OnlyFAN: Office Desks as Diffuser of Air Flow and Comfort Induced by Ceiling Fan

Can office desk layouts diffuse the air flow induced by ceiling fan effectively and expand the comfort zone around the desks to achieve collective thermal comfort?

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Abstract

Ceiling fans offer a low-energy solution for improving thermal comfort in offices, yet their ability to provide collective comfort, serving multiple occupants, remains underexplored, especially when airflow is diffused by desk layouts.

This thesis examines whether office desks can diffuse ceiling fan-induced airflow and expand the comfort zone. A mixed-methods approach was used, combining CFD simulations, lab-based airspeed measurements, and human-subject experiments to assess airflow distribution and perceived comfort across multiple desk configurations and fan speeds.

Results show that desks redirect downward airflow horizontally, increasing airspeed at seated height (0.85m). While higher air speeds lowered thermal sensation votes, comfort levels did not increase. At 28°C and 49.2% RH, participants preferred an average airspeed of 0.49 m/s without group control. With group-selected fan speeds, preferences varied between 0.49–0.78 m/s, indicating diverse comfort needs.

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1 Introduction

1.1 Background & context

Fans have been proven to be an energy- and cost-efficient way to provide cooling by increasing air movement (Arens et al., 2009, André et al., 2024). Desk fans and ceiling fans are capable to provide comfort in warm and humid condition at 30°C/60% RH in typical summer clothing (0.5-0.6 clo) at sedentary office activity level (1.0-1.1 met) for single occupant (Zhai et al. ,2013, Zhai et al., 2015, Zhai et al., 2017). Fans might still offset thermal discomfort when the indoor air temperature is 35 °C during a heatwave. (Tartarini et al., 2021). Ceiling fan has the potential to become a low-energy-demanding and heat-resilient design solution for existing, non-air-conditioned offices.

Gao et al. (2017) investigated how different desk (single) placements and partitions influence the air flow distribution under a ceiling fan. The desk redirects the downward jet to horizontal direction and increased the air velocity at sitting height and made the air speed more evenly distributed in the lab environment.

In real office environments, one can often observed from the previous research that the ceiling fans were installed for a group of people rather than a personal amenity. This thesis aims to explore the possibility for ceiling fans to achieve collective thermal comfort in office spaces.

1.2 Problem statement

Despite the known benefits of ceiling fans in enhancing thermal comfort and air movement in office environments, there is limited understanding of how different office desk layouts and control methods impact occupants' perceptions of air movement.

> *"Develop a model that estimates the comfort level around desks according to air speed distribution and a guideline for designers to place ceiling fans and desks properly that the comfort zone under the ceiling fan can be further expanded."*

1.3 Research objectives

This research aims to investigate the relationship between the spatial arrangement of office furniture, the placement of ceiling fans, and the interactive control behavior (of a group of people) on the occupants' perception of air movement and overall comfort.

1.4 Research questions

Primary Question:

How effective are ceiling fans under different desk layouts in warm and hot environments to diffuse air flow and expand thermal comfort zone to achieve collective thermal comfort?

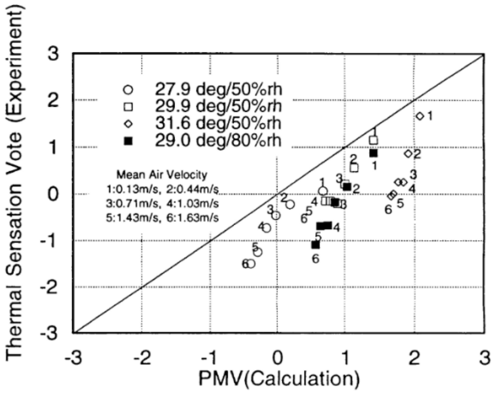
Sub-Questions:

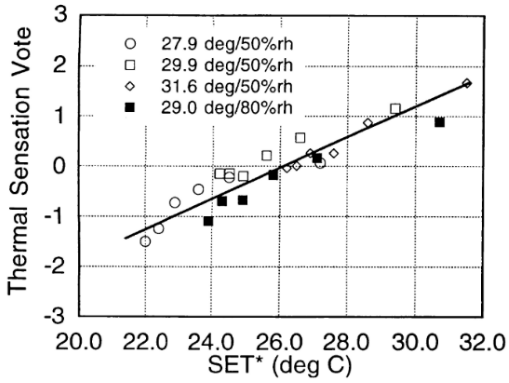
- *To what extent can the simplified CFD simulation predict the air speed with different layout cases?*
- *How do the desk layouts impact the air speed distribution and perceived thermal comfort across various seating locations?*
- *Can a single ceiling fan provide collective thermal comfort for a group of (up to) 4 people?*
- *Does the prediction of thermal comfort models (PMV, SET*, modified SET*, etc.) match the experiment result of human subjects?*

2 Literature research

2.1 Thermal comfort under elevated air speed

There are several early research in the 1990's that investigated the prediction power of thermal comfort models (PMV and SET*) under elevated air speed.





Tanabe et al. (1993) suggested that the TSV (thermal sensation vote) in the experiment is lower than the prediction of PMV when air speed is over 0.5m/s. A modified SET* which took the reduction of clo value and skin diffusion into account was also presented in this research, and a better prediction of TSV under elevated air speed was achieved. Tanabe & Kimura (1994) proposed a chart of recommended air speed under different operative temperature and relative humidity, which gave a guideline to minimize thermal discomfort in warm and humid weather. The preferred air speed under several different conditions of air temperature and relative humidity is also presented. No significant difference was found between male and female. Kubo et al. (1997) found that the preferred air speed is higher than the prediction of SET* and PMV. Personal differences were also found to be greater than seasonal differences.

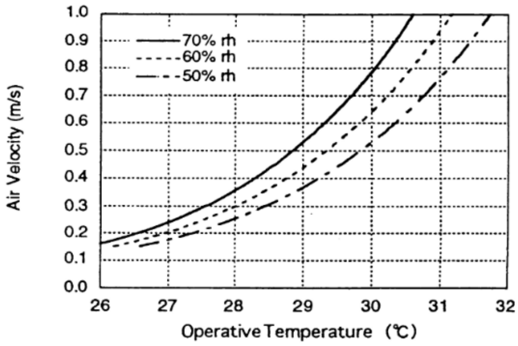


Figure 1: Suggested air velocity under different RH and operative temperature. (Source: Tanabe & Kimura, 1994)

TABLE 7
Preferred Air Velocity (m/s)

	Female	Male	Female and Male
27.8°C-50%rh	1.0	1.0	1.0
29.6°C-50%rh	1.4	1.1	1.2
28.8°C-50%rh	1.5	1.3	1.4
31.3°C-80%rh	1.5	1.7	1.6

Table 1: Preferred air velocity under different temperature and RH by gender. (Source: Tanabe & Kimura, 1994)

Huang et al. (2013) conducted a climate chamber study and identified the lower limit of air speed for 28 °C, 30 °C, 32 °C was 0m/s,1 m/s, and 2 m/s respectively. Zhai et al. (2013) conducted a lab experiment with 16 occupants to examine the cooling capability of personal controlled low-energy desk fan. The air temperature was set to 26, 28 and 30°C, with relative humidity of 60% and 80%. At 30°C/60% RH, fan can still provide comfort with the mean air speed of 1m/s. However, when the RH increased to 80%, even higher air speed was selected, some subjects did not feel comfortable. Rissetto et al. (2021) investigated participants' thermal comfort with ceiling fan providing air movement at upper part of body. Only the air speed measured at 1.1m was used for the analysis. It was found that air speed lower than 0.4m/s are still within acceptable comfort range. Pasut et al. (2014) tested 2 different air speeds and 3 different fan placement (at front, side, and right above the head of subjects' head), and found direct air flow at human body at speed between 0.8-0.9 m/s can improve subjects' thermal comfort.

2.2 Air flow induced by ceiling fan

Liu et al. (2018) conducted a detailed air speed measurement with both single and double fan within a climate chamber and found the air speed pattern along radial lines from the centre of the fan. It was also found that with the increasing of fan speed, the diameter of jet zone extends and the still are zone is reduced. An online tool was also developed to help users to determine the quantity and placement of ceiling fan with given room dimensions. P. Raftery et al. (2019) conducted another lab air speed measurement in 2 room sizes with 9 different types of fans with 7 diameters. It was found that the fan speed shows linear correlation with the rotation speed of fan (rpm). They defined a concept of "FAS (fan air speed)" that is the average air speed that air flow through the fan blade area. When normalizing the air speed with FAS, the air flow pattern becomes comparable across different types of fan.

2.3 Influence of office furniture on air flow distribution

The study conducted by Gao et al. (2017)is the main inspiration for my thesis. They tested the air flow distribution with different placement of office desk and types of partition. In the base case where there is no furniture in presence, a clear downward jet is shown under the fan blade area. The downward jet impinges the floor and is redirected outward horizontally until the surrounding walls. The walls redirect the air flow upward along wall surface until ceiling level and then flow horizontally towards the fan as a return air flow. Outside the abovementioned areas, the air speed is relatively low and was called the "still air zone". In the case where a desk measuring 120x60x75 was place under the centre of the fan, the fan jet was forced to spread outward after the impingement at desk level. It was found that air speed at 0.6m and 0.75m height increased because of the spreading, air speed at 0.1m decreased. The influence of impingement on desk surface has minor influence on air speed at 1.1m height and above.

2.4 Group Control

Lipczynska et al. (2018) conducted a field study in an office located in Singapore. The fans were shared by 1 to 3 people with shared control. The office is equipped with air conditioning and one focus of this research was "to what extent can the set point be increased?", which is slightly different from my research that the fan is the only cooling method. The most comfortable thermal condition was achieved 26°C with both AC and fans operating. Even with shared control, the occupants were able to feel thermally pleasant (acceptability increasing 59%–92%). However, the placement of fans and furniture seemed to be in a more random layout (see *Figure 11*), and did not provide detailed information about the influence of furniture layout on air flow distribution.

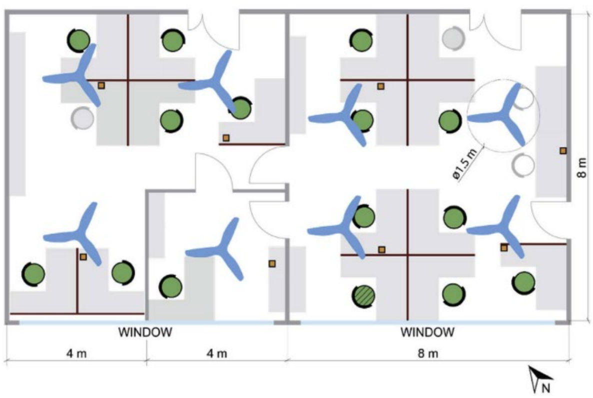


Figure 2: Office layout. Retrieved from "Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics" by Lipczynska et al. (2018).

2.5 Research gaps

Single fan, single occupant

In most of the previous studies, the fan is only providing air movement to a single occupant. This research explores the potential of providing airflow to multiple occupants simultaneously.

Desk surface larger than fan blade area

The desk surface area extends beyond the fan blade area in all horizontal directions. This opens an opportunity to investigate how effectively can the ceiling fan air flow be diffused by the desk surface.

Direct air flow vs diffused air flow

In previous studies, the participants are placed within the fan blade area, regardless of fan type (ceiling fan, desk fan, or stand fan). The participants are exposed to the air flow induced directly from the fan blade. In this research, the participants are exposed to the "indirect" air flow diffused by the desk surface.

3 Methodology

3.1 Overall research workflow

3.1.1 Literature research

The first phase of the research approach is finding relevant literature. From the literature, the essentials of air flow induced by ceiling fan are explained. The relationship between room temperature, relative humidity and preferred air speed will be investigated and plotted into diagrams to compare the result from different research. The results of literature research are stated in Chapter 3.

3.1.2 CFD simulation

The second phase is a CFD simulation with simplified model of a rectangular chamber which represents the geometrical dimensions of ~~the MATE Lab~~ a meeting room in office lab (The Green Village), with a circular-shaped wind outlet as a substitute of ceiling fan, and a desk surface. The simplified model might not provide the most accurate result, but still gives a initial glimpse into *"How does the desk layout diffuse the air flow induced by ceiling fan?"* The results of CFD simulations are shown in Chapter 4.

3.1.3 Lab measurement

The third phase includes 2 experiments that will be conducted in MATE Lab. The first experiment is a measurement to collect air speed data under several desk layouts to examine the effectiveness of diffusing air flow. The second experiment is an investigation of perceived thermal comfort and preference of air speeds of human subjects. The subjects will be placed in MATE Lab to be exposed to ceiling fan air flow diffused by desks and examine their preference by a survey. The results of lab measurements are shown in Chapter 5.

3.1.4 Lab experiment with human subjects

From the result in previous step, several layouts will be selected for a test with human subjects to investigate their preference over air speed. A survey is provided to the subjects to explore their thermal preferences. The results of lab experiments are shown in Chapter 6.

3.1.5 Data analysis

The data collected from CFD simulation and lab experiment will be analysed, and compared to identify how well different desk layouts diffuse the air flow and expand "comfort zone" around ceiling fan. The discussion about the data is shown in Chapter 7.

3.2 Planning and organization

3.2.1 Research schedule

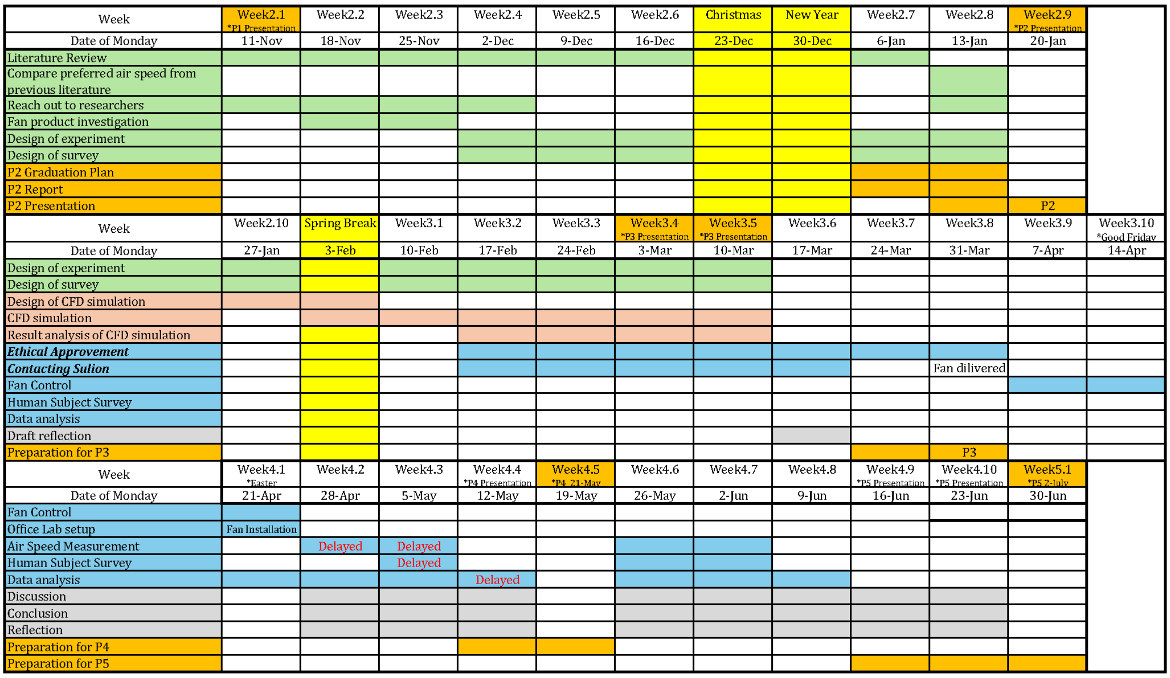


Figure 4: Planning of research timeline.

The research schedule is shown in *Figure 4*. The period before P3 was focused on CFD simulation, and the result provided initial ideas about how effective desks diffuse the air flow induced by ceiling fan. The preparation of lab environment was postponed to dates after P3, including the delivery and installation of ceiling fan, transporting required furniture (desks, chairs, partition, etc.) to site, and test the instrument for data collection. The delivery and installation took longer time than expected, because

The lab experiments started only 4 weeks before P4, leaving very limited time for air speed measurements and experiments with human subjects. The air speed measurements were only done for 3 layout cases and 3 fan speeds, which may not be sufficient for comparing with the results from the questionnaires of human experiments. I also managed to conduct one pilot test with 4 participants. Even though the results are very limited, but it still provide some preliminary insights and helped to revise the experiment procedure.

After P4, I planned to do more measurements and experiments between week 4.6 and 4.7 to collect more complete data. Air speed measurements will be done at all point surrounding the desk surface to understand the actual air speed distribution. The total participants of human experiments are optimistically to be 40 people, which will take 10 mornings on workdays to complete.

3.2.2 Research team

The first mentor is Atze Boerstra from group Building Services Innovation (Climate design), he provides knowledge of thermal comfort and application of ceiling fan. The second mentor is Alessandra Luna Navarro from group Design of Construction (Façade & Product), she guides me to sharpen the research topic and develop the experiment methodology. There is also an external expert, Sebastian Enevoldsen, from Ramboll (Denmark) who shares his professional experience in ceiling fan application in real-world building projects.

3.2.3 Industry partner & technical support

Sulion is a Spanish fan manufacturer that produces high quality, energy efficient ceiling fan with nice design. They provide the ceiling fan for this research and offer technical support especially for the logic behind fan control.

3.3 Lab overview

3.3.1 Lab selection

Initially, the experiment is planned to be conducted in MATE Lab (Luna-Navarro & Overend, 2021), which is located in The Green Village of TU Delft. The experimental area in the lab is 5 x 5 x 2.5 meters, with 3 windows on the east and west elevation, and 2 windows on the south elevation. The rectangular layout which minimises the influence of different distance to surrounding walls. The other advantage is that the lab has a climate control system, which helps to keep the room temperature and relative humidity stable. However, two overhead air ducts are installed in the centre of the lab along north-south direction, which might reduce the efficacy of ceiling fan due to the obstruction of inflow air above fan-blade level. The low ceiling height also caused the blade height to be less than 2.3 meters, which is the minimum height in safety regulation.

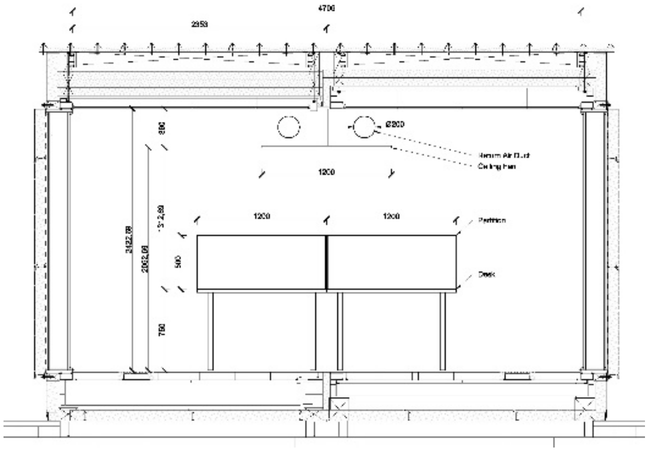


Figure 5: Schematical cross section of MATE Lab with fan installed in the center.

After discussion with my mentors and staff from Green Village, the experiment is relocated to a meeting room in the Office Lab of The Green Village. The meeting room is measured 5.10*3.26 meters, with 2.6 meters of ceiling height. The biggest advantage of the meeting room over MATE Lab is the higher ceiling height with no obstruction that may make the ceiling fan less efficient. However, the smaller room size means that the walls have bigger influence on air flow distribution, and the rectangular layout also cause difference along the long – and short-axis.

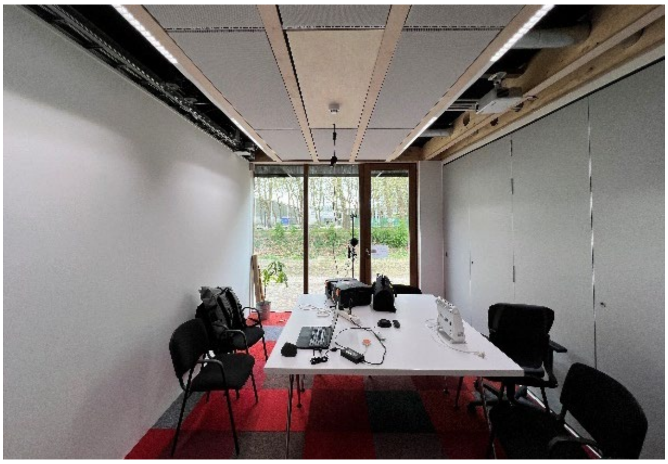


Figure 6: The meeting room in the Office Lab before the fan is installed. The ceiling panels are composed of 8 punch panels with heating/cooling pipes and a solid wooden panel in the center. The center panel can be removed for maintenance. (own source)

3.3.2 Limitations

The room provides a realistic office environment; however, it is neither designed to be a climate chamber, nor a lab for fan tests and air speed measurement. There are limitations of this room that might cause uncertainty to the result.

There is no dedicate climate control system to the room, thus the temperature and humidity might fluctuate during the experiment. The climate control system is also connected with the whole office building, so it is not possible to heat up the room to 28°C without making the whole office feeling over-heated. As an alternative, a 1800W electrical heater (Threesixty, Duux) is used for the experiment. However, the air temperature might not be perfectly uniform in different parts of the room.

The complicated configuration of the ceiling might have influence on air flow. The ceiling is not a completely smooth and flat surface, but with concave and convex. In the centre of the ceiling, there are punched plate ceiling panels that allows the air to flow through. Above the panels are the installations including electric pipes, air ducts, and several types of sensors. The pipes and ducts pass through the timber beams via the circular openings.

3.4 Fan overview

3.4.1 Fan selection & criteria

Ceiling fans are known for their energy efficiency, several research have shown that thermal comfort can be improved with very low energy consumption (Schiavon & Melikov, 2008). The type of motor (AC or DC) further improves the energy efficiency of ceiling fan, among the most common types of motors, DC motor is the most efficient one. Another benefit of DC motor is that it provides wider range of speeds than AC motors (Raftery et al., 2023), and sometimes even stepless control over fan rotation speed. This allows the end user (in this case, the subjects) to fine tune the air speed according to their preference.

The size of the fan models is selected based on the floor area, which is ~~between 12m2 (half of the lab) to 25m2 (whole lab)~~ 15m2 in this experiment setup. The suitable floor area for each fan product can be found from the category or websites provided by the manufacturer. The technical specs including power consumption (W), rotation speed (RPM), air flow (m3/min) and noise (dB) for the candidates are shown in *Table 2*.

In this thesis research, I’m excited to have Sulion, a Spanish fan manufacture, as industrial partner and technical support. They delivered a Balcony M fan (diameter 1.07m), which is capable of being controlled by third-party wireless controller, allowing greater freedom for control methods aside from the default remote controller.

The fan is composed of the following parts:

1. Mounting support: to mount the fan to the ceiling.
2. Down rod: to hang the fan from the ceiling with 15cm or 30cm length.
3. Receptor: to receive signal from default remote or wall-mounted controller to regulate the rotating speed and direction of fan motor. In this case, the default remote controller is not used, so the signal is received from the Shelly dimmers.
4. Motor: an energy-efficient DC motor.
5. Fan blade: pleasant wooden surface finishing.

Model Name	Diameter (mm)	Blade Area (m2) (Hollow Core)	Weight (kg)	Suitable Area (M2)	Specs	Speed Control (Step)					
						1	2	3	4	5	6
Balcony M	1070	0.882	5.5	13-20m2	Motor Power (W)	3	4	5	7	8	10
					Air Flow (M3/H)	2760	4320	5100	6300	7080	7920
					Air Flow (M3/min)	46	72	85	105	118	132
					Fan Air Speed (m/s)	0.87	1.36	1.61	1.99	2.23	2.50
					RPM	80	110	140	160	180	200
					Noise level (dB)	37	38	39	40	41	42
Balcony L	1420	1.566	5.5	>32m2	Motor Power (W)	4	7	11	16	24	33
					Air Flow (M3/H)	4620	6000	7920	9300	10740	12600
					Air Flow (M3/min)	77	100	132	155	179	210
					Fan Air Speed (M/s)	0.82	1.06	1.40	1.65	1.91	2.23
					RPM	80	110	140	160	180	200
					Noise level (dB)	22	27	29	35	40	45
Anne	1270	1.249	5.5	>20m2	Motor Power (W)	3	6	8	11	15	22
					Air Flow (M3/H)	3000	5100	5700	7800	8700	9300
					Air Flow (M3/min)	50	85	95	130	145	155
					Fan Air Speed (M/s)	0.67	1.13	1.27	1.73	1.93	2.07
					RPM	88	126	155	185	205	235
					Noise level (dB)	15	20	24	28	33	36

Table 2: Comparison of technical specs of ceiling fan candidates.

Figure 7:Final decision ceiling fan: Balcony M fan with 1070mm diameter. (Source: Sulion)

3.4.2 Fan Specifications

The main specifications of the fan include rotating speed (RPM), power consumption (W), air flow (m3/hr or m3/min), and noise level (dB). In the default 6-speed mode, the numbers can be found from the website of the manufacturer. The air flow shows a strong linear correlation with rotating speed, with R-square = 0.9926. The linear correlation helps to estimate the air flow in the customized 9-speed mode. The air flow is then used for calculating the "Fan Air Speed", a conceptual average air speed through the entire fan blade area.

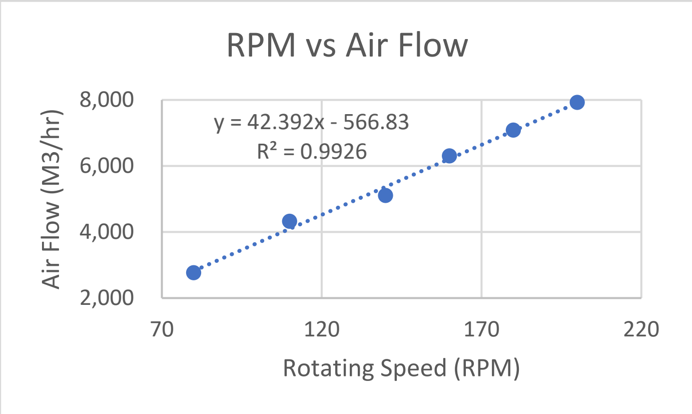


Figure 8: Fan rotating speed vs generated air flow (m3/hr).

Specs	Default 6-speed Mode								
Speed Step	1		2		3		4	5	6
Air Flow (M3/H)	2760		4320		5100		6300	7080	7920
Fan Air Speed (m/s)	0.87		1.36		1.61		1.99	2.23	2.50
RPM	80		110		140		160	180	200
Noise level (dB)	37		38		39		40	41	42
Specs	Customized 9-speed Mode								
Speed Step	1	2*	3	4*	5	6*	7*	8*	9
Voltage Control	1.5V	2.5V	3.5V	4.5V	5.5V	6.5V	7.5V	8.5V	9.5V
Measured Power (W)	5.5		7.3		10.1				
Air Flow (M3/H)	2760	3672	4320	4775	5100	6004	6640	7276	7920
Fan Air Speed (m/s)	0.87	1.16	1.36	1.50	1.61	1.89	2.09	2.29	2.50
RPM	80	100	110	126	140	155	170	185	200

Table 3: Fan specifications with default 6-speed mode and customized 9-speed mode. The air flow of speed 2/4/6/7/8 in the 9-speed mode is estimated according to the linear regression in Figure 8.

3.4.3 Fan control system

The default remote control only allows 6 speed levels (from 80 – 200 RPM). For this research, I would like to examine people's preference in a higher "definition", especially at the lower speed levels.

The rotating speed and direction of the fan provided by Sulion can be regulate through voltage signals. To generate the voltage signal, 2 wireless controllers (Sheely 0/1-10V Dimmer Gen3) are used for the control system, one is for speed control, and the other for direction control. The dimmer was originally designed for lighting control by creating voltage signals ranging from 0-10V or 1-10V to adjust the brightness. In this case, the fan reacts differently depending on the input voltage.

For speed control, at 1.5V, the fan rotates at a minimum of 80 RPM. While at 9.5V it rotates at a maximum of 200 RPM. As for adjusting rotating direction (upwards and downwards air flow), if the voltage is less than 4.5V, it generates downward air flow; if the voltage is greater than 5.5V, the fan rotates reversely and generates upward air flow.

Default Speed Steps (6)									
Speed Step	1		2		3		4	5	6
RPM	80		110		140		160	180	200
Customized Speed Steps (9)									
Speed Step	1	2	3	4	5	6	7	8	9
Input Voltage	1.5V	2.5V	3.5V	4.5V	5.5V	6.5V	7.5V	8.5V	9.5V
RPM	80	100	110	126	140	155	170	185	200

Table 4: Comparison of default speed steps and customized speed steps. More speed choices are available in the low-speed range.

The wiring diagram for the control system is shown as follows. The power is supplied from a regular AC socket at ceiling level. The fan receptor and the Shelly dimmers are connected to the power supply. The receptor is connected to Shelly dimmers for voltage signal input and connected to fan motor with DC to drive the fan.

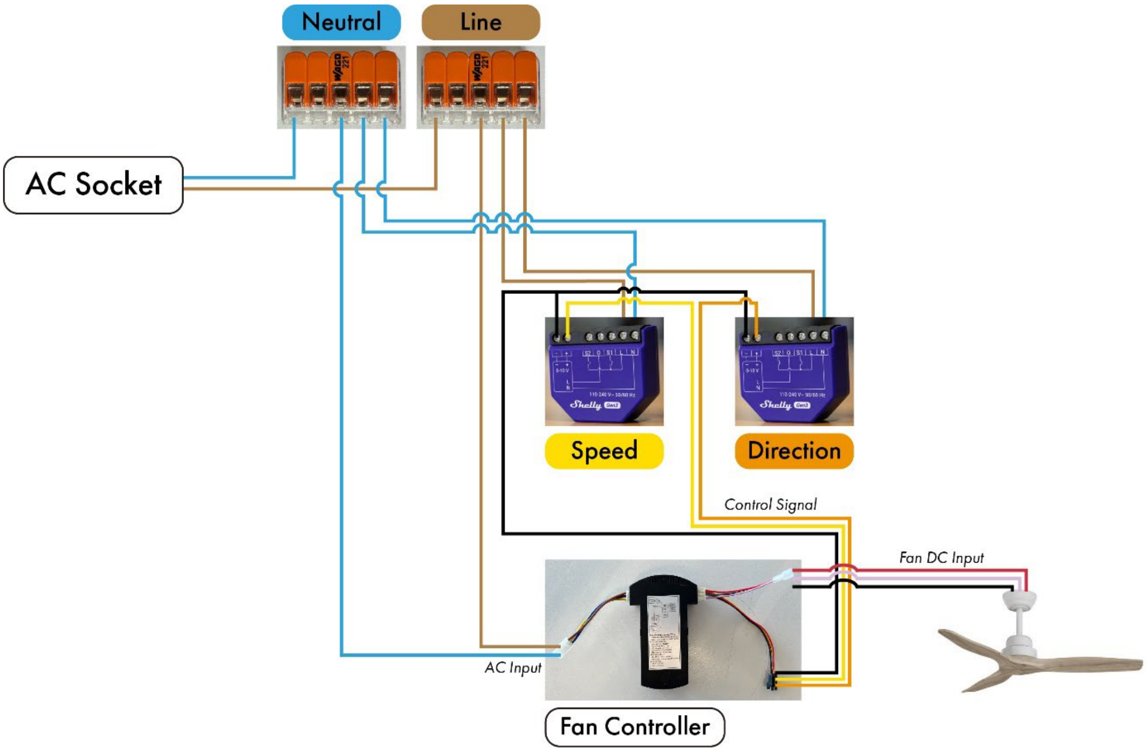


Figure 9: Wiring diagram of fan control system.

3.4.4 Fan control interface

The interface is built on Home Assistant, an open-source smart home system. It allows you to customize control interface and personalize automated control. The default interface for the dimmers is a button for switching on/off and an arc-shaped slider for stepless brightness control. The slider represents the brightness percentage from 0% to 100%, or a 0 to 255 scale, which is translated to a 0-10V signal by the dimmer.

2 different approaches were tried to build the control interface. Starting with "direct control" that is easier to design, but less intuitive for the user. By thinking about different user scenarios, I tried to define the most essential functions that the user will need and designed a "indirect control" that incorporates the highly customizable "automation" functions in Home Assistant.

Direct control: The buttons and arc-shaped sliders on the control interface triggers the dimmers directly (see *Figure 10*). When the button is pressed, it switches on the dimmer to a preset voltage. When sliding the slider, the dimmer generates voltage signals from 0 to 10V. For controlling the speed of fan, this interface still makes sense for the user. However, this is especially unintuitive when one is trying to change the rotating direction. The user might be confused about relating an arc-shaped slider to upward/downward air flow.

Figure 10: Interface of "direct control" where the fan speed can be selected steplessly on the left panel, and fan direction can be adjusted with the panel on the right. However, it is less intuitive for the user to understand which "interval" of the arc-shaped slider are for downward or upward air flow.

Indirect control: To create an interface that is more intuitive for fan controls, I have to build my own customized interface (see *Figure 11*). The main features for fan control includes (1) speed control (either with steps or stepless), (2) direction control (upward and downward), and (3) turn off both controls with one tap.

The slider and buttons are used as an "input" from the user, they don't send direct signals to the dimmers. They trigger "automation" that are defined by me, and the automation triggers the dimmers to generate voltage signals. First, A slider is created with 9 steps to control fan speed, each step triggers the dimmer to generate voltage signals from 1.5V, 2.5V, ..., to 9.5V. The triangular-shaped slider makes it clear for the users to see whether the fan is at low or high speed. When the user slides the slider, the fan generates downward airflow as default. Two dedicated buttons are created for selecting upward and downward air flow. When the user presses the "up" button, the voltage is set to XX%, and XX% when the "down" button is pressed. Finally, there is another button that turns off the fan and switches off both dimmers completely.

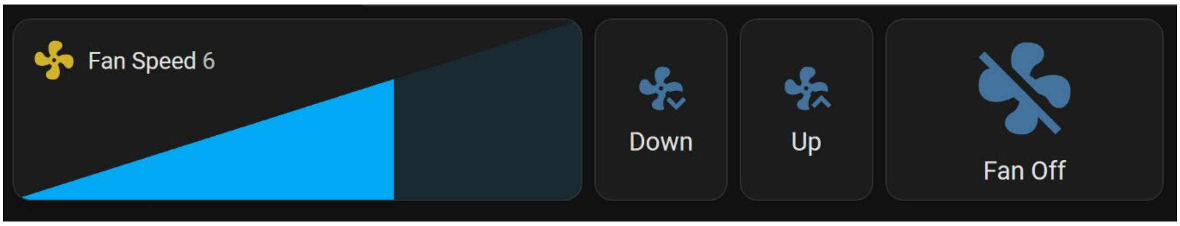


Figure 11: Interface of "indirect control" which allows users to select fan speed in 9 steps with the slider on the left. The triangular slider indicates how fast the fan will be spinning. There are also dedicated buttons to adjust fan directions and turning off the fan.

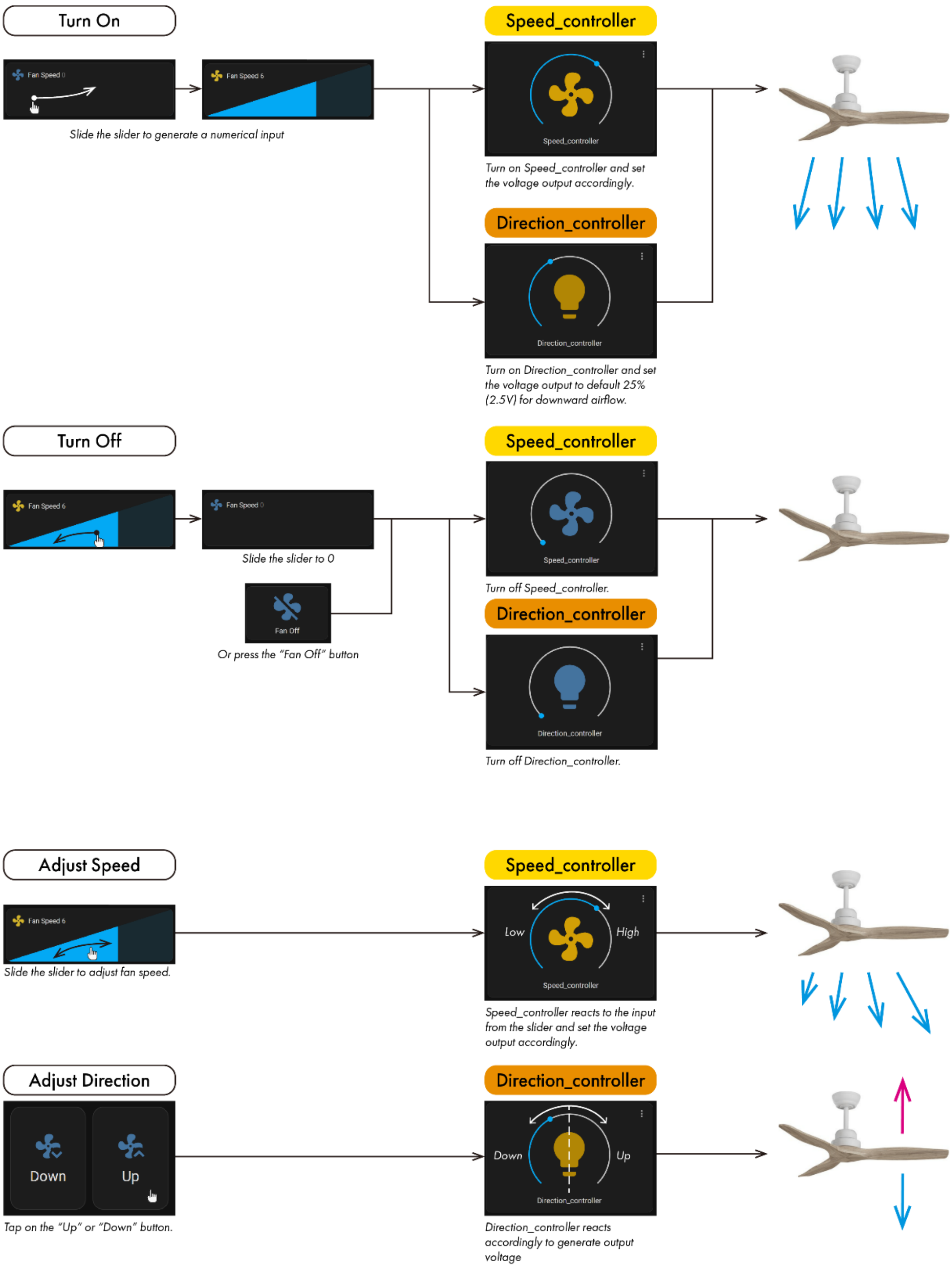


Figure 12: The diagram shows how the sliders and buttons for "indirect control" triggers the dimmers (speed_controller and direction_controller).

4 CFD simulation

4.1 Introduction

CFD (Computational Fluid Dynamics) simulation is a technique that analyse and solve problems related to fluid (liquids or gases) flows. It is a computation-power demanding and time-consuming if one wants to get very detailed results from the simulation. Due to the limited computation power and time, simplified methods are used in this research. Even though the result might not be super precise, but the main purpose of doing CFD simulation are to give a preliminary understanding into the air flow pattern under different layout cases and help to select the (more interesting) layouts for further air speed measurements. In this chapter, the software and parameter settings of CFD simulation will be introduced, followed by the results of several layout cases with various fan air speed. The comparison across layout cases will be presented to show how different placement of desks and partition, the FAS and direction affect the simulated air speed around the desks.

4.2 Methodology

4.2.1 Software

The software used for the research is Butterfly, a Grasshopper plugin that is based on OpenFoam, an open-source CFD application. The integration with Grasshopper provides a graphical interface that is more familiar and approachable for architects and designers. All the geometry that is required for CFD simulation can be generated parametrically in Grasshopper, which makes it easy to manipulate through different design options.

4.2.2 Room geometry

The room for simulation is a simple cubic geometry with dimension of 5m(L) * 3m(W) * 2.6m(H). To reduce the complexity and simulation time, all the 6 surfaces of the cube are flat and smooth surface without any concave or convex that appears in reality as mentioned in Chapter 2.3.2.

4.2.3 Simplified fan

The rotating fan blade is not simulated in this research due to the limitation of computation power. Instead, a hollow-core circular is adapted to represent the fan blade area. The simplified fan consists of a hollow-core circular surface which represents the fan blade area letting in the air flow into the lab boundary, another hollow-core circular surface that is 10cm above the previous surface for air outlet (return air). The dimension of the circular surface is 1.07m, and the diameter of the hollow core is 0.15m, matching the actual dimensions of the Sulion Balcony M fan. A tilted air foil is placed under the inlet surface, which redirects the airflow to simulate the actual swirling airflow induced by the rotating blades. The accuracy of this method is not yet validated while the simulation is conducted. The results will be compared with lab measurements in *Chapter 7.1*. Note that the air foil is only applied when simulating downward air flow.

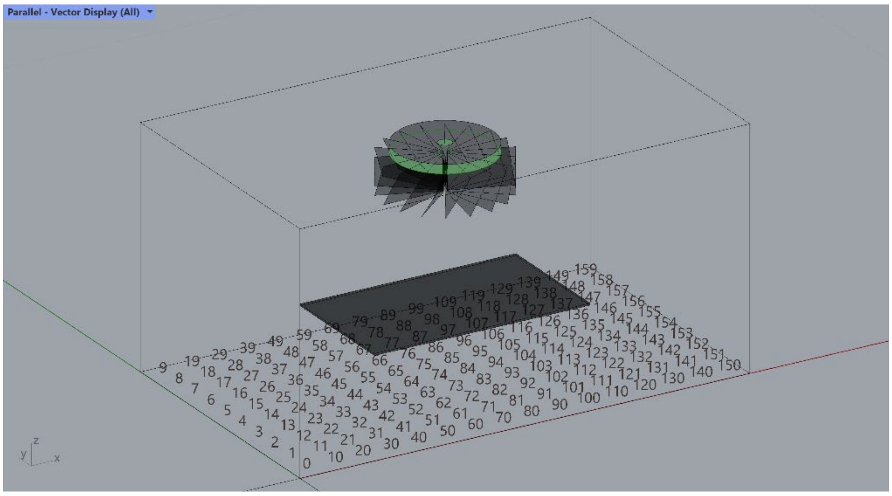


Figure 13: Simplified fan geometry for CFD simulation. (own source)

The inlet air speed is not given in spec sheets from most manufacturers. Hence the conceptual "fan air speed (FAS)" is adopted from P. Raftery et al. (2019),which is calculated as:

FAS = [airflow (m3/min) / 60] / fan blade area (m2)

4.2.4 Probes

The "probes" are the points where air speed data is collected. The probes are placed on a planar 16*10 grid with 30 cm spacing, and the planar grids are placed at 8 different heights including

0.1m, 0.6m, 0.85m, 1.1m, 1.7m, 2.2m and 2.5m. The probes are numbered from 0 to 159, for each layout cases, a set of probes are used for assessing the air speed at each seat location around the desks. For example, in Case 1, the average air speed from probe number 52 and 62 represents the air speed at seat A. Probe 57 and 67 represents seat B, probe 97 and 107 represents seat C, and probe 92 and 102 represents seat D.

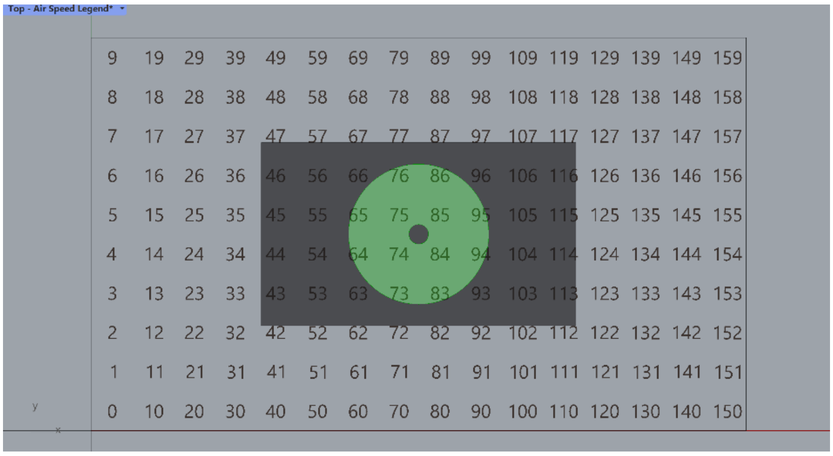


Figure 14: The probes are placed on a 10x16 grid with 30cm spacing, leading to 160 probe points per level.

4.2.5 Simulation parameters

The main parameters for CFD simulation include parameters for meshing and parameters for solution. The first step of meshing is “BlockMesh”, and the only non-default parameter “_cell_count_” is set to (100, 60, 52), representing that the room geometry is meshed into 5*5*5cm cubes. The second step is “SnappyMesh” that meshes all the geometries within the boundary.

The cubic boundary is meshed with 5*5*5cm units which results in the mesh_count of 100*52*26. The selected turbulence model is k-ε turbulence model, which has been proved effective by Chen et al. (2018).

4.2.6 Visualization

To visualize the simulation results, to types of diagrams are used. The first diagram is a planar “heat map”, with a 30*30 grid that represents the location of the “probes”. The heat map shows the magnitude of simulated air speed with a legend that when the air speed is high, is shows red and when the air speed is low, it shows blue. The second diagram is a 3D “vector view” that shows both the magnitudes and directions with arrows. The arrows are also coloured with the same legend as heatmap, so it is easier to relate the 2 types of diagrams. Two sections along the long and short axis are also presented to show the sectional pattern of air flow.

4.2.7 Simulated air speed at seat locations

To show how effective the ceiling fan air flow is diffused by desks, the simulated air speeds at seat locations are shown on the heat map. There are 4 seat locations defined for each layout. For the 2x2 layouts (Case 1, 2 and 3), seat locations are shown as **Error! Reference source not found.**. The air speed at seat locations is the average air speed at 0.85m of the 2 probe points close to the seat location. As for 2-side layouts (Case 4, 5 and 6), the air speed is calculated as the average air speed at 0.85m of the 4 probe points close to the seat location. The main reason to calculate the average of 4 probe points is because the air flow at seat locations comes from different directions, so I assume it to me more representative.

4.3 Simulation cases

4.3.1 Variables

The controlled variables of the fan are the location and the type of the fan. The fan is always located in the centre of the room. The diameter of the fan is also constant 1.07m which is the same size as the actual fan that we will test in air speed measurement. The independent variables of the fan are the fan air speed (which represents the rotation speed) and the rotating direction.

The controlled variables of the desks are the dimension and surface material. All the desk are 120cm(L) * 70cm(W) * 75cm(H), with the same surface material. The independent variables for desk layouts include:

1. Desk placement:
    - no desk
    - 2*2 layout: combining all the 4 desks together and forms a large rectangular surface.
    - 2-side: 2 desks are placed in a row on the 2 sides of the room
2. Desk offset:
    - Centered

- 60cm offset along the long axis of the room

3. Orientation:
   - Aligned with long axis (rotation = 0°)
   - Aligned with short axis (rotation = 90°)
4. Partition:
   - No partition
   - Linear partition
5. Fan air speed:
   - Fan Air Speed: derived from the 6 default air flow (m3/min) values on the spec sheets
   - Direction: downward (direct) air flow and upward (reverse) air flow

The dependent variable is the simulated air speed at each seat locations.

4.3.2 Layout cases

From the independent variables mentioned above, several layout cases are created to test with CFD simulation. The numbers from 0 to 6 indicates the different desk layouts. The suffix letter A indicates "no partition", and letter B indicates "linear partition.

Case	Fan Diameter	Desk Placement	Desk Orientatio	Desk Center (m)		Partition
				X-offset	Y-offset	
Case_0	1.07	No	N/A	N/A	N/A	No
Case_1A	1.07	2x2	0	0	0	No
Case_1B	1.07	2x2	0	0	0	Linear
Case_2A	1.07	2x2	0	0.6	0	No
Case_2B	1.07	2x2	0	0.6	0	Linear
Case_3A	1.07	2x2	90	0	0	No
Case_3B	1.07	2x2	90	0	0	Linear
Case_4A	1.07	2-side	0	0	0	No
Case_5A	1.07	2-side	0	0.6	0	No
Case_6A	1.07	2-side	90	0	0	No

Table 5: Layout cases and the corresponding variables.

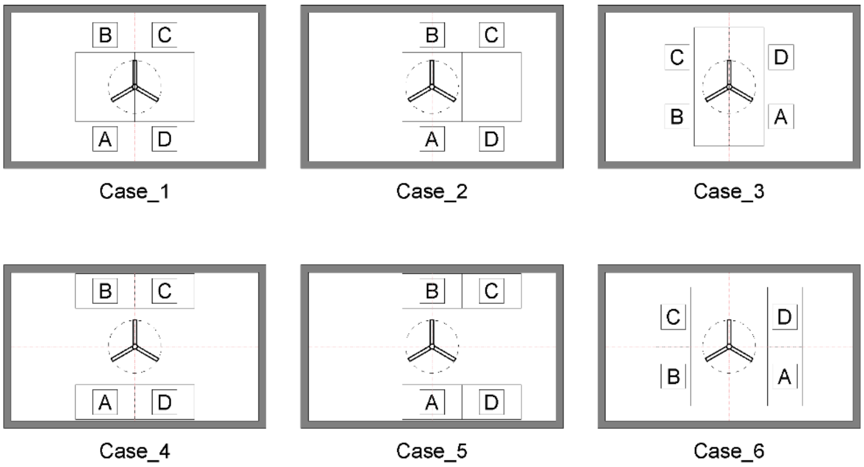


Figure 15: Layout cases 1 to 6 with indication of seat locations A to D. (Own source)

4.3.3 Fan Speed cases

The fan has six default speed steps, the corresponding air flow ranges from 2760 to 7920m3/hr, which can be translated to FAS between 0.87 to 2.5 m/s. The fan can also rotate reversely to generate an upward air flow, and for the simulation the FAS are assumed to be the same as downward air flow. There are 12 FAS cases in total. Due to time limitation, not all the 12 FAS were simulated for all layout cases. Most of the layout cases are simulated with 2.23 m/s for both air flow directions (upward and downward), which is the 2nd highest FAS from the 6 default speed steps. Only Case 1B was simulated with all 6 default speed steps for downward (direct) air flow.

Manufacturer	Model Name	Diameter (mm)	Blade Area (m2) (Hollow Core)	Weight (kg)	Suitable Area (M2)	Specs	Speed Control (Step)					
							1	2	3	4	5	6
Sulion	Balcony M	1070	0.882	5.5	13-20m2	Motor Power (W)	3	4	5	7	8	10
						Air Flow (M3/H)	2760	4320	5100	6300	7080	7920
						Air Flow (M3/min)	46	72	85	105	118	132
						Fan Air Speed (m/s)	0.87	1.36	1.61	1.99	2.23	2.50
						RPM	80	110	140	160	180	200

Table 6: Spec sheet and calculated FAS for the 6 default speed steps.

4.4 Results

4.4.1 Case_0

FAS = 2.23m/s (Speed 5, downward)

In this base case without the presence of desks, the air flow pattern is similar to those shown in previous research. A horizontal downward jet can be seen beneath the blade area. Lower air speed occurs where the jet impinges the floor under blade area at 0.1-0.6m height. The air flow is then redirected outwards horizontally, where the higher air speed occurs at 0.1m above floor level. When the outwash air flow impinges the surrounding walls, it is redirected upwards along the wall surface, and redirected again at ceiling level as the return air flow. The air speeds are relatively low beyond the abovementioned zones. This can be clearly observed on the heatmap of air speed at 0.85m height that outside the jet zone, the colours are blue, and also in the vector view that the length of the arrows are shorter and also in blue colour. The swirling air flow generates centrosymmetric air flow pattern can also be observe from the colour pattern of the heatmap, causing higher air speed (average 0.73m/s) at Seat A (bottom-left) and C (top-right), and lower air speed (average 0.44m/s) at Seat B and D, that is almost 40% lower.

FAS = -2.23m/s (Speed 5, upward)

The upward airflow impinges the ceiling directly and causing a high-speed outwash air flow along ceiling level. The air flow is redirected downwards after the impingement with surrounding walls. There is no concentrated "return air flow" under the blade area. The air speed distribution is more evenly distributed comparing to the downward fan air flow. On the heatmap of air speed at 0.85m height, more areas are in yellow to light green colours, meaning higher air speed occurred than when the fan is inducing downward airflow. The air speed at 4 seat locations are nearly identical between 0.67-0.68m/s, but since the air foil for simulating swirling air flow is not applied in all upward air flow cases, the current result might differ from reality.

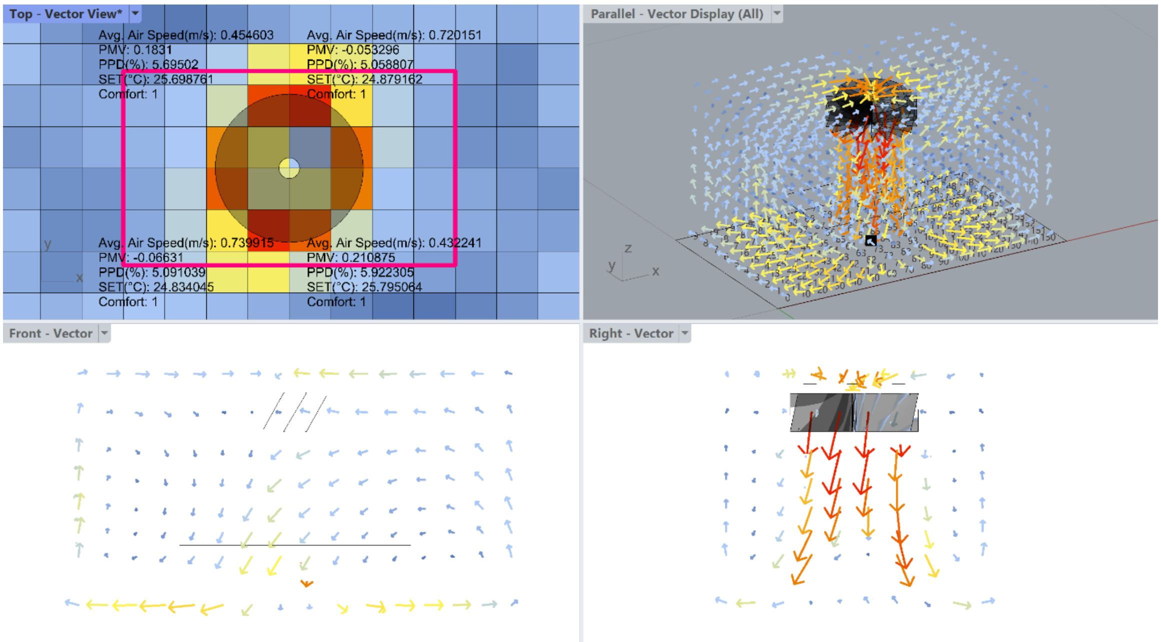


Figure 16: Air flow pattern of Case_0 at downward fan speed 5 (FAS = 2.23m/s). Higher air speed can be seen at Seat A and D (bottom-left and top-right) because of the swirling air flow.

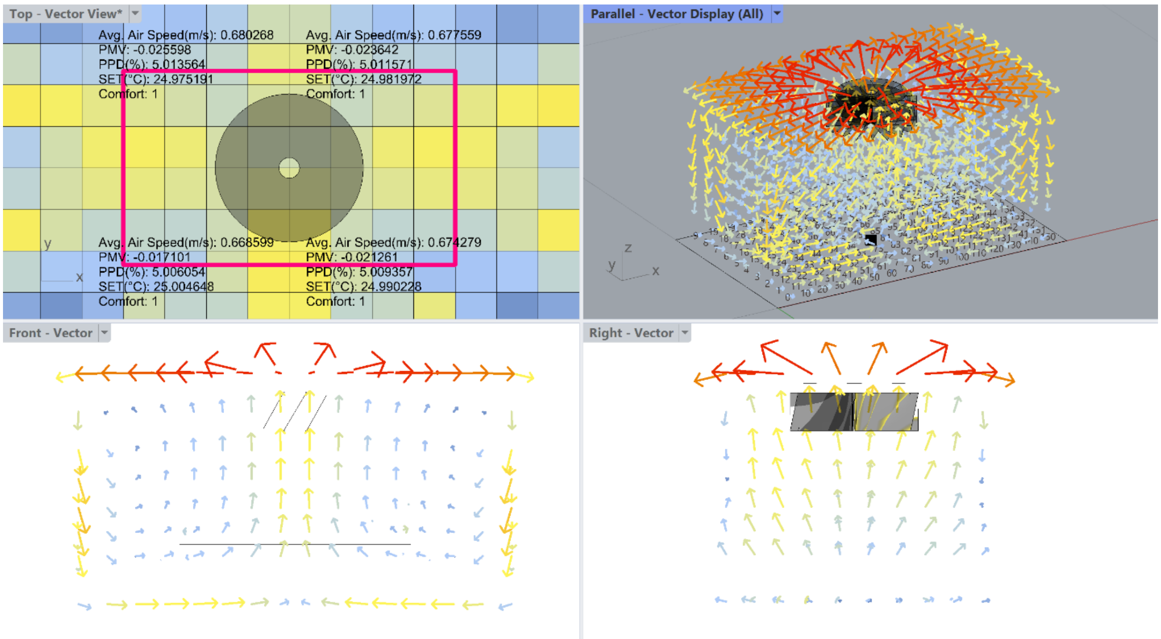


Figure 17: Air flow pattern of Case_0 at upward fan speed 5 (FAS = -2.23m/s).

4.4.2 Case 1A

FAS = 2.23m/s (Speed 5, downward)

In Case_1A, four desks are placed in a 2x2 layout at the centre of the room. The downward jet is redirected at the height of desk surface that cause the outwash airflow to be elevated from floor level to desk surface. Higher air speed can be observed on the heatmap of 0.85m with more cells in yellow and orange colours. The average air speed of 4 seat locations is 1.3m/s.

FAS = -2.23m/s (Speed 5, upward)

The air speed is significantly slower than the previous Case_1A with downward fan air flow especially at 0.85m around the desk surface. The presence of the desks might be obstructive to the upward return air flow.

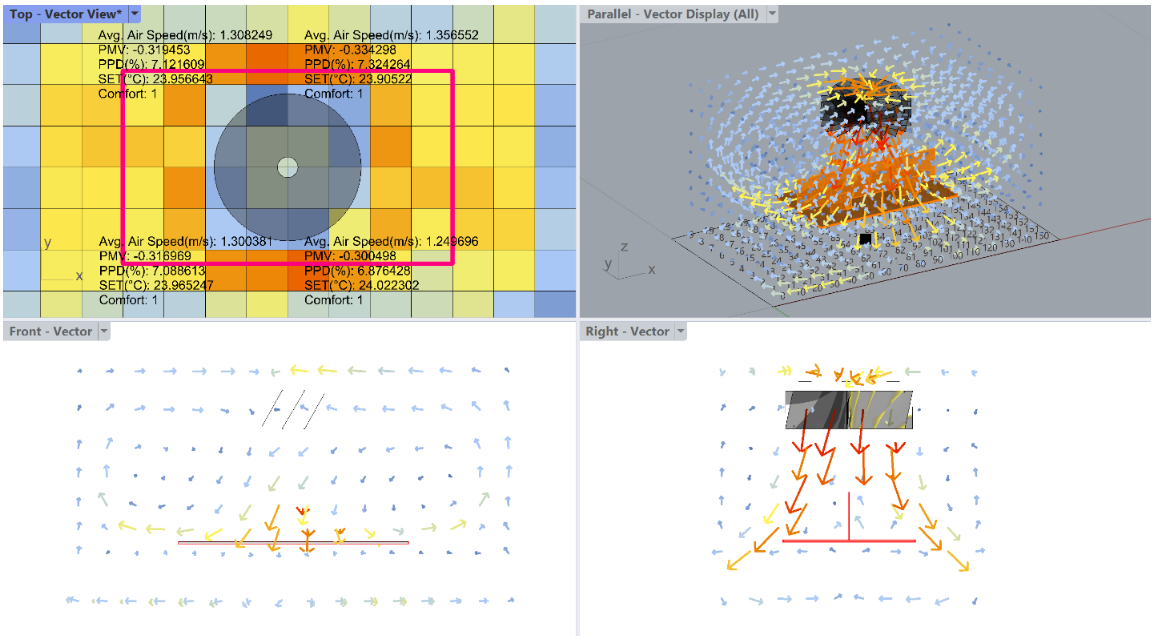


Figure 18: Air flow pattern of Case_1A at downward fan speed 5 (FAS = 2.23m/s).

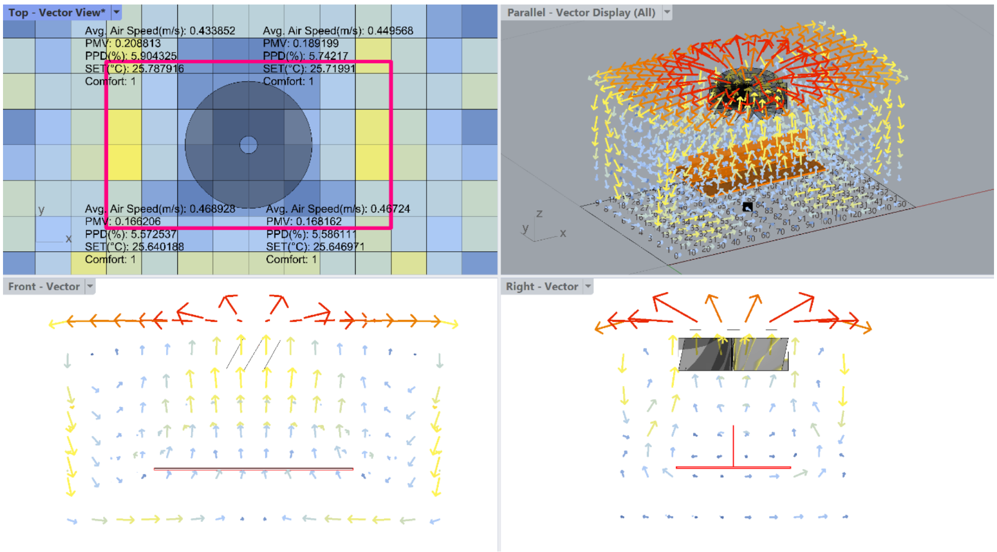


Figure 19: *Air flow pattern of Case_1A at upward fan speed 5 (FAS = -2.23m/s).*

4.4.3 Case 1B

A linear partition with height of 50cm is placed in the center of the desk surface along the long axis to assess its influence on air flow pattern. The result shows a clearer ***centrosymmetric*** air flow pattern, where two horizontal jets can be observed along the partition. The clockwise-swirling airflow impinges on the partition and is redirected outwards horizontally especially at the top-right and bottom-left of the partition.

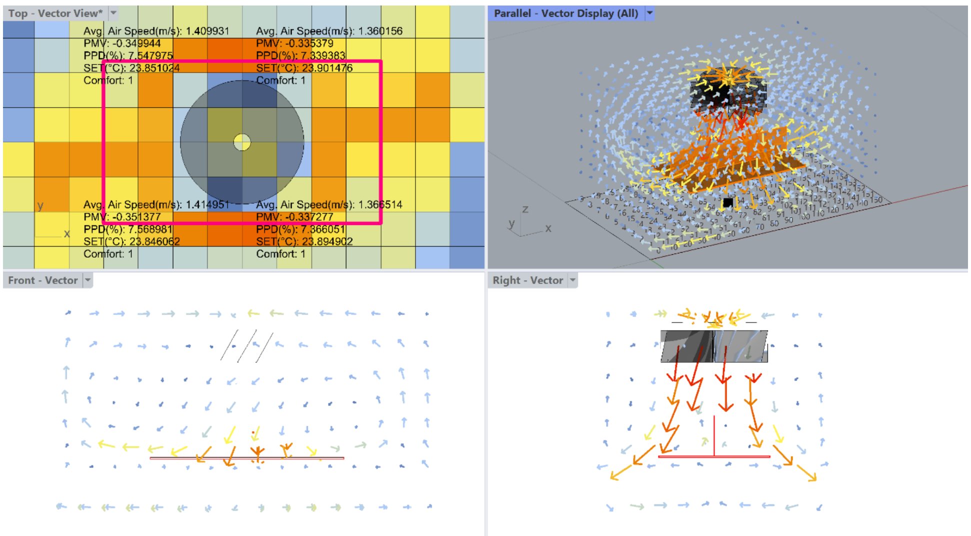


Figure 20: Airflow pattern of Case_1B at fan speed 5. Two horizontal jet redirected by the linear partition can be clearly observed at the top-right and bottom-left of the partition.

In this layout case, 5 FAS (speed 1 to 5) were simulated. Although seat-level differences are small, the average air speed of all seat locations can be accurately described by a single linear regression (see *Figure 21*) where: *Seat air speed=0.64×Fan air speed−0.03 (R^2 = 0.9998)*. For every speed the difference between the fastest and slowest seat is tiny (0.01–0.05 m/s, i.e. < 6 % of the mean).

It can be found that at fan speed 2 (the second lowest setting), the average of simulated air speed already exceeded the 0.8m/s threshold, which is the upper limit of air speed when there is no personal control. At fan speed 4, the average air speed is even above 1.2m/s, the upper limit of air speed when there is personal control. The limited speed selection at lower fan speed may not be sufficient for fan users to find the most suitable fan speed.

Fan Speed	Fan Air Speed	Seat A	Seat B	Seat C	Seat D	Average
Fan Speed 1	0.87	0.52	0.52	0.52	0.51	0.52
Fan Speed 2	1.36	0.87	0.83	0.85	0.82	0.84
Fan Speed 3	1.61	1.02	1.00	1.00	0.98	1.00
Fan Speed 4	1.99	1.26	1.25	1.23	1.22	1.24
Fan Speed 5	2.23	1.41	1.41	1.36	1.37	1.39

Table 7: Simulation results of 5 FAS at all seat locations and the average air speed

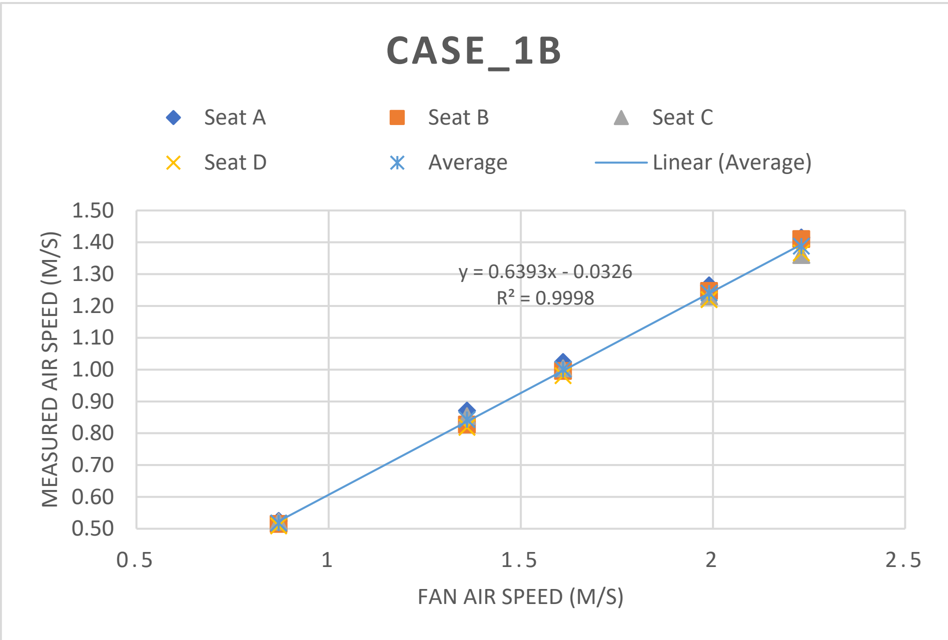


Figure 21: Air speed at seat location can be well predicted from the initial FAS.

4.4.4 Case 2A

The desks are moved 60cm to the right that results in 2 different distances from seat locations to the centre of fan. The aim is to assess how much the air speed differs at each seat locations.

The result shows that the simulated air speed at near-end seats are nearly twice as the ones at the far-end seat.

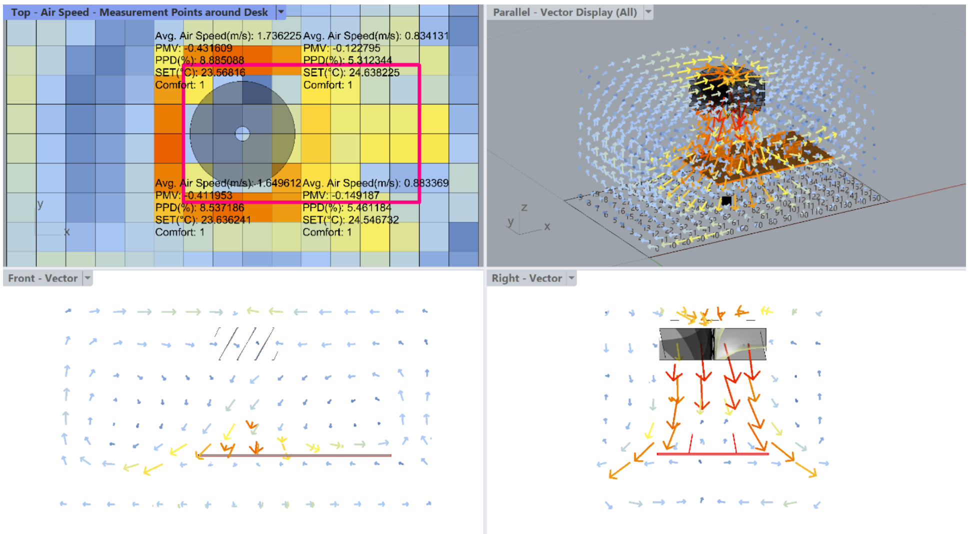


Figure 22: Air flow pattern of Case_2A.

4.4.5 Case 4A

FAS = 2.23m/s (Speed 5, downward)

The desks are placed on the 2 sides of the room, with seat locations closer to the centre of the room as well the blade area. At the seat locations, the direction of air flow might be coming from the back or the side of human body, thus the air speed data from the 4 probe points are taken into account for the calculation of average air speed at each seat locations as explained in previous *Chapter 4.2.7*. The air flow pattern is very similar to that in Case_0, with high air speed zone at 0.85m height concentrated under blade area.

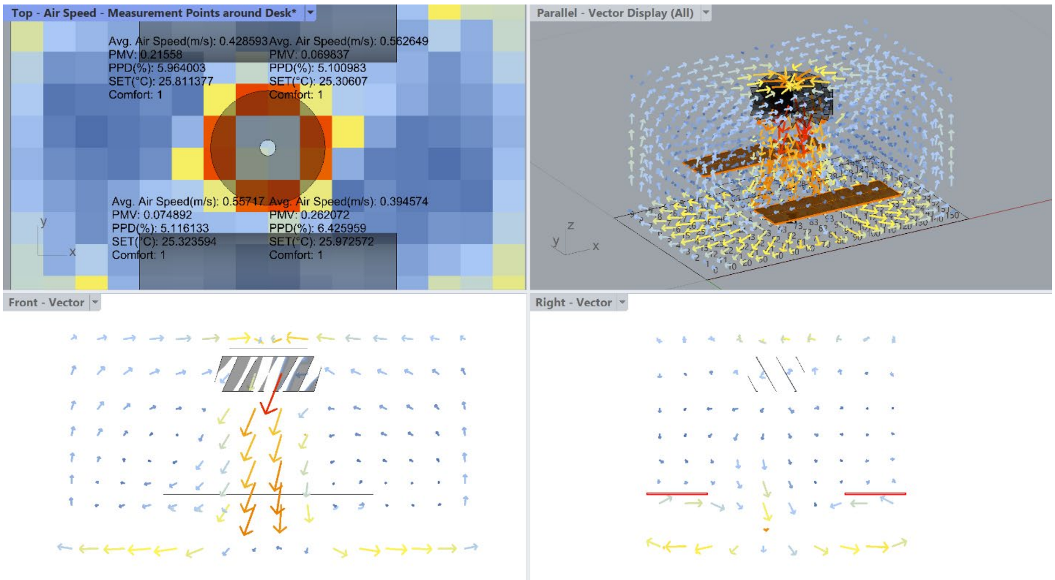


Figure 23: Air speed pattern of Case_4A with downward air flow.

FAS = -2.23m/s (Speed 5, upward)

The air speed in with upward air flow is surprisingly higher than with downward air flow. As the air flow is redirected downward by the surrounding walls, it impinges the desk surface and is redirected horizontally towards the seating locations. If this pattern can be validated in the actual air flow measurements, it might be a new approach of placing fans and desks.

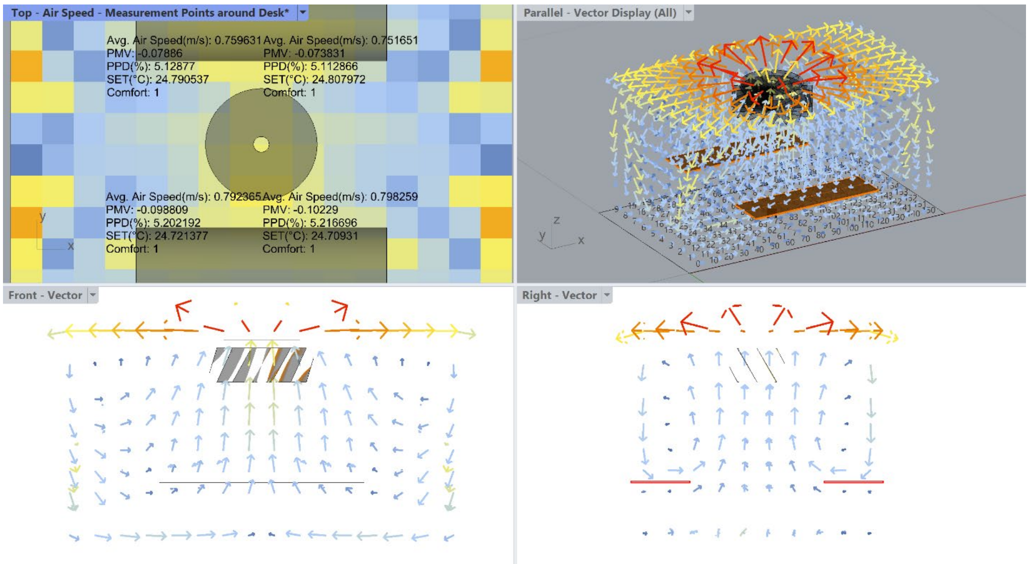


Figure 24: Air speed pattern of Case_4A with upward air flow.

4.5 Discussion

4.5.1 Comparison between Case_0 and Case_1A

To understand how the presence of desks influences the air speed at seat-level, the simulation results are compared in this section. To focus more on the sitting zone, only the air speed data from the probe points around the desk surface at 0.85m height (that is above the desk surface) are used in this analysis.

Among all cases, CFD_Case_0_8(R) showed the most uniform air distribution, with a coefficient of variation (CV) of 0.20 and an average air speed of 0.75 m/s, suggesting a well-balanced airflow pattern around the desk zone. CFD_Case_1A_8(R) followed closely with a CV of 0.28. In contrast, CFD_Case_0_8 showed the highest variability (CV = 1.02), with air speeds ranging from as low as 0.07 m/s to peaks above 2.1 m/s, indicating uneven airflow and potential discomfort zones. Although CFD_Case_1A_8 provided the highest average air speed (0.91 m/s), its variability was higher than that of the (R) cases. These findings suggest that upward air flow (denoted by the suffix "R") may contribute to more consistent airflow at the seated occupant level.

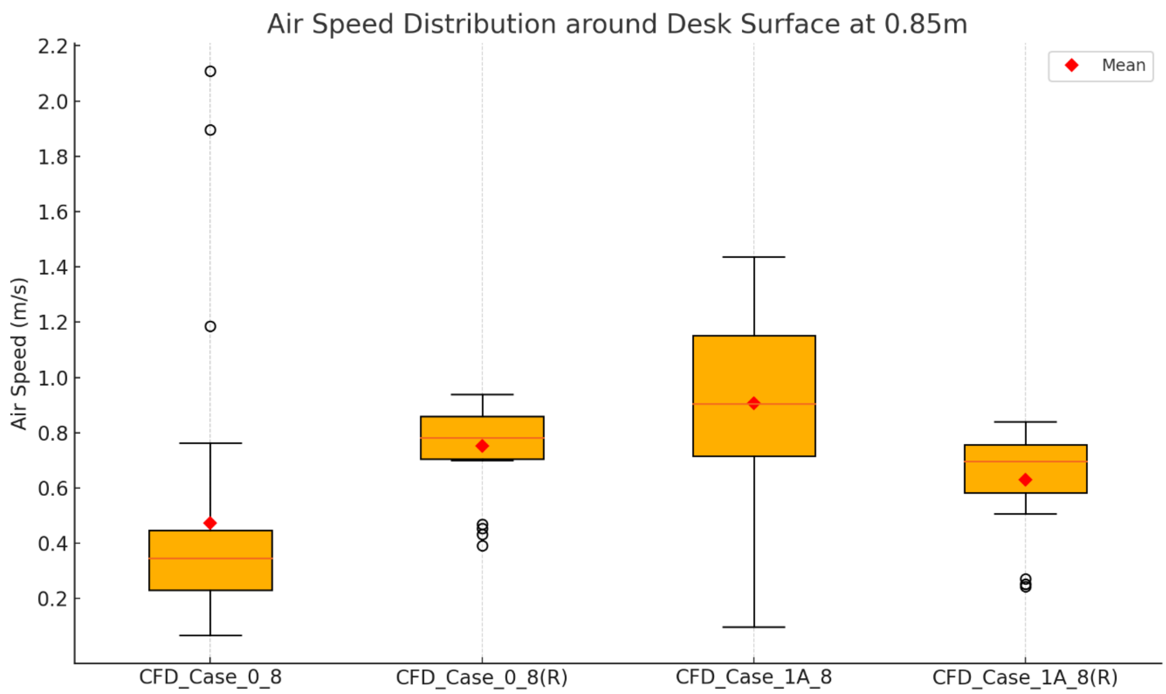


Figure 25: Air speed distribution around desk surface at 0.85m of Case_0 and Case_1A for both downward and upward air flow.

4.5.2 Comparison of all cases with downward airflow

The comparison of simulation results of all layout cases with downward FAS=2.23m (speed 5) are presented in this section to assess how different layouts influence the magnitude and uniformity of air speed at seat locations.

In *Figure 26*, the yellow bars show the average air speed of the 4 seats, and the black dots are the air speed value of each seat. To facilitate interpretation, comfort threshold lines based on ISO 7730 and ASHRAE 55 are overlaid on the chart:

- 0.2 m/s: sensation threshold; below this, airflow may be stagnant.
- 0.8 m/s: upper limit for comfort without personal control.
- 1.2 m/s: upper limit for comfort with personal control.

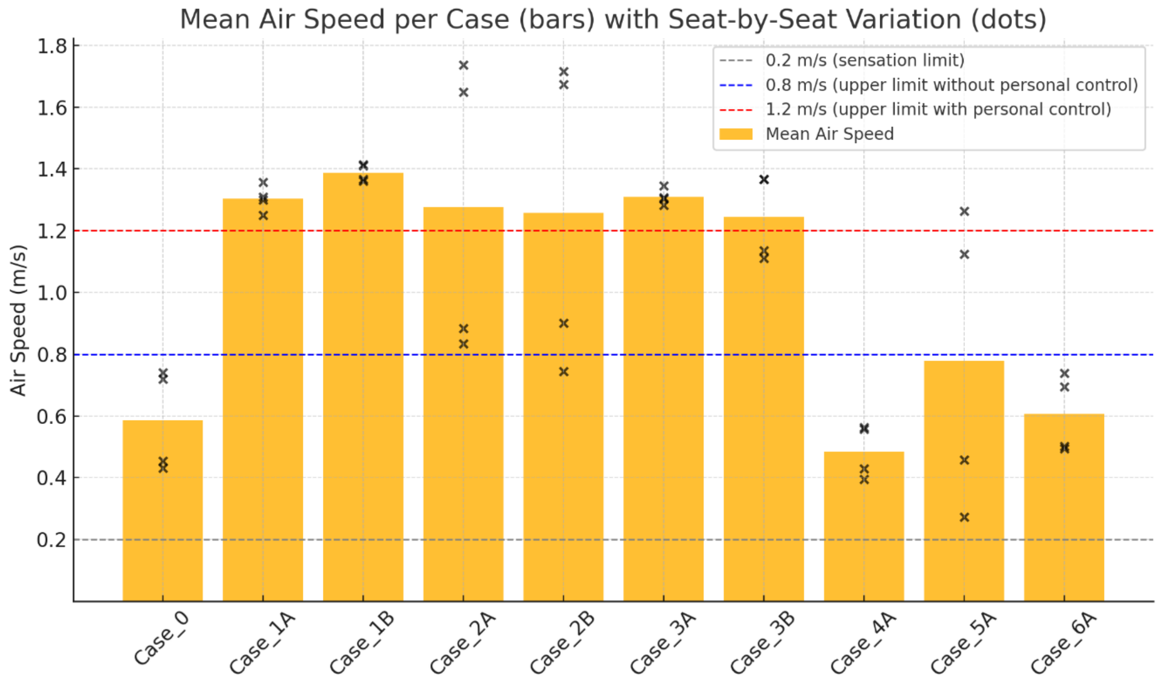


Figure 26: Comparing average air speed and seat-by-seat variation across all 10 layout cases.

Case_1B, Case_1A and Case_3A exhibit the top 3 highest and most uniform air speeds, with mean values around 1.39 m/s and 1.30 m/s respectively. The air speeds in these layouts remain tightly clustered, suggesting a well-balanced airflow distribution. Case_0 shows the lowest mean air speed (~0.59 m/s), which may result in insufficient air movement under warm conditions. Cases 2A and 2B have moderately high mean air speeds (1.26–1.28 m/s), but also the highest seat-to-seat variation, indicating localized airflow peaks and potential comfort disparities.

In *Figure 27*, seat-by-seat air speeds are mapped on a 2×2 seat grid (Seats A–D) with legend showing highest air speed in colour red, and lowest air speed in colour blue.

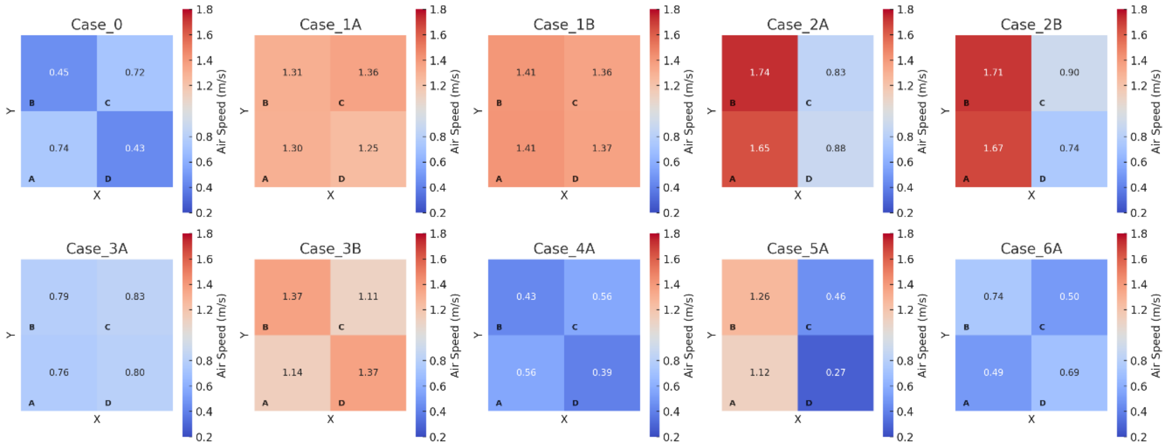


Figure 27: Comparing seat-by-seat air speed.

5 Measurement for air speed

5.1 Measurement facilities and instruments

5.1.1 Room setup

The air speed measurement is conducted in a realistic meeting room in Office Lab (The Green Village, TU Delft). The dimension of the room is 5.1m(L) * 3.25m(W) * 2.6m (H). We tested a Balcony M fan provided by Sulion with 1.07m of diameter. The fan is not installed in the centre of the room due to the location of existing installations (pipes, ducts, etc.) and sensors. The fan centre has 12cm offset along short axis and 35cm offset along long axis. The eccentric location of the fan causes different distance to the 4 surrounding walls, which might have influence on air speed distribution. The fan blades are 2.3m from floor level, and 0.3m from the ceiling panels.

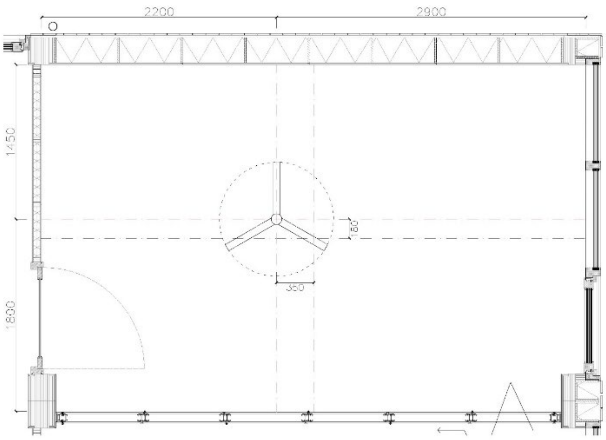


Figure 28: Room setup for air speed measurement.

5.1.2 Measurement instrument

Two main categories of data are measured during the experiment, the room conditions and fan conditions. The required measurements for room condition are indoor air temperature, mean radiant temperature (MRT), relative humidity (RH) and air speed. These measurements are crucial for the calculation of thermal comfort models, e.g. PMV or SET*. Fan conditions including fan speed, power consumption, and noise level are also recorded. Noise caused by the operation of ceiling fan is measured to investigate the influence of noise level on human subjects.

Figure 29: The setup of Testo 400 with other sensors on a tripod.

A Testo 400 IAQ kit is used for measuring the room conditions and air speed. The included instruments and sensors are:

- TESTO 400 Universal IAQ instrument: data logging
- Turbulence probe (digital) – wired (omnidirectional hot wire anemometer): measurement of air speed and degree of turbulence
- CO_2 probe (digital): measurement of CO_2 concentration, humidity and air temperature
- Globe probe: measurement of globe temperature (according to ISO 7726).

With the built-in measurement setting, one can set the MET (metabolic rate) and clo (clothing insulation value) manually and combine the measured data for calculating PMV/PPD to evaluate thermal comfort level. The data can be exported to a .csv file for further analysis.

The power consumption is measured with a smart plug (Shelly), and the data is stored via Home Assistant. The noise level is measured by Sauter SU 130 sound meter.

5.2 Measurement workflow

5.2.1 Measurement cases

The measurements were done for 3 layout cases. Starting for Case 0 without any furniture. Followed by Case 1 in a 2x2 layout and Case 4 in a 2-side layout of desks. The dimensions of the desks are 125x76x72 cm, which is slightly larger than the ones that were used for CFD simulation.

5.2.2 Measurement points

The measurement points for air speed are on a 30*30cm grid, which is aligned with the probe points from CFD simulation, so that the results can be easily compared. Ideally, the anemometers should be placed at 4 heights (0.1m, 0.6m, 1.1m, and 1.7m) according to ASHRAE 55 and NEN-EN-ISO 7726 standards for sitting position. An additional height is added at 0.85m to measure the air flow above desk surface. Due to time limitation, not all the 160 points in the room were measured. Air speed measurements are only done at single height due to that only 1 anemometer was available during the period of measurement.

For Case_0, air speed was measured at 15 points located at the bottom and the left side of the desk surface. For Case_1A, air speed was measured at 28 points surrounding the desk surface. The actual measurement points also have a 6-cm offset from the planned points, so that the actual measurements are 5cm away from the edge of desks as the probe points are in the CFD simulation (see *Figure 30*).

For Case_4, air speed was measured at the sitting zones along the long edge of desk surface were measured. The actual measurement points do not align with the planned measurement points, but are 5cm away from the edge of desks (see *Figure 31*).

5.2.3 Measurement time

Measurements were conducted 3 minutes after the ceiling fan was turned on, ensuring that the airflow had reached a steady-state condition. Each measurement session lasted 2 minutes, with airspeed readings recorded at 1-second intervals. For each measurement point, the average airspeed over the 2-minute duration was used as the representative value. Although previous research has recommended a longer measurement duration of 3 minutes, the reduced 2-minute interval was adopted here to improve efficiency and save time. Comparative analysis in

Chapter 5.3.1 showed that the shorter duration produced results consistent with the longer measurements, without introducing meaningful differences.

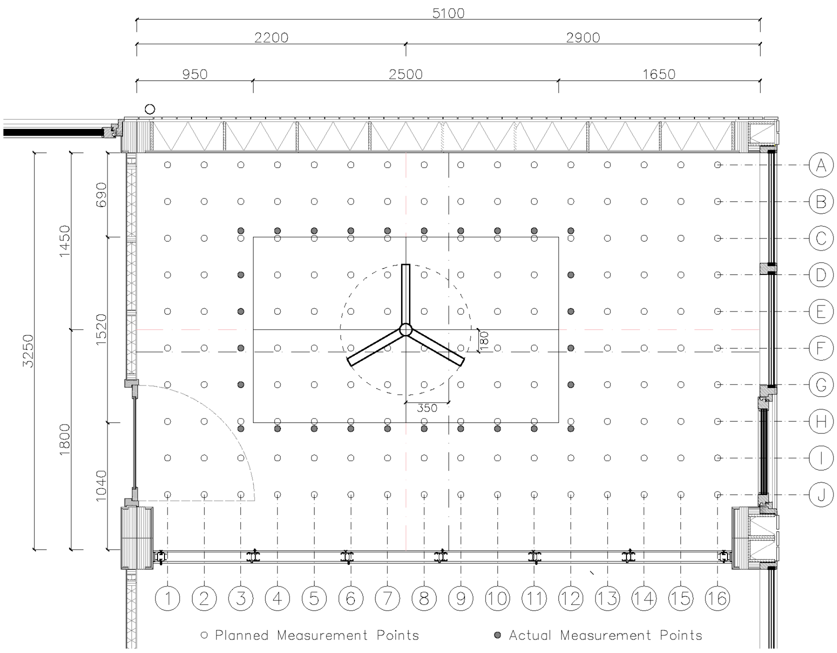


Figure 30: Measurement points layout for Case_0 and Case_1A. (Own Source)

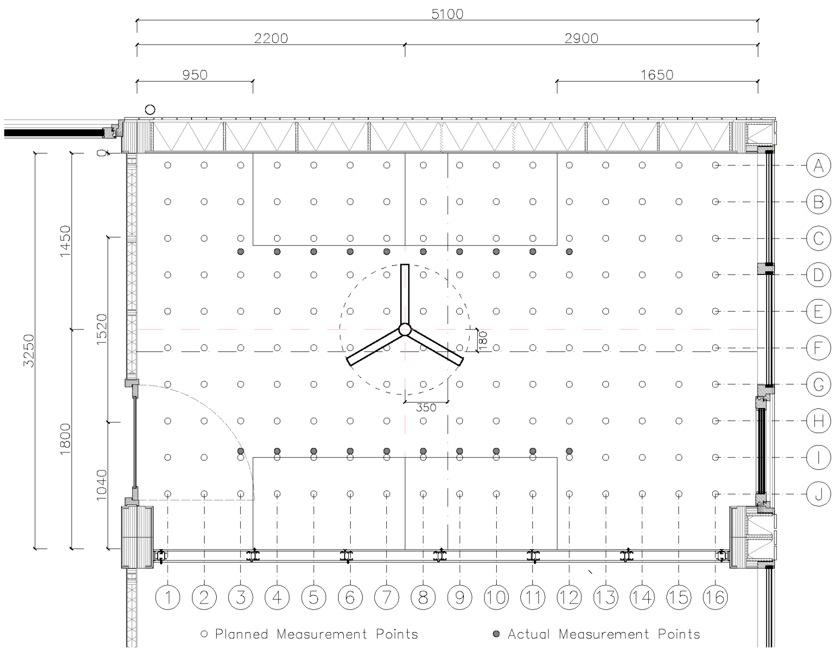


Figure 31: Measurement points layout for Case_4. (Own Source)

5.3 Results

5.3.1 Case_0: Measurement for 9 fan speeds at 1.7m height at single point within fan blade area

To understand the air speed under fan blade area, and the relationship between measured air speeds and the 9 fan speeds. The measurements were done at measurement point E8 at 1.7m height. Each setting was measured over a 3-minute period, with a 1-second interval

Figure 32 shows the fluctuation of measured air speeds over time. Despite local variability due to small turbulence effects and environmental micro-disturbances, no persistent pattern was observed over the 3-minute window duration. *Figure 33* summarizes the distributions of measured air speeds per fan speed setting. A linear regression analysis on the average air speeds shows a strong, statistically significant correlation between fan speed and average airflow ($R^2 = 0.994$, $p < 0.001$).

Comparisons of average air speeds over different time windows (1 minute, 2 minutes, 3 minutes) reveal no statistically significant differences (paired t-tests, $p \approx 0.98$ for 1 min vs. 3 min; $p \approx 0.07$ for 2 min vs. 3 min). Moreover, the magnitude of differences between these time windows (~0.005–0.015 m/s) falls well within the anemometer's specified accuracy margin of ±(0.03 m/s + 4% of the measured value). This suggests that extending measurements beyond 2 minutes does not meaningfully improve the reliability of the average airflow readings.

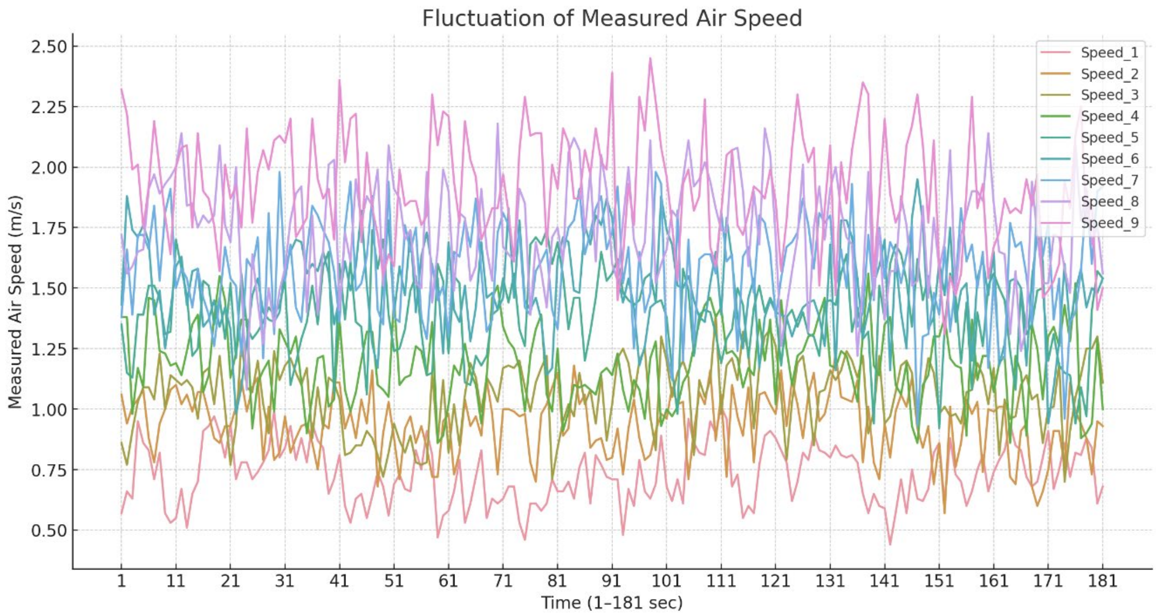


Figure 32: Fluctuation of measured air speeds. (Own Source)

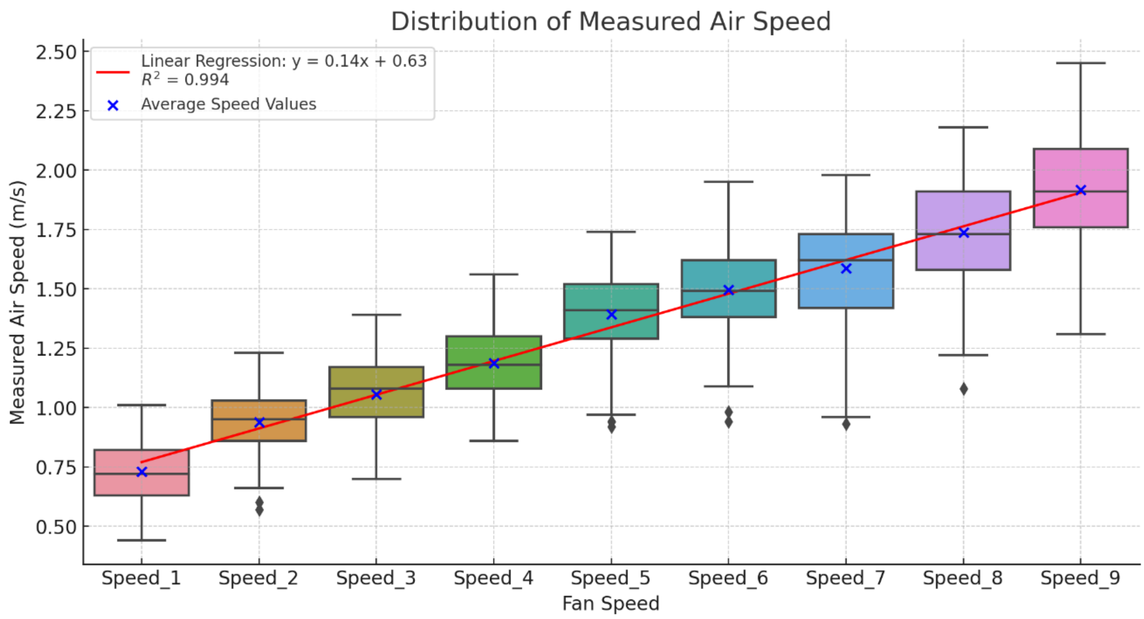


Figure 33: Distribution of measured air speeds and the linear regression of average air speeds for each fan speed.

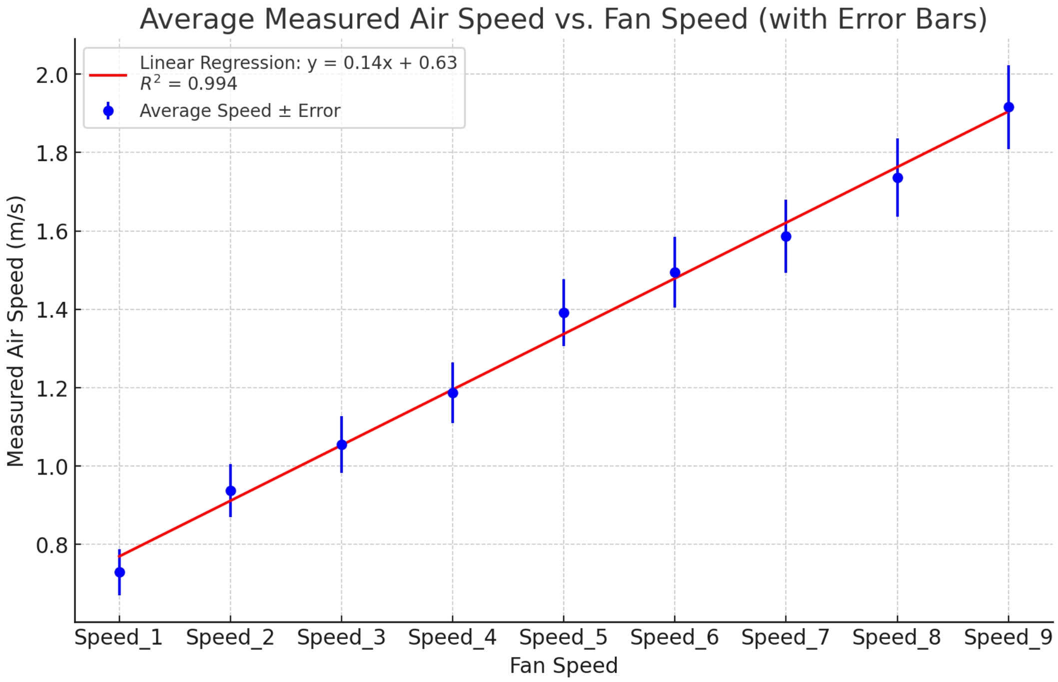


Figure 34: Average air speeds and error bars of the anemometer's specified accuracy margin.

5.3.2 Case_0: Measurement for 3 fan speeds at 0.85m height

The air speed measurement of Case_0 provides a baseline data to be further compared to those when desks are presence. The 15 measurement points are in an L-shape along the sitting zone of desks starting from H3 till H12, then turning a 90-degree angle followed by G12, F12, E12, D12 and C12. The measurement points are all located beyond the fan blade area. Only 3 fan speeds (Speed 3, 5 and 8) were measured at 0.85m height, with 2-minute duration and 1-second interval.

Figure 35 shows the average measured air speeds across points H3 to C12. Fan speed 3 produces an average airspeed of 0.103 m/s, fan speed 5 increases this to 0.162 m/s, and fan speed 8 further raises it to 0.180 m/s. The percentage increase from speed 3 to 5 is substantial, reflecting a strong airflow gain, while the further increase from speed 5 to 8 yields a more modest additional gain.

A clear peak area can be seen between point H6 and H7. In this analysis, the peak area was statistically defined as the set of measurement points where the average measured airspeed exceeded the overall mean plus one standard deviation. This approach objectively identified points H6 and H7 as the peak airflow zone, matching closely with the visually observed high-airflow region beneath the fan. At fan speed 3, the average airspeed at H6 and H7 is 0.174 m/s, which is approximately 90% higher than the average airspeed of the non-peak points (0.092

m/s). At fan speed 5, the peak average rises to 0.324 m/s, representing a 136% increase over the non-peak average (0.138 m/s). At the highest fan speed, speed 8, the peak average reaches 0.392 m/s, showing a 165% increase compared to the non-peak average (0.148 m/s).

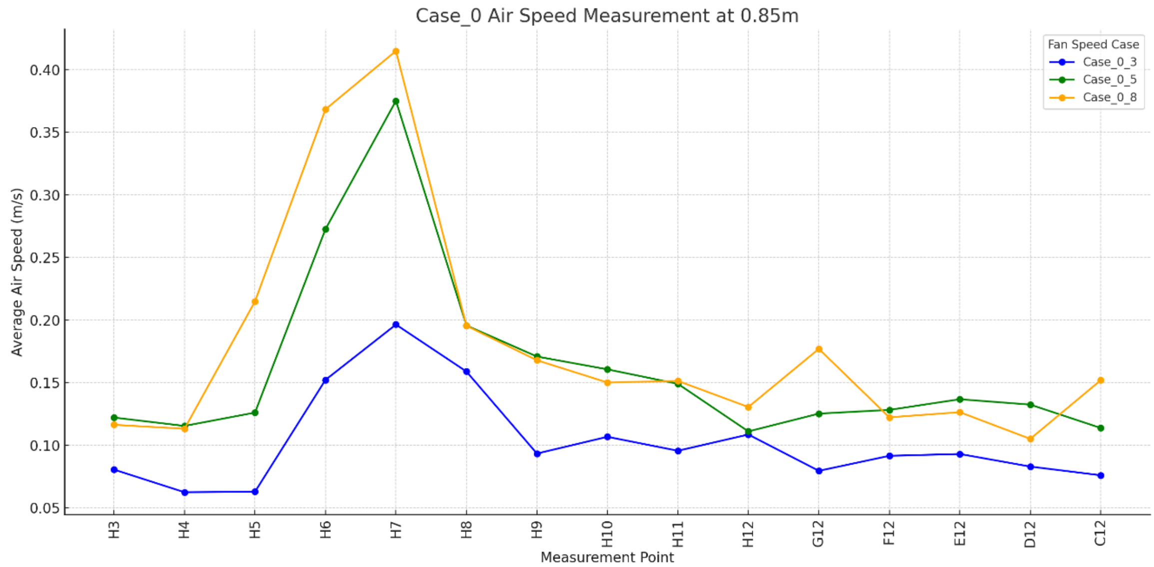


Figure 35: Air speed measurement of Case_0 with 3 different fan speeds (Speed 3/5/8).

Case	Peak Area (H6-H7) Avg (m/s)	Non-Peak Avg (m/s)	Percent Difference (%)
Case_0_3	0.174	0.092	90.1%
Case_0_5	0.324	0.138	135.5%
Case_0_8	0.392	0.148	164.8%

Table 8: Average air speed comparison between peak and non-peak area.

The distribution of average air speeds across all measurement points shows that fan speed 3 consistently yields the lowest airspeed values, while speeds 5 and 8 show greater variability and higher peaks but also overlap in some peripheral zones. These findings highlight the nonlinear relationship between fan speed settings and delivered airflow across the full measurement area.

5.3.3 Case_1A Measurements with All Fan Speeds at 0.85m

This is a full-set measurement with all 9 different fan speed settings, at all the 28 measurement points (see *Figure 30*) around the desks. The measurement points were placed at 0.85m height, 11cm above the desk surface, to capture the speed of diffused airflow. Figure 36 showed that the peak air speeds showed clearly at the mid-point (H7 & C8) of the long edges of the desk surface and decrease gradually as it reaches the short edges of the desk surface. The higher fan speed does not constantly produce higher air speed at all measurement points, some local "reversed" results, meaning that higher air speed was measured at the lower fan speed, can be found (e.g., fan speed 2 & 3, between points C8 and C5). However, when looking at the overall distribution and average air speed, it still shows a clear trend of increase from 0.31m/s at speed 1 to 0.83m/s at speed 9.

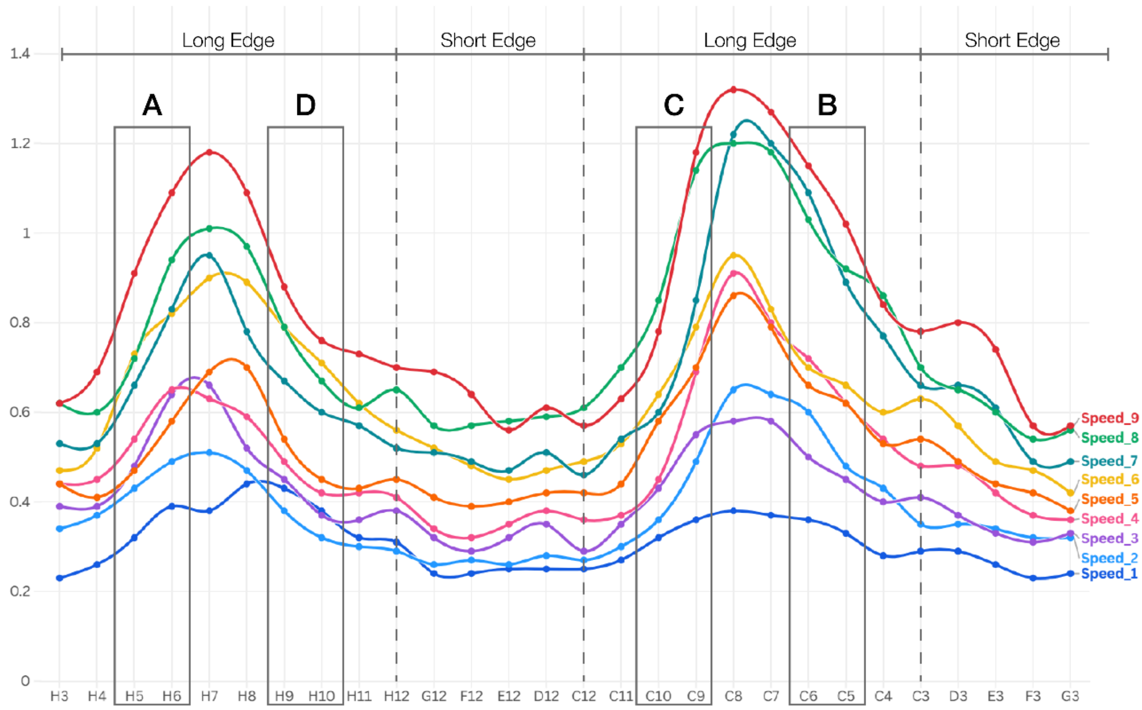


Figure 36: Measured air speed around desk surface at all 9 different fan speeds.

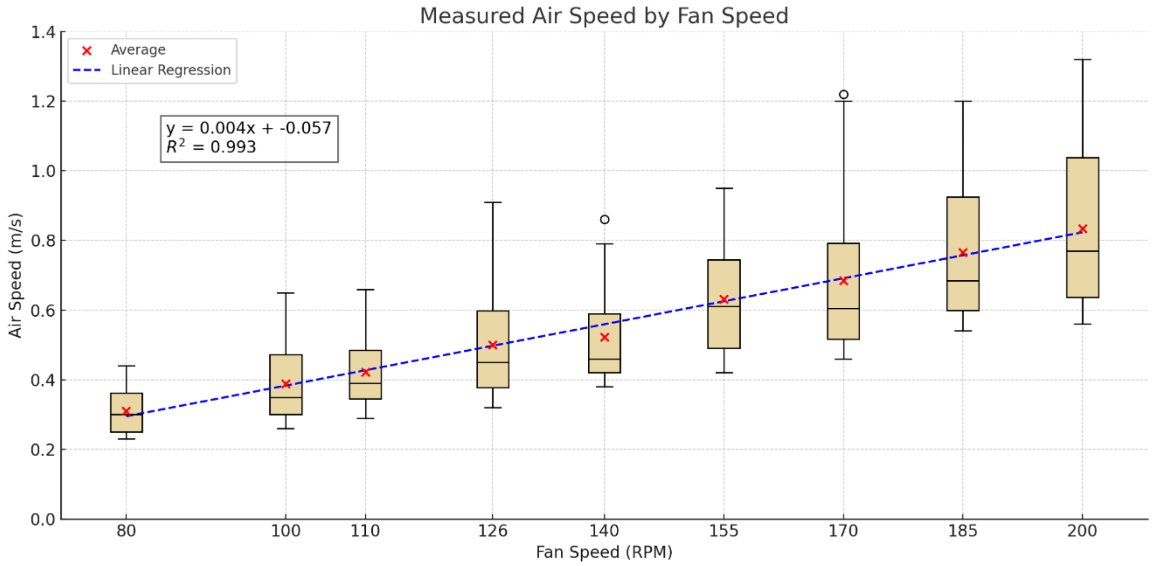


Figure 37: Air speed distribution and average air speed per fan speed.

5.3.4 Air Speeds at Seats (0.85m and 1.1m)

The air speeds for each seat are calculated from the measured air speed at the 2 closest measurement points. Together with the seat-average air speed and average overall air speed (from 28 measurement points) are shown in *Table 9*.

Measurement height	Speed	Speed_1	Speed_2	Speed_3	Speed_4	Speed_5	Speed_6	Speed_7	Speed_8	Speed_9
	RPM	80	100	110	126	140	155	170	185	200
0.85m	A	0.36	0.46	0.56	0.6	0.53	0.78	0.75	0.83	1
	B	0.35	0.54	0.48	0.67	0.64	0.68	0.99	0.98	1.09
	C	0.34	0.43	0.49	0.57	0.64	0.72	0.73	1	0.98
	D	0.41	0.35	0.41	0.46	0.5	0.75	0.64	0.73	0.82
	Avg_seat	0.37	0.45	0.49	0.58	0.58	0.73	0.78	0.89	0.97
	Avg_all	0.31	0.39	0.42	0.5	0.52	0.63	0.68	0.77	0.83
1.1m	A	0.1	N/A	0.26	N/A	0.34	0.24	0.27	0.33	0.27
	B	0.17		0.16		0.2	0.25	0.21	0.27	0.26
	C	0.24		0.16		0.23	0.27	0.21	0.31	0.23
	D	0.09		0.18		0.26	0.21	0.33	0.28	0.38
	Avg_seat	0.15		0.19		0.26	0.24	0.26	0.30	0.29

Table 9: Air speeds for each seat per fan speed.

The individual air speed at the 4 seats against rotating speed (in RPM) at both 0.85m and 1.1m are plotted on **Error! Reference source not found.**. Note that the air speed at 1.1m with fan speed 2 and 4 were not measured. The measured air speeds at 1.1m were 55.6% to 70.6% lower than the ones at 0.85m height. Both measurements at 0.85 m and 1.1 m show a clear linear increase with ceiling fan RPM, with a stronger correlation observed at 0.85 m (R^2 = 0.84) compared to 1.1 m (R^2 = 0.48). This suggests that airflow is more concentrated and consistent closer to the torso/chest level (0.85m), while it becomes more diffused and variable at head level (1.1 m) for sitting position. Notably, Seat B and Seat C consistently exhibit higher air speed values, while Seat D tends to have the lowest across most fan speeds. These differences occur despite all seats being equidistant from the fan, indicating possible asymmetries in the airflow pattern caused by different distance to the surrounding walls.

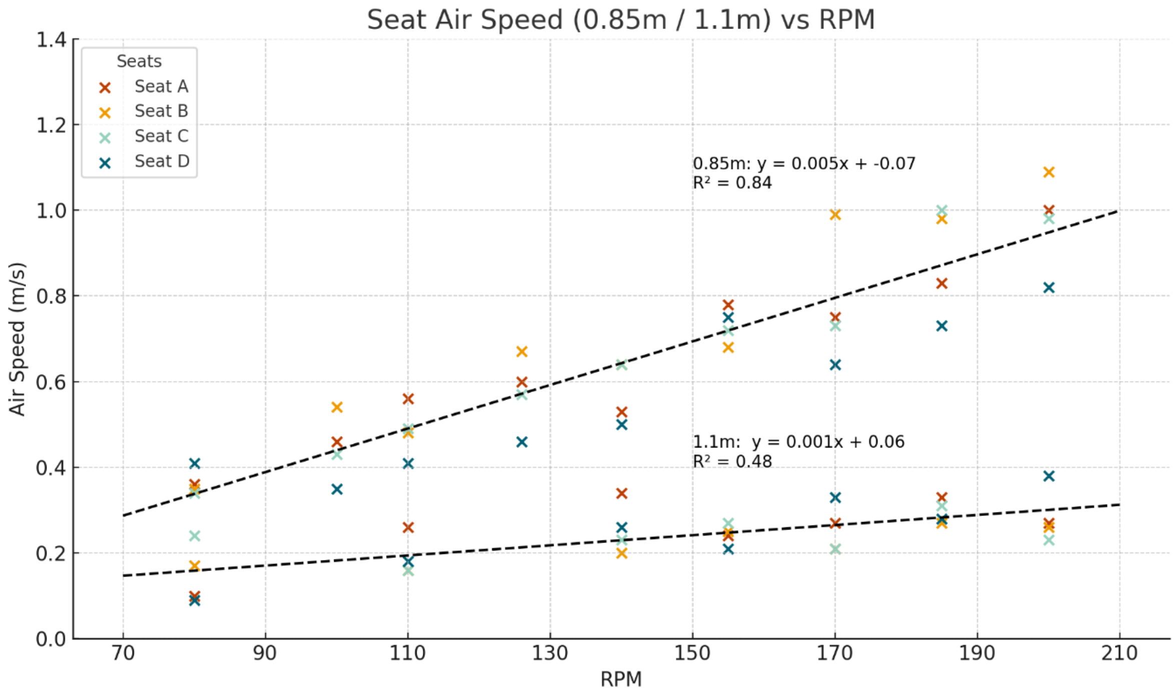


Figure 38: Individual air speed and the average air speed at seats (0.85m).

5.3.5 Case_1A Sectional Measurement at Speed 8

The sectional measurement was done at fan speed 8 along column 9, passing through areas under the fan blade and seats (C and D). The anemometer was place at 0.85m and 3 other standard heights (0.1m, 0.6m, and 1.1m) according to ISO 7726 to capture a more complete picture of air speed distribution for sitting position. The highest air speed (0.91m/s) occurred under the fan blade area with a slight offset from the fan centre at 0.85m height, even slightly higher than the measurement at 1.1m height (0.88m/s). The air speeds at 1.1m height decreased sharply as the distance from the fan centre increased. The air speeds at 0.85m height decreased less, and were still able to maintain 62.6% and 76.9% of the peak speed respectively at H9 (Seat D) and C9 (Seat C). Air speeds at 0.6m height were the lowest at most measurement points especially at the area “shaded” by the desk surface. Air speeds at 0.1m height showed slightly higher air speed at an average close to 0.3m/s. At point A9, the air speeds at 1.1m and 0.6m showed a sharp increase, these are caused by the air flow redirected by the surrounding wall. The increase did not appear at point J9 because the distance to the wall was further (0.46m) than at A1 (0.1m).

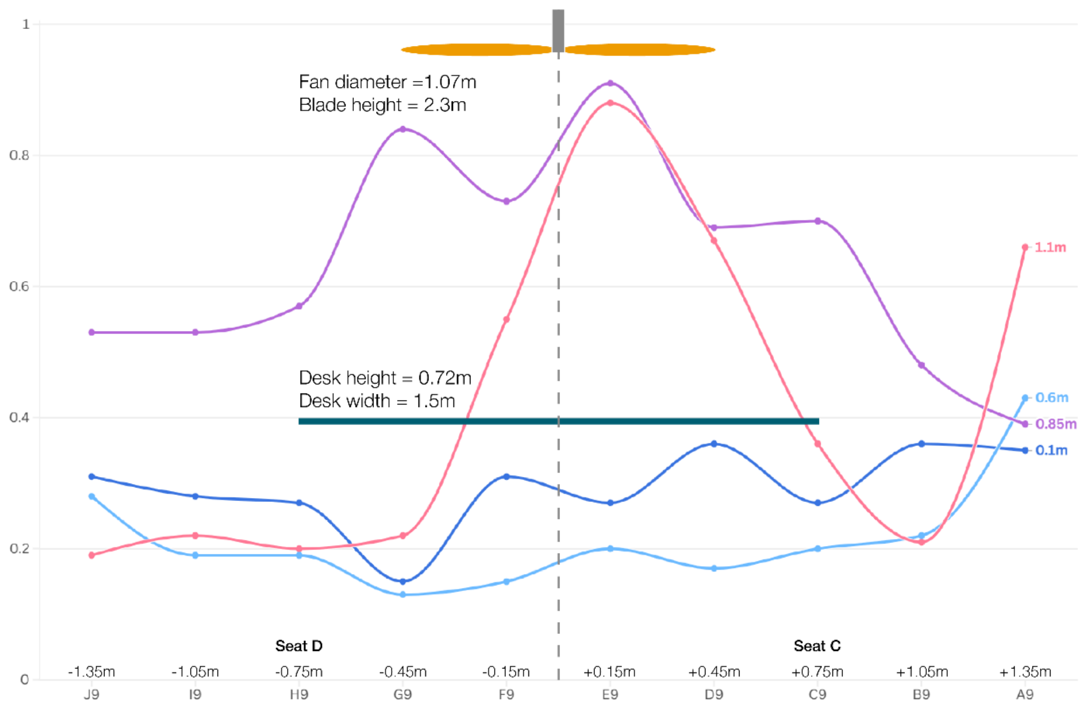


Figure 39: Sectional air speed measurement at fan speed 8 along column 9.

5.3.6 Case_1A Measurement with Reversed Fan Speed 8 at 0.85m

This measurement was done with the same layout as previous chapter, but with the fan rotating in a reversed direction that generates upward air flow. There is no clear peak of the air speed as with the downward airflow. The air speed is distributed more evenly but also significantly lower that the average air speed is only 0.18m/s.

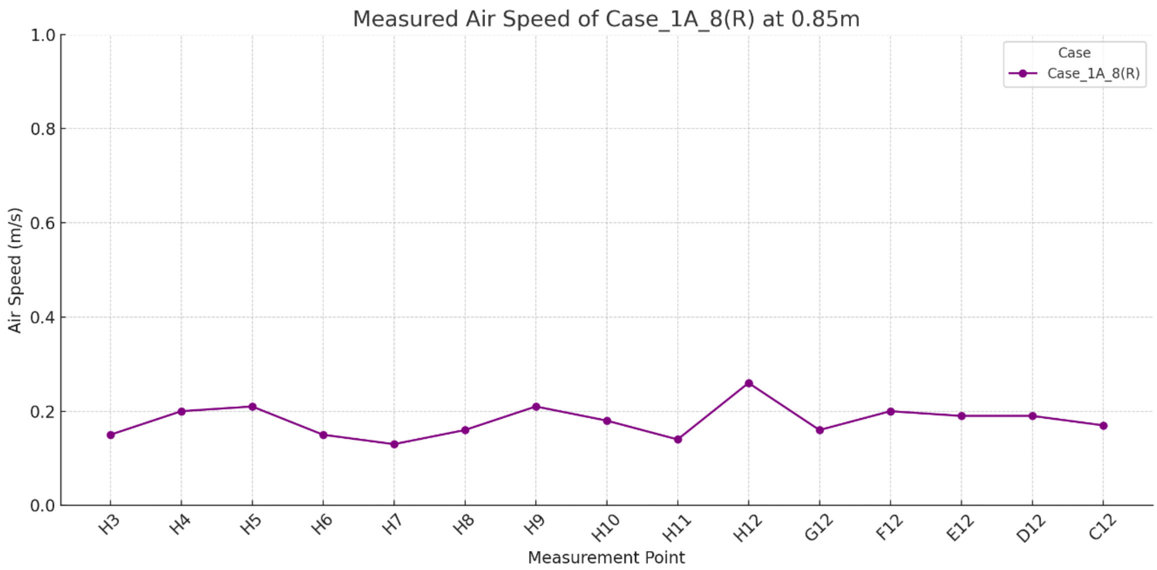


Figure 40: Air speed profile of Case_1A(R) with reversed fan speed 8.

5.3.7 Power Consumption

The measurements of power consumption were done with fan speed 1, 3, and 5-9 with 30-minute duration and 15-second of interval. Power consumption increases nonlinearly with fan speed, following a convex upward trend that is best approximated by a second-degree (quadratic) polynomial (see Figure 41). This indicates that as the fan rotates faster, the rate of increase in power consumption also grows, particularly at higher RPM.

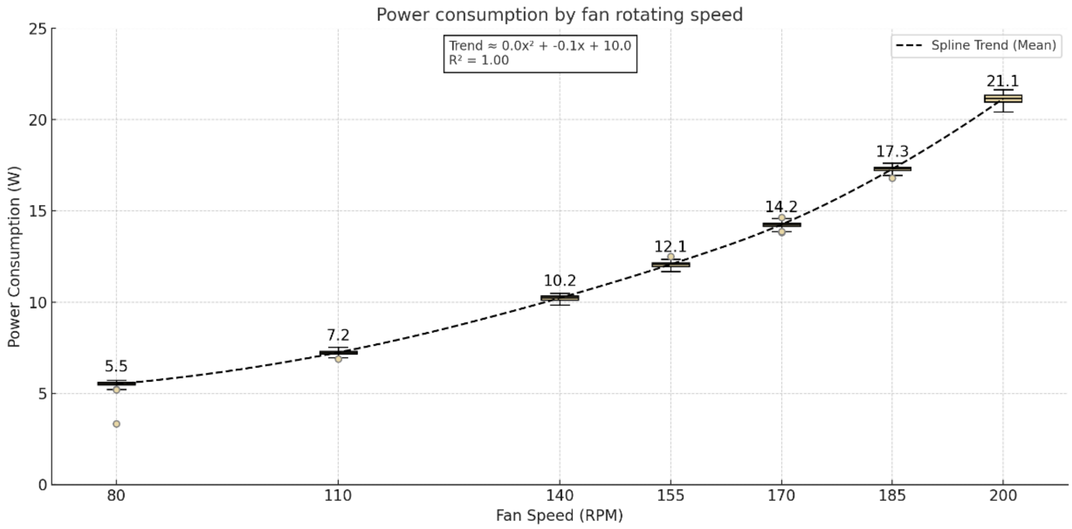


Figure 41: Power consumption (W) of the fan by rotating speed (RPM).

5.3.8 Noise Measurement

The lab was not well-soundproofed, and since it is located in an actively working office building, the noise from adjacent space had noticeable interference on the measurement of noise level cause by the operation of ceiling fan itself. Generally, the noise level was between 33dB to 38 dB, while at higher fan speed like speed 8 and 9, the noise level could reach 43dB to 45dB.

5.4 Discussion

5.4.1 Comparison of Measured Air Speed with Case_0 and 1A

This analysis compares airflow pattern between Case_0 (layout without desks) and Case_1A (layout with desks), with air speed measurements taken at 0.85 m height from 15 measurement points at the bottom and left edge of the desk surface (H3 to C12). Measurements were collected at three fan speeds (3, 5, and 8), with an additional case (Case_1A_8R) where the fan operated in reverse rotation, generating upward airflow.

Figure 42 shows the air speed pattern across the 2 layout cases and 4 fan speeds. The peak speeds occurred between points H6 to H8 locating in the centre of the long edge of desk surface. With the downward air flow, significantly higher air speeds were observed in Case_1A_3, Case_1A_5, and Case_1A_8 compared to their Case_0 counterparts. The average airspeed with fan speed 3, 5 and 8 showed an increase of 303%, 194% and 286% respectively. These differences are both visually evident in box and line plots and statistically confirmed with t-tests (p-values < 0.001). Case_1A_8R, with upward airflow do not show any improvement, resulting in similar average air speed as Case_0_8 (see Table 10). The results suggest that desks may function as passive airflow diffusers under downward ceiling fan flow, amplifying local air movement at seated head/torso height beyond fan blade area.

Case/Fan Speed	Case_0_3	Case_1A_3	Case_0_5	Case_1A_5	Case_0_8	Case_1A_8	Case_1A_8R
Avg_all (m/s)	0.10	0.41	0.16	0.48	0.18	0.70	0.18
Increase	303%		194%		286%		

Table 10: Average air speed of each case.

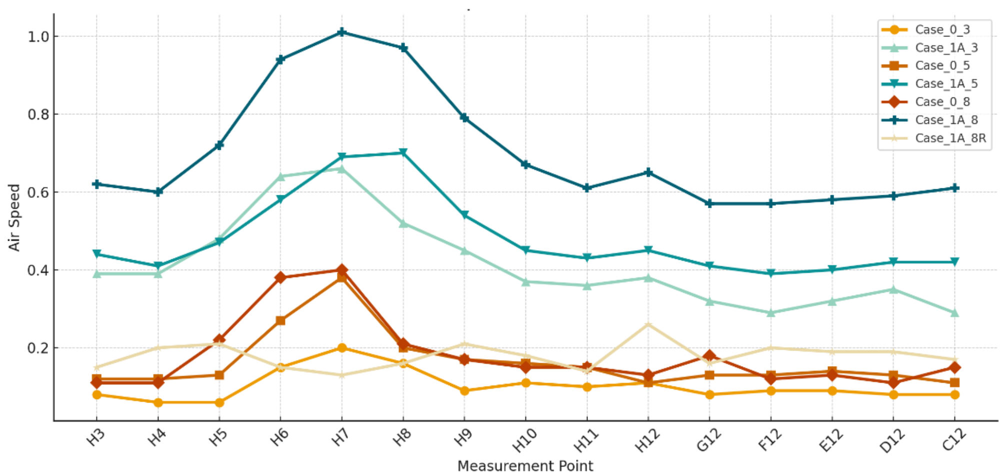


Figure 42: Comparing the air speed pattern of Case_0 and Case_1A.

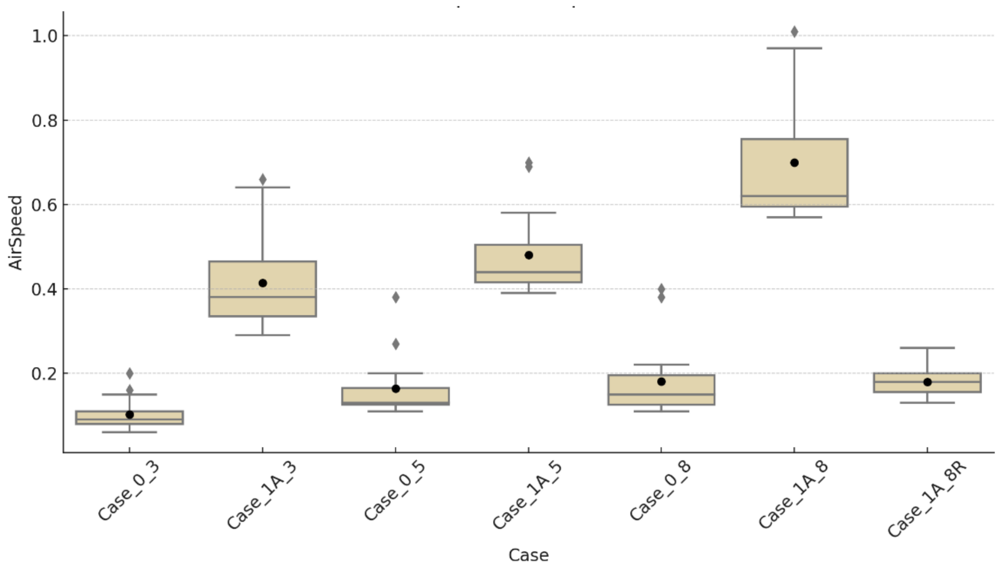


Figure 43: Comparing the air speed distribution of Case_0 and Case_1A.

5.4.2 Normalized Air Speed Pattern across Different Fan Speeds

To analyse the air speed pattern around desks under various ceiling fan speeds, air speed data was normalized using min-max scaling for each fan speed (see *Figure 44*). This normalization enabled direct comparison of distribution shapes, independent of magnitude differences. A single average line (see *Figure 45*) was then computed by averaging the normalized air speeds across all fan speeds at each measurement point. The resulting line chart revealed that most fan speeds exhibited a remarkably consistent spatial airflow pattern, with high R-squared (R^2) values observed when individual fan speeds were compared to the overall normalized average. Notably, Speed_4, Speed_5, Speed_8, and Speed_9 achieved R^2 values above 0.93, indicating strong alignment with the average trend. In contrast, Speed_1 showed a lower R^2 at only 0.6, suggesting that airflow at the lowest fan setting exhibited greater variation. These findings suggest that the normalized average line is a robust and representative descriptor of the general air speed distribution pattern across fan settings, particularly for moderate to high rotation speeds.

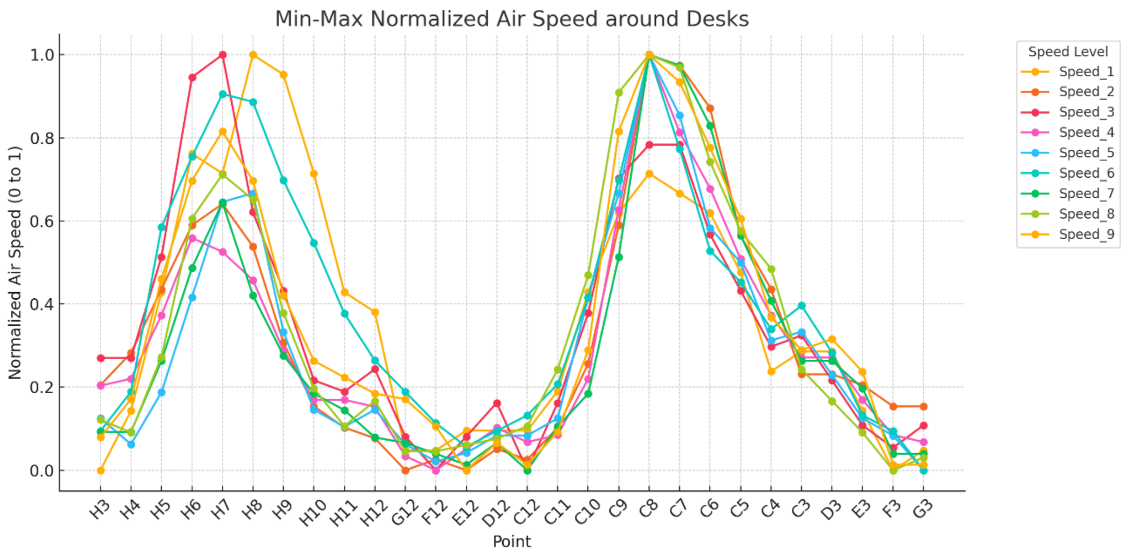


Figure 44: Normalized air speed per fan speed.

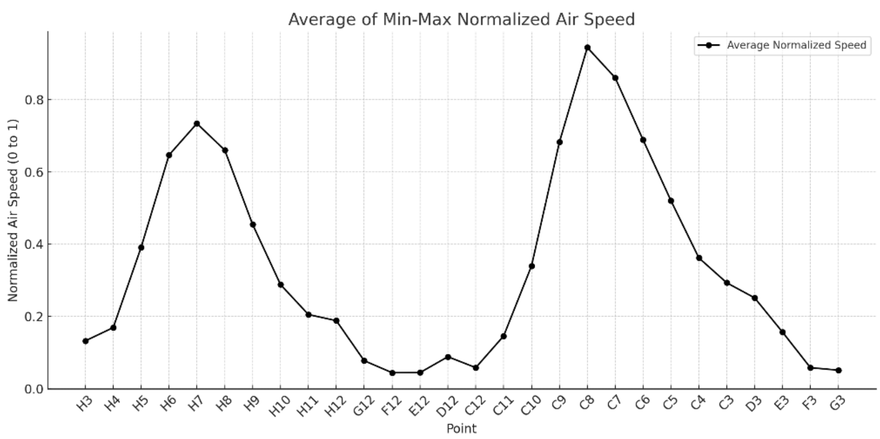


Figure 45: Average of normalized air speed.

Fan Speed	Speed_1	Speed_2	Speed_3	Speed_4	Speed_5	Speed_6	Speed_7	Speed_8	Speed_9
R-squared	0.60	0.89	0.85	0.91	0.91	0.81	0.86	0.91	0.95

Table 11: R^2 values for all fan speeds

To evaluate whether the overall air speed distribution around the desks could be accurately captured by a normalized average line, multiple average curves were generated using different subsets of fan speed data (e.g., by excluding the ones with the lowest R^2 values or including only the ones with the higher R^2 values) in *Figure 46*. These curves were then statistically compared using a one-way ANOVA. The results showed no significant difference between the average patterns ($F = 0.026$, $p = 0.994$), confirming that the shape of the air speed distribution remains consistent regardless of the specific fan speeds included. Furthermore, high R^2 values (>0.9) for most individual fan speeds against the normalized average line reinforce this conclusion. Thus, the normalized average curve can be considered a robust and representative depiction of the air speed distribution across all measurement points.

An isometrical view with the location of fan and desk surface is presented in *Figure 47* for an easier understanding of air speed pattern and the relationship with the relative position of fan and desk surface.

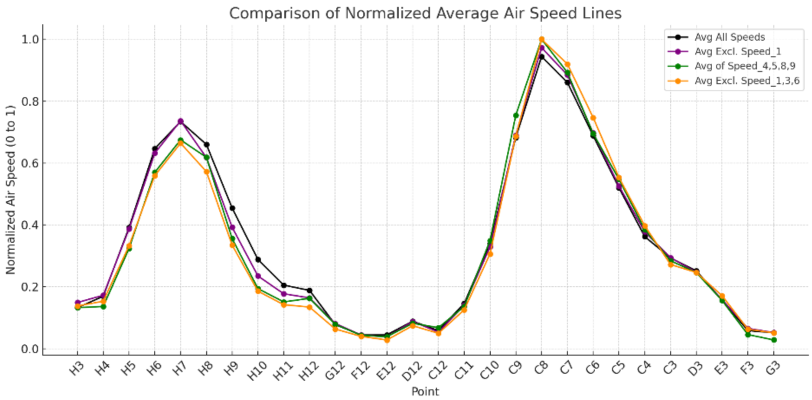


Figure 46: Comparison of normalized curve with different subsets of data.

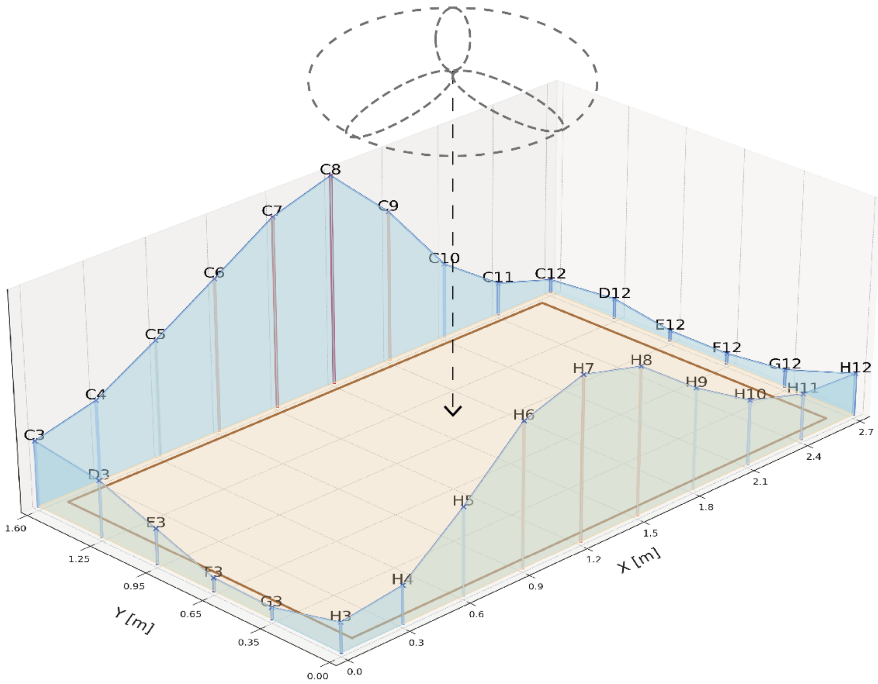


Figure 47: An isometric view of normalized air speed pattern surrounding the desk surface.

5.4.3 Diffusion Power

To better represent the diffusion efficacy, the diffusion power (DP) is defined as the equation:

$$DP = \frac{Measured\ Air\ Speed\ (AS)}{Fan\ Air\ Speed\ (FAS)} \times 100\%$$

The DP for each fan speed and an average value is plotted on the line chart (Figure 48) with light grey band showing the ±1 standard deviation. The overall pattern is very similar to the normalized air speed distribution (*Figure 45*).

Table 12 reveals the R-squared values of diffusion power by each fan speed. Except fan speed 1 and 3, the average DP shows a moderate to high prediction power for most of the fan speed. Figure 49 compares the measured air speed with the predicted one calculated by FAS and average DP at each point. For fan speed 5 and 8, the patterns show high alignment, while speed 3 shows slightly lower alignment.

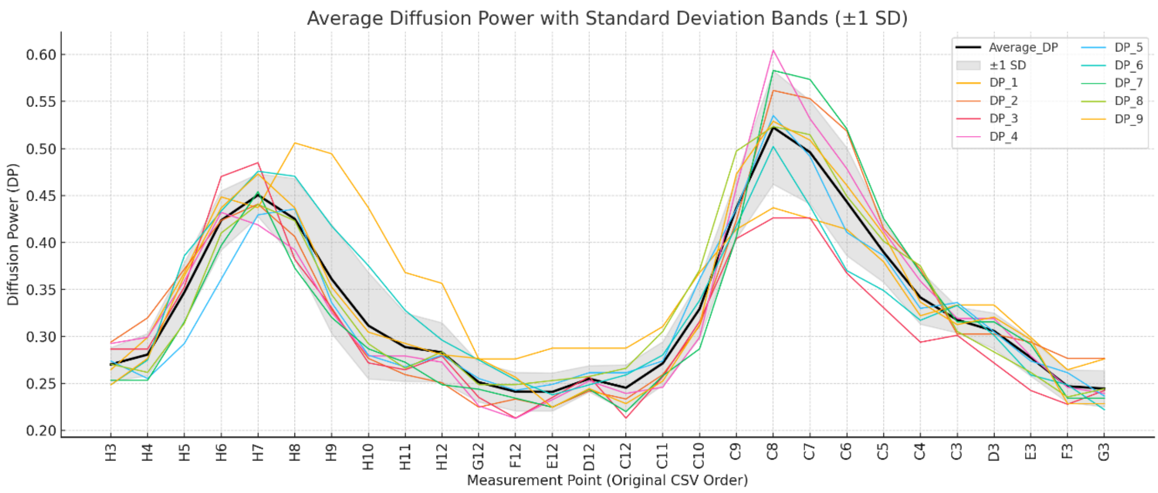


Figure 48: Diffusion power of all air speeds and average curve with ±1 standard deviation band.

Fan Speed	Speed_1	Speed_2	Speed_3	Speed_4	Speed_5	Speed_6	Speed_7	Speed_8	Speed_9
R_squared	0.58	0.88	0.79	0.90	0.93	0.86	0.84	0.93	0.96

Table 12: R^2 values of diffusion power for all fan speeds.

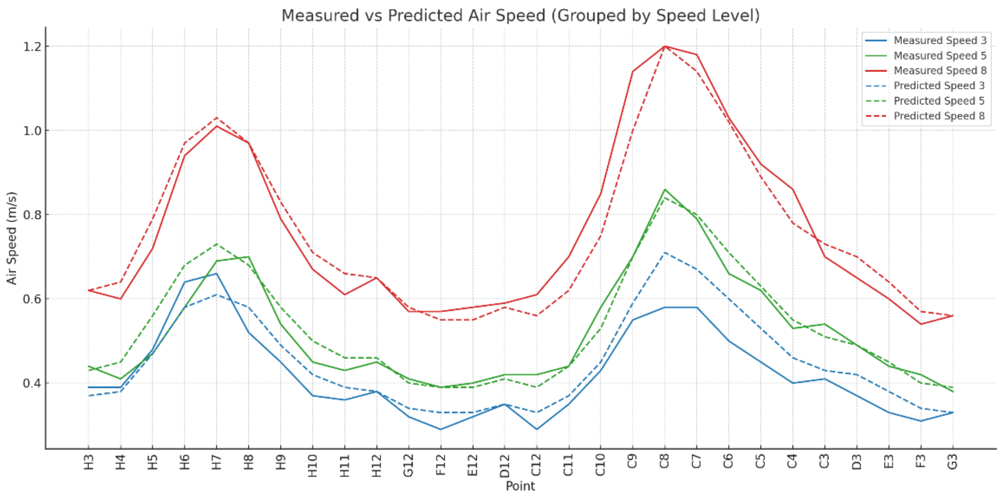


Figure 49: Comparison of measured air speed and predicted air speed (by FAS and DP) for fan speed 3/5/8.

Speed	Speed_1	Speed_2	Speed_3	Speed_4	Speed_5	Speed_6	Speed_7	Speed_8	Speed_9	Average
Avg_seat	42.5%	38.9%	36.0%	38.5%	36.1%	38.6%	37.3%	38.8%	38.9%	38.4%
Avg_all	35.6%	33.7%	30.9%	33.2%	32.4%	33.3%	32.5%	33.6%	33.3%	33.2%

Table 13: Diffusion power at seats and overall average around desk surface.

The diffusion power does not show big difference across the 9 fan speeds, only slightly higher at fan speed 1 (see *Table 13*). At the seats, the air speed can still maintain 38.4% of the FAS (the imaginary initial air speed from the fan blade) while the overall average for all measurement points around the desk surface is approximately 5% lower.

6 Experiment with human subjects

6.1 Experiment facilities and conditions

The experiments are conducted in the same room where the air speed measurements were conducted. The location of the fan remained the same. Four desks measuring 125x76x72cm (LxWxH) are placed in a 2x2 layout forming a 250x152cm surface area. The centroid of the surface is aligned with the centroid of the fan. Each desk is equipped with a meeting room chair with cushioned backrest which may increase the insulation value of human body. A Testo 400 is placed at the corner of the desk surface at the window-side of the room, measuring the thermal conditions of the room at 1.1m height (see *Figure 50*).

During the experiment the room temperature was maintained at 28°C with an 1800W electrical heater (Threesixty, Duux). The heater is equipped with a thermal meter that can adjust its power level based on the set point meter reading. However, the reading from the built-in thermal meter is less representative when comparing to the measurement data from Testo 400. The automatic adjustment of the heater is often lagged behind the actual change of room air temperature, and the examiner had to adjust the power level manually based on readings from Testo 400 to prevent overheating or overcooling. Despite the technical limitations, the temperature during the test sessions were maintained between 28°C ± 0.5°C, with overall average of 28°C. The globe temperature varied between 27.9°C to 28.2°C, with an average of 28.1°C. The experiments were only conducted in the morning (from 10:00-12:00 to minimize the influence of solar radiation from the west-facing façade. The relative humidity was not controllable and varied from 38.6% to 48.7%, with overall average of 42.9%. The outdoor weather was still cool and even rainy during the experiment period (see *Table 14*).

Room temperature 28°C was chosen specifically because the PMV value is between 0.94 to 1.03 when the relative humidity is between 40% and 50%, clo =0.57 and MET = 1.1. The PPD value is between 24% and 28%, which does not comply with EN-16798. By increasing the air speed to 0.5m/s, which is an easily achievable air speed based on previous measurement, the PMV is reduced to 0.46 and PPD to 9%. The PMV at 28°C, 42.9%RH, MRT=28.2°C, clo=0.57, MET=1.1 with air speed from 0m/s to 1.6m/s is plotted on *Figure 51*.

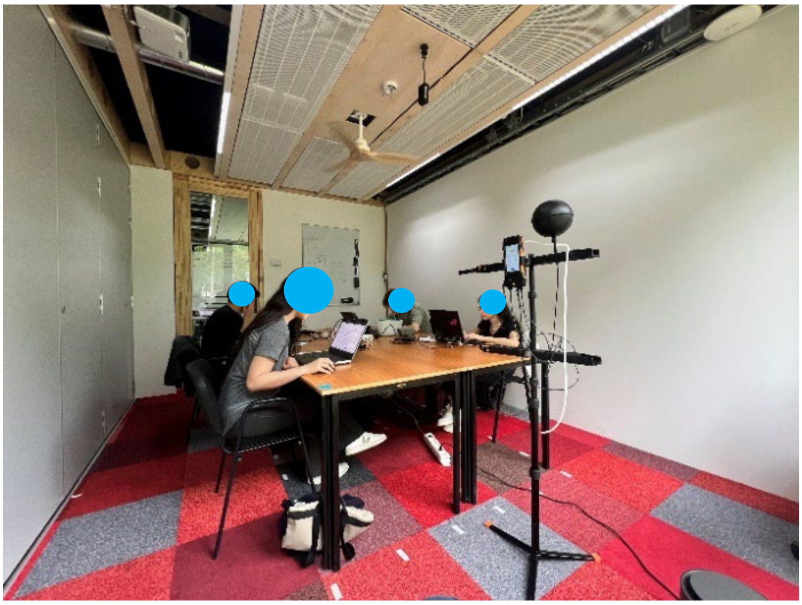


Figure 50: Participants during the test session.

Date	Outdoor_T	Rain	Air_T	RH	Globe_T	Participants
26-May	15.9	No	28.0	38.6	28.2	4
27-May	15.8	Yes	28.0	47.8	27.9	4
2-Jun	16.4	No	28.0	42.2	28.1	4
4-Jun	18.0	No	28.2	42.6	28.5	4
5-Jun	16.5	Yes	28.3	40.6	28.2	2
6-Jun	17.0	Yes	27.9	39.9	28.2	3
10-Jun	14.4	No	27.9	48.7	27.9	3

Table 14: Weather data from 09:00-10:00 on experiment dates and indoor measurement of room condition

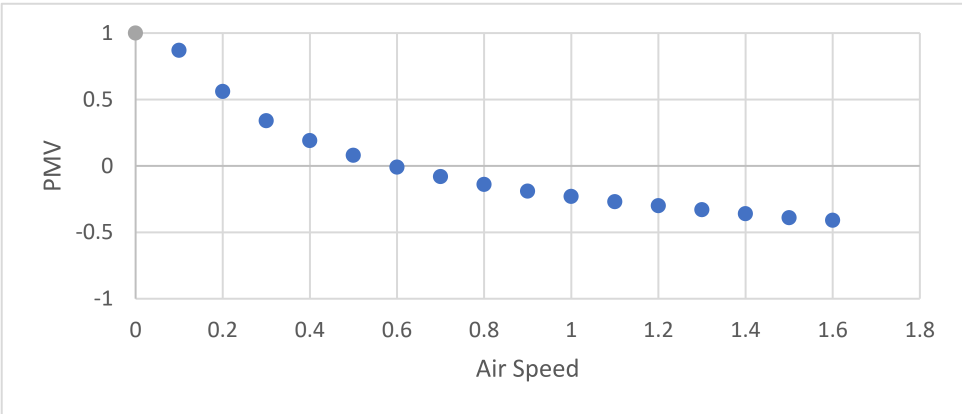


Figure 51: PMV (28°C, 42.9%RH, MRT=28.2°C, clo=0.57, MET=1.1) with different air speed.

6.2 Experiment workflow

The experiment takes approximately 2 hours to complete. Four participants come together into the room and sit at the 4 seat locations around the desks. The participants are allowed to bring laptops, tablets, phones or book to do sedentary works like reading, typing or scrolling their phones or tablets. The experiment begins with a 30-minute adaptation and introduction session with the fan switched on at low speed (random fan speed between 1 to 3). They sit in the room to stabilize their metabolic rate and adapt themselves to the room condition. The examiner introduced the experiment procedure to the participants. They also fill out the opening questionnaire that collects the background data of the participants and their experience with using fans for cooling.

Following the adaptation and introduction session are the 5 test sessions in random order including 1 still air session (fan switched off), 3 given fan speed sessions (speed 3,5 and 8) and 1 group-selected fan speed session. Each session lasts for 15 minutes and at the last 3 minutes of each session, participants were requested to fill out a session questionnaire. For the group-selecting session, there is an extra 5-minute session that the participants are introduced to the fan control interface and are allowed to try out different fan settings during the period. There is also a 5-minute break after the first 2 sessions were done that allowed the participants to go to the lavatory.

At the end of the experiment, an ending questionnaire will be answered to understand how the participants' overall experience was, and how they feel about the process of group-selecting fan speed.

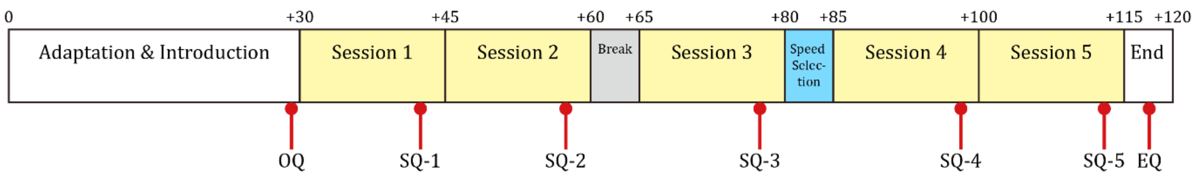


Figure 52: Example of the experiment procedure. Note that the speed-selection session (in blue) occurs depending on the actual order of experiment.

Date		26-May	27-May	2-Jun	4-Jun	5-Jun	6-Jun	10-Jun
		Monday	Tuesday	Monday	Wednesday	Thursday	Friday	Tuesday
Nr. Participants		4	4	4	4	2	3	3
Session	1	0	5	3	8	Selected-3	3	5
	2	5	Selected-3	0	5	3	8	Selected-4
	3	8	3	8	Selected-6	0	5	0
	4	3	8	Selected-6	0	5	0	8
	5	Selected-7	0	5	3	8	Selected-5	3

Table 15: Order of test sessions and the number of participants per day.

6.3 Design of questionnaire

The opening questionnaire collects the background data of the participants including biometrics (sex, age, height, weight), climate background, the experience of using fans for cooling either at home or at school / work, and thermal preferences over warmer or cooler temperature.

The session questionnaire records the perception, comfort level, acceptability and preference of the participants in following aspects:

1. Temperature:
    - A. Thermal Sensation Vote (TSV): 7-point (cold – hot)
    - B. Thermal Comfort Vote (TCV): 5-point (comfortable – extremely uncomfortable)
    - C. Thermal Acceptability (TA): 4-point (clearly acceptable – clearly unacceptable)
    - D. Thermal Preference (TP): 3-point (lower – higher)
2. Air movement:
    - A. Air movement Sensation Vote (AMSV): 5-point (no air movement – strong breeze)
    - B. Body parts that felt air movement
    - C. Air movement Acceptability (AMA): 4-point (clearly acceptable – clearly unacceptable)
    - D. Air movement Preference (AMP): 3-point (weaker – stronger)
    - E. Feeling of local draft discomfort (yes-no)
    - F. Body parts that felt local draft discomfort
3. Noise:
    - A. Noise Sensation Vote (NSV): 5-point (quiet – extremely noisy)
    - B. Noise Acceptability (NA): 4-point (clearly acceptable – clearly unacceptable)
    - C. Noise Preference (NP): 3-point (lower – higher)
4. Air Quality:
    - A. Air Quality Sensation Vote (AQSV): 5-point (fresh – extremely stuffy)
    - B. Air Quality Acceptability (AQA): 4-point (clearly acceptable – clearly unacceptable)

The ending questionnaire collects data about the participants overall experience throughout the experiment, including:

1. Feeling during the group decision-making process for selecting fan speed
2. The engagement level during decision-making process

3. Intuitiveness of control interface
4. The effectiveness of ceiling fan for cooling
5. Positive and negative effects or experience with ceiling fan during the experiment

6.4 Participants

24 volunteers participated in the experiment, consisting of 12 males and 12 females. 18 of them are between 20-29 years of age, and 6 are between 30-39 years of age. The participants came for diverse climate background (the climate zone that they spent the longest span of their lifetime). The climate categorization is based on the widely adopted Köppen climate classification (Köppen and Wladimir, 1884). The 7 climate zones are sub-classified to 2 groups based on warm or mild summer temperature. For oceanic and humid continental climate, the warmest month has a mean temperature below 22 °C. The participants were required to wear typical summer clothing (trousers, short-sleeve shirt, socks, shoes underwear) with clothing insulation clo = 0.57. They were allowed to do sedentary work, which are their daily work for study or office work on their laptop or books. They were also asked not to have caffeine and alcohol 2 hours before the experiment starts.

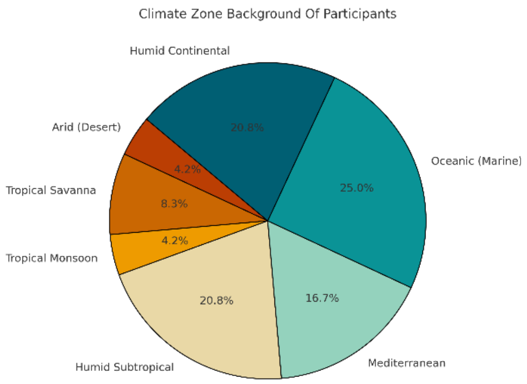


Figure 53: Distribution of participants' climate background.

Climate	Count	Warm / Mild
Arid (dessert)	1	13
Tropical Savanna	2	
Tropical Monsoon	1	
Humid Subtropical	5	
Mediterranean	4	
Oceanic (Marine)	6	11
Humid Continental	5	

Table 16: Counts of participants' climate background.

6.5 Results

6.5.1 Climate Background and Fan Usage

For participants from warm-summer climate, the percentage of using fan for cooling both at home or and school/work are higher than the participants from climate zones with mild summer climate, more than 1/3 of the participants from mild-summer climate have never used fan for cooling at home. The usage at home is also higher than at school/work. One possible explanation is that air conditioning is used in school or office environments and reduced the need of using fan as extra cooling method. However, this is not validated from the questionnaire and requires further investigation.

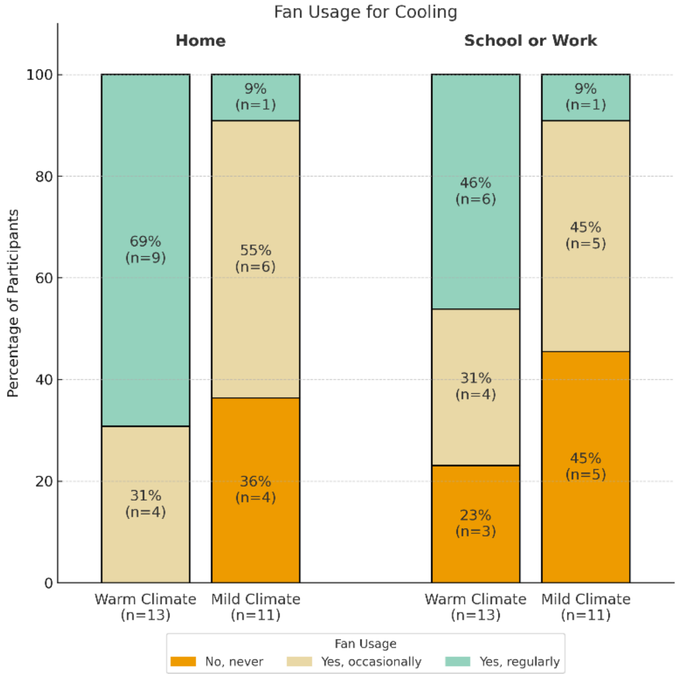


Figure 54: Fan usage at home and school/work by climate background.

6.5.2 Self-reported Thermal Preference

The thermal preference of the occupants was obtained by asking "In general, are you more tolerant of warmer or cooler temperatures?", with 4 options "Cooler temperatures", "Warmer temperatures", "Equally tolerant of both" and "Not sure". Regardless of climate ground, half (12) of the occupants preferred warmer temperatures, 33% (8) preferred cooler temperatures, 12.5% (3) are equally tolerant of both and only 1 occupant responded "not sure" (see Figure 55). When comparing the thermal preference by climate background, more than 50% of the participants from 5 out of 7 climate backgrounds showed preference over warmer temperatures (see Figure 56).

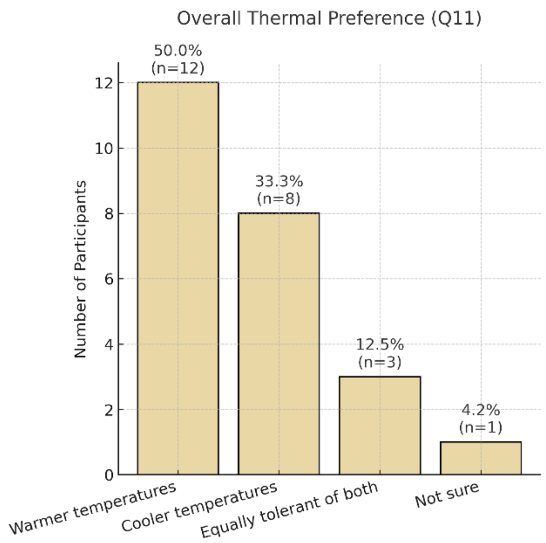


Figure 55: Participants' self-reported thermal preference.

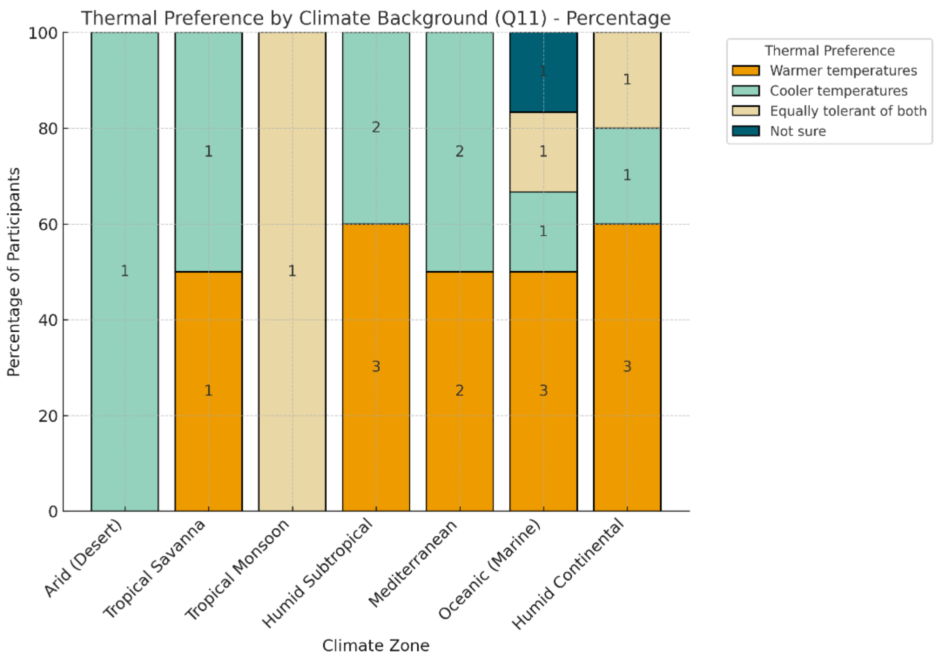


Figure 56: Participants' self-reported thermal preference by climate backgrounds.

6.5.3 Given Fan Speed

Thermal Perception

The thermal perception including sensation vote, comfort vote, acceptability and preference are analysed by the 4 given fan speed (0/3/5/8). Figure 57 shows that thermal sensation vote decreased as fan speed increased, showing thermal sensation shifting from slightly warm (0.71) towards slightly cool (-0.42). Despite the decrease in thermal sensation, the comfort vote and acceptability did not show clear improvement as the fan speed increased.

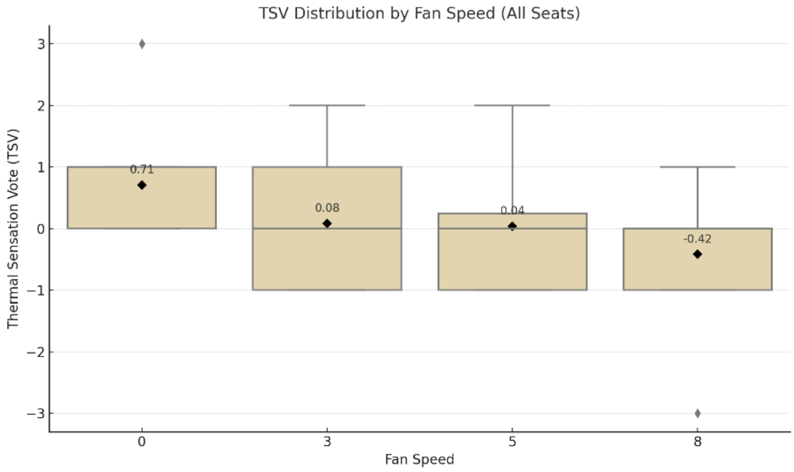


Figure 57: Thermal sensation votes at 4 given fan speed.

Distribution of thermal comfort vote (Figure 58) and thermal acceptability (Figure 59) were plotted against fan speed and revealed only minor variations across the range. Statistical testing using one-way ANOVA confirmed these observations, showing no significant differences across fan speeds for either thermal comfort ($F = 0.11$, $p = 0.95$) or temperature acceptability ($F = 1.24$, $p = 0.30$). These high p-values indicate that any observed differences are likely due to random variation rather than a consistent effect of increasing air speed. Overall, the results suggest that increasing fan speed alone did not result in meaningful improvements in participants' perceived thermal comfort or acceptability of the thermal environment.

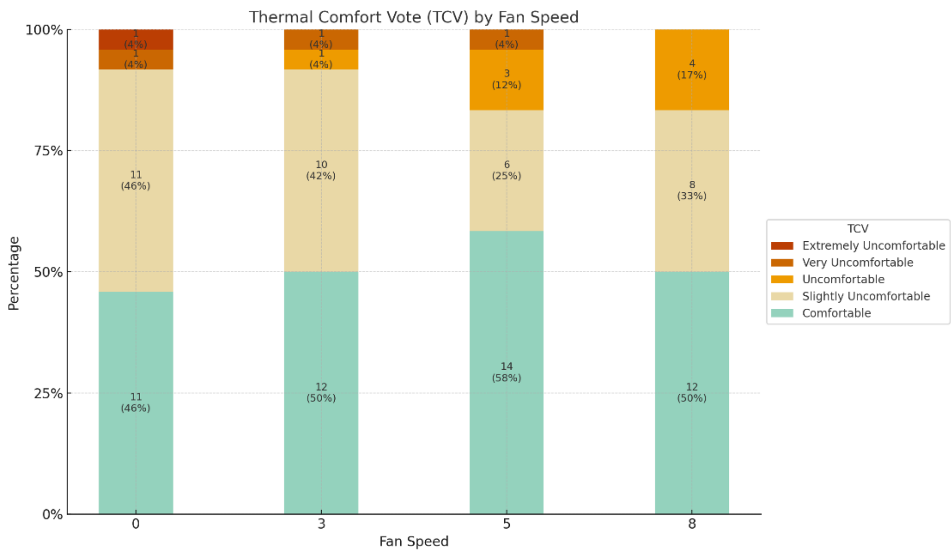


Figure 58: Thermal comfort votes at 4 given fan speeds.

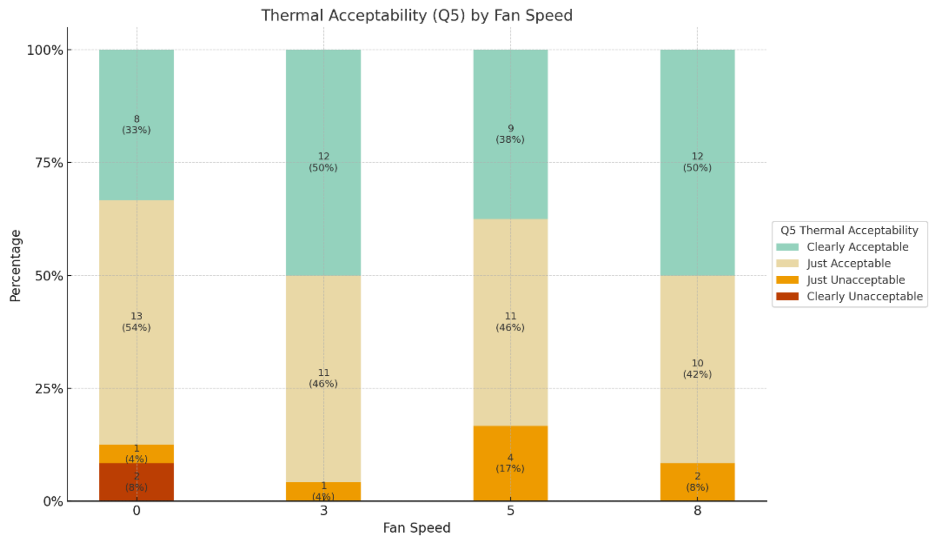


Figure 59: Thermal acceptability at 4 given fan speeds.

The thermal preference is plotted on Figure 60. The column chart reveals that participants requesting lower temperature decreased significantly once the fan is switched on. However, as the fan speed increased, more participants requested for lower temperature.

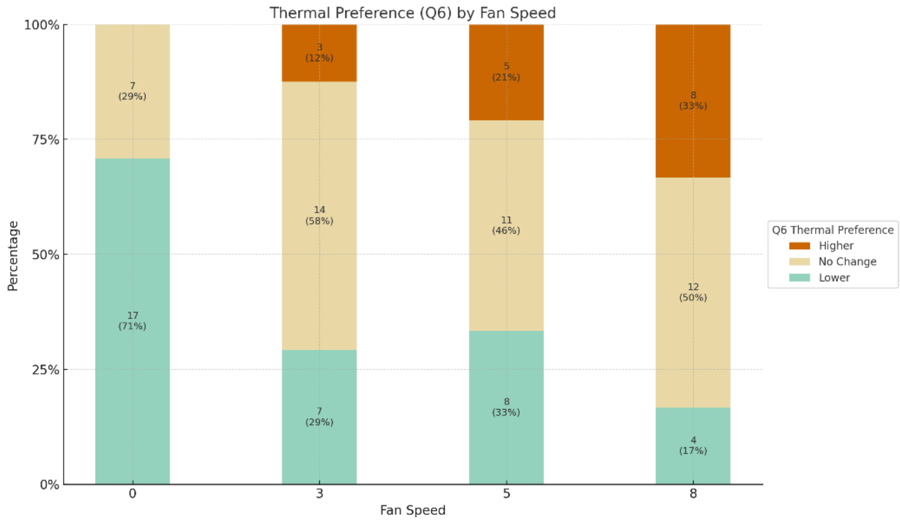


Figure 60: Thermal preference at 4 given fan speeds.

Air Movement Perception

The acceptability of air movement is plotted on Figure 61. At 28°C / 42.9% RH, 75% of participants reported that "no air movement (fan speed 0)" is acceptable. Fan speed 3 with an average air speed of 4 seats at 0.49m/s has the highest acceptability, with 92% of participants feeling just acceptable to clearly acceptable (see Figure 61*)*. Interestingly, 79% of participants requested stronger air movement at fan speed 0 (see Figure 62) despite the high percentage in acceptability.

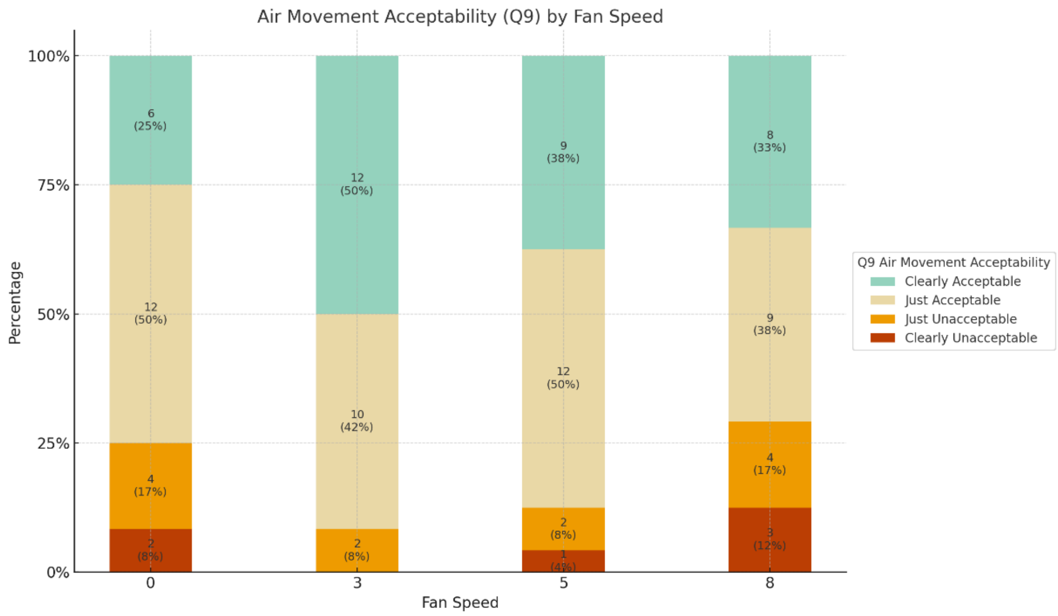


Figure 61: Air movement acceptability at 4 given fan speeds.

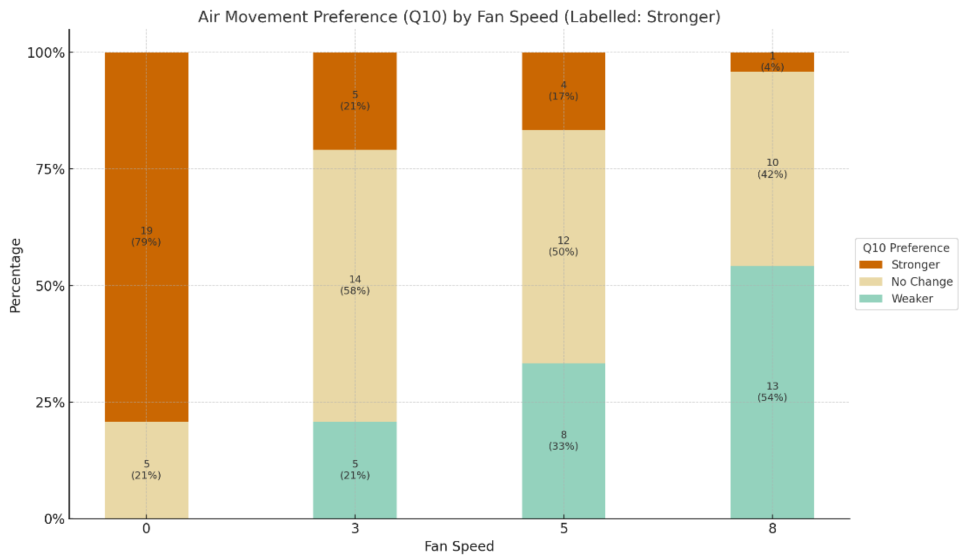


Figure 62: Air movement preference at 4 given fan speeds.

Air Movement Perception by Body Parts

The body parts that felt air movement are plotted on *Figure 63*. Air movement is mostly felt at face, left arm and right arm, followed by top of head. The feeling of air movement at chest increased as the fan speed increased. Only a few participants felt air movement at back of head and upper back at fan speed 9. Compared to the sectional measurement result in *5.3.5*, the high air speed at 0.85m (chest level) did not reflect to high perception of air movement. Since the participants are mostly doing their (study) work with their laptops or tablets placed on the desk, they sat in a leaning-forward position that also made there head and face located in the (slightly) higher air speed zone of 1.1m, but the measured air speeds are still lower than the ones measured at 0.85m. This may suggest that the air speed measurement without occupants in the room might differ with the actual condition with occupants sitting in the room.

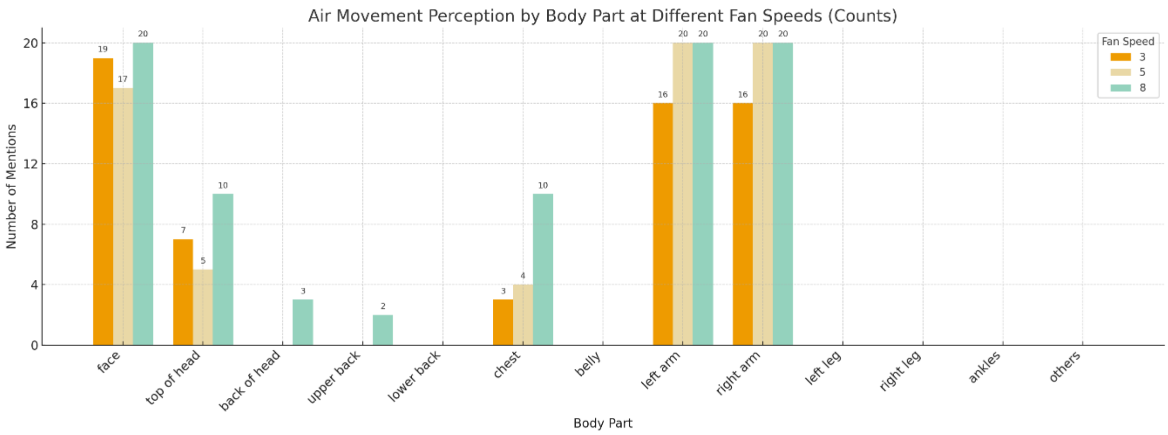


Figure 63: Body part feeling air movement at different given air speed.

Local Draft Discomfort

The number of participants that felt local draft discomfort are plotted on Figure 64. A higher percentage of participants felt the local draft as the fan speed increased, but still more than half of the participants did not feel local draft discomfort. The most complaints for local draft were left and right arms (see Figure 65), followed by face, especially at fan speed 8.

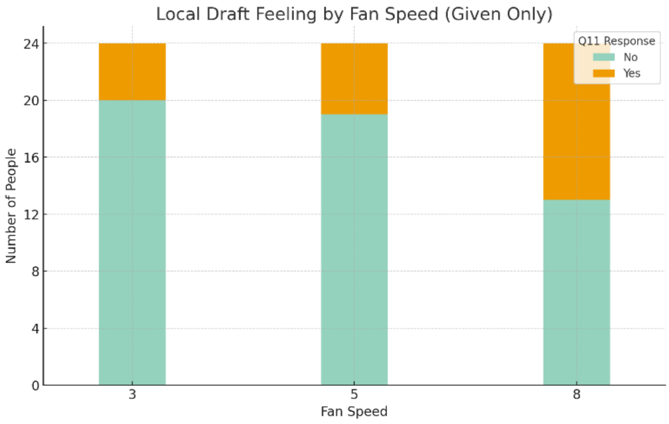


Figure 64: Participants' feeling of local draft discomfort.

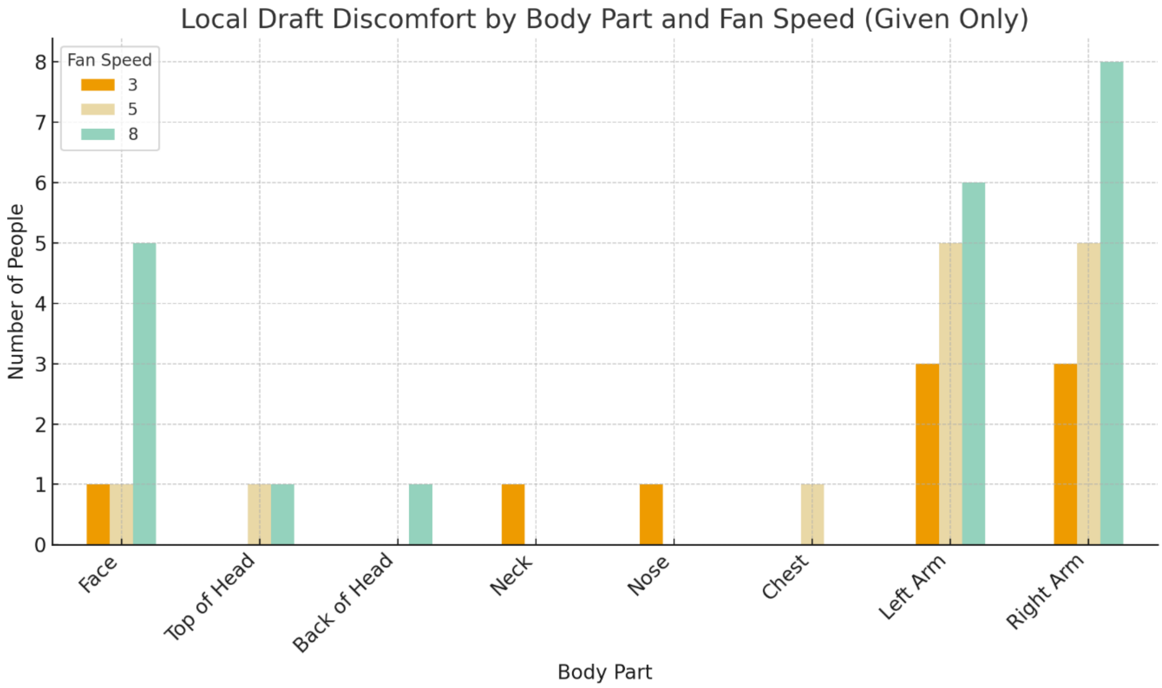


Figure 65: Body parts feeling local draft discomfort.

Air Quality Perception

The perception of air quality is plotted on *Figure 66.* The participants felt the air quality to be fresh increased significantly once the fan was switched on, from only 4% with fan speed 0 (no air movement) to 50% with fan speed 3.

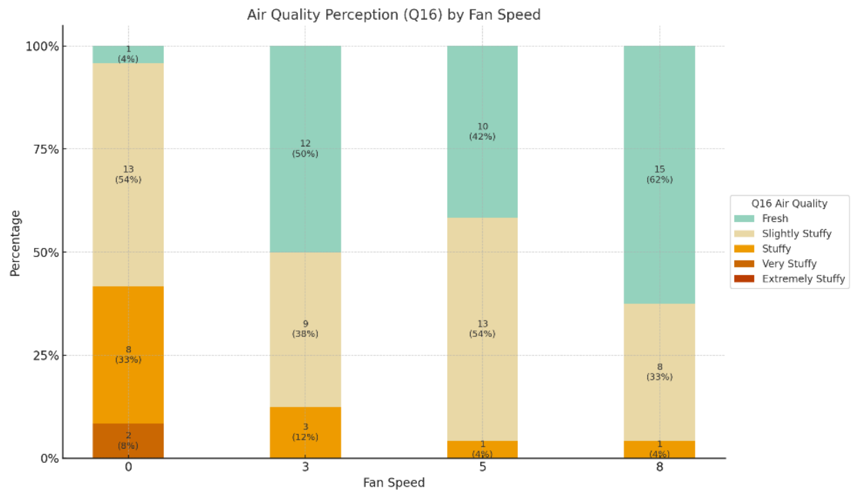


Figure 66*: Air quality perception at 4 given fan speeds.*

Noise Perception

The acceptability of fan noise is plotted on *Figure 66.* For all the given fan speed, no participant felt the noise caused by the operation of ceiling fan to be unacceptable.

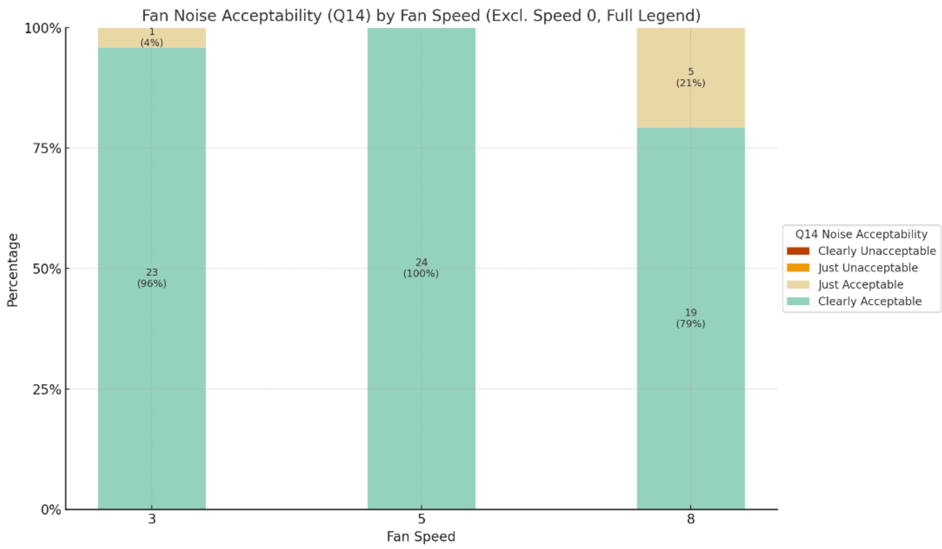


Figure 67: Fan noise acceptability at 4 given fan speeds.

6.5.4 Group-Selected Fan Speed

Selected Air Speed

The selection for each group varies from fan speed 3 to 7, showing a wide range of preference. The average air speed of all seats varies from 0.49m/s (speed 3) to 0.78m/s (speed 7). Among the selected fan speeds, speed 3 and 7 were selected twice, while the others were selected once (see *Table 15*).

Thermal Perception

The thermal sensation votes for group-selected fan speed sessions are plotted on *Figure 68*. The number of samples is not the same per fan speed because the number of the groups and number of participants per group differs. TSV shows a gradual decrease as the fan speed increases.

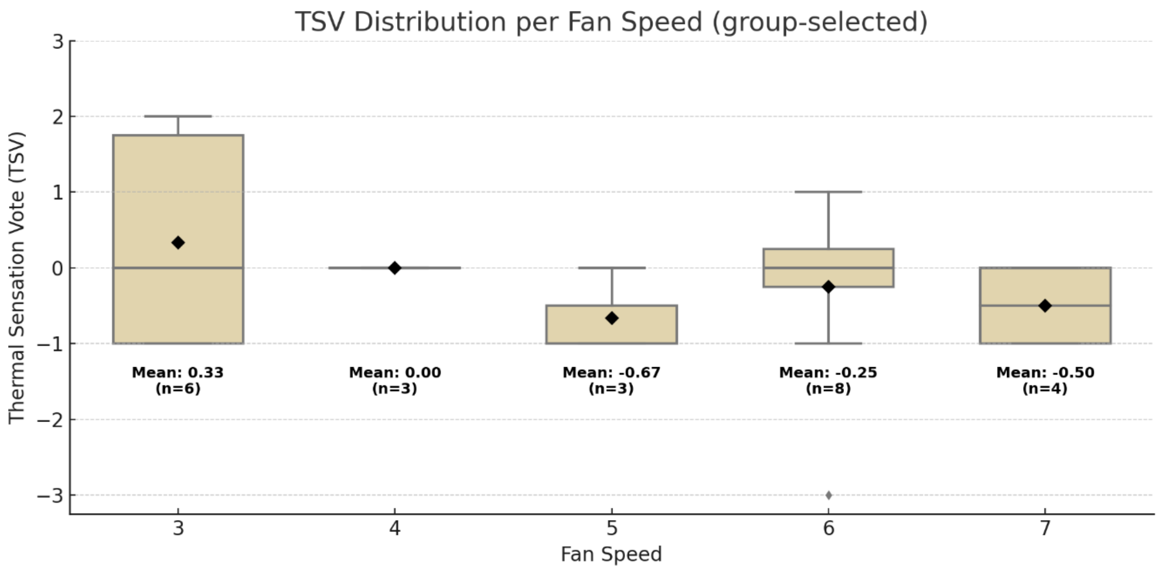


Figure 68: Thermal sensation votes by group-selected fan speed.

Thermal Comfort Vote and Acceptability

The thermal comfort vote for each group is plotted on *Figure 69*. The comfort level differs per group with the highest being able to achieve 100% comfort for all group members, while the lowest is only 25%. The thermal acceptability for each group is plotted on *Figure 70*. All the groups showed acceptability for the thermal condition above 75%.

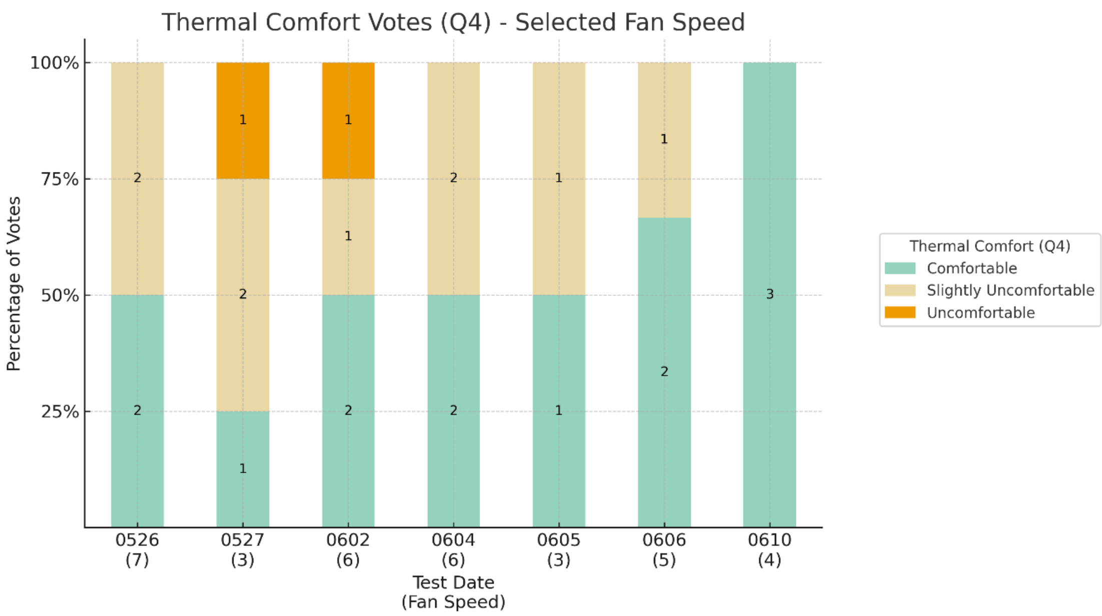


Figure 69*: Thermal comfort vote by test groups.*

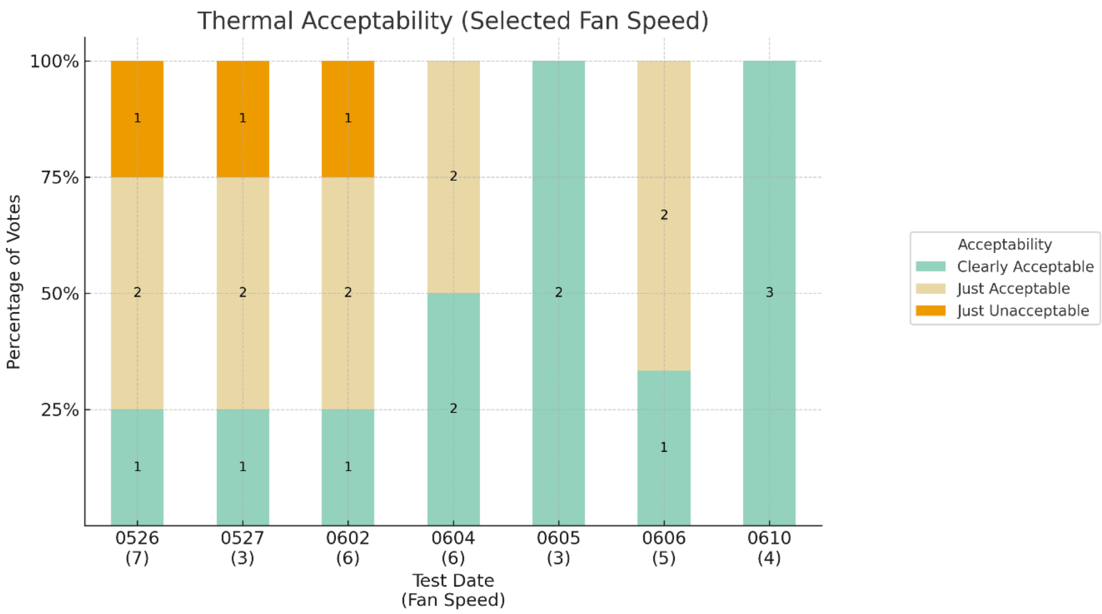


Figure 70: Thermal acceptability by test groups.

Air Movement Acceptability

The air movement acceptability for each group is plotted on *Figure 71.* For most of the groups, the percentage of acceptability are mostly above 75%, only 1 group has moderate acceptability at 50%. Still there are some occupants feeling just unacceptable or even clearly unacceptable. The results point to clear individual differences in air movement preference, even when participants were given control over fan speed. For instance, while some participants selected higher fan speeds (e.g., 5 or 7) and reported 100% acceptability, others (3 out of 6 participants) chose the lower fan speed 3 and still indicated that the airflow was too strong. This variation suggests that personal sensitivity to airflow differs significantly among individuals—some may prefer a pronounced cooling effect, while others are more sensitive to even minimal air movement.

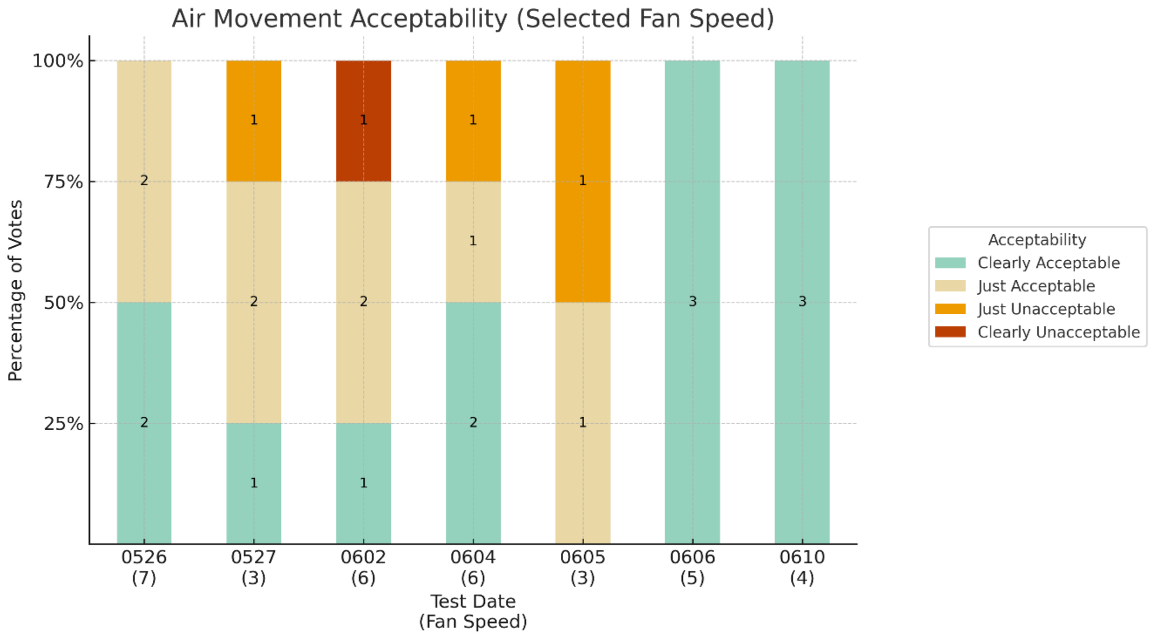


Figure 71*: Air movement acceptability by test groups.*

6.5.5 Group-Selecting Process

The satisfaction level and engagement level was asked to the participants in the ending questionnaire, both with a 5-point scale and an open-ended question that allowed them to express their experience during the group-selecting fan speed process. The results from the 5-point scale are shown in *Figure 72.* Both satisfaction and engagement had a mean value above 1, suggesting that most participants had a moderately positive experience.

Participants' open-ended responses to satisfaction indicate that the group selection process was generally smooth and collaborative. Many respondents noted that they were able to reach a consensus on fan settings quickly, with most feeling comfortable with the final decision. While a few participants mentioned minor mismatches in preferences—such as desiring slightly higher or lower fan speeds—these were often accompanied by an expressed willingness to compromise for the sake of group comfort. Overall, the responses reflect a positive experience of shared decision-making.

Participants' responses to engagement highlighted varied experiences of engagement during the group interaction. Several individuals felt actively involved because they could share their opinions, voice discomfort, or influence the final decision. Others, however, reported limited engagement due to brief or minimal discussions, or because their input was not explicitly invited. Some participants appreciated that no one dominated the conversation, which created a comfortable decision-making environment, while a few noted that controlling the interface (e.g., the iPad) increased their sense of involvement. Overall, the level of engagement appeared to depend largely on the group dynamics and the extent to which individual contributions were encouraged.

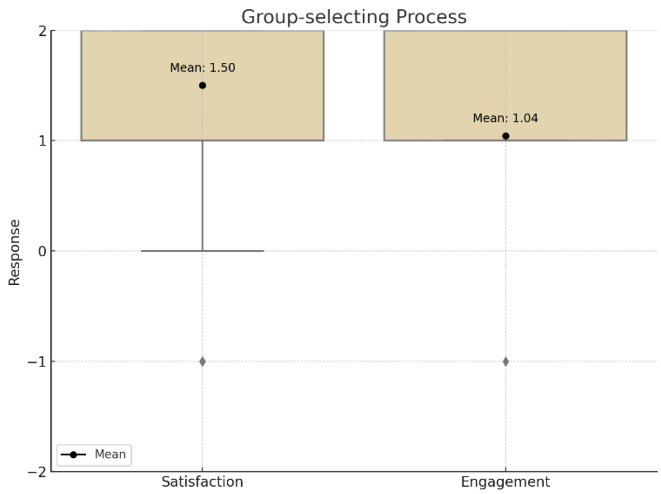


Figure 72: Satisfaction and engagement level during group-selecting process.

6.5.6 Experience with Ceiling Fan during Experiment

The effectiveness of ceiling fan for improving thermal comfort and the intuitiveness of the control interface are shown in *Figure 73*. The participants found the ceiling fan setup both effective and user-friendly. Specifically, in response to “effectiveness of ceiling fan for improving thermal comfort”, most participants rated the fan as very effective, with a mean response close to 2. Similarly, for “intuitiveness of the control interface”, responses were also clustered near the top of the scale, suggesting that the interface was perceived as very intuitive. The low variability and lack of negative outliers in both questions highlight a consistently positive experience, both in terms of thermal comfort and interaction design.

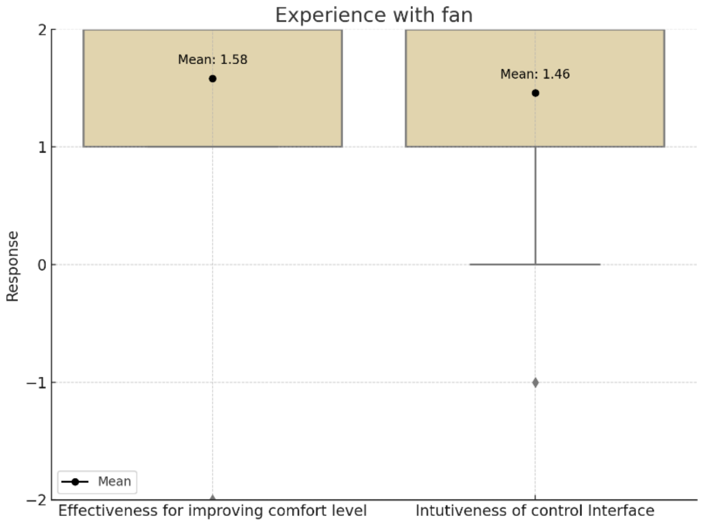


Figure 73: Effectiveness of ceiling fan for improving thermal comfort and the intuitiveness of the control interface.

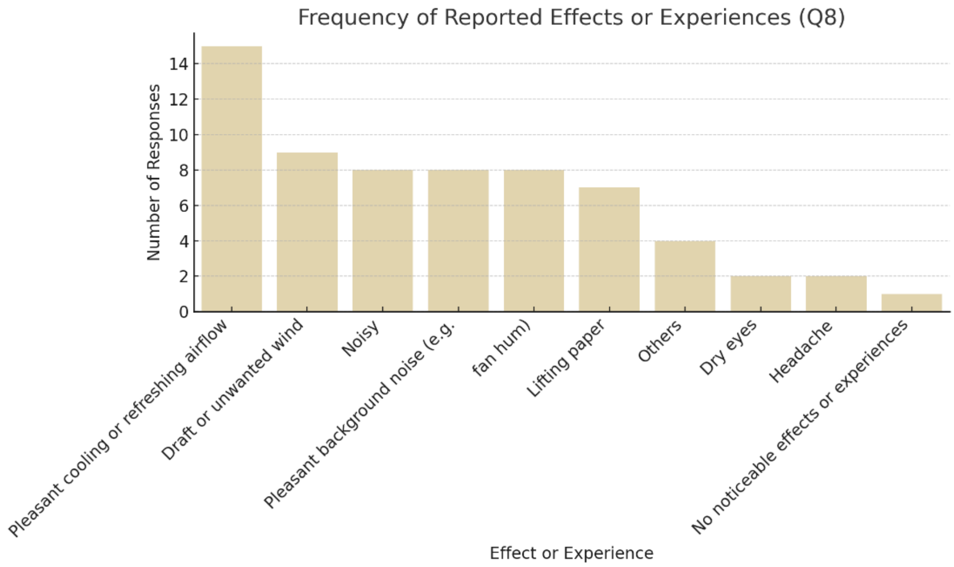


Figure 74: Other effects or experience with ceiling fan.

Participants were also asked to select any noticeable effects or experiences related to the fan (see *Figure 74*). The most frequently reported effect was “Pleasant cooling or refreshing airflow,” followed by “Pleasant background noise (e.g., fan hum),” selected by 8 respondents. Other commonly noted experiences included “Draft or unwanted wind” and “Noisy.” These findings indicate that participants generally perceived the fan’s airflow and background sound positively, with only a few reporting discomforts like draft, noise, or dryness.

6.6 Discussion

6.6.1 Limited Improvement of Comfort Level and Acceptability as Air Speed Increases

The results presented in *Chapter 6.5.3* reveal that increasing fan speed did not consistently improve thermal comfort votes or thermal acceptability. As illustrated in *Figure 75* , the perception of an acceptable thermal condition generally aligned with a thermal comfort vote between comfortable and slightly uncomfortable.

At 28°C / 42.9% RH, over 83.3% of participants rated the thermal environment as acceptable across all fan speed conditions. The high acceptability at fan speed 0 (still air) agreed with the findings from Huang et al. (2013) that the lower limit of air speed at 28°C is 0m/s. However, the percentage of participants who felt comfortable was considerably lower: only about 50% reported feeling comfortable with fan speeds 3, 5, and 8, and 45.8% felt comfortable in still air (fan speed 0).

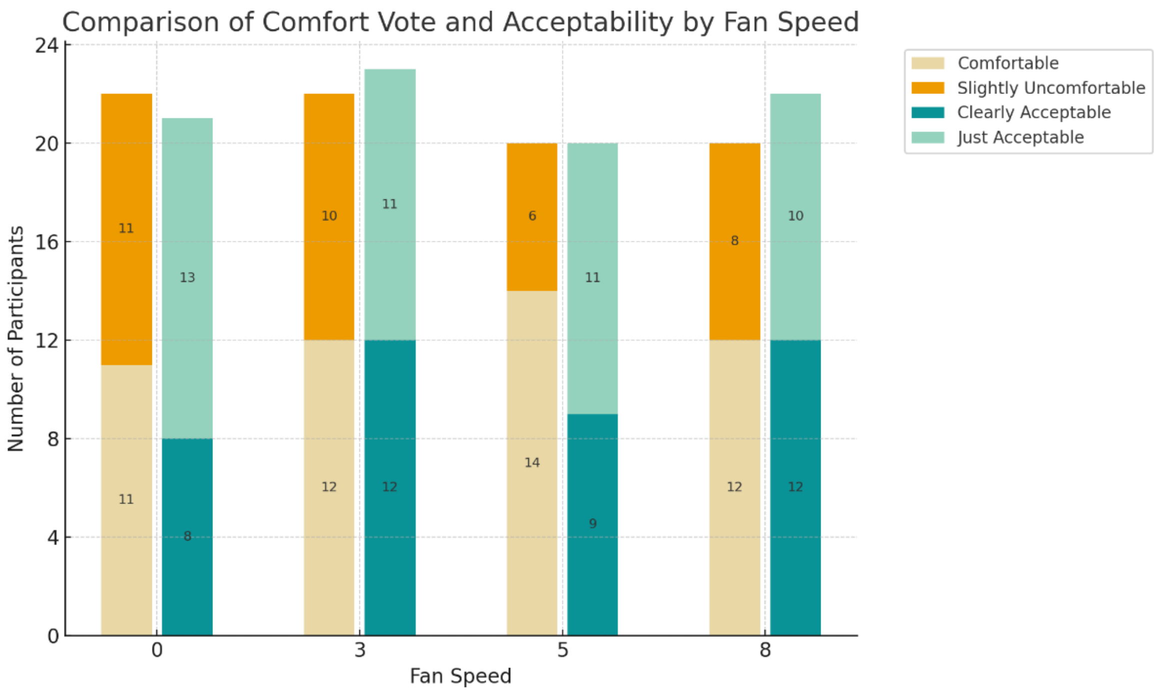


Figure 75: Number of participants voted TCV for “comfortable” or “slightly uncomfortable” and TA for “just acceptable” or “clearly acceptable” in the given fan speed sessions.

To explore potential causes of this discrepancy, the thermal sensation data were filtered to include only participants who reported discomfort (votes from slightly uncomfortable [-1] to extremely uncomfortable [-4]) during sessions with assigned fan speeds. As shown in Figure 76, in still air (fan speed 0), discomfort was primarily associated with warmer thermal sensations, with no participants reporting cool sensations. As fan speed increased, the number of participants reporting warm sensations declined, while those reporting cool sensations increased.

Moreover, participants' preference for a lower temperature (see Figure 77) and weaker air movement (see Figure 62) also increased with fan speed. These findings suggest that while higher fan speeds improved the objective air movement, they may have introduced secondary discomfort through overcooling or excessive draft (see *Figure 64: Participants' feeling of local draft discomfort.*), which impacted subjective thermal comfort perceptions.

Participants

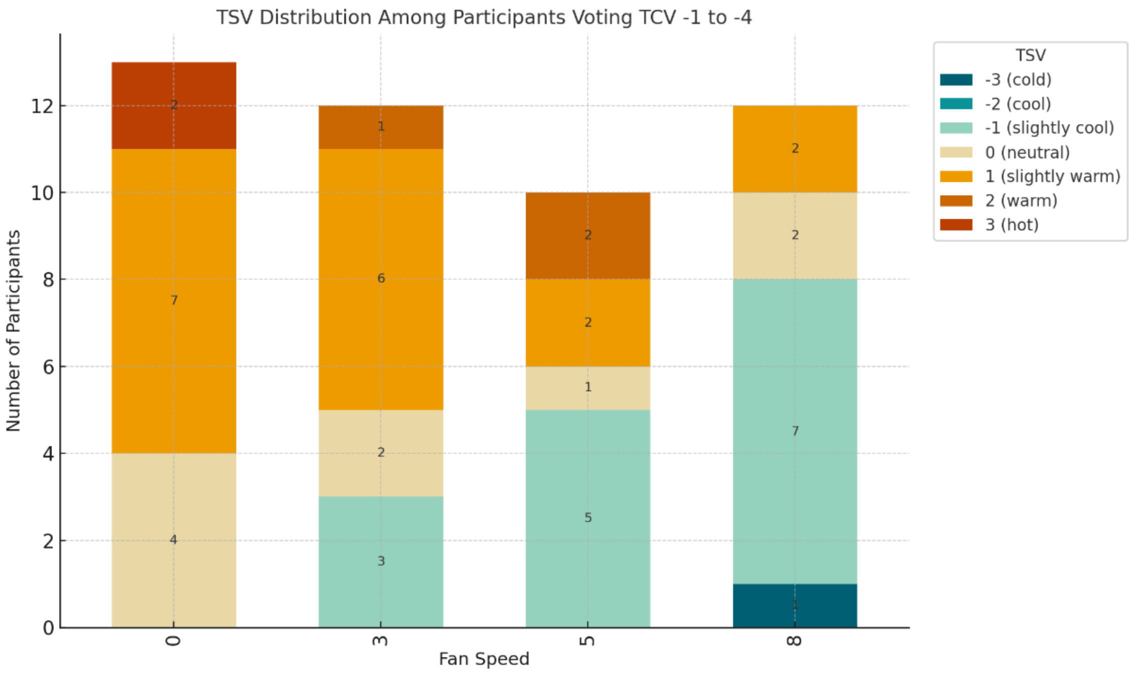


Figure 76: TSV distribution among participants feeling uncomfortable.

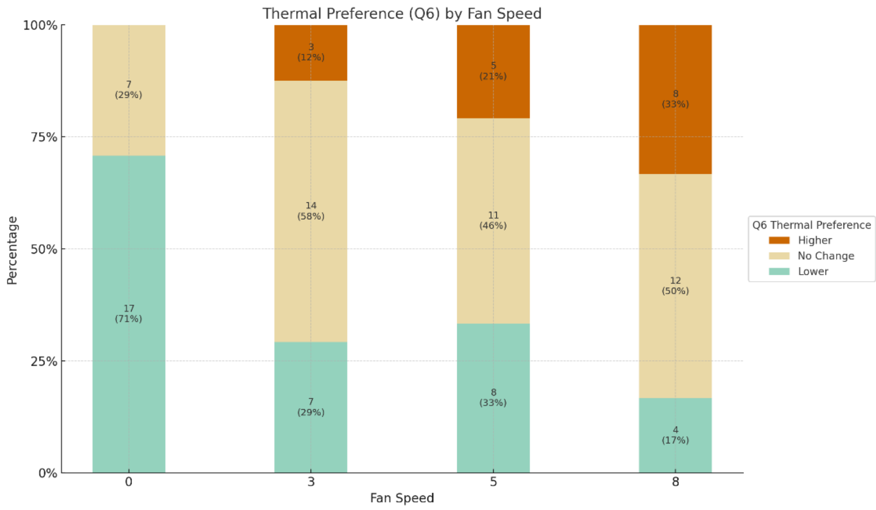


Figure 77: Thermal preference by fan speeds.

TSV	Count	TCV	Count	Total Counts	%	TA	Count	Total Counts	%
Neutral	6	Comfortable	8	11	72.7%	Clearly Acceptable	5	8	52.4%
Slightly Warm	5	Slightly Uncomfortable	3			Just Acceptable	6	13	
Warm	0	Very Uncomfortable	0			Just Unacceptable	0		
Hot	1	Extremely Uncomfortable	1			Clearly Unacceptable	1		

Table 17: Cross comparison of the thermal perception (at fan speed 0) of participants with personal thermal preference towards warmer temperature reported in opening questionnaire.

Table 17 revealed the thermal perception of the participants who reported their personal thermal preference towards warmer temperature at fan speed 0. Among the participants who felt comfortable in the still air condition, 72.7% are warm-preferring participants. As for thermal acceptability, the warm-preferring participants also occupied 52.4% of the total counts. This might also explain why the comfort level at still air condition is higher than expected.

Aside from the statistical analysis, participants also reported “the room condition felt quite nice when coming from a cold and rainy weather”, and “I felt comfortable during the experiment. Not until when I leave the room during the break did I notice how cool and fresh it feels outside the room (still within the same building with indoor air temperature around 22°C -24°C)”, showing that the outdoor climate before the experiment and experiment procedure also has influence on thermal perception.

6.6.2 Comparison Between Given and Group-selected Fan Speed

This study explored the impact of control method (no control vs group control) on thermal comfort by comparing thermal comfort votes across different fan speeds. While descriptive analysis indicated that higher fan speeds (e.g., 5 and 8) were generally associated with slightly improved comfort, mean votes trending closer to 0 (comfortable), statistical testing revealed no significant difference between comfort votes at fan speed 0 and those at speeds above 0. Specifically, a Welch's t-test yielded a p-value of 0.54, suggesting that the observed difference (e.g., mean comfort vote of -0.75 at fan speed 0 vs. slightly higher values with airflow) may be attributed to random variation. This implies that while air movement may offer some perceived benefit, it did not produce a statistically robust improvement in thermal comfort in this sample. Further research may be needed to assess whether personal preferences or other factors mediate the effectiveness of airflow in improving comfort.

While personal control over fan speed is often assumed to enhance thermal comfort, the current results do not provide statistical support for this assumption. A comparison between the Given Speed and Selected Speed conditions revealed no significant difference in reported thermal comfort votes (Welch's t-test, p = 0.44).

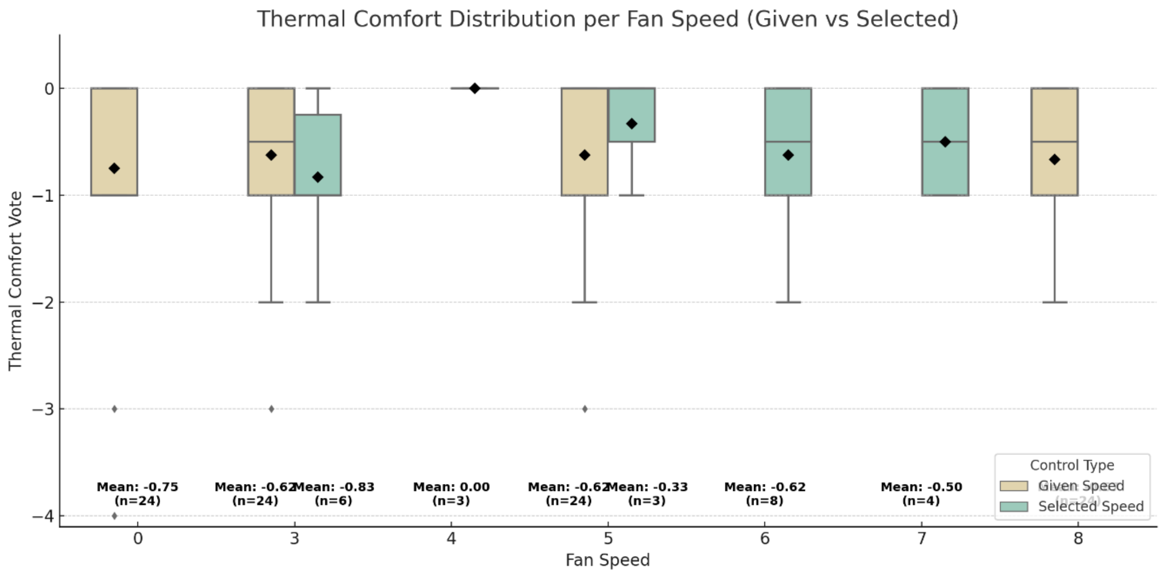


Figure 78: Thermal comfort vote of given and group-selected fan speed.

6.6.3 Preferred Air Speed

Preferred Air Speed without Group Control

Among the given fan speed sessions, fan speed 3 has the second highest votes for thermal comfort (50%, the highest is fan speed 5 at 58%), highest votes for thermal acceptability (96%), no change in temperature (58%), air movement acceptability (92%), no change for air movement (58%) and lowest probability of feeling local draft discomfort (16.7%, except fan speed 0). The measured air speed at the seats varies between 0.41m/s to 0.56m/s, with a seat-average at 0.49m/s.

Preferred Air Speed with Group Control

The group-selected fan speeds ranged from fan speed 3 to 7, corresponding to seat-average air speeds between 0.49 m/s and 0.78 m/s. Fan speeds 3 and 6 were each selected by two groups, while the remaining speeds were selected by only one group. This non-uniform and relatively small sample size makes it more challenging to define a clear "preferred" air speed.

Among the five chosen fan speeds, fan speed 4 received the highest rating for thermal comfort, with 100% of participants reporting comfort. It also shared the highest thermal acceptability (100%) with fan speed 5. Furthermore, fan speeds 4, 5, and 7 all achieved 100% air movement acceptability. Based on these criteria, fan speed 4 can be considered the most preferred. The measured air speeds at the seats for fan speed 4 ranged from 0.46 m/s to 0.67 m/s, with an average of 0.58 m/s.

In contrast, fan speed 3, despite being selected twice and ranking high in given fan speed sessions, received the lowest votes for thermal comfort (33%), thermal acceptability (75%), and air movement acceptability (67%) during the group-selected sessions.

7 Cross-chapter Discussion

7.1 Comparison of Simulated and Measured Air Speed

7.1.1 Case_0 at Fan Speed 8

To assess if the air speeds from CFD simulation align with measurement results, air speed data of 2 CFD simulation settings and 1 measurement result at fan speed 8 are compared. In the configuration of CFD_Case_0_8_C, the fan is located in the centre of a 5x3x2.6m (L x W x H) room. In the second CFD configuration, CFD_Case_0_8_EC, the fan is placed eccentrically as in reality, and the room dimension is 5.1x3.25x2.5m.

Difference between simulated and measured air speeds

The CFD simulations predict significantly higher average air speeds (more than double) compared to the measured Case_0_8. The average measured airspeed across all points was 0.181 m/s, whereas the CFD simulations predicted substantially higher average airspeeds: 0.437 m/s for CFD_Case_0_8_C and 0.455 m/s for CFD_Case_0_8_EC. These simulation results are more than double the measured values, highlighting a consistent overprediction by the CFD models in terms of absolute airflow magnitude. A possible explanation of the overestimation is that the real-world factors like surface roughness, measurement obstructions are not fully taken into account.

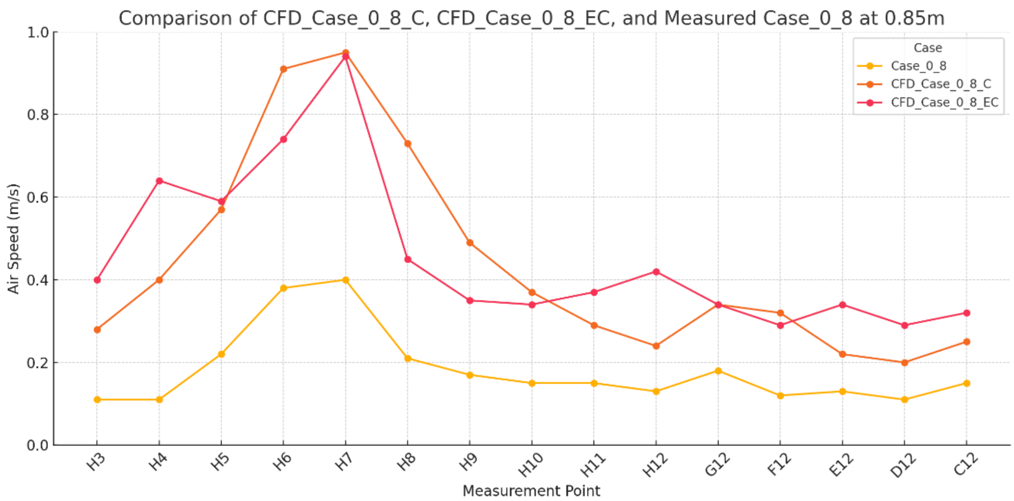


Figure 79: Air speed profile of CFD simulation results and measurement data of Case_0 at fan speed 8.

When comparing which CFD configuration aligns better with the measured airflow pattern, Pearson correlation coefficients were calculated between the measured Case_0_8 data and the CFD-predicted data. CFD_Case_0_8_C has a high correlation coefficient of 0.925 with the measured data, indicating a very strong alignment in the spatial distribution pattern of airspeeds. In contrast, CFD_Case_0_8_EC has a slightly lower correlation of 0.824, reflecting a somewhat weaker but still strong pattern similarity even though the geometrical setup is more similar to reality.

Prediction power of CFD simulation

The linear regression analysis comparing the CFD_Case_0_8_C predictions to the measured Case_0_8 airspeeds resulted in an equation y = 0.344x + 0.031 and R^2 value of 0.856. This indicates that approximately 85.6% of the variation in the measured airspeed data can be explained by the CFD predictions, reflecting a very strong predictive alignment between the simulation and experimental results despite the magnitude difference.

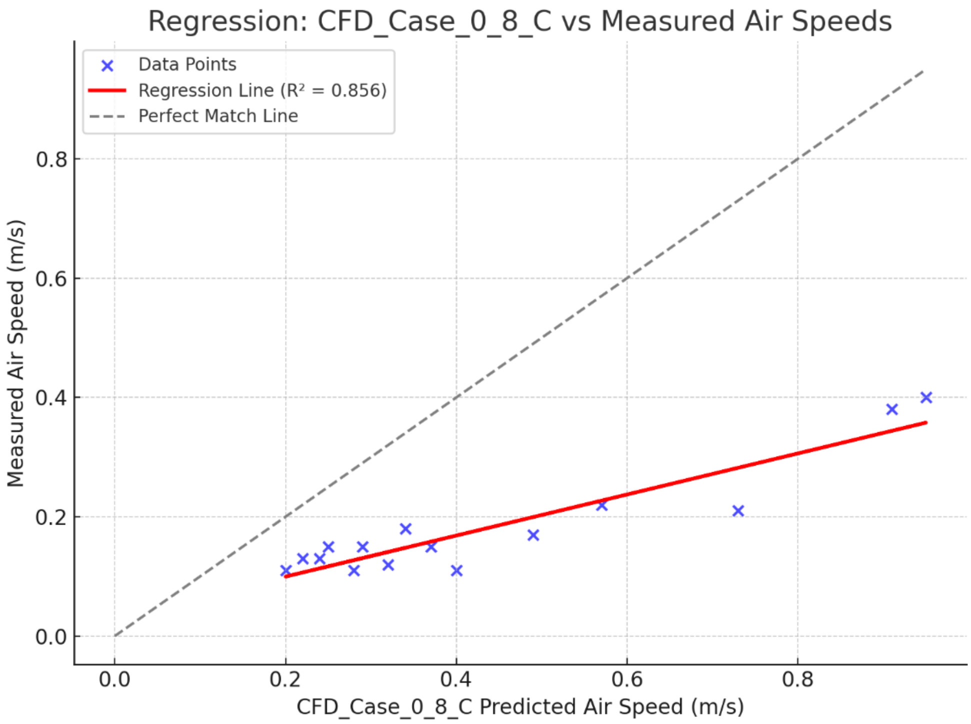


Figure 80: Regression of CFD_Case_0_8_C against measured air speeds with equation y=0.344x+0.031.

7.1.2 Case_1A at Fan Speed 3/5/8

The comparison between measured and CFD-predicted air speeds reveals a consistent pattern of overestimation by the CFD model across all examined fan speeds. In average, the measured air speed for fan speeds 3, 5 and 8 are only 56.2%, 59.7%, and 65.7% of simulated air speed respectively, showing more than 30% of overestimation. The overestimation are even higher at the low fan speed. The line charts (*Figure 81*) show that the CFD results generally follow the overall trend of the measured data, except at areas between H11 - C11 and C4 – H4, located at the short edges of the desk surface, showed higher misalignment. The XY scatter plots with linear regression (*Figure 82*) indicate only a moderate degree of correlation. Specifically, the coefficient of determination (R^2) values range between approximately 0.5 and 0.75, which suggests that the CFD simulations capture some of the variability observed in the experimental measurements. This moderate correlation points to limitations in the accuracy of the CFD model, particularly at lower fan speeds where deviations tend to be larger.

These findings imply that while the CFD model can be useful for identifying general air flow patterns and relative differences between configurations, it should be used cautiously for absolute air speed predictions. Model calibration on the simplified fan geometry or the application of correction factors may be necessary to improve the predictive accuracy for practical applications.

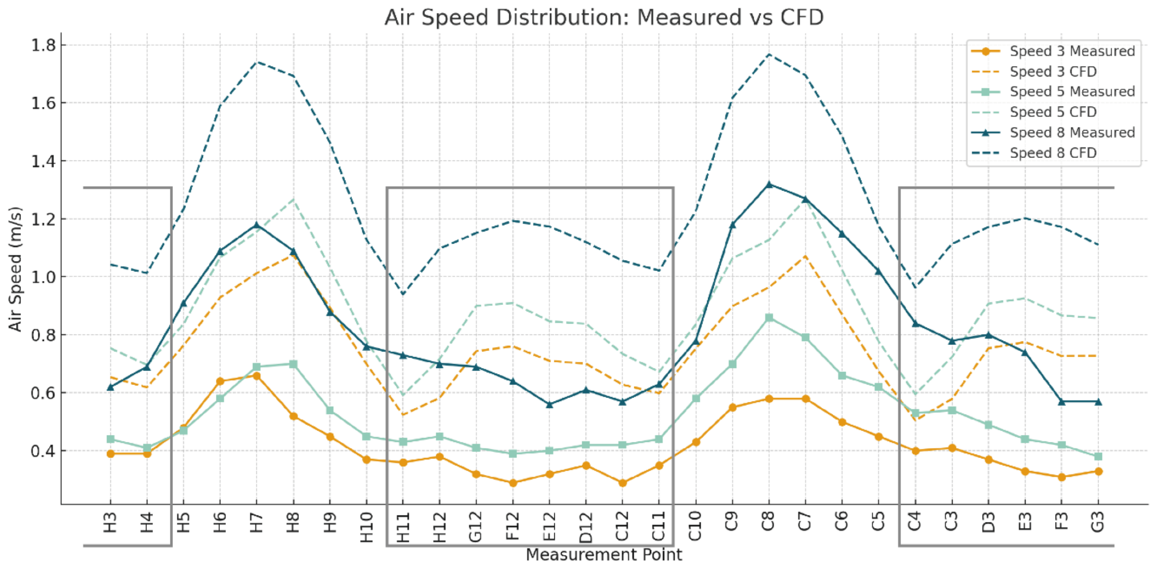


Figure 81: Air speed distribution of simulation and measurement results.

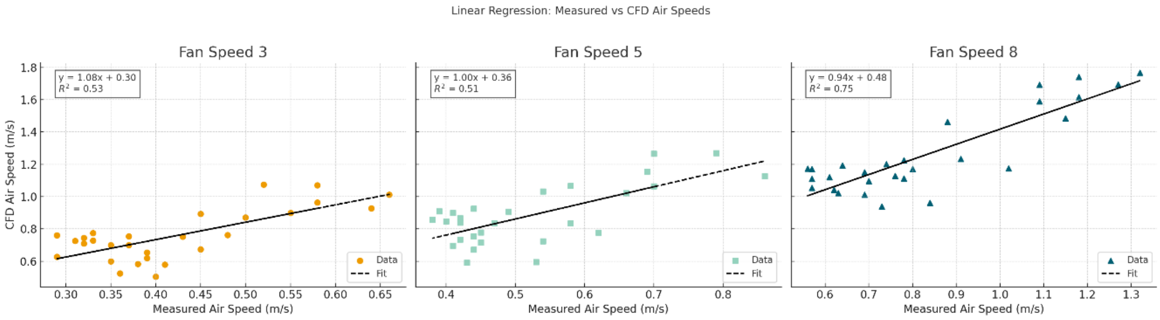


Figure 82: Prediction power of CFD model with different fan speed.

7.2 Comparison of PMV with TSV

The PMV is calculated based on the measurements of room condition (air temperature, globe temperature, and relative humidity) mentioned in *Chapter 6.1*, and the air speed measurement from *Chapter 5.3.3* (Table 9 and Figure 38*: Individual air speed and the average air speed at seats (0.85m).*)*.* The mean radiant temperature (MRT) was first derived air temperature, globe temperature, air speed with globe diameter of 0.15m and globe emissivity of 0.95. Later the PMV was calculated based on clothing insulation clo = 0.57 (typical summer clothing) and metabolic rate MET = 1.1 (sedentary work) with CBE Thermal Comfort Tool developed by Tartarini et al. (2020). Since PMV is sensitive to air speed, the air speed is calculated seat-by-seat to accurately capture thermal comfort distribution, making it comparable with average TSV also calculated seat-by-seat. Only datapoints from the given fan speed session are analysed in this chapter.

Figure 83: Thermal sensation vote (per seat and average) by given fan speed. reveals that the TSV varies between the seats as the air speed also differs per seat. The mean TSV of seat B and C also show lower values constantly. The results align with the higher air speed measured at seat B and C.

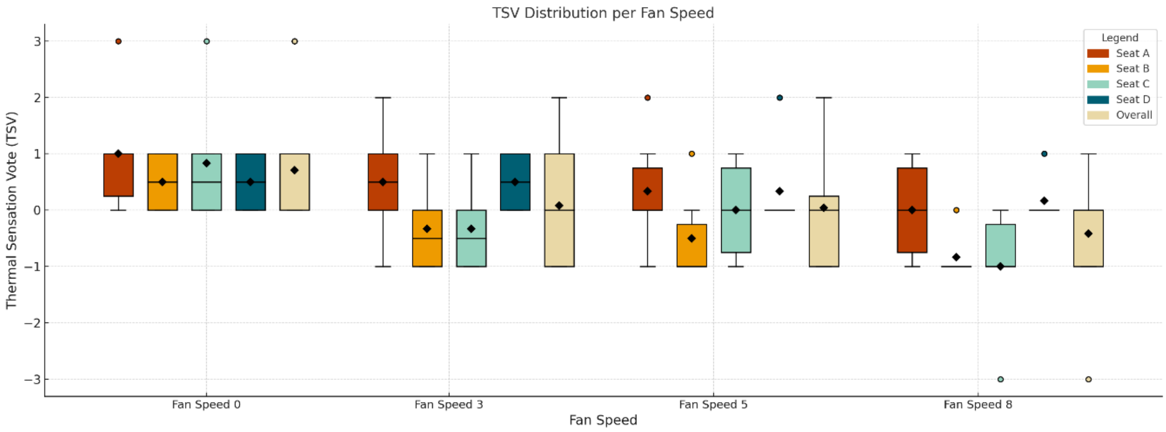


Figure 83: Thermal sensation vote (per seat and average) by given fan speed.

The scatter plot (Figure 84) illustrates the relationship between individual datapoints of TSV and PMV across different fan speeds. A dashed grey line representing the ideal prediction line (where TSV equals PMV) is included to visualize how closely or vast the model aligns with perceived thermal comfort of participants. A black solid regression line shows the actual linear relationship between PMV and TSV, indicating a moderate correlation between the model predictions and subjective votes. Notably, in 53 out of 96 cases (55.2%), TSV was lower than PMV, meaning occupants often felt cooler than what the PMV model predicted. The individual difference of thermal perception is noticeable on the chart.

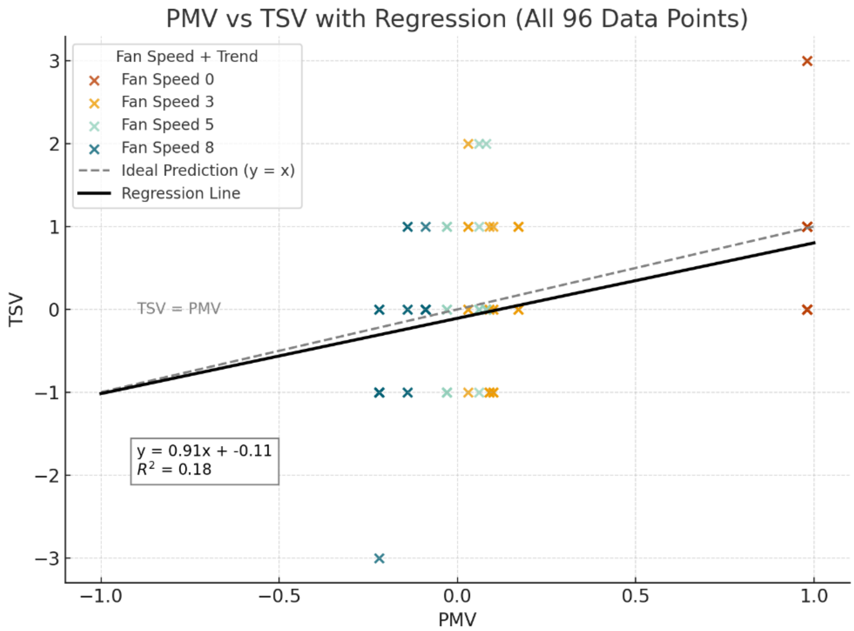


Figure 84: PMV vs individual datapoints of TSV from given fan speed sessions.

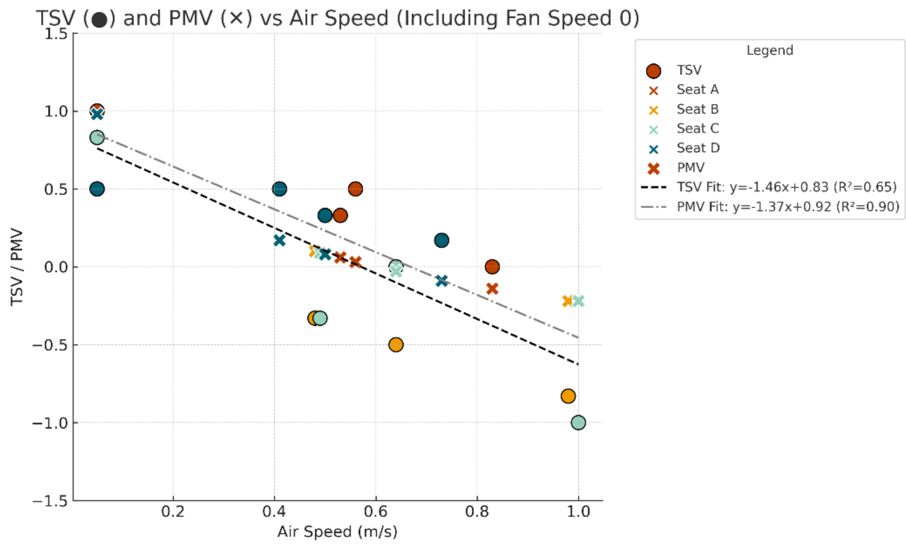


Figure 85: TSV and PMV vs air speed.

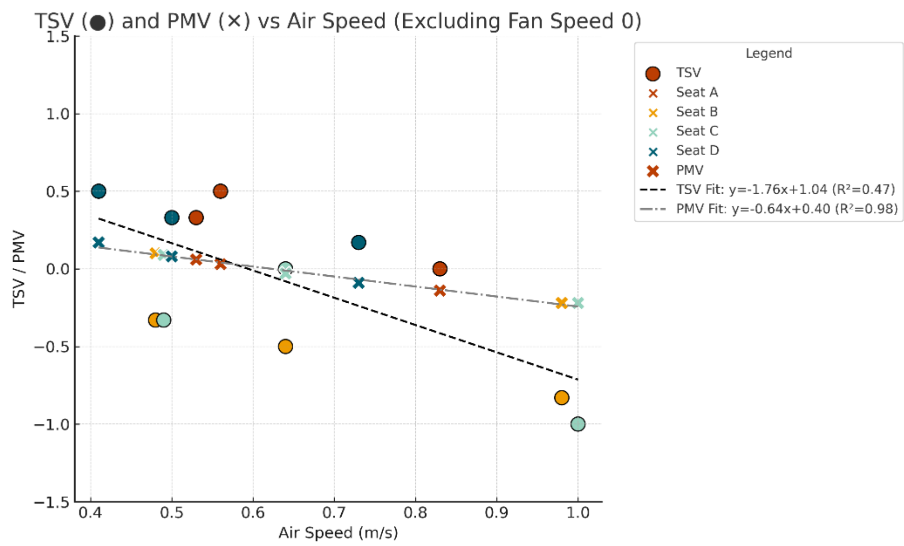


Figure 86: TSV and PMV vs air speed. Excluding datapoints from fan speed 0.

The comparison between seat-average TSV and PMV across varying air speeds (see Figure 85) reveals a consistent trend: participants generally perceived the environment as cooler than what the PMV model predicted. Even at still air condition (<0.05 m/s), TSV is already lower than PMV. Difference grew as air speed increased. This divergence suggests that PMV underestimates the cooling effect of elevated air movement. On average, TSV values were 0.13 units lower than PMV, indicating that subjective thermal comfort was greater than predicted. This is especially evident at air speeds above 0.6 m/s, where participants reported neutral to slightly cool sensations despite PMV values hovering near neutrality. These findings support existing critiques of the PMV model's limitations in accounting for dynamic air movement and point to the need for air-movement-sensitive models.

Interestingly, when the datapoints from fan speed 0 are excluded, the trendline of TSV shows a greater decrease while the slope of PMV is much "flatter" and even intersects at around 0.6m/s (see Figure 86). This also suggest that air speed above 0.6m/s has stronger cooling effect than prediction of PMV model.

7.3 Comparison with Previous Studies

The preferred air speed in this research is compared with the ones from previous research. The chart below (Figure 87) shows the air speed t for neutral sensation votes (TSV=0). The preferred air speed for given fan speed session is between 0.41m/s to 0.56m/s (shown in the blue line) with an average TSV=0.08, very close to neutral sensation. The preferred air speed for group-selected fan speed sessions between 0.46 m/s to 0.67 m/s is also shown in the chart with the red line. Nevertheless, the preferred air speed found in this study falls within the range of previous studies and is far lower than the prediction by PMV model (higher than 1.5m/s to achieve neutral thermal sensation).

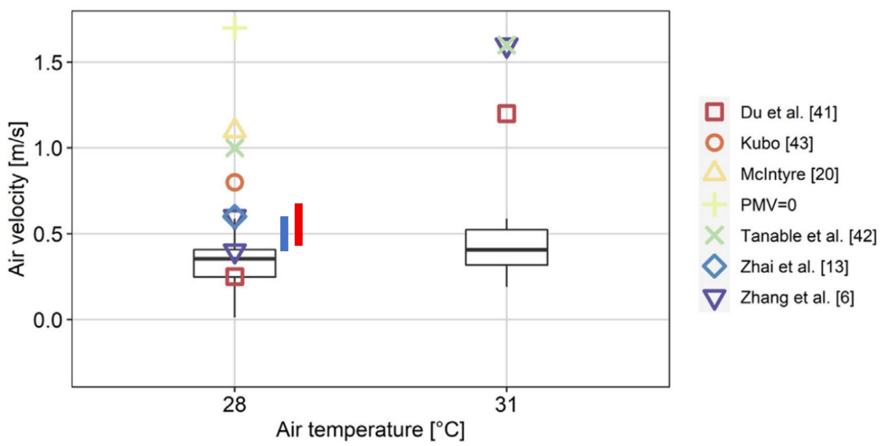


Figure 87: Air velocities measured for neutral sensation votes from previous studies. Derived from "Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort", Rissetto et al. (2021)

7.4 Limitations and Future Work

The main limitation of this research is the limited measurement points of air speed. The air speeds were mostly measured at only 0.85m height, with only 1 sectional measurement at all 0.1/0.6/0.85/1.1m height, which does not fully comply with standards like ASHRAE 55 and NEN-EN-ISO 7726. The measurement points were done only at the points surrounding the desk surface, which is only 17.5% of the total planned measurement points. Further research could measure the air flow diffused by desks at more measurement points at different height to improve the understanding of air speed distribution in a whole-room level. The complete data of air speed measurement can also help to fine tune the CFD simulation model. The air speed measurements were done separately with the human experiments. The presence of occupants and their working equipment (e.g., laptop, tablet, charger and cables, etc.) might also influence the actual perceived air speed comparing to the measurements without these obstructions.

The prediction of air speed by the product of Fan Air Speed (FAS) and Diffusion Power (DP) showed good prediction accuracy for most of the fan speeds, showing a potential of creating a dimensionless model that can be adapted to different FAS and predict the air speed around the desk surface. However, the current model is limited to the geometrical conditions (single room dimension, fan type, blade height and desk layout, etc.) used in this research. Future research can expand the scenarios and examine the diffusion power under different conditions to expand the prediction model with other input parameters.

The sample size for the experiment (24 participant) is relatively small, and the participants came from diverse background. The influence of climate background on thermal perception and air movement preference was not analysed in this study. Future research can expand the scenarios and examine the diffusion power under different conditions.

To examine how the ceiling fan performs in real life, installing multiple fans in an office environment like The Green Village (which was built to be a field lab for sustainable innovation), or the studios in BK faculty (which often suffer from overheating in warm season especially in afternoons) and conduct a long term assessment of the occupants' preference and comfort level could also be an interesting topic. Since the fans are also recommended to be used in heating season with upward air flow to distribute the warm air more evenly, the energy saving potential is also worth to be further investigated.

8 Conclusion

Prediction power of CFD simulation

CFD models can reliably predict airflow trends in simpler setups without obstructions (like desks) but struggle to maintain the same predictive accuracy when applied to more geometrically complex configurations (like Case_1A). For Case_1A, the predictive accuracy at higher fan speeds is also higher than at low fan speeds.

There is a consistent overprediction of absolute airspeed magnitudes (over 30%) by the CFD simulations across both cases, underscoring the need for calibration against measured data to improve quantitative accuracy.

Overall, while CFD remains a valuable tool for exploring airflow patterns and informing design decisions, this study emphasizes that its outputs should be critically evaluated and validated, especially when applied to complex or modified environments.

Diffusion Power

The existence of desks increased the average air speed around the desk at 0.85m for more than 196% when comparing with the no-desk scenario, suggesting the desk surface is able to effectively diffuse the ceiling fan air flow to a wider zone. The average of diffused air speed is able to maintain over 30% from the initial FAS. The idea of “diffusion power (DP)” is introduced, providing a dimensionless model that can be adapted to different FAS and still able the predict the diffused air speed effectively. However, the application of current model is limited to the same geometrical condition as this research.

Preferred Air Speed

At 28°C / 42.9% RH, fan speed 3 with air speed between 0.41m/s to 0.56m/s (seat-average of 0.49m/s) can make 50% of the participants feel comfortable and over 90% of the participants feel the thermal condition to be acceptable even without group control. The range of group-selected air speed is wider between 0.49 m/s and 0.78 m/s (seat-average), which is from fan speed 3 to 7. Among the wide range, fan speed 4 with air speed 0.46 m/s to 0.67 m/s, (seat-average of 0.58 m/s) is the most preferred.

TSV, PMV, and Improvement of Comfort Level

Despite substantial individual variation, the overall trend indicates that PMV tends to overpredict actual thermal sensation, particularly at higher air speeds above 0.6 m/s. Notably, a decrease in Thermal Sensation Vote (TSV) does not necessarily correspond to an improvement in perceived comfort. For instance, at 28 °C and 42.9% RH, the comfort level does not show a clear increase with rising air speed. Instead, it remains consistently around 50% of comfort votes. The "side effects" of increasing air speed, e.g., cool or cold thermal sensation and draft discomfort, may reduce the comfort vote.

Suggestion for Practitioners

1. **Preliminary Understanding of Air Flow Pattern with Simplified CFD:** With the simplified method of CFD simulation, it is possible to gain an initial understanding of how the overall air flow pattern is and how air speed per seat varies (more uniform or more diverged).
2. **Design for Collective Comfort Zones:** With careful placement of desks and ceiling fans, the serviceable area of a single ceiling fan can be extended beyond the fan blade area, increasing average air speed at torso level (0.85 m). The power consumption in this study at preferred fan speed 3 is only 1.8W per person (7.2W) in total.
3. **Enable Personal or Group Control:** To cope with the individual difference of thermal perception and the effect of adaptation (not addressed in this research), allowing group-control enables the occupants to adjust the air speed to meet their preference according to the change of room condition.
4. **Recognize Limits in Comfort improvement from Air Speed Alone:** In this study, only half of the participants felt comfortable at 28°C and 42.9% RH even with elevated air speed. However, incorporating fan as a hybrid cooling method together with air conditioning system can still be an effective solution. For example, the set point can be increased to higher temperature like 26°C with fan rotating at low speed. The energy consumption is reduced, and comfort can still me maintained with elevated air speed.

9 Reflection

Relevance

Research of ceiling fans is a "fresh" topic in this faculty. Integrating ceiling fan to office layout has the potential to provide sustainability values in terms of "well-being of people", "energy efficiency" and "heat resilience". With the experiment of ceiling fan and desk layouts, integrated with thermal comfort knowledge that I learned during my master's study, an innovative way to utilize ceiling fan and desks will be proposed for better built environment.

Ceiling fans have been widely used in warmer climate zone, e.g., China, Japan, south-east Asia, California (USA). However, in The Netherlands, the presence of ceiling fans is rare due do the moderate climate. As global warming is a foreseen trend, extreme heat occurs more often in summer season and a heat-resilient solution is needed especially for existing non-AC building stock. Ceiling fan is a cost-efficient and energy-efficient option to offset thermal discomfort by providing elevated airflow. This thesis provides an insight of how the thermal comfort level and the air speed preference vary when a ceiling fan is shared by multiple occupants, which can be adopted into climate design process for more sustainable buildings. With this thesis I hope to raise the attention in The Netherlands for utilizing ceiling fan.

Before P2

The overall approach worked quite well. In the "research" phase before P2, I found the research gaps from the literatures, and it helped to sharpen my research questions. I focused more on the layouts that the desk surface area is larger than fan blade area and planned to investigate how the ceiling fan is diffused and how much the comfort zone can be expanded. I also had a meeting with Sebastian Enevoldsen, a building physics expert working in Danish consultant Ramboll, who also di his master's thesis on the topic of ceiling fan. His expertise also provide me more insight to the topic.

I struggled a lot when I started to do CFD simulation. The simulation itself can already become a thesis topic for fine-tuning all settings like comparing mesh resolution and trying different turbulence model. I am very lucky to have Arghyanir Giri (PhD candidate from Sense Lab) as my CFD consultant that helped me setup the simulation parameters and check if the results are reasonable.

Industrial partnership and the long waiting period for fan installation

Thanks to my second mentor Alessandra, I had chance to build connection with a Spanish fan manufacturer Sulion that supported my research. I am really proud of myself that in our first meeting, both of my mentors were busy and was not able to attend the whole meeting, and I handled the meeting by myself and convinced them to provide a fan for my research. This is something that I have never done before in my life. However, it took a month to arrange the second meeting that was for discussing details about intellectual property rights (how Sulion can access and share the result of this thesis) and fan delivering. It took another 2 weeks until the fan was finally delivered to Delft. Unfortunately, the waiting did not end here and there were still uncertainty of when the fan can be installed. I had a meeting 2 weeks after the arrival of the fan with Tim Jonathan (staff from The Green Village) and Marcel Bilow (lecturer on building construction and product design) to decide how the fan can be installed safely. With the help of Marcel, the fan was mounted firmly onto the ceiling on the next week. One more week later, the wiring was done thanks to Tim who had arranged a certified technician to connect all the electronics safely. The fan finally started spinning after almost 2.5 months since the first meeting with Sulion.

During this long waiting period, I still did things that could help me speed up the process after receiving the fan. I decided together with both of my mentors to change the location for conducting the experiment because the ceiling height in MATE Lab is not high enough to operate the fan safely. Thus, I had to adjust the CFD configuration to fit the dimensions of the new lab (a meeting room in the office building of The Green Village). I had to run the simulations again based on the new layout cases that I designed specifically for the new lab, so that I can compare the results from simulation with actual air speed measurement. Atze once mentioned that the default fan speed settings (e.g., 3 steps (low-medium-high) or 5-6 speed steps) in most of the fans that are available in the market are much higher than what users usually need. I had discussion with people from Sulion to ask if their fans can be customized to have more speed selections at lower speed range, or can it be controlled with stepless controller for the users to have more flexibility when selecting air speed. They suggested using 0-10V dimmers (that are originally designed for lighting control) to regulate the rotating speed of fan. I want to thank Pedro de la Barra Luegmayer (PhD candidate of Alessandra) that he helped me to select the suitable product and guided me through how the dimmers interact with the fan, how are the wires connected, and how to build a control interface. Alessandra helped me with the application of HREC and sharpen the questionnaires so that I can collect higher quality data from human subjects.

Thanks to these preparation works, I started working on air speed measurements flawlessly after the fan was installed. Even though there were only 2 weeks left until the date that I have to hand in my P4 report, I still managed to do measurements with several layout and fan speed cases which provide results that can validate whether the CFD simulation results are accurate. I also did one pilot test with 4 participants to check if everything worked smoothly during the experiment procedure. Luckily few critical problems were identified so I can make adjustment before the larger scale experiment.

After P4

The measurements and experiments after P4 greatly improved the quality of this research, with 2 validations across the different phases of my research. The first validation is using air speed measurement results to validate the results from CFD simulation, which turned out to be a significant difference between simulation and reality. The second validation was done by collecting thermal perception data from experiments with 24 participants and compare the results with PMV values derived from measured air speed. The individual difference in thermal perception is also more widespread than I imagined. In contrast, the improvement of thermal comfort with elevated air speed was not as significant as I expected. Nevertheless, being able the validate “simulation” or “prediction” with what happens in the real world is a great pleasure.

If I can redo the project...

I would try to collect more anemometers to make the air speed measurement more efficient, or somehow try to collaborate with a laboratory (maybe the new lab of Sulion, or the lab in UC Berkeley) with better measurement instruments (the anemometer tree). I would also incorporate skin temperature sensors to compare the subjective questionnaire results of thermal sensation with objective physiological data. I would also try to use a symmetrical scale for thermal comfort vote, (-3 very uncomfortable to +3 very comfortable), and maybe adding another question for satisfactory.

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Annex A: CFD simulation results

9.1.1 Case 2B

It can be observed that the air speed is the lowest at Seat D (bottom-right), because the air flow is "shaded" by the linear partition. The shaded air flow is redirected along the linear partition as a horizontal jet that stretched beyond the edge of desk surface and partition.

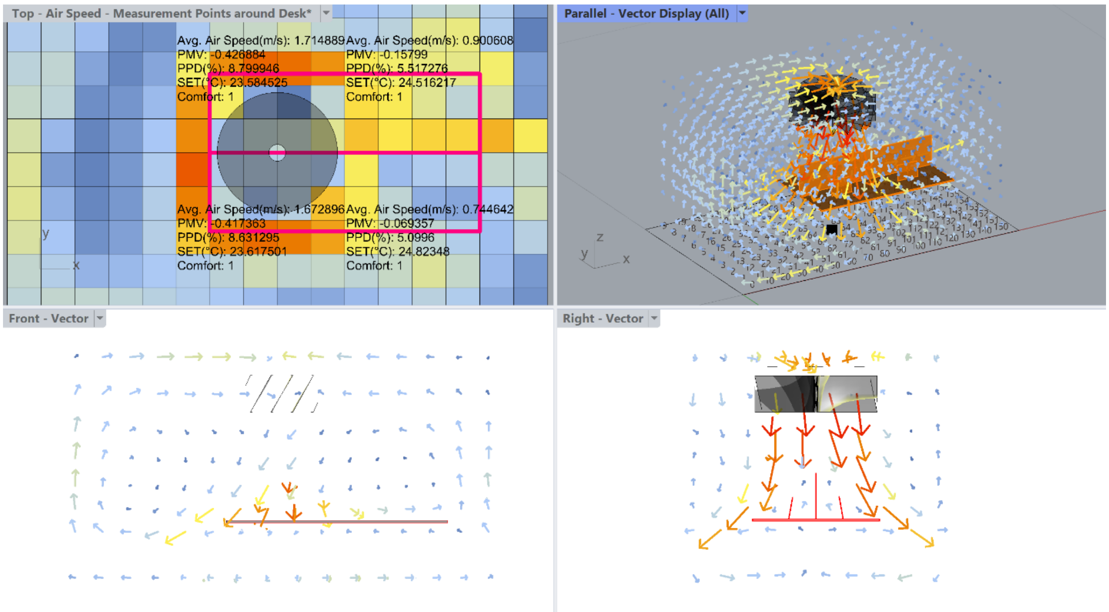

Figure 88: Air speed pattern of Case_2B.

9.1.2 Case 3A

The desks are rotated 90 degrees that increased the distance between desk edges (longer ones) from 80cm to 180cm. The aim of this rotated layout is to examine if the changing of distance between desk edge and surrounding walls has influence on the simulated air speed. A tendency that the seat at top-right has the highest air speed, the bottom-right seat has the lowest air speed, and the 2 seats on the left have similar air speed is similar to the result of Case_1A.

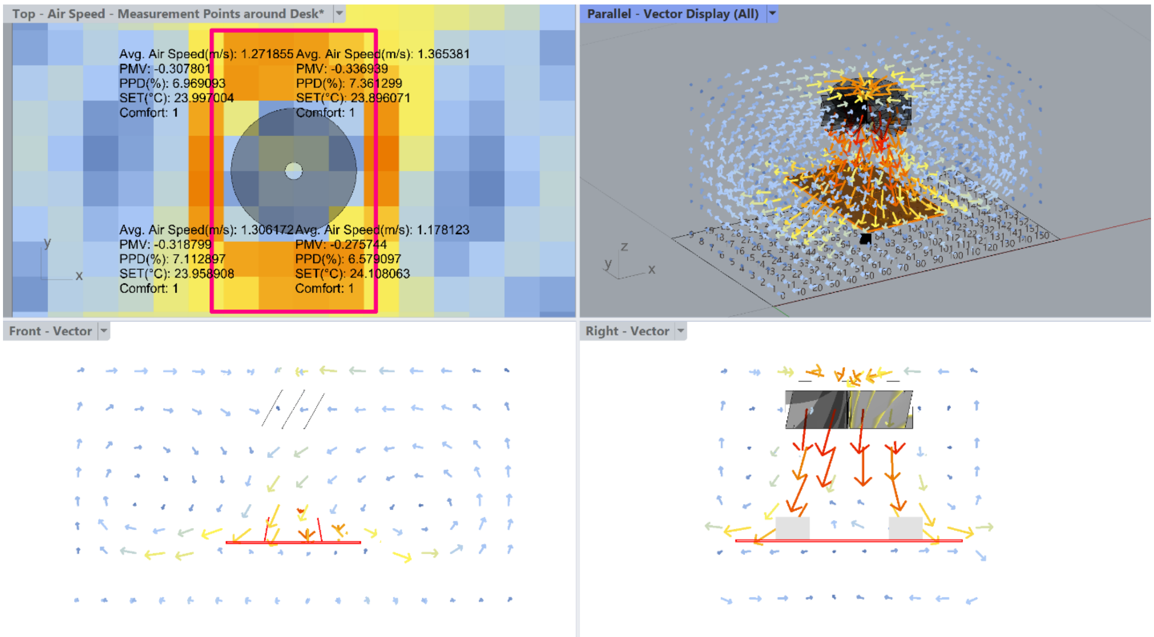

Figure 89: Air speed pattern of Case_3A.

9.1.3 Case 3B

In this case, the seats at top-right and bottom-left as higher air speed (average 1.37 m/s) than the other seats (average 1.12m/s), with 0.25m/s difference.

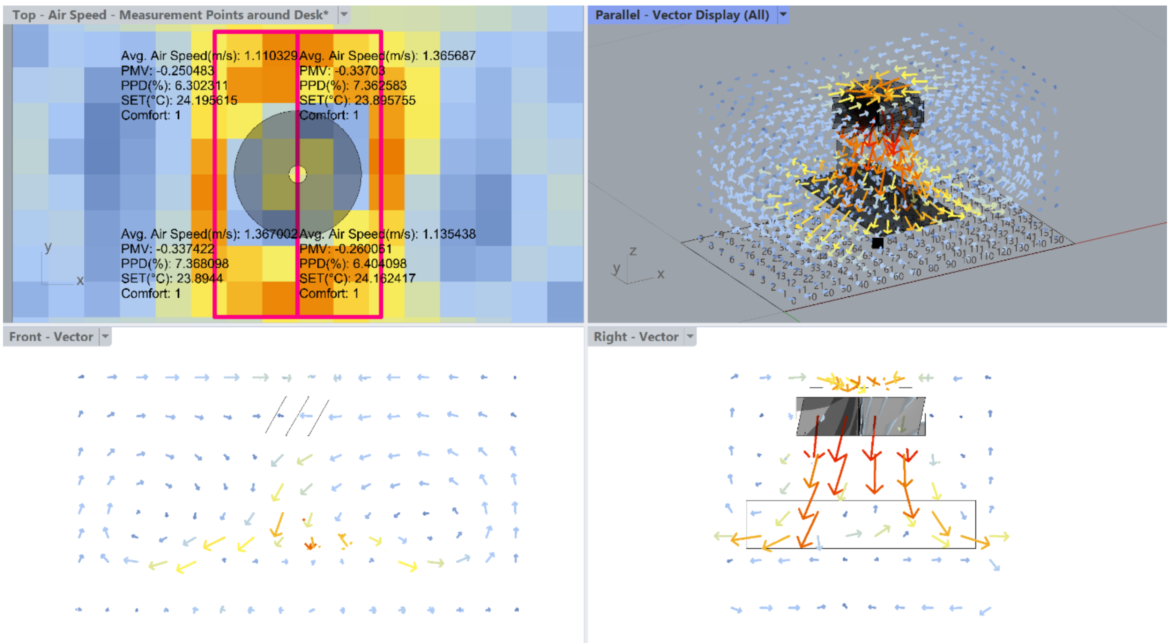

Figure 90: *Air speed pattern of Case_3B.*

9.1.4 Case 5A

FAS = 2.23m/s (Speed 5, downward)

In this case, the desks are moved 60cm towards the right. The seats at the near-end are located directly under the blade area within the jet zone, while the seats at the far-end are located in the still-air zone, causing great difference (nearly 70%) in the air speed at seat locations.

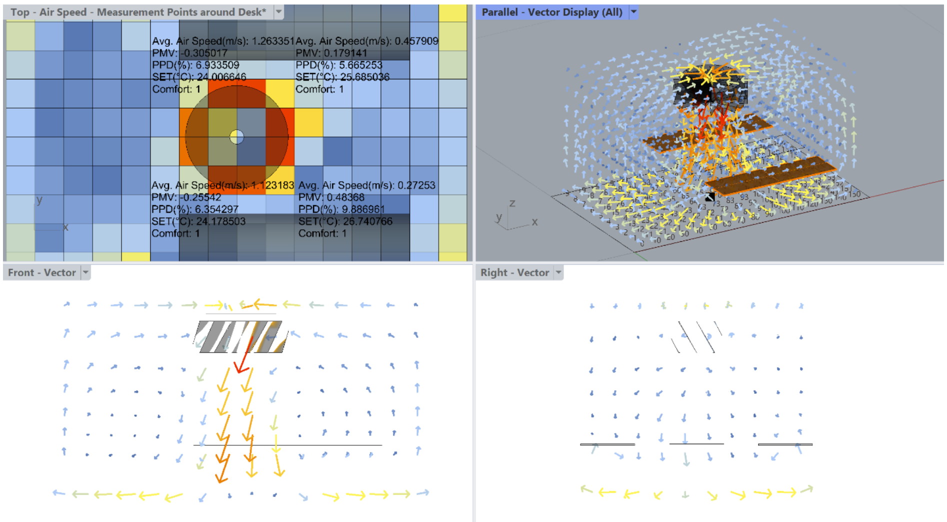

Figure 91: Air speed pattern of Case_5A with downward air flow.

FAS = -2.23m/s (Speed 5, upward)

The air speed difference is not as much as the previous case, but there is still 33% difference when comparing the average air speed of the near-end seats with far-end seats.

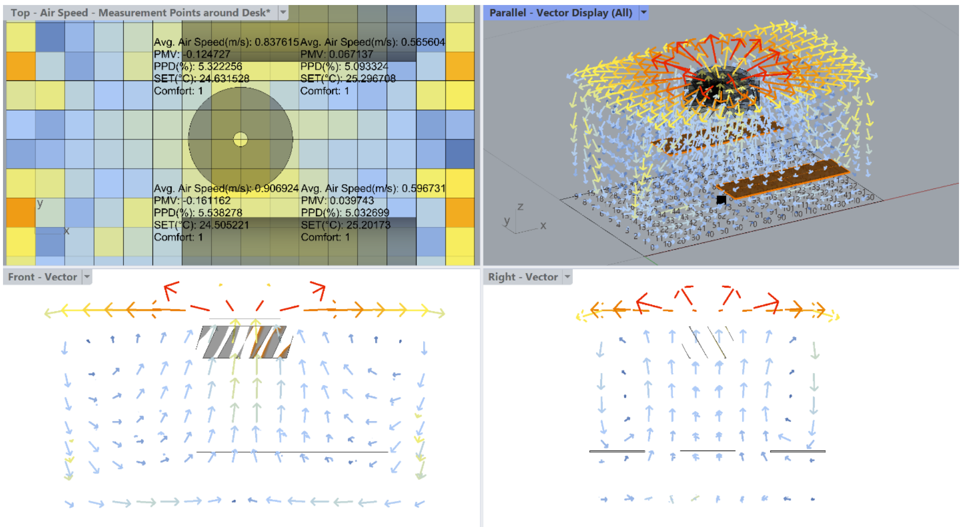

Figure 92: Air speed pattern of Case_5A with upward air flow.

9.1.5 Case 6A

FAS = 2.23m/s (Speed 5, downward)

In this case, the desks are rotated 90 degrees. The seat locations are close to the fan blade area, resulting in higher air speeds.

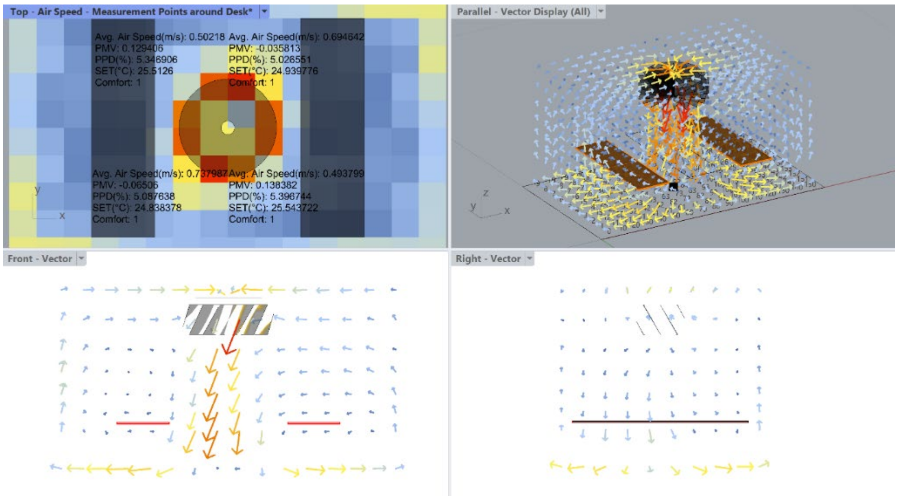

Figure 93: *Air speed pattern of Case_6A with downward air flow.*

FAS = -2.23m/s (Speed 5, upward)

Even though the desks do not have direct contact with the surrounding walls to redirect the downward are flow along the wall surfaces, the return air flow still results in medium air speed at seat locations.

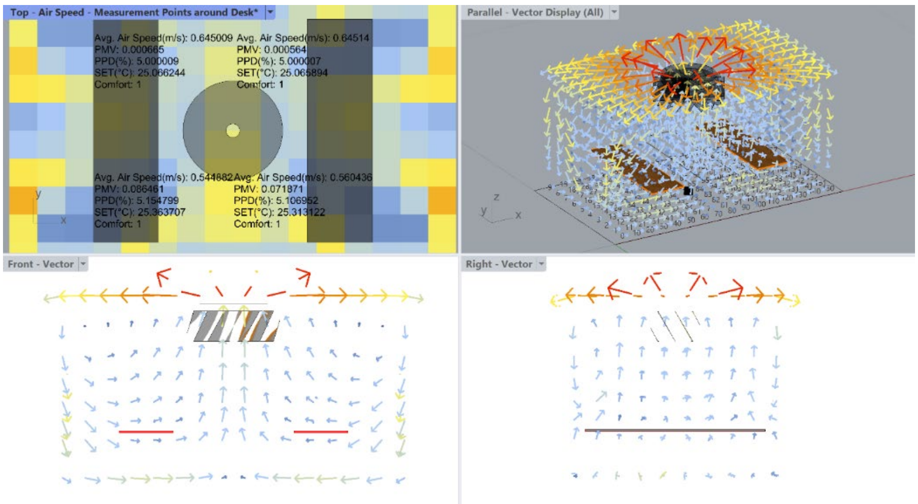

Figure 94: *Air speed pattern of Case_6A with upward air flow.*

Annex B: Questionnaires

- Opening Questionnaire
- Session Questionnaire
- Ending Questionnaire