public Health and the Environment (RIVM)

The DECOS and RIVM assess occupational exposure risks and provide health-based recommendations for PPE standards. They focus on scientific validation, ensuring PPE effectively reduces long-term dust exposure for worker protection. The accessibility of the PPE should also be taken into account.

European CE Regulations - Notified Bodies (NBs) for CE Certification

Notified Bodies (NBs) for CE Certification establish safety standards and certify PPE before market entry, ensuring compliance with filtration grades, durability, and usability requirements for workplace safety.

European Agency for Safety and Health at Work (EU-OSHA)

The European Agency for Safety and Health at Work (EU-OSHA) provides guidance and enforcement on workplace safety. PPE design should follow its standards for effective dust protection in occupational settings.

Research and Development Parties

Manufacturers and Distribution Channels, These stakeholders develop, produce, and supply PPE and related technologies. They are responsible for market viability, cost-effectiveness, and maintaining access across supply chains.

Manufactures

Manufacturers focus on cost-effective production, scalability. The product should consider ease of use, durability, and ensuring affordable mass production.

Distribution channels

Retailers and suppliers prioritize market demand, logistics efficiency, and product compatibility with existing safety equipment. They seek high-demand, easily marketable products that align with industry trends and regulations.

Stakeholder Mapping

This stakeholder mapping on the next page (see Figure. 3) visualizes the ecosystem surrounding occupational safety practices and PPE adherence in the painting and construction industries. Stakeholders are positioned along two axes:

- Horizontal axis: Prioritization of comfort versus regulation
- Vertical axis: Level of direct interaction with the PPE (primarily painters)

Circle size indicates relative influence over PPE usage and adoption, while line thickness reflects the frequency or strength of interaction between stakeholders.

Stakeholder Relationship

This project involves a network of stakeholders whose decisions shape the development, regulation, and adoption of PPE. These actors are connected through functional dependencies and collaboration pathways.

The HRI Lab works closely with SUSAG and MUZUS to align technical innovation with user needs and policy directions. SUSAG and OnderhoudNL connect sector-wide goals with practical implementation. Employers, safety officers, and maintenance staff adapt safety tools like the air curtain into daily operations—providing feedback on usability, compliance, and upkeep. Painters, as the primary users, influence design through their acceptance or rejection of the product in real-world tasks. Regulators set standards that define legal and performance thresholds, which are implemented by manufacturers and distributors to ensure availability and compliance (see Appendix A. for detailed stakeholder relationship analysis).

These interlinked relationships shape the air curtain's feasibility, desirability, and potential for long-term adherence.

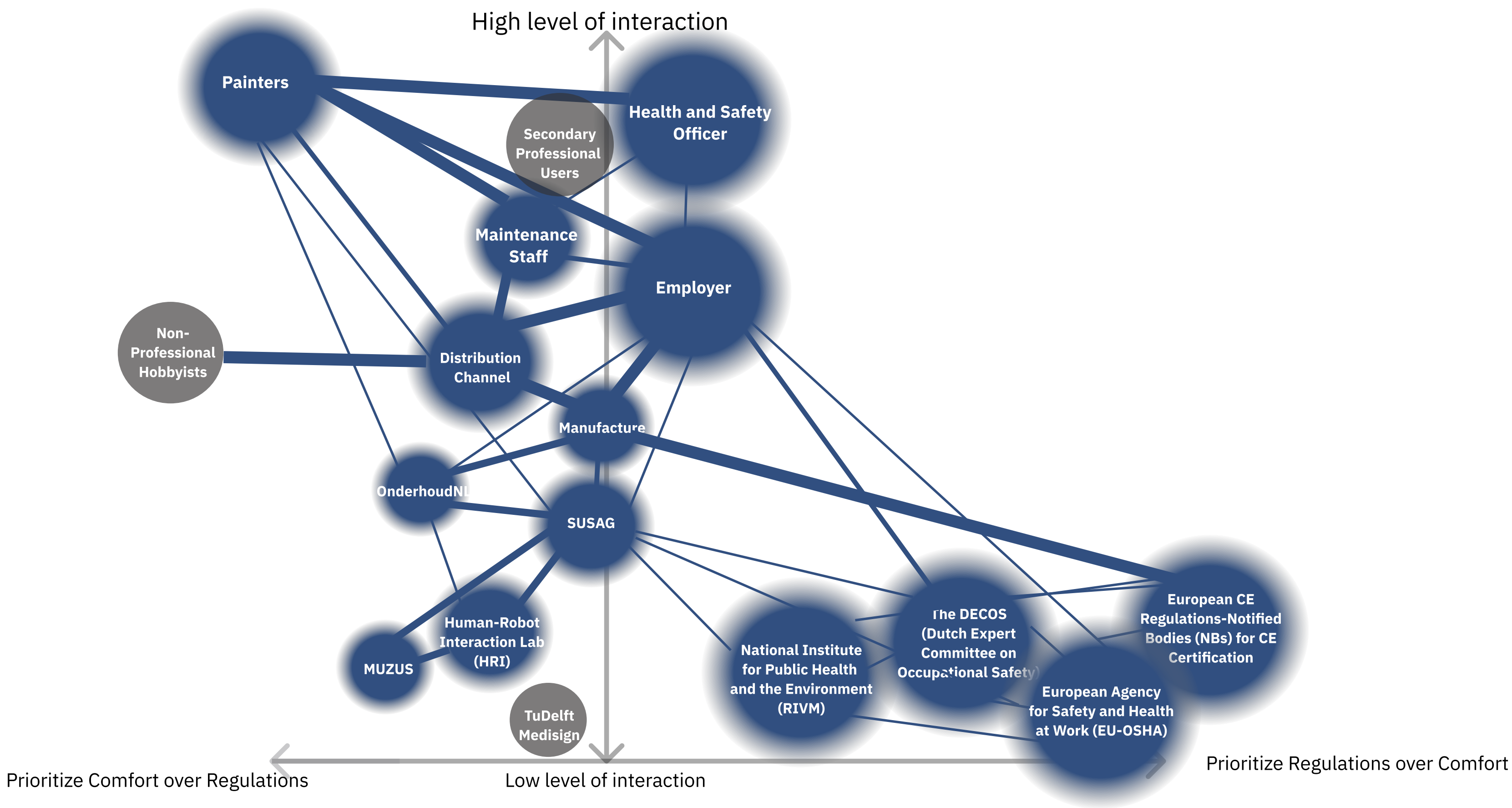


Figure 3. Stakeholder Mapping

Stakeholders Positioning

Stakeholders are positioned based on their role in shaping PPE usage.

Painters are placed high and toward comfort, as they directly use the equipment and are most affected by discomfort.

Employers and health & safety officers balance regulation and usability, interacting frequently with users.

Regulatory bodies are placed lower and toward regulation, as they set standards but have limited user contact.
Manufacturers and distribution channels sit centrally due to their role in shaping availability and usability.

SUSAG and OnderhoudNL bridge policy and practice, hence their central position.
HRI: focuses on user-centered design and innovation, especially around wearable safety technologies.

Gray nodes include **Medisign, Secondary professional users**, and **Non-Professional users**. These stakeholders are not actively involved but represent relevant expertise or future application domains.

Project Scope

This project is a collaboration between Stichting Uitvoeringsregelingen Schilders-, Afwerkings- en Glaszetbedrijf (SUSAG) and the Human Robot Interaction Lab (HRI) at TU Delft. SUSAG represents the Dutch painting, finishing, and glazing sectors. Their role focuses on improving workplace conditions, with particular attention to minimizing exposure to harmful dust. Their involvement ensures the project aligns with industry needs and regulatory requirements.

The chair and the mentor from TUDelft provides technical and research supervision. With expertise in ergonomics and wearable technologies, the lab supports the development of smart protective systems that integrate into real-world work environments.

The core aim of this project is to develop and evaluate a wearable air curtain system for dust protection, specifically targeting painters. These workers often operate in poorly ventilated spaces and frequently reject conventional masks due to discomfort.
The project investigates two key questions:

1. **Is the air curtain system technically feasible? Can it reliably reduce dust exposure in practice?**
2. **Is the product desirable for users? Is it comfortable, acceptable, and usable enough to encourage long-term adoption?**

While painters are the primary focus, the system could potentially be adapted for other dust-exposed professions such as construction workers, woodworkers, and waste handlers. Future extensions to protect against fumes or bio-aerosols are possible but fall outside the current scope.

By combining iterative prototyping with user-centered research, the project aims to deliver a solution that balances certified protection with everyday usability—bridging the gap between regulation and real-world practice.

2.PROBLEM FRAMING

Overview

This section outlines the foundational steps taken to define the problem space for the Air Curtain for Dust Protection project. The process began with a literature review to establish theoretical grounding and understand the health risks and behavioral barriers associated with current respiratory protective equipment (RPE). From this, key knowledge gaps were identified—particularly around psychosocial factors, long-term adherence, and emerging alternatives such as wearable air curtains.

To address these gaps, user-centered field research was conducted, including product reviews, observational studies in high-exposure settings, and sensitizing interviews with professional painters. These activities helped uncover real-world constraints, user behaviors, and motivations that shaped the direction of the project.

Insights from both literature and fieldwork were then synthesized into a design goal, a set of core requirements, and a focused set of design priorities. Together, these form the foundation for the conceptual development in the next phase.

2.1 Literature Review: Aim and Scope

This phase defines key occupational exposure challenges in professions such as painting, construction, and woodworking, where workers face sustained contact with airborne particulates, aerosols, and chemical fumes. Dust exposure is used as a representative baseline due to its ubiquity and measurable health risks (Kauppinen et al., 2006).
Prolonged inhalation of these substances is linked to severe respiratory conditions, including lung impairment and nasal cancers (Boadu et al., 2023), underscoring the need for protective measures that are both effective and usable in practice.
Building on prior work by TU Delft's Human-Robot Interaction Lab, the SUSAG Foundation, and the 2024 BRISA Concept Design, this review evaluates the viability of air curtain technology as a user-accepted alternative to conventional PPE.

This literature review aims to systematically define the nature and extent of occupational exposure to dust and related airborne hazards, evaluate current PPE limitations, investigate barriers to adherence, and explore the potential of air curtain technology as an alternative solution. The review is structured thematically, covering the following key areas:

It addresses four thematic areas:

1. **Prevalence of Occupational Dust Exposure and Its Long-Term Health Impact**
   Summarizes key findings on exposure sources, affected professions, and associated health risks.
2. **Chronological Literature Review on the Historical Evolution and Emerging Trends in Respiratory Protective Equipment**
   Traces major shifts in PPE design, identifies gaps in adoption and comfort, and outlines directions informed by past innovations.
3. **Design Challenges and Considerations for Respiratory Protective Equipment**
   Explores usability constraints, technical feasibility, and behavioral factors affecting long-term adherence and real-world implementation.

While not addressing every question that may arise during the design process, this review establishes the foundational knowledge necessary to inform the design requirement, design and research focus, conceptual development of a practical, user-centered, and regulation-aligned protective device.

Prevalence of Occupational Dust Exposure and Its Long-Term Health Impact

Occupational dust exposure refers to the inhalation of airborne particles present in workplace environments. According to the Health and Safety Executive, even seemingly harmless substances—such as paper or tissue dust—can pose health risks when airborne concentrations exceed certain thresholds. Specifically, inhalable dust, which can enter the nose or mouth, is considered hazardous at concentrations of 10 mg/m³ or more, while respirable dust—smaller particles capable of reaching the gas-exchange region of the lungs—is hazardous at 4 mg/m³ or more, averaged over an eight-hour workday (Health and Safety Executive, n.d.).

Sanding dust exposure is particularly widespread in industries such as construction and woodworking. Although exact figures on overexposure are limited, existing studies consistently highlight the prevalence of hazardous dust levels in these environments. Kauppinen et al. (2006, as cited in RIVM, 2021), in the WOODEX study, estimated occupational exposure to inhalable wood dust across the 25 EU member states between 2000 and 2003. Using a combination of national labor force statistics, country questionnaires, company surveys, exposure measurements, and expert judgment, the study found that **approximately 3.6 million workers—or 2.0% of the employed population in the EU-25—were exposed to inhalable wood dust.** The construction industry accounted for the largest share (1.2 million workers), followed by furniture manufacturing (700,000), builders' carpentry (300,000), sawmilling (200,000), and forestry (150,000). C**ritically, about 560,000 workers (16% of those exposed) were subjected to concentrations exceeding 5 mg/m³ (Rijs et al., 2021).** In the United States, The Occupational Safety and Health Administration (OSHA) reports that **approximately 2.3 million workers are exposed to respirable crystalline silica, a common component of materials such as concrete and sand, particularly during sanding, cutting, or drilling.**
Inhalation of fine silica particles is associated with severe long-term health risks, including silicosis, chronic obstructive pulmonary disease (COPD), and lung cancer(Occupational Safety and Health Administration, n.d.). Given the scale and severity of workplace dust exposure, especially in physically demanding and dusty trades, it is critical to understand the associated health impacts in order to inform more effective protection strategies (OSHA, n.d.). Occupational dust exposure is closely linked to a range of serious health issues.

A systematic review published by the National Library of Medicine analyzed global evidence on respiratory conditions among construction workers—one of the most at-risk populations due to regular exposure to airborne hazards. The study followed the CoCoPop framework (Condition, Context, Population) and PRISMA guidelines, reviewing literature from Scopus, PubMed, Web of Science, and Google Scholar. Of the 256 studies initially identified, 25 met the inclusion criteria and were published between 2012 and 2022. **The review identified 16 respiratory health conditions, with cough, breathlessness, and asthma being the most frequently reported. It included both symptoms and chronic diseases such as cancer, silicosis, and lung fibrosis. Key exposure risks included dust, respirable crystalline silica, fumes, vapors, asbestos, and gases.** Risk levels were significantly elevated by smoking and prolonged exposure durations (Boadu et al., 2023). the findings underscore the need for integrated protective strategies combining PPE, environmental modifications, and policy measures, particularly in high-risk sectors like construction and painting where exposure levels and health impacts can be severe.
These findings highlight the widespread presence of hazardous dust in occupational environments and the high prevalence of related health conditions, particularly in sectors like construction and woodworking. **The research also reveal that current exposure standards often classify airborne risks by particle size rather than specific material types, suggesting that sustained exposure to any form of inhalable dust can be harmful.** This underscores the need for comprehensive workplace health strategies that extend beyond PPE for painters alone. **From a design perspective, it reinforces the importance of considering broader use cases for protective technologies instead of for specific tasks but for a range of dusty work scenarios across industries.**

Chronological Literature Review on Historical Evolution and Emerging Trends in Respiratory Protective Equipment

Historical Evolution

In contrast to modern standards, where facial hair can create gaps in face masks and reduce their effectiveness **Emerging TrendsEmerging Trends**, firefighters in the 18th and 19th centuries were required to grow full beards to as preparation for battling fires, they would soak their beards in water and clamp wet hair in their teeth to filter out ashes out of the mouth, and consume large amounts of steam beer believing that will to cleanse their lungs (Spelce et al., 2017). While these early techniques were primitive and based largely on anecdotal practices, they reflected a growing awareness of the need to protect the respiratory system in hazardous environments.

The development of modern respirators began in the 18th century, evolving from rudimentary methods like animal bladders and wet cloths. A pivotal moment came in 1827 with Robert Brown described the continuous, random motion of pollen particles in water (Wu & Buyya, 2015), marking Brownian motion as a foundational observation in particle behavior (Centers for Disease Control and Prevention, 2019). Brownian motion along with advances in filter media, laid the foundation for particulate respirators.

By the mid-1800s, respiratory health began receiving scientific attention, with German research into industrial dust exposure and the 1877 Nealy Smoke Mask—an English patent using water-saturated sponges—marking early innovations in protective technology(CDC, 2019). However, there were relatively few advancements in respirator development between 1900 and the onset of World War I in 1914(Spelce et al., 2017).

Institutional efforts gained momentum in the early 20th century, particularly during World War I, when the need for chemical protection accelerated the development of respiratory equipment. This progress continued into World War II. In the United States, the Bureau of Mines—established in 1910—launched the first respirator certification program in 1919. This initiative led to the creation of the Gibbs Breathing Apparatus in 1920 by the MSA Safety Company, a closed-circuit self-contained breathing apparatus (SCBA) using compressed oxygen and a soda lime scrubber.

Initially developed for mining and firefighting, the device was later adopted by the Navy and aviation sectors, reflecting the growing cross-sectoral importance of effective respiratory protection (CDC, 2019).
Formal regulatory enforcement came decades later. The Occupational Safety and Health Administration (OSHA), established in 1970, began issuing enforceable standards for workplace safety. Notably, 29 CFR (Code of Federal Regulations) 1910.134 became applicable to the construction industry in 1979, transitioning respiratory protection from voluntary guidance to mandatory regulation. The emergence of occupational respiratory diseases and respiratory-related fatalities further emphasized the importance of consistent PPE use. As the field matured, studies on usability and adherence became crucial. **A 1995 study conducted in an automobile plant (N = 208) found that only 8% of workers considered half-mask respirators as comfortable, with 62% rating them as**

uncomfortable (Akbar-Khanzadeh et al., 1995)—pointing the need of improvement on physical ergonomics design in personal respiratory protection.

Recent evaluations of existing respirator technologies—such as those compiled in the 2025 update of the U.S. Department of Health and Human Services' Radiation Emergency Medical Management (REMM) guide—offer a comprehensive overview of available PPE types and their olimitations. Disposable Air-Purifying Respirators (APRs) are lightweight and low-cost but lack oxygen supply and full-face protection. Reusable APRs provide more robust filtration but require fit testing and can permit leakage. Powered Air-Purifying Respirators (PAPRs) enhance comfort and airflow but are bulky and battery-reliant. Supplied-Air Respirators (SARs) deliver high protection with positive pressure but reduce mobility due to tethered hoses and reliance on clean air sources. Self-Contained Breathing Apparatuses (SCBAs) offer the highest level of protection but are heavy, limit usage time, and hinder communication(REMM, 2025).

This historical and regulatory trend analysis reveals recurring challenges across all types of respiratory PPE: physical discomfort, restricted mobility, communication barriers, and maintenance demands. These issues collectively point to the need for more ergonomic, user-centered innovations. Emerging priorities for next-generation respirators include reduced weight, improved battery performance, integrated eye protection, and enhanced usability—features essential for encouraging consistent use in occupational settings.

Emerging Trends in Respiratory Protective Equipment and Market Reflection

To inform innovative PPE development, this literature review examines both emerging design trends and evaluations of current market solutions. The analysis identifies key design directions, highlighting promising opportunities alongside persistent limitations.

Smart Technology Integration and Real-Time Feedback

The integration of smart technologies into PPE can enhance both safety and the user experience(European Agency for Safety and Health at Work [EU-OSHA], 2021). Wearable sensors and IoT connectivity allow real-time monitoring of environmental conditions and worker health (Hughes, 2024). Wearables that work in tandem with machinery or safety systems—such as haptic feedback for filter saturation or airflow blockage—can drastically improve user awareness and timely response (Foy, 2023). For example, the CleanSpace CST ULTRA (see figure 4.) incorporates advanced reporting technology that supports workplace compliance by providing detailed data on respirator performance. Within approximately one minute, the device's dashboard updates to display connection status, battery level, filter condition, alarm notifications, and a mask protection score (CleanSpace Technology, n.d.).

Figure 4.CleanSpace CST ULTRA smart powered respirator system

A review on the Agile Equipment YouTube channel praised the CleanSpace CST ULTRA's app for detecting when air needs to be delivered . However, a user comment noted the mask slips when sweating, the headband fit is poor, and the high price does not include a case—raising concerns about comfort and perceived value (Agile Equipment, 2023). Future iterations should improve sweat resistance, headband ergonomics, and include a protective case to meet user expectations for both function and value.

Customization, Comfort, and Ergonomics

Comfort and usability remain essential for long-term adherence to PPE, especially in urban, mobile contexts (Hughes, 2024). The Dyson Zone (see figure. 5) , a wearable air purifier integrated with noise-canceling headphones, exemplifies advanced ergonomic features designed to improve user comfort while tackling city air pollution. Its dual-layer filtration system captures particles as small as 0.1 microns and city gases like NO_2 and SO_2 using K-Carbon filters (Dyson, n.d.). Ergonomically, the product offers a non-contact visor to reduce facial pressure, pivoting ear cups for fit flexibility, and a microfiber-lined headband with cushioned ear pads to enhance long-term wearability. The magnetic visor attachment enables quick donning and removal, while the balanced weight distribution —by placing compressors in the ear cups—minimizes front-heaviness and preserves the user's field of vision (Dyson, n.d.).

Figure 5.. Dyson Zone headphone with integrated air purifier (Dyson, n.d.).

Despite these strengths, reviewers criticized the device's total weight (~650g), which can cause fatigue during extended use or physical activity (PCMag, 2023; Smart Air, 2023). Battery limitations (1–3 hours depending on fan speed) and dual-fan noise further compromise **continuous usability**. The absence of a facial seal also raises concerns about the **backflow of polluted air** near the mouth, especially in dynamic or high-particulate environments (Smart Air, 2023). Song (2023) characterizes the Dyson Zone as “not the most practical” for everyday use, citing factors such as physical fatigue due to its weight, limited comfort over extended periods, and the instability of the magnetic visor during removal. Additionally, Song questions its effectiveness in real-world scenarios, given the absence of a proper facial seal, which may allow contaminated air to bypass the filtration stream. Aesthetically, the device's **unconventional and bulky appearance attracted public attention**, which may affect user acceptance in social contexts. Song also raises concerns about **situational awareness**, noting that the device's effective noise-canceling capabilities reduced her ability to detect environmental cues in public spaces, potentially compromising personal safety. While the product demonstrates strong app integration and advanced filtration, its practical applicability appears limited to specific urban or experimental contexts rather than broad, daily adoption.

Future wearable air purifiers should reduce weight, enhance long-term comfort, and improve visor stability. A partial facial seal could increase protection without sacrificing wearability. Integrating ambient sound pass through would help maintain situational awareness, while a more discreet aesthetic could improve social acceptance. These refinements would support broader daily use beyond niche or experimental contexts.

Communication, Education, and Behavioral Support

User-centered PPE must integrate communication tools that reduce stigma and improve usability. Visual cues, instructional tags, and easy-to-understand warnings enhance compliance (National Academies of Sciences, Engineering, and Medicine, 2022). The wearable air curtain developed by University of Michigan startup Taza Aya offers an alternative approach by integrating protective functionality directly into headgear, avoiding traditional face coverings. This solution improves facial visibility and reduces the muffled speech and visual obstruction typically caused by masks—issues that can hinder communication on industrial lines where many workers speak different languages. Field testing at Michigan Turkey Producers highlighted the value of unobstructed face-to-face interaction in improving workplace communication without compromising protection (Lynch, 2024). While the system is still in development, its design illustrates how PPE can minimize behavioral and communication barriers while enhancing perceived comfort and social acceptance.

Figure 6. Worker wearing Taza Aya's wearable air curtain system in an industrial food processing environment (Little, 2024).

Sustainability and Advanced Materials

Environmental sustainability is becoming an increasingly important consideration in PPE design. Current guidelines encourage the use of recycled, recyclable, or biodegradable materials to reduce environmental impact throughout the product lifecycle (National Academies of Sciences, Engineering, and Medicine, 2022). In addition to material selection, some manufacturers are adopting modular and system-oriented design strategies to extend product longevity and reduce waste. For example, Sundström

Safety (2023) emphasizes the development of versatile PPE components designed for cross-compatibility—allowing elements such as filters, headgear, and air supply systems to be used interchangeably across different configurations. This system-oriented design approach promotes reusability, reduces redundancy, and has the potential to lower material consumption over time.
Although specific sustainability data is not available, the SR 575's modular design points to a more sustainable direction.

Figure 7. Sundström SR 575 Industrial Safety Helmet with flip-up visor and powered air supply unit (Sundström Safety, n.d.).

Design Challenges and Considerations for Respiratory Protective Equipment

The Despite the widespread use, respiratory protective devices face persistent issues with comfort, usability, and user compliance, particularly in occupational and healthcare settings. Research shows that **discomfort—driven by factors such as heat, humidity, and breathing resistance—is a major barrier to effective use across various types of devices and user populations** (Al Naam et al., 2021; Cheok et al., 2021; Liu et al., 2020). Users frequently report **dermatological irritation**, sizing problems, and physiological strain, including shortness of breath, elevated heart rate, and even psychological symptoms like anxiety and claustrophobia (Riden et al., 2020; Wu et al., 2011). These issues are exacerbated under physically demanding conditions or in warm environments, reducing the likelihood of consistent and correct use.

Furthermore, **while surgical masks are commonly used, they lack NIOSH certification and do not meet OSHA standards for airborne hazard protection—especially for pathogens** like tuberculosis. However, NIOSH's test protocols, such as flow rates of 85 L/min, are based on occupational standards and may not reflect the actual conditions faced by the general public, whose resting inhalation rates are significantly lower. This mismatch raises questions about the

applicability of standard testing methods and underscores the need for adaptable evaluation criteria. Other concerns include proper donning and doffing, maintenance and reuse, and the impact of user beliefs, risk perception, and cultural attitudes on compliance.

A recent systematic review found that 88% of studies reported a significant impact of PPE fit on occupational performance. Poor fit was linked to reduced mobility, endurance, and pulmonary function, as well as slower reaction times and muscle strain. Despite these findings, research in this area is limited and often methodologically weak. The authors call for future studies to consider sex, equipment integration, and all aspects of fit—static, dynamic, and cognitive—to better inform PPE design(Brisbine et al., 2022).

Effective design must address both physical and psychological dimensions of use while also considering variations in risk environments, user demographics, and regulatory requirements. Future respiratory protection should therefore prioritize ergonomic fit, breathability, thermal comfort, simplified user interaction, and flexible performance metrics to ensure broader usability and compliance across diverse settings:

Effective respiratory protective equipment must address both functional performance and user experience to ensure safety, usability, and widespread adoption. **Minimizing breathing resistance and reducing heat and humidity buildup are critical,** as these factors significantly impact wearer comfort and are recognized barriers to sustained use. **To minimize physical discomfort, equipment should prevent facial pressure, skin irritation, and fit-related issues by incorporating adaptable sizing and ergonomic construction.** Psychological comfort is equally essential; **features that alleviate feelings of claustrophobia, anxiety, or social**

stigma can substantially improve user compliance. Ease of use remains a priority, with intuitive donning and doffing mechanisms necessary to support correct and hygienic application, particularly in occupational settings.

In addition to usability, filtration efficiency must meet or exceed standards such as NIOSH's N95 rating, while accounting for real-world variables such as varying breathing rates and environmental conditions. For reusable equipment, the design should facilitate easy cleaning, disinfection, and storage without degrading performance.

Beyond technical specifications, cultural perceptions, risk awareness, and trust in protective technologies strongly influence adoption rates. Thus, designs should be visually acceptable and psychologically reassuring. Finally, respiratory protective equipment should be adaptable across occupational and public health contexts, anticipating regulatory expectations and behavioral responses, particularly in scenarios of prolonged or repeated exposure.

Literature Review Takeaways

The literature review reveals a clear tension between the proven efficacy of current respiratory protective equipment (RPE) and the significant barriers to its real-world use. While devices like Powered Air-Purifying Respirators (PAPRs) offer robust protection, their adoption and consistent use are compromised by a range of human factors. The review highlights a critical need to shift the design focus from just technical specifications to a more holistic, user-centered approach.

Key insights from the documents include:

The Problem of User Discomfort

The review repeatedly emphasizes that traditional RPE is poorly tolerated due to physical and psychological discomfort. Specific issues cited include heat buildup, restricted mobility, physical strain from weight (e.g., the Dyson Zone is noted as being ~650g), and psychological distress like claustrophobia, anxiety, and social stigma.

A Lack of Focus on Behavioral Barriers

A major knowledge gap identified is the lack of research into socio-cultural factors that influence user compliance. While studies acknowledge issues like stigma, worker autonomy, and cultural attitudes, there is a significant need for this understanding to be translated into practical strategies for long-term behavioral change.

The Promise of User-Centered Design and Alternative Technologies: The review presents several emerging technologies as potential solutions to these problems:

Wearable Air Curtains

An example of aircurtan by Taza Aya, is proposed as a way to maintain face-to-face communication and reduce the muffled speech and visual obstruction caused by masks, thereby addressing behavioral and social barriers to adoption.

Smart and Integrated Systems

Devices like the CleanSpace CST ULTRA demonstrate the value of incorporating smart technology to improve user experience. Features like real-time feedback via apps (e.g., filter saturation and battery level) are seen as crucial for encouraging consistent use.

Customization and Ergonomics

The Dyson Zone headphone and the Sundström SR 575 helmet are examples of attempts to improve ergonomics and comfort. However, the review notes that some of these designs can still be bulky or have a "backflow of polluted air near the mouth," indicating there are still design challenges to overcome.

In conclusion, the literature makes it clear that a shift is needed from traditional, one-size-fits-all RPE to more advanced, user-centric designs. The next generation of respiratory protection must be comfortable, intuitive, and address the human and psychological factors that currently prevent sustained, real-world use.

Aim

Building on literature research, this study explores the gap between conventional PPE design and how users interact with protective equipment in real-world contexts. The overarching goal is to improve behavioral adherence to PPE usage among workers in high-risk occupations by identifying the psychological, contextual, and design-related factors that influence sustained use.

Rather than focusing solely on compliance rates, the research aims to uncover the motivations, emotional responses, and situational barriers that shape daily PPE behavior. It evaluates practical and experiential challenges, considers how behavioral models can inform product development, and identifies design opportunities that support long-term behavior change. Ultimately, the objective is to enable more intuitive, acceptable, and habitual use of PPE through better integration of user experience, workplace culture, and individual agency.

Research Questions

Building on the research aim, the main question is:

How can electric-powered respirators be designed to improve usability and drive behavioral adherence in high-exposure work environments?

Focus on Desirability

To break down the main question, the following sub-questions are considered during the preliminary research:

User Experience and Perceptions

- How do workers perceive air quality and health risks in their work environments? How does this perception shape their motivation to use (or avoid) protective equipment?
- What is the current user experience with electric-powered or air-assisted respiratory PPE? Which design features support use, and what causes discomfort, rejection, or misuse?
- What design strategies (e.g., comfort, aesthetics, usability, feedback, integration into routines) can improve the desirability and adoption of protective gear?

Long-term Behavioral and Organizational Practices

- How consistently do professionals use PPE in practice? What are the key behavioral, contextual, or ergonomic barriers to adherence?
- How can PPE design support not only individual adoption but also organizational routines, training practices, and longer-term behavior change?

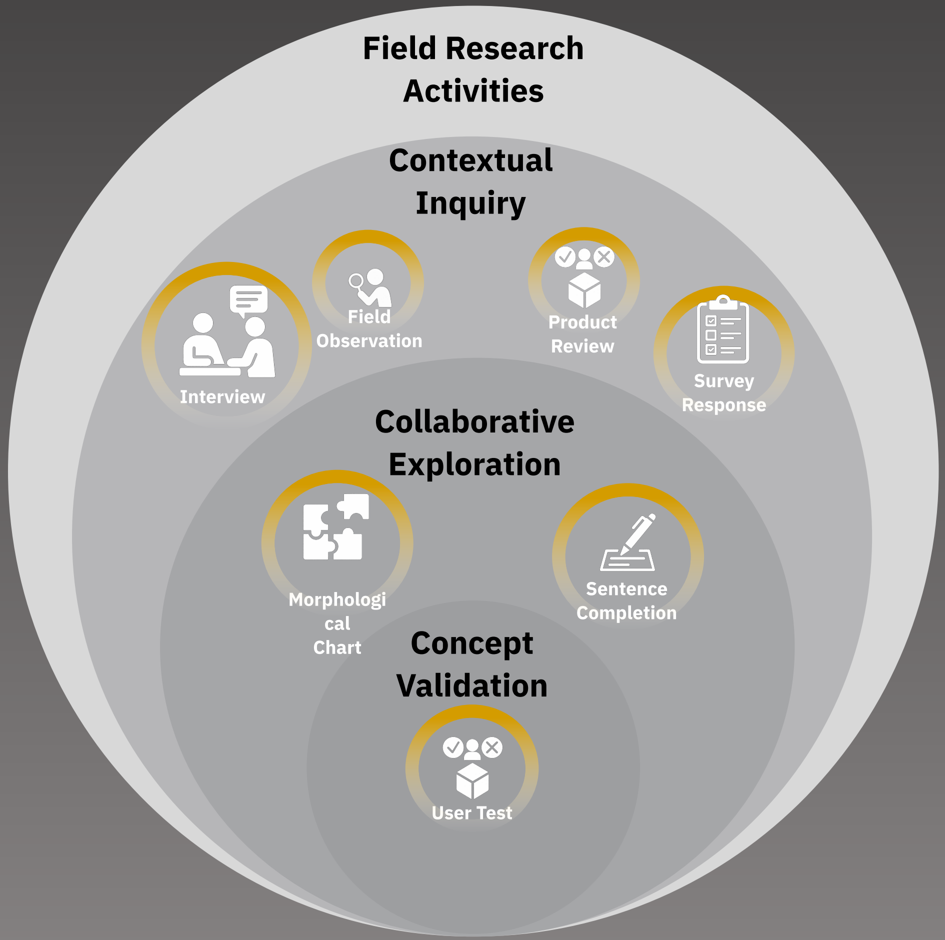


Figure 8. Overview of Desirability Research Methods and Activities

Field Research Activties

To inform the early design process and validate emerging concepts, a mixed-methods user research approach was employed. The research was deliberately broad and iterative, aiming to avoid narrowing the scope prematurely. All data—including annotated materials, environmental photos, and audio notes—was archived in both analog and digital formats for traceability.
Methodological choices were shaped by site access, participant availability, and real-world constraints. Rather than following a rigid protocol, the activities conducted varied depending on the participants, their job roles, locations, and availability. The next section provides an overview of participant recruitment.

Research activities were divided into three categories : Contextual Inquiry, Collaborative Exploration, and Concept Validation. Each phase was designed to engage users at different stages of the design cycle and uncover diverse dimensions of product experience.

1. Contextual Inquiry
   - Field Observation
     Observations took place across three job sites, including one industrial chemical plant and two non-industrial painting sites. Guided walk-throughs by staff covered equipment storage, work zones, and training facilities. The site visits (approx. 20–30 minutes each) allowed the researcher to document painter workflows, safety procedures, and PPE routines through notes and photographs (see page 20-22).

   - Interview
     Semi-structured interviews were conducted on-site with three participants: a senior industrial painter, an HSEQ officer, and a junior residential painter. These conversations explored daily routines, pain points with current PPE, and behavioral drivers related to mask usage. Sessions were audio-recorded and later transcribed for analysis.

   - Supplementary Quantitative Input : Survey Response
     A complementary online survey was distributed to professionals in various painting-related roles across different exposure environments. It aimed to broaden understanding of market perceptions, explore behavioral patterns, and triangulate findings from qualitative sessions. Results are discussed in relation to the identified themes from interviews and co-creation activities (see Appendix B-F).

2. Collaborative Exploration
Morphological Chart
A co-design session was held with four painters who collaborated in completing a morphological chart. This session enabled participants to discuss trade-offs, express preferences, and suggest improvements on various design elements (e.g., form factor, airflow direction, materials). The structured chart served both as a creative ideation tool and a validation mechanism for emerging concepts (see page 21–24).

Sentence Completion
Participants responded to sentence prompts (e.g., “Wearing a mask makes me feel…”) using sensitizing booklets. This method aimed to elicit emotional and psychological responses to current protective gear. However, reflection was found to be more effectively stimulated through direct interaction with visual materials and product cards rather than through abstract writing prompts.

3. Concept Validation

User Test
After initial ideation, participants reviewed and tested a low-fidelity prototype. The product was evaluated in terms of comfort, wearability, fit, and usability. Feedback helped refine key design aspects such as filter access, airflow coverage, and ergonomic fit (see page 115–117 for detailed feedback visuals and iterations).

Particpants Recuitment

Twelve participants were recruited through SUSAG, encompassing industrial workers and HSEQ officers from Bilfinger at duty at Shell’s Chemical Plant, as well as painters specializing in commercial, community, and residential buildings through Kloet. The participants are detailed in Figure 9. Selection criteria included individuals within the working age range of 18 to 65, aligning with regulations stipulating that workers handling hazardous substances must be above 17 years old (Netherlands Enterprise Agency, n.d.)and reflecting the average retirement age in the Netherlands(Cbs, 2023).

Additionally, the online survey expanded the participant pool to professionals from diverse fields, facilitating the collection of broader insights and the exploration of potential market opportunities for the product.

The following tools are designed to capture comprehensive data for thorough analysis at later stages:

Participant Number	Age	Current Job Tittle	Recent Work Environment
Participant 1	57	All-round Painter	Community Buildings
Participant 2	28	HSEQ Officer	Chemical Plants
Participant 3	24	All-round Painter	Historical Building
Participant 4	53	All-round Painter	Community Buildings
Participant 5	60	Painting Company Owner	Community Buildings
Participant 6	49	All-round Painter	Community Buildings

▲Figure 9. List of participants

Research Materials

Multimedia Documentation Tools

- iPhone 14 Pro Max: Used for capturing high-quality audio, video, and photographs to document participant interactions and site visits comprehensively.

Note-Taking Tools

- Physical Notebooks: Traditional notebooks for jotting down observations and insights during activities.
- iPad and Digital Note-Taking Apps: Tools for efficient and organized digital note-taking.

Survey and Feedback Tools

- Printed Interview Questions: Used to ensure a structured approach during interviews and observations.
- Anonymous Online Survey Platforms: Platforms like Google Forms were utilized for broad participant data collection and to capture participant reviews and opinions on existing products and conceptual designs.

Sensitizing and Co-Creation Tools

- Sensitizing Booklets: Custom-designed physical or digital booklets to encourage participants to reflect on their experiences and perceptions.
- Morphological Charts: Templates that provided structure for brainstorming and co-creation sessions.
- Collaborative Tools: Whiteboards, sticky notes, and markers of various colors were used to support participant visualization and collaboration.

AI Tools

- Adobe: Adobe transcribes the recording.
- ChatGPT 4.0 : ChatGPT is used to translate the Dutch Audio into English.

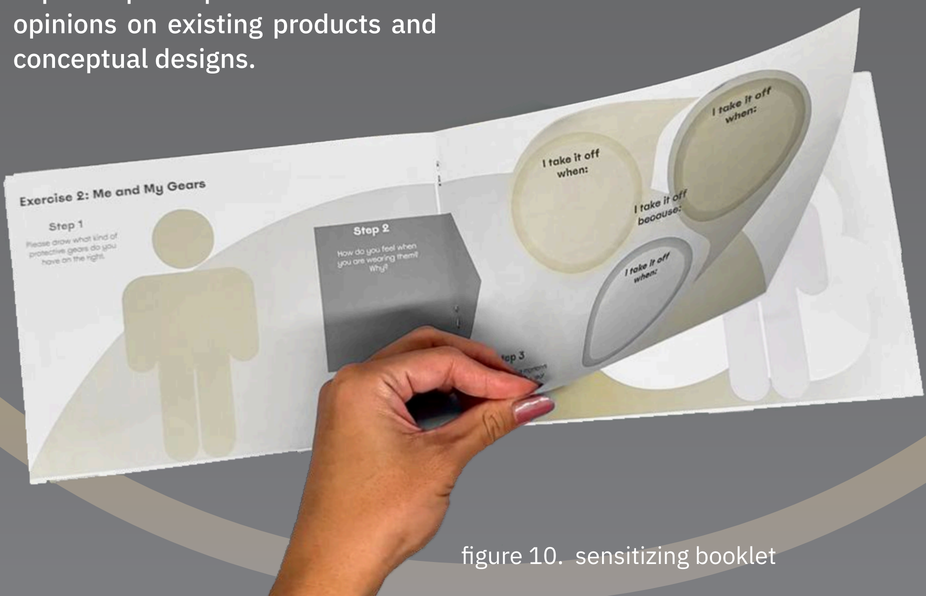


figure 10. sensitizing booklet

figure 11. sensitizing booklet

Data Collection and Processing

The data collection strategy was intentionally open-ended and non-presumptive. Audio recordings of the sessions were transcribed for further analysis. Additionally, participants interacted with printed cards showcasing existing products, which facilitated discussion and comparison.
A morphological chart was co-created during these sessions to map potential design directions collaboratively.
The subsequent section outlines how the collected data informed and inspired the idealization process.
All information was anonymized, and recordings were deleted upon completion of this report.

Activities and Participant Involvement

To gain diverse insights, participants were involved in different activities throughout the different phases of the research process. As a result, the collected data reflects a broad and exploratory scope. Given the limited sample size, the emphasis is placed on qualitative analysis rather than statistical accuracy.

Prior to the idealization stage, a series of user research sessions were conducted with three intended users of the product: an experienced painter, a health and safety officer, and a younger, less experienced painter. These participants were selected to represent a range of perspectives within the target user group. The following section gives an overview of the sessions.

figure 12. The painters reviewing cards of electric powered respirators on the market or innovative respirator under development.

Session 1: Exploratory Interview with Late-Career Painter

Setting	Demographic Information	Duration	Activities
Outside a school building where painters are working, interviews are conducted during their break.	Painters with Decades of Expertise	1 hour	Interviewing with a sensitizing booklet as guide, Observing outdoor painting, Visiting mobile workstations, Gathering product feedback for existing products

New table

▲Figure 13. nterview takes place inside of the worker's mobile work station.

▲Figure 14. The exterior of the worker's mobile work station.

▲Figure 15. The worker is demonstrating their outdoor painting workflo

Late Career Painters in Residential Settings

Understanding Non-Industrial Painters' Perspectives on Air Quality and PPE

This first exploratory interview focused on a late-career residential painter, aiming to understand real-world behavior and attitudes toward PPE in low-regulation environments. Unlike industrial settings, residential worksites often lack enforcement, making user mindset and habit key to adoption.
The painter demonstrated strong attachment to traditional methods and showed clear resistance to change—especially regarding protective equipment. His responses reflected a habitual dismissal of newer PPE, rooted in long-standing routines rather than lack of knowledge. A important insight from this session was that raising awareness of air quality risks would have little to no effect on behavior. Despite understanding the dangers, the painter did not see them as relevant or urgent. **This interview session shifted the research direction: rather than focusing on educational strategies, it became clear that reviewing existing PPE and improving its practical fit and usability would be a more impactful path forward.**
These findings align with earlier research by Muzus (insert citation), which also noted low PPE adherence among experienced professionals.

Session 2: Safety Expert Interview in Industrial Setting

Setting	Demographic Information	Duration	Activities
Chemical Plant	Young HSEQ Officer	3 Hours	Visiting industrial job sites and learning painter safety protocols at the safety center, conducting interviews, creating morphological charts, and reviewing proposed product designs.

▲ Figure 16. interview takes place at shell chemical plant

▲Figure 17. Safety centre

▲Figure 18. The worker is demonstrating their outdoor painting workflow.

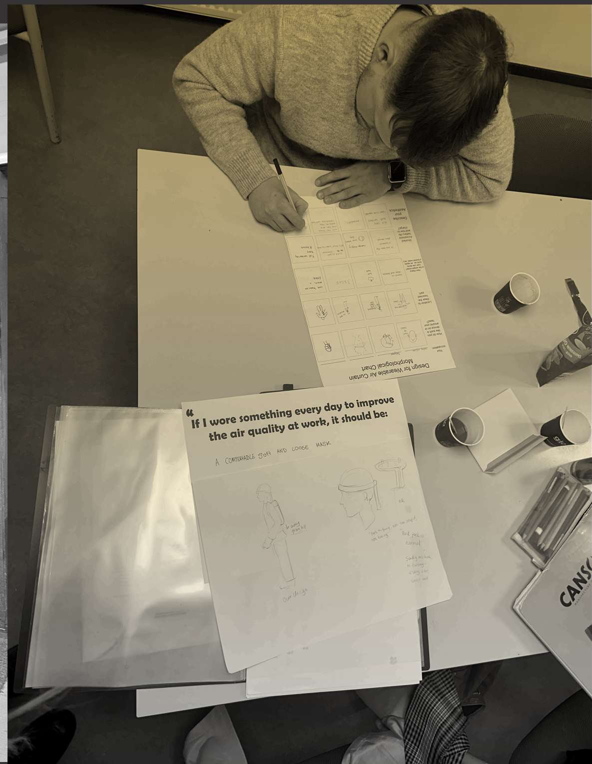
Insight from **The Expert of Safety:**

Experiencing PPE regulations in Industrial Site

Insights were gathered in this field research from an industrial safety officer responsible for overseeing PPE implementation at a high-risk site. Conducted at a chemical plant. The session involved a guided visit to the painting operations area, a walk-through of the safety center, and an interview with a young HSEQ (Health, Safety, Environment, and Quality) officer. The officer explained how PPE is regulated, monitored, and perceived within a highly standardized industrial environment. The session provided detailed exposure to standard safety practices and enforcement protocols, risk mitigation strategies, and training procedures used to ensure compliance. Discussions included reflections on worker attitudes toward PPE, challenges in enforcing consistent use, and feedback on existing and proposed product designs. In addition, the session involved co-designing a morphological chart of design options and gathering expert feedback on usability, certification, and integration feasibility. This visit offered contrast to community-based fieldwork and revealed how structured environments impact PPE acceptance and behavior.

Session 3: Co-Creation with Young Painters in Workshop	Setting	Demographic Information	Duration	Activities
	In the Paintshop	Young Painters with Experience	1.5 hour	Interviewing with a sensitizing booklet as guide, Gathering product feedback for existing products, reviewing designs, Co-creation through Morphological Chart

▲ Figure 19. Painters also work for glass installations in most of the cases.



▲ Figure 20. Co-design Session

▲Figure 21. Paint storage

Insight from **Young Painter in Residential Setting:**

Understanding Non-Industrial Painters' Perspectives on Air Quality and PPE

This session took place inside a paintshop and involved young painters with hands-on experience in both painting and glass installation. Using a sensitizing booklet as a guide, the session combined semi-structured interviews with interactive design activities to explore their views on existing PPE and desired improvements.
The conversation focused on practical challenges during painting tasks, such as discomfort, interference with precision work, and limited airflow. Participants reviewed current PPE solutions and discussed perceived barriers to consistent use. A morphological chart was used to co-create and evaluate new design directions based on real work scenarios.
By engaging painters who are early in their careers, this session offered valuable insights into emerging attitudes, task-specific needs, and user-driven ideas—reinforcing the importance of ergonomics, flexibility, and intuitive use in future protective solutions.

2.3 Result From Guided Conversations Using Sensitizing Booklets

This activity involved open-ended conversations guided by a sensitizing booklet (see Appendix X for all booklet pages). The flow of discussion followed the booklet prompts, which were designed to elicit painters' reflections on their experiences with air quality, protective gear, and daily work routines.

Participants' comments were transcribed, and selected quotes were extracted afterward for analysis. These quotes were not only reflective of users' needs but also served as sources of design inspiration in later phases of the project.

“ Yes, **if it's absolutely necessary, then I'll wear it, of course. The only downside, not just for me, is that your glasses fog up. That's the only issue.** That's the downside of wearing a mask. It's really true. Your glasses fog up. It's really annoying. And at some point, if you... Look, a dust mask doesn't do that. You have those regular dust masks, the M3 masks. Those are just for dust and solid particles, yeah, fine dust.But if it'snot for fumes... **Then you often wear a filter mask. But that also gets wet inside because of the condensation from your breath. And that's so gross.** And then your glasses fog up as well. I don't like that at all. And it's obviously heavier. Well, not necessarily heavier, but I always compare it to a firefighter wearing a full mask with oxygen tanks and everything during a big operation. They train for that, and it's apparently really exhausting in terms of walking and breathing. They really have to train for that. ”

-Quotes from an older painter working in a residential setting expressed that moisture was particularly unpleasant.

“ **they don't want to wear the full face mask for example because it's really hot inside and they are sweating** it's not really comfortable they have to wear the helmet above it so it's really conflicting all kinds of those things so you can you understand more why they don't want to wear it. **And then for me, for example, is the challenge to find a good alternative. What they say about example that it's more comfortable because you get a little bit of fresh air stream inside of your head and overall it's just more, it's not really annoying like it's on your face** but it's less annoying than if you have the **full face mask on with the filters it's really harder to breathe so if you do physically hard labor** for example if it's **30 40 degrees inside of the workplace and sometimes it really is even more yeah then it's already hot sweating it's hard to breathe already** then you have to everything go through the mask yeah it's just annoying so that's why we try to look at the other ”

-Quote by a safety officer, despite being responsible for enforcing PPE policies, expressed empathy for painters who avoid wearing masks due to heat and difficulty breathing during physically demanding tasks.

“ My colleagues, **if they are sanding, they put on masks. But that is only for the inside...** I do want to say that for carpenters and woodworkers, they don't have much paint. **Our place is full of paint. We need to replace it from time to time,** so it is good for it not to be so expensive. **It needs to be tight,** because you need to put it on the... If you need to charge it every day, **it is good to charge overnight.** Then you can use it in the morning, then you can use it all day. Depends... I don't mind changing the battery during a work shift. We have a sanding machine; we have one with a battery and cable, another one with a battery every two hours. Because it is small... **It needs to look nice, but not fancy. Sometimes new stuff looks like you are going to Mars— not too basic, but not too fancy, and not too stupid.** ”

-Quote by a young, fluent-English-speaking painter who regularly wears PPE expressed clear expectations for improved comfort and usability in future designs.

It is required. I do not wear it. It is just annoying. Niet geinteresseerd.A warning? No, not really. but I smoke. Yeah. Right?

“ **When I walk in the city too, I think, yeah, I might as well smoke because of all the fumes.** Do you get what I mean? Look, I live in a small village, in the countryside, but... I mean, we’ve got cow manure here, but yeah, there’s always going to be something. The air we breathe is naturally just... Here in the **Randstad, the industry isn’t great either, but because you live and work here, you don’t notice it. Only when I go to the Ardennes in the summer and then come back, driving into the village, I think, wow, what an air here, you get so used to it.** Do you see what I mean? ”

-Quote by an older painter noted he only noticed poor air quality when leaving the city, suggesting that integrating comfort-based sensory cues could enhance awareness and promote PPE adoption.

Insights from Interview and Observations

Air Quality Awareness

Painters generally do not express concern about air quality or assume it to be poor, especially in residential settings. However, across all interviews, heat and humidity of the air emerged as a major concern, affecting not only personal comfort and productivity, but also the quality of paint application. Thermal discomfort may serve as a stronger motivation for PPE adoption than airborne risks alone.

While industrial users value air quality monitoring and view it as integral to safety protocols, residential painters showed little interest. This contrast is also evident in survey responses: participants from healthcare and chemical industries rated air quality awareness as highly important, while painters did not prioritize it.

Context Focus

These findings reinforce the need to differentiate design approaches. Industrial users already operate within strict safety frameworks, whereas residential painters may require more intuitive, comfort-driven solutions to encourage use. Thus, future development will focus on residential settings, where behavioral adoption remains a larger barrier.

Sensory Feedback & PPE Habits

Smell was mentioned across both settings: in industrial environments, being able to smell chemical hazards is seen as important for situational awareness. This indicates a design challenge—how to filter air effectively without completely blocking sensory cues.

Painters frequently remove PPE to talk to people, take breaks, or relieve discomfort, especially when the device is too heavy or hot. Both safety officers and older painters emphasized the importance of setting a good example, while younger painters tended to follow PPE protocols more consistently and showed greater openness to new solutions.

Physical Discomfort as a Barrier

Importantly, resistance to PPE use was not mainly rooted in psychological or cultural stigma, but rather in pure physical discomfort. This confirms that enhancing we arability, breath ability, and thermal comfort is likely the most direct path to improved adherence.

Appearance

Participants consistently stated that PPE should look professional, not flashy. Designs that appear too futuristic or attention-grabbing may discourage use, especially in residential settings. One participant even described some advanced designs as looking like “you’re going to Mars”—highlighting a desire for functional yet understated aesthetics.

Wishes of Painters in Residential Context

Painters working in residential environments emphasized the need for:

- Reduced weight
- Improved breathability
- Moisture and heat management
- Minimized bulk and entanglement risk, particularly important for working on scaffolding or in confined areas
- Freedom of movement should be ensured.

The points above were most frequently mentioned. More specific wishes were translated into actionable design requirements (see pages 33-34).

Summary Takeaways

- Thermal comfort, not air quality, is the more immediate driver for PPE adoption among painters.
- Residential and industrial settings differ significantly in needs and behavioral patterns; future development should target the residential context.
- Smell awareness and entanglement risks must be considered in design.
- Discomfort is the primary reason for resistance, offering a clear opportunity to improve adoption through sensory and ergonomic enhancements.
- Aesthetic expectations favor practical, low-profile designs over flashy or unfamiliar appearances.
- Final product requirements should focus on physical ease, subtle design, and comfort across long work shifts.

The use of the sensitizing booklet revealed certain limitations. Language barriers and the abstract nature of several prompts made it less effective in eliciting clear or actionable responses. While the transcribed quotes offer interpretive value and can inform later analysis, this method proved less effective compared to co-design sessions and product review activities. The following section presents users’ evaluations of existing respiratory protection designs.

Product Reviews and Survey Responses

During the first three sessions of context inquiry activities, painters were asked to review a set of electric-powered respiratory protection products. This method proved to be more effective in capturing clear user reactions, as their preferences, wishes, and criticisms emerged quickly and directly.

Alongside the reviews, participants filled out a short survey to provide structured input (see Appendix.J for survey results). This survey included questions about product appeal, usability, and likelihood of use, helping to validate and expand upon the qualitative feedback. The following list summarizes key likes and dislikes gathered from this session, offering actionable insights for future product development.

Main Takeaway

Painters responded positively to products that appear professional and industrial, suggesting that visual cues of reliability and workplace legitimacy play an important role in acceptance.

There is openness to innovative designs, especially if they offer functional benefits and physical comfort, such as improved breathing or cooling effects.

Professionals across all fields expressed reluctance to wear products that look too attention-grabbing or futuristic, indicating the importance of visual subtlety and social acceptability in product adoption.

The shape of a face mask alone does not offer an advantage, even when the product is electrically powered. Painters noted that they already use several powered respirators and still find it difficult to breathe during high-intensity tasks. This highlights the need to prioritize breathing comfort and airflow design, especially for labor-intensive work.

Preferences varied across professional backgrounds, suggesting that PPE solutions may need to be context-specific and adaptable to different work environments, task types, and user habits.

This product is the LG PuriCare™ Wearable Air Purifier (2nd Gen.). According to survey responses across various professions, it was perceived as protective and innovative, yet also described as uncomfortable. Among painters interviewed,one remarked that it strongly evokes memories of the COVID-19 pandemic, other two described it as uncomfortable (see Appendix E for the user feedback).

This product is the CleanSpace HALO. According to survey responses across various professions, it was perceived as professional and cool, yet also described as uncomfortable. Among the painters interviewed, it was seen as professional and reliable, but considered “overkill” for typical sanding tasks (see Appendix E. for the user feedback).

This product is Aō Air – Atmos Faceware.
According to survey responses across various professions, it was perceived as cool but also doubtful and confusing, with some noting it was hard to evaluate from the image alone. Among painters, it was viewed as professional and protective (see Appendix E for the user feedback).

This product is the CleanSpace Respirator: EX (Intrinsically Safe). According to survey responses across various professions, it was perceived as protective and innovative, but also described as uncomfortable. Among the painters interviewed, the product was seen as effective and professional (see Appendix E for the user feedback).

This product is the air curtain by Taza Aya.
According to survey responses across various professions, it was perceived as cool, though some expressed doubts. Among the painters interviewed, all three responded positively and considered it ideal for their tasks (see Appendix E for the user feedback).

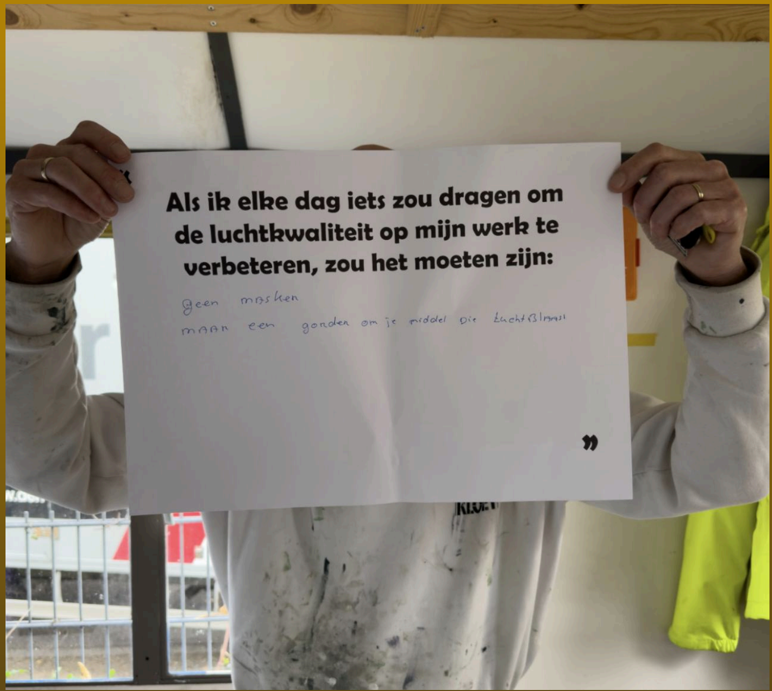
This product is the Dyson Zone Absolute+ Air-Purifying Wireless Over-Ear Headphones. According to survey responses across various professions, it was perceived as skeptical, doubtful, absurd, awkward, or was directly disliked. Among the painters interviewed, all expressed that they found it strange and would not wear it (see Appendix E for the user feedback).

Product Images from products’ official pages

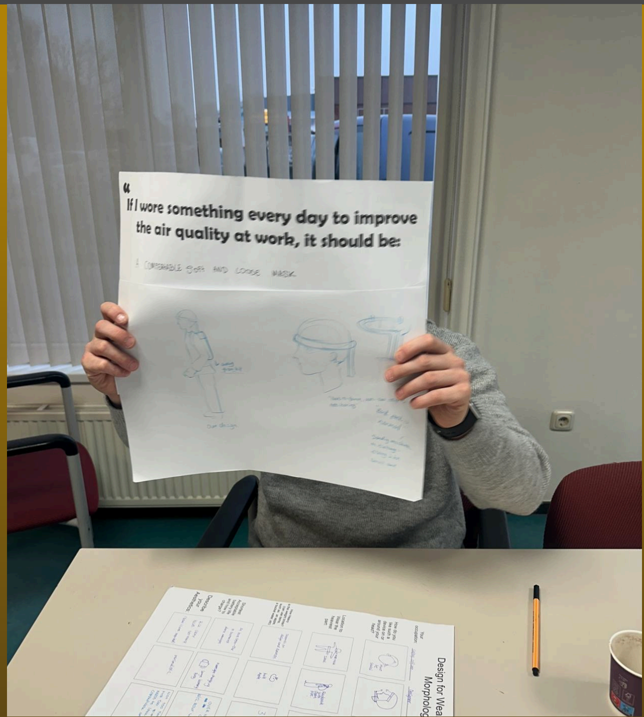
Sentence Completion Activity: Eliciting User Expectations for Wearable Air Quality Solutions

To conclude the co-design sessions, a sentence completion activity was conducted to encourage participants to reflect on their preferences regarding daily wearable solutions for air quality improvement. Participants were asked to complete the sentence: "If I wore something every day to improve the air quality at work, it should be..." This prompt was provided both in Dutch and English to allow participants to respond in the language they felt most comfortable with.The activity was printed on A3 sheets and completed using markers, fostering a casual and expressive environment for sharing thoughts.

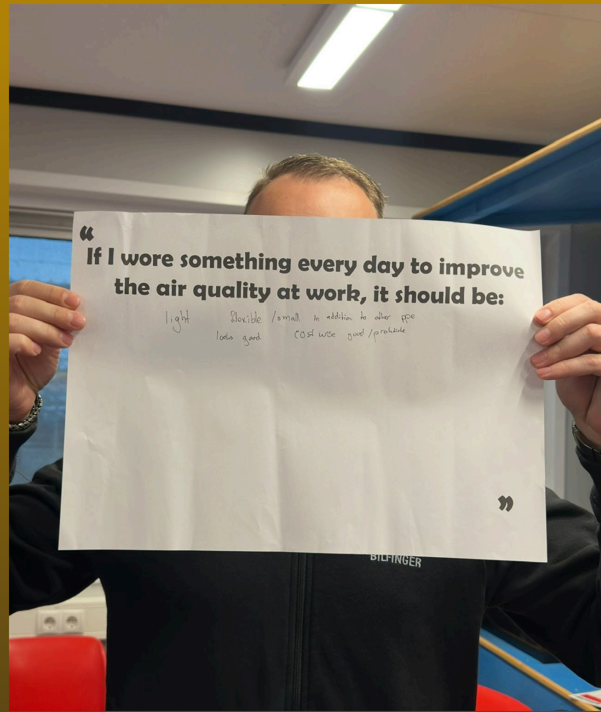
The goal of this exercise was to capture intuitive, user-centered requirements that may not emerge during structured interviews or discussions. This method helped surface qualitative insights related to the wishes of primary users.



Participant 1 Response (Dutch): "Als ik elke dag iets zou dragen om de luchtkwaliteit op mijn werk te verbeteren, zou het moeten zijn: geen masker, maar een gordel om je middel om lucht af te blazen." (Translation: "If I wore something every day to improve the air quality at work, it should be: no mask, but a belt around the waist to blow air.")



Participant 2 Response (English, with sketch): "If I wore something every day to improve the air quality at work, it should be: a comfortable and loose mask."



Participant 3 Response (English): "If I wore something every day to improve the air quality at work, it should be: flexible/ small in addition to other PPE, and look good, cost wise good and practical.

Analysis and Relevance

These responses demonstrate a shared desire for wearable solutions that are comfortable, discreet, and socially acceptable. There is a clear rejection of conventional face masks, with participants favoring alternatives such as waist-mounted systems or garments with integrated airflow. Other key criteria that emerged include lightness, l flexibility, and professional aesthetics. These qualitative insights played a significant role in informing the design requirements for the air curtain prototype.

2.4 Synthesis and Evaluation of the Field Research

Main research question: “How can the design of electric-powered respiratory protective equipment improve user experience, promote consistent use, and encourage sustainable behavioral change among professionals in high-exposure industries, considering their perceptions of air quality, health impacts, and barriers to adoption?”

Preliminary Insight:
Improving user experience with respiratory PPE requires prioritizing comfort, ease of use, and visual alignment with the wearer’s professional identity. Both painters in the study expressed a clear aversion to face-covering equipment and preferred wearable alternatives that are lightweight, breathable, and easy to carry—such as belt-mounted or backpack for heavy battery (if heavy battery is required) . Recurring key words and themes emerging from the field research and interviews included aesthetic acceptability, physical comfort, and unobtrusiveness.

While long-term behavioral change was not directly assessed, the findings suggest that PPE perceived as socially acceptable (i.e., not "looking strange") and easily integrated into daily routines (e.g., convenient to charge) is more likely to be used consistently. Organizational factors such as training and enforcement were acknowledged, particularly by the health and safety officer. Noticeably, contrast to the assumption that the lack of awareness of air quality might be the reason of inconsistent use of PPE, user research found that air quality itself did not appear to be a strong motivator for PPE use among painters. The safety officer at chemical plant expressed concern for air quality and used monitoring equipment, but residential painters showed little to no curiosity about environmental measurements. Instead, sensory cues—especially the smell of chemicals—were a more immediate trigger for PPE usage. As a result, the design focus has shifted away from integrating air quality monitoring and toward developing solutions that respond to practical, embodied cues and daily usability.

Sub-question 1
How do workers perceive air quality and health risks in their work environments? How does this perception shape their motivation to use (or avoid) protective equipment?
Insight:
Workers’ awareness of air quality varied across roles and environments. The online survey, distributed to professionals from different fields, suggests that concern about air quality is often career-dependent. 3 out of 5 respondents indicated that they were concerned about air quality; however, painters working in residential settings appeared largely indifferent. Some participants expressed concern about long-term exposure, whereas others only took protective action when symptoms were immediate or when hazards were visibly or sensoriall apparent (e.g., dust, strong chemical smells). Motivation to use PPE was therefore closely linked to personal experience and direct environmental cues. While the research revealed meaningful patterns, a broader and more diverse sample—along with contextual field studies—would be needed to generalize findings and design targeted interventions.

Sub-question 2
What is the current user experience with electric-powered or air-assisted respiratory PPE? Which design features support use, and what causes discomfort, rejection, or misuse?
Insight:
The preliminary insight for this question is well supported by the findings of this research. Insights were drawn from the literature review, an online survey (see Appendix E), a review of existing products, and participants’ open-ended descriptions during the user research sessions. Participants consistently described traditional respiratory PPE as physically uncomfortable and socially undesirable. Key complaints included heat buildup, moisture accumulation, facial obstruction, and interference with communication. In contrast, the painters expressed strong interest in alternative design features, particularly equipment that is lightweight and avoids covering the face entirely.

Sub-question 3
What design strategies (e.g., comfort, aesthetics, usability, feedback, integration into routines) can improve the desirability and adoption of protective gear?

Insight:
This question is well addressed. The co-design process produced clear, user-driven design strategies for the future development of the product. Participants emphasized that protective gear should be lightweight, discreet, and visually neutral—avoiding a "futuristic" or overly technical appearance. Preferred wearable formats included vests, backpacks, and belts, as these are familiar and easy to integrate into existing routines. Users consistently highlighted that lightness and moisture-free breathing would offer significant advantages over traditional PPE. In terms of integration, compatibility with existing PPE systems is crucial. For instance, in chemical plant environments where goggles are mandatory, any new product must either incorporate goggles into its design or fit comfortably between goggles and helmets. It is important to consider that different helmets are used for different tasks, further reinforcing the need for adaptable, compatible designs.
Current PPE often presents fitting issues, which negatively affect both physical comfort and psychological acceptance, ultimately compromising the effectiveness of the equipment. Therefore, designing for a universal, non-personalized fit could offer a major advantage by ensuring ergonomic compatibility across a wide range of users and work settings.

Sub-question 4
How consistently do professionals use PPE in practice? What are the key behavioral, contextual, or ergonomic barriers to adherence?

Insight:
Users reported inconsistent PPE use, often avoiding it when it interfered with breathing or speaking. Although PPE was sometimes required, participants admitted to using it only when working with particularly toxic substances that caused immediate physical discomfort. This preliminary insight is well supported by qualitative feedback gathered during interviews and co-design sessions. However, further observational studies conducted during actual work shifts could provide deeper insights into behavioral patterns and context-specific barriers to consistent PPE use.

Sub-question 5
How can PPE design support not only individual adoption but also organizational routines, training practices, and longer-term behavioral change?

Insight:
This aspect was only partially explored in the current study. Future research should involve a broader range of stakeholders—including employers, procurement officers, and maintenance staff—to better understand organizational requirements and constraints. For instance, employers can provide insights into acceptable cost thresholds, while maintenance personnel can assess whether the product is realistically easy to clean and maintain over time.
This topic was briefly addressed during the interview with the health and safety officer, who emphasized that PPE must be intuitive and low-effort to encourage regular use. However, other organizational factors—such as training procedures, enforcement strategies, and workplace culture—were not examined in depth.
Another practical consideration highlighted was worker mobility. PPE is often retained by the employee, even when changing employers, which reinforces the need for a universal fit that does not require customization.
From the perspective of non-primary users (e.g., management and support staff), key purchasing factors include cost, ease of cleaning, replaceability, and long-term maintenance. While compliance, safety, and cost remain top priorities, the HSEQ officer noted that comfort can still play a decisive role in purchasing decisions if the product is significantly more wearable than current alternatives.

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Conclusion of Field Research

Through thematic analysis of the discussions, key problem areas were identified. This process also led to the formulation of design goal, design focus, and a preliminary list of user requirements and preferences (See page 33-34).

2.5 Design Goal

The following Design Goal was developed based on insights gathered from both the literature review and field research.

"harmful aerosols and particulates"

Covers a range of airborne threats—dust, fumes, and fine droplets—common in painting and construction.

Effectively Reduce

It must demonstrably reduce the amount of harmful airborne substances in the user's breathing zone by 80%-99%

"The Design Goal is to create an air curtain that effectively reduces workers' exposure to **harmful aerosols and Particulates** across various workplace environments, while seamlessly integrating into daily activities **without disrupting workflow or comfort.**"

"various workplaces"

The design should function across diverse environments—from residential sites to industrial spaces —with varying ventilation, space, and task setups.

"without disrupting workflow or comfort"

The product must fit naturally into routine tasks, allowing users to work as usual without disruption. The design should Emphasizes wearability and ease of use—it must be comfortable, lightweight, and not interfere with movement or breathing.

To translate this goal into actionable design directions, the key elements of the statement were broken down into specific contextual requirements in the next section.

2. 6 List of Requirements as Industrial grade PPE

1. **PERFORMANCE**
- 1.1 Air Quality and Filtration
  - Must ensure that only filtered air reaches the nozzle outlet, using filters meeting HEPA H13-equivalent standards (≥99.95% efficiency for ≥0.3 micron particles).
  - Filtration must remain effective under varying humidity and temperature without clogging.
  - System should allow for modular integration of different blower/filter types based on exposure type (dust, chemical, etc.).
  - Filters must be easy to access, replace, and maintain with minimal downtime.
- 1.2 Airflow Direction, Comfort, and Temperature
  - Nozzle must deliver stable, directional airflow to the breathing zone without blowing into eyes or skin.
  - Flow should not impair visibility or focus.
  - Air velocity must be effective enough to displace contaminants.
  - Airflow should maintain thermal comfort (not too warm or cold), including protection against cold drafts in winter conditions.
- 1.3 Noise Level
  - Maximum noise level should not exceed 65 dB in quiet settings and 70 dB in industrial environments.
  - Noise around the ear should remain comfortable over prolonged use.
- 1.4 Power and Efficiency
  - Minimum 2 hours runtime on full charge.
  - Swappable battery system recommended for continuous shift work.
  - Device must include low battery alerts and indicators.
- 1.5 Durability and Environmental Resistance
  - Device must withstand dust, moisture, and minor shock/vibration.
- 1.6 Safety Features
  - Auto shutoff in case of airflow blockage or overheating.
  - Alerts for battery, filter status, and system malfunction.
  - No flame hazard or entrapment risk from cables or hanging parts.

2. **USABILITY AND INTEGRATION**
- 2.1 Wearability and Comfort
  - Total worn system weight: ≤500g; head-mounted parts ≤200g.
  - Even weight distribution with minimal pressure points.
  - Adjustable for different users and work postures.

- 2.2 **Compatibility**
  - Must integrate with standard PPE (goggles, helmets, etc.)
  - Tubing and wires must not restrict movement or cause entanglement.
  - Design should avoid blind spots, maintain situational awareness.
- 2.3 **Donning, Doffing, and Intuitive Use**
  - Easy to put on and take off, with minimal setup time.
  - Operation should be intuitive for users with various skill levels.
- 2.4 Maintenance
  - Filters and components must be serviceable without tools.
  - Clear maintenance intervals; affordable upkeep.
- 3. CONTEXTUAL & ENVIRONMENTAL FIT
  - Adaptable to informal, mobile, and freelance work settings.
  - Must function indoors and outdoors for unpredictable situations, including exposure to mold, rot, and bioaerosols.
  - Compact and portable for transport and storage.

4. LIFESPAN AND STORAGE
- Designed for multi-year daily use in chemically and thermally varied environments.
- Should retain material integrity and function during long-term storage.

5. MATERIALS AND APPEARANCE
- Non-toxic, hypoallergenic materials for skin contact.
- Durable, recyclable, and environmentally responsible where possible.
- Professional, ergonomic, and discreet industrial design.

6. TESTING AND VALIDATION

- Subject to lab and real-world testing: aerosol blocking, wear trials, usability.
- Performance to be verified under industrial conditions.

7. REGULATORY COMPLIANCE

- Must comply with EU Regulation 2016/425 and applicable CE marking.
- Should align with EN 149 or EN 12941, depending on classification.
- If used with eyewear, must consider EN166 standards.
- ATEX compliance only if used in explosive settings.

8. PRODUCT STRATEGY AND FUTURE FIT

- Cost-effective over time: affordable filter replacement, low energy draw.
- Compatible with efficient manufacturing and scalable production.
- Packaging should protect the device and reflect tool-like familiarity.
- Must fit within employer PPE portfolios and client safety protocols.

9. USER ACCEPTANCE AND SOCIAL FACTORS

- Design should avoid stigma, encourage consistent use, and promote protective behavior.
- Product should be psychologically comfortable and blend into varied work cultures.
- Should raise awareness of long-term health risks and empower safer work habits.

10. LIABILITY AND SAFETY ASSURANCE

- Must define liability protocols in case of failure or malfunction.

Design Requirements as Evolving Guidelines

The design requirements were initially defined during the early phase of the project and continuously refined throughout the research process. As new insights emerged from literature, fieldwork, co-design sessions, and stakeholder input, the criteria evolved to better reflect actual user needs and workplace constraints.

The following section outlines the key design priorities that emerged from translating these requirements into actionable focus areas. It highlights how specific user needs—such as comfort, behavior, and maintainability—shaped the direction of concept development and guided early prototyping efforts.

Evaluation Priorities

With the core requirements in place, this section introduces the Evaluation Priorities —the key priorities that guide concept development and form the basis for evaluating potential design directions. These criteria reflect the specific demands of mobile, freelance, and small-team environments, where safety practices are often informal. To support consistent use in such contexts, the design emphasizes portability, intuitive operation, and low maintenance—ensuring accessibility for users with varied experience levels and unpredictable work conditions.

Targeted Airflow Control

The design prioritizes a precise and stable airflow to protect the breathing zone. Nozzle geometry and placement are optimized through iterative simulation and prototyping, ensuring effective contaminant shielding.

Wearability and Integration

The device is designed to be lightweight (under 500g on head), non-intrusive, and easy to wear over long periods. It integrates with existing PPE and clothing without interfering with movement or daily tasks. Proper fit is essential for PPE effectiveness. The device fit should be an open air curtain design, ensuring a universal fit that accommodates diverse users across gender, age, and facial features.

Design for Behavior change

The research focuses on understanding how users interact with respiratory protection and identifies behavioral barriers to consistent PPE usage, and the goal is to develop the product that painters would like to wear during the entire work-shift as a long term habit.

Maintenance and Modularity

The product focus on design with a modular system compatible with off-the-shelf blowers and filters. Components are simple to clean, replace, or upgrade —making the device cost-effective and suitable for long-term, real-world use.

The following section, Ideation, introduces how initial design ideas were generated in response to these evolving requirements. It also explains the rationale behind some of the key criteria, demonstrating how user insights directly informed the design direction.

3. IDEATION APPROACH

Section Overview

User Context : Air Curtain for Sanding Tasks in Residential Settings

This use case focuses on freelance and residential painters exposed to dust during sanding tasks. These tasks can generate fine particulate matter—including sanding dust and potentially other airborne contaminants—where protection equivalent to FFP1 or higher may be necessary. This research narrows the scope to residential settings, where regulations are less strictly enforced than in industrial environments, making user comfort and practicality especially important for PPE adoption.

This section outlines how user experience data was processed from user centric research. The insights were synthesized using the following two tools:

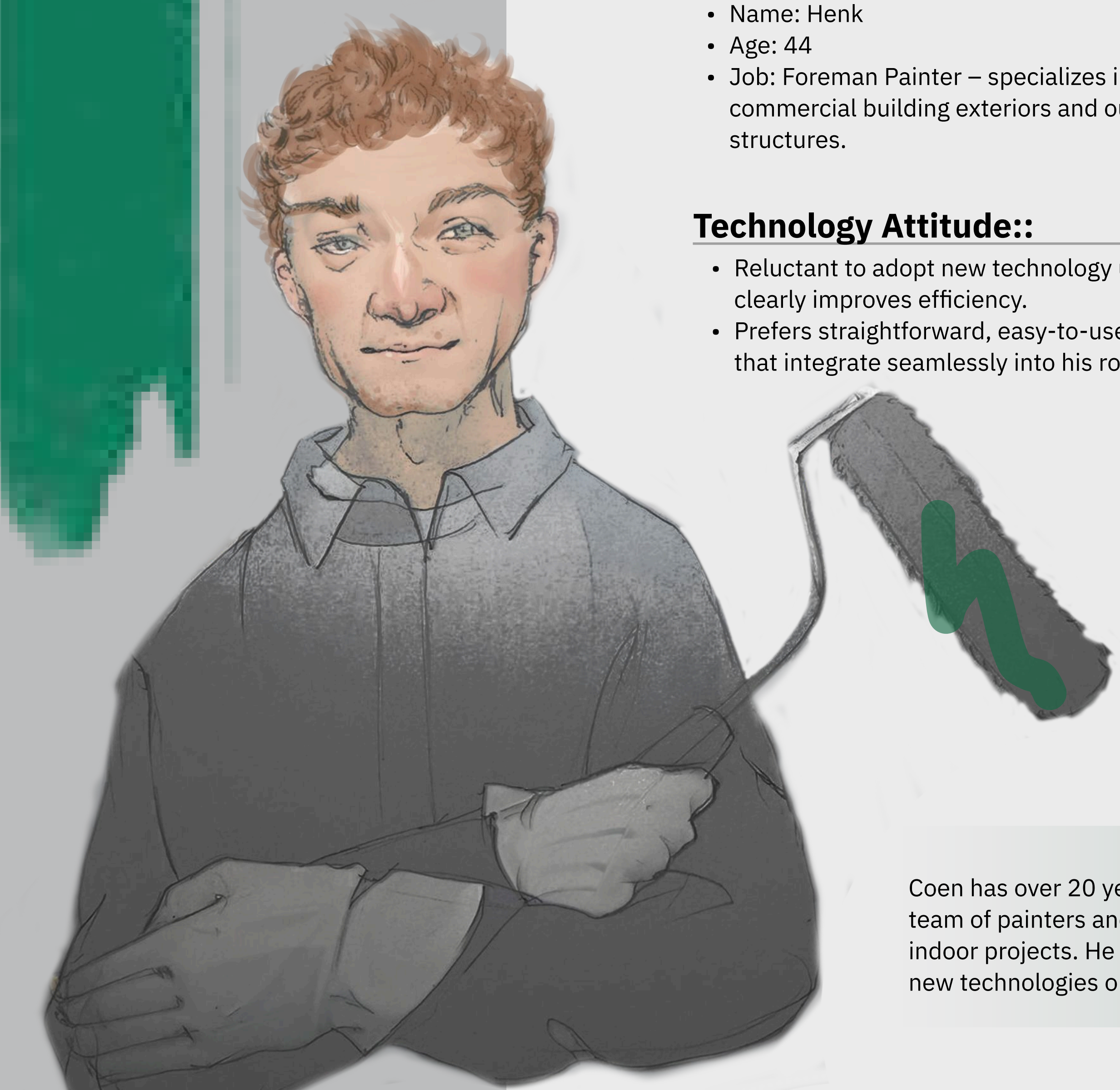
Persona and Journey Mapping
Based on interview data and observation notes, a representative user profile was developed to visualize the painter's workflow in residential settings, highlighting pain points, motivations, and decision moments. This helped frame the user's daily experience and identify where interventions would be most impactful.

Causal Mapping with Behavioral Design Strategies
Although the sample size was limited, insights from the fieldwork were triangulated with existing PPE studies. A cause-effect map was created to explore how specific design features might influence behavior through psychological mechanisms such as trust, effort, or social stigma. These insights informed an Initial System Function Tree, which guided concept development.

Henk

3.1 Persona -The Reluctant Adopter

Henk represents a difficult user type: a highly experienced foreman painter who values efficiency and routine over regulation or innovation. He is skeptical of new technologies unless they clearly improve productivity and prefers straightforward, low-effort tools. This persona is based on field interviews and observational insights from painters in residential and commercial settings. His behavior reflects a broad group of users who often neglect protection during low-odor tasks like sanding, where risk perception is low but exposure is high.



About

- Name: Henk
- Age: 44
- Job: Foreman Painter – specializes in painting commercial building exteriors and outdoor structures.

Technology Attitude::

- Reluctant to adopt new technology unless it clearly improves efficiency.
- Prefers straightforward, easy-to-use solutions that integrate seamlessly into his routine.

Habbit

- Prioritizes completing tasks quickly and efficiently.
- Often skips using PPE if it feels cumbersome or slows down the job.
- Relies on experience and intuition to assess job site conditions.

Motivations:

- Delivering high-quality work efficiently.
- Completing jobs on time so he can go home and relax.
- Maintaining the respect and trust of his team.

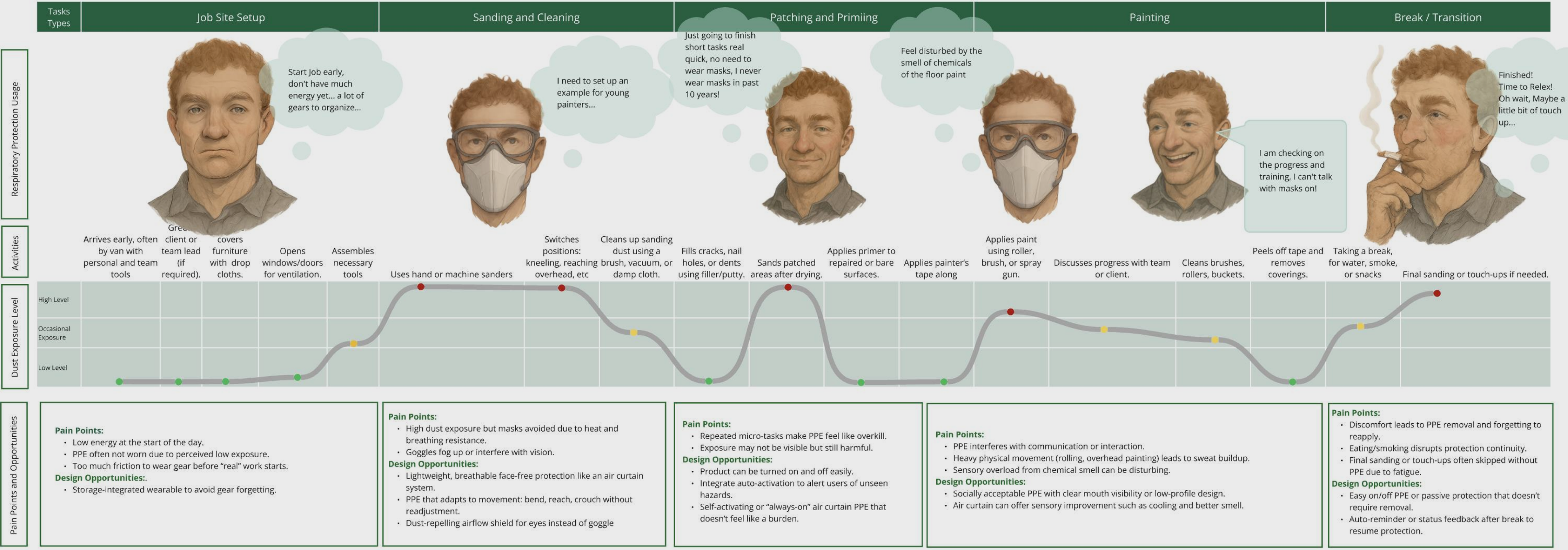
Frustrations:

- PPE that is uncomfortable, restrictive, or interferes with work.
- Regulations or requirements that feel impractical or unnecessary.

“ I do not care about air quality, I smoke anyway. ”

Background

Coen has over 20 years of experience in the painting industry. He leads a team of painters and is responsible for overseeing various scale outdoor or indoor projects. He prefers traditional methods and is often skeptical of new technologies or changes to his workflow.



3.2 User Journey Map

This user journey map below is developed based on the persona Henk. This journey illustrates the typical experience of a painter performing a sanding task in a residential setting—where regulations are minimal and PPE usage is often neglected. The journey highlights critical moments that influence **PPE engagement or avoidance** and critical moments of **high or occasional dust exposure**. These insights help identify design opportunities that could enable more consistent and comfortable protective behavior, even among skeptical or efficiency-driven users. The journey focuses on the daily practicalities and decision-making triggers that shape behavior.

Design Implication fromUser Journey Map

In this journey map, each stage was analyzed to identify key pain points and behavioral triggers that lead to PPE avoidance or inconsistent use. The design ideas that emerged from this map emphasize the need for:

- **Free- From-Face** respiratory protection, such as an air curtain system, to avoid the discomfort and communication barriers associated with traditional face masks.
- **Non-intrusive PPE** that does not interfere with physical movement or social interaction on site.
- **Seamless integration with routine tasks**, particularly during transitional moments like breaks or light-duty activities, where PPE is often forgotten or deemed unnecessary.
- **Behavioral nudges**, such as passive activation or automated reminders when dust exposure increases, to reinforce consistent use.
- **Secure and stable attachment** mechanisms that prevent the product from shifting or falling off during dynamic movements.
- **Accessible operation**, allowing users to control the system without removing it or interrupting their workflow.

These insights lay a strong foundation for early-stage design opportunities. However, the limited sample size of participants and field sessions posed challenges in validating broader behavioral trends or contextual variations.

3.3From Behavioral Mapping to System Function Strategy

While the user journey map highlighted key behavioral triggers and pain points during PPE use—especially among painters performing sanding tasks—it was primarily scenario-based and limited by small sample size. To extend these findings and explore underlying mechanisms more systematically, a causal map was developed.

The causal map visualizes how specific factors such as discomfort, social influence, perceived usefulness, and habitual behaviors interconnect to shape PPE decisions—from full compliance to complete avoidance. The causal map allows for cross-comparison of behavioral pathways of different types of users (See appendix G-H for the reference and system mapping made from this mapping).

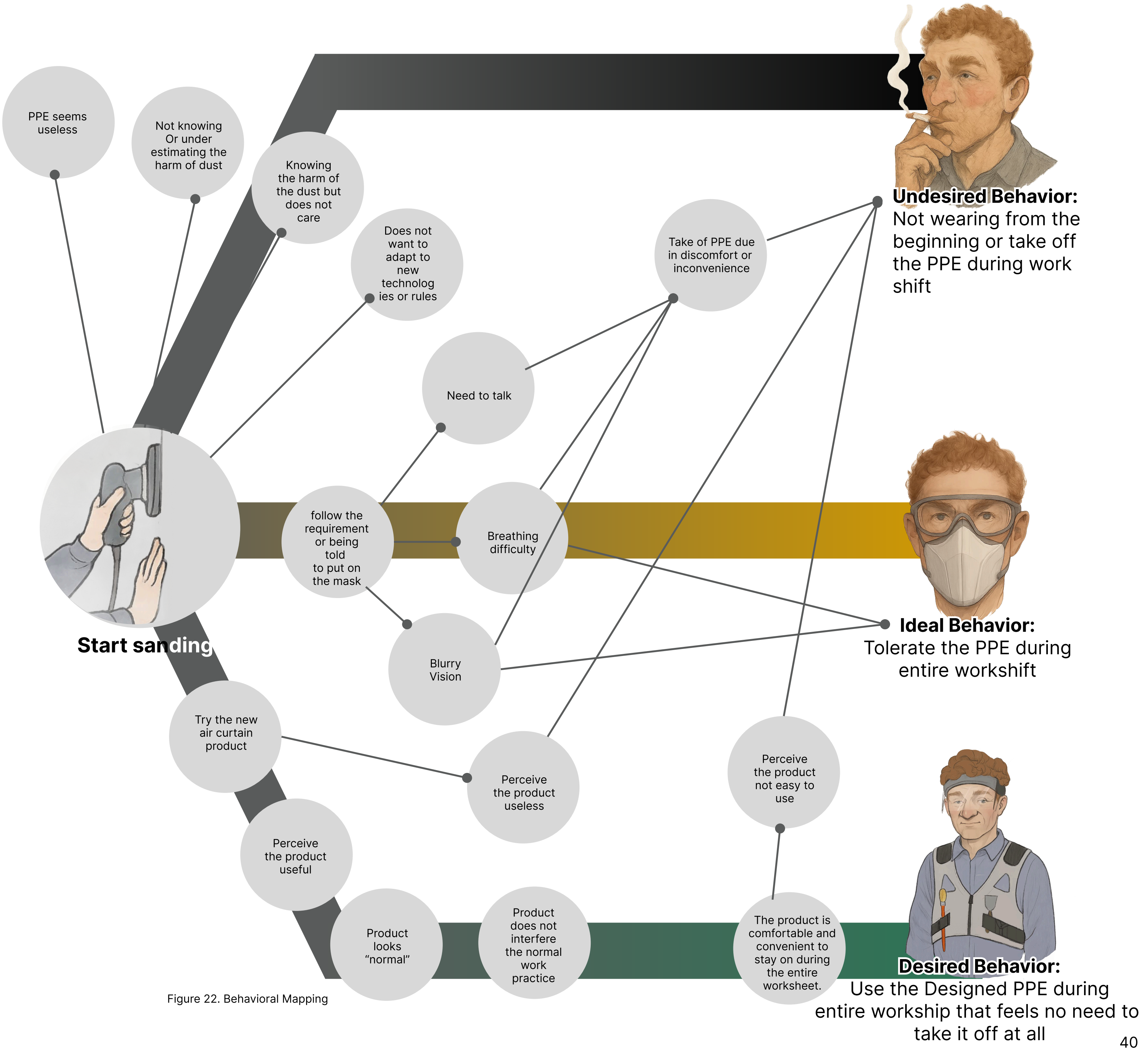


Figure 22. Behavioral Mapping

3.4 Design Directions Shaped by Behavioral Mapping

The early design exploration was directly shaped by insights from the behavioral mapping of PPE use. The mapping revealed the main reasons painters remove or avoid protective equipment: discomfort, breathing resistance, blocked vision, heat buildup, and interference with communication. At the same time, regulatory demands and workplace routines required that any new system integrate smoothly with existing PPE standards.
From these behavioral findings, the initial design directions were derived.

Supports habit formation → Make use feel natural and routine
Habitual use is more likely when PPE does not interrupt daily tasks. Early design ideation therefore focused on forms that could be worn continuously without adjustment—lightweight, stable on the head or body, and requiring no frequent repositioning. The goal was to create PPE that becomes part of routine, much like clothing.

Minimizes removal triggers → Reduce heat buildup and communication barriers
Users often remove PPE when it becomes hot, fogs up, or prevents speaking with colleagues. In response, the design exploration tested airflow systems that reduced condensation, ventilated the face naturally, and left the mouth area unobstructed to allow conversation. These ideas aimed to remove the common "reasons to take it off."

Builds trust and acceptance → Ensure users perceive reliable protection
Trust in PPE depends on whether users feel it is protective and worth the effort of wearing. Sketches and early prototypes emphasized physical barrier in breathing zone, reinforcing the perception of protection. By making the protective effect "felt" rather than hidden, designs aimed to increase confidence in the system.

Normalizes adoption → Align with everyday work practices
Behavioral mapping showed that PPE use increases when equipment feels "normal" and socially acceptable. Ideation therefore emphasized unobtrusive forms that integrate with helmets, goggles, and clothing, while avoiding bulky or stigmatizing shapes. The direction aimed to create PPE that blends into existing work routines and feels natural rather than exceptional.

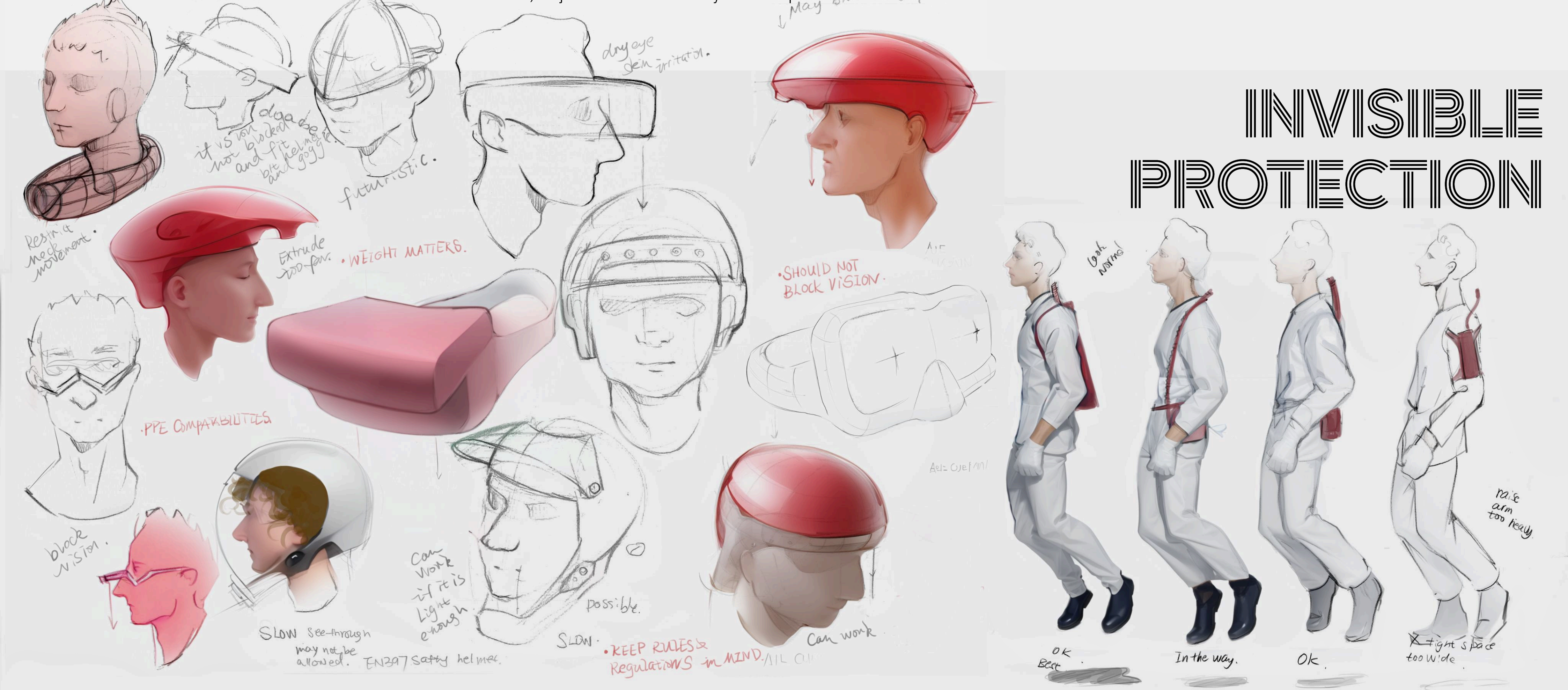
Behavior Mapping to Design Conceptualization

The behavior-informed principles above provided the foundation for early ideation sketches, guiding the search for concepts that workers would not only tolerate but choose to keep wearing.

4. Design Process: Concept Development

4.1 Ideation
The First Draft

These sketches served as an initial brainstorming exercise to explore potential integrations of an air curtain, including configurations as part of a helmet, safety goggles, or a standalone device. At this stage, the designs did not focus on the detailed geometry of the air nozzles. Consideration was also given to the placement of heavier components, such as the battery, with possible locations including a backpack, a belt-mounted piece with air supply pipes extending from both the front and back, or an armband.
The sketches were shown to HSEQ officers and painters to collect feedback, which was noted directly on the paper sketches. After the feedback session, adjustments to the layout and presentation were made.



Initial Concept Ideation for Feedback

Several key design considerations were identified during this round:

Obstructed vision
Some helmet and goggle integrations risked blocking the wearer's field of view or creating glare and skin irritation around the eyes.

Weight distribution
bulky or front-loaded configurations highlighted the importance of locating heavier elements (battery, pump) elsewhere, such as the belt or back, to avoid neck strain.

Compatibility
Concepts needed to integrate smoothly with existing safety helmets and goggles without violating PPE standards.

Regulatory and safety compliance
Reminders were made to keep occupational health and safety requirements in mind, particularly around respirator classification and entanglement risks.
These observations clarified what should not carry forward into later concepts and highlighted critical design challenges that the project had to resolve.

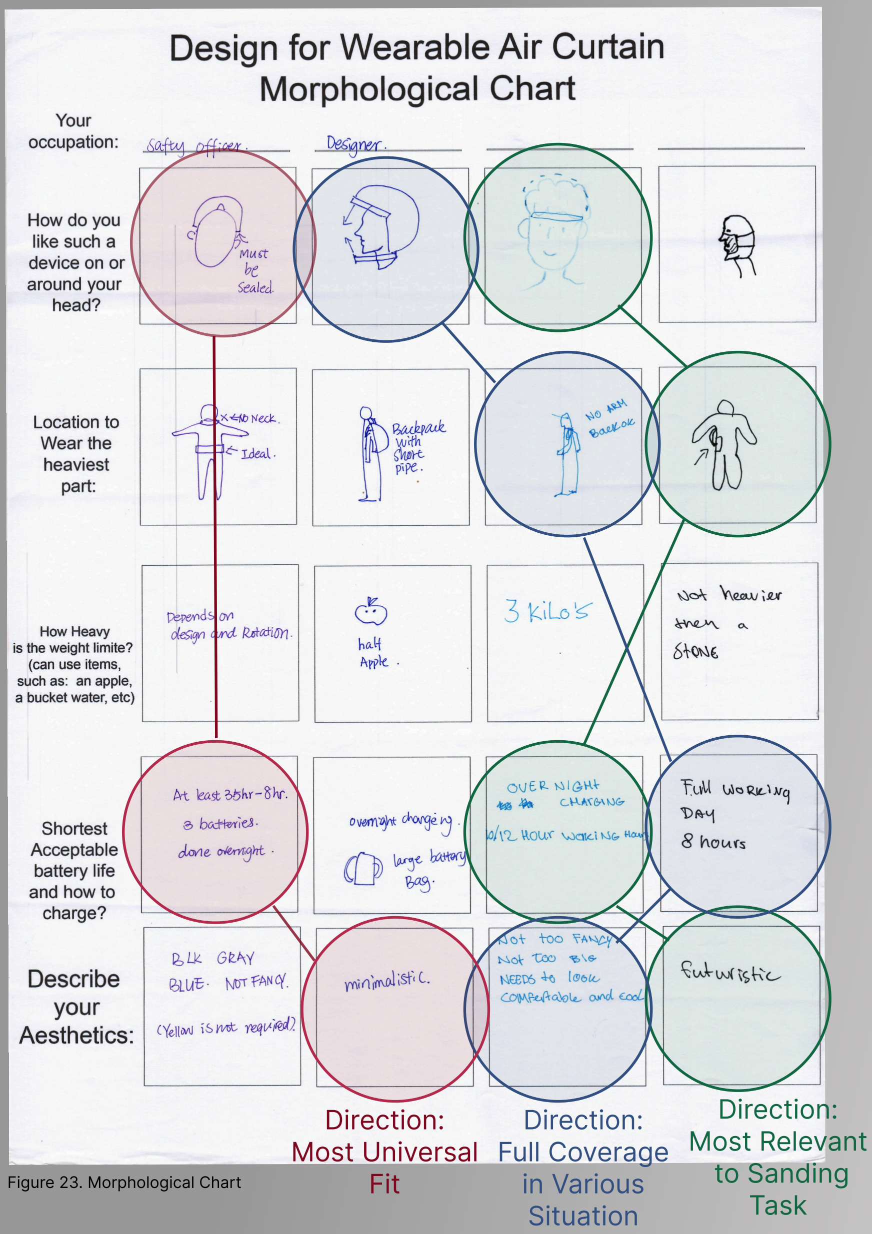


Figure 23. Morphological Chart

This morphological chart was collaboratively developed with a Safety Officer and a Painter to explore potential design directions for a wearable air curtain. The morphological chart shown is a structured tool used to generate and explore different design possibilities for a wearable air curtain. **In the Morphological Chart is divided into columns representing different user groups who contributed their insights: Safety Officer, Designer and Painter.** Each row represents a design consideration or functional requirement. These criteria are essential for ensuring the air curtain is effective, safe, and user-friendly. The main criteria include: Wearable Piece Placement Preferences, Location for the Heaviest Component, Weight Limitation, Battery Life and Charging style, and Aesthetics: Visual design and appearance preferences. The combination of different solutions lead to different design direction.

3 Design Directions

The following sections outline three distinct design directions derived from the morphological chart. Each direction addresses specific user needs and work scenarios while maintaining the shared features outlined above:

D1. Most Universal Fit: Versatility and adaptability to different work environments and and compatible with existing PPE.

D2. Full Coverage in Various Situations: Comprehensive protection and coverage for diverse tasks and unpredictable conditions.

D3. Most Relevant to Sanding Tasks: Specific protection against hazards encountered during sanding, such as fine dust particles and debris.

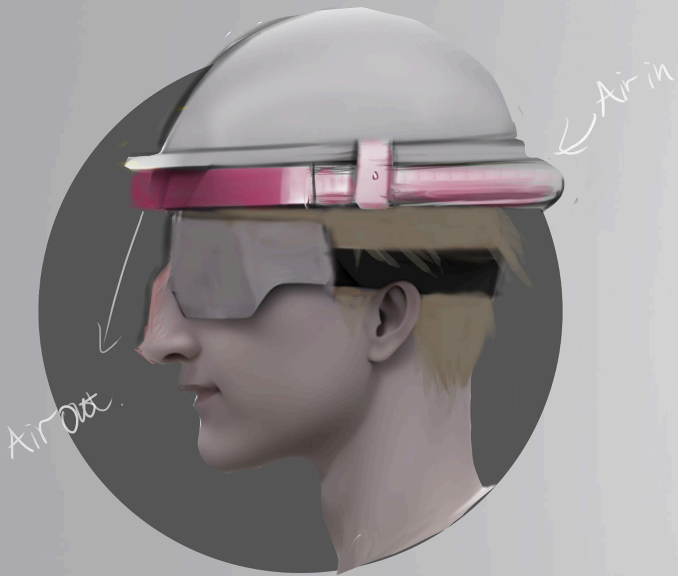
Common Features Across All Design Directions

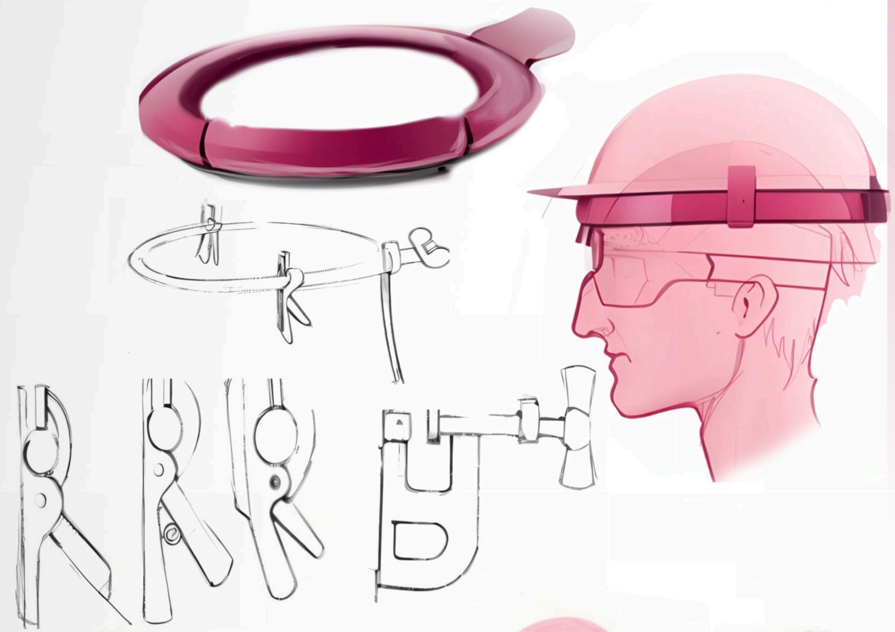
Despite the difference of these 3 design directions, the following requirement were taken into account during visualizing the final product:

1. **Continuous Operation:** The device must allow for uninterrupted use throughout a work shift without concerns about battery life.
2. **Lightweight Design:** To prevent discomfort and strain, the weight should be distributed evenly. The head area should carry as little weight as possible.
3. **Unobstructed Face Area:** The design must ensure the user's face feels free and unrestricted, avoiding interference with vision or facial movements.
4. **Safety:** The device should not creating hazards, such as entanglement or restricted movement.
5. **Comfortable Airflow:** Airflow should be enjoyable and refreshing, preventing moisture build-up and ensuring temperature regulation for prolonged comfort.
6. **Aesthetics:** The design should be unobtrusive and not draw unnecessary attention. It should seamlessly integrate into current PPE (Personal Protective Equipment) and work attire, avoiding any overly unusual appearance.

Design direction I : AirLoop

The AirLoop Pro is a standalone air curtain designed for seamless integration with existing PPE. Its lightweight, minimalist design offers respiratory protection with a flexible, pressurized airflow barrier. Featuring a multi-unit charging station for quick, convenient battery swaps, it ensures uninterrupted use throughout the work shift. The AirLoop easily clips onto helmets and goggles, fit in between or work by itself, providing adaptable protection.





EASE OF CHARGING
Multiple units on a single charging station allow for easy swapping throughout the work shift, ensuring uninterrupted use.

VERSATILALITY
Can be clipped onto various PPE like helmets or safety goggles, providing adaptable protection based on tasks.

EASY TO USE
Intuitive design with minimal setup steps, automatic charging, requiring little to no learning curve for operation.

MINIMAL MAINTENANCE
No additional cleaning needed, only need to replace filter

LIGHT WEIGHT
Made with lightweight materials, featuring a simple structure and lightweight.

COMFORTABLE AIRFLOW
It delivers clean, filtered air without restricting movement

Prototyp for Design direction I : AirLoop

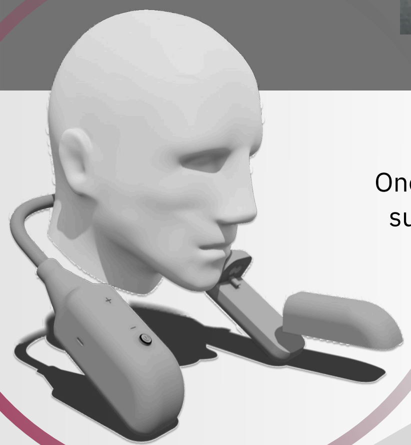
The desirability of the AirLoop concept was strongly established during the selection process, as it was identified by SUSAG as the preferred design direction. This choice was based on its compatibility with existing PPE, novelty, and ease of use, making it a promising candidate for further development. Several models were therefore created to investigate how the required functionality could be achieved within a wearable form.

Early prototyping demonstrated that the system was capable of generating a stable sheet of airflow, confirming the feasibility of producing an air curtain effect. However, at this stage the airflow strength was limited, revealing the need for further optimization of nozzle geometry and air supply integration. The use of 3D printing allowed rapid iteration of components, which could be easily combined into different wearable shapes for evaluation.

Figure 26. Smoke visualization test of early prototype showing formation of a stable but weak air curtain, confirming feasibility while revealing the need for stronger airflow.

Figure 24. Section view of early nozzle concept, illustrating airflow channel geometry intended to produce a thin, stable sheet of air.

Figure 25. Digital renderings showing how the air curtain system could be fitted onto the head, demonstrating ergonomics and integration with wearable components.



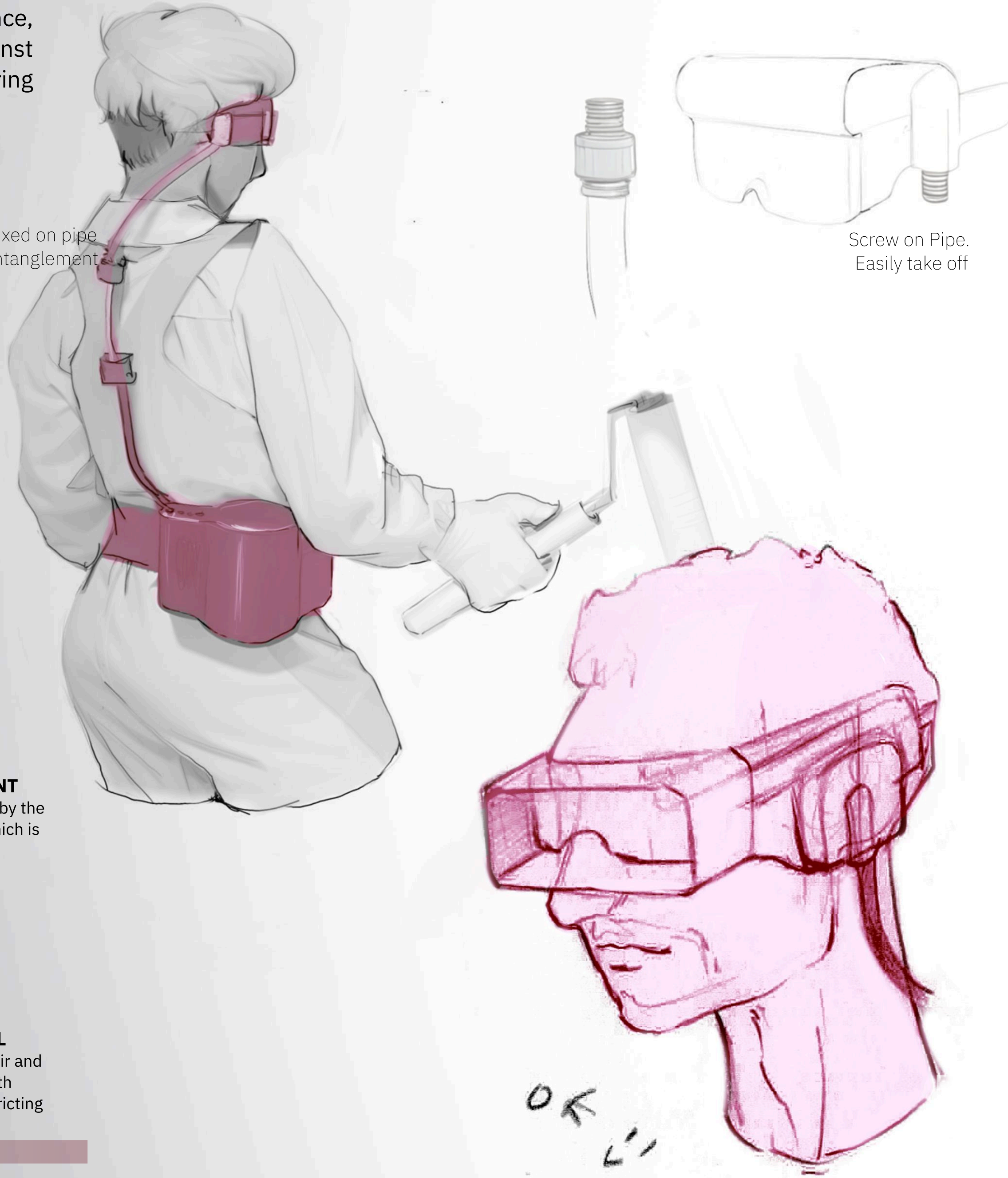
One proposed configuration of power supply involved placing the power supply at the neck. While technically functional, user testing revealed concerns about the unit potentially falling off and restricting neck movement, making this placement less desirable. Such insights highlighted the importance of ergonomic integration and weight distribution in ensuring long-term wearability.

Figure 27. Concept model of a neck-mounted power supply configuration with detachable battery.

Overall, integrating a self-contained airflow system—without relying on external compressed air—posed significant design challenges. A series of physical prototypes were produced and tested in parallel with CFD simulations, allowing performance to be systematically evaluated and guiding the refinement of the AirLoop design.

Design direction II : FortiFlo

FortiFlow is a versatile and innovative wearable air curtain designed to incorporate protective goggles, offering comprehensive eye protection and respiratory safety for industrial workers. Engineered for convenience, durability, and performance, FortiFlow provides seamless protection against unexpected splashes, large particles, and airborne contaminants, ensuring comfort and efficiency throughout the workday.



LONG BATTERY LIFE
The large battery is on the waist, easy to replace.

INTEGRETION
The product can be used as carrier of other PPE.

EASY ADJUSTMENT
AirFlow can be modified by the buttons by the waist, which is easy to reach.

VARIOUS OPTIONS
Can set to multiple speed and temperature.

GOOD ENOUGH
Have all the protection needed against dust in air during sanding.

LOW NOISE LEVEL
It delivers clean, filtered air and maintains comfort with temperature without restricting movement

Design direction II : FortiFlo

The concept prioritizes familiarity by adopting a packaging design that resembles store-bought consumer products, which may attract interest from a broader range of users. It features multiple replaceable lenses, helping to prevent eye dryness, and includes a soft rubber band to ensure a universal, comfortable fit. The use of soft materials further enhances wearability and user comfort.

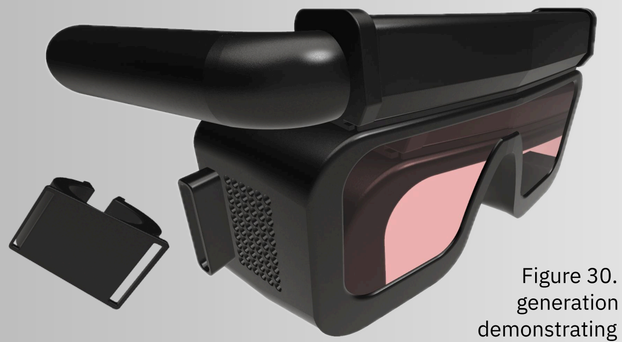


Figure 28. 3D render of the FortiFlo goggle design, featuring interchangeable lenses and a soft sealing band for universal fit.

Prototyping involved 3D modeling, printed components, and evaluation of ergonomic integration. SUSAG's review concluded that the FortiFlo concept did not offer a clear advantage, as the face area remained framed and restricted, limiting comfort and user acceptance.

Figure 30. Rendering of 3D model combine with AI generation of the FortiFlo goggles worn on the head, demonstrating ergonomic fit, full protection and unobtrusive breathing zone.

SAFE TO SEE

EASY TO BREATHE

Figure 29. Proposed consumer-style packaging for the FortiFlo system, emphasizing familiarity and ease of adoption.

Figure 31. Concept rendering of a portable "Better Air Supply" canister designed to provide a lightweight, refillable airflow source carried at the waist.

Figure 32. Early 3D-printed prototypes and assembly components, used to test functionality and ergonomic fit.

Design direction III : AirCore

AirCore is a comprehensive protective solution designed for industrial environments. Combining a helmet with a flip-down mask, integrated headphones, and an airflow system for respiratory protection, AirCore ensures seamless, all-in-one safety. The accompanying backpack organizes all essential protective equipment, reducing the burden of carrying multiple items and helping workers stay prepared for any situation. Its compact design and short air supply pipe prevent entanglement, ensuring freedom of movement and ease of use.

LONG BATTERY LIFE
Long battery life after all night charging. covers 7-8 hours workshift.

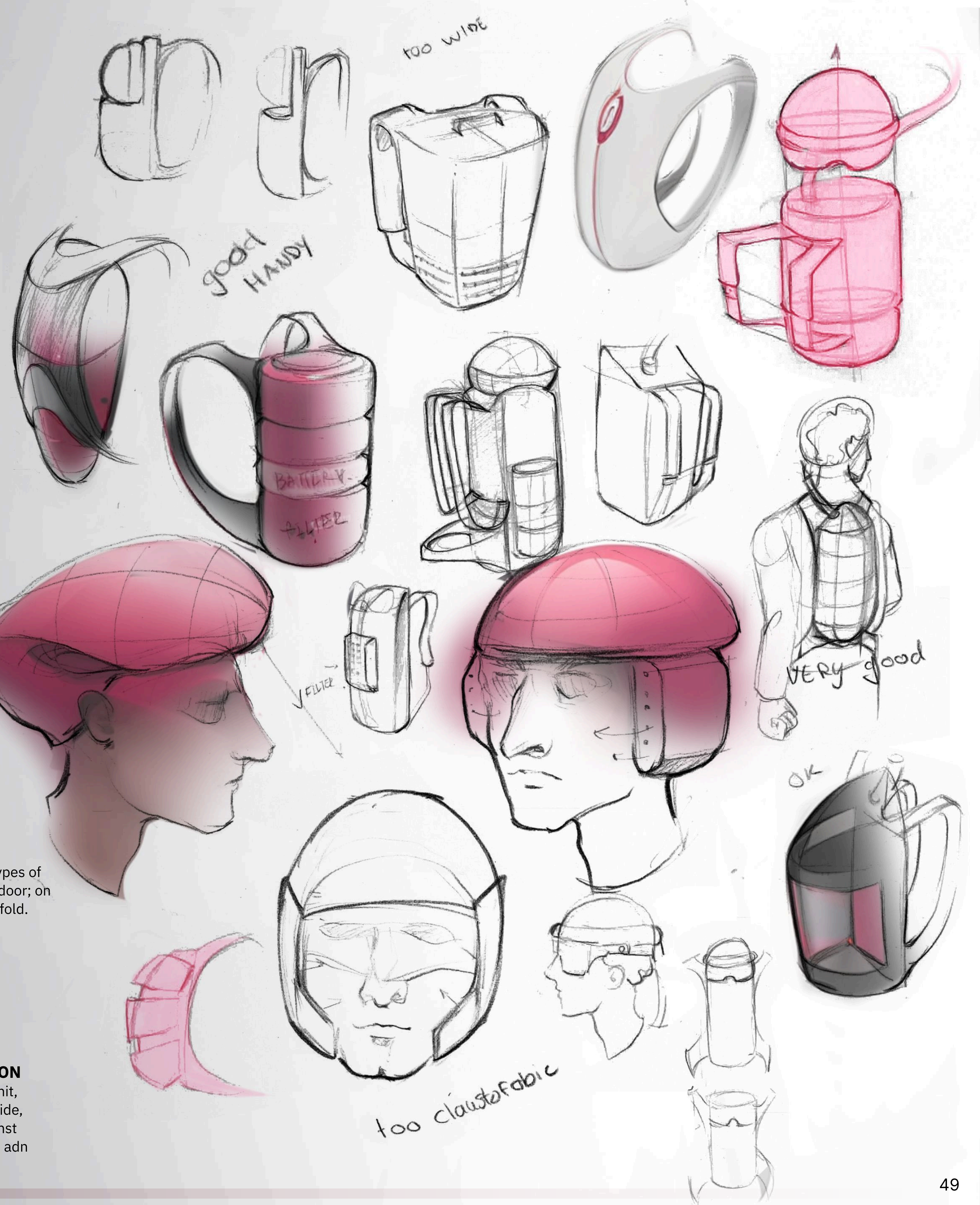
PRODUCTIVITY BOOST
All-in-one, covers all need during sanding and painting tasks.

VERSATILITY
Can be use in various types of job, both in door and outdoor; on the ground or on scaffold.

STAY ORGANIZED
All PPE in one unit, which helps to reduce visual cluster, encourage habit for staying organized.

BALANCED WEIGHT DISTRIBUTION
The pressure points are evenly distributed. reduce fatigue for long wear.

STRONG PROTECTION
Strong large function unit, include plasma filter inside, offeres protection against various types of aerosols adn particulates.



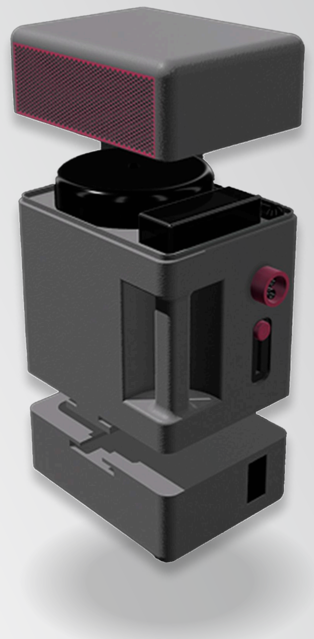
Design direction III : AirCore

This 3D model represents an internal insert within the helmet, designed to channel airflow directly to the user. It aims to provide full coverage from head to chin, eliminating the need for additional respiratory PPE during sanding tasks.

This concept did not advance to full 3D prototyping, as the internal airflow structure presented significant challenges for realization through additive manufacturing. Furthermore, since not all painting activities require the use of a helmet, integrating respiratory protection within it would introduce unnecessary weight and impose an additional layer of PPE.

Figure 33. 3D model of the AirCore helmet concept, showing airflow channels integrated into the helmet structure, with air entering from the back.

Figure 34. Renderings of the external blower and filter unit, designed to connect to the helmet and optionally be placed in a backpack to reduce head-borne weight. The unit was also 3D printed and tested as a physical prototype, which revealed that the filter placement needs to be made more convenient for practical use.



Renderings of the external blower and filter unit, which can be connected to the helmet and placed in a backpack for reduced head-borne weight.

4.3Determine the Design Direction

	Independent Piece (loop shape)	Goggle	Helmet	Neck Fan	Electric half Mask (Current Product)	Headphone from Dyson
Light weight	+1	+1	+1	+0	-1	+1
Easy to carry	+1	+1	+1	+1	+1	+1
Compatible with Existing Equipment	+2	+0	+0	+2	+2	-2
Easy to Clean and to Maintain	+2	+2	+1	-2	-2	-1
Not Creating Blind Zone	+0	-1	+0	+2	+2	+2
Free From Risk of Entanglement	+0	+0	+0	+1	-1	+0
Allow Free Movement in narrow space	-1	-1	+0	-1	-1	-1
No or Limited Airflow on Skin and the Eyes	+0	+2	+0	-1	+0	+1
Comfortable for long hours	+2	-2	+1	-1	-2	+1
Does not Look Weird	+1	+1	+2	+0	+2	-2
Does not Interfere Work Flow	+2	+1	+1	+0	-2	+0
Total	10	4	7	1	-2	0

Figure 35. Concept evaluation Table

The evaluation table presented here is derived directly from the requirement list outlined on page 33-34. Each requirement identified in the earlier analysis was translated into assessment criteria, allowing for a structured comparison of the different design directions.

Evaluation Criteria

The design concepts under consideration—such as Airloop, FortiFlow, Aircore, and other market-inspired forms—are not strictly distinct from one another, as they may share functional components or structural elements. However, the focus of the evaluation lies in the **wearable piece itself**, which significantly influences user perception, habit change, and usability. To determine the optimal way the wearable component should be worn, it is essential to first select a general direction: whether it should function as an independent loop worn on the head (as in the Airloop concept), be integrated with goggles (FortiFlow), be helmet-based (Aircore), resemble neck-worn consumer products like neck fans, or be similar to existing solutions such as electric half-masks or Dyson's headphone-style air purifiers.
The evaluation criteria were developed based on insights from professional painters and safety personnel, focusing solely on the wearable form factor—**assuming each device is otherwise fully functional.** To assess the overall desirability of each concept, a qualitative scoring system was used: +2 represents a major advantage and highly desirable feature,+1 indicates a positive feature, though not critical, 0 means the aspect is neutral or has no particular benefit or drawback, –1 suggests a minor drawback or potential issues, –2 signifies a serious disadvantage that could negatively impact adoption or usability.

Result

Based on the evaluation, the Independent Piece (loop shape) achieved the highest score of +10, excelling in compatibility with existing equipment, ease of cleaning, extended wear comfort, and minimal interference with workflow. It also performed well in aesthetics and portability, with only a minor drawback in mobility within narrow spaces if it connects to the function unit via long pipe. The Helmet concept followed with a score of +7, and the Goggle concept scored +4, both showing potential but with some trade-offs in visibility and movement, Improvements are still needed in reducing entanglement risk. Furthermore, the Goggle and Helmet designs must comply with CE requirements, which may impose limitations on certain geometries and restrict overall design flexibility. Dyson's headphone and the Neck Fan scored +1 and –2 respectively, while the Electric Half Mask scored 0, besides issues in comfort, hygiene, and workflow integration, the Dyson product is reported look "too much" by the participants based on interviews and survey results; see Appendix E. As a result, the design focus will move forward with the loop-shaped concept, while helmet and goggle integration remain secondary options depending on technical feasibility. The next step will assess technical viability and refine the concept into a wearable, functional product.

Limitation

As a future improvement, the evaluation method could be refined by introducing weighted scoring to account for how important each criterion is in influencing user adoption. Some features may carry more weight in real-world use than others. However, due to the current limitations in sample size and available user data, all criteria have been treated equally in the present evaluation. Incorporating user-weighted priorities in future studies would enable a more accurate and context-sensitive assessment of design performance.

5. Feasibility and Validation

Technological Feasibility and Validation

Overview

The technical feasibility study investigates whether an air curtain system can provide effective respiratory protection for workers, particularly painters, by creating an air barrier that blocks airborne particulates. The study includes physical testing, computational fluid dynamics (CFD) simulations, and ergonomic evaluation.

Part 1 Foundational Research for Nozzle Design

Before starting the nozzle design, a literature review was conducted to understand the fundamental principles of air curtains and to identify key factors that influence airflow performance and effectiveness.

Part 2 Ideal Airflow Simulation

Simulated airflow patterns were first analyzed without any product geometry constraints to better understand the optimal airflow behavior required for an effective protective barrier. Key considerations included nozzle size, nozzle width, and airflow speed. This approach was based on the assumption that specific airflow characteristics could be achieved in later design stages.

Part 3 Pilot Test for physical test

Pilot test to test the test flow

Part 4 Air Supply System Evaluation

test what type of air supply is needed, how many air supply

Part 5 Internal Nozzle Structure Testing

Various nozzle geometries were simulated to examine how design parameters affect airflow stability around the breathing zone. Both physical testing and CFD simulations were conducted at this stage. The nozzle was designed not only to achieve functional airflow performance but also to ensure ergonomic fit and comfort for the user.

Part 6 Contextual Performance Validation

The optimized design was developed based on foundational research, ideal flow simulations, and both CFD and physical testing of validated nozzle geometries. The final design was evaluated in a virtual environment that mimics real-world conditions—such as human breathing, thermal plumes, and varying postures (standing/sitting)—to assess performance under contextual influences. This step aimed to validate how the air curtain interacts with ambient airflow and external disturbances.

Part 7 Performance Trade-off Analysis and Recommandations

Comparative analysis examined the balance between airflow performance, user comfort, and practical implementation constraints.

Part 1 :Foundational Research for Nozzle Design

Objective

The objective of the foundational research was to gather theoretical insights into air curtain behavior, airflow dynamics, and nozzle design principles. The future research is based on main takeaways from this research.

Preliminary Research

The following foundational study is organized into thematic areas, summarizing the key factors influencing the design assumptions, simulation setup, and performance criteria for the air curtain system.

Desired Airflow Type

Airflow behavior can be unpredictable—even under still ambient conditions—due to the inherently unstable and complex nature of turbulence, which is difficult to model and control. This research considers both **laminar flow**, a smooth and orderly pattern where air moves in parallel layers with minimal mixing, and **turbulent flow**, which is chaotic and promotes mixing with surrounding air. These two regimes form the basis for exploring two distinct approaches to aerodynamic protection:

1. Optimizing Air Curtain Design for Stable Laminar Flow

One approach is to strengthen and extend the laminar flow region to minimize the entrainment of contaminated air into the respiratory zone, effectively separating two air masses without mixing (Chovanec & Bursíková, 2022). The system uses air as a separation medium, forming a controlled barrier that prevents mixing between zones, with careful consideration of flow properties and composition. The project focuses on directing air via forced convection, supplied by a laminar flow fan, to form an air curtain that separates two zones containing air of differing quality. This is achieved using components such as nozzles, a connected laminar chamber, and flow-directing elements like paddles or tailored nozzle systems. **The primary objective is to prevent airborne particles—such as dust, droplets, and other contaminants—from entering the user's breathing zone.**

A study by Chovanec and Bursíková (2022) highlights the potential of air curtains not only as climate-control solutions in buildings, but also as non-intrusive barriers capable of separating two environments with a visible yet optically transparent flow of air. Common in commercial and architectural settings, air curtains show potential for broader applications. The authors propose several design strategies, such as integrating a laminar chamber at the fan inlet to stabilize the flow, redesigning the outlet nozzle for improved geometry, or omitting the nozzle entirely to allow a smoother, open-air exit. Additional approaches include the use of internal flow-directing vanes or a ceiling-mounted system using multiple nozzles powered by a compressor.

Building on these findings, this research further explores the effect of nozzle geometry and internal components through simulation. Preliminary results suggest that both nozzle shape and flow-guiding elements substantially influence the velocity profile. Achieving a more stable and efficient air curtain depends on careful refinement of the laminar chamber and outlet design, supported by pressure-flow calculations and loss coefficient analysis. For wearable applications, this research also considers how the system can be adapted to human body geometry and maintain performance during user movement.

2. High-Volume Airflow Strategies for Respiratory Zone Protection

Alternatively, **high-volume turbulent airflow may assist in dispersing airborne contaminants by displacing dust particles away from the user's breathing zone.** One study found that increasing inlet ventilation rates significantly impacted indoor pollutant concentrations, primarily due to enhanced turbulent diffusion (Cao, Zhu, & Yang, 2016). Interestingly, this effect appeared relatively insensitive to higher slot Reynolds numbers ($Re \geq 3000$), with pollutant concentration trends showing asymptotic behavior. These findings challenge the conventional assumption that greater ventilation rates consistently lead to improved indoor air quality (IAQ). In this context, volume flow rate emerges as a critical factor—potentially more important than maintaining perfectly uniform flow (Cao, Zhu, & Yang, 2016).

Airflow types within the product system can vary across different stages. At the source, air may be generated as a vortex flow, depending on the fan and inlet conditions. Inside the internal piping or ducting, the airflow often develops into shear flow, shaped by the pipe geometry and surface interaction. Upon exiting the system, the flow can become a jet flow or maintain shear characteristics, depending on the nozzle shape and outlet configuration.

The airflow exiting the nozzle in this system qualifies as jet flow due to its high velocity and discharge into a lower-pressure ambient environment—creating a free shear layer that defines jet behavior. Studying this jet flow is essential for analyzing how the air curtain forms, how stable it remains, and how effectively it blocks particle intrusion. As Wang and Tan (2009) emphasize, jet characteristics such as vortex evolution, entrainment, and mixing are strongly influenced by nozzle geometry and initial conditions, which are critical to optimizing air curtain performance.

Regardless of jet geometry, both round jets and slot jets (rectangular openings) exhibit similar flow development zones, as illustrated in Figure 36 (Felix, 2018). Jets may initially exhibit laminar flow but typically transition to axisymmetric turbulence as they interact with the surrounding ambient air (Felix, 2018). Although different studies use varying terminology to describe the regions of jet flow, the categorisation methods remain largely consistent. The commonly observed regions include:

- **Initial Region:**

The initial region of a jet, also known as the convergent zone or potential core, features laminar flow occurring immediately at the nozzle exit (Felix, 2018). In this region, the centreline velocity remains equal to the nozzle outlet velocity, and the flow remains largely undisturbed.(National Digital Library of Ethiopia, n.d.).

- **Transitional Region:**

Transitional Zone and Developed zone, Formation of vortex rings due to Kelvin-Helmholtz instabilities, marking the start of turbulence(Felix 2018). The transitional region follows, marked by the onset of turbulence. Vortex rings emerge due to Kelvin–Helmholtz instabilities, indicating the breakdown of laminar characteristics (Felix, 2018). The centreline velocity begins to decay, following a trend approximately proportional to $x^{-0.5}$, where x is the axial distance from the nozzle. The transitional region generally spans 6d to 20d and is also known as the interaction region, where shear layers from opposing sides of the jet merge (National Digital Library of Ethiopia, n.d.).

- **Developed Region:**

Beyond the interaction zone lies the developed region, where the jet becomes fully turbulent and self-similar. Transverse velocity profiles appear consistent across different axial positions, and the centerline velocity decays proportionally to x^{-1} (National Digital Library of Ethiopia, n.d.).

- **Full Turbulent Region:**

Full turbulent flow as coherent structures collapse downstream (Felix, 2018). Due to its complexity, detailed analysis is often limited.

Figure 36 illustrates the four jet flow regions, based on a diagram from Zou (2001).

To design an air curtain that effectively protects the face—whether from the mouth to the chin or from the top of the head to the chin—the nozzle must be dimensioned so that the jet flow adequately covers the targeted region. The hypothesis is that if the potential core—or a combination of the potential core, transitional, and developed flow zones—remains within the vertical extent of the user's face, mixing between ambient contaminated air and the clean air within the breathing zone will be minimized.

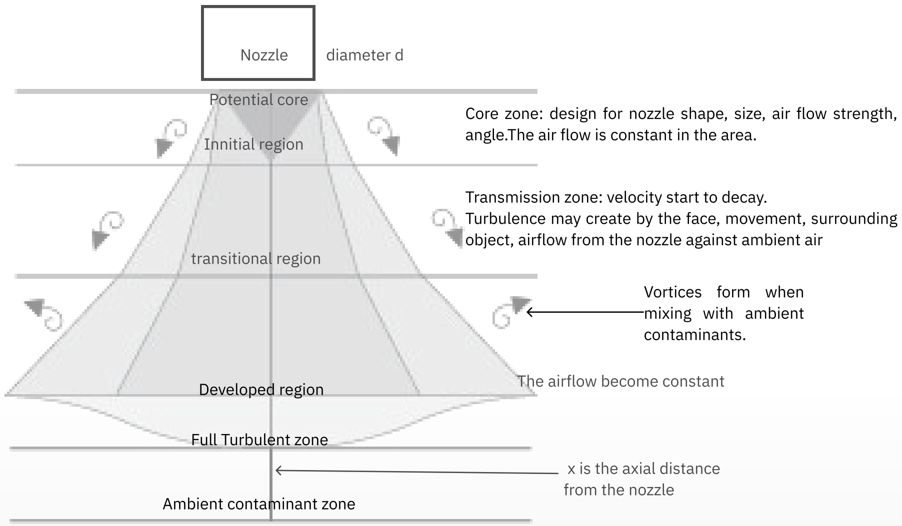


Figure. 36 A airflow with both laminar and turbulent zone after existing the air nozzle referenced flow structure of free jet diagram by Zou 2001

A key takeaway is that the structure of airflow—specifically how far it travels before becoming turbulent—is primarily governed by the nozzle's geometry, particularly the size and shape of its opening, rather than by fan power alone. While fan power influences the velocity and overall reach of the jet, it is the nozzle dimension that defines the scale and behavior of flow development zones. This relationship is further supported by physical tests conducted in this study .

The commonly referenced 4d–6d potential core length applies to circular nozzles, but in wearable air curtain designs, outlets may instead consist of multiple small holes or a single rectangular slit. These alternative geometries significantly influence jet development and must be considered independently when evaluating flow behavior and core length.

Air Curtain Behavior Upon Impact

Although studies on the influence of wind on air curtain performance are limited, Yang et al. (2019) provide insights by experimentally examining how varying wind speeds and angles affect air curtain jets at building entrances. The findings show that crosswinds and head-on winds can significantly penetrate and destabilize the air curtain, particularly in the lower regions, thereby reducing its effectiveness in blocking infiltration.

This observation is can be relevant to wearable applications, based on assumption that body movement and ambient air disturbances—such as wind or motion-induced flow—can mimic similar cross-flow challenges. The study also demonstrates that adjusting jet velocity and discharge angle can partially recover performance, and that the presence of a pedestrian can serve as a physical buffer against wind intrusion, implying that physical barriers may help stabilize the air curtain. While the research focuses on fixed architectural systems, it highlights a critical gap in understanding air curtain behavior during motion—an essential consideration for wearable devices. The findings shed light on the hypothesis that air curtains may still function under external impact; however, in wearable contexts, the technical feasibility remains uncertain. This underscores the need for further investigation into how desired airflow patterns can be reliably achieved through optimized nozzle design and flow control. The prototype used in the test experiment (see Figure 37) incorporates an extended nozzle design, which acts as a physical barrier to help stabilize the jet flow. It was tested against a reference nozzle without such an extension to compare performance. In the simulation, crosswind was also introduced to mimic the relative airflow generated by the motion of the wearer, allowing for evaluation of jet stability and protective coverage under realistic dynamic conditions.

How to Achieve the Desired Airflow

To achieve a predictable airflow, a review of nozzle types was conducted to identify the most suitable geometry for wearable air curtain applications. Among the types examined were standard convergent nozzles and convergent-divergent (C-D) nozzles, which are commonly used in supersonic jet propulsion systems. A convergent nozzle narrows toward the exit, accelerating subsonic flow by converting pressure into velocity. A convergent-divergent nozzle, on the other hand, first narrows (converges) and then widens (diverges), allowing the flow to accelerate to supersonic speeds if inlet conditions permit. Although the wearable air curtain does not aim to achieve supersonic flow, understanding the performance characteristics of these nozzle types was essential for informed design decisions, particularly regarding flow stability, velocity distribution, and pressure behavior.

Supersonic nozzles—particularly C-D nozzles—are engineered to accelerate airflow beyond the speed of sound when the inlet pressure significantly exceeds ambient pressure. In theory, they can generate highly directional and high-velocity jets. However, in practical applications such as wearable systems, this configuration introduces multiple challenges. Supersonic flow requires not just elevated inlet pressure but also precise environmental conditions to avoid the formation of shock waves, which can cause turbulence, increased noise, and pressure losses. Moreover, safety constraints—such as OSHA Standard 1910.242(b), which limits compressed air used in proximity to humans to a maximum of 2.1 bar (30 psi) when dead-ended—further restrict the feasibility of high-pressure or supersonic airflow in wearable designs.

Although wearable systems typically avoid supersonic nozzles due to complexity and sensitivity to environmental conditions, prior studies have demonstrated that supersonic airflow can technically be achieved with inlet pressures as low as 1 bar, using a convergent-divergent nozzle design under ideal conditions (Chavan & Shaikh, 2017). However, the practical challenges of flow control, stability, and safety in proximity to the body limit their application in wearable air curtains. Additionally, supersonic nozzles are more sensitive to misalignment, obstructions, and design variation—making them less stable under dynamic, real-world conditions such as user motion or variable airflow resistance near the body. For the design decision, this project adopts a convergent nozzle design. Convergent nozzles accelerate airflow up to sonic conditions at the exit (choked flow) without transitioning into supersonic speeds.

Following this decision, attention was directed toward optimizing the exit region of the nozzle.

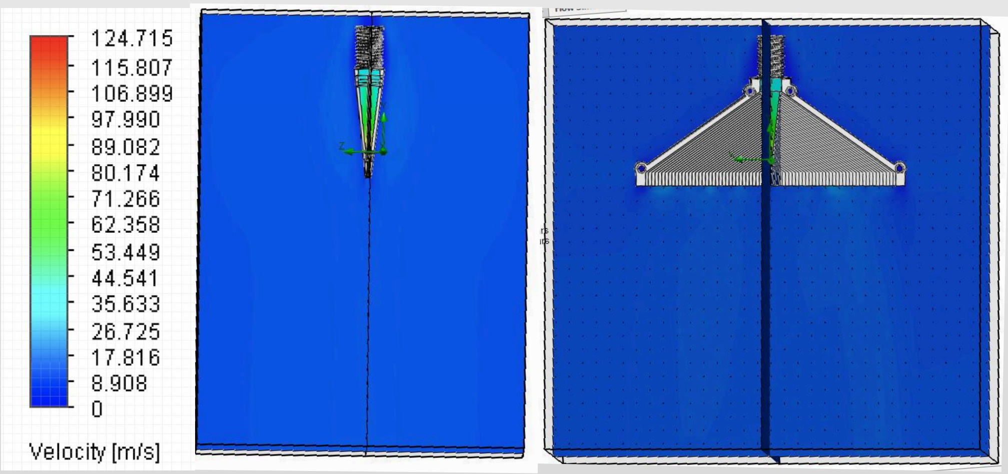


Figure 37. The CFD cut plots show side and top-down sectional views of an early converging nozzle design. Air enters from the top and accelerates through narrowing channels, reaching peak velocity internally, as indicated by the red zone. In a brief test described in Appendix I, the physical prototype—supplied with 30 m/s airflow through a 21 mm round pipe—produced a 9 m/s sheet of air at the outlet, demonstrating the potential of this nozzle design. However, velocity dropped significantly near the exit, and the prototype generated sharp noise and turbulence due to abrupt internal transitions and a lack of curvature. These findings informed subsequent design revisions aimed at achieving smoother flow, lower noise, and more stable performance for wearable use.

Nozzle Exist Geometry

Instead, wearable air curtains should focus on subsonic flow design, where the goal is to produce a stable, well-directed jet that forms an effective barrier around the user's respiratory zone. The Geometry of the Studies by Xu et al. (2020) emphasize the critical role of nozzle geometry in achieving this. In their CFD simulations, square nozzles outperformed circular and triangular designs, delivering 3% higher efficiency than circular and 4.1% higher than triangular nozzles. Square nozzles generated 31% stronger streamwise vortices, which promote stability and mixing, while also reducing undesirable spanwise vortices, which can cause backflow and energy loss.
Further supporting the importance of shape, Yadav et al. (2020) compared slotted and circular jets in an aircraft intake system and found that slotted synthetic jets offered superior lateral coverage, better flow control, and reduced distortion. These findings reinforce the idea that elongated, non-circular nozzles—such as slots or square shapes—are more effective for wearable applications, where a directed and stable airflow must adapt to body movement and environmental variability (see figure. 38 for design implement of slotted nozzle). While these design features may not appear significant individually, they were incorporated into the prototyping and design iterations so their impact on overall performance can be evaluated in further testing.

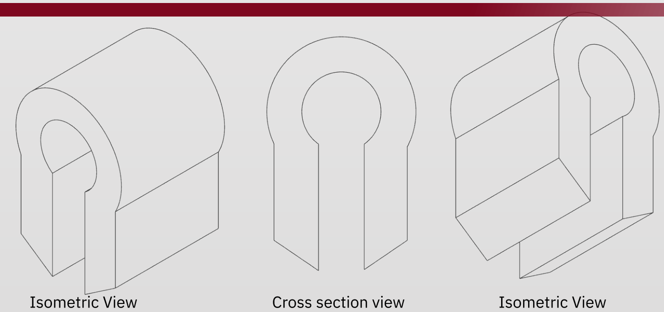


Figure 38 shows a design geometry iteration for one of the prototypes. In this version, the air nozzle utilizes cross-sectional flow, with the opening positioned on the side of the pipe and the nozzle lip offset from the outlet. The final product design features a slotted nozzle with a rectangular opening. This design element was later integrated into one of the nozzle variants (see Appendix J.) and tested in both physical prototypes and CFD simulations, using various aspect ratios between the air inlet and outlet. The results revealed a mix of advantages and disadvantages, which will be discussed in detail in later sections.

Coanda Effect

Flow guidance can also be enhanced using the Coanda effect, where air naturally follows a nearby surface . Designing nozzle outlets adjacent to curved forms—such as around the face or helmet—can help anchor the jet and reduce dispersion, improving directional stability without adding mechanical complexity (see figure. 39 for design implement with Coanda effect).

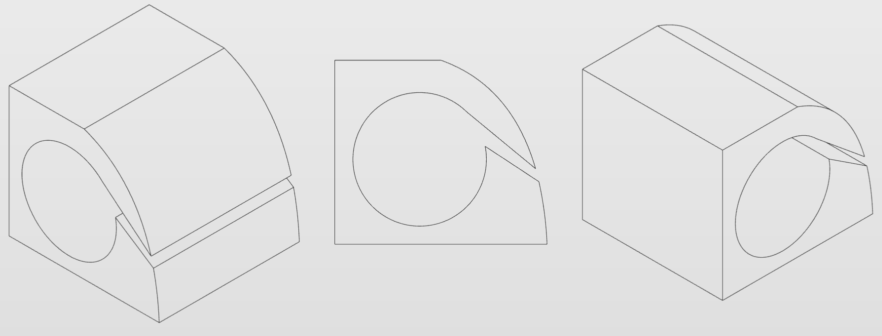


Figure 39. Design Iteration: This design element utilizes the existing product surface to guide a sheet of air in the desired direction. Initial evaluations were conducted using both physical tests with smoke visualization and CFD simulations. This image shows the first draft, in which sharp internal edges were later refined. The Coanda-style exit nozzle demonstrated promising effects in shaping and stabilizing the air curtain. However, a key drawback is that the nozzle requires additional structural support, as it tends to deform under pressure when made with PEG and PLA filament. It also significantly reduces the volume flow rate. Further details are discussed on page.

Honey Comb Structure

Another structural element worth considering in wearable air curtain design is the honeycomb flow straightener. These components help improve airflow stability by reducing turbulence and swirl, leading to a more uniform jet. Their application is well-established in wind tunnels, HVAC systems, and ducts with fans—especially in conditions prone to flow separation or unstable velocity profiles.

A study shows that screens and honeycombs placed within ducts can reduce flow separation and improve airflow consistency, screens with higher porosity are more effective at controlling separation, but this comes at the cost of increased pressure loss (Fadilah & Erawan, 2018), especially when multiple layers are used. The study also found the best performance was achieved when placing three fine-mesh screens (57% porosity) at the critical transition section and a honeycomb just downstream of the last screen. This combination minimized turbulence while maintaining acceptable pressure conditions(Fadilah & Erawan, 2018). These findings suggest that miniaturized honeycomb or grid structures could be integrated near the nozzle exit and transition section of wearable air curtains to stabilize flow (see figure. 40), especially in dynamic environments such as walking or turning. However, there are trade-offs. Designers must carefully balance the benefits of improved flow uniformity against drawbacks such as pressure drop, added weight, and manufacturing complexity—all critical constraints for wearable systems.

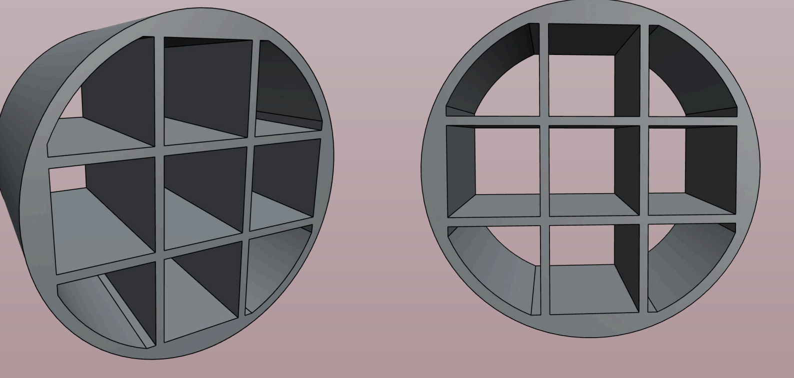


Figure 40. Design Implication: Several removable grid inserts like this were 3D printed in various sizes to fit inside pipes or nozzles at different locations. These components enabled quick experiments to evaluate the effect of honeycomb structures on airflow behavior. Their modular design allowed for flexibility—making it possible to test whether such flow straighteners were beneficial without needing to alter the entire model structure at an early stage.

Noise Level and Nozzle Relationships

Despite these established theories and principles, questions regard what type of airflow is optimal for wearable air curtains that blocks aerosols and particulates remains unknown. How to apply those principles into wearable designs still need to be explored. While higher velocities improve sealing and resistance to disturbance, they also introduce trade-offs such as increased entrainment, noise, and energy use. The next section, therefore, explore some key design considerations for designing for wearable air curtains.

Figure 41. Convergent nozzle design of the Dyson Airblade 9KJ hand dryer.
Source: Dyson (n.d.) https://www.dyson.ie/commercial/hand-dryers/airblade-db-white

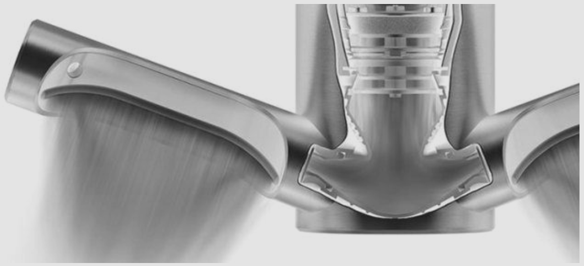


figure. 42 . Dyson Airblade V crossflow nozzle
Source: stratigicssupply (n.d.), retrieved from https://strategicsupplyllc.com/product/dyson-9kj-hu03-hand-dryer-aspx/

In the development of wearable air curtain systems, noise generation is an important factor influencing user comfort and acceptance, to establish a practical performance benchmark, the Dyson Airblade dB and Airblade V hand dryer is referenced as a high-performing commercial product that uses an air curtain for hygienic drying. The Airblade V is rated at 79 dB(A) and has received the Quiet Mark certification from the Noise Abatement Society for its relatively low noise emission. Dyson achieved this reduction by incorporating an aerodynamic motor housing, a redesigned impeller, an inner diffuser, and by narrowing its air apertures to 0.55 mm, compared to the conventional 0.8 mm. These refinements minimize turbulence and optimize the acoustic performance of the airflow path (QBIC Washrooms, n.d.). Despite its relative quietness, the Dyson Airblade still exceeds thresholds set by the National Institutes of Health (NIH) regarding long-term noise exposure. According to NIH guidance, continuous exposure to sound levels above 70 dB(A) can begin to impact hearing health, and levels above 85 dB(A) are considered potentially damaging hearing with long-term exposure (National Institute on Deafness and Other Communication Disorders [NIDCD], 2020). Therefore, while 79 dB(A) is considered acceptable for brief exposure in restroom environments, a wearable air curtain—especially one positioned near the ears—requires even stricter noise control to ensure comfort and safety during extended use.

To design for reduced noise levels, it is essential to understand how nozzle geometry and flow conditions contribute to sound generation. Research by Zaman stated that in convergent-divergent (C-D) nozzles, several distinct noise components are known to emerge when the pressure ratio does not match the nozzle's ideal operating conditions, Among these are: 1. Screech tones are sharp, high-pitched noises that happen when air patterns (vortices) hit certain points inside the nozzle and create a repeating loop of sound. This loop feeds back into the nozzle and keeps generating the noise. 2. Broadband shock-associated noise (BBSN) sounds like a deep, loud whooshing. It's caused when turbulent air hits stable shock waves inside or near the nozzle. Unlike screech, this noise doesn't involve a repeating feedback loop—it happens more randomly but over a wide range of frequencies. 3. Transonic tones are another kind of sharp noise, but these come from shock waves trapped inside the expanding part of the nozzle. The shape of the nozzle acts like a musical instrument (like a pipe), and the sound bounces back and forth, creating a tone. 4. Excess broadband noise is a newer finding by this study. It happens when shock waves inside the nozzle move around randomly and don't settle in one place. This leads to a loud, unsteady noise across many frequencies. It's most likely to occur when the nozzle is operating under lower-than-ideal pressure (Zaman, 2028). To minimize high noise levels, the nozzle geometry will be specifically designed to reduce shock formation.

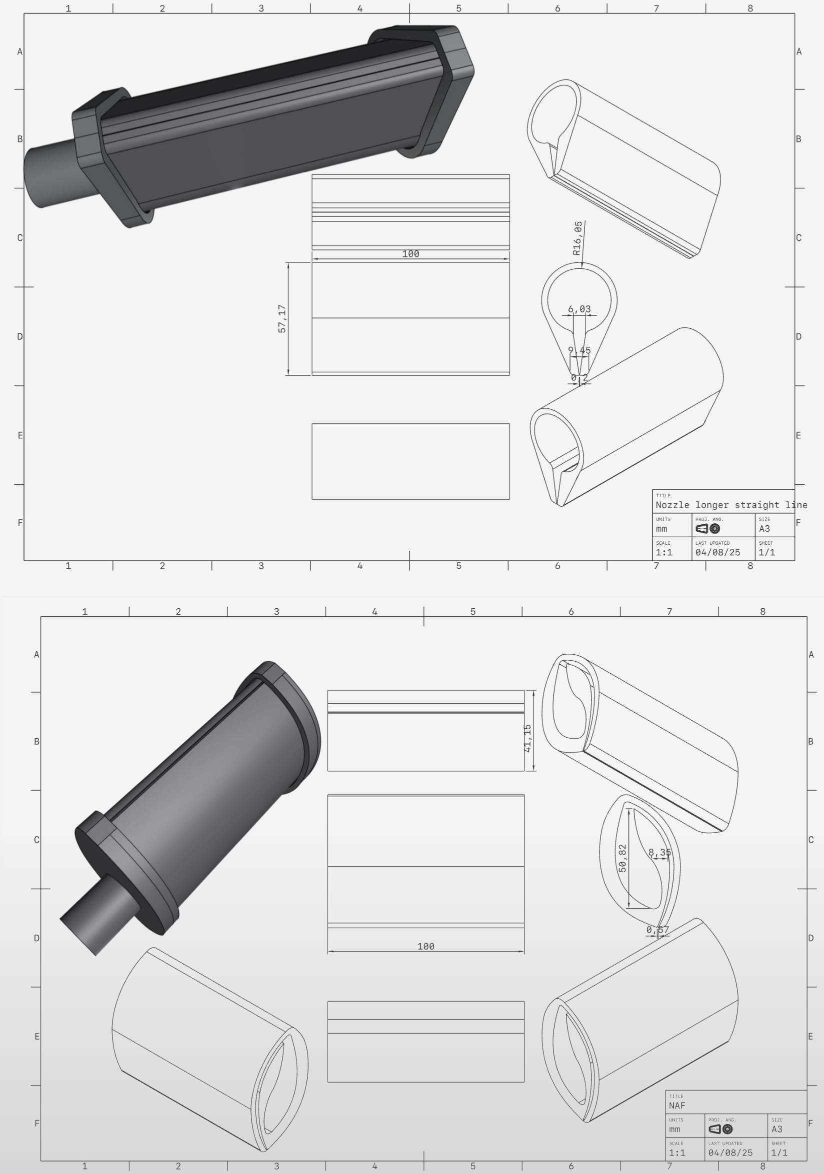


Figure 43. Design Implications of Two Nozzle Variations.

Figure 43 shows two types of nozzle designs. The nozzle design on the top produced a sharp noise during physical testing, whereas the version on the bottom significantly reduced noise levels. However, both designs were limited by their small outlet size. A revised version of the right-hand nozzle with a larger opening was later implemented to address this issue .

Jeon et al. (2023) investigated strategies to reduce noise generated by air nozzles by testing the effects of nozzle shape, airflow rate, and the distance between the nozzle tip and a reflection plate.The findings show that when the diameter ratio (diameter inlet : diameter outlet) exceeds 12:8, the noise level increases by more than 10 dB(A), regardless of the reflection plate's presence or position. Additionally, nozzle tip lengths shorter than 10 mm—particularly around 5 mm—are associated with significantly higher noise levels. The study attributes this increase in noise to sharp reductions in nozzle diameter, which lead to higher air velocities and the formation of intense vortices and turbulent flow, both of which amplify noise. The authors recommend designing nozzles with a diameter ratio below 12:8 and a tip length of at least 10 mm to effectively minimize sound intensity (Jeon et al., 2023).

Further validation of the nozzle geometry's impact on noise will be conducted through a combination of CFD simulations and physical testing, enabling comprehensive analysis and visualization. The following section presents a literature review of existing air curtain studies to inform and guide the design process.

From Air Curtain Performance to Aerodynamic Control : Applying Laminar Airfoil Principles to Wearable PPE Design

Drag refers to the resistance encountered by airflow as it moves through and around surfaces, and reducing it is critical for maintaining stable, efficient jet performance in wearable air curtain systems. The design references laminar flow airfoils, particularly those developed by Franz Xavier Wortmann (FX-series), which were originally created for sailplanes and optimized for smooth, low-drag airflow (Eagle Pubs, n.d.). These airfoils are geometrically distinct in that their maximum thickness occurs closer to the mid-chord, generating a favorable pressure gradient over the leading edge. This shape encourages the development of a laminar boundary layer over a larger portion of the surface, significantly reducing skin friction drag.

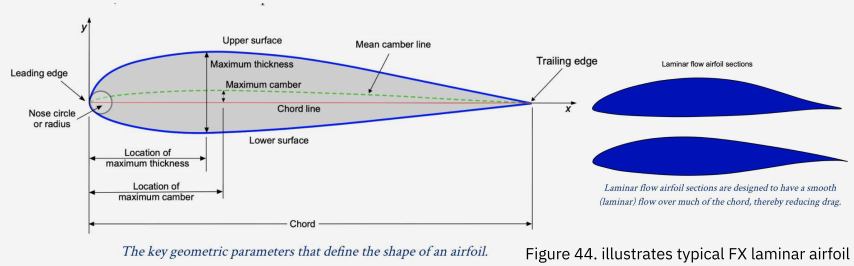


Figure 44. illustrates typical FX laminar airfoil profiles, which informed this design direction Retrieved from https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/airfoil-geometries/

For the design implication, Franz Xavier “FX” Wortmann developed a series of such airfoils—known as FX-airfoils—explicitly for sailplane applications. These airfoils are geometrically distinct from conventional aircraft wings, with the maximum thickness positioned closer to mid-chord. This configuration creates a favorable pressure gradient over the leading edge, encouraging a smoother and more sustained laminar boundary layer across the surface (Eagle Pubs, n.d.). The present design references this aerodynamic profile in its structural shell and nozzle casing to support directional jet stability. The rationale for applying this principle to a wearable structure lies in its ability to stabilize and streamline airflow

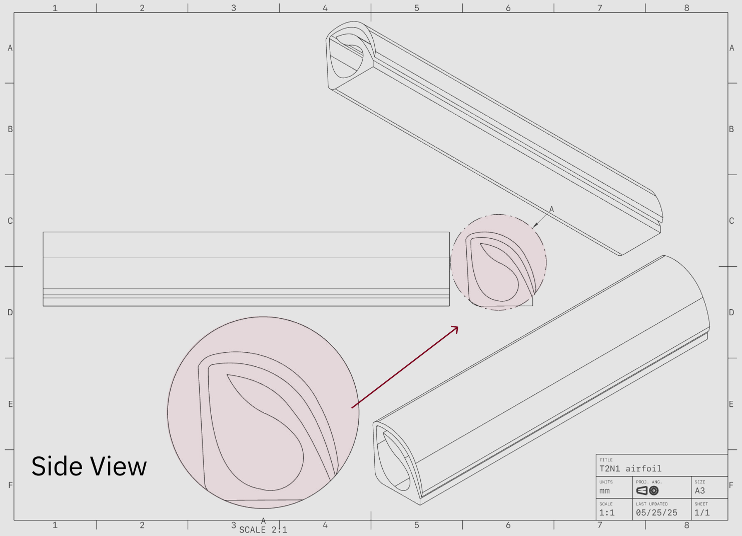


Figure 45. Design Implication of Laminar airfoil-Inspired Nozzle Cross-Section

Figure 45 shows a side view cross-section of a nozzle, where the exit geometry is inspired by the profile of a laminar flow airfoil. This nozzle demonstrated smooth, laminar flow behavior in both CFD simulations and physical prototyping. However, it delivered a lower volume flow rate compared to other nozzle configurations with similar opening size and length. The test proves that when the nozzle was slightly curved, the directional stability of the airflow is enhanced. Despite its aerodynamic advantages, the reduced flow rate compromised its ability to form a strong protective air curtain, **suggesting that achieving laminar flow should not necessarily be the top design priority**. In later iterations, the leading edge of the nozzle was further rounded, and this profile was adapted—with modifications—in the final design. Further details are discussed on pages.

around the head or body, particularly in designs involving directional jets or shielded zones. By mimicking the aerodynamic efficiency of sailplane wings, the nozzle casing or structural shell of the wearable device aims to reduce unwanted turbulence and drag forces. Sailplanes are designed to maximize glide efficiency by minimizing energy loss due to air resistance—principles that translate well to wearable airflow systems, where maintaining a stable, low-resistance jet is essential. Applying similar aerodynamic shaping helps guide airflow smoothly along the surface, reducing sudden pressure changes and flow separation. This contributes to maintaining flow coherence, improving directional control, and extending the effective range of the air curtain—especially in compact systems with limited power (see Figure 45 for design implication).

While laminar airfoil shapes are advantageous for reducing drag, they come with trade-offs. Their sensitivity to surface quality requires a clean, smooth finish to maintain aerodynamic performance, and their lower maximum lift coefficients can reduce corrective responsiveness in highly dynamic conditions.
While airfoils were developed for wings in flight, the underlying aerodynamic principles—minimizing drag, managing pressure gradients, and stabilizing laminar flow—are applicable to any situation where air needs to move smoothly over a surface or through a confined space. In wearable air curtain systems, even though the scale, speed, and function differ from aircraft, the goals are similar: to control airflow, reduce energy loss, and avoid premature turbulence.
For example, just as an airfoil shape delays flow separation along a wing, a carefully shaped nozzle casing or outer shell in a wearable device can help guide air more efficiently, reduce resistance, and maintain a coherent jet—critical for protective performance. Therefore, borrowing these principles allows wearable designs to benefit from decades of aerodynamic optimization, even in a very different context.
For wearable devices, this means the airflow shell must maintain cleanliness and precision to achieve optimal results.
Although the shape was adapted without extensive aerodynamic calculation, the design lays the groundwork for future refinement. Tools like XFoil, a widely used software for airfoil analysis, can predict aerodynamic performance with high confidence and may be used to fine-tune nozzle and shell shapes in subsequent development phases. The image referenced in Figure 44 illustrates typical FX laminar airfoil profiles, which informed this design direction.

Physical Ergonomic Consideration for Nozzle Design

The product design of the wearable air curtain prioritizes both comfort and functionality to maximize user engagement and acceptance. As the device is intended to be worn on the head to protect the breathing zone, the study focuses on the ergonomic aspects of the head and neck area, which were defined during the conceptualization phase.

A primary consideration is the weight of the device, as this serves as a critical benchmark for assessing whether the proposed solution represents a meaningful improvement over existing head-mounted PPE. Current market alternatives are often reported to be excessively heavy, contributing to discomfort and reduced compliance among users. A study published in the National Library of Medicine, titled The Effects of Head-Mounted Weight on Comfort for Helmets and Headsets, investigated the concept of "comfortable wear time." stated even the lightest tested headset (500 g) was not tolerable for all participants over the full two-hour period. Discomfort extended beyond expected issues such as neck fatigue or contact pressure, manifesting in symptoms associated with motion sickness, including headaches and dizziness. Moreover, an average reduction of 11 minutes in comfortable wear time for every additional 33 g of weight (Odell & Dorbala, 2024). To ensure both functionality and usability, the integration of functional components into head-mounted systems must not exceed 500g. the function unites, if the weight exceed 500g, will be considered to move to other wearable location.

Another key design factor is size and anatomical fit, as the air nozzle must form a reliable seal around the user’s breathing zone to function effectively. In this context, proper coverage width and depth are critical to ensure performance, comfort, and user compliance. To define the dimensional envelope, anthropometric data was sourced from the CAESAR (Civilian American and European Surface Anthropometry Resource) database, focusing on Dutch male adults aged 18–66, in alignment with the legal working age range in the Netherlands and the intended occupational use of the product (Netherlands Enterprise Agency, n.d.).

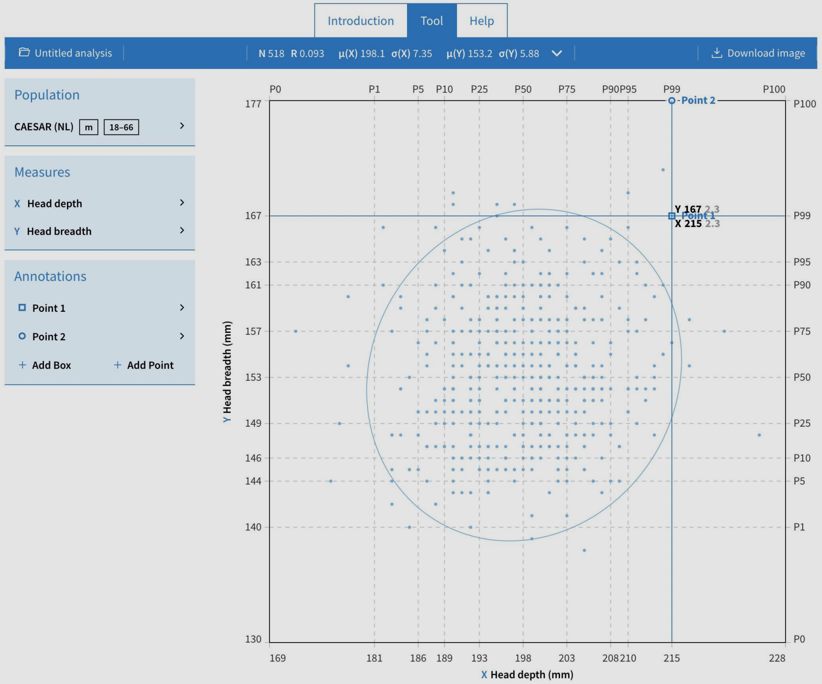


Figure. 46 CAESAR (Civilian American and European Surface Anthropometry Resource) database, the head breadth and depth for Dutch males aged 18–66

The selected parameters—head breadth (Y-axis) and head depth (X-axis)—are critical for ensuring that the product conforms closely to the wearer’s head without excess bulk or gaps. According to the dataset in figure. 46, the mean head breadth for Dutch males is approximately 153.2 mm, and the mean head depth is 198.1 mm, with standard deviations of 5.88 mm and 7.35 mm respectively. To ensure sufficient coverage for nearly all users, a maximum head breadth of 167 mm (16.7 cm) was selected, corresponding to the 99th percentile of this population group. This sizing ensures that the air curtain device can accommodate 99% of Dutch working-age men. while minimizing the need for individual adjustment or multiple size options.

Beyond the physical dimensions and ergonomic fit of the product, user comfort during use also depends heavily on the sensory experience of airflow. In wearable air curtain systems, this means not only ensuring the device fits well, but also that the wind generated does not cause discomfort. One of the key factors in this regard is the sensation of airflow on the skin, which can influence perceived comfort, acceptance, and prolonged wearability.A study published in Applied Ergonomics examined the impact of draught in relation to air velocity, air temperature, and workload. The experimental research was designed to test the hypothesis that draught-induced discomfort increases with higher air velocity, lower air temperature, and reduced physical workload. Thirty healthy young males were exposed to horizontal airflow for 55 minutes while operating an arm ergometer in a standing posture. The results indicated that, in order to reduce draught-related annoyance, air velocity should be maintained below 0.2 m/s, particularly when turbulence intensity reaches approximately 50% (Griefahn et al., 2001).

In addition, the Sauermann Group reported that air velocity near the body surface must be carefully regulated, as flows exceeding 0.2–0.3 m/s can cause discomfort, cold sensations, and user dissatisfaction—especially in seated or inactive individuals. For the air velocities: Between 0.2 and 0.3 m/s may lead to noticeable discomfort in low-activity settings. Between 0.3 and 0.4 m/s are generally unsuitable for offices but may be tolerated during physical exertion. Above 0.4 m/s are effective for cooling during active tasks or in heat-intensive environments (Sauermann Group, n.d.).

Implications for Physical Ergonomics Design

To meet the dual goals of user comfort and functional effectiveness, the wearable air curtain must balance weight, fit, and airflow performance. These parameters are guided by both ergonomic data and sensory comfort thresholds.

The total weight of the product should not exceed 500 grams, addressing common complaints about head-mounted PPE being too heavy for long-term use. The design must also be adjustable to accommodate a range of head sizes, with horizontal coverage of at least 167 mm, ensuring it fits up to the 99th percentile of Dutch working-age males. To support a universal fit, soft or flexible materials can be integrated to allow adaptability without compromising seal integrity.

Equally important is the aerodynamic comfort of the device. During performance evaluations, air velocity directly contacting the skin should remain below 0.2 m/s, as higher speeds can cause discomfort or cold sensations. However, in regions not in direct skin contact—such as areas buffered by clothing or redirected airflow—velocities up to 0.4 m/s are permissible, especially during physical activity, where moderate cooling is beneficial.

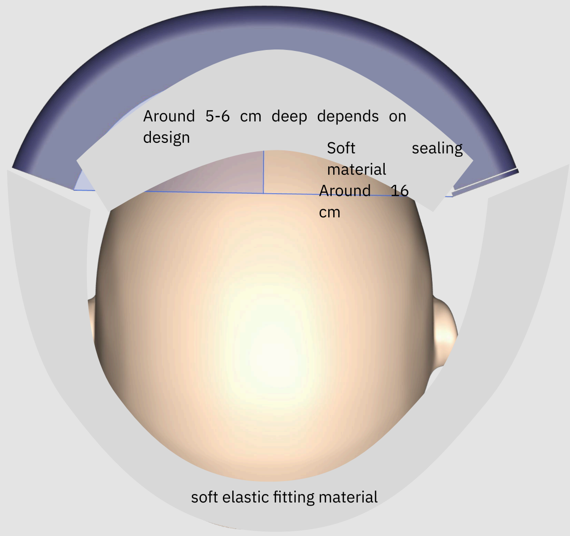


Figure 47. CAESAR-Based Design Implication for Air Curtain Coverage

The Figure 47 shows the CAESAR-based design implication for air curtain coverage: The purple zone represents the targeted coverage area of the air curtain, focused on protecting the breathing zone while maintaining clear visibility. The shaded area indicates soft material zones intended to secure the headpiece and enhance ergonomic fit. This configuration aims to achieve a tight seal and a universal fit across a wide range of head sizes, while ensuring comfort and unobstructed sight.

Established Findings and Open Questions for Air Curtain Development

The development of a wearable air curtain requires balancing aerodynamic performance, user comfort, and environmental adaptability. Literature shows that nozzle geometry strongly influences airflow stability: convergent or square nozzles, slotted jets, and features like flow straighteners or Coandă surfaces can improve directionality, reduce turbulence, and enhance jet performance. Comfort studies indicate that air velocity on skin should remain below 0.2 m/s, with up to 0.4 m/s acceptable if buffered by clothing. Insights from devices such as the Dyson Airblade highlight noise reduction strategies, including narrowed apertures, optimized flow paths, and careful control of nozzle lips, angles, and shock formations.

Despite these advances, critical unknowns remain. The airspeed and coverage width needed for effective respiratory protection in dynamic, wearable contexts are undefined, and little data exists on performance during human motion or under disturbances like wind and thermal plumes. The real-world protective effectiveness—how well contaminated air is excluded in practice—also remains unclear.

Taken together, these findings establish the theoretical foundation for defining assumptions, setting up CFD simulations, and determining key performance criteria for the air curtain design. They also inspired local elements of the product structure that govern the properties of the airway. Building on this foundation, the next section focuses on defining the characteristics of the ideal airflow required for personal respiratory protection and examining whether such designs can reliably deliver airflow—albeit primarily under static rather than dynamic conditions.

Part 2 :Ideal Airflow Simulation

Objective

The primary objective of the simulations was to evaluate and optimize the airflow behavior and aerodynamic sealing effect of the air curtain system. The goal was to inform design decisions related to airflow direction, velocity uniformity, and coverage of the user's breathing zone, ultimately enhancing comfort and protective performance.

Part 2.1 Independent Mesh Setting CFD Mesh Settings for Accurate and Efficient Simulation

A mesh study was conducted prior to the simulations to ensure numerical accuracy and solution stability.

Simulation Objectives

The aim of this mesh independence study is to identify the optimal mesh setting that balances computational efficiency and result accuracy for CFD simulations of a simplified air nozzle model, as a foundation for more complex future models that will evaluate velocity distribution and stream precision, particularly at the nozzle outlet.

Assumptions and Set up

The simulation setup is based on several simplifying assumptions. It employs a simplified 20 cm nozzle that is assumed to cover 99% of all relevant faces. The area near the nozzle is treated as the primary critical airflow region because it directly corresponds to the breathing and eye zones. Therefore, the mesh is very coarse outside of this localized region. This simulation does not consider gravity, wall friction, heat transfer, or material conduction, since the primary focus at this stage is airflow, assuming that it will not make a significant difference in airflow. Air is treated as an ideal fluid, and interactions with wall materials are not included in the analysis.The inlet velocity at the nozzle is defined as 30 m/s, corresponding to an available blower speed. This choice facilitates future comparison between simulation results and physical test data.

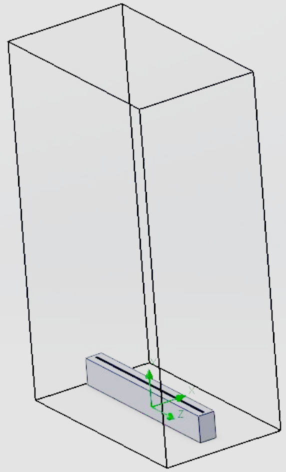


Figure 48. 3D model visualization of the computational domain, showing the simplified nozzle geometry embedded in the simulation box. The domain dimensions represent the localized breathing zone and surrounding airflow region.

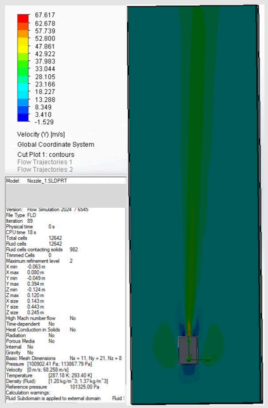


Figure 49. Velocity contour plot of coarse mesh simulation (~12,600 cells). Simulation time: ~18 s

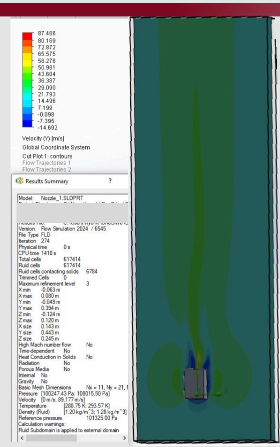


Figure 50. Velocity contour plot of a coarse mesh (~617,000 cells, refinement level 3). Simulation time: ~24 minutes.

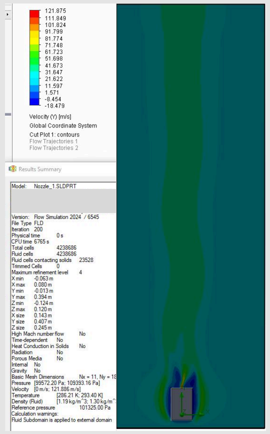


Figure 51. Velocity contour plot of medium-resolution mesh (~4.2 million cells). Simulation time: ~1.9 hours.

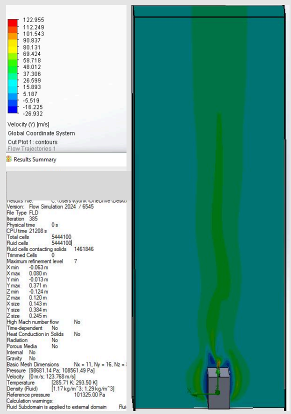


Figure 52. Velocity contour plot of refined mesh (~5.4 million cells).

Simulation time: ~5.9 hours.

Result

The mesh strategy began with a coarse global mesh applied to the overall geometry, followed by gradual refinement focused around the nozzle exit, the region critical for accurately capturing airflow characteristics. Initially, the coarse mesh contained approximately 12,642 cells, resulting in disconnected airflow patterns on the velocity cut plot. Incremental refinements improved streamline continuity significantly at around 4.8 million cells. Further refinement from 5 to 6 million cells produced nearly identical cut plot results (see figure 49-52).

Implication

Based on this analysis, a mesh of approximately 5 to 6 million cells was found to provide sufficient resolution for accurately capturing airflow behavior in a product with a width of 20 cm. The simulation domain approximates the user's breathing zone and primary airstream, with dimensions of 22 cm × 30 cm × 10 cm (± 5 cm). This mesh density balances computational efficiency with the need for detail in critical flow regions. While this resolution is suitable for the current setup, specific mesh requirements may vary depending on the geometric complexity of different nozzle configurations and domain size.

Discussion and limitations

The mesh refinement process involved incrementally increasing mesh resolution until further improvements in airflow visualization became negligible, thus indicating convergence. At around 5 million cells, computational demands became significant, requiring approximately 25 hours on the available computing resources. A coarse global mesh was maintained due to the geometric simplicity of the domain, while local mesh refinement around the nozzle region was prioritized to ensure accurate airflow results.

Limitations of this study include simplified assumptions, such as neglecting gravity, wall friction, heat transfer, and material conduction. Additionally, airflow dynamics related to movement or realistic room interactions were not considered. The geometric simplicity also represents a limitation, as more complex internal geometries could significantly influence the airflow patterns.

Part 2.2 Simulate airflow under static conditions

Assumptions

The following assumptions were made in this simulation to estimate the ideal nozzle opening size and determine the minimum airflow velocity required to achieve effective particle blocking for this study:

- Airflow can be achieved through design; therefore, this simulation focuses solely on flow behavior rather than fan or compressor constraints.
- The airflow is considered to be steady-state and incompressible.
- The temperature effects are assumed to be negligible/constant at 20°C.
- The surrounding environment is modeled as quiescent air with no crossflow or obstructions.
- Human thermal plume or breathing effects are not included at this stage are represented as simplified volumetric sources.
- The simulation domain approximates the user breathing zone with dimensions of approximately 22 cm × 30 cm × 10 cm (± 5 cm). These dimensions reflect an average adult facial region and provide a realistic test volume for assessing directional airflow behavior and blockage efficiency.

Set Up

The Solidworks CFD simulation setup included five types of nozzle configurations: 1 mm nozzle opening, 2 mm nozzle opening, 3 mm nozzle opening, 2 mm nozzle with a 5 cm side extension, representing the distance from the eyebrows to the eyes (to explore future design options for preventing drought around the eye area, 2 mm nozzle with a 10 cm side extension, covering the nose area for potential airflow control over the mid-face zone (see figure. 56)The technical drawing of the nozzle configurations can be found in Appendix. J.

If the results indicate that airflow performance scales proportionally with nozzle size—without compromising jet stability or pressure—the design will be adjusted accordingly to include larger openings. This approach allows performance-driven refinement, rather than assuming optimal dimensions in advance.

Each nozzle was tested with air exit velocities of 1 m/s, 5 m/s, and 10 m/s. The simulation ignored the effects of gravity and nozzle orientation, focusing purely on the behavior of the air jet. The mesh refinement level is set to 5 million cells referencing the result from independent mesh setting.

A tracer gas study was also conducted using SO_2 (sulfur dioxide), selected from the database due to its molar mass of 64.066 g/mol, which is heavier than that of air (28.96 g/mol). This choice ensures that the gas behavior simulates heavy particle behavior more realistically in the flow analysis. The simulation environment was set up as follows: The nozzle was placed in an L-shaped configuration (see Figure 53-55). A wall surface parallel to the nozzle was treated as the source of chemical contamination, with a mass fraction of 1.0 assigned at the surface. The initial condition of the surrounding environment was set with a mass fraction of 0.0 (no contamination initially). The configuration is shown in figure 53-56.

It must be noted, however, that SO_2 remains a gaseous species and does not replicate all aspects of particulate behavior. In particular, particles are subject to inertia, gravitational settling, deposition on surfaces, and size-dependent dispersion, none of which are fully captured by a gas-phase tracer. Therefore, the SO_2 tracer should be interpreted as a qualitative proxy that highlights airflow patterns and potential leakage pathways, rather than a direct quantitative substitute for dust exposure.

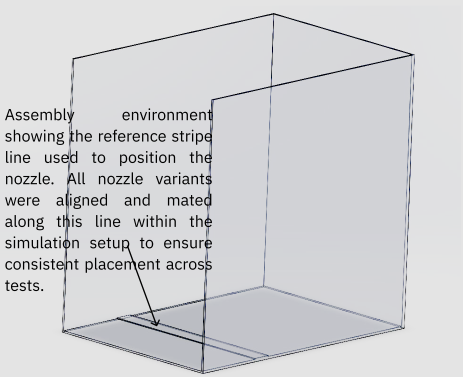


Figure 53. Assembly environment used for simulations. The walls define the contained region for measuring airflow and contaminant dispersion before and after nozzle operation. The enclosure is not fully closed to avoid unrealistic pressure buildup.

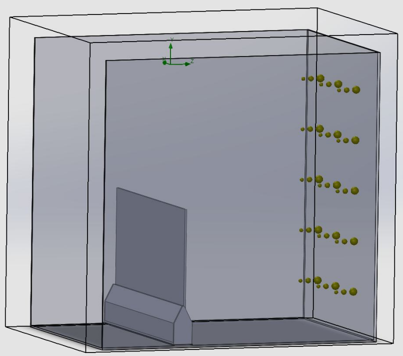


Figure 54 TBoundary condition setup for contaminant dispersion. The vertical wall with yellow particles represents the contaminant source (initial mass fraction = 1), while the surrounding environment starts at mass fraction = 0.

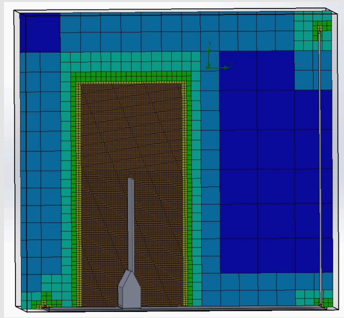
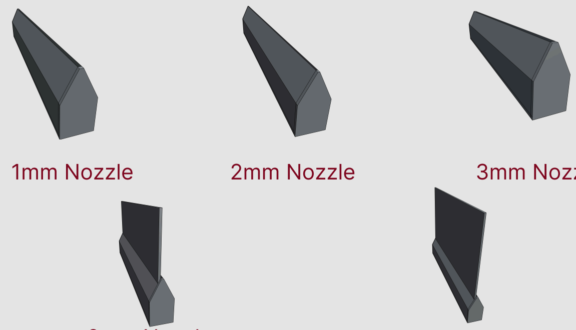


Figure 55. Mesh configuration. A refined local mesh is applied around the nozzle to capture detailed flow features, while a coarser global mesh is used to enclose the overall setup and reduce computational time.



Performance Criteria

The airflow performance was assessed based on two main aspects: how concentrated and stable the airflow remained with Velocity Cutplot , and how effectively the air curtain blocked contamination with Tracer Study Cutplot.

Velocity Cutplots were used to assess:

1. Jet Stability – whether the air jet remains narrow and coherent after exiting the nozzle.
2. Penetration Length – the distance over which the jet maintains sufficient momentum, identified as regions where velocity remains above 50% of the exit value.
3. Laminarity vs. Turbulence – determined by whether the velocity contours form smooth, continuous profiles or break into irregular eddies.

Tracer Cutplots were used to assess:

1. Blocking Efficiency – the degree to which the tracer gas is excluded from the protected zone, quantified by mass fraction reduction.

2. Leakage Pathways – the presence of regions where tracer gas bypasses the curtain (e.g., side flow, recirculation).
Combined Criteria included:
3. Sensitivity to Nozzle Geometry – how different nozzle openings and extensions alter jet stability and blocking performance.
4. Energy Efficiency – inferred by comparing the velocity required for effective tracer blocking to the overall aerodynamic stability.

Velocity Cutplot Result and Analysis

The primary evaluation focused on how well the air stream remained concentrated and how long it maintained laminar flow. This criterion is critical because a stable, laminar jet minimizes turbulence and entrainment of surrounding air, thereby preserving directional control and extending effective reach. For protective applications, this directly influences the air curtain's ability to form a consistent barrier around the breathing zone, improving both aerodynamic performance and protective efficiency. The detailed velocity cut plot results for the different nozzle geometries are presented on the next page in Figure 57.

1 m/s Condition-The velocity fields at 1 m/s revealed unstable and weak jets. For the 1 mm and 2 mm nozzles, the flow dissipated rapidly and broke into vortices, leaving no clear separation. The 3 mm nozzle produced a slightly stronger jet but still lacked sufficient momentum to maintain coherence. The 5cm extension geometry produced weak, unstable flow. The confined outlet geometry caused premature separation and low-velocity recirculation zones directly at the nozzle lip, however, the 10cm extension geometry shows a strong airflow. The reason need to be further studied.

5 m/s Condition-At 5 m/s, all nozzle geometries exhibited stable and coherent jets that extended significantly further into the domain. The 2 mm and 3 mm nozzles produced the most efficient velocity profiles, with high momentum concentrated in the core and limited dispersion. The extensions still displayed some recirculation effects near the outlet but maintained overall coherence.

30 m/s Condition -At 30 m/s, all jets were highly coherent and sustained across the domain. The 3 mm nozzle produced the thickest, most uniform jet, while the 2 mm nozzle showed similarly stable flow. The 1 mm nozzle maintained high velocity but with a narrower jet and signs of shear-layer instabilities. Extended geometries generated asymmetric velocity distributions due to confinement at the outlet walls, with the 10 cm extension showing the strongest deviation.

Tracer Study Cutplot Result and Analysis

The tracer study evaluated how effectively the air curtain prevented the spread of airborne contaminants. The detailed result can be found on figure. 58 on page67.
The performance was calculated using the following efficiency formula:

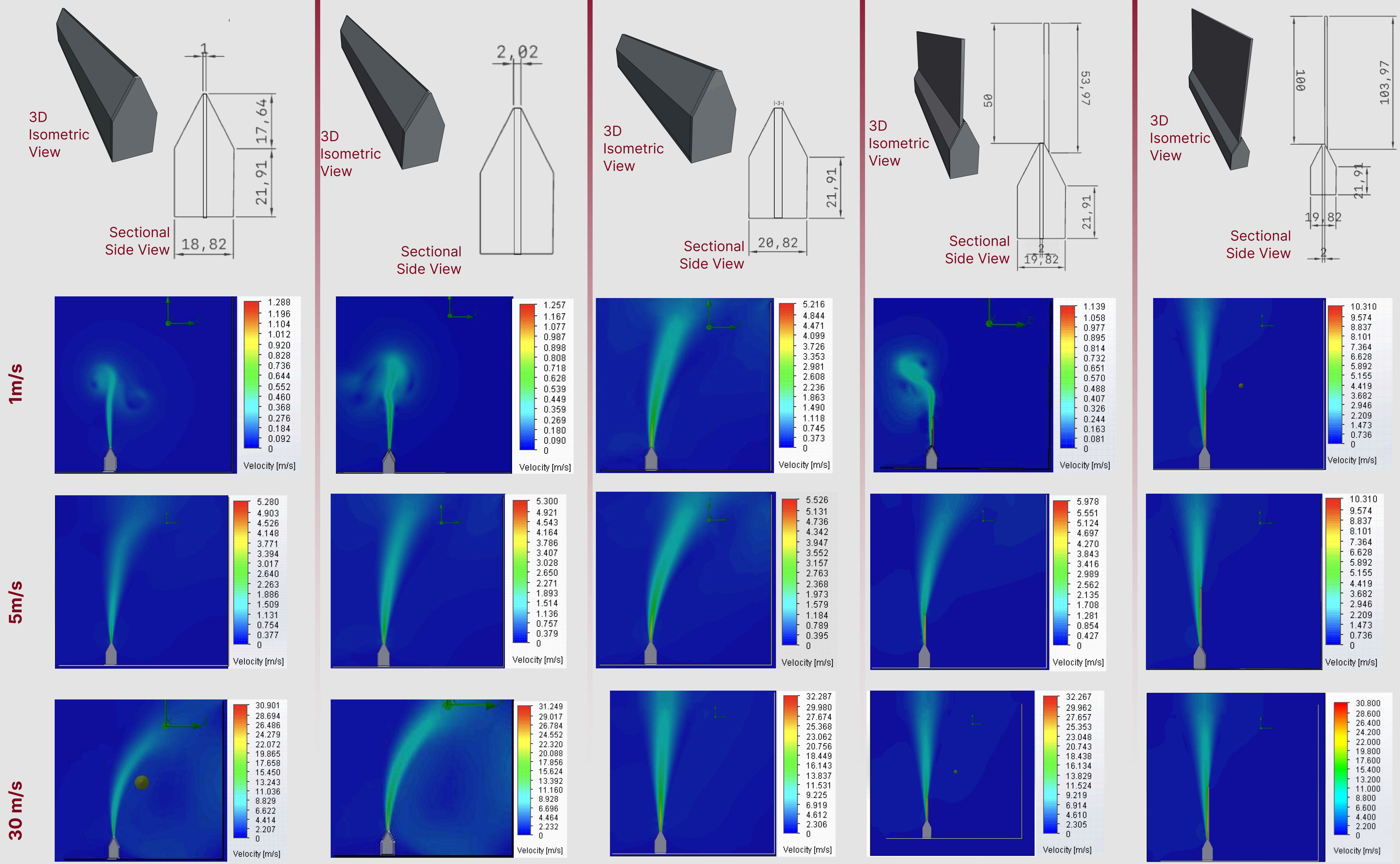
$$\eta = \frac{M_{\text{before}} - M_{\text{after}}}{M_{\text{before}}} \times 100\%$$

- Mbefore = the average mass fraction in the region upstream of the air curtain, taken from the contaminant source before interacting with the curtain.
- Mafter = average mass fraction in the protected zone behind the air curtain.
- η=0% → no improvement (same contamination as baseline).
- η=100% → complete removal (no contamination behind curtain).

At 1 m/s Condition, Assuming a baseline contamination of Mbefore = 1.0 (100% contamination at the source), the tracer cutplots reveal varying levels of leakage into the protected zone. For the 1 mm nozzle, a large light-blue region appeared on the left side of the flow field, corresponding to a downstream tracer concentration of 0.29. The calculated effectiveness was η = (1.0 - 0.29) / 1.0 × 100% = 71%. For the 2 mm nozzle, smaller patches of tracer were observed, with concentrations of 0.14 and an effectiveness of η = (1.0 - 0.14) / 1.0 × 100% = 86%. The 2 mm nozzle with 5 cm extension showed localized leakage between 0.07 and 0.14, giving an effectiveness range of η = 86–93%. The 2 mm nozzle with 10 cm extension and the 3 mm nozzle both maintained tracer-free protected zones, corresponding to ~100% effectiveness. Both 5 m/s and 10 m/s Conditions shows all nozzle configurations were fully blocked tracer crossover. The protected zone on the left side appeared entirely blue, corresponding to η = (1.0 - 0.00) / 1.0 × 100% = 100%.

Discussion

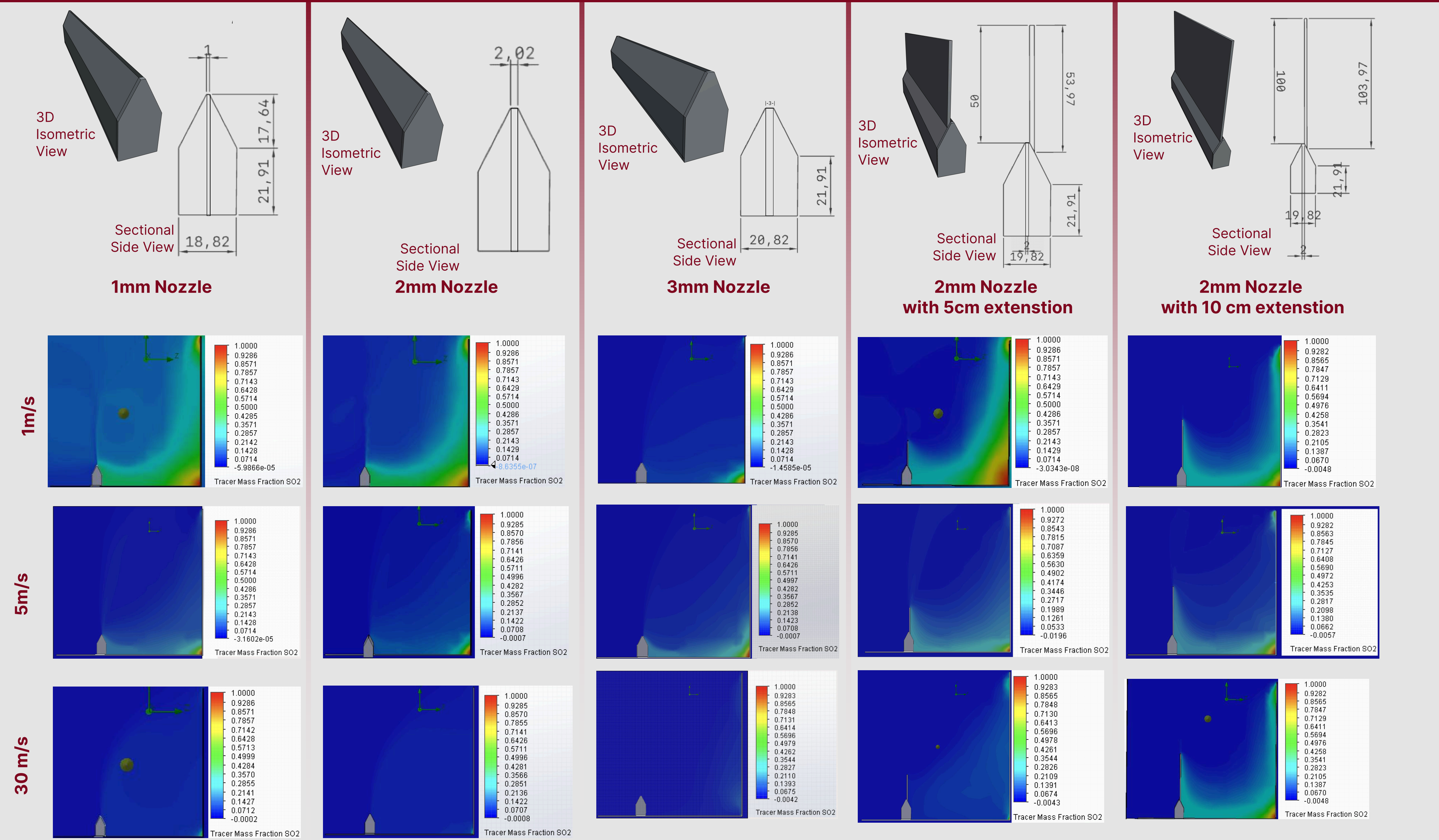
At 1 m/s, the 1 mm nozzle, 2 mm nozzle, and 2 mm + 5 cm extension allowed tracer penetration, showing that low turbulence and weak jet momentum reduce barrier effectiveness. In contrast, the 3 mm nozzle and 2 mm + 10 cm extension provided cleaner separation, suggesting that higher volumetric flow and longer barriers improve blocking. At 5 m/s and 30 m/s, both velocity and tracer cutplots consistently showed complete protection, indicating that the optimal operating speed lies between these ranges. The tracer study only captures gaseous contaminant behavior, while the transport of particulates remains uncertain. A particle study is therefore introduced in the next section (see page figure 59.). Finally, although some nozzle geometries achieved high effectiveness, their current shapes are unsuitable for wearable integration, underscoring the need for further design refinement.



Velocity Cutplot

The table above (Table Comparative visualization of nozzle geometries and velocity cut plot results at three inlet velocities (1 m/s, 5 m/s, 30 m/s). Each column represents a different nozzle configuration (1 mm, 2 mm, 3 mm, 2 mm + 5 cm extension, 2 mm + 10 cm extension), showing the 3D isometric view, sectional side view, and corresponding velocity contours.

Figure 58. Tracer Study Cut Plot Matrix for Different Nozzle Geometries



Tracer Study Cutplot Analysis

The table above is tracer study cutplot for different nozzle geometries (1 mm, 2 mm, 3 mm, 2 mm with 5 cm extension, and 2 mm with 10 cm extension) under three inlet velocities (1 m/s, 5 m/s, and 30 m/s). The nozzle is represented by the gray block at the bottom, with contaminants introduced from the right side wall with 100% tracer concentration. Effective blocking is indicated by the absence of tracer crossover into the left side of the nozzle as protected zone.

Particle study

In addition to velocity and tracer mass-fraction cutplots, a particle study was performed to examine the behavior of discrete particulates in the vicinity of the air curtain. Unlike tracer gas, which disperses diffusively and is deflected by velocity gradients, discrete particles interact with the jet primarily through drag forces.

The simulation results indicate that particles released near the contaminant source boundary are not consistently deflected away from the breathing zone. Instead, many particles are entrained into the high-momentum jet core, as shown by their alignment with the central velocity streamlines. Rather than forming a protective “barrier,” the air curtain in this case acted as a conveyor, capturing particles at the shear layer and accelerating them downstream. This finding suggests that the jet’s entrainment capacity dominates over its repelling capacity for particles of the size and density tested.

The implication of this behavior is twofold. First, while the air curtain demonstrates high blocking efficiency for gaseous contaminants, its effectiveness against particulate matter may be limited if entrainment pathways are present. Second, nozzle geometry and operating velocity must be carefully selected to minimize this effect. Narrow, high-velocity jets enhance entrainment, whereas wider or more diffuse jets may act more effectively as deflecting barriers. In practical terms, if entrainment cannot be avoided, the air curtain must be integrated with downstream capture or filtration strategies to prevent inhalation of particles transported by the jet

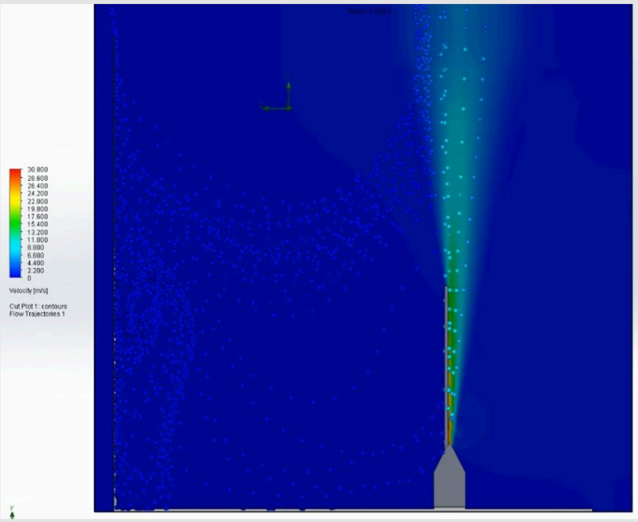


Figure 59. Particle study showing the trajectories of discrete particles entrained within the air curtain jet. The visualization illustrates how particles interact with the velocity field: rather than being deflected away, many are captured within the high-momentum core and transported downstream. The color scale represents airflow velocity [m/s], while particle traces highlight the entrainment effect and potential transport of contaminants along the jet path.

Integrated Interpretation

The velocity cutplots illustrate the persistence of the coherent jet core and the onset of shear-layer separation or recirculation, while the tracer cutplots translate this flow behavior into blocking efficiency, as indicated by contaminant mass fractions in the breathing zone. The most effective protection occurs when the jet maintains a stable, sheet-like core that extends to the breathing zone without breaking into vortical structures. The 1 mm nozzle generates a thin, high-shear jet that is highly susceptible to roll-up, producing vortex-induced leakage pockets even at 30 m/s. In contrast, the 2 mm and 3 mm nozzles without extensions create thicker, more stable jets, with smoother velocity gradients and deeper penetration, corresponding to consistently low downstream tracer concentrations. Nozzles with 5–10 cm extensions extend the coverage region at moderate velocities but introduce sharp-lip separation and wall-bounded recirculation, leading to localized tracer accumulation, particularly at higher speeds. At 1 m/s, all jets dissipate rapidly, allowing contaminants to penetrate the breathing zone. At 5 m/s, the jets remain coherent and largely exclude tracer, with only minor edge leakage. At 30 m/s, near-complete exclusion is achieved across all geometries, although geometry-induced instabilities in the 1 mm nozzle and long extensions still generate localized leakage pockets.

Limitations

Simplified Contaminant Source – The tracer release was modeled as a uniform wall boundary with constant concentration, which does not fully capture transient or spatially varying emission patterns that may occur in real occupational settings.

Steady-State Assumption – The analysis focused on quasi-steady cutplots, while in practice the jet–contaminant interaction is inherently transient, with vortex shedding and turbulence fluctuations that could alter short-term exposure.

Limited Geometric Variants – Only three baseline nozzle widths and two extension lengths were tested, restricting conclusions about other potentially effective geometries such as tapered, curved-lip, or slot-diffuser designs.

Boundary Condition Constraints – The velocity inlet conditions were idealized (1, 5, and 30 m/s) without accounting for real blower performance curves, pressure losses, or variability in operating conditions.

Single Contaminant Type – The tracer was modeled as a passive scalar (SO_2), neglecting particle inertia, humidity, or reactive chemical properties that may influence transport and deposition.

Ignoring Human Interaction – The simulations assumed a static breathing zone without modeling thermal plumes, human movement, or respiratory cycles, which strongly affect exposure dynamics.

Implication

The combined velocity, tracer, and particle studies indicate that airflow performance depends not only on jet stability but also on volumetric flow. At low speeds (1 m/s), small openings such as 1 mm or 2 mm failed to form an effective barrier, allowing tracer penetration. By contrast, the 3 mm opening at 5 m/s maintained clean separation, suggesting that higher volumetric flow, supported by physical barriers, can compensate for turbulence and achieve stable containment. The particle study, however, demonstrated that entrainment remains problematic, as discrete particles tend to be carried within the jet core, underscoring the limitation of relying solely on airflow. A separate clean-air supply may therefore be required to ensure robust protection. Incorporating physical barriers could also reduce airflow demands while maintaining efficiency, helping to balance protection, comfort, and energy use.

Whether such airflow rates can realistically be achieved in a wearable system remains uncertain, and the feasibility of integrating these requirements into personal protective equipment has not yet been established. The findings further suggest that an airflow speed of around 5 m/s provides sufficient coverage, while higher speeds (up to 10 m/s) may help reduce the buildup of surrounding contaminants. The optimal operating range is therefore expected to fall between 5 m/s and 30 m/s.

Part 3 :Preliminary Evaluation of Air Supply and Initial Nozzle Designs

Theoretical Basis and Objective

The first prototype featured a triangular nozzle geometry designed to diffuse air evenly along a linear path. The primary aim was to assess its potential for blocking airborne particles and determine its feasibility for integration into a wearable helmet-based air curtain system. This geometry was chosen to create a uniform air curtain emerging from a central pipe outlet through an angled, triangular dispersion mechanism.

Methodology

The paint spray blockage test (PSBT) was conducted in the TU Delft Model Making and Machine Lab (PMB Lab), within its designated spray paint room —a motor-free zone meeting safety regulations. Compressed air was supplied through a centralized pipeline connected to a regulator, allowing pressure adjustments between 1–8 bar, and routed to the spray room via rubber piping. The spray room is equipped with a ventilation system that maintains a continuous left-to-right airflow. While this airflow creates slight turbulence, it remained consistent across all tests, ensuring comparable and reliable results.

For the test, neon yellow aerosol paint was directed at A4 paper targets positioned 60 cm downstream from the nozzle outlet. Tests were conducted at inlet pressures of 1, 2, 3, 4, 5, and 6 bar. The aerosol can was fixed in position with a spray duration of 10 seconds per trial to standardize exposure. Volume flow was not recorded, as the air supply system did not specify flow rate.

Effectiveness was quantified by scanning the resulting paint patterns and performing histogram analysis in Photoshop to extract mean luminance, standard deviation, and median luminance. Higher mean luminance values indicated greater paint deflection (brighter paper surface), while higher standard deviation suggested uneven deposition due to turbulence or unstable airflow. Noise was not measured instrumentally, but qualitative observations were noted during testing.

A pilot test was conducted to observe the test flow, as shown in Appendix I.

Test Equipment and Materials

The following tools and materials were used to support the nozzle performance evaluations:

- Air Regulator (1–8 bar): Used to control and vary input pressure for each nozzle.
- Anemometer: For measuring the airspeed at the nozzle outlet.
- Decibel Meter: To monitor and log noise levels during operation.
- 100 A4 Paper Sheets Mounted vertically to observe paint spray penetration.
- Clamp Mounts (3–4 pcs): To hold the nozzles securely in a fixed position during testing.
- Timer: To maintain consistent exposure time across all tests.
- Pencil and A4: For on-site note taking and labeling.
- Smartphone (Mounted with tape on door): Used for informal video recording since the footages were not used for data analysis.

Figure 60. Corridor view from the laboratory entrance, showing the table and wall setup.

Figure 61. View from the spray paint test room toward the air supply system outside,

Figure 62. Air supply outlets on the wall, connected via blue piping to a pressure regulator.

Spray Paint Test Environment Setup

Figures 60–65 illustrate the experimental setup for the paint spray blockage test, including the air supply, pressure regulation, spray paint room, ventilation system, and test board arrangement.

The next page presents the scanned Photoshop results used to analyze paint deposition and airflow effectiveness.

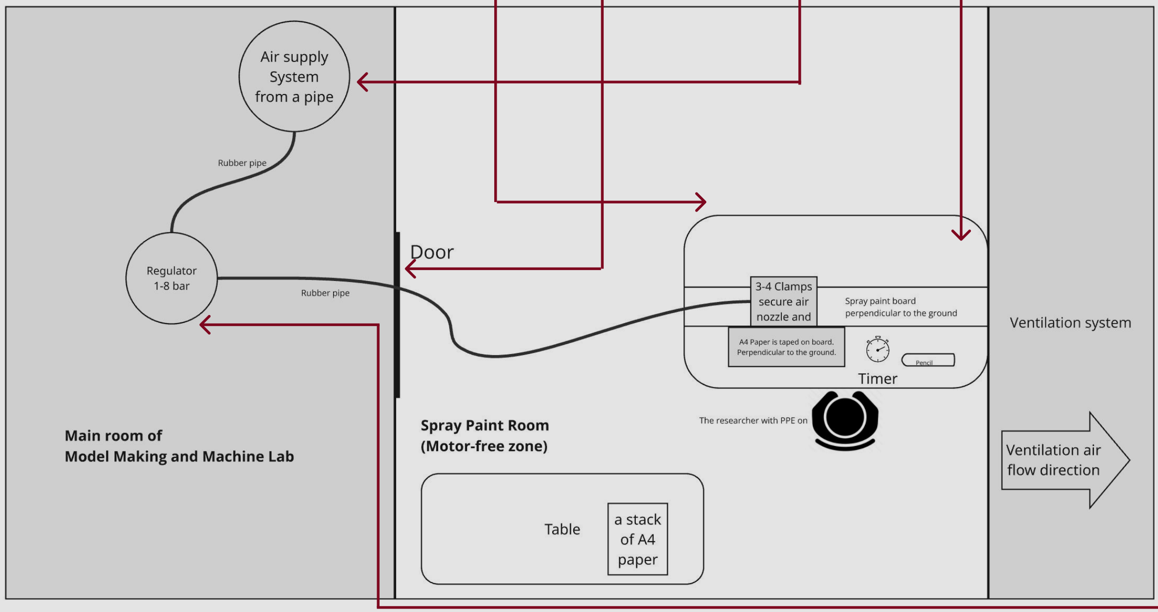


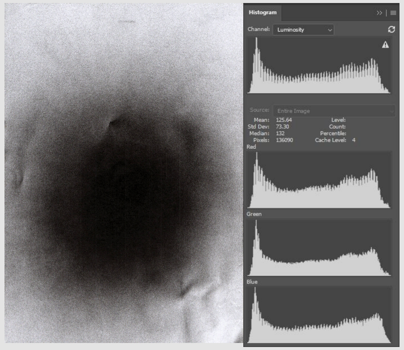
Figure 63. Schematic layout of the spray paint test environment, including air supply, regulator, spray room, and ventilation system.

Figure 64. Air pressure regulator with integrated pressure meter.

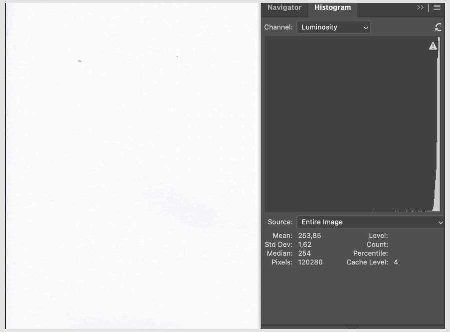
Figure 65. Test board for attaching A4 paper targets and securing the nozzle during experiments.

Figure 66. Spray Paint Blockage Test Results at Varying Air Supply Pressures

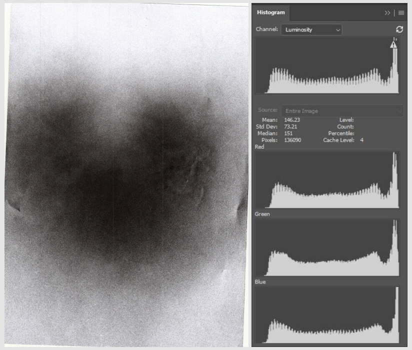
The images on the rights present scanned paper samples analyzed in Photoshop after exposure to paint spray at supply pressures from 1 to 6 bar, alongside baseline (no nozzle) and blank paper references. Mean, median, and standard deviation luminance values were calculated to quantify blockage effectiveness and airflow uniformity: higher mean values indicate stronger deflection (brighter paper), the median reflects central tendency while reducing skew from extreme values, and the standard deviation captures variability linked to turbulence or uneven deposition. The results show progressive improvements in coverage and stability with increasing pressure, though gains diminish beyond 5 bar. The blank paper provides the theoretical upper limit of blockage performance (0% contamination).



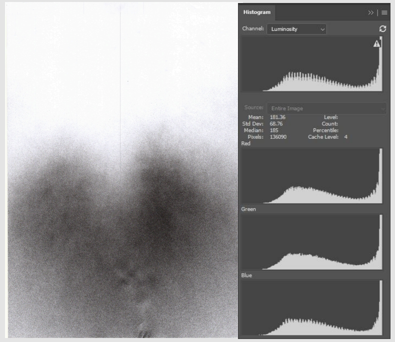
Baseline – No nozzle, no air supply: As shown, the air spray aims at the center of the A4 paper, which is the same for the rest of the test. The paper surface shows a dense, centrally concentrated deposit with a mean luminance of 125.64, median of 132, and high standard deviation (73.30).



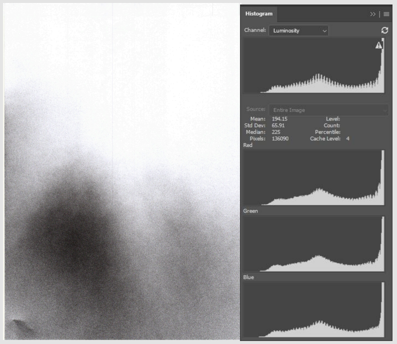
Blank Paper Reference Measurement: A clean, unused A4 sheet was scanned under identical conditions to the spray test samples to establish a maximum brightness reference for calculating blockage effectiveness. Image histogram analysis yielded a mean luminance of 253.85 (standard deviation 1.62, median 254) on a 0–255 grayscale scale, This value represents the theoretical upper limit (0% contamination)



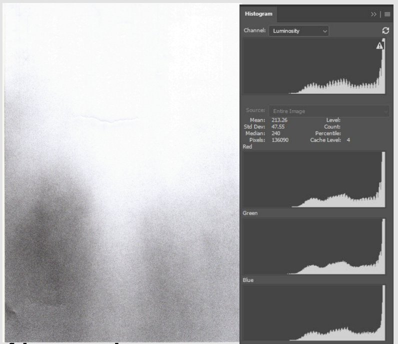
1 bar air supply pressure: Mean luminance 187.55, median 151, standard deviation 61.44. Substantial brightening compared to baseline, with a distinct central zone of deflection. The SD remains high, suggesting uneven airflow distribution and possible turbulence at the nozzle exit.



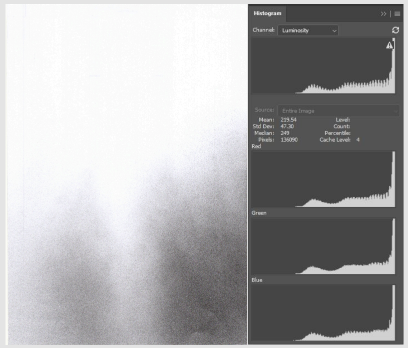
2 bar supply pressure: Mean luminance 181.36, median 185, standard deviation 68.76. Improvement over baseline is evident, with a larger deflected area, but non-uniformity is still present. Some darker peripheral regions indicate incomplete coverage.



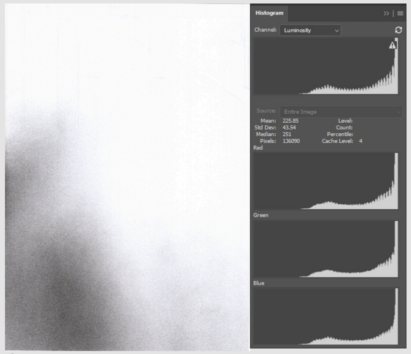
3 bar supply pressure: Mean luminance 194.15, median 225, standard deviation 65.91. Strong central blockage with brighter peripheral areas compared to 2 bar, but increased turbulence results in higher variability. Subjectively noted as producing an “unacceptably sharp” noise, which would limit comfort in wearable use.



4 bar supply pressure: Mean luminance 213.00, median 240, standard deviation 47.00. Marked improvement in both brightness and uniformity compared to lower pressures. The lower SD indicates a more stable jet and reduced turbulence effects across most of the target.



5 bar supply pressure: Mean luminance 219.54, median 249, standard deviation 47.30. The deflected area is bright and evenly covered, with uniformity comparable to 4 bar. Gains in blockage performance are smaller than the jump from 3 bar to 4 bar, indicating the onset of diminishing returns.



6 bar supply pressure: Mean luminance 225.85, median 251, standard deviation 43.54. This produced the highest measured luminance values, indicating maximum blockage. However, visual inspection shows minimal difference from 5 bar, suggesting further pressure increases mainly raise airflow velocity without significant functional benefit.

Rationale for Extreme Case Testing with Spray Paint

The extreme case of applying spray paint continuously for 10 seconds was selected because repeated testing within the project's limited timeframe was not feasible. This approach provided a more reliable assessment under accelerated conditions.

The use of a pressurized spray paint jet was chosen as an extreme test case, not as a direct analogue of walking-induced turbulence. While the two phenomena differ in scale and structure, both introduce strong unsteady disturbances into the airflow. Thus, the spray jet served as a conservative proxy to assess the curtain's robustness under highly turbulent conditions.Airsupply System Evaluation

Blockage Performance (Mean-Based Effectiveness Calculation)

Relative to the no-air baseline, the triangular nozzle improved blockage across all tested pressures. Effectiveness was calculated using the mean luminance of a clean white A4 sheet (L_{blank} = 253.85) as the 0% contamination reference, and the no-nozzle baseline mean luminance (L_{baseline} = 125.64) as the 100% contamination reference, according to:

$$\text{Effectiveness (\%)} = \frac{L_{\text{test}} - L_{\text{baseline}}}{L_{\text{blank}} - L_{\text{baseline}}} \times 100$$

1 bar: $\frac{187.55-125.64}{253.85-125.64} \times 100 \approx 48.3\%$

2 bar: $\frac{181.36-125.64}{253.85-125.64} \times 100 \approx 43.5\%$

3 bar: $\frac{194.15-125.64}{253.85-125.64} \times 100 \approx 53.5\%$

4 bar: $\frac{213.00-125.64}{253.85-125.64} \times 100 \approx 68.3\%$

5 bar: $\frac{219.54-125.64}{253.85-125.64} \times 100 \approx 73.3\%$

6 bar: $\frac{225.85-125.64}{253.85-125.64} \times 100 \approx 78.2\%$

Using the clean white paper luminance (L_blank = 253.85) and no-nozzle baseline (L_baseline = 125.64) as references, blockage effectiveness increased with supply pressure, but the rate of improvement was not uniform. At 1 bar, effectiveness was 48.3%, indicating a modest but noticeable reduction in particulate deposition compared to the baseline. Increasing to 2 bar produced a slight reduction in performance to 43.5%, which may be attributed to test variability, turbulence, or spray plume inconsistencies during the single trial.

At 3 bar, effectiveness rose to 53.5%, marking a significant gain and suggesting that jet momentum at this pressure consistently overcomes particle momentum for most of the spray plume. The largest performance jump occurred between 3 bar and 4 bar, where effectiveness increased from 53.5% to 68.3%. This improvement coincided with a marked reduction in standard deviation, indicating more uniform coverage.

Further increases yielded diminishing returns. At 5 bar, effectiveness reached 73.3%, an increase of only 5.0% over 4 bar. At 6 bar, the performance plateaued at 78.2%, showing just a 4.9% increase over 5 bar despite higher airflow velocity. These diminishing returns indicate that once the jet momentum exceeds a certain threshold for particle deflection, additional pressure primarily increases turbulence and noise rather than providing proportional gains in blockage efficiency.

From a practical perspective, the results support limiting operating pressure to below 3 bar for wearable use, as the largest functional benefits occur in the 1–3 bar range while avoiding excessive noise, energy use, and safety concerns. For maximum performance in stationary or non-wearable applications, 4–5 bar offers near-optimal blockage, but gains beyond this level are minimal and unlikely to justify the trade-offs.

Flow uniformity

Standard deviation values decreased from 61.44 at 1 bar to 43.54 at 6 bar, with the lowest variability observed at higher pressures (≥ 4 bar). Higher SD values at lower pressures reflected uneven airflow coverage, likely caused by turbulence at the nozzle exit, instability of the target paper, or localized entrainment effects.

Noise

At 3 bar, the airflow produced a subjectively "unacceptably sharp" noise level, posing a potential ergonomic and safety concern for wearable application despite moderate performance gains.

Visual pattern analysis:

All pressure levels demonstrated partial paint penetration, with increased brightness corresponding to higher blockage. At lower pressures, deflection was concentrated in the central zone, while higher pressures produced broader coverage with fewer dark peripheral regions. CFD analysis later confirmed non-uniform velocity distribution, with peak velocities near the centerline and reduced flow intensity toward the edges, matching the luminance patterns observed in the physical tests.

Conclusion

While the concept showed potential in particle deflection, the prototype required refined geometrical optimization to reduce noise and improve flow uniformity. Integration into a wearable form factor necessitated further design iteration, especially considering user comfort and aerodynamic efficiency. Based on the noise observations and the diminishing returns in blockage efficiency beyond moderate pressures, the operational air supply for future prototypes will be limited to below 3 bar. This threshold balances particle deflection performance with acceptable acoustic and ergonomic conditions for wearable use.

Change in PSBT Air Supply Equipment

Subsequent experiments were conducted with a portable blower system (800 L/min) instead of the laboratory's fixed compressed-air supply. This change was made to better mimic realistic application conditions, since a large industrial compressor would not be feasible for wearable or field use. Initial spray tests had already shown that pressure differences between 2 and 3 bar produced no significant improvement in performance, supporting the use of a more practical, shop-grade blower. Other aspects of the test setup remained unchanged.

Air Supply Path: Single vs Dual Side Air Supply

A comparative Paint Spray Blockage Test (PSBT) was conducted to evaluate airflow supplied from a single side versus both sides using a Y-pipe with a blockable cap. Luminance analysis showed that both configurations produced substantial brightening compared to the baseline, with mean luminance values of 187.55, median 151, and a standard deviation of 61.44. These results confirm that both single- and dual-side supply achieved comparable performance in terms of airflow distribution and blockage effectiveness.

Figures 67 The figure shows the Y-pipe assembly for evaluating single versus dual-side airflow supply. The left image illustrates the single-side configuration with one branch capped, while the right image depicts the dual-side configuration with both branches supplying air simultaneously. The central image shows the Y-connector and tubing components used in the tests.

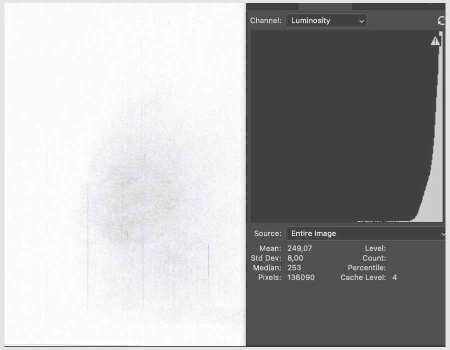


Figure 68. Air-supply from one sided
Mean luminance 187.55, median 151, standard deviation 61.44. Substantial brightening compared to baseline, with a distinct central zone of deflection. The SD remains high, suggesting uneven airflow distribution and possible turbulence at the nozzle exit.

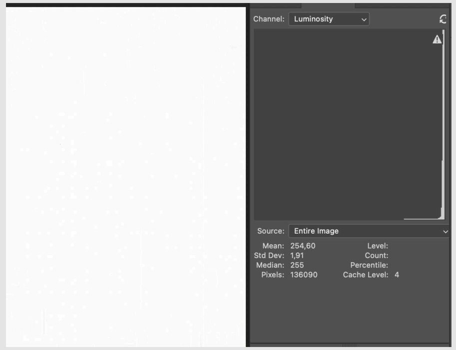


Figure. 69Air-supply from both sides
Mean luminance 187.55, median 151, standard deviation 61.44. Substantial brightening compared to baseline, with a distinct central zone of deflection. The SD remains high, suggesting uneven airflow distribution and possible turbulence at the nozzle exit.

While both approaches were effective, the choice between them relates more to ergonomic considerations. A single-side supply simplifies the setup and reduces components, while a dual-side supply provides a more balanced weight distribution, which may benefit wearable integration.

Multi-Nozzle Configuration Test

The CFD simulations evaluated four different nozzle angle configurations to test whether dual-jet systems could merge into a stable and effective air curtain.

The results (figure 70-73) showed that while certain angles promoted partial convergence of the two jets, turbulence rapidly developed in the interaction zone. This turbulence destabilized the flow, reduced uniformity, and introduced undesirable mixing with the surrounding air.

The results indicate that dual-nozzle systems have potential to enhance airflow strength if outlet angles are precisely tuned. However, they are highly sensitive to misalignment, with small deviations generating turbulence and reducing effectiveness. From a user-centered perspective, earlier design feedback highlighted discomfort with structures around the face, raising concerns about ergonomics, visibility, and claustrophobic sensations. Given these challenges, the angled dual-nozzle concept was not pursued further, despite theoretical aerodynamic benefits.

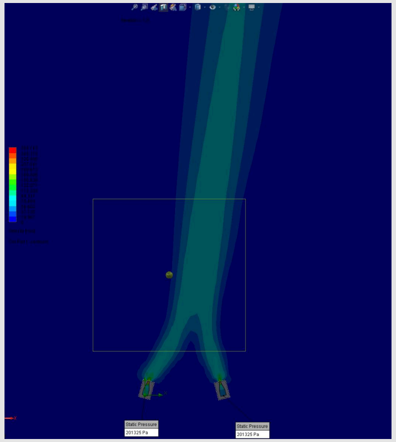


Figure 70. Shows two inward-angled nozzles where the jets partially converge, producing a stronger central flow. This suggests that angled nozzles could enhance jet stability if aligned precisely, reinforcing one another and increasing effective reach.

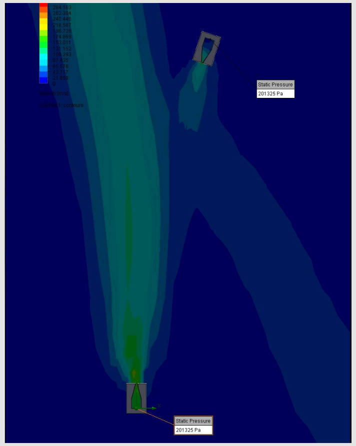


Figure 71. Demonstrates a misaligned configuration where the jets intersect prematurely, generating localized turbulence and significant flow distortion. The unstable interaction zone reduced uniformity and compromised barrier formation.

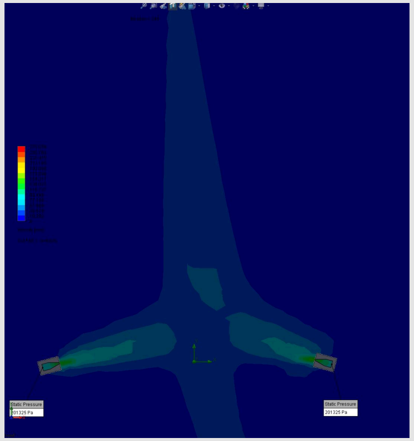


Figure 72. Depicts a wider angle separation, where the jets diverge instead of merging. The airflow coverage is broader, but the reduced central velocity weakens protective performance.

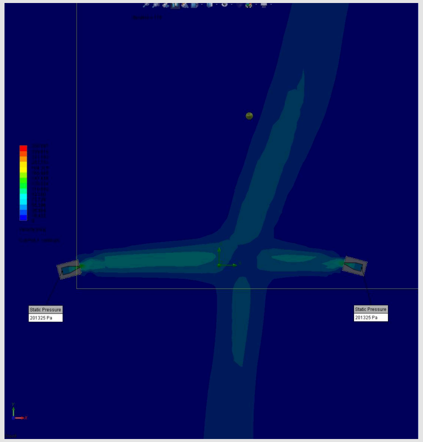


Figure 73. Illustrates a near-parallel orientation where flows intersect asymmetrically, leading to shear-layer turbulence and entrainment of surrounding air. This configuration amplified instability rather than strengthening the curtain.

Part 4 : Internal Nozzle Structure Testing

Objective

To evaluate how variations in internal nozzle geometry influence airflow performance, particle deflection, and ergonomic suitability. Six internal geometries were developed based on prior testing, where outlet openings between 2 mm and 3 mm were found to provide sufficient jet velocity without excessive pressure drop. All designs tested here maintained openings within that range to isolate the effect of internal shape from outlet size.

Methodology

In parallel, CFD simulations were performed using SolidWorks Flow Simulation. The inlet condition was initially prescribed at 2 bar pressure to approximate the experimental air supply. Attempts to directly match airflow volume with the physical system encountered convergence issues, as the solver failed to process the results under those constraints. The outcome indicates that in real-world conditions, airflow cannot be defined by volumetric flow rate alone; sufficient inlet pressure is also required to sustain the target flow volume through the nozzle. The finding emphasizes the need to consider both pressure capacity and volumetric supply when translating between CFD models and physical experiments.

The set of six geometries was not a strict A/B test, but rather a progression of design hypotheses, where each iteration introduced targeted modifications. Examples included:

- Straight versus curved outlet channels.
- Nozzles with and without internal extensions
- Addition or removal of perforated holes.
- Adjustments to convergence or divergence angles.
- Changes to cross-sectional shaping for aerodynamic smoothing.

This approach allowed testing of design features in isolation and in combination, guiding decision-making toward an optimal geometry. The comparative results are summarized in Figure 76-77.

Effectiveness Calculation Method

To quantify the effectiveness of each nozzle design in blocking airborne particles, luminance values from spray paint tests were analyzed using scanned A4 paper samples. The calculation followed these steps:

Step 1 : Reference values

- A blank, unused A4 sheet was scanned to provide the upper limit of brightness, corresponding to 0% contamination. L stands for Luminosity.

Lblank=253.85

A nozzle-free baseline test (spray applied directly, no air curtain) provided the lower bound, corresponding to 100% contamination.

Lbaseline= 124.64

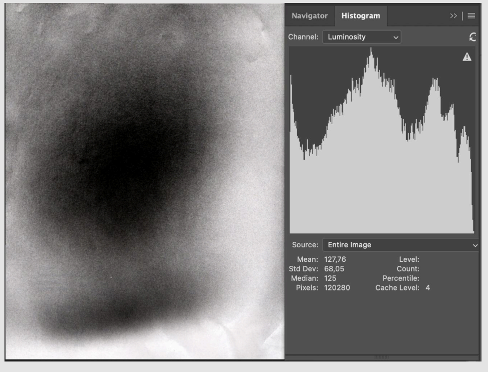


Figure 74 . Baseline spray paint test without nozzle.The left image shows the scanned A4 sheet, where the darkened central region indicates heavy paint deposition from direct exposure to the aerosol jet. The right panel displays the Photoshop histogram used for luminance analysis, with the extracted mean value (Ltest = 127.76) and standard deviation (SD = 68.05). This baseline establishes the reference for 100% contamination.

Figure 75. Collection of digital CAD models and corresponding 3D-printed physical prototypes used in spray tests. The set includes variations in outlet geometry and internal structures.

Step 2. Scan the result on Photoshop and record the mean luminance for each test condition

For every nozzle configuration, the A4 spray test image was scanned, and the mean luminance (Ltest) was extracted from the histogram on Photoshop. This value represents the average lightness of the surface, with darker values indicating more deposited paint (higher contamination).

The comparative results of different air configureations are summarized in Figure 76

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Objective

 To evaluate how variations in internal nozzle geometry influence airflow performance, particle deflection, and ergonomic suitability. Six internal geometries were developed based on prior testing, where outlet openings between 2 mm and 3 mm were found to provide sufficient jet velocity without excessive pressure drop. All designs tested here maintained openings within that range to isolate the effect of internal shape from outlet size.

Methodology

Each nozzle configuration was evaluated using both physical spray paint tests (see Figure 65 for the spray paint tests set up) and CFD simulations to cross-validate performance. The physical tests measured particulate deflection using bright-color spray paint applied to A4 targets at a distance of 60 cm for 10 s, under a controlled air supply. The resulting target patterns were scanned and analyzed for luminance (median as primary metric; mean ± SD as secondary uniformity measure).

In parallel, CFD simulations were conducted using SolidWorks Flow Simulation. The inlet was prescribed at 2 bar pressure. initially it was set to match the air flow volume of power supply, however, the difficulty in simulation encountered as the result will not process, to match the lab air supply performance, and outlet velocity, pressure drop, and flow patterns were recorded. Velocity cut-plots and pressure distribution plots were generated for each design.

The set of six geometries was not a strict A/B test, but rather a progression of design hypotheses, where each iteration introduced targeted modifications. Examples included:

- Straight versus curved outlet channels.
- Nozzles with and without internal extensions
- Addition or removal of perforated holes.
- Adjustments to convergence or divergence angles.
- Changes to cross-sectional shaping for aerodynamic smoothing.

This approach allowed testing of design features in isolation and in combination, guiding decision-making toward an optimal geometry. The comparative results are summarized in Table 77.

Effectiveness Definition

Effectiveness was expressed as the proportion of contaminants blocked relative to the reference values:

$$\text{Effectiveness (\%)} = \frac{L_{\text{test}} - L_{\text{baseline}}}{L_{\text{blank}} - L_{\text{baseline}}} \times 100$$

Where:
L_{blank}= mean luminance of clean A4 paper (0% contamination)
$L_{baseline}$=mean luminance with no nozzle (100% contamination)
L_{test}=mean luminance with nozzle in place

Result

Effectiveness was expressed as the proportion of contaminants blocked relative to the reference values:

imple Perforated Nozzle
Effectiveness (%) = (253.91 – 125.64) / (253.85 – 125.64) × 100 = 100.05%
Short Convergent Circular Opening Nozzle
Effectiveness (%) = (209.54 – 125.64) / (253.85 – 125.64) × 100 = 65.48%
Extended Convergent Nozzle
Effectiveness (%) = (179.81 – 125.64) / (253.85 – 125.64) × 100 = 42.35%
Curved Exit Nozzle
Effectiveness (%) = (157.50 – 125.64) / (253.85 – 125.64) × 100 = 24.89%
Physical-Barrier-Augmented Nozzle
Effectiveness (%) = (253.86 – 125.64) / (253.85 – 125.64) × 100 = 100.01%
Airfoil-Shaped Nozzle
Effectiveness (%) = (127.76 – 125.64) / (253.85 – 125.64) × 100 = 1.65%
Extended Airfoil Exit Nozzle
Effectiveness (%) = (214.98 – 125.64) / (253.85 – 125.64) × 100 = 69.58%
Coandă Effect-Enhanced Nozzle
Effectiveness (%) = (219.36 – 125.64) / (253.85 – 125.64) × 100 = 73.22%

Note: Effectiveness values exceeding 100% likely reflect minor inconsistencies in the blank reference sheet or scanning process. For analysis and interpretation, such cases are capped at 100% effectiveness.

Discussion

The physical spray paint tests revealed substantial variation in effectiveness across nozzle geometries, confirming that nozzle design plays a decisive role in shaping the performance of the air curtain.

The Simple Perforated Nozzle and the Physical-Barrier-Augmented Nozzle demonstrated the best performance, achieving near-perfect effectiveness (100%). Their luminance values were virtually indistinguishable from the blank reference paper, indicating strong particulate blocking. However, the results above 100% suggest possible inconsistencies in paper reflectance or scanning artifacts, meaning the values were capped at 100% for interpretation. Despite this, these configurations showed clear potential for highly effective particulate exclusion.

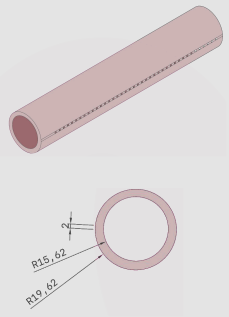
A group of designs showed moderate effectiveness, including the Coandă Effect-Enhanced Nozzle (73.1%), the Extended Airfoil Exit Nozzle (69.7%), and the Short Convergent Nozzle (65.4%). Their shaping and flow-guiding geometries helped improve directional control, but residual turbulence limited uniformity and reduced overall protection. These results partially support the design hypotheses, suggesting that entrainment effects or gradual extensions can stabilize flow, but only to a moderate degree.

Several designs performed significantly worse. The Extended Convergent Nozzle (42.3%), Curved Exit Nozzle (24.8%), and especially the Airfoil-Shaped Nozzle (1.7%) were underperforming configurations. The convergent and curved designs suffered from unstable jets and strong vortex formation, which undermined particulate deflection. Most notably, the airfoil-shaped nozzle—originally intended to reduce drag and maintain jet stability—delivered almost no improvement over the nozzle-free baseline (0%). This unexpected result suggests severe flow separation or misalignment effects that cannot be explained by physical testing alone.

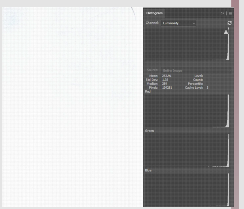
Taken together, the results validate the assumption that nozzle geometry critically influences air curtain effectiveness, with some designs offering strong potential (perforated, barrier-augmented, Coandă-enhanced) and others failing due to turbulence or misdirected flow. Some other factors may also influence the result, such as smoothness of the surface, and how whele the rtesucture can be maintainet, some of the curved exit nozoole need to be supported because the nozzle was keep collapsing. At the same time, the extreme values—both near-perfect blocking and near-complete failure—highlight the limitations of spray paint tests in fully capturing flow dynamics.

Name | Isometric View | Cross-section | hypothesis | Spray Paint Test Scan | SPT Result in Luminosity | Effectiveness

Simple Perforated Nozzle

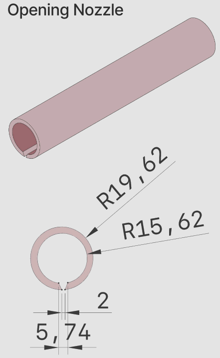


The original cylindrical nozzle with uniformly spaced holes aims to deliver an even airflow shield. While simple in structure, this design serves as a baseline for comparative analysis and provides a reference for evaluating the effectiveness of subsequent geometry refinements.

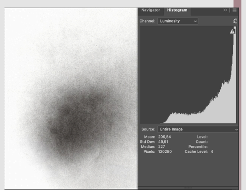


Mean: 253.91
Standard Deviation: 1.38

Short Convergent Circular Opening Nozzle



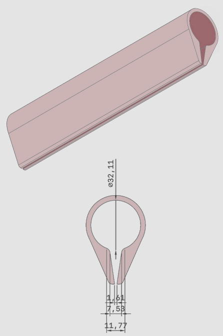
Modifying the outlet shape to a convergent nozzle is expected to accelerate airspeed due to reduced outlet diameter, enhancing jet momentum and potentially improving the spray deflection efficiency.



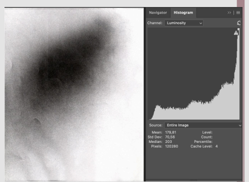
Mean: 209.54
Standard Deviation: 49.91

65.4%

Extended Convergent Nozzle



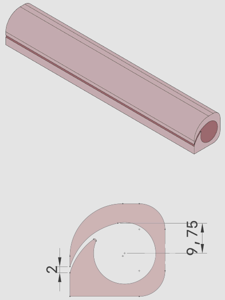
By lengthening the nozzle body, the airflow experiences a more gradual transition, minimizing turbulence at the outlet and improving the laminarity of the air curtain stream.



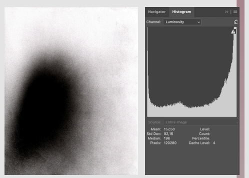
Mean: 179.81
Standard Deviation: 70.56

42.3%

Curved Exit Nozzle



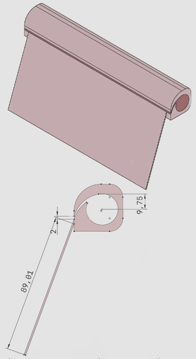
Introducing a curved exit geometry allows the nozzle to redirect and guide airflow around the user's head more precisely. This aims to enhance directional control and reduce lateral dispersion due to ambient airflow disturbance.



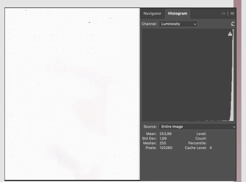
Mean: 157.50
Standard Deviation: 92.15

24.8%

Physical-Barrier-Augmented Nozzle



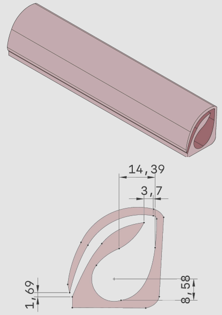
Adding the physical barrier to further protection Incorporating a physical barrier after the nozzle exit is hypothesized to create an additional deflection zone, increasing protection against rebound particles or overspray in close-range scenarios.



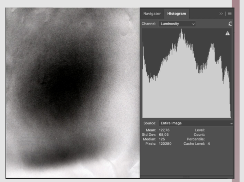
Mean: 253.86
Standard Deviation: 1.99

100%

Airfoil-Shaped Nozzle



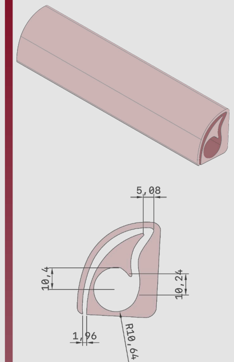
Utilizing an airfoil-inspired cross-section seeks to minimize flow separation and maximize streamline adherence. This aerodynamic shaping is theorized to reduce drag while maintaining consistent jet velocity.



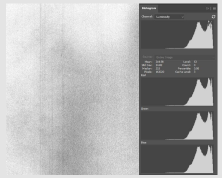
Mean: 127.76
Standard Deviation: 68.05

1.7%

Extended Airfoil Exit Nozzle



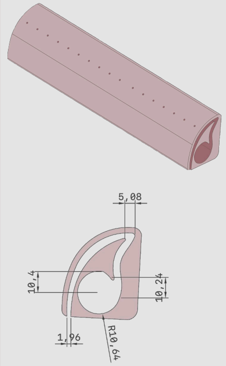
Extending the nozzle structure beyond the airfoil exit could regulate and stabilize the flow even further, acting like a diffuser to smooth out minor perturbations introduced by body sway.



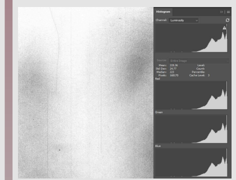
Mean: 214.98
Standard Deviation: 24.02

69.7%

Coandă Effect-Enhanced Nozzle



the a row of holes were added as coanda effect, grabbing air into the nozzle. supposingly to perform better than the ones without nozzle.

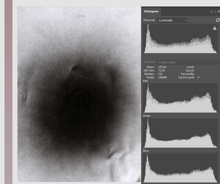


Mean: 219.36
Standard Deviation: 24.77

73.1%

Nozzle-free configuration

Represents the baseline ambient airflow performance of the system without nozzle attachment. This configuration helps isolate the effect of nozzle geometry by separating airflow unit behavior from nozzle influence. It provides a reference point for evaluating the added value of nozzle-based modifications in shaping, directing, or accelerating the jet stream.



Mean: 125.64
Standard Deviation: 68.05

0

Figure, 76 Comparative results of nozzle configurations from physical spray paint tests, showing luminance analysis and calculated effectiveness.

Transition to CFD Analysis

While the spray paint method provided clear comparative data, it could not explain the underlying mechanisms that produced such divergent results. For example, it remains unclear why the airfoil-shaped nozzle underperformed so drastically, or why some designs exhibited moderate but inconsistent improvements. To resolve these unknowns, the next section introduces Computational Fluid Dynamics (CFD) simulations, which allow detailed investigation of velocity fields, turbulence structures, and tracer transport. Through CFD, the hidden flow behaviors behind the physical results can be analyzed, providing a deeper understanding of both successful and failed nozzle configurations.

CFD Simulation Set UP

A CFD simulation was conducted using SolidWorks Flow Simulation with the goal of reflecting the same boundary conditions and performance factors observed during physical testing. This was done to compare internal airflow behavior, pressure drop, and velocity profiles across different nozzle geometries. The mesh refinement and solver settings were chosen based on previous studies (as described in Part 2.0), aiming for consistency and result validity.

The following settings were considered:

Mesh Refinement: The global mesh is set to 25 cm × 25 cm × 100 cm, defining the total simulation domain and ensuring the jet could develop without artificial boundary effects. Local mesh refinement was applied over a region of 30 cm × 20 cm × 40 cm surrounding the nozzle, where velocity gradients and shear-layer roll-up are most pronounced. This refinement allowed accurate resolution of narrow geometries and near-field turbulence while the global mesh ensured coverage of far-field dissipation. The resulting mesh contained significantly more than 5–6 million cells.

Turbulence Model: The default k-epsilon turbulence model was selected.

Inlet Boundary Condition: A static pressure inlet of 2 bar absolute was imposed. The air was introduced from one side of the supply pipe to match the physical test configuration. However, the air supply differed from the physical test model. The reason is further explained in the limitation section.

Outlet Boundary Condition: Atmospheric pressure (1 bar absolute) was used at the outlet to reflect the spray room's open ventilation environment.

Wall Conditions: Adiabatic and no-slip wall conditions were assumed for all nozzle walls.

Gravity: Gravity was included and directed downwards (–z axis), consistent with the physical test orientation.

Limitation

Idealized surfaces: Nozzle walls were modeled as perfectly smooth, ignoring roughness or deformation.

Air supply consistency: A constant inlet pressure was assumed, whereas real compressors deliver fluctuating flow.

Steady-state assumption: Transient jet instabilities and vortex shedding were not captured.

Limited validation: Comparison to experiments was indirect, based on spray patterns rather than velocity probes.

Performance Requirements for Air Curtain Nozzle

Performance Evaluation

The performance of each nozzle was evaluated using both qualitative flow observations and quantitative jet length measurements.

Qualitative assessment

CFD velocity cutplots reveal the structural characteristics of each jet, including vortex formation, symmetry, shear-layer growth, and the presence of recirculation pockets. These visual patterns allow identification of whether a nozzle produces a stable, directed flow or whether the jet breaks down rapidly into turbulence. Such qualitative indicators are crucial, as they highlight the mechanisms responsible for nozzle success or failure.

Quantitative assessment

To compare designs systematically, jet length was expressed relative to the internal pipe diameter (D). Two normalized ratios were defined:

Potential core length (Lp/D): distance along the jet axis where velocity remains close to the outlet value before major decay.

Effective reach (Le/D): distance where the jet retains sufficient momentum to displace surrounding air before dissipating.

By normalizing to D, the analysis relates performance to a practical design parameter: the supply pipe diameter, which determines how wide the nozzle must be in a wearable PPE configuration. A higher L/D ratio indicates more efficient conversion of inlet momentum into coherent downstream flow.

Nozzle-by-nozzle CFD velocity results

Simple Perforated Nozzle

Near the outlet a toroidal vortex ring forms, followed by rapid shear-layer roll-up and asymmetric recirculation around the core. Potential core length: short, ~2–3 outlet diameters (D). High internal losses from multiple perforations is observed from the color transition in projectile.

Short Convergent Circular Opening Nozzle

Converging section produces a narrower, faster core than the perforated tube. Lip shear remains strong. Core length: ~3–5 D. Exit acceleration helps, but abrupt geometry still seeds early instabilities.

Extended Convergent Nozzle

Longer convergent passage smooths acceleration and reduces the abruptness of the contraction. Velocity contours are cleaner than the short convergent case, although residual turbulence appears at the lip. Core length: ~2-3D. Wall friction and any minor internal separation prevent further gains.

Curved Exit Nozzle

Curvature redirects the jet but induces asymmetric separation along the inner bend. A persistent recirculation pocket forms just off the lip, deflecting and weakening the jet. Core length: ~2–3 D. Reach: ~4–5 D. Directional control is offset by separation losses; coherence remains poor.

Physical-Barrier-Augmented Nozzle

Barrier plate immediately downstream of the outlet thickens and straightens the emerging jet. Lateral spread is constrained, and early shear-layer growth is suppressed. Core length: ~5–7 D. Reach: ~9–12 D. Momentum is preserved close to the outlet, yielding a compact, well-directed plume.

Airfoil-Shaped Nozzle

Despite the aerodynamic intent, velocity fields show edge separation and rapid shear-layer roll-up off the trailing surface. The jet breaks up early and becomes asymmetric. Core length: ≤2–3 D. Reach: ~4–5 D. Section choice and incidence appear mismatched to the internal pressure field, producing high loss and short reach.

Extended Airfoil Exit Nozzle

Downstream extension conditions the exit flow and reduces curvature-induced separation. The jet emerges more axisymmetric and maintains direction better than the plain airfoil. Core length: ~5–6 D. Reach: ~9–11 D. Exit conditioning restores momentum delivery and delays mixing.

Coandă-Effect-Enhanced Nozzle

Wall perforations/slots promote attachment and controlled entrainment along the surface. The plume remains compact with limited lateral wandering and delayed roll-up. Core length: ~6–7 D. Reach: ~10–12 D. Attachment reduces effective spreading and sustains velocity over the longest distances among the set.

Discussion

TThe comparison between CFD simulations and physical spray paint tests revealed both alignment and divergence in performance outcomes. CFD predicted that extended and flow-conditioning geometries would generate longer jet cores and greater momentum stability. Yet, in practice, these designs did not consistently outperform more turbulent alternatives. The Simple Perforated Nozzle, for example, appeared highly unstable in simulation, with rapid momentum loss and turbulent roll-up, but nonetheless achieved complete effectiveness (100%) in physical testing. Conversely, the Extended Convergent Nozzle produced a concentrated, stable jet in CFD yet underperformed in experiments, achieving only 42.3% effectiveness.

The Physical-Barrier-Augmented Nozzle offered closer agreement between simulation and reality. CFD suggested that downstream barriers would create a compact and stable plume, and this was confirmed in physical tests with near-perfect effectiveness (100%). In contrast, the Airfoil-Shaped Nozzle, which was designed to reduce drag and improve flow attachment, performed very poorly (1.7%), indicating that mismatched pressure fields and severe separation dominated its real-world behavior. These inconsistencies illustrate the limitations of CFD as a predictive tool when used in isolation. While valuable for visualizing flow fields, CFD cannot fully capture fabrication imperfections, surface roughness, or particle entrainment effects, all of which strongly influence actual nozzle performance.

Design Implications

The findings emphasize the importance of downstream structural control. Incorporating physical barriers after the outlet significantly enhances performance by stabilizing the jet and reducing over spray.

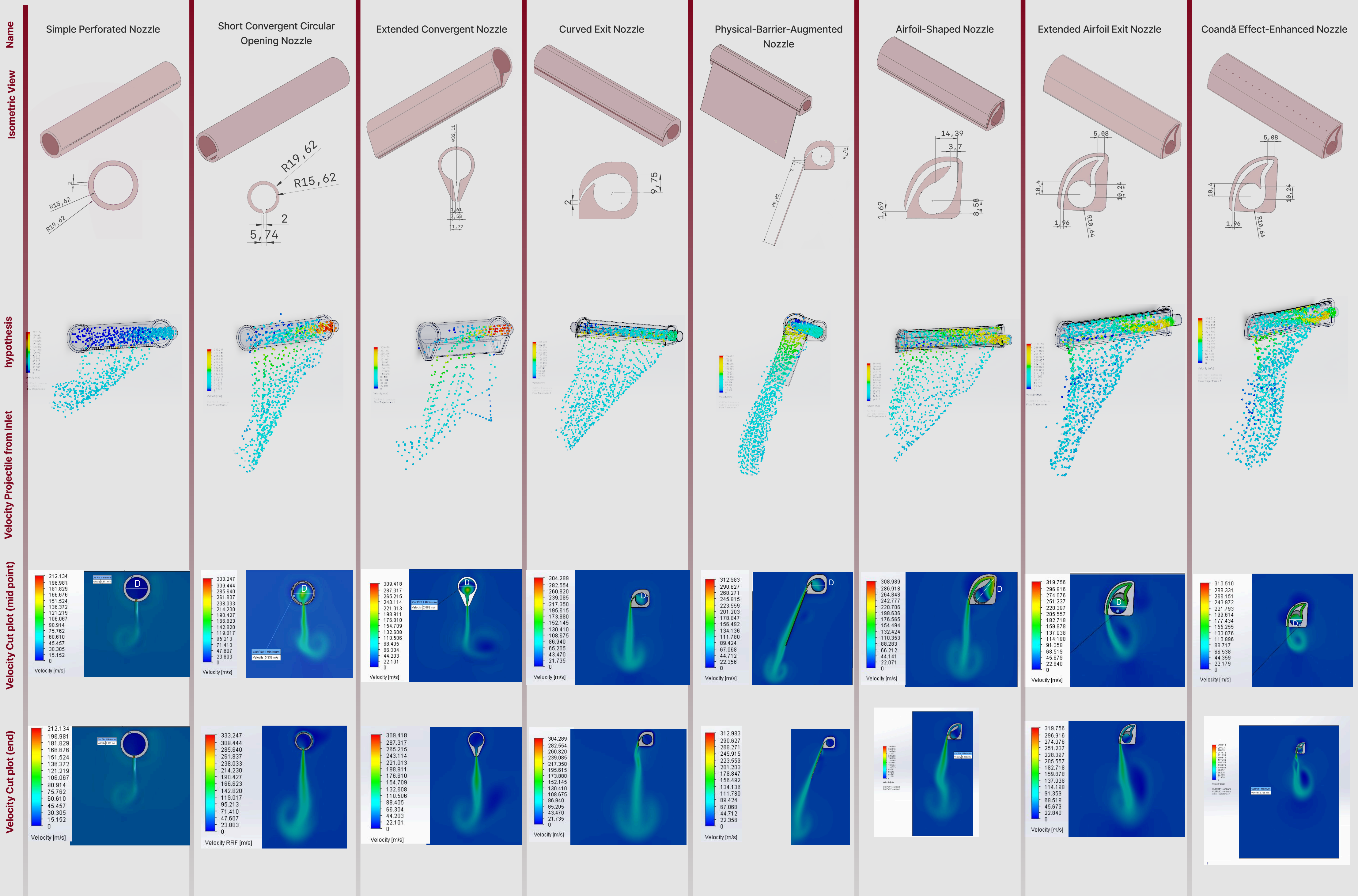


Figure. 77 CFD Simulation Results of Various Nozzle Geometries

Design into Wearable

As the nozzle concept transitioned from standalone testing to integration within a wearable form, new design implications emerged. CFD simulations (Figure 78) revealed that strongly curved nozzle geometries reduced airflow efficiency, causing velocity losses and uneven jet spread. The wider flared shapes, though visually conforming to the forehead curvature, disrupted flow coherence and diminished barrier effectiveness.

Future designs should minimize curvature in the nozzle body, keeping the internal channels as straight and smooth as possible while only accommodating the necessary curvature to follow the forehead contour. Flattened geometries are expected to preserve airflow momentum, reduce pressure losses, and maintain jet stability when embedded into a wearable system.

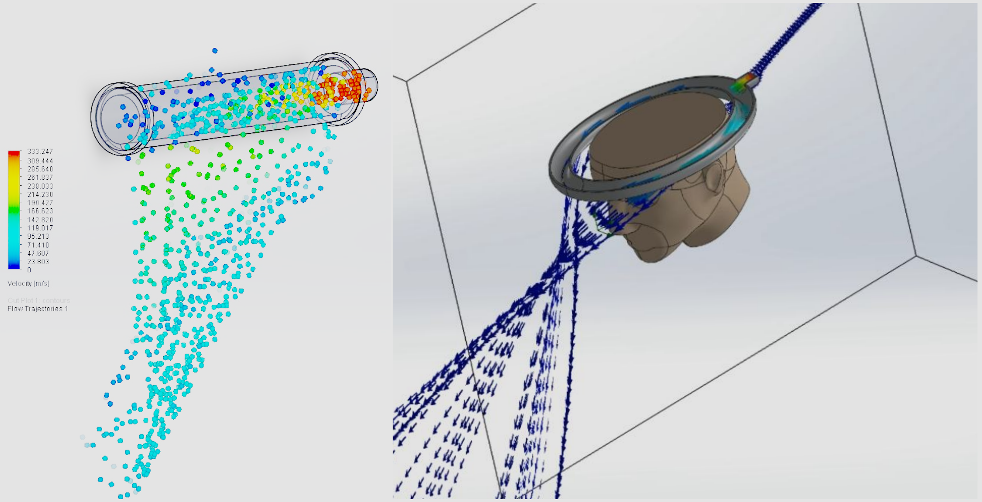


Figure 78 . CFD simulations of nozzle airflow. The left image shows a straight nozzle, where airflow exits with relatively high velocity and a more coherent plume. The right image illustrates the nozzle integrated into a wearable forehead-mounted design, where the curved geometry needed to follow the head contour reduces jet stability and coherence.

Part 5 :Final Design Testing

Three final nozzles tested, they have similarities in the overall shape but differ in detail,

Straight-Down Barrier Design

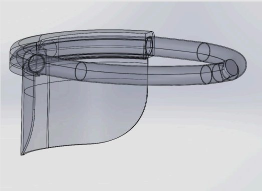


Figure. 79 Perpendicular barrier: the air flow outside of the barrier, the physical barrier added as a simple splash guard to block large droplets without altering the core airflow path.

Inward-Curved Barrier Design

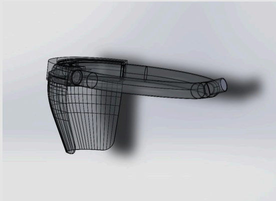


Figure. 80 The internal barrier directs the physical protection layer outward, ensuring that external airflow does not mix into the breathing zone.

Barrier with Air-Straightening Grid

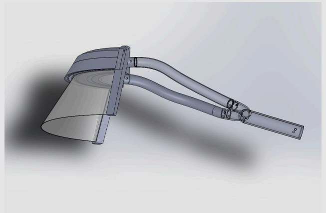


Figure. 81 single barrier inside, with direction of physical protection goes outward, so the air does not mix into the breathing zone

Elongated Nozzle Barrier Design

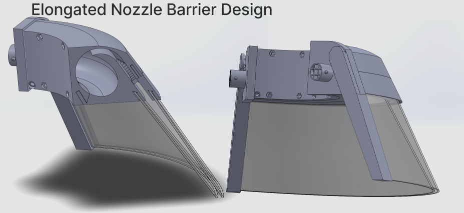


Figure. 82 Outward-blowing barrier: Designed to direct clean air outward along the barrier surface to form a protective curtain in front of the user, while keeping airflow away from the face to avoid discomfort.

Objective

To evaluate three final nozzle geometries that share the same overall wearable form factor but differ in internal flow guidance and barrier configuration. At this stage, the external shape had been validated through painter review sessions, ensuring ergonomic fit, minimal facial obstruction, and acceptable weight distribution for prolonged wear.

Design Rationale

From earlier curved-nozzle designs, the geometry was straightened as much as possible while still conforming to the curvature of the forehead. This change aimed to improve jet coherence compared to earlier iterations while ensuring the air curtain followed the arc around the head for complete frontal coverage. The design also accounted for:

- Forehead mounting for ergonomic balance and unobstructed vision.
- Smooth internal channels to minimize resistance and pressure loss.
- Avoidance of inward airflow, which could cause discomfort from recirculating warm, exhaled air.

Integration of a physical barrier (transparent visor-like element) to enhance user trust and protection against large particles or splashes. Previous tests indicated that a barrier can improve particle-blocking performance.

Research Methodology

Physical tests were conducted at a fixed supply pressure, using spray-paint deflection as the primary method for evaluating physical airflow performance. This was complemented by CFD simulations to examine velocity distribution, flow coherence, and pressure behavior.
Spray-paint patterns were scanned and analyzed to determine median luminance (as an indicator of effectiveness) and standard deviation (as a measure of uniformity).
CFD outputs provided the inlet–outlet pressure differential, velocity cut-plots, tracer fields, and streamline visualizations to characterize the airflow behavior of each configuration.
Figure 88. summaries the CFD simulation results, while Figure 90. presents the corresponding wearable prototype test outcomes.

CFD Simulation Set Up

the model balances computational efficiency with realistic situation.
Key Justifications:

- Regulatory alignment: Ensures findings are actionable within legal frameworks.
- Physiological realism: Inhalation rates reflect actual worker respiration.
- Practical simplification: Adiabatic walls and omitted exhalation streamline the analysis of particulate deflection efficacy.

The simulation assumes a homogeneous air distribution within the room, with no internal obstructions or objects that would significantly influence the airflow dynamics. The selected room size of 3.5 × 3.5 meters is considered sufficient to represent a realistic indoor environment for the purposes of the study. It is assumed that the entire wall surface acts as a uniform source of pollutants, delivering tracer gas (SO_2) toward the breathing zone. Although such uniform pollution distribution is unlikely in real-life scenarios, it is intentionally used to represent a worst-case exposure condition where contaminants diffuse throughout the entire space.
SO_2 is used as a tracer gas to represent fine dust particles (e.g., PM2.5 and smaller), based on evidence in the literature that supports its effectiveness in characterizing similar dispersion behavior. The tracer gas is initialized with a mass fraction of 1.0 on the wall surfaces. Chemical interactions between particles are not considered; the dust is treated as non-reactive. The influence of body heat is neglected, under the assumption that its thermal buoyancy effect is minor compared to forced convection from the air curtain. Similarly, the thermal and aerodynamic effects of clothing materials are assumed to be negligible, in line with conclusions from prior research.

Inhalation is modeled at an elevated (exercise-level) breathing rate, based on EPA, the breathing zone used a volume outlet boundary with an inhalation rate of 0.000389 m^3/s (1.40 m^3/hour), based on United States Environmental Protection Agency (2011) data for male construction workers, to quantify particulate intake risk. Exhalation was omitted to prioritize inhalation exposure assessment, the primary health concern.
One air inlet is positioned at the lower corner of the room, and a pressure-free outlet is used to represent natural room ventilation without active pressurization.

Boundary Condition	Boundary Type	Description and Parameter Settings
Pollutant Source (Wall)	Velocity Inlet (Tracer) as input data	tracer study innitially set to 1 apply to the whole wall facing 20 cm to the air nozzle wearing on the mannequin, it represent ewith So2 as it is heavier than air and the air does not
Pollutant Source (Wall)	Particle studies run from Result	0.1 micrometres / PM1.0 from entire wall
in room enviroment	Inlet	room size 3.5 m x3.5m, wall height 270. Turbulence intensity: 10 %; Temperature: 295 K; Room air flow speed is 0.1225 m/s
Room inlet air	Outflow	the exist of air is open on the top corner, the room is set to external study, so there is no pressure
room out let air	pressure opening enviroment pressuer	standard atmospheric pressure at sea level.. pressure opening 101325 Pa atomsphere pressure to let the air flow out naturally.atural ventilation, passive outflow, or when airflow should "freely exit
Air-Curtain Inlet	fluid subdomain 1, fluid type air	the lid was made at the pipe of the product pipe connector blow into the product with air speed 10 m/s, 30 m/s. the lid diameter is 21mm refer to market available pipe come with the available air blower. the projectile dots is set up at the inlet to simulate how air blows. 0.0517 m^3/s
Face Shield	Wall	adiabatic igrnored friction
Physical PPE	Wall	adiabatic
Nose	Volume outlet	0.000389m3/s reference 1.40 m^3/hour a plate is made at nostril location, to mimic inhale the air breathout is ignored for now because the air breathing in the the key factor of health indication.
Walls of the room	Wall	Adiabatic
standing person	obstacle or wall	adiabatic download form internet opensource, height 176 cm, igrnored body temp

It is further assumed that the nozzle airflow rate is ideally maintained, with a consistent and uninterrupted supply from the air system. A perfect fit between the wearable device and the user's face is also assumed, eliminating potential leakage from gaps between the sealing interface and the skin.The boundary conditions and simulation parameters were carefully designed to replicate realistic occupational exposure scenarios while adhering to regulatory and physiological benchmarks. The room dimensions (3.5 m × 3.5 m × 2.7 m)

The pollutant source was configured as a velocity inlet with a uniform tracer concentration (set to 1) to model aerosolized paint particles (e.g., SWIFT 502), positioned 20 cm from the air nozzle to simulate a plausible proximity between the worker and contamination source when sanding the wall .

Ventilation parameters strictly comply with Bouwbesluit 2012 Article 3.29, mandating a minimum airflow of 0.9 dm^3/s per m^2 floor area, and Article 3.30, which limits air velocity to <0.2 m/s in occupied zones to prevent discomfort. The inlet's flow rate (0.011 m^3/s) and velocity (0.1225 m/s) were derived from these standards, while the pressure opening boundary at the outlet enabled passive airflow—to represent natural ventilation in residential spaces. The adiabatic wall conditions simplified thermal interactions to isolate aerodynamic effects, a justified assumption given the study's focus on particulate deflection rather than thermal comfort.

Assumptions

1. Homogeneous Air Distribution
   The simulation assumes uniform air properties throughout the room, which may not fully capture the complexity of real indoor air mixing and thermal layering.
2. Simplified Room Geometry
   The room is modeled as an empty, unobstructed space without furniture, partitions, or other objects that could affect airflow or pollutant behavior.
3. Idealized Pollutant Source
   Pollutants are uniformly released from the entire wall surface, representing an extreme-case exposure scenario not typically found in real environments.
4. Perfect Sealing Assumption
   A perfect seal between the wearable interface and the face is assumed, eliminating the possibility of leakage or bypass airflow.
5. Unidirectional Breathing Model
   Only inhalation is modeled. Exhalation is neglected, despite its potential to influence local airflow and contaminant dispersion.
6. No Chemical Reactions or Humidity Effects
   The simulation excludes effects of humidity, condensation, or chemical interactions between airborne substances.
7. Stationary Manikin Model
   The study assumes a static human subject. Movements such as walking, turning, or head motion are not simulated, though these actions can significantly alter airflow patterns and exposure.
8. Steady-State Conditions
   The simulation assumes steady-state airflow, meaning the flow does not change over time. This simplifies the modeling process but may not reflect dynamic conditions such as user movement or speech.
9. Incompressible Airflow
   Air is modeled as an incompressible fluid, which is a valid approximation at low velocities typical in indoor environments.
10. Ambient Conditions
    The simulation environment reflects a standard indoor residential setting with controlled temperature and pressure, aligning with Dutch building codes (NEN 1087 and Article 3.29 of Bouwbesluit).
11. Idealized Geometry and Human Posture
    The mannequin used represents an average adult male standing 20 cm from the wall, with no head movement or variation in breathing rate.
12. Tracer Gas Behavior
    Sulfur dioxide (SO_2) is used as a surrogate tracer to visualize particle flow, under the assumption that it behaves similarly to airborne pollutants due to its higher density than air.
13. Constant Airflow at Inlets and Outlets
    The air curtain inlet and nostril outlet flows are defined by fixed volumetric flow rates and assumed to remain stable during the simulation.
14. SO2 as Dust Tracer
    SO2 is used to represent dust particles, assuming similar dispersion behavior. Particle-specific effects such as inertia, gravitational settling, or deposition are not considered.
15. Neglected Thermal Effects of Human Body
    Body heat and thermal plumes are excluded from the simulation, although they may influence airflow near the breathing zone.
16. Neglected Clothing and Surface Properties
    Clothing material and surface textures are assumed to have no significant influence on airflow, consistent with previous literature findings in low-velocity indoor airflows.

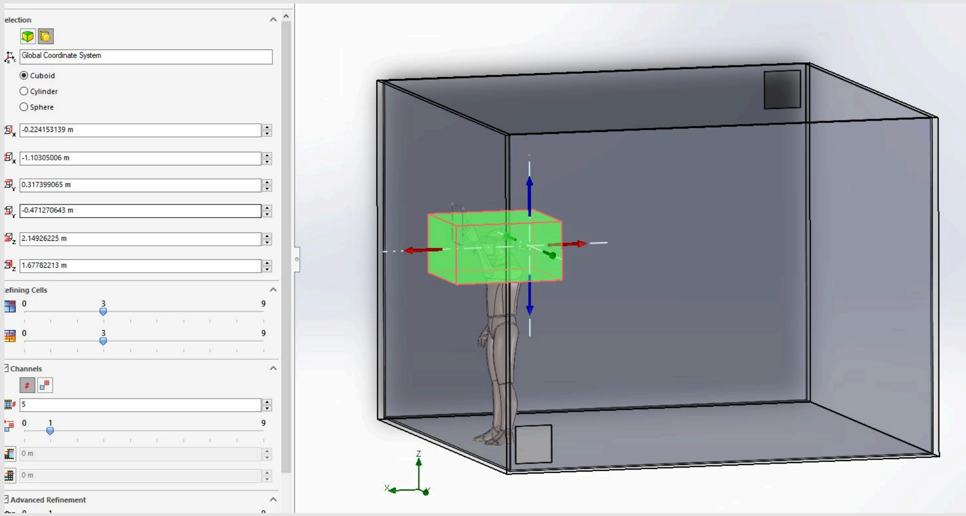
Simulation Configurations

Figures 83–87 present the configurations used to set up the CFD simulations for evaluating the wearable air curtain. The simulations were conducted in a cubic room environment with defined air inlet and outlet boundaries to approximate non-pressurized conditions (Figure 84). The manikin was placed at a distance of approximately 20 cm from the wall (nose tip to wall) to represent realistic user positioning in confined workspace.

A refined mesh was applied locally around the head region (Figure 85) to capture detailed flow behavior in the breathing zone, defined from the forehead to the neck.

For breathing zone evaluation, airflow outlet conditions were applied directly at the nostrils (Figures 86 and 87), each set to a volumetric flow rate of 0.000389 m^3/s. This configuration enabled the quantification of protective efficiency (PE) through tracer gas analysis and the assessment of draught risk (DR) based on velocity and turbulence values near the face.

Figure 83. The CFD interface panel on the left displays the applied mesh refinement settings.



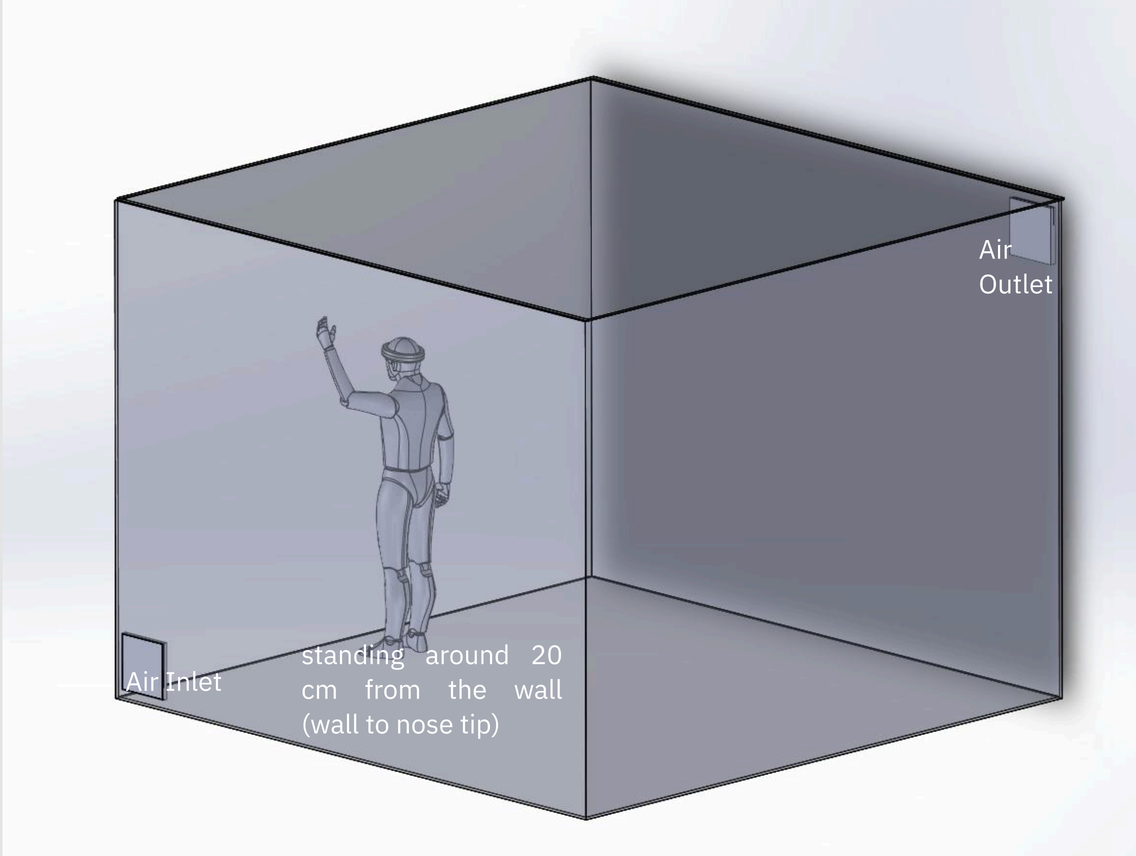
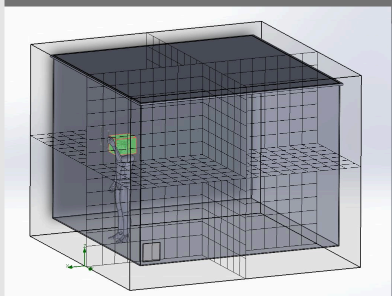
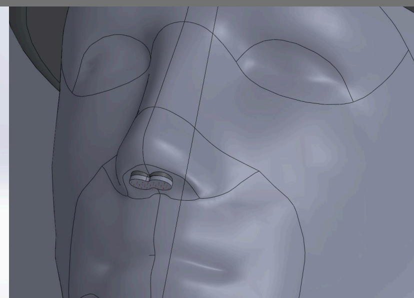


Figure 84. the simulation simulate room enviroment external analysis: to achieve non-pressurized room





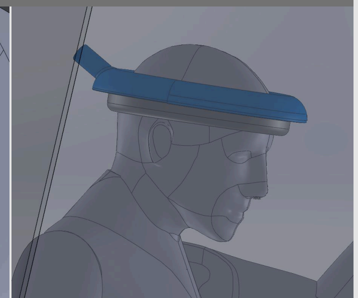


Figure 85. Local mesh is set around the head focus on breathing zone.

Figure 86. Air out let as nostril, with outlet volume flow 0.000389m3/s

Figure. 87 Air out let as nostril, with outlet volume flow 0.000389m3/s

Limitations

1. Homogeneous Air Distribution
   The simulation assumes uniform air properties throughout the room, which may not fully capture the complexity of real indoor air mixing and thermal layering.
2. Simplified Room Geometry
   The room is modeled as an empty, unobstructed space without furniture, partitions, or other objects that could affect airflow or pollutant behavior.
3. Idealized Pollutant Source
   Pollutants are uniformly released from the entire wall surface, representing an extreme-case exposure scenario not typically found in real environments.
4. SO2 as Dust Tracer
   SO2 is used to represent dust particles, assuming similar dispersion behavior. Particle-specific effects such as inertia, gravitational settling, or deposition are not considered.
5. Neglected Thermal Effects of Human Body
   Body heat and thermal plumes are excluded from the simulation, although they may influence airflow near the breathing zone.
6. Neglected Clothing and Surface Properties
   Clothing material and surface textures are assumed to have no significant influence on airflow, consistent with previous literature findings in low-velocity indoor airflows.
7. Ideal Air Supply Conditions
   The nozzle airflow is assumed to be constant, uniform, and unaffected by external factors or system fluctuations.
8. Perfect Sealing Assumption
   A perfect seal between the wearable interface and the face is assumed, eliminating the possibility of leakage or bypass airflow.
9. Unidirectional Breathing Model
   Only inhalation is modeled. Exhalation is neglected, despite its potential to influence local airflow and contaminant dispersion.
10. No Chemical Reactions or Humidity Effects
    The simulation excludes effects of humidity, condensation, or chemical interactions between airborne substances.
11. Stationary Manikin Model
    The study assumes a static human subject. Movements such as walking, turning, or head motion are not simulated, though these actions can significantly alter airflow patterns and exposure.
12. Simplified Breathing Model
    The simulation does not model realistic inhalation/exhalation cycles or breath humidity/temperature, which can influence airflow near the face.
13. Static Posture and Environment
    The user is modeled in a fixed standing position; real-world usage involves movement, head rotation, talking, or task variation, which may affect air curtain behavior.
14. Limited Environmental Variables
    Factors such as ambient dust loading, external airflows (e.g. doors opening, fans), and human thermal plumes were not fully integrated or varied.
15. Single Subject Representation
    The anatomical model used does not reflect diversity in facial structure, height, or posture, limiting generalizability to other body types or work scenarios.
16. No Biological or Long-Term Exposure Assessment
    The study does not assess biological protection efficacy (e.g., viral inactivation), only airflow redirection and physical containment in a controlled setting.
17. Prototype-Stage Validation
    The results are based on simulations and early-stage physical tests; further testing in real operational environments is needed to assess long-term performance and user compliance.

Performance Criteria

System performance was evaluated using five main criteria.

1. Energy Efficiency
   Assessed by the ratio of pressure drop or increase between inlet and outlet, indicating how much driving pressure is required to sustain the air curtain.
2. Velocity Distribution
   Examines whether the air curtain adequately covers the breathing zone (forehead to neck). Insufficient velocity leads to poor protection and a short jet core, while excessive velocity on the skin surface causes draft discomfort.

3. Protective Efficiency (PE)
   Calculated from the mass fraction difference between ambient air and inhaled air at the breathing zone, providing a direct measure of contaminant blocking effectiveness.
4. Drought Risk (DR)
   Determined using local velocity, temperature, and turbulence intensity near the manikin's face. A DR of ≤20% is typically acceptable for thermal comfort (Fanger et all, 1988).

Fanger et all [4] derived a specific equation to predict the percentage of people dissatisfied by draught, the so-called Draught Rating index (DR).

$$DR=(34-T_a)(\tilde{v}-0.05)^{0.62}(3.14+0.37.Tu.\tilde{v}) \quad [\%]$$

With:
T_a: air temperature (°C) (range is limited to 19-27°C)

5. Pressure and Pollutant Distribution
   Pressure fields are used to analyze jet formation, flow resistance, and possible leakage of polluted air into the breathing zone. Tracer gas distribution visualizes contaminant transport, supports PE calculation, and highlights potential leakage paths.

Result:

Figure 88 presents the CFD outputs for four nozzle–barrier configurations: Straight-Down Barrier Design, Inward-Curved Barrier Design, Barrier with Air-Straightening Grid, and Elongated Nozzle Barrier Design. For each configuration, the figure displays velocity contours, pressure fields, tracer mass-fraction distributions, and streamline trajectories. The velocity plots show the jet exit speeds and the direction of the airflow relative to the face. The pressure cut-plots report the local static pressure at two reference points (A and B), indicating whether pressure rises or drops along the nozzle. The tracer plots illustrate the extent of external-air infiltration into the breathing zone. The streamline visualizations show the jet path, coherence, and extent of downward travel for each configuration.
Based on the CFD results described above, the following discussion examines how each configuration performs when assessed against the five defined performance criteria.

Energy Efficiency (Pressure Difference)
Energy efficiency is reflected by the pressure change between inlet and outlet. Straight-Down Barrier Design exhibits a moderate pressure drop (≈8.6%), indicating acceptable efficiency but some internal loss.
Inward-Curved Barrier Design shows the smallest pressure drop (≈4.8%), representing the most efficient pressure behavior and smoothest flow passage among the configurations. Barrier with Air-Straightening Grid produces a substantial pressure increase (≈36%), reflecting added resistance from the grid structure and reduced energy efficiency. Elongated Nozzle Barrier Design shows the largest pressure increase (≈53%), indicating significant internal resistance and low energy efficiency.

Velocity Distribution (Breathing-Zone Coverage)
The Straight-Down configuration produced a downward jet that decayed rapidly and only partially intersected the breathing zone.
The Inward-Curved configuration maintained a coherent jet along the facial contour and provided the most consistent breathing-zone coverage.
The Air-Straightening Grid created a broader, more uniform downward flow with only partial coverage of the breathing region. The Elongated Nozzle showed rapid momentum loss and limited reach, resulting in weak coverage.

Protective Efficiency (Tracer Concentration)
Tracer mass fractions indicated substantial ambient-air infiltration for the Straight-Down configuration. The Inward-Curved configuration maintained the lowest tracer concentrations (0–0.28) in the breathing zone, representing the highest protective efficiency. The Air-Straightening Grid and Elongated Nozzle configurations showed elevated tracer levels (0.42–0.57 and 0.43–0.57), indicating limited protective performance.

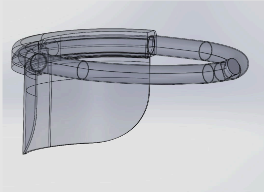
Drought Risk (Facial Velocity Magnitude)
Facial velocities remained low for the Straight-Down configuration, suggesting minimal drought exposure. The Inward-Curved configuration exhibited the highest facial velocities, indicating a higher potential drought risk. The Air-Straightening Grid produced moderate facial velocities and a correspondingly moderate drought potential.
The Elongated Nozzle showed low facial velocities consistent with a low drought risk.

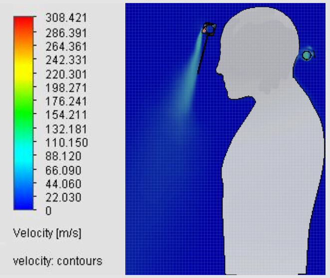
Pressure and Pollutant Distribution (Leakage Behavior)
The Straight-Down configuration showed clear side infiltration and minimal formation of a protective layer. The Inward-Curved configuration generated a compact flow around the face with reduced lateral leakage.
The Air-Straightening Grid displayed a long but leaky flow field with partial separation of clean and ambient air. The Elongated Nozzle exhibited early jet breakup and high ambient-air presence in the breathing zone.

Overall, the CFD analysis demonstrates clear differences in airflow behavior, pressure characteristics, and protective performance across the four nozzle–barrier configurations. Among them, the Inward-Curved Barrier Design exhibited the most efficient pressure behavior, the most coherent breathing-zone coverage, and the lowest tracer infiltration, while the other configurations showed varying degrees of energy loss, leakage, and jet degradation. To corroborate and extend these findings, the following section presents the results of paint spray blockage test (PSBT experiments, which provide a physical evaluation of breathing-zone coverage and flow containment. These combined insights will form the basis for the subsequent design implications.

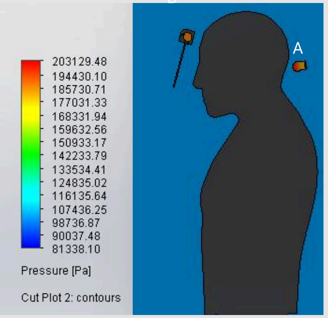
Name | 3D rendering | Velocity Cutplot (CFD) | Pressure Cutplot | Tracer Study | Projectile Visualization

Straight-Down Barrier Design



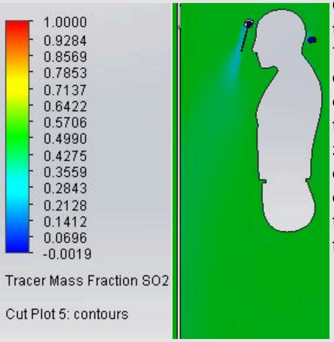


The velocity contour shows that the jet exits at approximately 88 m/s, forming a downward-directed stream.
The potential core of the jet extends in front of the face and continues downward across the breathing zone, as indicated by the color gradient in the velocity field.

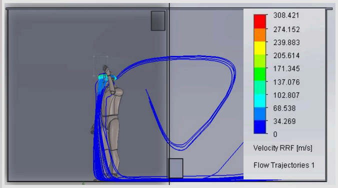


Pressure at the entrance is approximately 203,132 Pa (point A).
At the nozzle exit, the pressure drops to around 185,750 Pa (point B).
The resulting pressure drop is:

$$\text{Percentage drop} = \frac{203132 - 185750}{203132} \times 100\% = 8.56\%$$

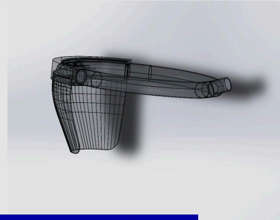


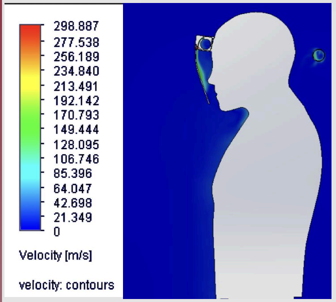
Clean-air coverage around the face remains limited.
The tracer concentration distribution shows that external air infiltrates from the sides of the breathing zone, confirming that the downward-directed jet does not effectively isolate the nose–mouth region from the surrounding air.



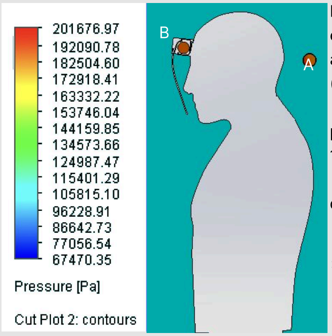
The velocity near the face initially lies within approximately 102–68 m/s, before decaying further downstream to around 34–68 m/s.

Inward-Curved Barrier Design



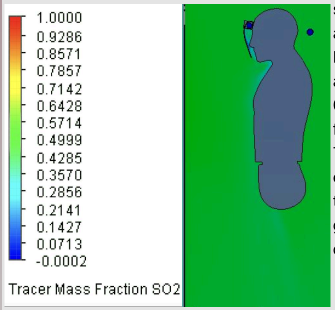


The velocity contour shows that the jet exits at approximately 128 m/s, at the upper region of the nozzle and forms a curved, inward-directed stream.
The flow bends toward the face before traveling downward, as indicated by the color gradient in the velocity field.

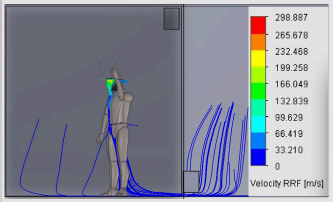


Pressure near the entrance is approximately 201677 Pa (point A).
At the nozzle exit, the pressure drops to around 192091 Pa (point B).
The resulting pressure drop is:

$$\text{Percentage drop} = \frac{201677 - 192091}{201677} \times 100\% = 4.75\%$$

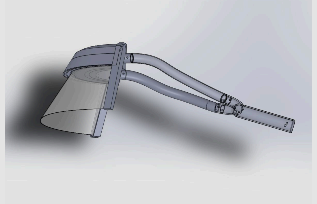


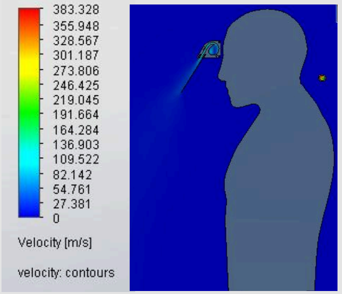
The tracer visualization shows a clean-air region around the face, indicated by the blue to light-blue area corresponding to 0–0.28% contaminant mass fraction.
The protected zone extends along the face as the inward-curved jet guides the clean-air path downward.



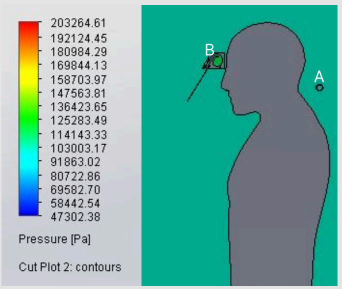
The air stream is focused coverage along the facial region. The velocity along the face ranges from approximately 99 m/s to 232 m/s, showing the curved barrier maintains jet momentum before the flow travels further downward.

Barrier with Air-Straightening Grid



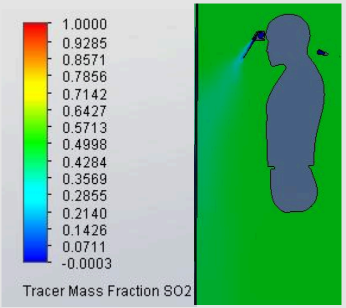


The velocity contour shows that the jet exits at approximately 82-109 m/s, forming a downward-directed stream.
The potential core of the jet extends in front of the face and continues downward across the breathing zone, as indicated by the color gradient in the velocity field.

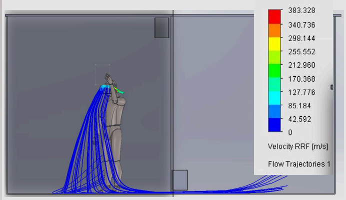


Pressure near the entrance is approximately 91,863 Pa (point A).
At the nozzle exit, the pressure decreases to around 125,283 Pa (point B).

$$\text{Percentage increase} = \frac{125283 - 91863}{91863} \times 100\% = 36.39\%$$

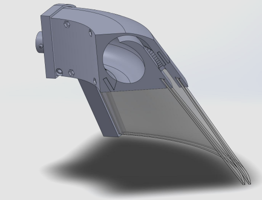


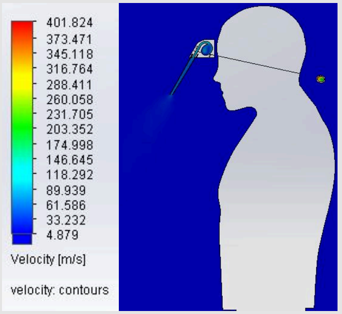
The breathing-zone tracer concentration remains within 0.42–0.57 mass fraction.
The tracer distribution shows that external air infiltrates from the sides of the breathing zone.
However, the air stream produced by this configuration is wide and long, suggesting a more extended repellent zone.



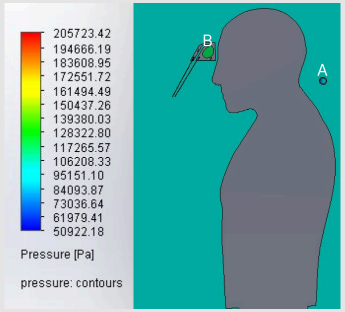
The velocity near the face initially lies within approximately 42–85 m/s, before decreasing further downstream.
The streamlines indicate that while the air-straightening structure generates a more uniform downward flow,

Elongated Nozzle Barrier Design



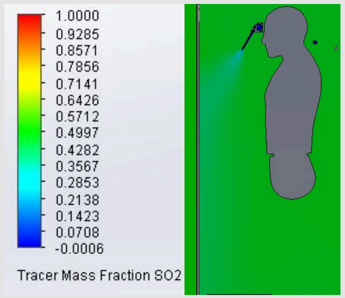


The velocity contour shows that the jet exits at approximately 33–90 m/s within the upper flow layer.
However, the jet loses momentum almost immediately after leaving the nozzle.

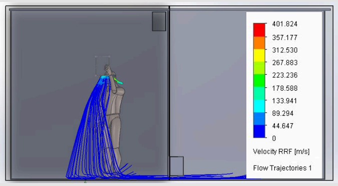


Pressure near the entrance is approximately 84,094 Pa (point A).
At the nozzle exit, the pressure increases to around 128,323 Pa (point B), as shown by the contour scale.
The corresponding percentage rise in pressure is:

$$\text{Percentage increase} = \frac{128323 - 84094}{84094} \times 100\% = 52.6\%$$



The tracer visualization shows a clean-air region concentrated in front of the face within the 0.43–0.57 mass-fraction range.
Although the elongated nozzle forms a physical barrier, it does not provide clean airflow to the breathing zone.



The jet does not remain coherent once it leaves the nozzle.
The elongated shape causes rapid velocity loss and premature jet breakup, indicating that the nozzle design is excessively long for effective air delivery to the face.

Figure 88. Wearable CFD Simulation Result

PSBT Test Set up

Following the initial PSBT setup, wearable-scale prototypes were tested to evaluate performance under realistic conditions. Each prototype nozzle was integrated into a head-mounted configuration to assess airflow coverage, particle-blocking effectiveness, and user-related factors such as noise and velocity comfort.

The test employed the same methodology as the earlier feasibility studies, with air supplied by a high-capacity blower (800 L/min) and spray paint used as a tracer to visualize airflow blockage on A4 paper targets. Luminance analysis of the spray patterns provided quantitative effectiveness measures, reported as median values and standard deviations. Additional measurements included outlet velocity (m/s) and noise levels (dBA), allowing a multi-criteria evaluation of both protective efficiency and ergonomic suitability.

Figure 89. A 3D-printed nozzle prototype mounted vertically, with A4 paper target placed behind for paint deposition measurement.

Evaluation and Discussion

Blockage effectiveness was quantified using the luminance-based metric introduced in page. X.X (Eq. Y), where effectiveness expresses the proportion of contaminants blocked relative to the clean reference sheet and the nozzle-free baseline. the same effectiveness metric was applied here:

$$\text{Effectiveness } (\%) = \frac{L_{\text{test}} - L_{\text{baseline}}}{L_{\text{blank}} - L_{\text{baseline}}} \times 100$$

The wearable PSBT results were normalized using the same reference luminance values as the main PSBT campaign, with the clean A4 sheet defined as the 0% contamination reference (L_blank = 253.85) and the nozzle-free blower serving as the 100% contamination baseline (L_baseline = 125.64; median luminance = 125.64).

Straight-Down Barrier Design

Effectiveness (%) = (156.13 − 125.64) / (253.85 − 125.64) × 100 = 23.78%

Inward-Curved Barrier Design

Effectiveness (%) = (134.73 − 125.64) / (253.85 − 125.64) × 100 = 7.09%

Barrier with Air-Straightening Grid

Effectiveness (%) = (224.49 − 125.64) / (253.85 − 125.64) × 100 = 77.10%

Elongated Nozzle Barrier Design

Effectiveness (%) = (208.73 − 125.64) / (253.85 − 125.64) × 100 = 64.84%

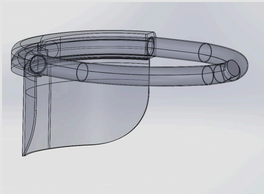
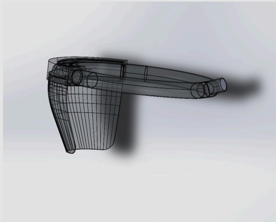
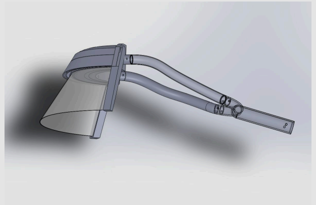
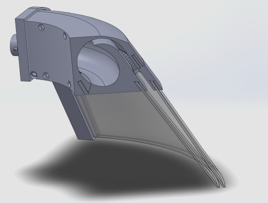
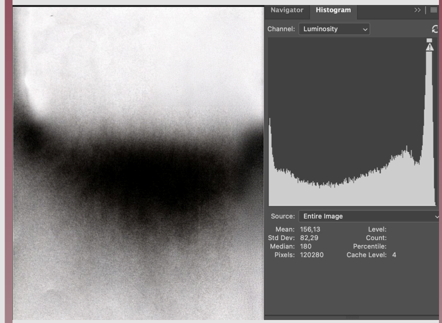
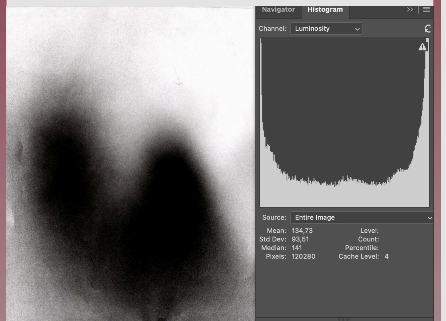
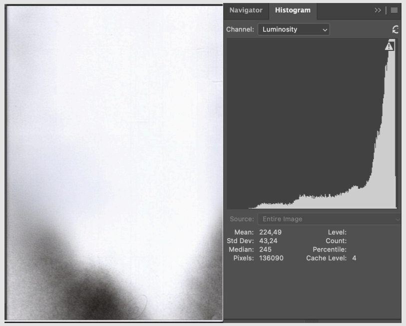
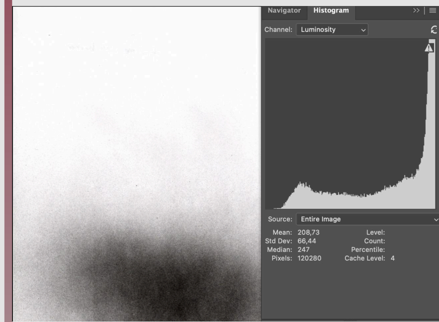
The effectiveness values provide an overall measure of spray-blocking performance and indicate that outward-directing nozzles perform better than straight-down or inward-curved geometries. To identify where leakage occurred on the target surface and to understand the spatial patterns behind each score, the spray-paint images were examined. Figure 90 summarises the characteristic deposition patterns for each configuration. The following qualitative observations describe how paint accumulated across the sheet. The underlying hypothesis is that an outward-guiding shape deflects contaminants away from the breathing zone more effectively, whereas a downward or inward jet tends to introduce mixing between clean air and ambient particles towards the breathing zone.

Comparison with CFD Findings

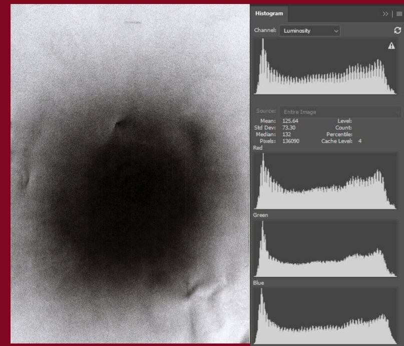
The physical results show good alignment with the CFD predictions:

- Straight-Down Barrier
  CFD predicted limited breathing-zone isolation, consistent with the weak spray-blocking seen in PSBT.
- Inward-Curved Barrier
  CFD suggested improved coherence, but the physical prototype underperformed, likely due to surface imperfections and unmodelled flow separation—indicating CFD idealisation effects.
- Air-Straightening Grid
  High PSBT effectiveness matched CFD predictions of a coherent downward jet and reduced lateral entrainment.
- Elongated Nozzle
  CFD indicated rapid decay of velocity below 33 m/s and inconsistent jet formation. This matches the partial protection and lower-region leakage observed in the spray test.

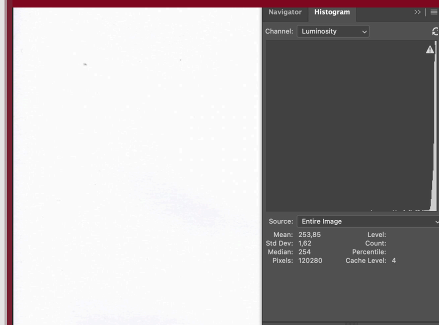
Overall, physical testing confirmed CFD-identified weaknesses (flow decay, recirculation zones) and validated the grid-assisted design as the most consistent performer.

Name	Straight-Down Barrier Design	Inward-Curved Barrier Design	Barrier with Air-Straightening Grid	Elongated Nozzle Barrier Design
3D X-Ray View				
inlet pressure (CFD) / outlet pressure (CFD)	 Mean 156.13 , std dev 82.9	 Mean 134.73, std dev 93.51	 Mean 224.49 , std dev 43.24	 Mean 208.73 std dev 66.44
Effectiveness	23.78%	7.09%	77.10%	64.84%
Qualitative Observation	Spray deposition accumulated heavily along the lower edge of the barrier, indicating insufficient downward jet momentum and incomplete breathing-zone protection. The flow did not maintain coherence, allowing substantial particle intrusion beneath the barrier.	The pattern shows a large central penetration region, suggesting that the inward curvature redirected the jet prematurely toward the face. This outcome contradicts the CFD prediction, likely due to flow separation at the curved surface and instability in the physical prototype.	The breathing zone remained largely clear, with only minor deposition along the lower region. The straightening grid appears to stabilize the flow, producing a coherent, uniform jet consistent with CFD findings. The nozzle does not provide strong enough flow to block the contaminants at the bottom.	The upper facial region exhibited good protection; however, spray penetration occurred in the lower zone. This suggests that the elongated nozzle does not deliver enough velocity at the exit and the jet breakup rapidly.

Control Group



Baseline – No nozzle, no air supply: As shown, the air spray aims at the center of the A4 paper, which is the same for the rest of the test. The paper surface shows a dense, centrally concentrated deposit with a mean luminance of 125.64, median of 132, and high standard deviation (73.30).



Blank Paper Reference Measurement: A clean, unused A4 sheet was scanned under identical conditions to the spray test samples to establish a maximum brightness reference for calculating blockage effectiveness. Image histogram analysis yielded a mean luminance of 253.85 (standard deviation 1.62, median 254) on a 0–255 grayscale scale, This value represents the theoretical upper limit (0% contamination)

Figure 90. Wearable Prototype Test result

Power Consumption Analysis (2-Hour Use Scenario)

The airflow demand for the wearable system is primarily governed by the volumetric flow rate required to maintain a stable downward jet across the breathing zone. Based on the laboratory setup, a representative flow rate of 800 L/min $(Q = 0.0133\ \mathrm{m^3/s})$ is needed to reproduce the protective effect observed in the prototype testing. Computational fluid dynamics (CFD) analysis revealed that the internal nozzle geometry accounts for a 36.39% pressure drop between the supply inlet and the outlet, indicating that the nozzle–barrier assembly is the dominant source of aerodynamic resistance.

Volumetric flow: $Q = 800\,\mathrm{L/min} = 0.0133\,\mathrm{m^3/s}$

Total pressure drop (nozzle + HEPA H12):

$\Delta P_{\mathrm{total}} = 1284\,\mathrm{Pa}$

Target runtime: $t = 2\,\mathrm{h}$

CFD simulation results show that the nozzle produces a pressure drop of 1092 Pa, while a new HEPA H12 filter contributes an additional 192 Pa (Ku et al., 2023). Neglecting tubing losses, the total pressure drop is therefore:

$$\Delta P_{\mathrm{total}} = \Delta P_{\mathrm{nozzle}} + \Delta P_{\mathrm{H12}}$$

$$\Delta P_{\mathrm{total}} = 1092 + 192 = 1284\ \mathrm{Pa}$$

The corresponding air power required to sustain this flow is:

$$P_{\mathrm{air}} = \Delta P_{\mathrm{total}} \cdot Q$$

$$P_{\mathrm{air}} = 1284\,\mathrm{Pa} \times 0.0133\,\mathrm{m^3/s} \approx 17.1\,\mathrm{W}$$

To estimate electrical power consumption, blower efficiency must be considered. According to REHVA — Federation of European Heating, Ventilation and Air Conditioning Associations — field measurements of 767 HVAC fans showed an average total efficiency of 33%, with only a small fraction achieving 50–60% (REHVA, 2012). Since smaller fans and blowers exhibit reduced geometry efficiency (Greenheck, 2013), a 40% efficiency assumption (η=0.4)(\eta = 0.4)(η=0.4) was selected for this design estimate. The electrical power requirement therefore becomes:

$$P_{\mathrm{elec}} = \frac{P_{\mathrm{air}}}{\eta} = \frac{17.1\ \mathrm{W}}{0.4} \approx 42.7\ \mathrm{W}$$

To operate for 2 hours, the energy requirement is:

$$E = P_{\mathrm{elec}} \cdot t$$

$$E \approx 42.7\,\mathrm{W} \times 2\,\mathrm{h} \approx 85.4\,\mathrm{Wh}$$

a practical energy density of ≈175 Wh/kg (3M, 2023). This empirical value was adopted for the present design estimate. Using this density, the required battery mass is:

$$m_{\mathrm{battery}} \approx \frac{84.5\ \mathrm{Wh}}{175\ \mathrm{Wh/kg}}$$

$$m_{\mathrm{battery}} \approx 0.483\ \mathrm{kg}$$

yielding an estimated battery weight of approximately 0.48 kg.
Volumetric energy density was estimated using a conservative value of ≈250 Wh/L, consistent with typical packaged Li-ion battery modules used in wearable and portable equipment. Applying this density, the required battery volume becomes:

$$V_{\mathrm{battery}} = \frac{84.5\ \mathrm{Wh}}{250\ \mathrm{Wh/L}}$$

$$V_{\mathrm{battery}} \approx 0.338\ \mathrm{L}$$

corresponding to a physical volume of ≈0.34 L (340 cm³). This volume is compatible with multiple compact form factors and can be integrated into the wearable system’s backpack but can be too heavy for headcount.

Interpretation for Wearable Air-Curtain Design

The analysis indicates that, for a two-hour operating period, the required battery mass is approximately 0.48 kg. At this weight, a head-mounted configuration is no longer practical, and the system therefore requires a backpack-mounted battery to maintain comfort and avoid excessive load on the user’s head and neck. The nozzle–barrier assembly remains responsible for most of the pressure loss, meaning that aerodynamic refinement of the geometry offers the greatest potential for reducing power demand and improving protective performance.
The outward-directed air jet mixes rapidly with surrounding air due to turbulence. Because the airflow is not inhaled by the user and functions only to redirect contaminants downward, the air does not need to meet the purity requirements associated with respiratory protection systems such as PAPRs. The filter primarily serves to protect the blower from paint overspray, dust, and debris encountered in typical painting or construction environments.
A coarse prefilter is therefore the most suitable option at the current stage of development. It provides adequate blower protection, adds only a small pressure drop, lowers the required blower power, and keeps battery size and weight within a practical range—without the unnecessary energy cost associated with HEPA filtration. The potential advantage of finer filtration for ultrafine particulate exposure, such as welding or metal grinding, remains uncertain and should be examined in the next research phase.

Figure 91. Airflow visualization with smoke:
A smoke generator was connected to the air supply, and smoke was released througdh the nozzle to observe the jet trajectory and dispersion pattern. The objective was to identify the direction, spread, and stability of the airflow and to compare these observations directly with CFD-simulated flow fields.

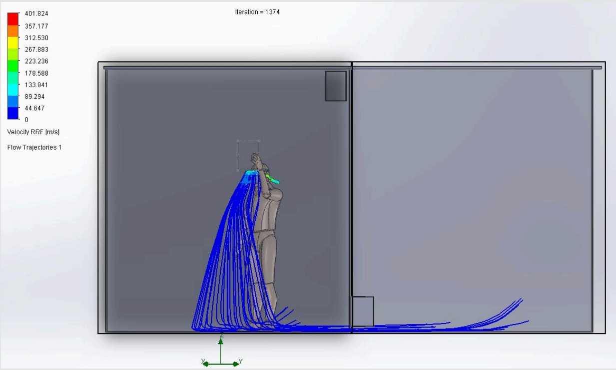


Figure 92. CFD Projectile Dot Analysis
In addition to standard CFD velocity and pressure field visualization, a projectile dot method was used to trace individual airflow paths from the inlet. This technique allowed each air parcel to be tracked as it exited the nozzle, providing an intuitive visualization of flow direction, jet cohesion, and dispersion patterns. Dense and uniform dot trajectories indicated stable flow, whereas diverging or chaotic trajectories highlighted turbulence, misalignment, or insufficient directional control. This method proved particularly useful for evaluating the impact of subtle geometric changes in nozzle design.

Figure 93. Smoke-blocking test:
A second smoke-based test was performed to evaluate the nozzle's ability to deflect airborne particles away from the breathing zone. This allowed visual confirmation of whether the generated airflow effectively redirected smoke away from the face, supporting its potential protective function.

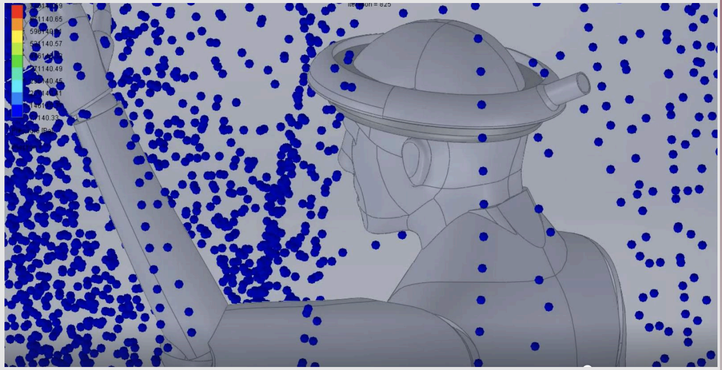


Figure 94. CFD Particle Tracking – Silica Dust Simulation
In SolidWorks Flow Simulation, a particle tracking study was performed to simulate silica concrete dust behavior under the influence of the air curtain. Particle sizes were based on typical respirable dust distributions (≤10 μm), with motion influenced by drag, gravity, and airflow. Results showed that an optimally directed jet could prevent the majority of particles from entering the breathing zone, although effectiveness decreased with oblique particle approach angles or reduced airflow volume.

Figure 94. Bright-color spray paint test:
The initial performance evaluation involved using brightly colored aerosol spray paint directed toward the target zone. While quantitative interpretation of A4 paper scan results was challenging due to scanning artifacts, video recordings provided clear visual evidence of the nozzle's deflection effectiveness.

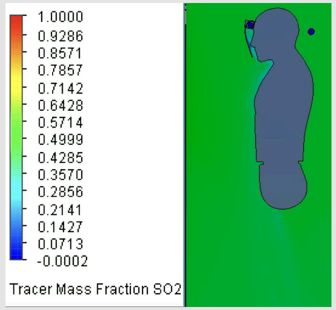


Figure 95. CFD Tracer Study – SO_2 Gas Dispersion
A tracer gas simulation was performed to model the dispersion of sulfur dioxide (SO_2) entering the computational domain from a vertical wall source. This setup evaluated the air curtain's capacity to mitigate gaseous contaminant infiltration under realistic boundary conditions. The CFD results indicated that while the air curtain substantially reduced the forward penetration velocity of SO_2, complete exclusion was not achieved, particularly when ambient air already contained contaminants. In addition, the simulation revealed that SO_2 could bypass the curtain by traveling through the gap between the wall and the product, as illustrated in Figure 95. These observations highlight the critical importance of maximizing volumetric flow rate and eliminating structural gaps through improved fit and sealing in order to enhance overall protective effectiveness.

Part 6 :Physical and Qualitative CFD Airflow Visualization

To qualitatively assess airflow behavior and compare it with CFD predictions, a series of visualization tests were conducted (Figure 91-95.).

Part 7 Design Implications

Shift in Design Goal

The original objective—to produce a thin, uniform "sheet" of air for particulate deflection—was reconsidered after both testing and user evaluation. Physical trials and CFD results demonstrated that while a narrow sheet could be formed under controlled conditions, it was highly vulnerable to disruption from user movement, crosswinds, or changes in head position. Consequently, the design goal shifted toward generating a robust, high-volume airflow capable of maintaining protective function under real-world variability.

Key Effectiveness Factors

Testing and simulation identified a clear hierarchy of performance factors:

1. Combination of nozzle angle and airflow volume – The most critical determinant of deflection performance, as it directly controls both momentum and coverage of the protective air stream.
2. Air pressure – Influences outlet velocity but shows diminishing returns beyond ~3 bar, where noise, turbulence, and safety concerns outweigh performance gains.
3. Airflow evenness – Contributes to uniform coverage, but its influence is secondary to total volume flow and directional stability.

Rationale for Change

Thin air sheets rely heavily on maintaining laminar flow, which is easily disrupted by external airflow, wearer motion, or obstacle interference. A high-volume jet, even if less aerodynamically "perfect," is more resilient to these disturbances and sustains higher protective effectiveness in uncontrolled environments.

Future development should prioritize stable, outward-directed, high-volume flow that resists environmental disruptions. Slightly higher power consumption is acceptable if the resulting airflow remains protective under motion and cross-drafts. However, airflow alone cannot ensure complete isolation: both CFD and spray imaging showed that clean air inevitably mixes with contaminated ambient air at the edges of the breathing zone. Therefore, a combined approach is needed for the next design phase:

- a simple but robust nozzle geometry,
- supportive physical barriers to prevent lower-edge penetration, and
- optional filtration for supplying consistently clean air.

Part 8 Recommendations

Filtration Integration and Energy Efficiency

Subsequent development should include the integration of a suitable filtration module, such as HEPA or multi-stage particulate filters, while maintaining adequate airflow volume for effective protection. The challenge will be balancing filter resistance, blower capacity, and battery sizing to achieve a target operational runtime of 2–3 hours without excessive weight. Energy efficiency must be improved through aerodynamic optimization of the flow path and the use of high-efficiency blowers to reduce power draw.

Real-World Testing and Validation

Laboratory spray and CFD tests should be supplemented with field trials in occupational environments, using particle sensors to quantitatively measure aerosol concentrations inside and outside the breathing zone during actual work tasks. Workplace trials will provide critical data on performance under varying conditions such as crosswinds, thermal plumes, and user movement.

Nozzle Optimization

Further refinement of nozzle size, outlet geometry, and flow rate is required to balance protective performance, comfort, and energy consumption. Ergonomic balance remains important; however, findings from this study indicate that effectiveness should take precedence over minor ergonomic inconveniences.

Dynamic Performance in Motion

To simulate real-world usage, future experiments should evaluate the system's effectiveness while the wearer is in motion. This may be achieved using a test rig that moves the nozzle assembly in controlled patterns mimicking worker head and body movements. The impact of motion-induced turbulence on air curtain stability will help determine optimal airflow volume and jet angle for mobile tasks.

Test Repetition and Statistical Reliability

The current spray paint tests were conducted in single trials for each condition. To ensure statistically robust conclusions, future testing must involve multiple repetitions under identical conditions, enabling the calculation of mean values, standard deviations, and confidence intervals for all measured metrics. This will strengthen the reliability of performance comparisons and design decisions.

FINAL PRODUCT

Designed for Active Tasks, Made for the Work You Do.

The model demonstrates how the wearable unit allows painters to carry tools comfortably while keeping the upper body unobstructed for sanding, drilling, or surface preparation.

This image was taken with a real model, but the face has been digitally altered with AI to protect privacy.

Deflect. Breathe.

Airflow Demonstration in a Dusty Environment

This scene visualizes the protective airflow around the face during dust-heavy work, highlighting how the air curtain interacts with airborne particles.

This image was taken with a real model, but the face has been digitally altered with AI to protect privacy.

Wear It. Forget It.

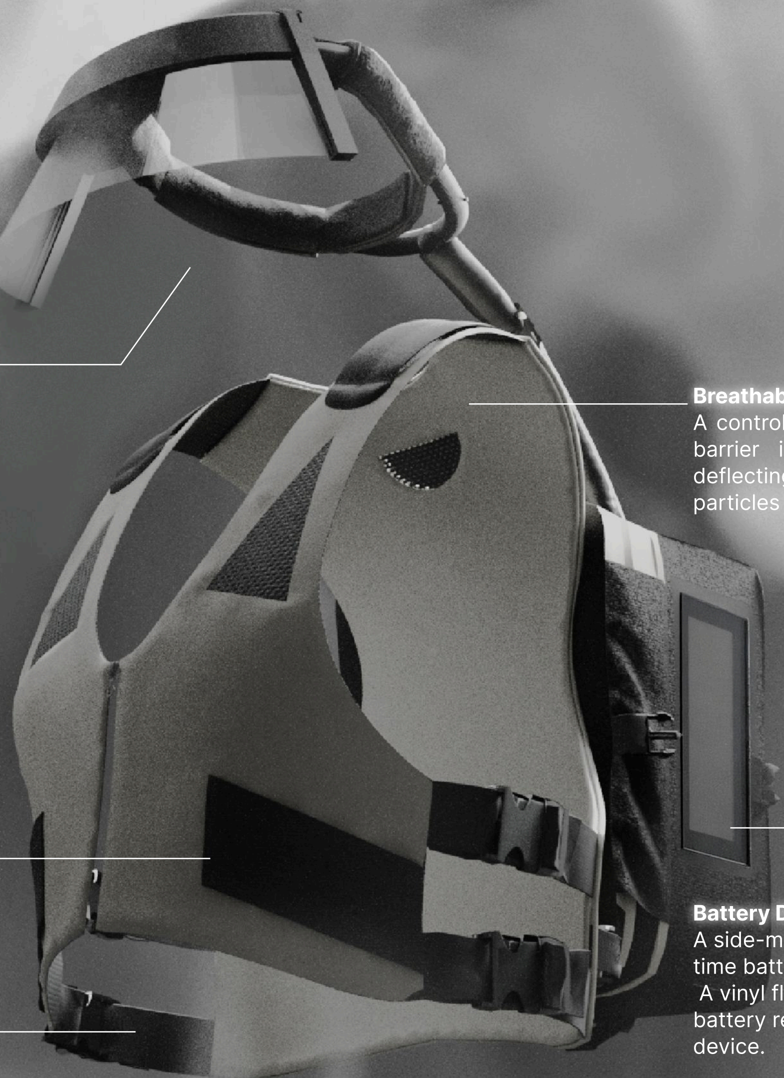
Headpiece Ergonomics and Hose Routing

During sanding tasks, where fine airborne particles are generated continuously and in close proximity to the face, the air-curtain system redirects dust away from the user’s breathing zone. This allows the painter to work comfortably and maintain clear visibility without relying on traditional tight-seal masks. The soft headband provides a secure, comfortable fit and was reported as comfortable by all users.

Active Dust Deflection

During sanding tasks, where fine airborne particles are generated continuously and at close proximity to the face, the air-curtain system redirects dust away from the user’s breathing zone. This allows the painter to work comfortably and maintain visibility without relying on traditional tight-seal masks.

Invisible Protection



Clean Breathing Zone
A controlled air curtain forms an invisible barrier in front of the face, actively deflecting dust, overspray, and fine particles away from the breathing area.

Extended Shielding Area
The airflow is engineered to push contaminants outward, creating a wider protective envelope that moves with the user.

Integrated Tool Belt
A minimal waist-mounted tool system keeps essential items accessible without interfering with movement or workflow.

Adjustable Waistband
Fully adjustable straps accommodate a wide range of body sizes, ensuring a secure fit and improved ergonomic support.

Breathable Inner Padding
A controlled air curtain forms an invisible barrier in front of the face, actively deflecting dust, overspray, and fine particles away from the breathing area.

Battery Display & Side Access Port
A side-mounted display provides real-time battery status.
A vinyl flap opens for quick charging or battery replacement without removing the device.

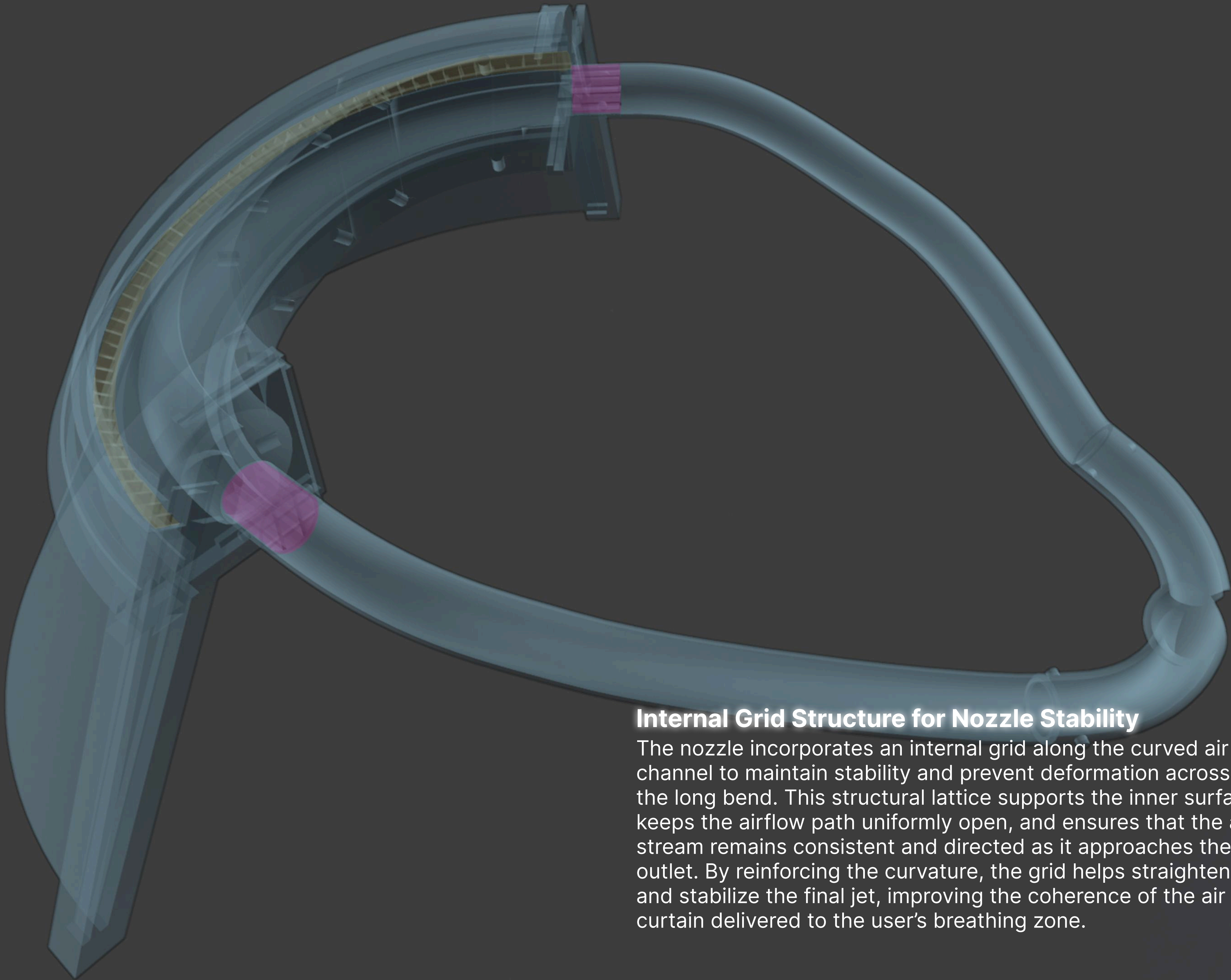
Twist-Lock External Filtration
This prototype features a fully external HEPA H12 filtration module secured with a twist-lock interface. The mechanism enables quick cartridge changes and eliminates the need to open the housing, minimizing downtime on the job site. External mounting also reduces thermal buildup inside the unit and preserves consistent airflow during prolonged use.

High-Performance Air Intake
The circular geometry of the intake increases filtration surface exposure while improving the uniformity of incoming flow.

Expandable Bag for PPE Compatibility
The backpack unit is designed with an expandable soft structure that accommodates all core components of the PPE system—including the garment, vest, and headpiece—within a single compact form. This ensures everything fits together seamlessly, making the setup easy to carry, store, and prepare for use.

Ergonomic Wearability
The structural harness evenly distributes load across the shoulders and torso. Soft, breathable padding reduces pressure points and heat accumulation, enabling all-day wearability for painters and construction workers.

Where Air Becomes Armor.



Internal Grid Structure for Nozzle Stability

The nozzle incorporates an internal grid along the curved air channel to maintain stability and prevent deformation across the long bend. This structural lattice supports the inner surface, keeps the airflow path uniformly open, and ensures that the air stream remains consistent and directed as it approaches the outlet. By reinforcing the curvature, the grid helps straighten and stabilize the final jet, improving the coherence of the air curtain delivered to the user’s breathing zone.

Filtration System

The final design uses a HEPA H12 filter, mounted externally with a twist-on mechanism for easy replacement. It is compatible with standard market filters, avoiding proprietary parts and improving usability.

While filter performance may vary by manufacturer, a comparative experiment conducted by Talhelm (2023)—though not performed under strict laboratory conditions—provides useful insight. Filter selection focused on balancing efficiency and airflow, both essential for maintaining a stable air curtain. H12 filters (≥99.5%) offer strong protection with moderate pressure drop. In contrast, H13 filters (≥99.95%) provide higher filtration but significantly reduce airflow. The test showed that H12 filters can deliver up to 23% more airflow, resulting in more overall clean air despite slightly lower per-pass efficiency. Filters below E11 may not offer sufficient protection. H12 was selected as a l trade-off between protection and performance, based on the cited study above. However, the system's actual filtration efficiency and airflow performance still need to be validated through testing.

Design Iterations

Three key filter integration concepts were explored during the design process:

Figure 96. Diffuse Filter Designer

This design explored using a diffuser-inspired attachment—similar to those found on hair dryers—to connect a filter to air delivery pipes. The concept aimed to allow compatibility with a variety of consumer-grade blowers, enabling any circular nozzle to fit securely into the extension.

Hairdryer-Inspired Diffuser Attachment

However, the idea faced several challenges. Achieving true universal compatibility proved difficult. The form was either too bulky or lacked sufficient surface area for effective filtration—resulting in high pressure and reduced airflow. Its divergent-to-convergent shape also reduced airflow efficiency. Despite being 3D modeled, the design was ultimately dropped due to its complexity and impracticality.

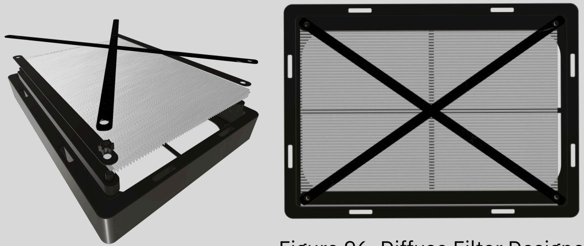


Figure 96. Diffuse Filter Designer

The second filter iteration explored a flat rectangular filter mount designed to accommodate universal filter shapes. While functionality and fit were successfully tested with a 3D-printed prototype and real filters, the design proved too bulky for wearable use. Fixation methods were still undeveloped, and further size reduction was needed. It was ultimately set aside in favor of a more compact, integrated solution.

Rectangular Universal Filter Housing

Figure 97. Twist-Lock External Filter

Twist-Lock External Filter (Final)

The final iteration adopts an external HEPA H12 filter secured with a twist-lock mechanism. This design allows the filter to be replaced quickly and without tools, improving usability during daily operation. Mounting the filter outside the device housing also prevents internal clogging, maintains consistent airflow, and reduces maintenance time. The standardized twist interface supports compatibility with commonly available market filters, eliminating the need for proprietary cartridges and lowering long-term operating costs.

Mounting Harness

This series of sketches explores different ways to carry the wearable air curtain function unit, with special consideration for painters who are constantly moving, bending, and switching positions. Given the mobile and physically dynamic nature of painting tasks, the design focuses on secure attachment, even weight distribution, and minimal interference with the hip area, which is often occupied by tool belts.

Figure 98. Mounting Harness Design Iterations

Each concept was evaluated by a painter based on ergonomics, fit, and perceived integration into typical painter attire. A key objective was to create a design that feels intuitive and non-obtrusive—one that blends naturally into the painter's existing workflow and gear.

During feedback sessions, the painter reviewed: Design 2 was found to slightly restrict arm movement, which is critical for overhead or wide-reach tasks. Design 3 raised concerns about universal fit and may not adapt well to different body types or clothing layers. Both Design 1 and 4 works for its simplicity and universal fit.

As a result, the final direction adopts the structure of Design 1, which integrates well with a painter's tool vest. It avoids the hip zone, offers quick on/off wearability, and supports a sense of seamless integration with other personal protective gear and avoided belt which may create more entanglement and visual clutter.

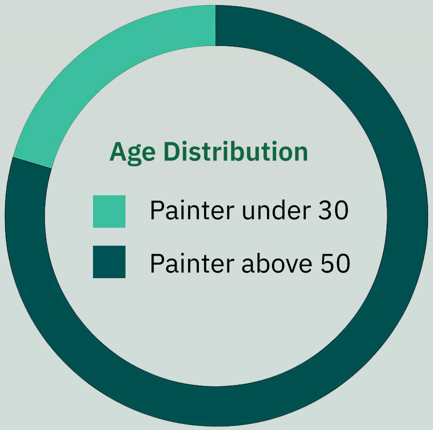
USER FEEDBACK

First Functional Prototype Test with Intended Users

Overview

To evaluate the potential of the prototype in real-world use, the session began with a project introduction and consent process, followed by a short product explanation. Participants then wore the device and shared their impressions, while the researcher observed usability behaviors and noted key interactions. A structured questionnaire captured feedback on comfort, fit, aesthetics, workflow integration, perceived safety, and long-term adoption—rated on a 1–7 scale. Results were visualized using scale bars and icons for clarity. The session concluded with a group discussion, offering valuable insights and suggestions to guide future design improvements.

Participants for the Prototype Test



Four participants were recruited for this user test. Participant profiles are detailed in Figure 99. The group included one younger painter and three older painters over the age of 50, offering a range of perspectives based on experience and age.

Figure 99. Mounting Harness Design Iterations

Test Procedure

Each session followed a semi-structured format to allow flexibility while ensuring all participants were exposed to the same core activities. The protocol proceeded as follows:

1. Introduction and Consent
   The session began with a brief introduction to the project and the goals of the user test. Participants were asked to read and sign a consent form and were informed about the recording procedures. This onboarding process took approximately 5 minutes per participant.

Product Demonstration

A short explanation of the prototype followed. Due to the clarity of the product's appearance and purpose, painters immediately understood the concept without the need for extended explanation. This phase took less than 2 minutes on average.

Hands-On Evaluation and Feedback

Each participant was invited to wear the prototype and provide immediate verbal feedback during and after use. This stage lasted 5–10 minutes per person. The first participant took slightly longer, while subsequent participants required less time, possibly due to peer discussions and prior observation. The flow remained informal and adaptive to maintain comfort and authenticity.

Observation and Note-Taking

Throughout the hands-on trial, the researcher made detailed observations regarding body language, ease of use, discomfort, confusion, and moments of hesitation or positive response. These notes were later analyzed alongside verbal feedback.

Data Collection and Questionnaire Completion

After trying the prototype, participants filled out a structured questionnaire available in Dutch or English, depending on preference. The questionnaire covered the following categories:

- Comfort and Fit
- Aesthetics and Appearance
- Integration into Work Flow
- Perceived Safety
- Possibility of Long-Term Adoption in Work-routine

Each category included statements rated on a 1–7 Likert scale, with 1 indicating low satisfaction and 7 indicating high satisfaction. Average scores per category were calculated and visually represented using a scale bar to indicate rough percentage scores.

Yes/no questions were simplified into icon-based formats for clarity and quick completion.

(Full questionnaire can be found in Appendix X; see Appendix L for detailed scoring breakdowns.) The next page shows the result and data visualization.

Comfort and Fit

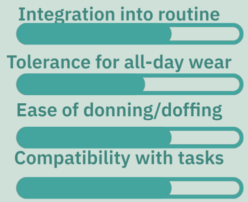
The vest section revealed fitting challenges: for three painters, it was too tight, while for one it was too loose. Most of the dissatisfaction with "fit and seal quality" stemmed from the one-size-fits-all limitation. Participants suggested that the vest needs to be more elastic or adjustable to accommodate different body types.

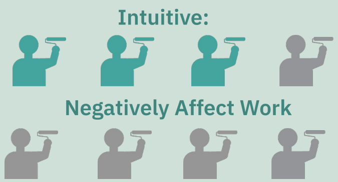
The headband fit well on all users without issue. Notably, the younger painter—who has experience with masks and is generally comfortable with protective procedures—responded positively to the design. **In contrast, the older painters, who are not in the habit of wearing PPE, felt that having anything around the face was still too much.** The shop owner also noted that the product would likely be more valuable for users who are already willing to wear protective equipment, rather than for those who consistently choose not to wear anything.

Testing took place in hot and humid weather conditions (approximately 26°C). When the device was turned on, painters commented that it felt similar to an air conditioner, and expressed that this cooling effect would be appreciated during summer work.

However, during the test, the prototype ran out of air, and the connecting pipe frequently became disconnected. These issues disrupted continuous use and highlighted the need for structural improvements to ensure stable airflow delivery and better connection reliability.

Workflow Integration





All painters agreed that the product integrated well into their work routine, with no interference reported during tasks.

Despite good overall integration, few usability issues were observed: locating and operating the power button can be confusing; one painter instinctively pushed the button toward the back, suggesting users expect the button to be either on the front or to require a backward push when swinging hands backwards.

Three out of four painters described the design as intuitive, and none felt it would require changes to their current work process. One painter who regularly wears PPE even said he would prefer this product over his current gear.

Painters suggests the product is comfortable for 3–5 hours, but not yet suitable for an entire 8-hour shift. This makes it acceptable for shorter jobs or half-day use, but it may require breaks or removal as fatigue or discomfort builds.

Some mentioned they would remove it when it feels too heavy or if any part fails, and one common suggestion was that the air supply pipe should be longer or more flexible to improve comfort and mobility. Addressing these concerns—such as weight distribution, heat buildup, and connection reliability—would help extend wear time and improve overall usability.

Safety

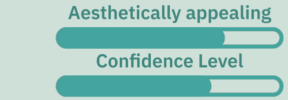
A major issue observed during testing was the airflow connection system. The prototype's tubing had multiple weak connection points, causing it to disconnect repeatedly. This significantly reduced the effectiveness of the product during use. Although painters commented that the product felt safe when it functioned properly, they also expressed doubt about whether it provides better protection than their current PPE.

Painters tried the device both with and without physical facial protection. They observed that a physical barrier is useful for unexpected situations (e.g., splashes or debris).

To improve adoption, the painters suggested the product should offer a stronger and more consistent airflow to build trust in its performance.

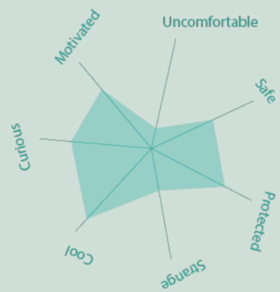
Additionally, they proposed broadening its use beyond sanding, identifying other relevant scenarios such as spray painting and sweeping, where dust and particle exposure are also common.

Appearance and aesthetics



Most painters stated that appearance was not a major concern for them. On a scale of 1 to 7 for aesthetic appeal, two painters rated the design a 7 (perfectly appealing), one rated it a 5, and one rated it a 3, describing the look as "strange and robotic." Overall, the product was seen as acceptable in appearance.

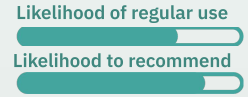
The confidence level rating is investigated to understand whether painters would feel comfortable wearing the product in a real work setting. The average score was moderately acceptable (5 out of 7), though opinions varied significantly. While two painters said it looked fine, others remarked that it felt too robotic or that it looked like they were "wearing an air conditioner." The small sample size and differing individual preferences suggest that appearance may influence acceptance for some users, even if not a top priority for all.



Painters were also invited to describe their impression and feelings about the product using their own words. For each word, they were asked to rate the intensity of that feeling on a scale from 2 to 7. A radar chart was created based on the average intensity scores, with each axis representing a cluster of emotional words provided by the participants.

Two painters who felt that the vest was too tight described it as uncomfortable noted that nothing worn on the head ever feels comfortable—unless it blows cooling air.

Long term adaption



Painters were asked about the potential for long-term use of the product. Their responses varied depending on whether they already had the habit of wearing masks. Those who regularly use protective equipment responded more positively, with some stating they would definitely consider long-term use. In contrast, painters who do not typically wear masks felt that the product did not provide enough incentive to change their current behavior.

Similarly, only painters who already wear PPE regularly indicated they would be likely to recommend the product to their peers. Several participants noted that they would be more inclined to recommend or adopt the product if the air supply tubing were more flexible and could move freely without disconnecting. Additionally, long-term use would be more likely if the device provided a consistently positive physical sensation, such as cooling airflow.

Issues Observed

A major issue observed during testing was the airflow connection system. The prototype's tubing had multiple weak connection points, causing it to disconnect repeatedly. This significantly reduced the effectiveness of the product during use. Although painters commented that the product felt safe when it functioned properly, they also expressed doubt about whether it provides better protection than their current PPE.

Painters tried the device both with and without physical facial protection. They observed that a physical barrier is useful for unexpected situations (e.g., splashes or debris).

To improve adoption, the painters suggested the product should offer a stronger and more consistent airflow to build trust in its performance.

Additionally, they proposed broadening its use beyond sanding, identifying other relevant scenarios such as spray painting and sweeping, where dust and particle exposure are also common.

Likes and Dislikes

Likes

Participants appreciated several aspects of the prototype, including:

- The absence of a facial mask, which allowed for unobstructed communication
- Improved breathability compared to traditional PPE
- The presence of a physical barrier that still felt non-intrusive
- The sensation of cool airflow when the device was powered on
- The lightweight feel of the system during use
- The integrated bag design, which conveniently stored all components
- The ease of charging, which made daily use more manageable

Dislikes

However, participants also expressed several concerns:

- Discomfort from any physical contact around the head, even when airflow improved breathability
- Poor fit of the vest—reported as either too tight or too loose—leading to reduced comfort and seal quality
- The rigidity of the connecting pipe, which felt restrictive and limited freedom of movement

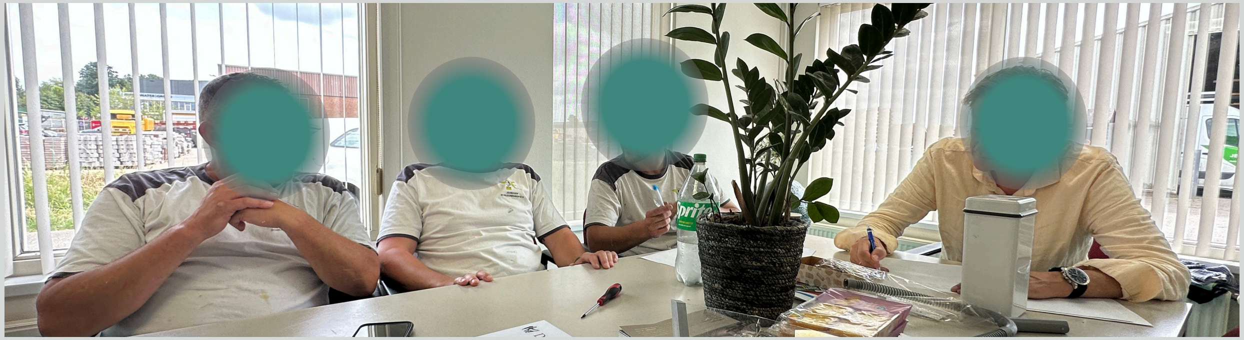


figure 99. the 4 painters participated the use test.

Group Discussion and Closing Reflection

Following individual feedback, participants gathered for a short informal group discussion to exchange opinions, highlight shared experiences, and propose improvements. This conversational format allowed for the surfacing of collective sentiments and insights (Figure 99-102).

In the final section of the test, participants were invited to make direct design suggestions or express wishes for future changes. These inputs were documented and are reflected in the final prototype modifications or proposed future iterations

figure 101. the painter trys the switch

figure 102. the expandable backpack.

figure 103. painters try the prototype on

User Feedback

User trials revealed that the cooling effect generated by the increased airflow was consistently perceived as a desirable secondary benefit. Painters and other participants reported that the cooling sensation enhanced comfort during work, especially in warm or poorly ventilated environments. Participants also provided practical feedback on ergonomics and usability. Several painters noted that the switch should be longer and designed to pull back rather than move up and down (Fig. 101). Fit testing showed size variation concerns: one participant found the prototype too large, another found it too small, while two others reported that it fit comfortably (Figure 102.). This highlighted the need for multiple size options or a more adjustable, simplified garment design. The expandable backpack (Fig. 103) received universally positive feedback. Users appreciated its ability to accommodate the full PPE setup and its flexibility for different work scenarios. The next section is refined design for better user interaction.

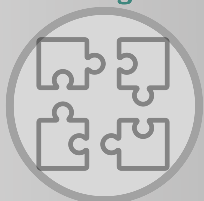
User Interaction

This sequence illustrates how the air curtain product is intended to be worn by painters working in residential, community, or commercial settings. The design emphasizes the following features to ensure ease of use and consistent adoption by professionals:

Comfortable and universal fit

Natural, unrestricted breathing

Seamless integration with existing PPE

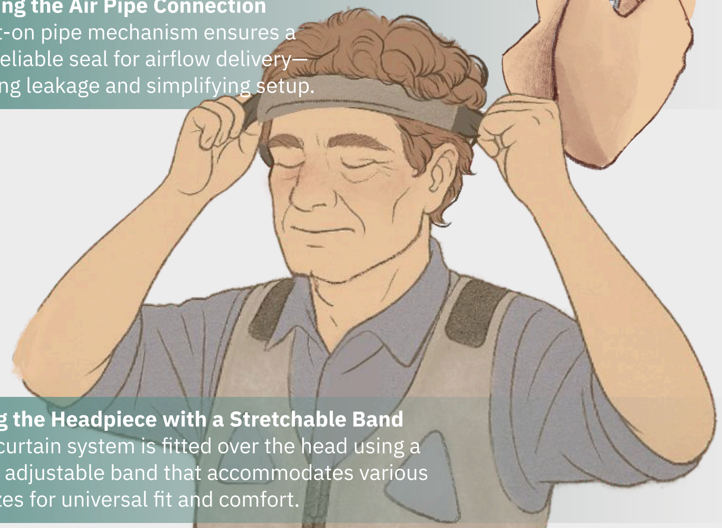


Convenient organization and storage

Opening the Charging Bag
The user approaches the storage bag where the device charges between uses.

Temporarily store the Device
The painter collects all necessary components, including the air curtain and accompanying PPE.

Securing the Air Pipe Connection
A twist-on pipe mechanism ensures a tight, reliable seal for airflow delivery—reducing leakage and simplifying setup.



Wearing the Headpiece with a Stretchable Band
The air curtain system is fitted over the head using a flexible, adjustable band that accommodates various head sizes for universal fit and comfort.

Wearing with a Helmet (Optional)
The design allows for use with a construction helmet, which may be necessary for tasks such as working on scaffolding.

Adding Protective Goggles
A detachable goggles can be worn with the air curtain to protect the eyes and enhance overall safety.

Wearing the Air Curtain Alone
In lower-risk conditions, the painter may choose to wear the air curtain without additional protective gear.

Wearing with Preferred Headwear
The system is compatible with various caps, allowing painters to retain their personal comfort and style preferences while staying protected.

Possible Ways of Wearing

AIR CURTAIN DURING WORK SHIFT

This page demonstrates the intended user interaction in a dusty environment—specifically during sanding tasks. The product is designed to ensure comfort, mobility, and protection, seamlessly supporting the painter's workflow without unnecessary interruptions.

Receiving a Low Battery Alert
The device notifies the user of low power with a vibration alert, a visible battery percentage display, and a buzzer. A modular battery system allows for seamless battery replacement.

Breathing Freely During Sanding
While sanding, the user remains protected by the air curtain system, enabling unrestricted breathing even in high dust exposure.

Maintaining Comfort While Bending or Crouching
The vest design leaves the waist area free, ensuring ergonomic flexibility during tasks that involve crouching or bending.

Reducing Risk of Entanglement
A short, well-secured pipe reduces interference and minimizes the risk of entanglement with other equipment or the user's body.

Drinking Water Without Removal
The product is designed to be non-intrusive, allowing the user to hydrate without needing to remove any part of the system.

Blocking Sweat With the Band
The fabric on head helps absorb or block sweat, improving comfort during physically demanding tasks and during hot weather.

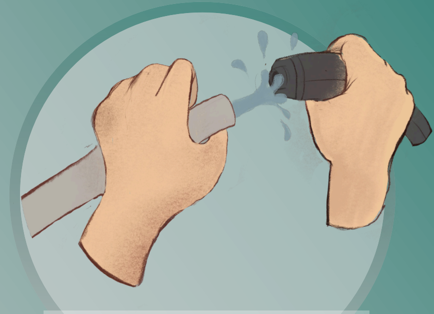
Communicating Freely
Users can keep the system on while talking to coworkers, allowing for quick transitions between social and work interactions.

Carrying Tools on the Belt
The belt provides convenient attachment points for small tools or accessories.

Temporarily store the Device
The painter takes a break and hangs the product using the hook attached to his belt.

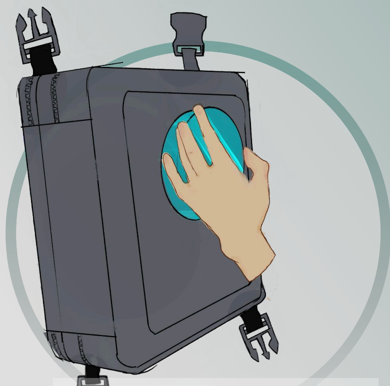
Store the Vest
The painter places the wearable vest into the backpack.

Pack Other PPE
The painter takes a break and hangs the product using the hook attached to his belt.



Rinse Nozzle
The painter rinses the air nozzle with clean water to remove residue or dust.

Clean the Surface
The waterproof surface of the bag is cleaned using disinfectant wipes.



Replace the Filter
The HEPA filter sheet can be purchased online.

Charge with Modular Battery
The painter removes the battery from the product for charging.

MAINTENANCE

This page illustrates the intended user interactions with product’s maintenance routine. By simplifying maintenance, the design encourages sustained behavior change and enhances the product’s long-term viability.

Charge Battery in Bag
The painter takes a break and hangs the product using the hook attached to his belt.

Prepare for the Next Shift
The unit is left connected to power, ready for use in the upcoming work period.

CONCLUSION

Design Goal Evaluation

"The Design Goal is to create an air curtain that effectively reduces workers' exposure to **harmful aerosols and Particulates** across various workplace environments, while seamlessly integrating into daily activities **without disrupting workflow or comfort.**"

Recap the Design Challenge:

The challenge lies in designing a solution that achieves the right balance between airflow effectiveness, energy efficiency, ergonomic wearability, and compliance with ventilation regulations—all while maintaining compatibility with existing equipment and minimizing disruption to users' daily tasks.

Evaluation by Design Focus

Targeted Airflow Control

The Design Goal outlined in the previous section emphasized the importance of delivering precise airflow to ensure reliable protection. However, through simulations and nozzle prototyping, achieving precision proved challenging—particularly due to the impact of external disturbances. Literature also indicates that airflow remains stable only within a short distance from the nozzle. Despite these limitations, the findings reveal a promising direction: by extending the controllable airflow zone and combining it with a physical barrier, it is possible to enhance protective performance and mitigate instability.

Level of Goal Realization: ●●●○○

Validation Method: CFD, physical prototype test, Literature Review and theoretical analysis.

Wearability and Integration

The device is designed to be lightweight, and the weight is evenly distributed, which giving users a sense of freedom and ease. It accommodates personal preferences by allowing painters to wear a helmet or cap, and it is compatible with various types of goggles or prescription glasses. The product offers a universal fit that adapts to different head shapes and sizes. Painters who tested the prototype reported that it felt comfortable and unobtrusive, allowing them to work without restriction. In this sense, the design successfully meets its goal of seamless integration and wearability.

Level of Goal Realization: ●●●●○

Validation Method: Co-design, User Test

Design for Behavior change

Research shows that painters often forgo PPE during short tasks. This design aims to improve adherence by enhancing wearing comfort so that the painter would not take the PPE off During the process.. Further validation through larger sample testing is recommended.

Level of Goal Realization: ●●●○○

Validation Method: User Journey Map, Casual Mapping, Interview, Observation, Literature Research, User Feedback

Maintenance

The filter is easy to replace and compatible with commonly available HEPA sheets, making replacements simple and accessible. The integrated waterproof backpack keeps components neatly organized and easy to manage.

Level of Goal Realization: ●●●●●

Validation Method: Prototype, Tested with Market-available filter

Feasibility – Desirability Evaluation - Viability

Feasibility

The process far shows strong potential:

- CFD simulations that validate airflow behavior and sealing effectiveness
- User research that informs ergonomic and psychological aspects
- Prototype testing that demonstrates functional integration

However, to achieve further technological readiness level, the further design improvement should proof or improve on:

- Air curtain stability in turbulent or semi-open spaces and **when the user is in motion.**

Technology Readiness Level 3

The project is classified as Technology Readiness Level (TRL) 3 due to the following achievements:

- Established Basic Principles: Foundational knowledge on aerosol behavior, respiratory PPE limitations, and airflow control was synthesized through literature review and field research, forming the scientific basis for the concept.
- Formulated Technology Concept: A wearable air curtain system was clearly defined to address limitations in existing PPE, focusing on aerodynamic sealing, filtration efficiency, and user comfort.
- Demonstrated Feasibility: CFD simulations and physical testing of air flow production provided analytical and experimental evidence supporting the concept's viability under controlled conditions.

Technology Readiness Levels (TRL) – Horizon 2020 Work Programme 2014-2015
Definitions:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in lab
- TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – System prototype demonstration in operational environment
- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

HORIZON 2020 – WORK PROGRAMME 2014-2015 General Annexes
Extract from Part 19 - Commission Decision C(2014)4995

Desirability

The design demonstrates a high level of desirability, as it effectively addresses user discomfort, fit, and social acceptance—earning consistently positive feedback in early and review-stage testing for the following reasons:

Discomfort during prolonged wear emerged as a common concern. To reduce physical strain, the design incorporates a lightweight and modular structure that minimizes fatigue and improves overall wearability over extended periods.

Poor adherence caused by heat buildup, humidity, and breathing resistance was frequently mentioned. An open-face configuration was introduced to improve air circulation, reduce heat and moisture accumulation, and support natural breathing and clearer communication.

Lack of proper fit across diverse user groups highlighted the need for inclusive sizing. A universally adjustable soft band was implemented to adapt to different head sizes and shapes, while also offering improved sealing, sweat management, and user guidance.

Psychological discomfort—including feelings of claustrophobia and culture acceptance of current electric powered PPE was noted as a barrier to regular use. The visual design was intentionally kept close to familiar PPE styles to avoid drawing unnecessary attention. Feedback from early and review-stage testing confirmed that users found the appearance familiar, non-intimidating, and more socially acceptable. Some described the product as looking "normal and easy to wear," making it more desirable compared to other bulkier or high-tech alternatives.

Viability

Preliminary exploration suggests promising viability, supported use of off-the-shelf components, and positive user response—highlighting potential for potential adoption.

Furthermore, the solution incorporates a replaceable nozzle with universal connectors, enabling compatibility with existing blowers. An optional air-filter extension is available for improved performance. The nozzle is constructed from durable, washable plastic, and its standalone form supports comfortable integration with existing protective gear.

However, a full viability assessment, including detailed economic modeling and market analysis, falls outside the scope of this thesis. These aspects are noted here only as future considerations for development beyond the technical and design focus of this research.

General Discussion

This project builds on Phase 1, where the core problem and initial "air curtain" concept were defined. The focus of this phase was to realize the "curtain-like" protective airflow, prioritizing the physical formation of the barrier regardless of filtration performance at this stage.

Building on well-documented studies and literature, the problem—discomfort and low adherence to traditional PPE in hot, demanding environments—was clearly validated. While the field research had limited participants, its findings aligned with larger-scale studies and helped ensure behavioral insights were coherently integrated into a single product design. Co-design sessions and user interviews informed the system's form: a backpack-mounted filter and fan unit delivering air through a curved frame around the face. This configuration prioritized comfort, accessibility, and freedom of movement.

Technical development combined physical tests and CFD simulations to optimize nozzle geometry, airflow uniformity, noise, and spray deflection. While the current prototype does not represent the final solution, it effectively explains design trade-offs and offers a foundation for future refinement.

User testing confirmed high desirability, with positive feedback on comfort and perceived protection. Feasibility was supported by both simulation and physical tests, though further work is needed to improve airflow control and energy efficiency—particularly the fan system.

In conclusion, this project validates the air curtain concept as a viable alternative or supplement to traditional PPE. It balances user-centered design with technical feasibility and opens pathways for future development in performance optimization, smart sensing, and regulatory approval.

Limitations

Despite the promising direction of this project, several limitations must be acknowledged:

- Technology Readiness Level (TRL)
  The air curtain is currently in an early development stage (TRL 3–4), meaning that while the concept has been validated in a lab or design setting, it has not yet undergone real-world field testing. This limits the immediate understanding of its performance under variable and harsh workplace conditions.
- Context Specificity
  Although the project aims for cross-sector applicability, much of the initial research and design has focused on the painting industry. The insights, ergonomics, and environmental factors may not fully translate to other contexts such as healthcare or welding without further adaptation.
- Limited Testing with Target Users
  While earlier phases included valuable user engagement, large-scale usability testing with diverse worker groups has not yet been conducted. This may limit the generalizability of the results and insights across various work environments and demographic profiles.
- Regulatory Complexity
  Ensuring compliance with international health, safety, and PPE standards across different industries and countries presents a major challenge. These evolving regulatory landscapes may slow down the implementation or require ongoing redesign efforts.
- Physical and Design Constraints
  Air curtain effectiveness depends on consistent airflow, ergonomic integration, and environmental sealing—all of which can be difficult to achieve in
- dynamic, dusty, and mobile work settings. Noise, power requirements, and weight may also affect adoption and user satisfaction.
- Desirability vs. Feasibility Trade-offs
  Striking a balance between what users find desirable (e.g., lightweight, wearable, discreet design) and what is technically feasible (e.g., sufficient airflow and filtration) can result in design compromises that may limit either performance or adoption.
- Limited Duration and Resources
  With a fixed timeline of 100 working days, the scope for iterative prototyping, in-situ testing, and longitudinal studies is constrained. As such, the focus may lean more toward conceptual and early-stage functional development rather than robust validation.

Recommandations

Below are suggestions for the next development phase:

Structure to Improve

The current nozzle was optimized for wearability, limiting the pipe diameter to under 2 cm to avoid blocking vision. While this benefits usability, it may not offer the most efficient internal airflow. Future iterations should explore structural redesigns that balance compactness and airflow performance such as nozzle shaping, material choices, internal flow channels, internal support structures.

Function Unit to Improve

The current design proposed simple solutions: 2 speed settings responding to different filtration grade. And buzz as indicator of low battery or need filtration. centralfugal fan. further need to invest on heat distributions, energy efficiency

Other Function to consider

Consider features such as cooling airflow during hot environments.
Consider integrated misting functions to set the dust.

For Broader User

Based on survey feedback, users in other sectors—such as healthcare, chemical industries, or cleanroom work—also expressed interest in air quality-focused wearables.
Design modular versions tailored to different roles and exposure types, potentially integrating smart sensors for real-time air quality monitoring, usage tracking, or adaptive control.

Compliance Testing

To proceed toward CE certification and practical deployment, the following areas require rigorous testing and validation:

- Filtration performance: Confirm HEPA or equivalent levels under various task conditions.
- Power system reliability: Evaluate battery life, recharge time, over-heating risks, and electrical safety.
- Test in Motion: test the effectiveness of the product when performing tasks.
- Mechanical robustness: Ensure components maintain integrity under daily wear and tear.
- If the product design continues with goggle/ head brand, according to E166 the frame should:
    - with stand: Low-energy impact (45 m/s or 162 km/h) Medium-energy impact (120 m/s or 432 km/h) High-energy impact (190 m/s or 684 km/h)
    - The lenses of the goggle should :
        - Protection against liquids (drops and splashes)4Protection against large dust particles with a grain size of > 5 µm5Protection against gases, vapours, smoke, fumes and fine dust particles with a grain size of < 5 µm8Protection against short-circuit electric at Protection against molten metal and hot solids

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Appendix

Appendix A. Stakeholder Analysis

Stakeholders and Project Phase Relationship

Instead of categorizing by influence and interest, the project maps stakeholder engagement by project phase:

Product Phase	Key Stakeholders	Stakeholder Value
Development Phase	R&D Labs, SUSAG	Technical feasibility, ergonomic validation, Product Feasibility
Validation Phase	End Users, Regulators	Usability testing, compliance verification, early feedback
Market Phase	Distributors, Insurance Companies, Employers	Market entry, liability coverage, implementation support

This Project addresses the Development Phase, with preliminary attention to Validation. At this stage, emphasis lies on ensuring technical feasibility, ergonomic fit, and alignment with industry needs. SUSAG supports sector-specific concerns, while R&D partners guide the evaluation of comfort and performance. Early-stage engagement with end users and regulators is essential for iterating design decisions that pre-empt future compliance or rejection.

Key Stakeholders

In many socio-technical projects, a standard Influence vs. Interest matrix helps to prioritize engagement. However, this approach is less effective for PPE design, where influence is distributed across multiple high-impact actors. In the context of PPE development, both regulators and end users are considered key stakeholders. While regulators hold institutional authority over compliance and certification, end users ultimately control the product's acceptance and real-world adaptions. The success of any innovation in this space hinges on meeting the standards of both groups.

- Regulators have institutional authority: they define mandatory certification frameworks (e.g., CE marking) and occupational safety standards. Their influence shapes what qualifies as a legal product.
- End users (e.g., painters, extended users) control usage in practice. Despite regulations, PPE non-compliance remains common—especially in residential or small business contexts—making their comfort and perception critical for adoption.

Both stakeholders simultaneously shape product design and experiences from different ends—regulators define legitimacy, and users define practicality. Their influence is not phase-specific only (though their involvement varies at different stage)—they impact both validation and long-term adoption.

Stakeholder Conflicts

Stakeholder tensions were identified and assessed to guide inclusive design strategies and anticipate resistance:

- Employers vs. Workers: Employers often aim to minimise costs and procurement complexity, while users emphasise comfort, ease of use, and real-world wearability.
- Regulators vs. Companies: Regulators enforce strict compliance, which can be perceived as burdensome by manufacturers or SMEs seeking faster time-to-market.
- Distributors vs. Innovation Advocates: Distributors may lean toward conventional, low-cost solutions, resisting innovation unless demand or policy shifts.

Conclusion

Understanding the roles, priorities, and interactions of stakeholders highlights the complex dynamics that shape PPE development and adoption. The stakeholder analysis not only informs who must be involved, but also when and why their input matters across the product lifecycle. With these relationships clarified, the following page outlines the structure of this report and how each chapter addresses critical aspects of the problem space—from user behavior and regulatory compliance to technical feasibility and design opportunities.

Appendix B: Consent Form

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT TEMPLATES AND GUIDE
(English Version: January 2022)

Introduction

You are being invited to participate in a research study titled Designing a Robot to Support Professional Painters, and Wearable Air Curtain for Respiratory Protection from Aerosols and Particulates. These are two projects under the Human-Robot Interaction Lab from TU Delft, aimed at advancing the painting industry by exploring the design of smart agents. This study is being conducted by Fleur Jansen and Jen Ji from TU Delft in collaboration with Muzus, SUSAG, and potentially other future collaborating partners. These partners will contribute to the project but will not have access to your personal data. This study is part of a Master's research program.

The purpose of this research study is to explore the implementation of smart technologies and protective equipment in the painting industry to improve health, safety, and productivity for workers in the painting and construction industry. The study may result in potential outcomes including academic publications, or products on the market. The implications of this study are likely to inform future industrial applications and could contribute to safer work environments in relevant sectors.

What to Expect

The researchers will observe you to get an understanding of the working context. Besides observations, you will be asked to participate in interviews, activities, and tasks designed to assess your perception of new technologies and to give feedback on the designed products. These activities will take no more than 1 hour. The activities may include interviews, workshops, games, fill-in a sensitizing booklet, and audio recordings to help the researchers understand user context.

Privacy

We will collect interview data and, in some cases, video/audio recordings of the sessions. All personal data will be handled carefully and securely. The collected data will be used for academic research, publications, applications, __and teaching purposes. Personal information will be anonymized/pseudonymized, ensuring that any identifying data is removed or coded to protect your identity.

Access control: Data will be stored securely and access will be restricted to the research team only. Data may be archived for five years, after which it will be securely deleted.nIf anonymized data is shared for academic purposes or published, no identifying details will be included. You will not be identifiable in any public report or publication. You have the right to request access to your personal data, rectify any errors, or request that your data be erased, within the lifetime of the study (until April 30).

Risks: There is a small risk of reputational impact in the unlikely event of a breach of confidentiality, but steps will be taken to mitigate this through anonymization and secure data storage.

Right to refuse/withdraw: Your participation is entirely voluntary, and you can refuse to answer any questions or withdraw from the study at any time, without providing a reason.

Reimbursement: Participants will not receive financial compensation, but reimbursement for travel expenses may be offered, if applicable.

For any further information or concerns, please feel free to contact the Responsible Researcher: Fleur Jansen (f.jansen-2@student.tudelft.nl) or Jen Ji (z.ji-4@student.tudelft.nl).

If you have any complaints regarding the study, you may contact the TU Delft ethics committee at HREC@tudelft.nl

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated __________________, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • This will be a recorded interview with the workshop. The recording will be used only for academic purposes, and your personal information, such as your name, address, company information, etc, will not be shared, and the data will be stored anonymously. Surveys and Questionnaires may be involved • For interviews, the interviews will be interviewed separately, take notes with paper or laptop, and the audio will be recorded for future analysis. • There will be a workshop with materials provided by researchers, such as cards, craft materials, and booklets. • Audio or video recordings will be transcribed as text, and the recording will be destroyed after the current project is finished (around April 2025).	☐	☐
4. I understand that I will not receive payment for participating in the interview, but I will receive travel reimbursement if there is any travel involved.	☐	☐
5. I understand that the study will end by the 30th of April 2025.		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks. I understand that these will be mitigated by my being able to stop the interview and ask to delete recording at the any point	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) about occupational role, age, and experience; and associated personally identifiable research data (PIRD) such as your view on your health, your willingness to change (your way of working), your personal views/beliefs with the potential risk of you being revealed.	☐	☐
8. I understand that some of this PIRD is considered sensitive data within GDPR legislation, specifically religion, political views, and data concerning criminal activities will/may be collected and processed, research has a Data Processing Impact Assessment (DPIA) in place	☐	☐
9. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: Anonymous data collection, aggregation, secure storage, no photos with visible faces will be documented at any stage.	☐	☐
10. I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed after the thesis is finished.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that the de-identified information such as images, quotes, drawings, and writings, I provide during this research may be used for reports, academic publications, websites, or video channels related to this project. Additionally, the data could contribute to product development, policy decisions, or workplace safety improvements, especially in the context of wearable air	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
curtain devices for painters. The information may also be shared with collaborating organizations for further research purposes.		
13. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
14. I agree that my real name can be used for quotes in research outputs.	☐	☐
D: (LONG-TERM) DATA STORAGE, ACCESS, AND REUSE		
16. I give permission for the anonymized interview transcript, survey, interview quotes, and anonymized photos that I provide to be archived in the TUDelft repository so it can be used for future research and learning.	☐	☐
17. I understand that access to this repository is open to public access.	☐	☐

Signatures

________________________	________________________	________
Name of participant [printed]	Signature	Date

We, as researchers, have accurately read out the information sheet to the potential participant and, to the best of our ability, ensured that the participant understands what they are freely consenting.

______________________	________________	________
Researcher name 1 [printed]	Signature	Date

______________________	________________	________
Researcher name 2 [printed]	Signature	Date

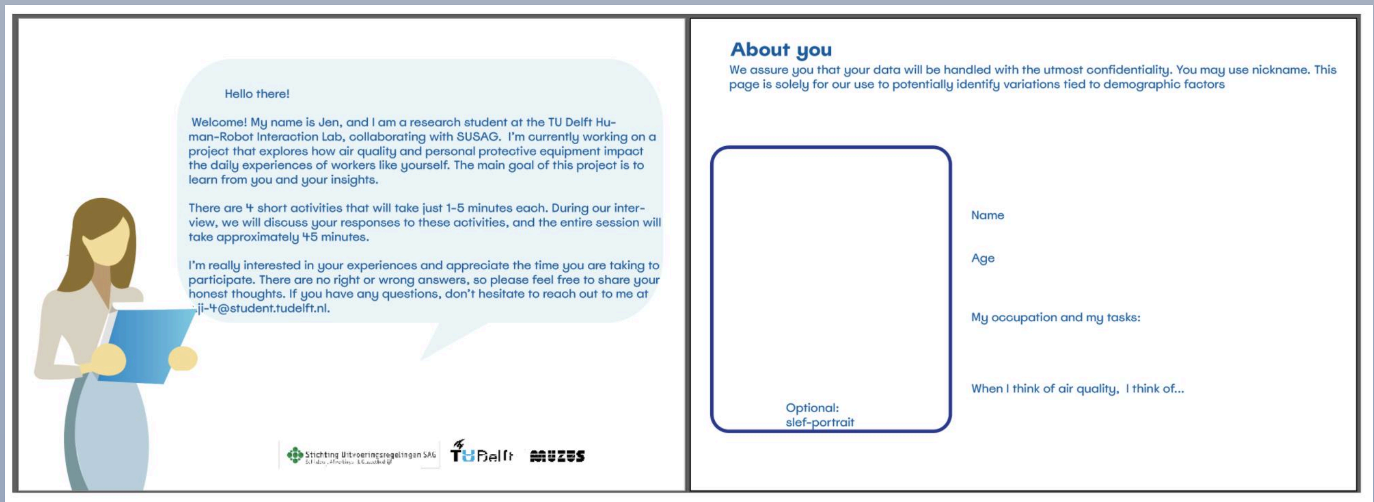
Study contact details for further information:

Fleur Jansen:
f.jansen-2@student.tudelft.nl
+31 6 29862247
Jen Ji:
z.ji-4@student.tudelft.nl
+31 6 21456980

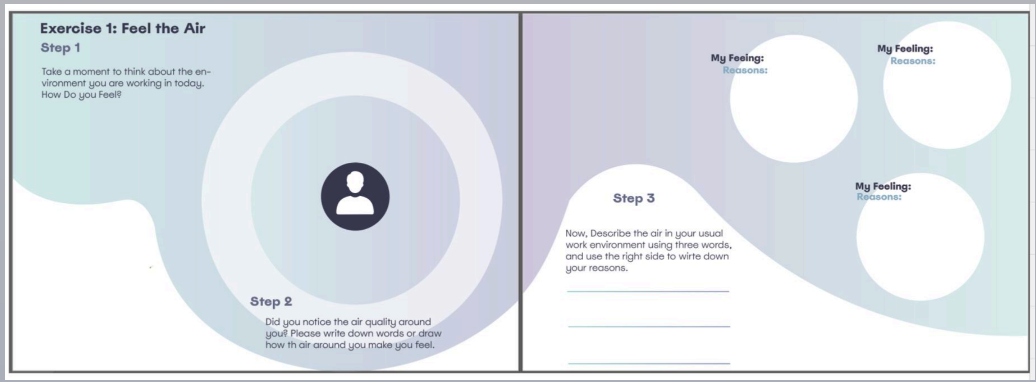
Appendix C: Exploring Workers' Perceptions on Air Quality and Protective Gear: A Sensitization Approach

Five exercises were designed to encourage workers to reflect on air quality and their feelings toward protective gear. The main questions are outlined in the booklet, and during the interview, sub-questions were asked to deepen the understanding and avoid miscommunication. These sub-questions were adjusted based on the flow of the conversation and the interviewee's situation. Each response was explored further by asking for the reasons behind the answers. Although the design goal is to improve workers' health by enhancing air quality, health-related topics were intentionally avoided to respect privacy and prevent triggering any discomfort.

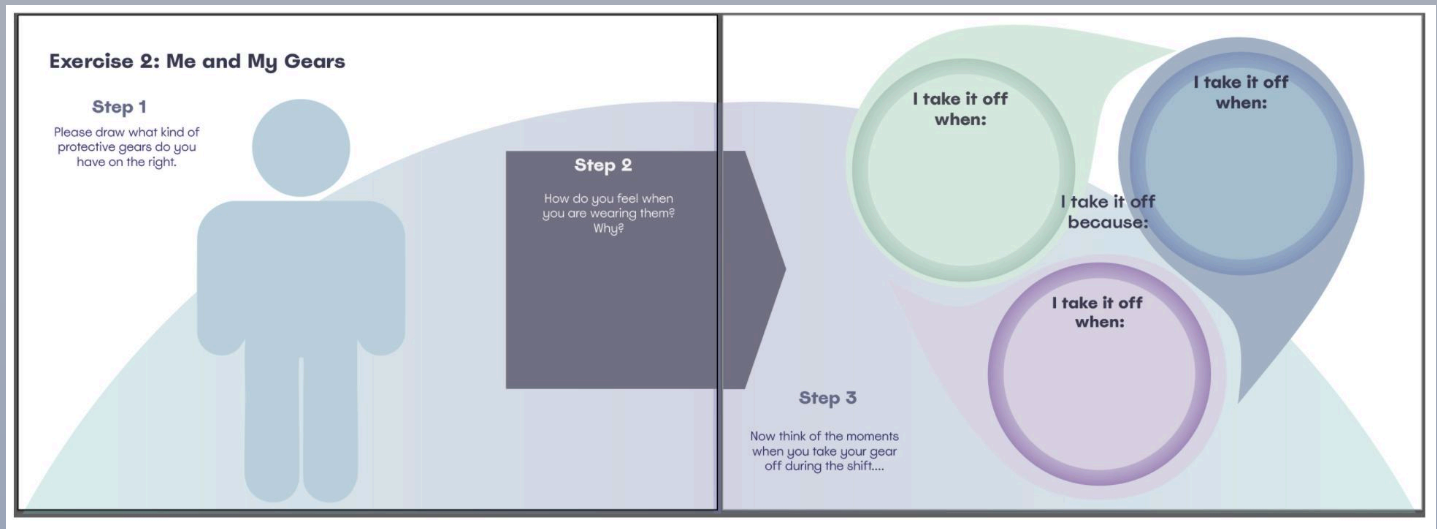
Cover page



Introduction page

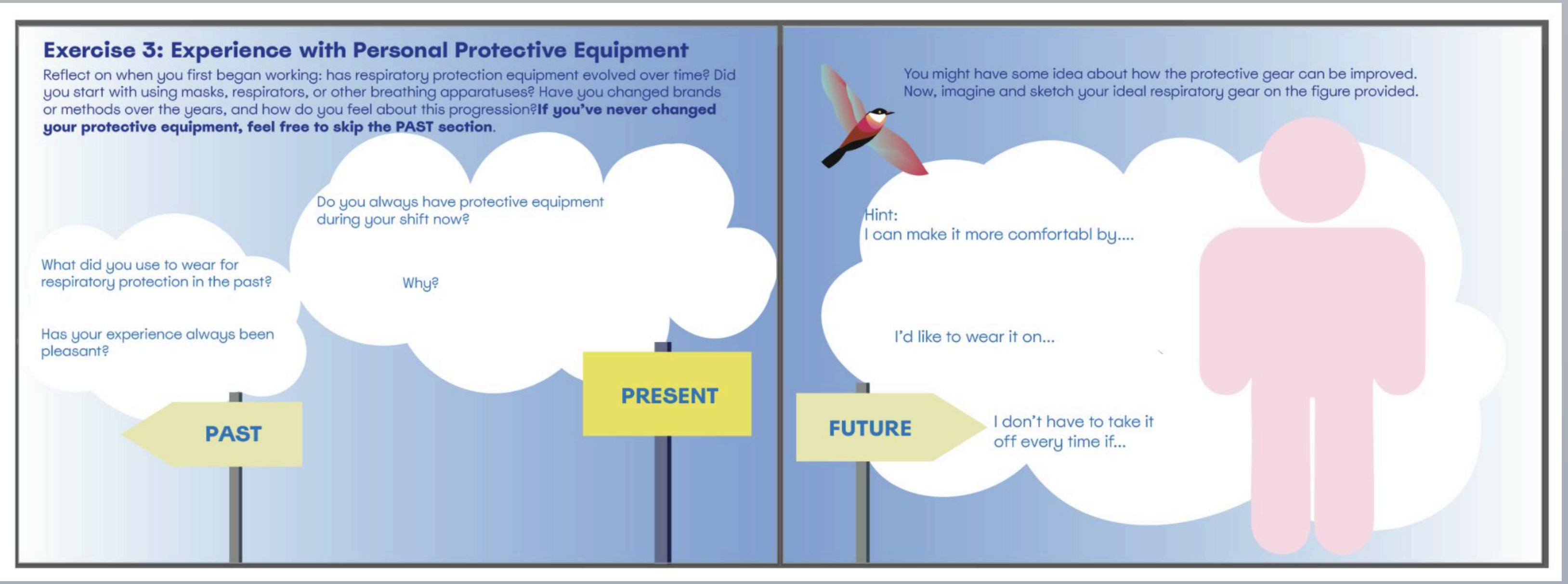


Exercise 1: Feel the Air
When did you first notice the air quality today? Was there something specific that made you aware of it?
Was it a smell, temperature, or another sensation?
Did it change during the day? If so, how?
What do you usually notice first about the air quality where you work?
Does it vary depending on the task or location you are working in?
How does the current air quality impact your mood or physical comfort?



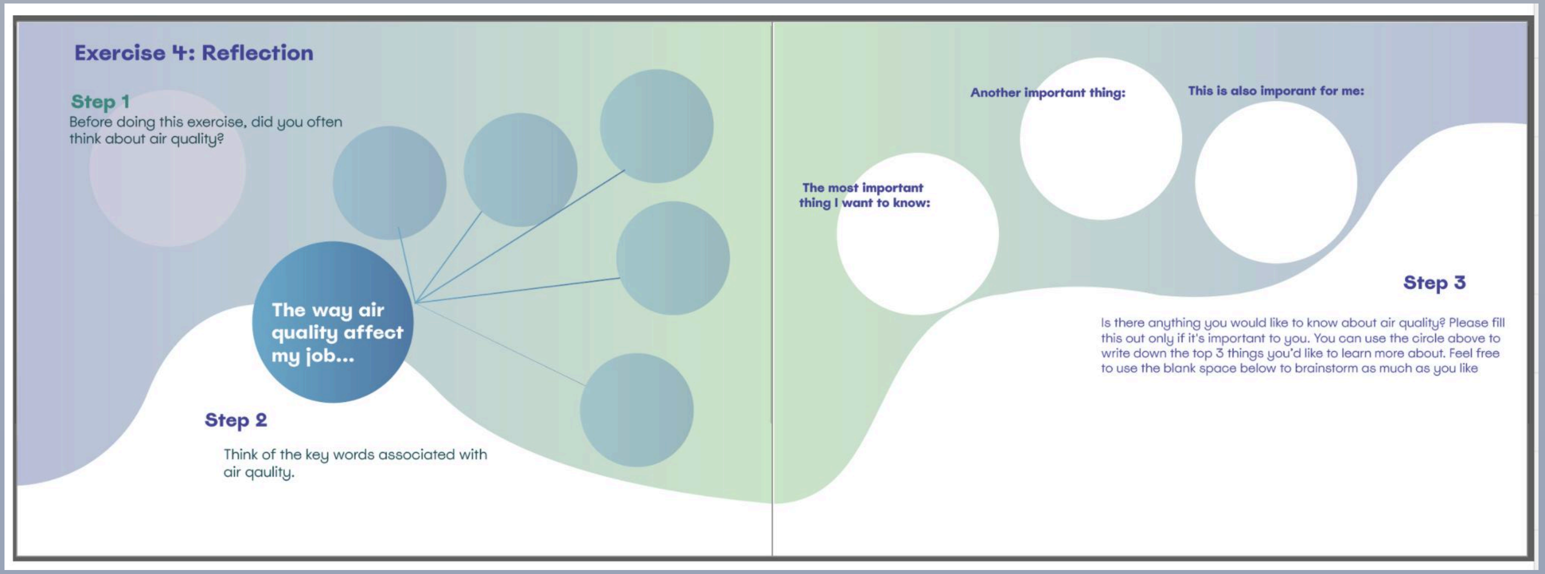
Exercise 2: Air at Work
Can you explain why you chose those three words to describe the air at work?
How do you feel about the air quality at work compared to the air quality outside of work?
In what specific situations does air quality impact your performance most?
How does poor or good air quality affect your ability to concentrate or complete tasks?
Have you ever discussed about air quality concerns with anyone at work or with friends and family?
Would you like to know the date of the quality of the air that you are breathing? Why or why not?

Exercise 3: Me and Protections
How long did you wear the protective gear today, and for what task?
Did the task require it, or was it your choice to wear it?
How does the protective gear influence your ability to move and communicate with others?
Does it make you feel more protected or hinder your work?
What factors (comfort, fit, weight) most affect how you feel when wearing protective gear?
Are there moments when wearing it becomes uncomfortable or inconvenient?



Exercise 4: Past, Present, Future

Can you describe a specific experience where protective gear significantly helped or hindered you in the past?
Was the gear comfortable and effective?
Are you happy with everything?
How consistent are you in wearing protective gear at work now?
Are there situations where you prefer not to wear it, and why?
What is the most important feature for you in your ideal protective gear for things that is worn on your head? What about a belt? Something in your pocket with wires? Backpack? Helmet?
How would this gear improve your daily work experience?
Would this ideal gear make you feel more willing to wear it all the time?
How do you feel about masks?
How do you feel about the air curtains?



Exercise 5: Reflection
How often do you think about air quality at work, or was this something you hadn't considered much before?
What moments or experiences have triggered you to think more about air quality?
If protective gear is provided, what would motivate you to wear it regularly?
Would ever be a habit for you to wear regularly?
Would changes in comfort or style make a difference in your decision to wear it?
Would you like to be notified when you breathe harmful aerosols or particulates?

Appendix D. Research Activity Template – Sentence Completion

At the end of the co-design session, participants were invited to complete a set of open-ended sentences using a language they felt most comfortable with. The activity was conducted on printed A3 sheets, and participants responded using markers.

“ Als ik elke dag iets zou dragen om de luchtkwaliteit op mijn werk te verbeteren, zou het moeten zijn: ”

“ If I wore something every day to improve the air quality at work, it should be: ”

The Ending
In the end of the interview, invite workers to complete the sentence: (the questions are printed on paper)
"If I wore something every day to improve the air quality at work, it should be ______________________________."

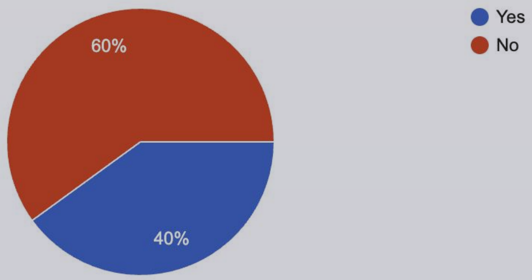
"Als ik elke dag iets zou dragen om de luchtkwaliteit op mijn werk te verbeteren, zou het ______________________________ moeten zijn.

Appendix E. Online Survey

Google form collected from random participants who need to wear respiratory protection at work place.

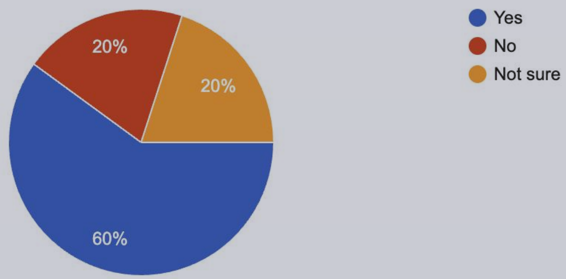
Have you thought about the air quality around you at work lately?

5 responses



Does air quality influence your mood or physical comfort?

5 responses



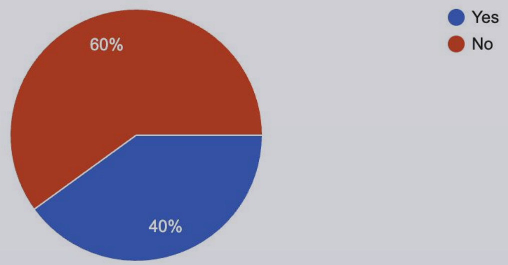
What best describes your occupation?

Copy chart

5 responses

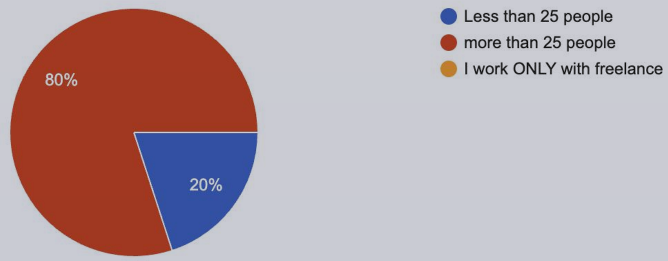
Do you wear respirator , mask, breathing apparatus, or any respiratory protection during the entire process when you are working on things produce harmful aerosols or particulates (such as dust, mold, virus, chemicals, fume)?

5 responses



How many people are there at your work place?

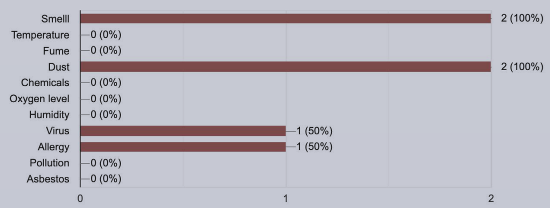
5 responses



What made you notice the air quality? (Select all that apply)

Copy chart

2 responses



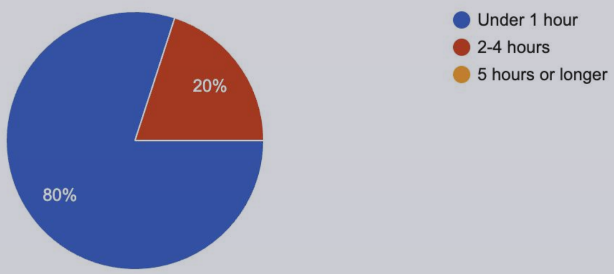
What makes you decide not to wear protective gear when needed?

3 responses

I don't think i need it
I will wear safety equipment if needed
These things are not present where I work

How long can you typically wear respirator , mask, or breathing apparatus before it becomes uncomfortable?

5 responses



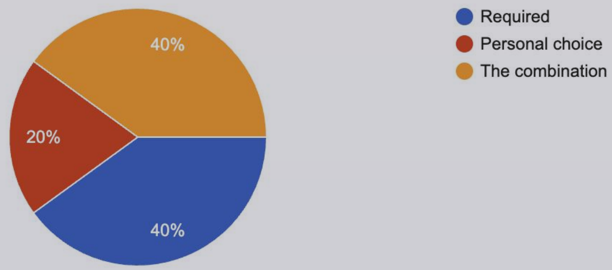
Please use 2-3 words to describe your feelings or emotions associated with your experience with protective gear:

5 responses

Hot and uncomfortable
Necessary, obliged
I don't like it , disturbing
Usually it is uncomfortable
Uncomfortable when it is hot.

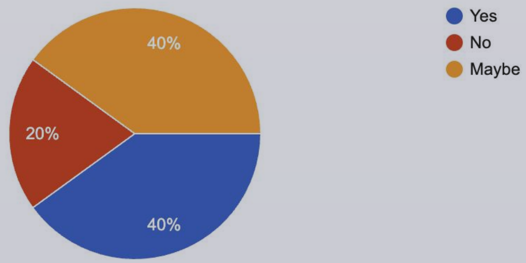
Was it required, or was it your choice to wear it?

5 responses



Does the appearance of protective gear influence your willingness to wear it?

5 responses



How do you feel about the air quality during your recent work shift?

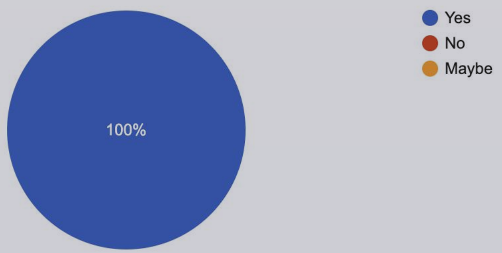
5 responses

It is very dusty and causes me to sneeze a lot. When my head is cloudy I don't feel I can work well.
I trust my company to fix this
So bad
I have no feelings about the air quality during my work recently
It's good.

Would you be open to trying new types of protective gear if it improved your comfort and safety?

Copy chart

5 responses



If you could change one thing about your current respirator , mask, or breathing apparatus, what would it be?

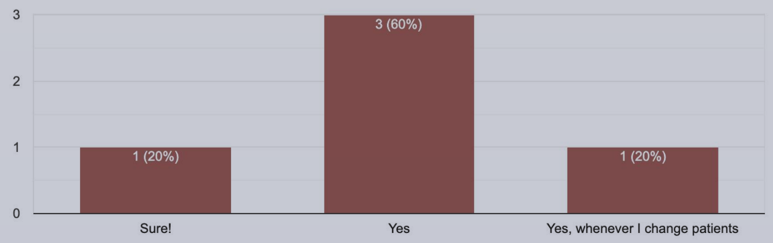
5 responses

- It always goes up my glasses and I can't see when wearing it. Or knocks my glasses off.
- More breathable
- Both
- Helmet with integrated safety glass
- Cooler

Do you change or remove your protective gear through different parts of the work shift?

Copy chart

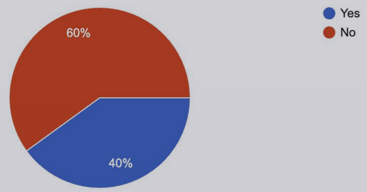
5 responses



Have you ever hear of electrical respirator, mask, or breathing apparatus?

Copy chart

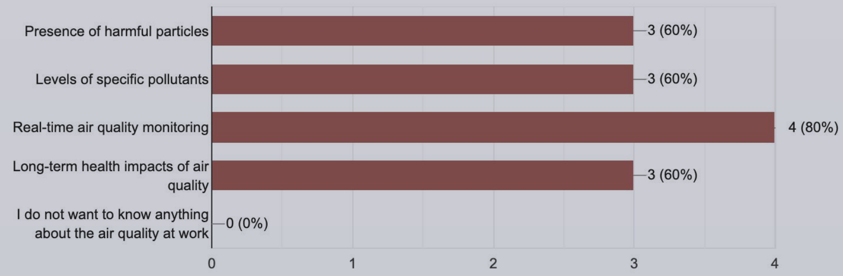
5 responses



What would you like to know about the air quality you are breathing in during work?

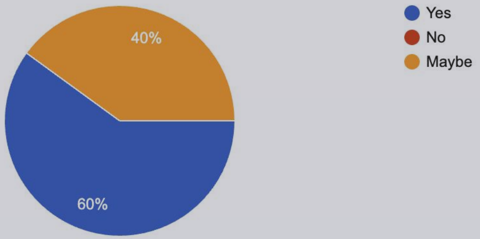
Copy chart

5 responses



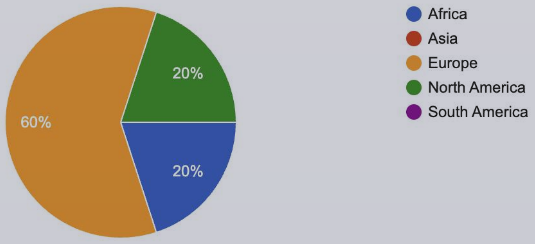
Would you like to get a report on your app about the air quality you breathe in?

5 responses



In which area do you primarily work?

5 responses



Complete the sentence:

"If I wore something every day to improve the air quality at work, it should be ___________________________."

5 responses

Light, comfortable, and easy to breathe

Comfortabele, like second skin

Mask

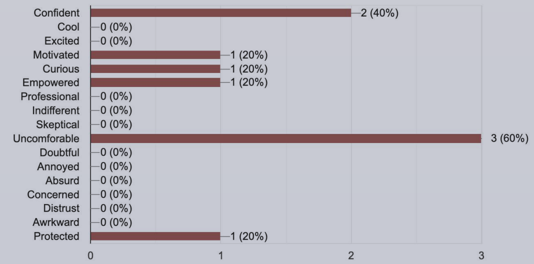
beneficial for my health

Comfortable

What does this medical-grade electrical respirator make you feel? (Select all that apply)

Copy chart

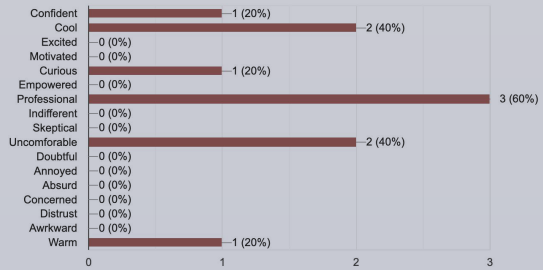
5 responses



How does this electrical filter facemask make you feel? (Select all that apply)

Copy chart

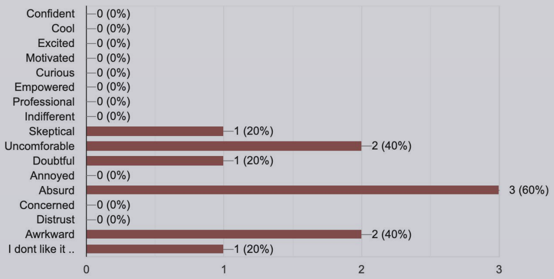
5 responses



How does this headphone combined with respiratory protection make you feel? (Select all that apply)

Copy chart

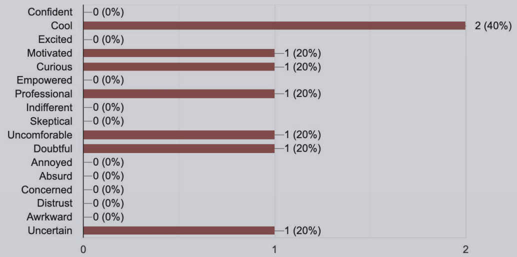
5 responses



What does this air-curtain with plasma filter in the backpack make you feel? (Select all that apply)

Copy chart

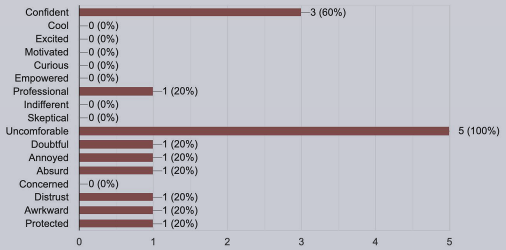
5 responses



How does this Industrial-grade electrical respirator make you feel? (Select all that apply)

Copy chart

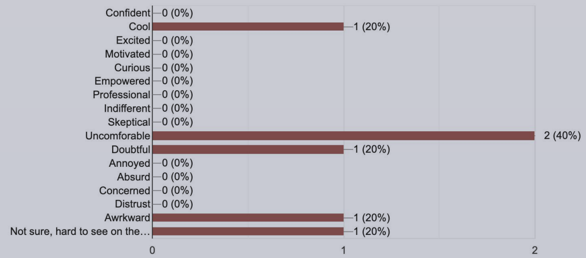
5 responses



What does this electric Industrial grade electrical respirator make you feel? (Select all that apply)

Copy chart

5 responses



Appendix F. Filled Morphological Charts

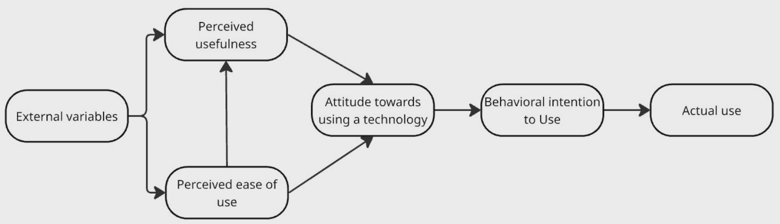
Design for Wearable Air Curtain Morphological Chart

Your occupation:				
How do you like such a device on or around your head?				
Location to Wear the heaviest part:				
How Heavy is the weight limite? (can use items, such as: an apple, a bucket water, etc)				
Shortest Acceptable battery life and how to charge?				
Describe your Aesthetics:				

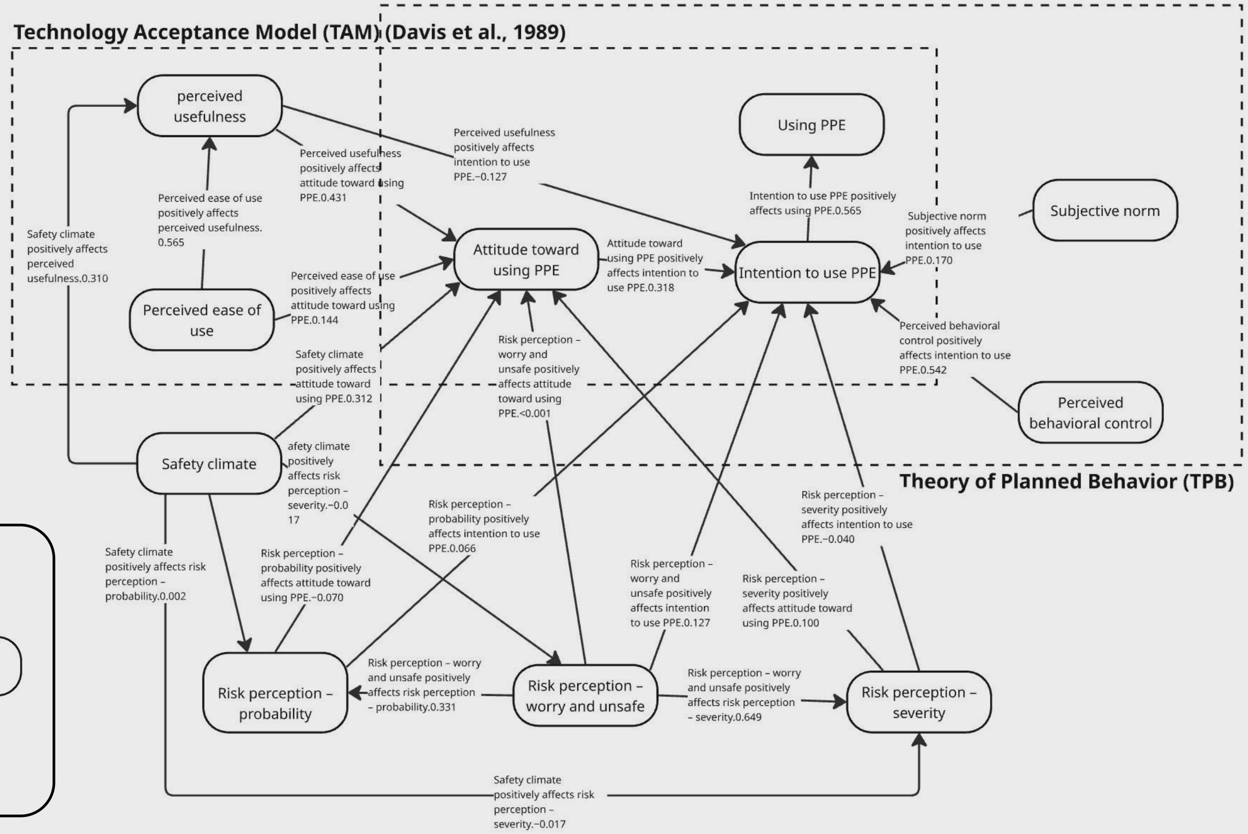
Appendix G. From User Journey Map Insight to Causal Mapping with Behavioral Design Strategies

While the user journey map revealed critical moments where painters avoid PPE—often due to discomfort, workflow interference, or social factors—**the small sample size limited** its generalizability. To enrich and validate these insights, additional literature was reviewed on PPE adherence, safety behavior, and smart technology adoption.

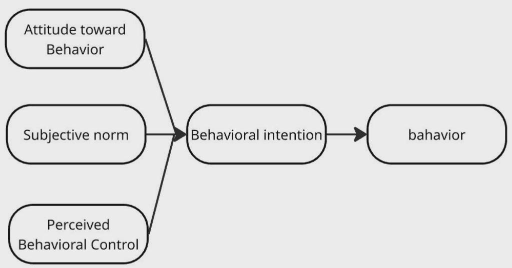
Findings from existing studies—such as the PPE Acceptance Model for Construction Workers (PAMCW), the Technology Acceptance Model (TAM), and the Theory of Planned Behavior (TPB)—aligned with the field data. These models emphasize perceived usefulness, social norms, emotional discomfort, and ease of use as central factors in behavioral adherence. This alignment strengthened confidence in the patterns observed during interviews and co-design sessions.



The Technology Acceptance Model (TAM), illustrating how perceived ease of use and perceived usefulness influence attitude, behavioral intention, and actual use. Adapted from Davis et al. (1989).



The Theory of Planned Behavior (TPB), showing how intention is influenced by attitude, subjective norm, and perceived behavioral control. Adapted from Ajzen (1985).



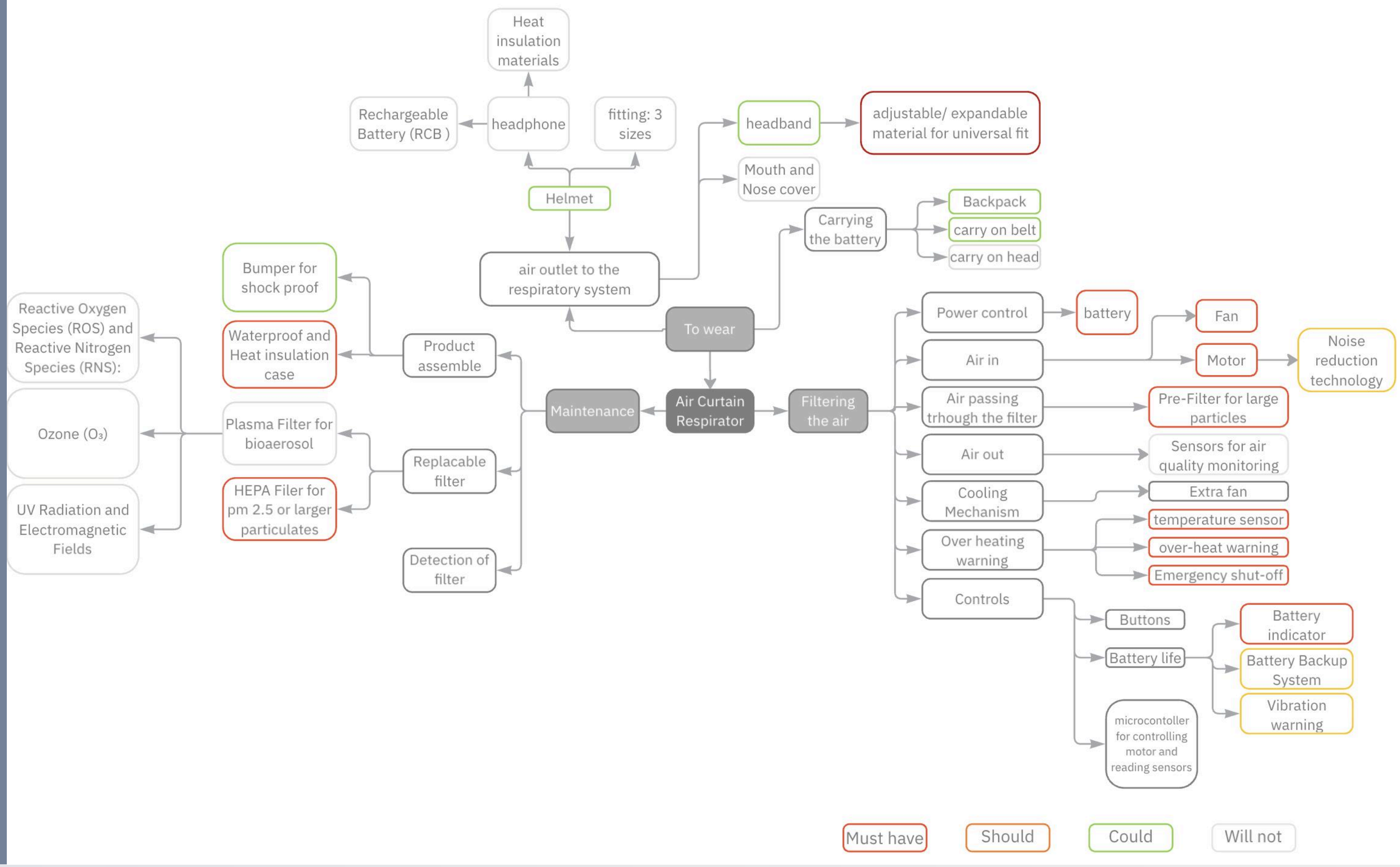
Appendix H. System function tree

System Function Tree: Translating Casual Mapping into Design Priorities

Insights extracted from the causal map were then translated into a System Function Tree, outlining the required and optional features of the air curtain respirator. This visual tool helped transform abstract behavioral goals (e.g., “must not interfere with communication”) into functional requirements (e.g., “face-free design,” “lightweight fit,” “helmet-compatible structure”).
Each function was categorized using a color-coded system:

- 🟥 Must Have – Essential to usability, protection, or adoption.
- 🟧Should Have – Beneficial but not essential for minimum viable design.
- 🟩 Could Have – Enhancements for specific user groups or future versions.
- ⬜ Will Not – Explicitly excluded from the current design scope.

This tool allowed decisions to be made not only based on available technologies but also designs that may encourage long-term behavior change.



Emotional Anchoring and Evaluation

With this foundation, the next step t focuses on emotional experience and design detail using the 9 Moments of Personal Experience (PE) framework. This method will guide the ideation of how the product is experienced before, during, and after use—especially how it supports comfort, ease, and a sense of control. Later, the same 9 Moments framework will be used during user testing to evaluate whether the final prototype successfully reduces negative emotional peaks and enhances positive ones .

Appendix I. Pilot Test for Paint Spray Blockage Test

The convergent–diffuser nozzle (see figure. 60) was first tested with a portable blower system (800 L/min) to evaluate whether airflow velocities in the range of 5–30 m/s could be achieved.

This pilot test focused on test flow before moving to compressor-based tests for determining required pressures. The 3D-printed nozzle prototypes (figure 60.) were used to visualize the flow with neon yellow paint in a spray experiment (figure 61.), recorded in slow motion to observe stability. However, the scanned results were difficult to interpret, as the paint appeared nearly white, leading to a later switch to black paint.

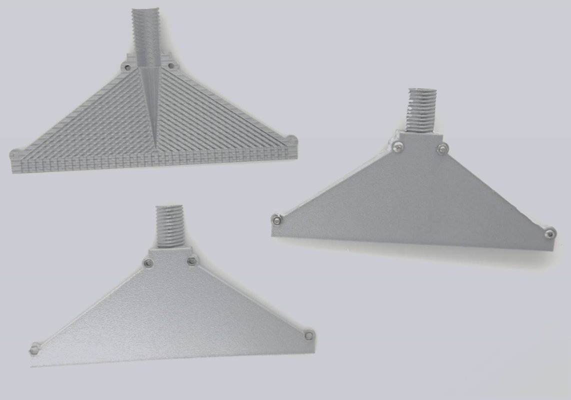
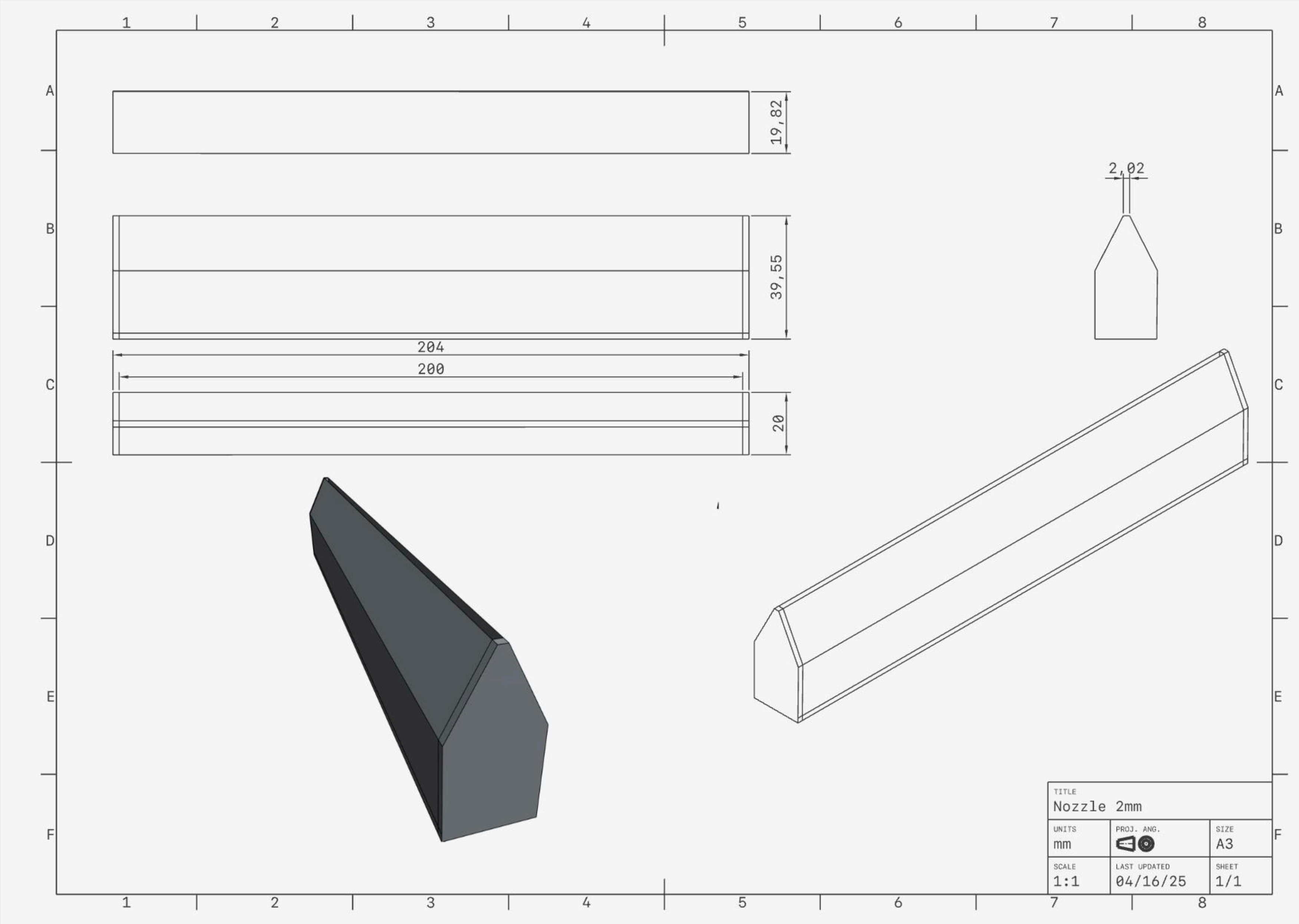
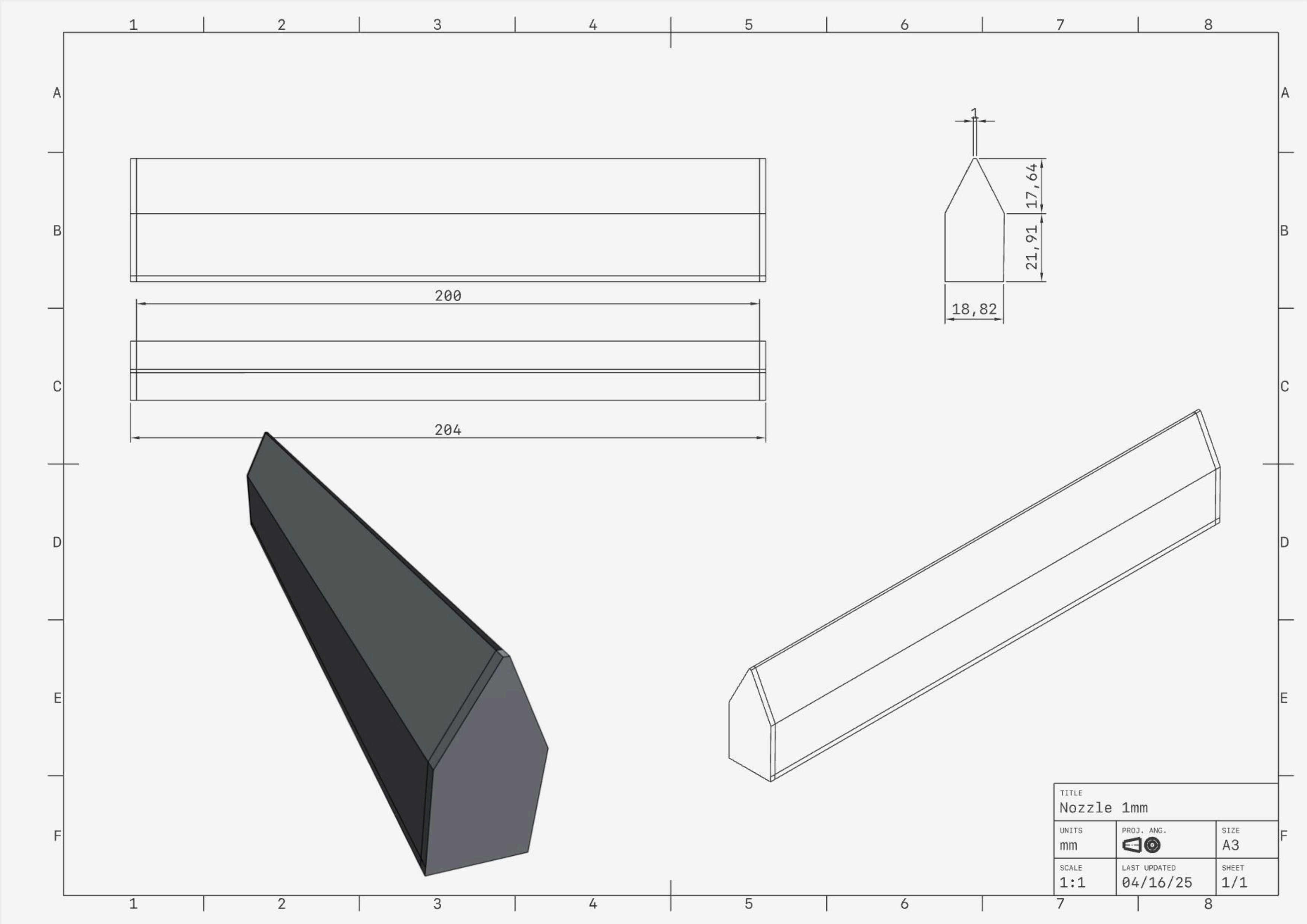


Image on the left shows 3D-printed nozzle prototypes, fabricated to validate the feasibility of the convergent-diffuser design

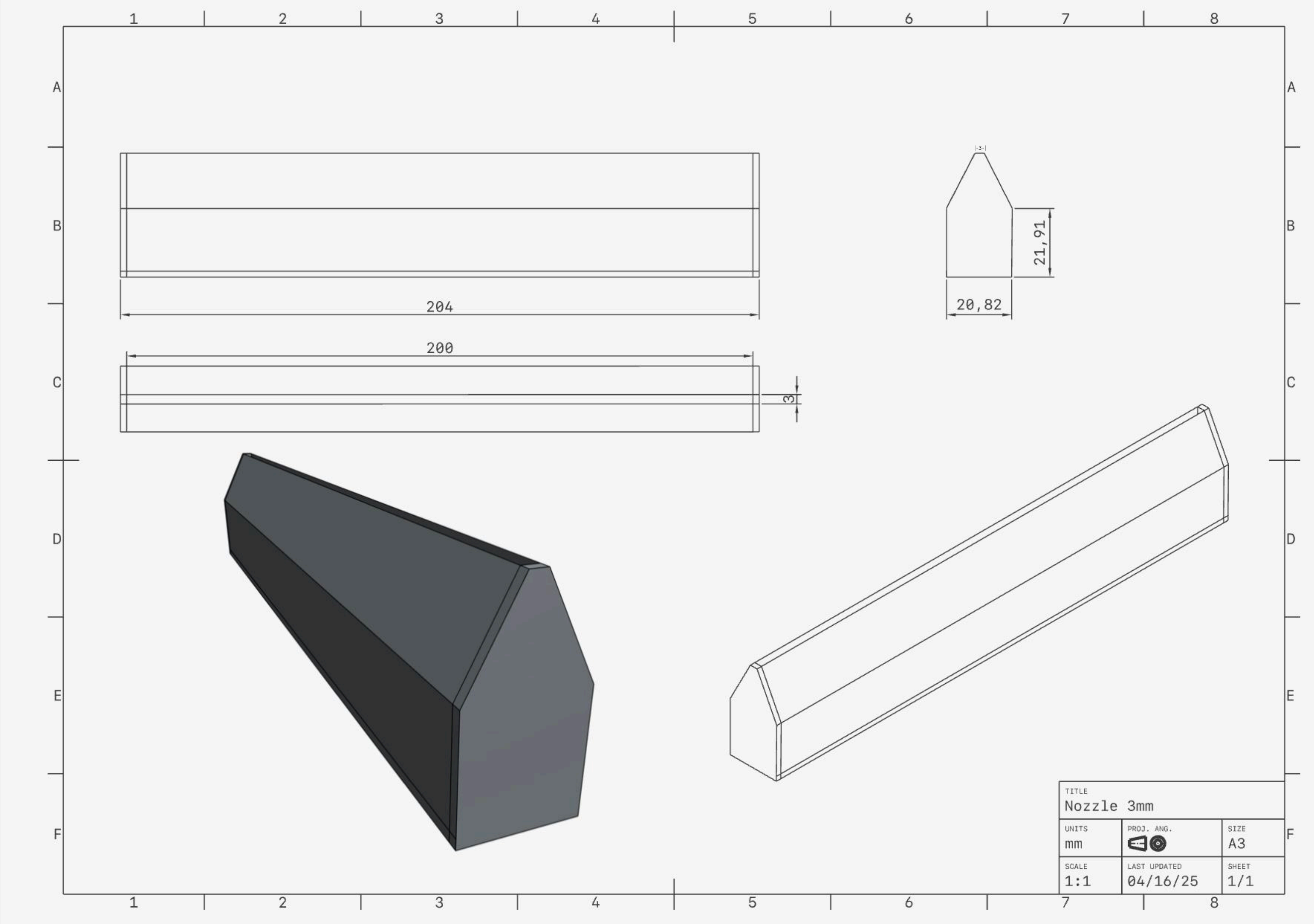
Image on the left presents a pilot spray test using neon yellow paint, visualized under slow-motion recording. The paint helped trace airflow behavior qualitatively; however, the results proved difficult to quantify, as the scanned sheets appeared nearly saturated white. To improve contrast and readability, subsequent tests employed black paint instead.

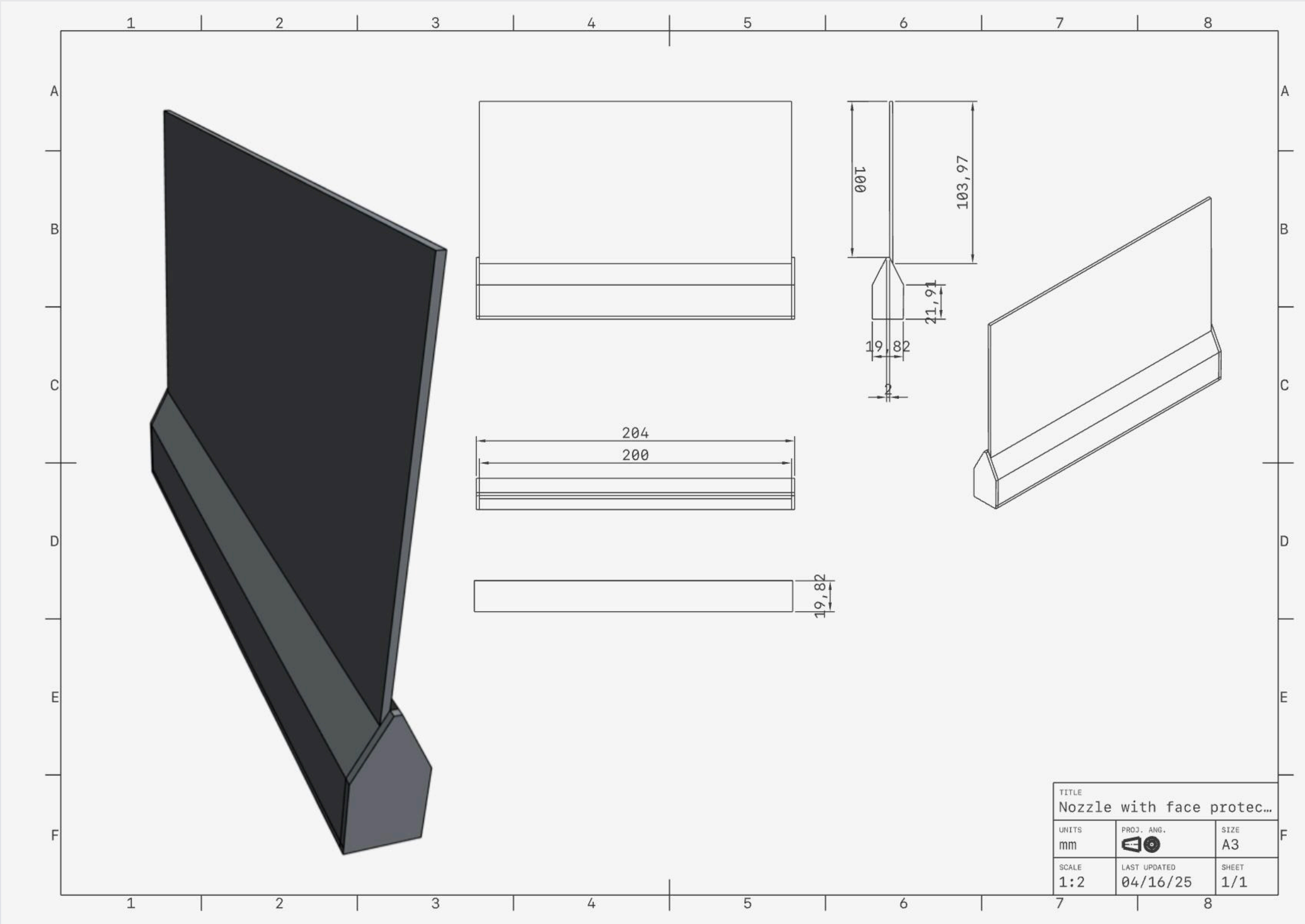
Appendix J. CDF Simulation Coarse setting



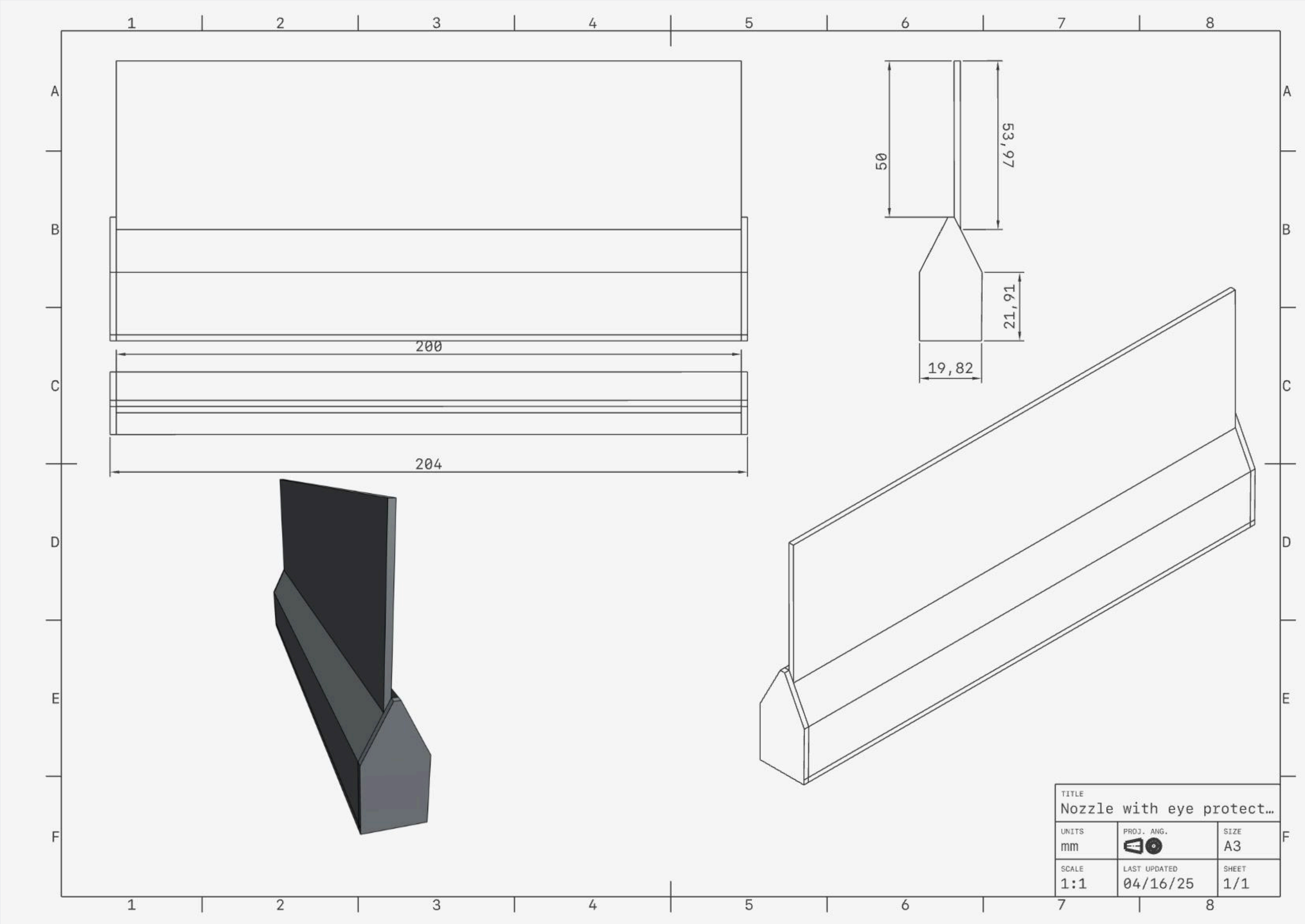


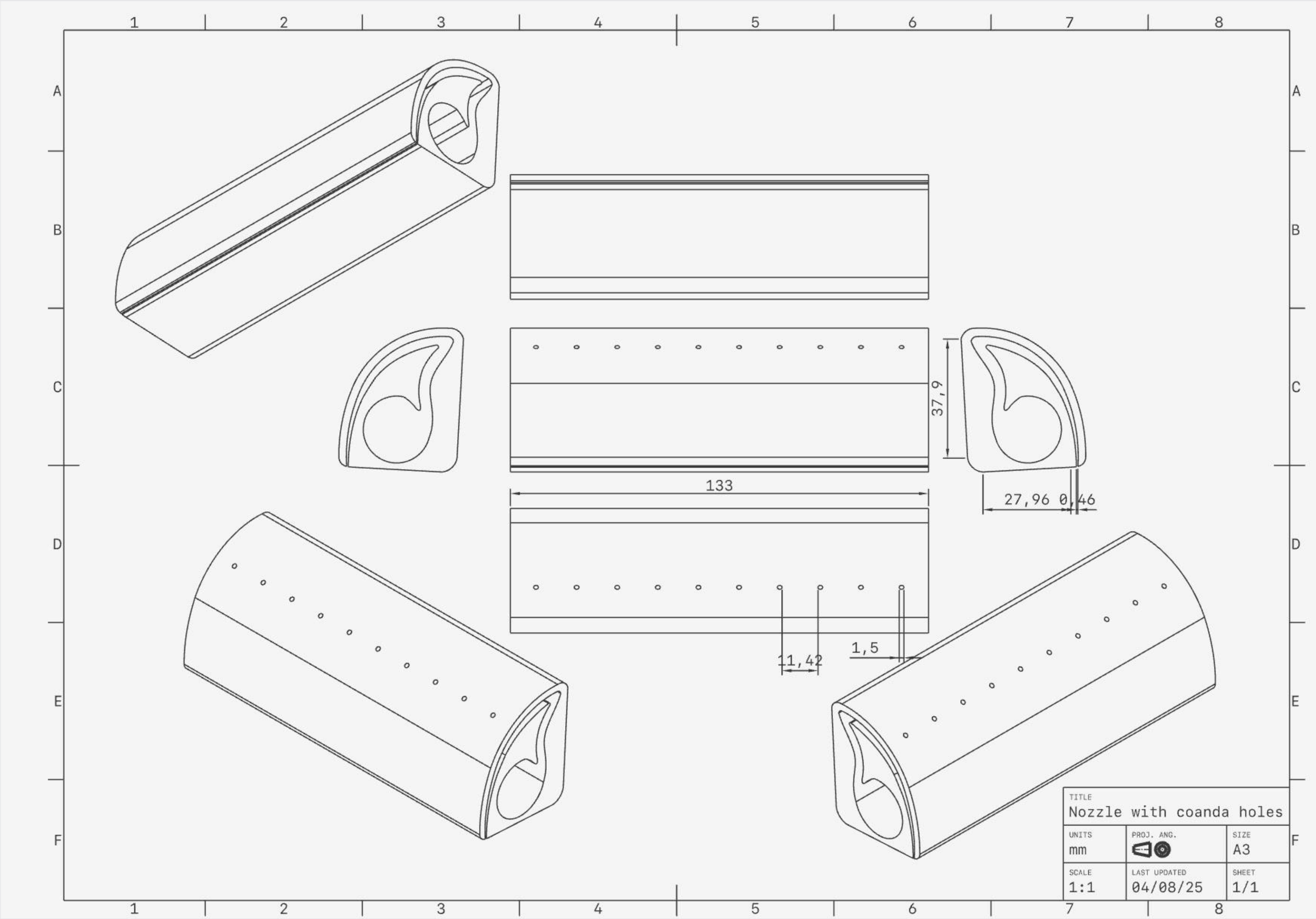
1
17,64
21,91
18,82
200
204
TITLE
Nozzle 1mm
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/16/25
SHEET
1/1

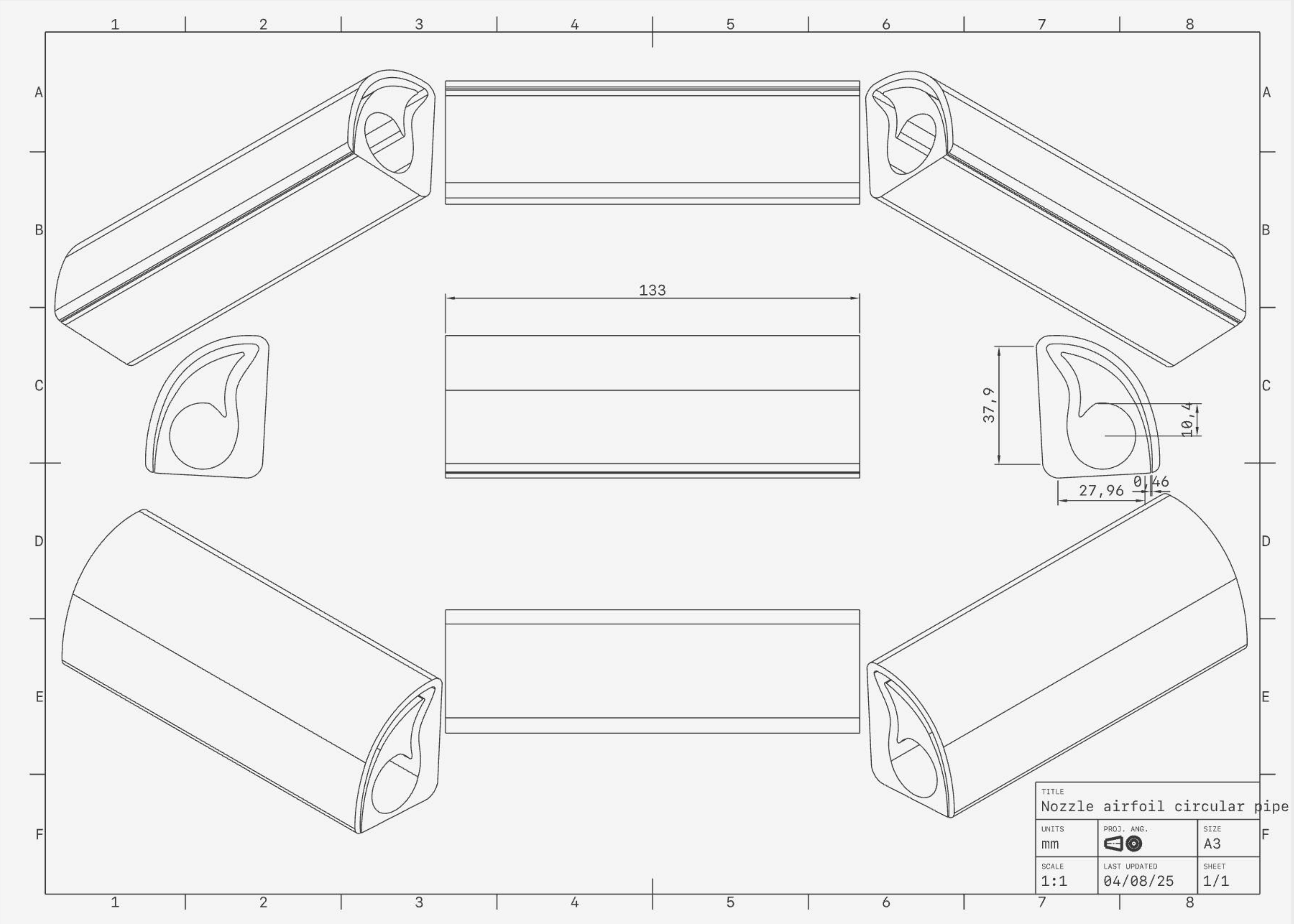

1
2
3
4
5
6
7
8
A
B
C
D
E
F
204
200
3
21,91
20,82
TITLE
Nozzle 3mm
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/16/25
SHEET
1/1

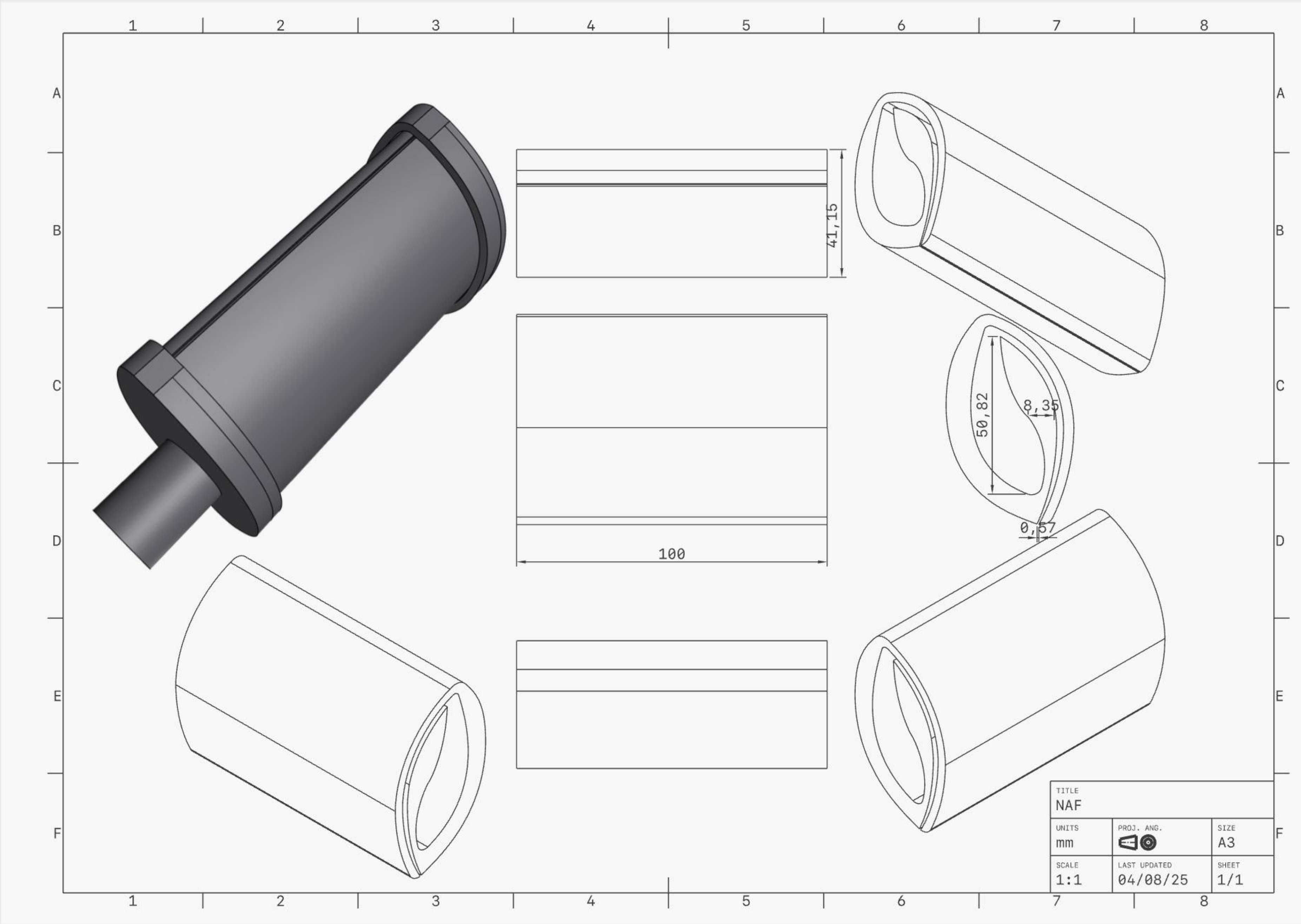


100
103,97
21,91
19,82
2
204
200
19,82
TITLE
Nozzle with face protec…
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:2
LAST UPDATED
04/16/25
SHEET
1/1


50
53,97
21,91
19,82
200
204
TITLE
Nozzle with eye protect…
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/16/25
SHEET
1/1


133
37,9
27,96
0,46
11,42
1,5
TITLE
Nozzle with coanda holes
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1


133
37,9
10,4
27,96
0,46
TITLE
Nozzle airfoil circular pipe
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1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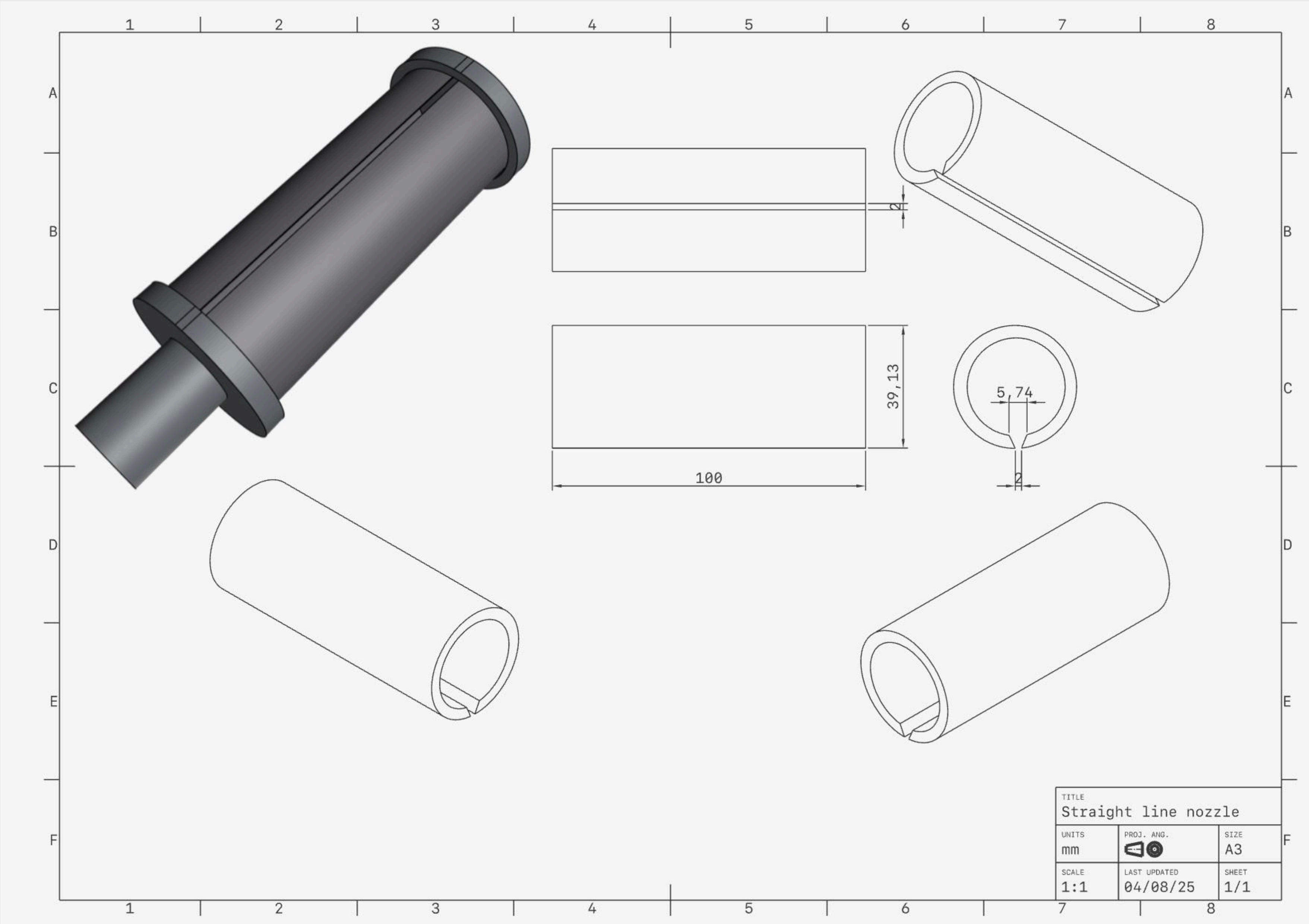
100
50,82
8,35
0,57
TITLE
NAF
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1


2
39,13
100
5,74
2
TITLE
Straight line nozzle
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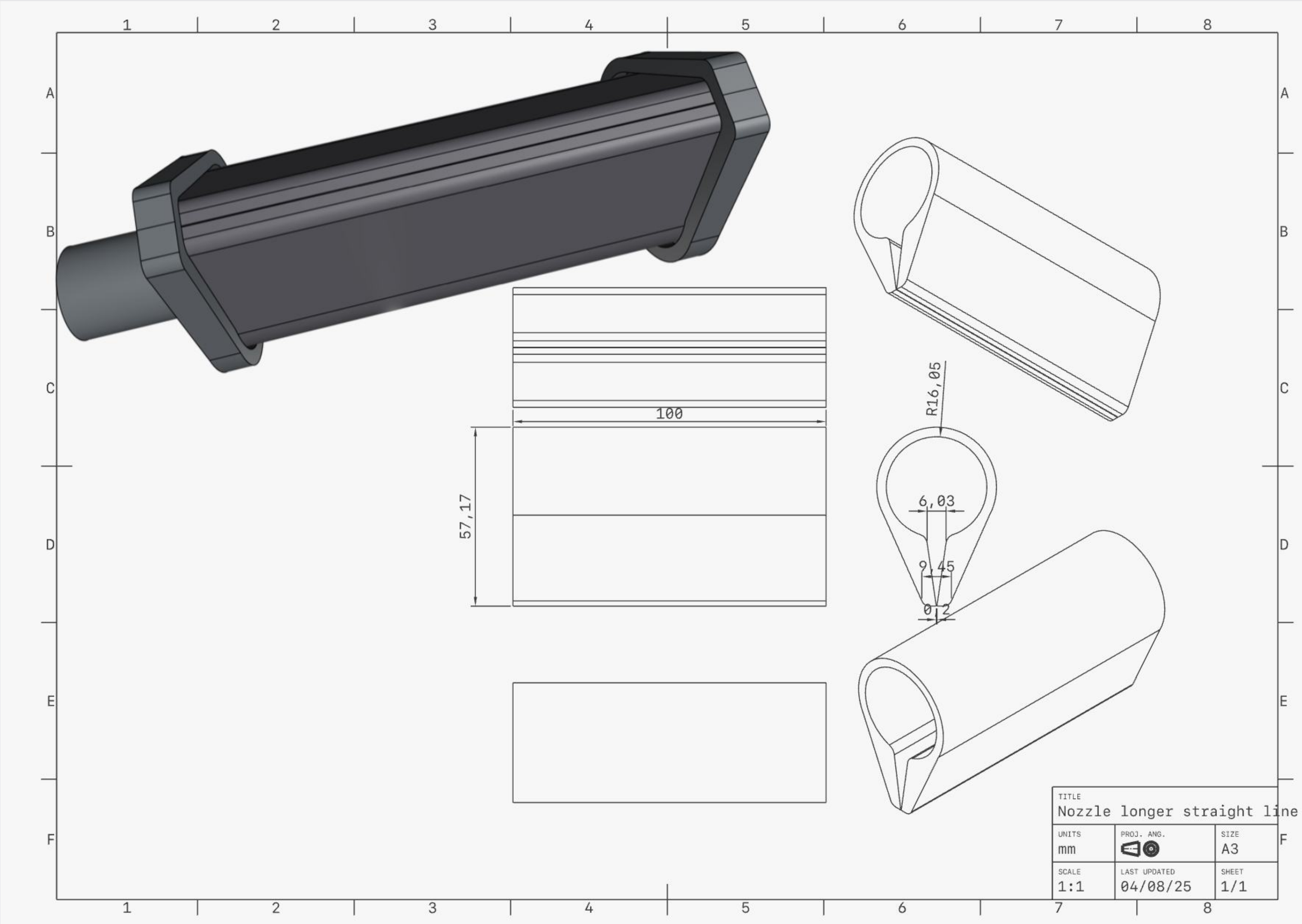
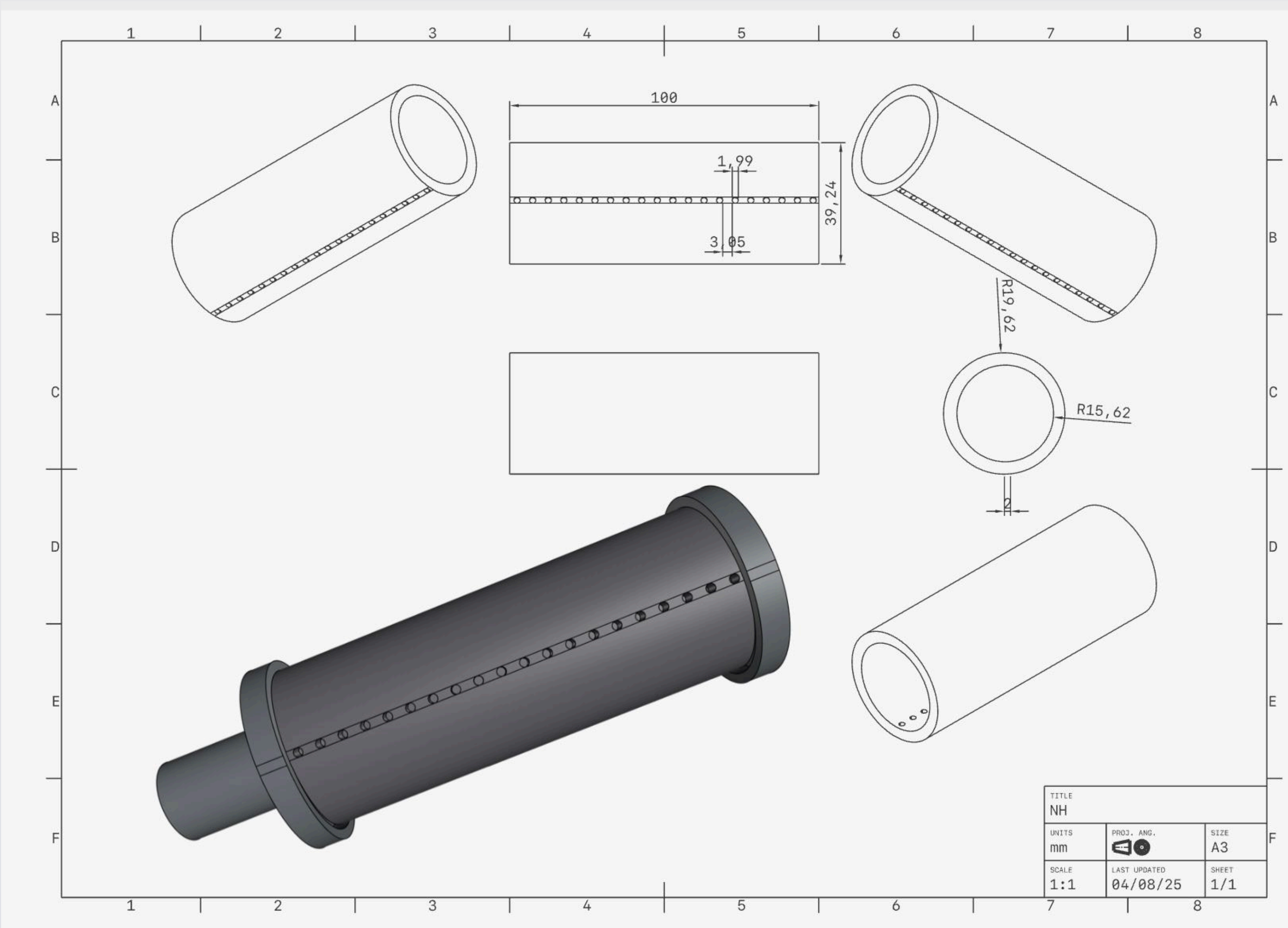
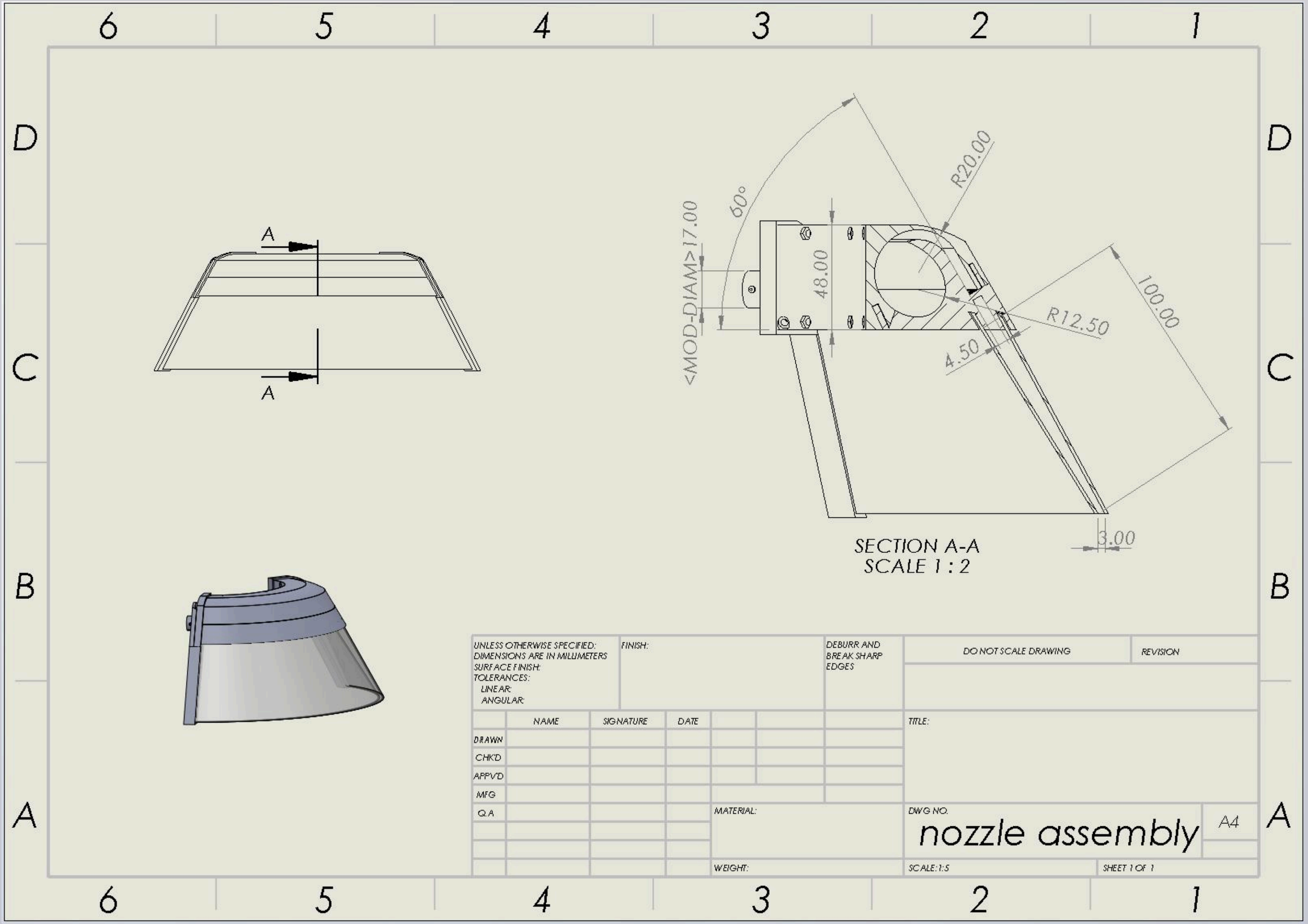
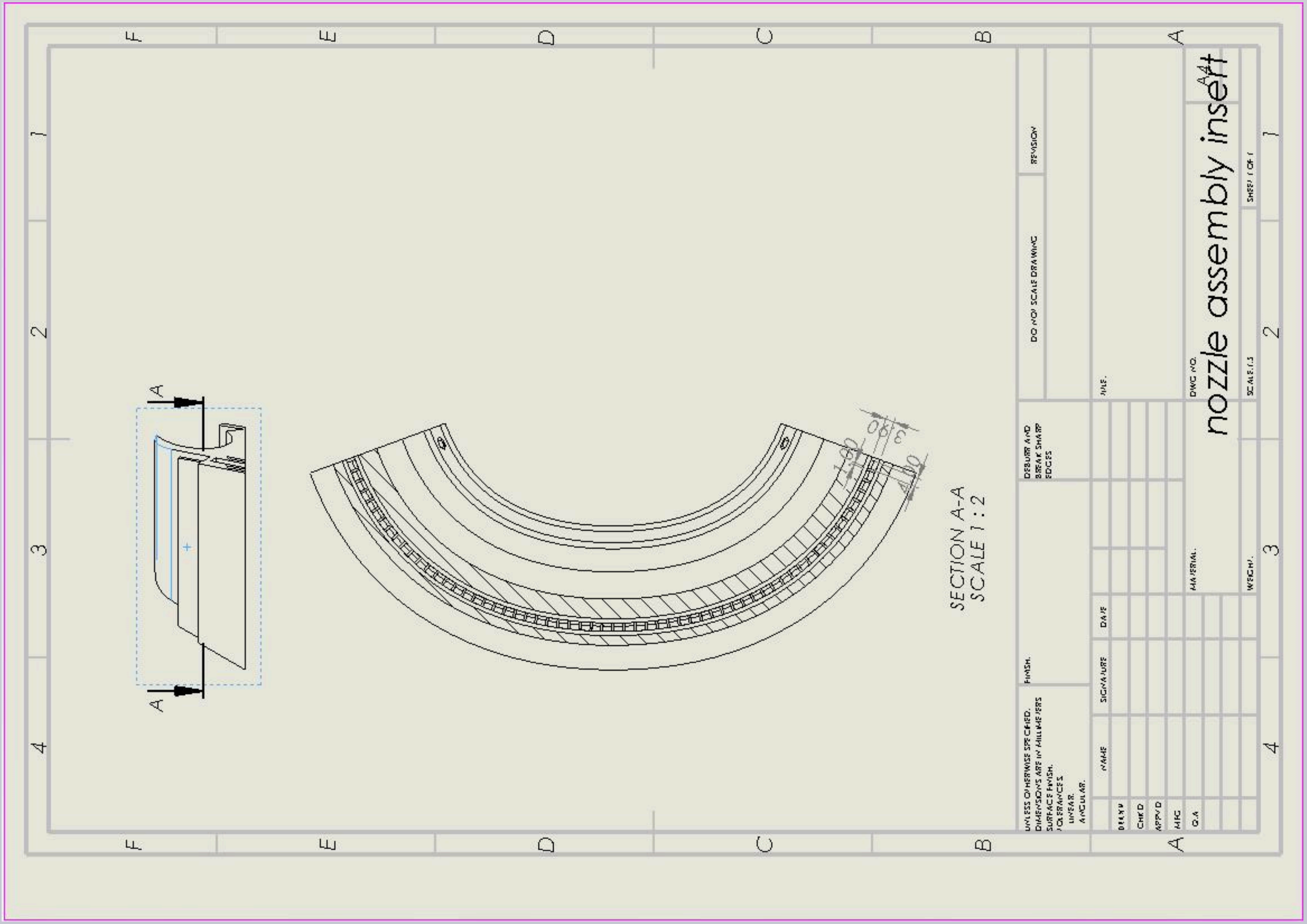
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1


1
2
3
4
5
6
7
8
A
B
C
D
E
F
100
57,17
R16,05
6,03
9,45
0,2
TITLE
Nozzle longer straight line
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1


100
1,99
39,24
3,05
R19,62
R15,62
2
TITLE
NH
UNITS
mm
PROJ. ANG.
SIZE
A3
SCALE
1:1
LAST UPDATED
04/08/25
SHEET
1/1

Appendix K. CDF Technical Drawing for the Final Product Design




nozzle assembly insert
A4
SECTION A-A
SCALE 1 : 2
DO NOT SCALE DRAWING
REVISION

AirLoop Gebruikerstest

Introductie:

AirLoop is een draagbaar beschermingssysteem dat is ontworpen om een schild van schone lucht rond de ademzone van de gebruiker te creëren met behulp van een compacte luchtgordijn. Het is bedoeld om blootstelling aan stof, dampen en verfdruppels te verminderen zonder het gezicht volledig te bedekken, waardoor er meer comfort, makkelijker ademhalen en betere communicatie tijdens het werk mogelijk is.

Deze test is bedoeld om te evalueren hoe het product presteert op het gebied van **comfort**, **gebruiksvriendelijkheid** en hoe goed het past in je dagelijkse werkpraktijk.

Je wordt gevraagd om het prototype **aan te trekken, Vervang het filter,Laad de batterij op**

(ongeveer 10 minuten), **het te dragen tijdens een korte taak of gewoon tijdens het invullen van de vragenlijst** (ongeveer 20–25 minuten), en het daarna **weer uit te doen en terug in de opbergzak te plaatsen**. De volledige sessie duurt ongeveer **40 minuten**.

Tijdens de test observeer ik je gebruik en meet ik de tijd. Foto's worden alleen genomen met jouw toestemming — je gezicht zal worden geblurd en je naam wordt anoniem gehouden.

Achtergrond deelnemer

Wat is je huidige beroep of type schilder?

Hoeveel jaar werk je al in dit beroep?
____ jaar

Jouw leeftijd:
____ jaar oud

Eerste indrukken

Voordat je het product aantrekt, kies het woord/de woorden die jouw eerste emotionele reactie op het prototype het beste beschrijven:

Zelfverzekerd – Cool – Enthousiast – Gemotiveerd – Nieuwsgierig – Bekrachtigd – Professioneel – Onverschillig –
Sceptisch – Oncomfortabel – Twijfelend – Geïrriteerd – Belachelijk – Bezorgd – Wantrouwend – Ongemakkelijk – Beschermd

(Of voeg je eigen woord toe: _______________)

2. Sterkte van de emotie

Op een schaal van **1 (heel zwak)** tot **7 (heel sterk)**, hoe sterk voel je je op deze manier?

2. Strength of Emotion

On a scale from **1 (very weak)** to **7 (very strong)**, how strongly do you feel that way?

Gebruikerstest – Vragen met Beoordelingsschaal

A. Gebruiksvriendelijkheid

Hoe gemakkelijk was het om te begrijpen hoe je het prototype moest dragen?
Schaal van 1 (zeer moeilijk) tot 7 (zeer gemakkelijk)

Waren er onderdelen die verwarrend of niet intuïtief waren om te gebruiken?
☐ Ja ☐ Nee
Indien ja, licht toe: ___________________________

Hoe gemakkelijk kon je je gebruikelijke taken uitvoeren terwijl je het product droeg?
Schaal van 1 (helemaal niet) tot 7 (zeer gemakkelijk)

B. Comfort & Fit

B. Comfort & Pasvorm

Beoordeel je fysieke comfort tijdens het dragen van het product:
1 (zeer oncomfortabel) → 7 (zeer comfortabel)

Hoe gemakkelijk was het om te ademen tijdens het gebruik van het product?
1 (zeer moeilijk om te ademen) → 7 (zeer gemakkelijk om te ademen)

Beperkte het product je beweging?
1 (zeer beperkend) → 7 (helemaal geen beperking)

Hoe zou je het gewicht en de omvang beoordelen?
1 (te zwaar / omvangrijk) → 7 (zeer licht en compact)

Hoe goed paste het product?
1 (slechte pasvorm) → 7 (perfecte pasvorm)

C. Integratie in Werkproces

Hoe goed integreert het product in je normale werkroutine?
1 (helemaal niet) → 7 (volledig naadloos)

Hoe lang zou je je comfortabel voelen om dit te dragen tijdens een werkdag?
1 (minder dan 15 minuten) → 7 (de hele dag is prima)

Zou het gebruik van dit product veranderingen in je werkproces vereisen?
◻ Ja ◻ Nee
Indien ja, leg uit: _______________________

D. Ervaren Veiligheid & Effectiviteit

Hoe goed voelde je je beschermd tegen luchtvervuiling tijdens het dragen van het product?
1 (helemaal niet beschermd) → 7 (zeer goed beschermd)

Vergeleken met je huidige PBM, hoe zou je de effectiviteit van dit prototype beoordelen?
1 (veel slechter) → 7 (veel beter)

E. Gebruik op Lange Termijn & Intentie

Hoe waarschijnlijk is het dat je dit product regelmatig zou gebruiken als het beschikbaar was?
1 (zeer onwaarschijnlijk) → 7 (zeer waarschijnlijk)

Hoe waarschijnlijk is het dat je dit zou aanbevelen aan een collega?
1 (zeer onwaarschijnlijk) → 7 (zeer waarschijnlijk)

Wat zou je kunnen doen stoppen met het gebruik van dit product?

F. Emotionele Beleving

Hoe voelde je je emotioneel tijdens het gebruik van dit product?
Noem 1–3 emoties en geef een score van 1–7 over hoe sterk je die voelde:

1. ________________ (score:___)
2. ________________ (score:___)
3. ________________ (score:___)

G. Uiterlijk en Ontwerp

Hoe zou je het uiterlijk van dit product beoordelen?
1 (helemaal niet aantrekkelijk) → 7 (zeer aantrekkelijk)

Zou je je zelfverzekerd voelen om dit te dragen in het bijzijn van anderen (zoals klanten of collega's)?
1 (helemaal niet zelfverzekerd) → 7 (zeer zelfverzekerd)

H. Algemene Feedback & Suggesties

Wat is één ding dat je zou veranderen of verbeteren aan het product?

Voor welke taak of situatie denk je dat dit product het meest nuttig zou zijn?

Denk je dat jouw team of collega's dit regelmatig zouden gebruiken als het beschikbaar was? Waarom wel of niet?

AirLoop User Test

Introduction:

AirLoop is a wearable protective system designed to create a shield of clean air around the user's breathing zone using a compact air curtain. It aims to reduce exposure to dust, fumes, and paint particles without fully covering the face, offering more comfort, easier breathing, and better communication during work. This test is intended to evaluate how the product performs in terms of comfort, usability, and how well it fits into your normal work routine. You will be asked to **put on the prototype, replace the filter, charge the battery** (about 10 minutes), **wear it while performing a short task or simply during the questionnaire** (approximately 20–25 minutes), and then take it off and put it back into the organizing bag. The full session will take around **40 minutes**. During the test, I will observe and time your interactions. Photos may be taken only with your permission — your face will be blurred, and your name will be anonymized.

Participant Background

What is your current occupation or painter type?

How many years have you worked in this profession?
____ years

Your age:
____ years old

First Impressions

Before wearing the product, please choose the word(s) below that best describe your first emotional response to the prototype:

Confident – Cool – Excited – Motivated – Curious – Empowered – Professional – Indifferent – Skeptical – Uncomfortable – Doubtful – Annoyed – Absurd – Concerned – Distrustful – Awkward – Protected
(Or add your own word: ____________)

2. Strength of Emotion

On a scale from **1 (very weak)** to **7 (very strong)**, how strongly do you feel that way?

User Testing Questions with Rating Scales

A. Usability

On a scale from 1 (very difficult) to 7 (very easy), how easy was it to figure out how to wear the prototype?

Were any parts confusing or unintuitive to use?
□ Yes □ No
If yes, please describe: ______________________

On a scale from 1 (not at all) to 7 (very easily), how easily could you perform your usual tasks while wearing the product?

B. Comfort & Fit

Rate your physical comfort while wearing the product: 1 (very uncomfortable) → 7 (very comfortable)

Rate how easy it was to breathe while using the product: 1 (very difficult to breathe) → 7 (very easy to breathe)

Did the product restrict your movement? 1 (very restrictive) → 7 (no restriction at all)

How would you rate the weight and bulkiness? 1 (too heavy/bulky) → 7 (very lightweight and compact)

How would you rate the fitting of the product? 1 (poorly fit) → 7 (perfectly fit)

User Testing Questions with Rating Scales

A. Usability

On a scale from 1 (very difficult) to 7 (very easy), how easy was it to figure out how to wear the prototype?

Were any parts confusing or unintuitive to use?
☐ Yes ☐ No
If yes, please describe: ______________________

On a scale from 1 (not at all) to 7 (very easily), how easily could you perform your usual tasks while wearing the product?

B. Comfort & Fit

Rate your physical comfort while wearing the product: 1 (very uncomfortable) → 7 (very comfortable)

Rate how easy it was to breathe while using the product: 1 (very difficult to breathe) → 7 (very easy to breathe)

Did the product restrict your movement? 1 (very restrictive) → 7 (no restriction at all)

How would you rate the weight and bulkiness? 1 (too heavy/bulky) → 7 (very lightweight and compact)

How would you rate the fitting of the product? 1 (poorly fit) → 7 (perfectly fit)

C. Workflow Integration

How well does the product integrate into your normal work routine? 1 (not at all) → 7 (completely seamless)

How long would you feel comfortable using it during a workday? 1 (less than 15 mins) → 7 (all day use is fine)

Would using this require changes to your workflow?
☐ Yes ☐ No
If yes, please explain: ____________________

D. Perceived Safety & Effectiveness

Rate how protected you felt from air contaminants while wearing the product: 1 (not protected at all) → 7 (very well protected)

Compared to your current PPE, how would you rate the effectiveness of this prototype? 1 (much worse) → 7 (much better)

E. Behavioral Intention & Long-Term Use

How likely are you to use this product regularly if it were provided? 1 (very unlikely) → 7 (very likely)

How likely are you to recommend this to a colleague? 1 (very unlikely) → 7 (very likely)

What might make you stop using it?

F. Emotional Experience

Hoe goed paste het product?
1 (slechte pasvorm) → 7 (perfecte pasvorm)

C. Integratie in Werkproces

Hoe goed integreert het product in je normale werkroutine?
1 (helemaal niet) → 7 (volledig naadloos)

Hoe lang zou je je comfortabel voelen om dit te dragen tijdens een werkdag?
1 (minder dan 15 minuten) → 7 (de hele dag is prima)

Zou het gebruik van dit product veranderingen in je werkproces vereisen?
□ Ja □ Nee
Indien ja, leg uit: _______________________

D. Ervaren Veiligheid & Effectiviteit

Hoe goed voelde je je beschermd tegen luchtvervuiling tijdens het dragen van het product?
1 (helemaal niet beschermd) → 7 (zeer goed beschermd)

Vergeleken met je huidige PBM, hoe zou je de effectiviteit van dit prototype beoordelen?
1 (veel slechter) → 7 (veel beter)

E. Gebruik op Lange Termijn & Intentie

Hoe waarschijnlijk is het dat je dit product regelmatig zou gebruiken als het beschikbaar was?
1 (zeer onwaarschijnlijk) → 7 (zeer waarschijnlijk)

Hoe waarschijnlijk is het dat je dit zou aanbevelen aan een collega?
1 (zeer onwaarschijnlijk) → 7 (zeer waarschijnlijk)

Wat zou je kunnen doen stoppen met het gebruik van dit product?

F. Emotionele Beleving

Hoe voelde je je emotioneel tijdens het gebruik van dit product?
Noem 1–3 emoties en geef een score van 1–7 over hoe sterk je die voelde:

1. ________________ (score:___)
2. ________________ (score:___)
3. ________________ (score:___)

G. Uiterlijk en Ontwerp

Hoe zou je het uiterlijk van dit product beoordelen?
1 (helemaal niet aantrekkelijk) → 7 (zeer aantrekkelijk)

Zou je je zelfverzekerd voelen om dit te dragen in het bijzijn van anderen (zoals klanten of collega's)?
1 (helemaal niet zelfverzekerd) → 7 (zeer zelfverzekerd)

H. Algemene Feedback & Suggesties

Wat is één ding dat je zou veranderen of verbeteren aan het product?

Voor welke taak of situatie denk je dat dit product het meest nuttig zou zijn?

Denk je dat jouw team of collega's dit regelmatig zouden gebruiken als het beschikbaar was? Waarom wel of niet?

AirLoop User Test

Introduction:

AirLoop is a wearable protective system designed to create a shield of clean air around the user's breathing zone using a compact air curtain. It aims to reduce exposure to dust, fumes, and paint particles without fully covering the face, offering more comfort, easier breathing, and better communication during work. This test is intended to evaluate how the product performs in terms of comfort, usability, and how well it fits into your normal work routine. You will be asked to **put on the prototype, replace the filter, charge the battery** (about 10 minutes), **wear it while performing a short task or simply during the questionnaire** (approximately 20–25 minutes), and then take it off and put it back into the organizing bag. The full session will take around **40 minutes**. During the test, I will observe and time your interactions. Photos may be taken only with your permission — your face will be blurred, and your name will be anonymized.

Participant Background

What is your current occupation or painter type?

How many years have you worked in this profession?
____ years

Your age:
____ years old

First Impressions

Before wearing the product, please choose the word(s) below that best describe your first emotional response to the prototype:

Confident – Cool – Excited – Motivated – Curious – Empowered – Professional – Indifferent – Skeptical – Uncomfortable – Doubtful – Annoyed – Absurd – Concerned – Distrustful – Awkward – Protected
(Or add your own word: ____________)

2. Strength of Emotion

On a scale from **1 (very weak)** to **7 (very strong)**, how strongly do you feel that way?

User Testing Questions with Rating Scales

A. Usability

On a scale from 1 (very difficult) to 7 (very easy), how easy was it to figure out how to wear the prototype?

Were any parts confusing or unintuitive to use?
☐ Yes ☐ No
If yes, please describe: ______________________

On a scale from 1 (not at all) to 7 (very easily), how easily could you perform your usual tasks while wearing the product?

B. Comfort & Fit

Rate your physical comfort while wearing the product: 1 (very uncomfortable) → 7 (very comfortable)

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F. Emotional Experience

How did this product make you feel emotionally? Name 1-3 emotions, and rate 1-7 how strong do you feel about the emotion.

1. ________________ (rate : __)
2. ________________ (rate : __)
3. ________________ (rate : __)

G. Appearance and Design

How would you rate the appearance of this product? 1 (not appealing at all) → 7 (very appealing)

Would you feel confident wearing this in front of others (e.g., clients, coworkers)? 1 (not at all confident) → 7 (very confident)

H. General Feedback & Suggestions

What one thing would you change or improve about the product?

What situation or task would this product be most useful for?

Do you think your team or coworkers would adopt and use this regularly? Why or why not?