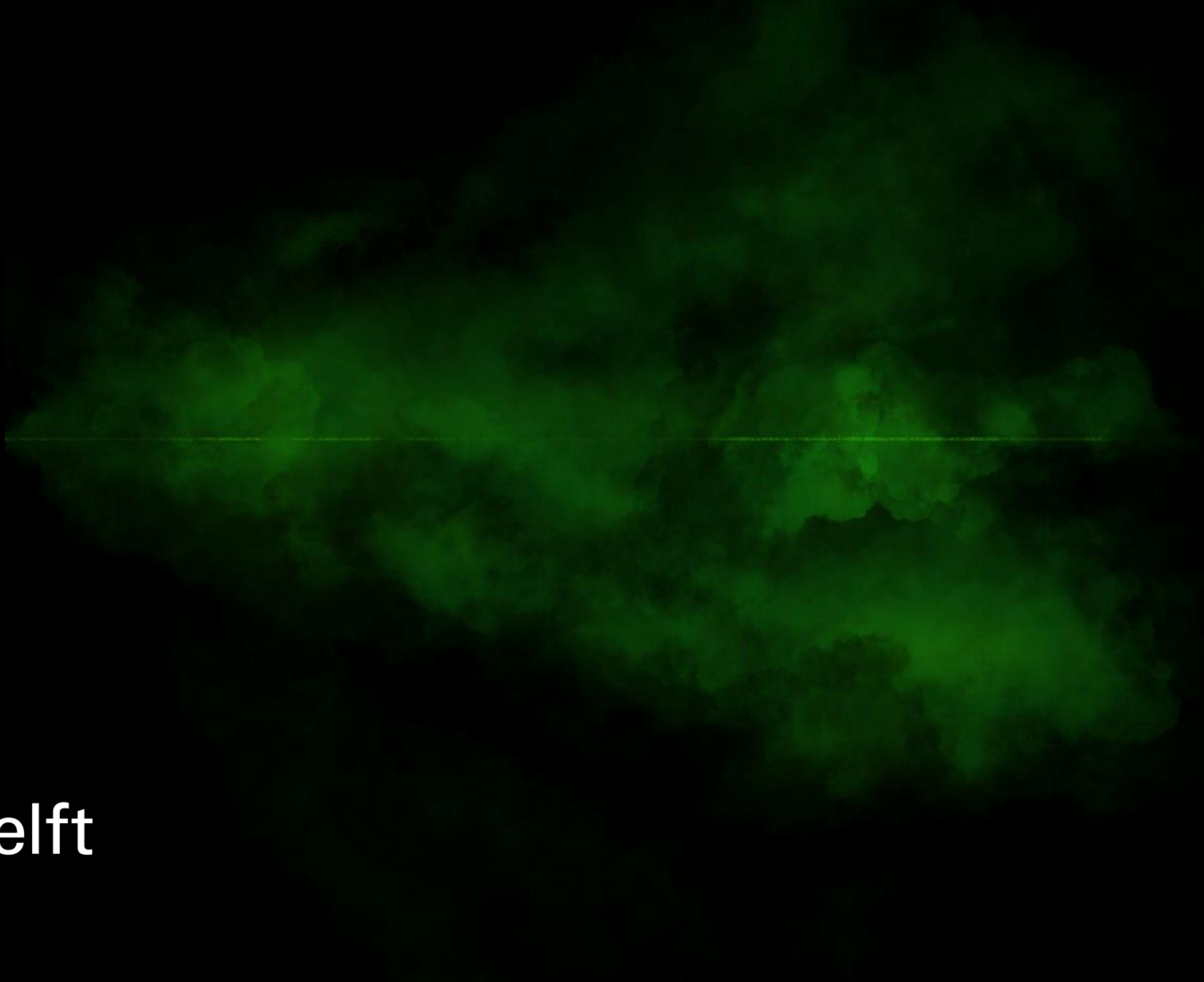
Visualisation of the airflow pattern of exhaled droplets in a classroom

Yat Long Liu

MSc Thesis – Defence

17th December 2021

TU Delft



Thesis committee

Prof. dr. ir. P.M. Bluyssen
Dr. ir. M.A. Ortiz Sanchez
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Dr. ir. H.R. Schipper

Outline

1. Introduction
2. Literature review
3. Methodology
4. Results and discussions
5. Conclusions and recommendations

1. Introduction

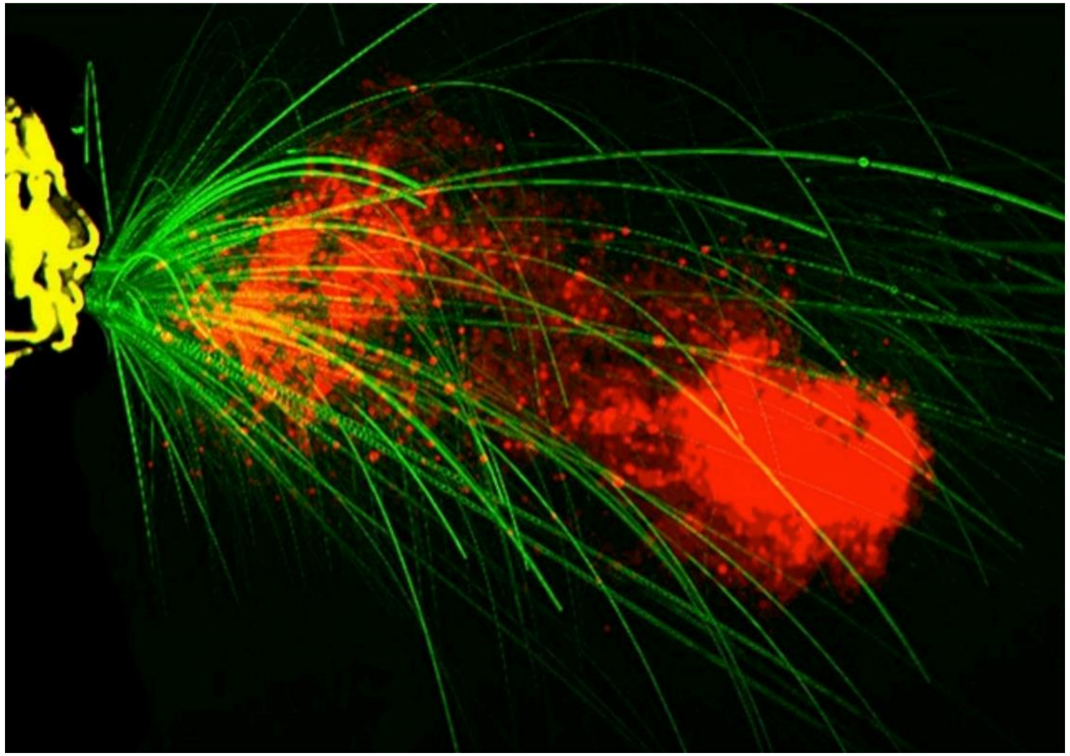
What is it?

Why is it relevant?

What is the goal?

What is the research question?

What is it?



L. Bourouiba (2020)

https://youtu.be/-ZZSmFev0Zk

What is it?

Stokes' law → how long it takes for a small spherical particle to fall

Particle diameter

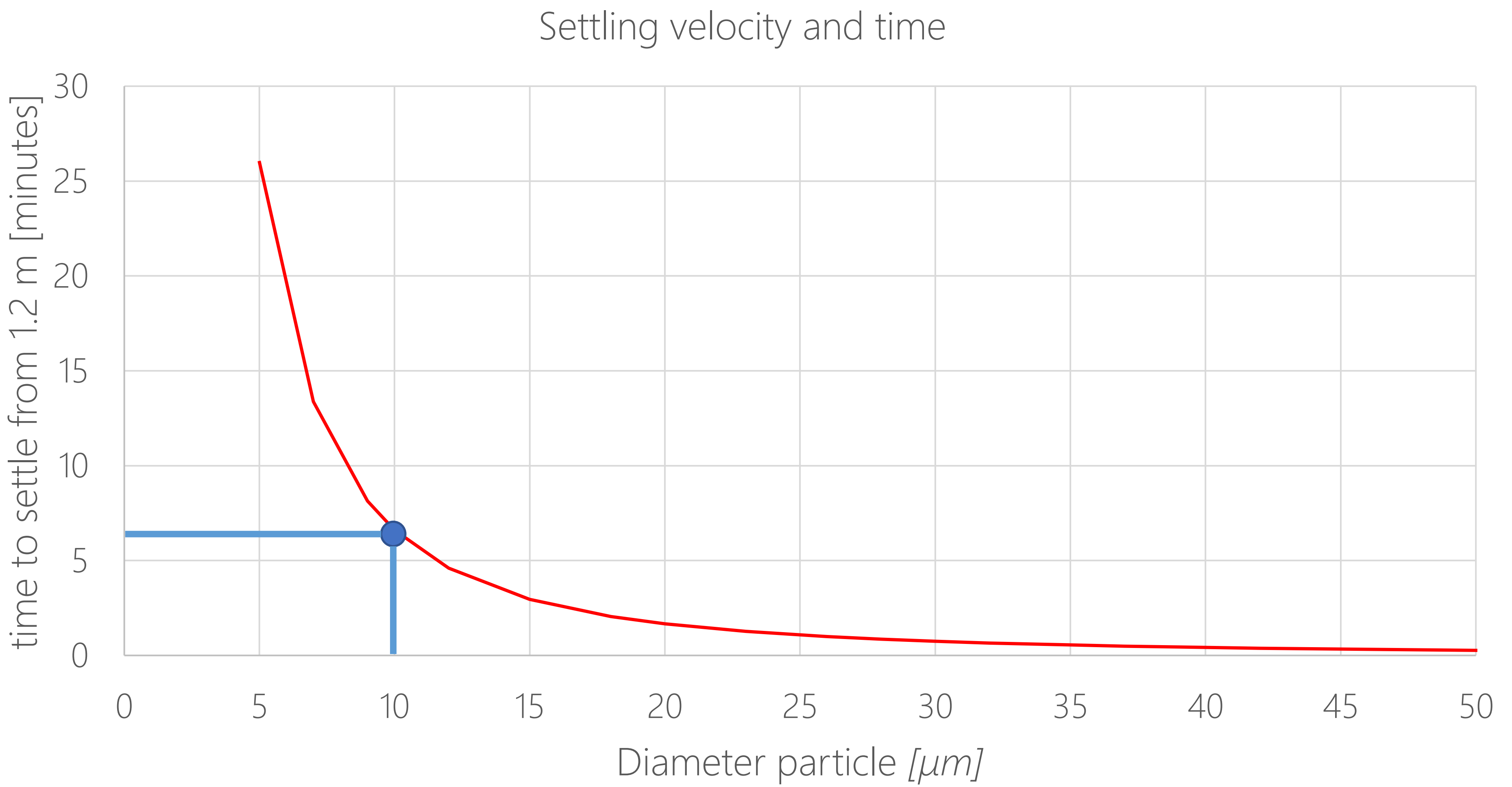
Particle density

$$v = \frac{g d^2 \rho_p C}{18\mu}$$

Dynamic viscosity

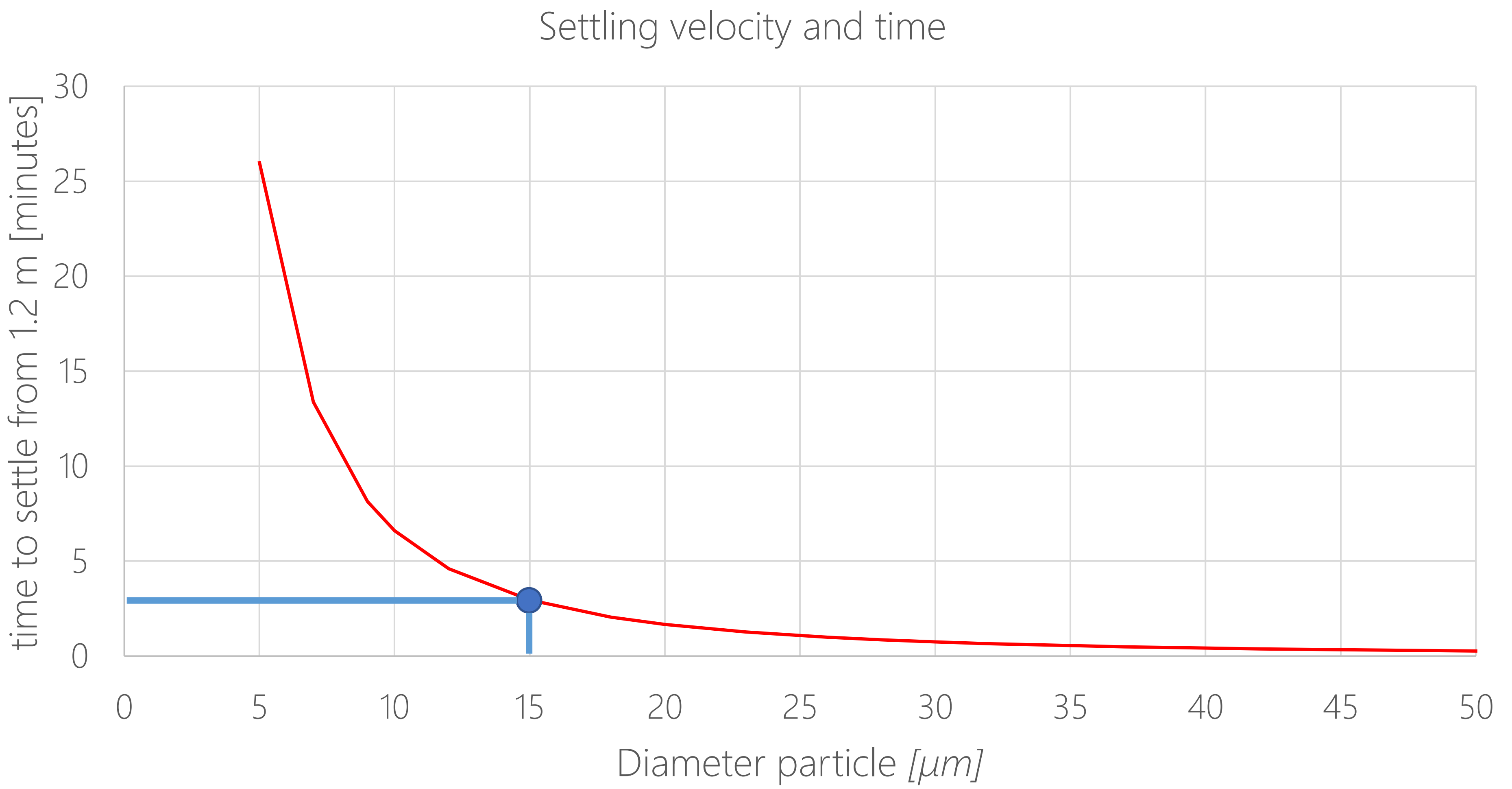
What is it?

$$v = \frac{g d^2 \rho_p C}{18\mu}$$

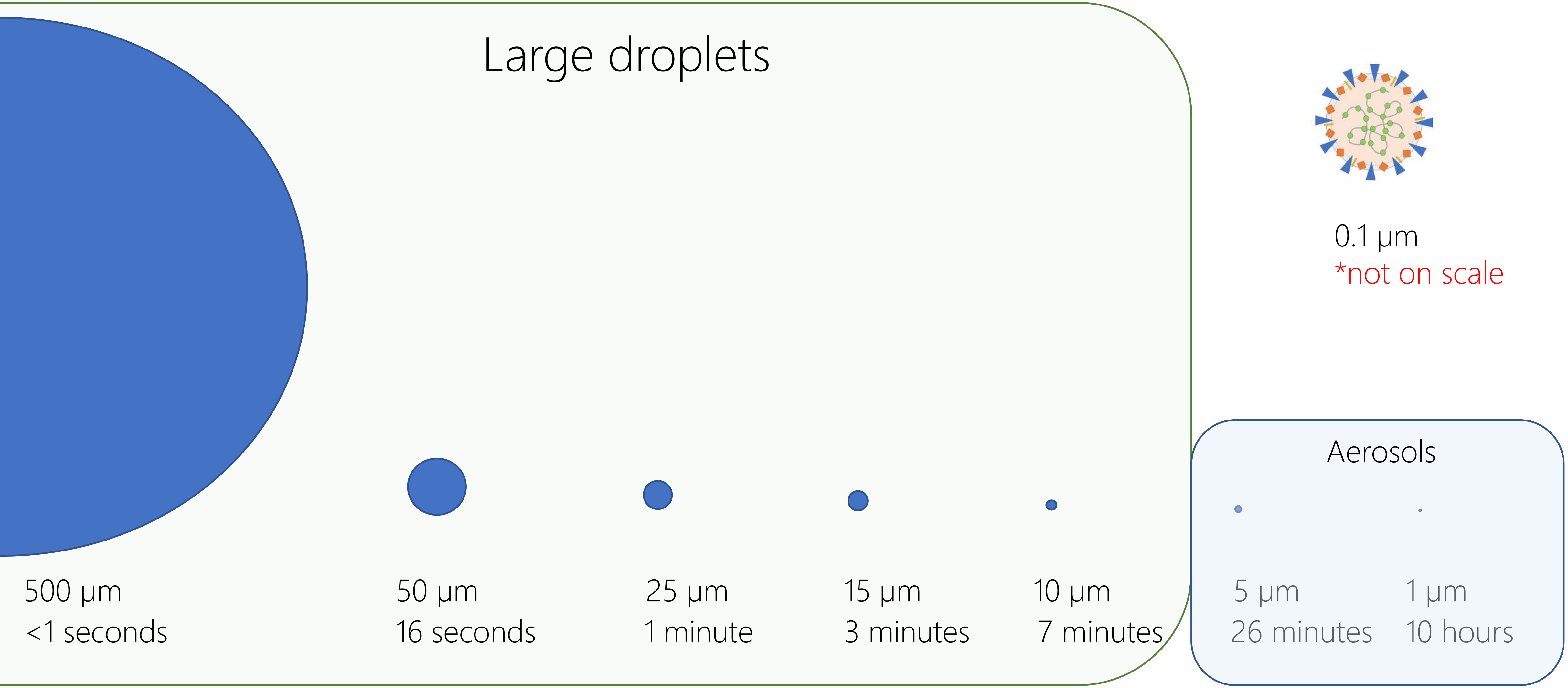


What is it?

$$v = \frac{gd^2\rho_p C}{18\mu}$$

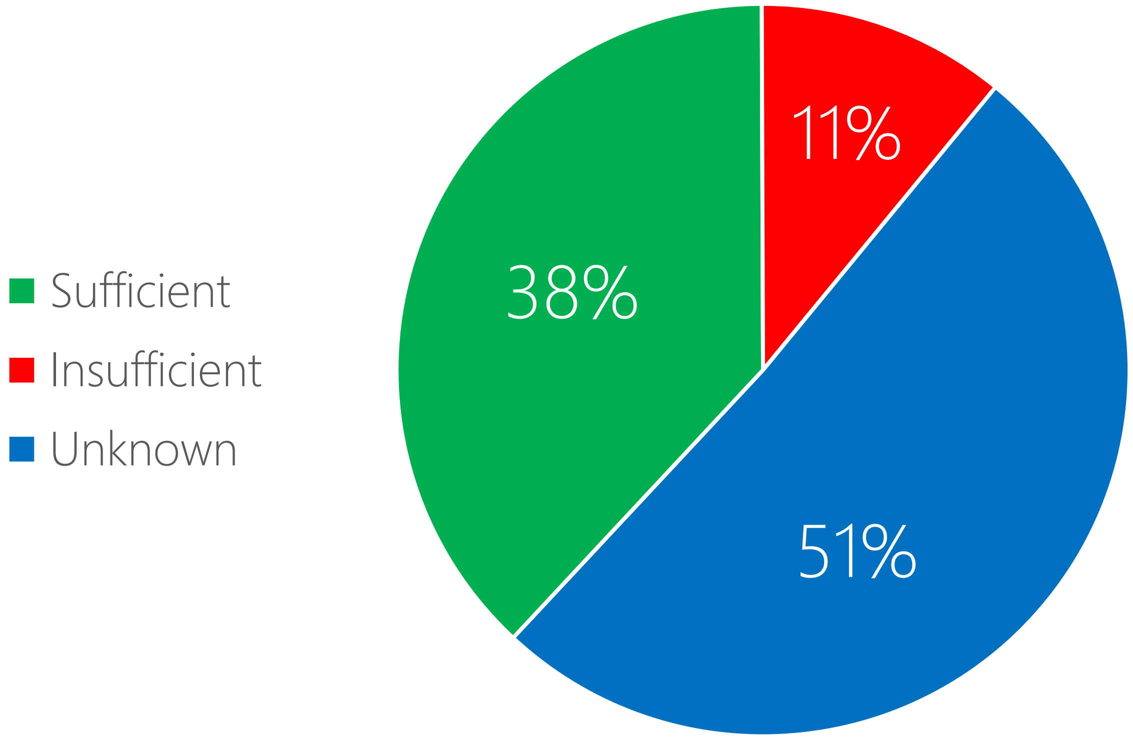


What is it?


Large droplets
0.1 µm
*not on scale
Aerosols
500 µm
<1 seconds
50 µm
16 seconds
25 µm
1 minute
15 µm
3 minutes
10 µm
7 minutes
5 µm
26 minutes
1 µm
10 hours

Why is it relevant?

Air quality at school (n=7340)



LCVS (2020)

30% = natural ventilation

NOS (2021)

What is the goal?

Visualise the airflow pattern of exhaled droplets

Sitting behind the desk in a classroom

Effect of the different ventilation systems

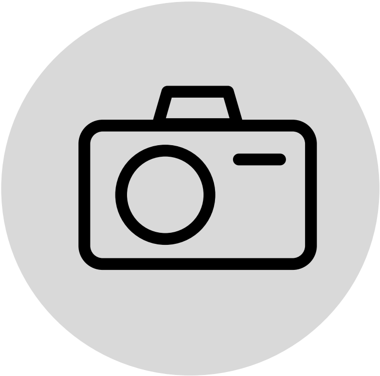
Portable system

What is the research question?

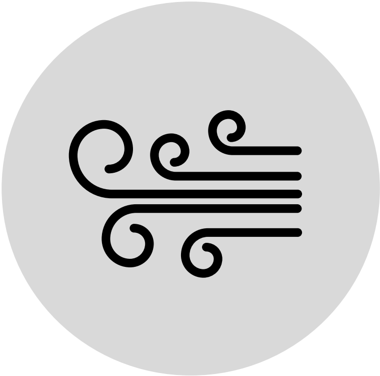
Main research question:

'How is the airflow pattern of 'exhaled' droplets affected in a classroom under different ventilation regimes?'

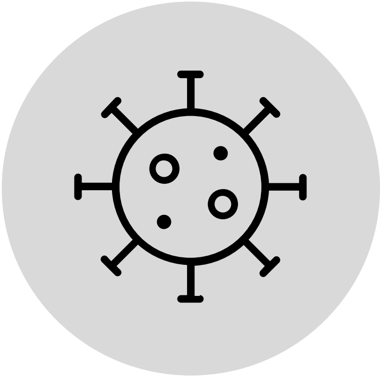
Instruments required



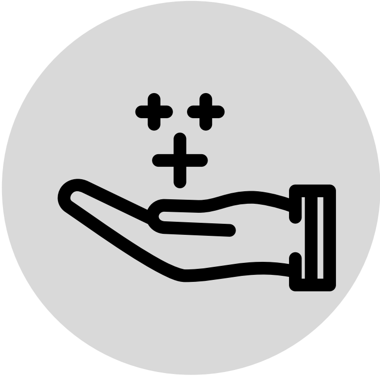
Record the experiment



Different ventilation regimes



Reduce the spread of aerosols



Added value of the setup

2. Literature review

Ventilation

Temperature

Relative humidity

Visualisation techniques

The role of ventilation

Applying ventilation = removes 'old air' (polluted)

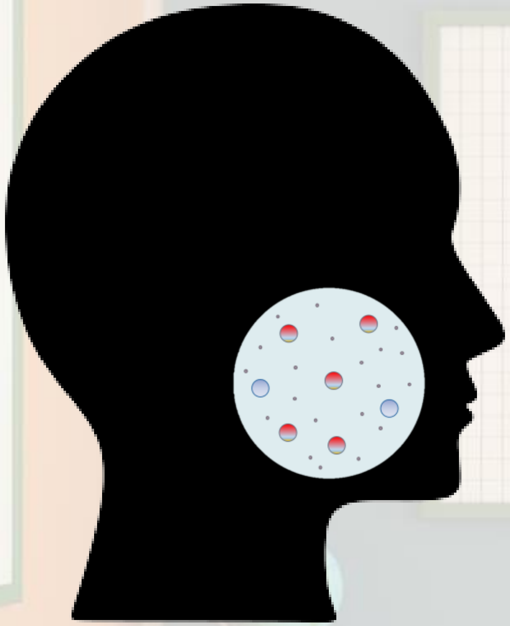
Low ventilation rate = more accumulation of respiratory droplets

Air distribution = how the droplets disperse (ceiling grilles, windows)

Limits the transmission of respiratory infections

Yang and Marr (2011)

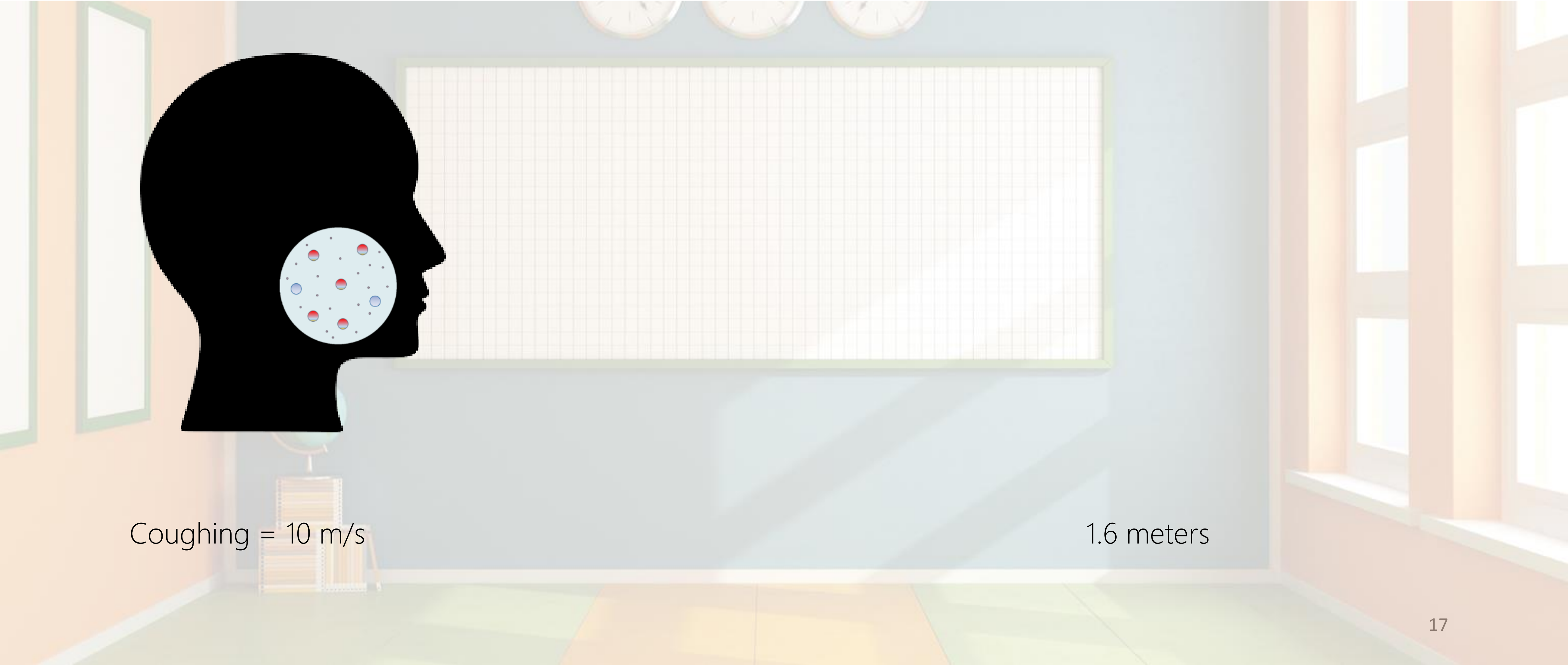
Breathing velocity (droplet = 500 μm)



Breathing = 1 – 4 m/s

1.1 meters

Coughing velocity (droplet = 500 µm)



Effect of the temperature on the droplets

Increasing the temperature → droplets evaporates much faster

Higher than 24°C → decreases virus' lifespan

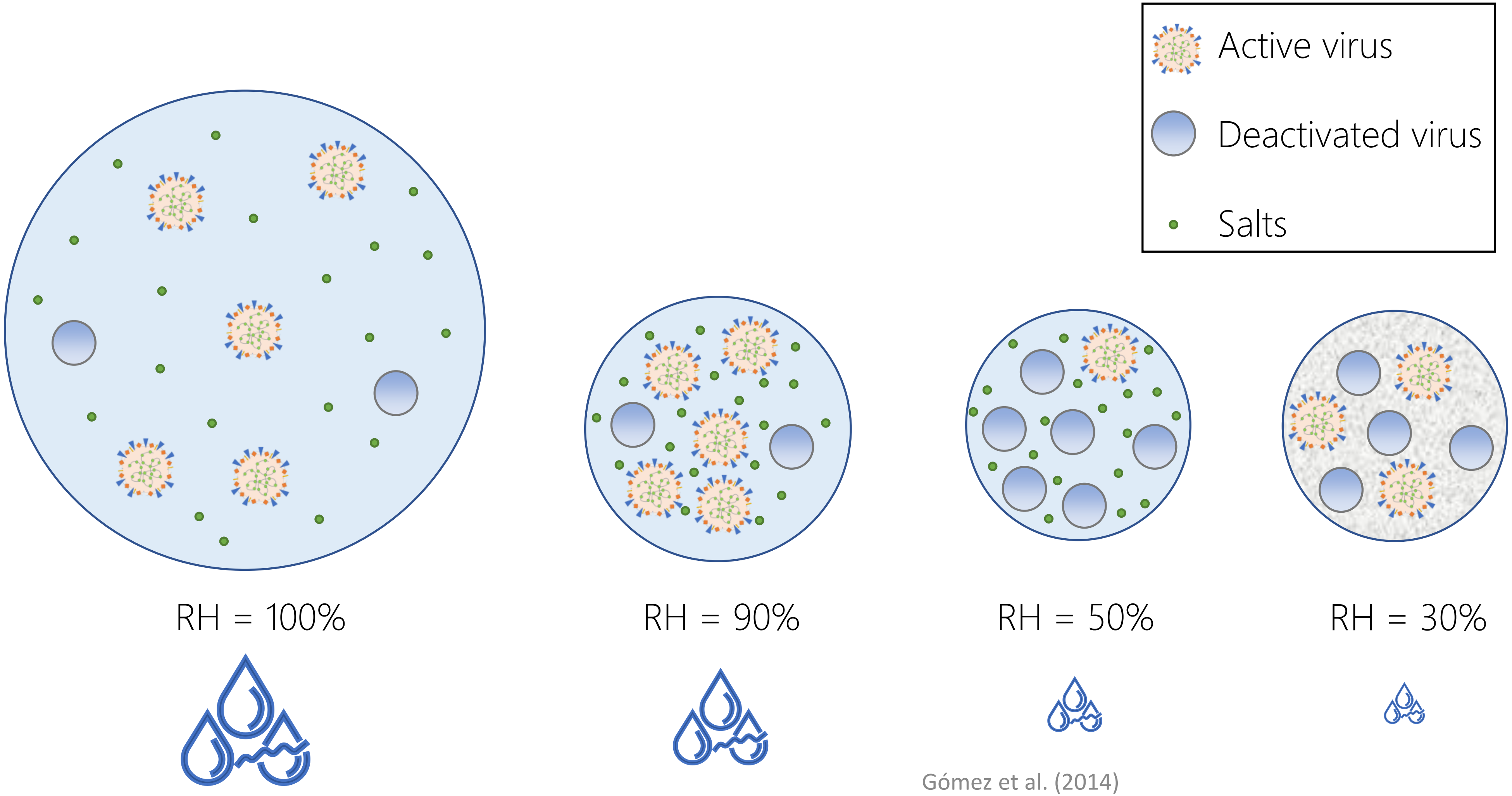
Virus viability stable at colder environments

Biryukov et al. (2020)

Relative humidity

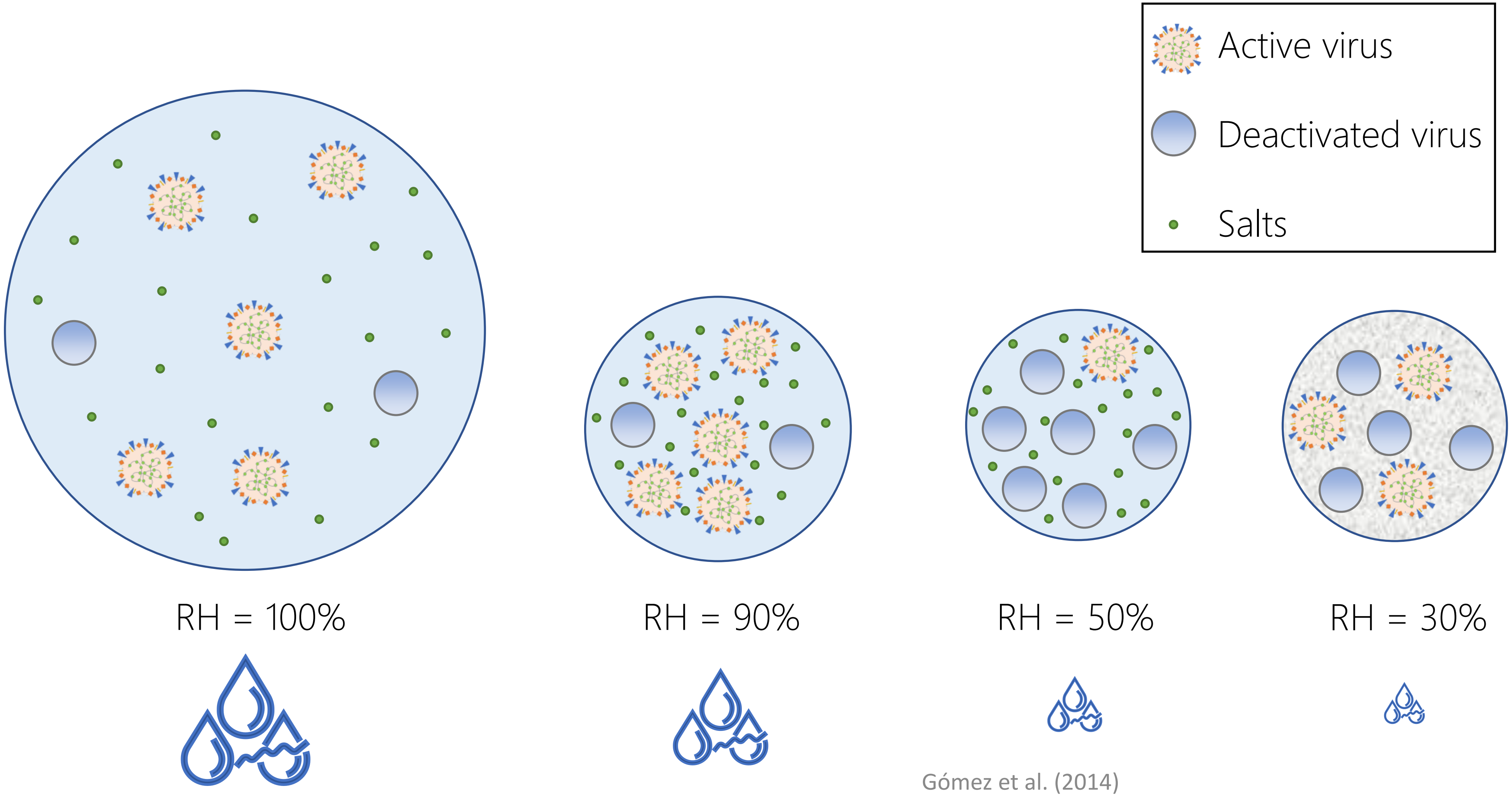
Relative humidity

Effect of the relative humidity on the droplets



Gómez et al. (2014)

Effect of the relative humidity on the droplets



Gómez et al. (2014)

Relative humidity

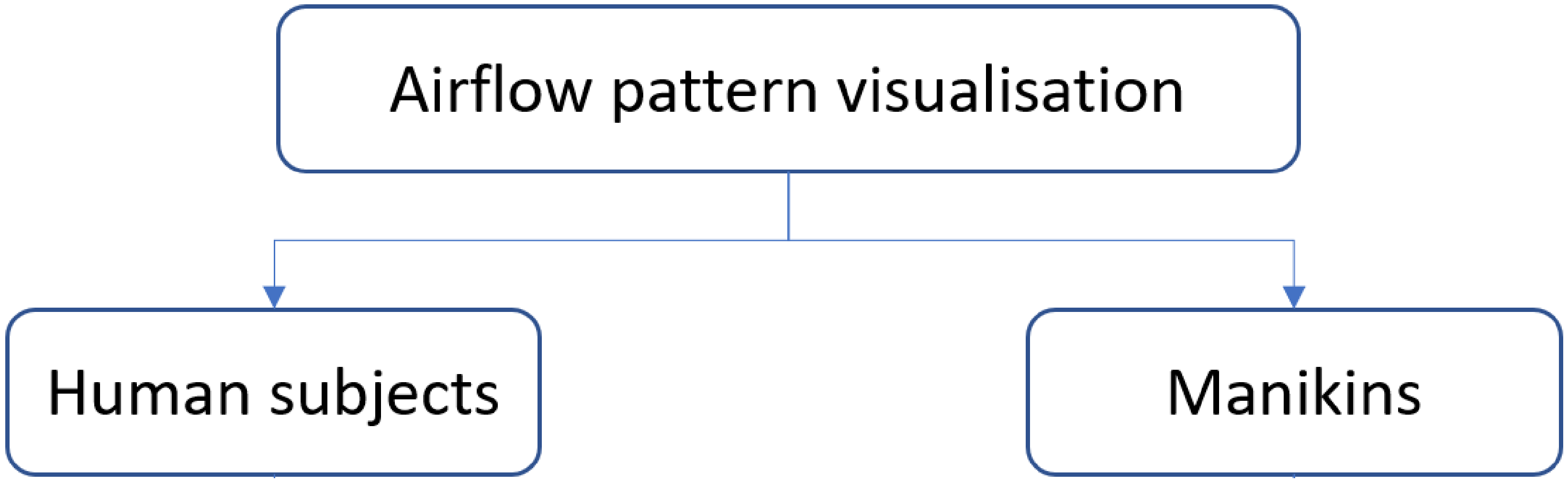
Keep RH between 40–70% → comfortable level

Dangerous when RH <30% → crystallisation

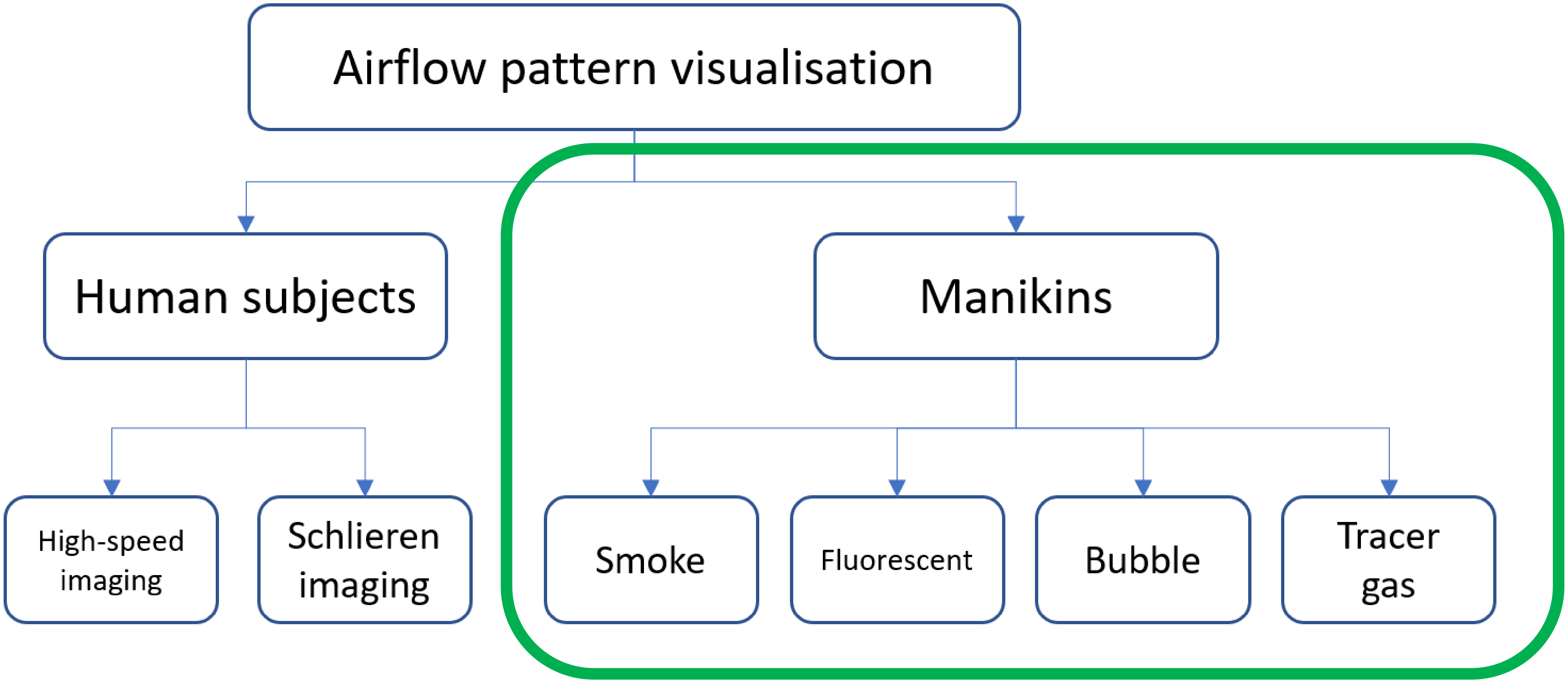
Humans are more susceptible when RH <20% → ‘dry air’ (mucous membrane)

Kudo et al. (2019)

Visualisation techniques

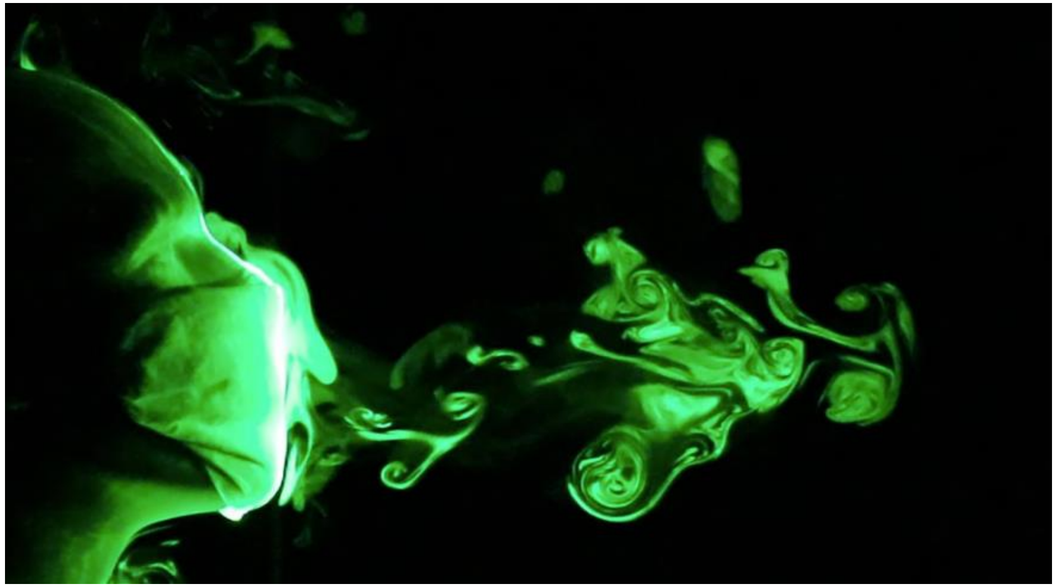


Visualisation techniques



Visualisation techniques – Manikins

Smoke



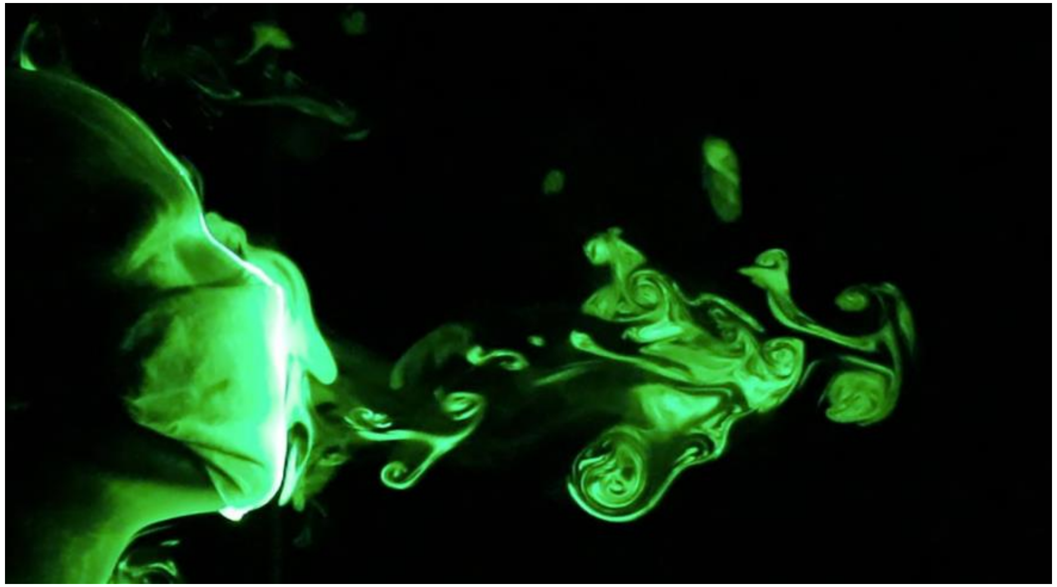
Verma, Dhanak, and Frankenfield (2020)

Fluorescent

Ortiz, Ghasemieshkaftaki, and Bluyssen (2021)

Visualisation techniques – Manikins

Smoke



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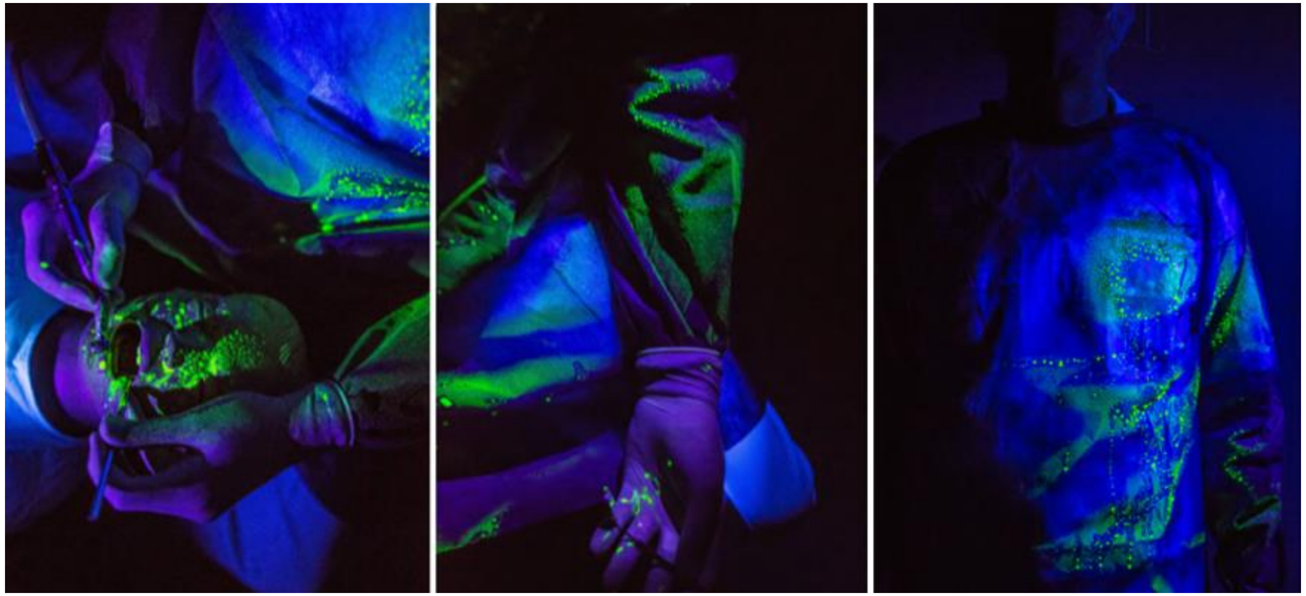
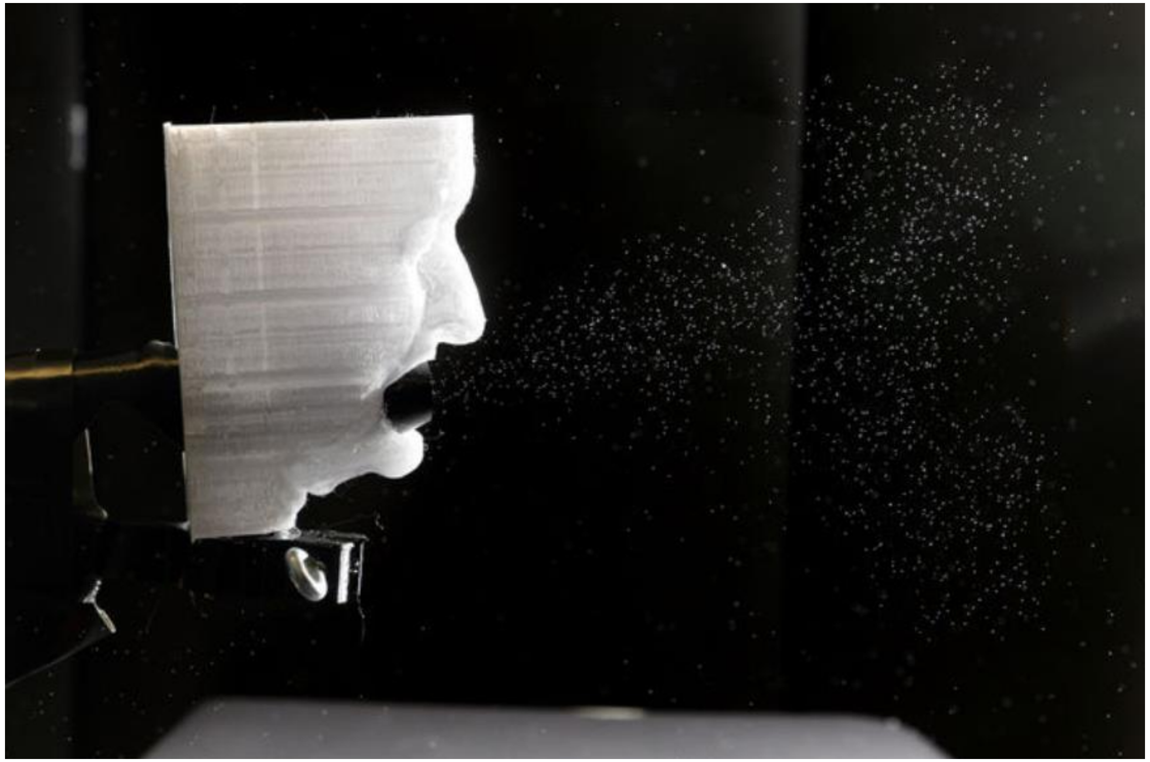
Fluorescent



Teichert-Filho et al. (2020)

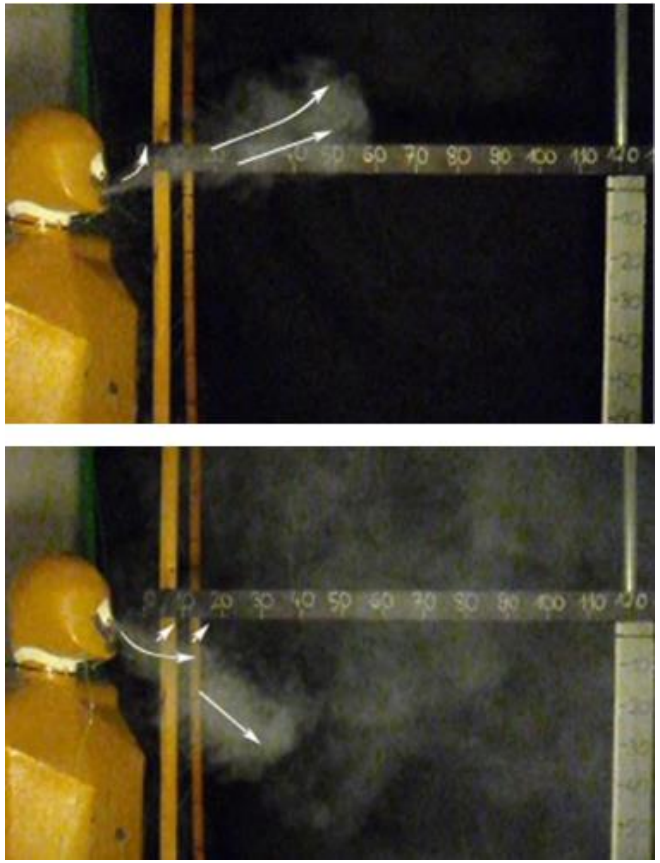
Visualisation techniques – Manikins

Bubble



Bluyssen, Ortiz, and Zhang (2021)

Tracer gas



Nielsen (2009)

3. Methodology

Location

Assembling procedure

Final setup

Ventilation regimes

Analysing the results

Where did the experiments take place?

Experience room

Study the effects of different combinations of environmental conditions

How to assemble the portable fog generator?

Medium

Fog generator

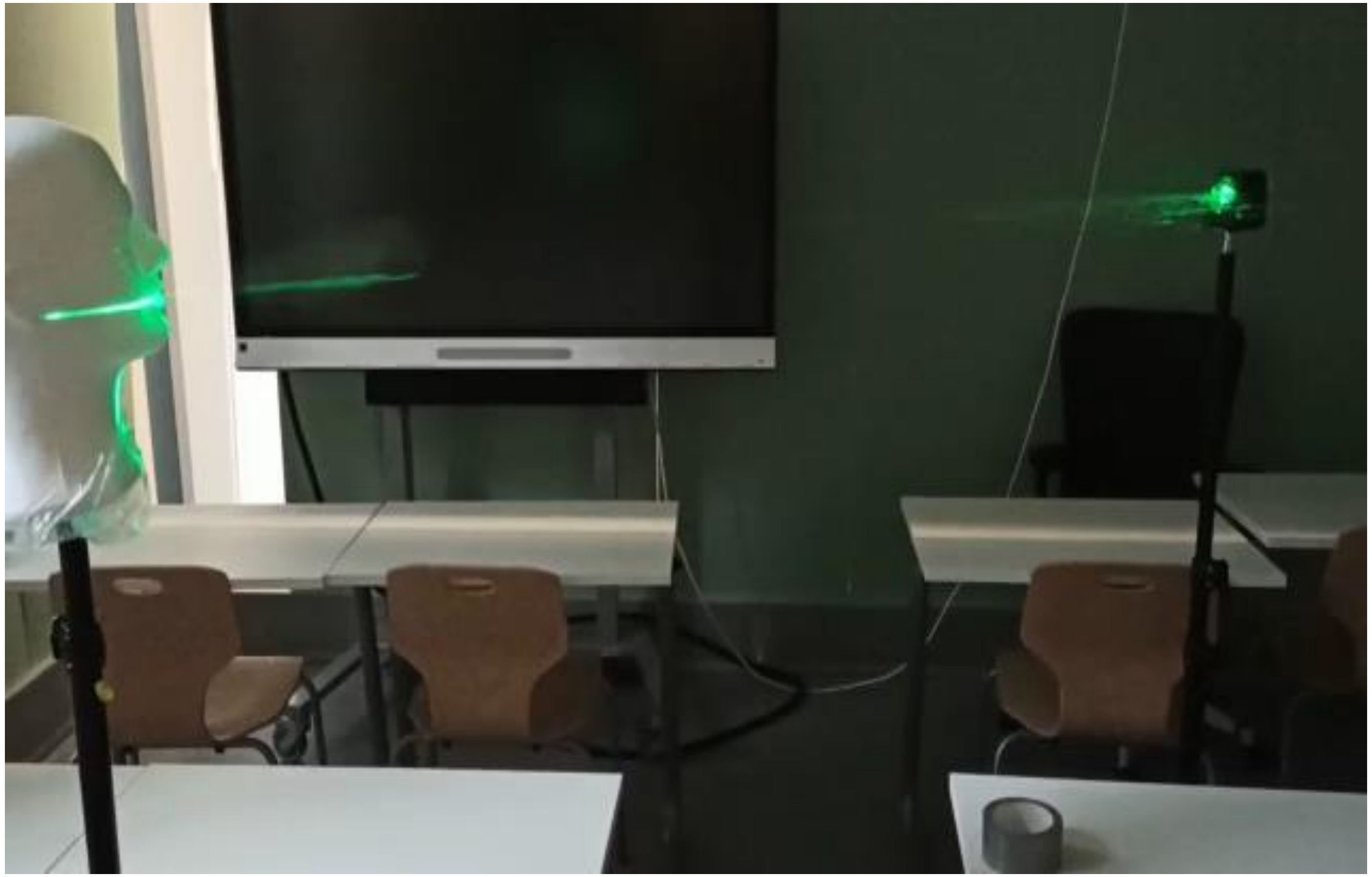

Buffer


Pump

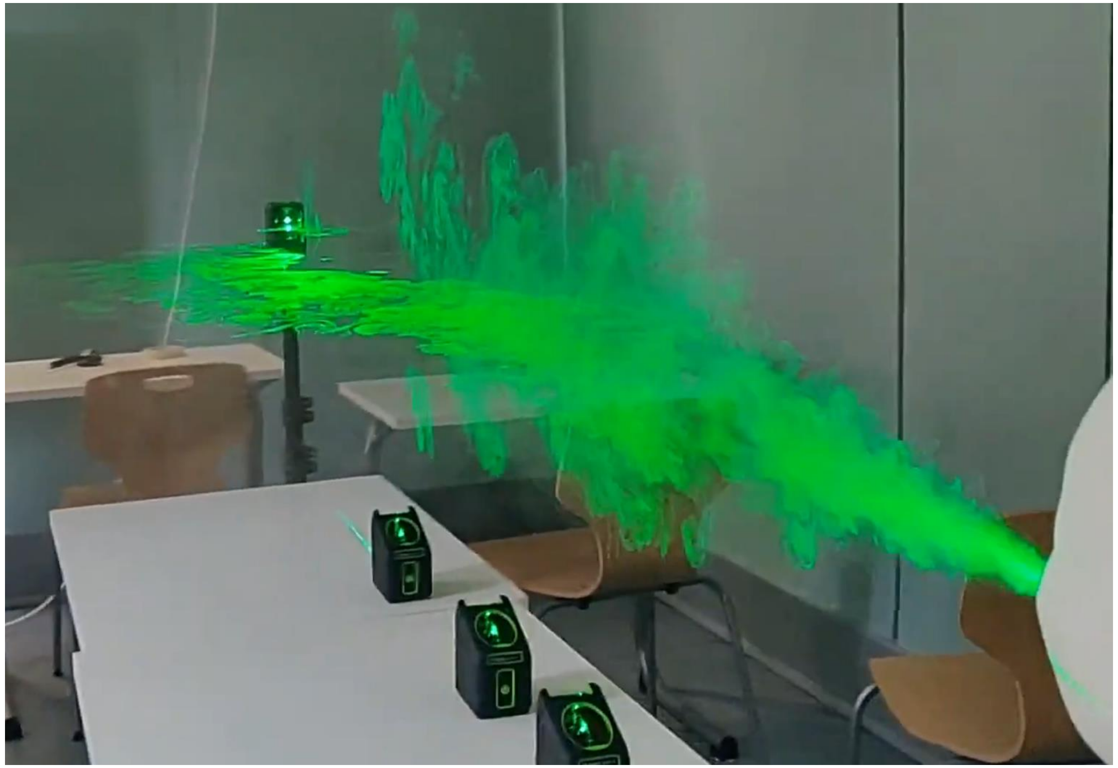

Head

Testing the setup

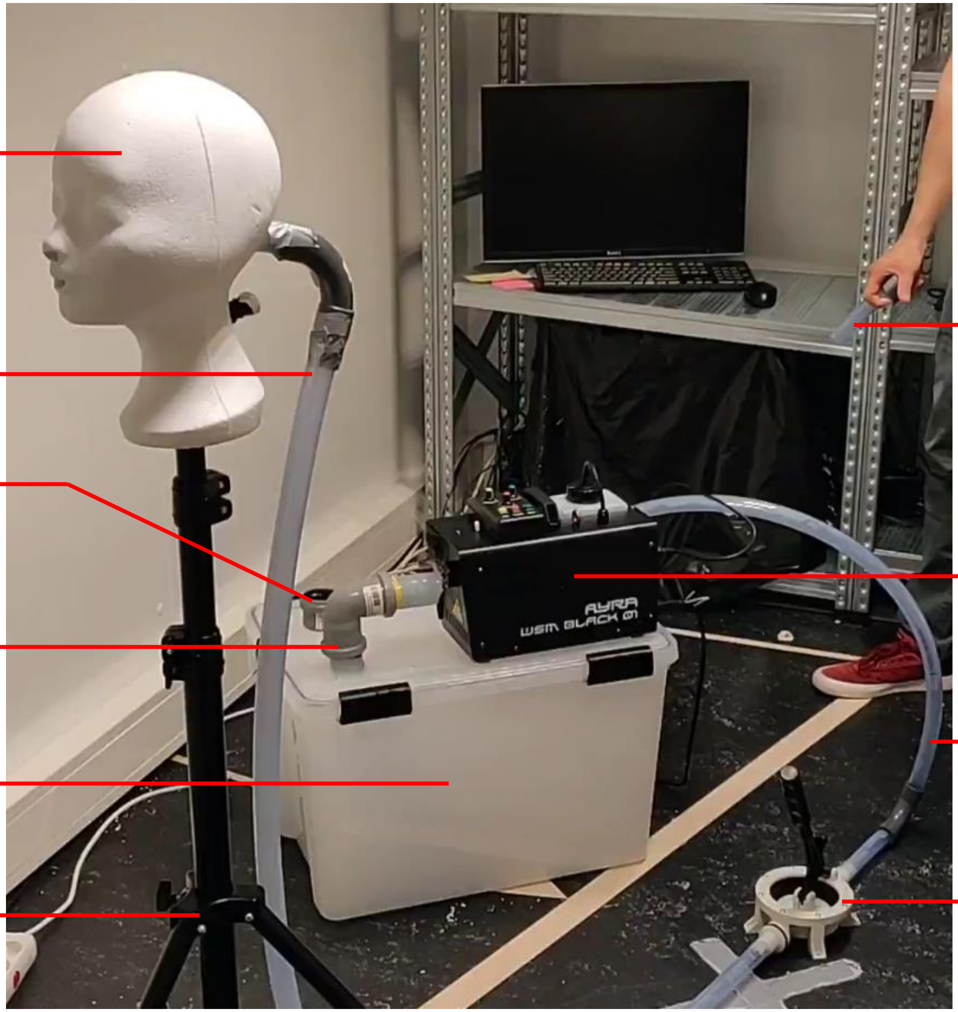
Visualisation with laser



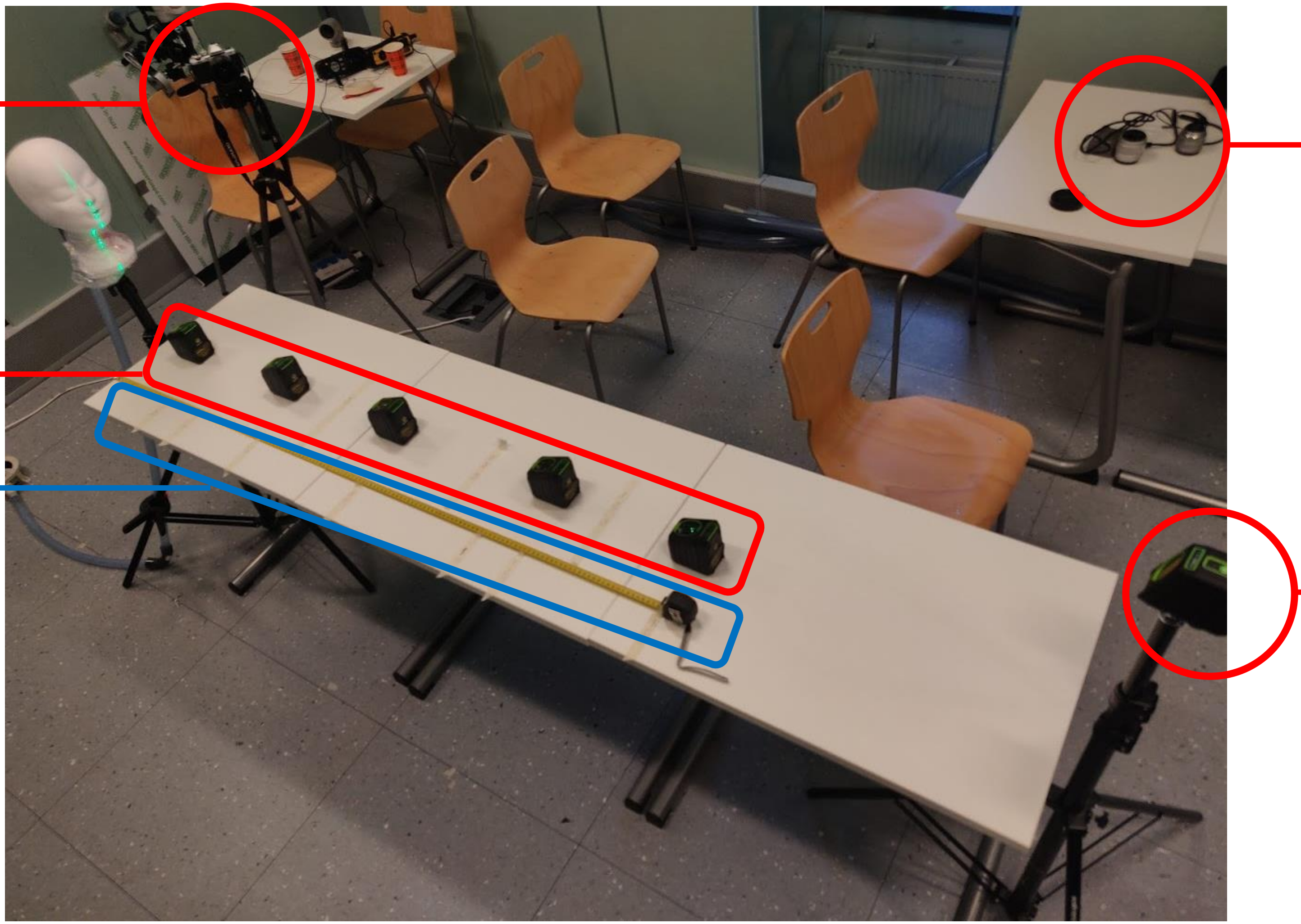
Increasing the visibility with more lasers



Final setup of the portable fog generator system

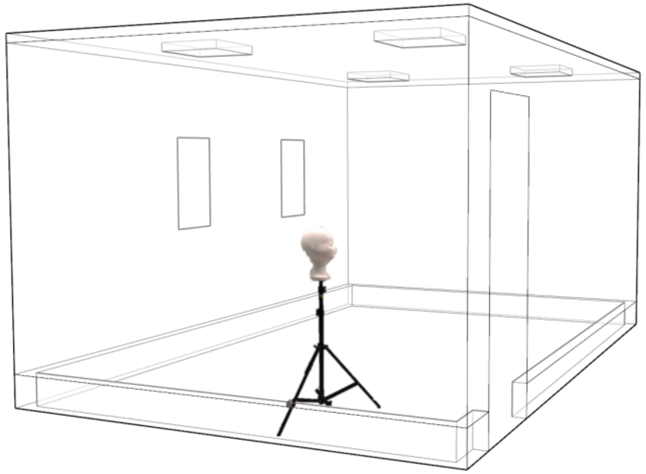


The final test setup for the experiment

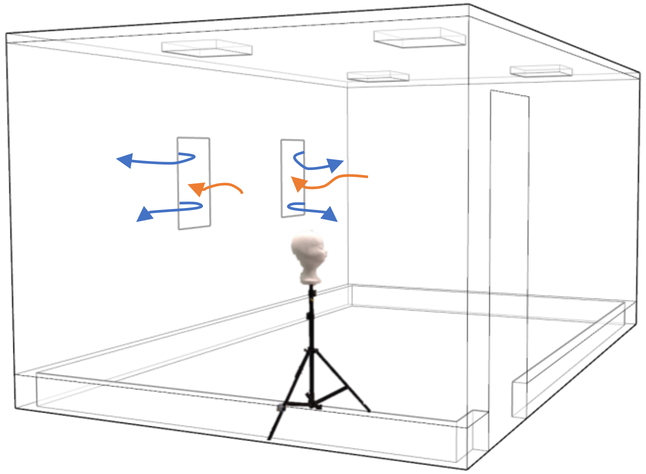


Which ventilation regimes were applied?

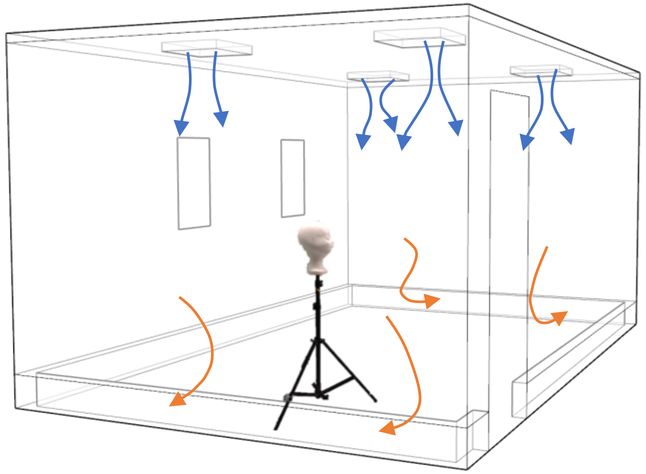
No ventilation
0.027 m/s



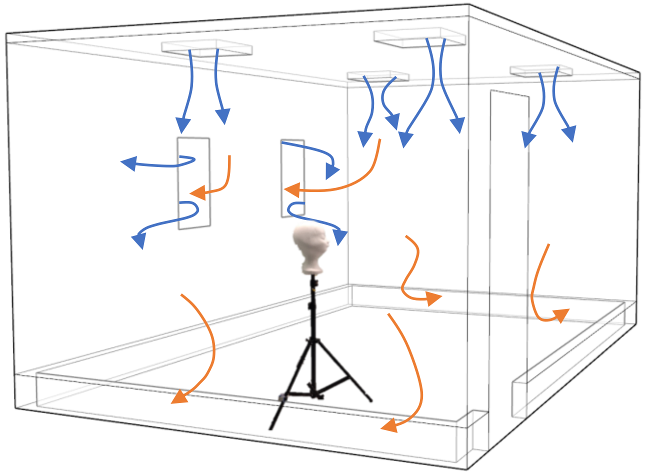
Natural ventilation
0.031 m/s



Mixing ventilation
600 m3/h
0.032 m/s



Natural +
mixing ventilation
0.058 m/s



How were the results analysed?

Distance

Duration

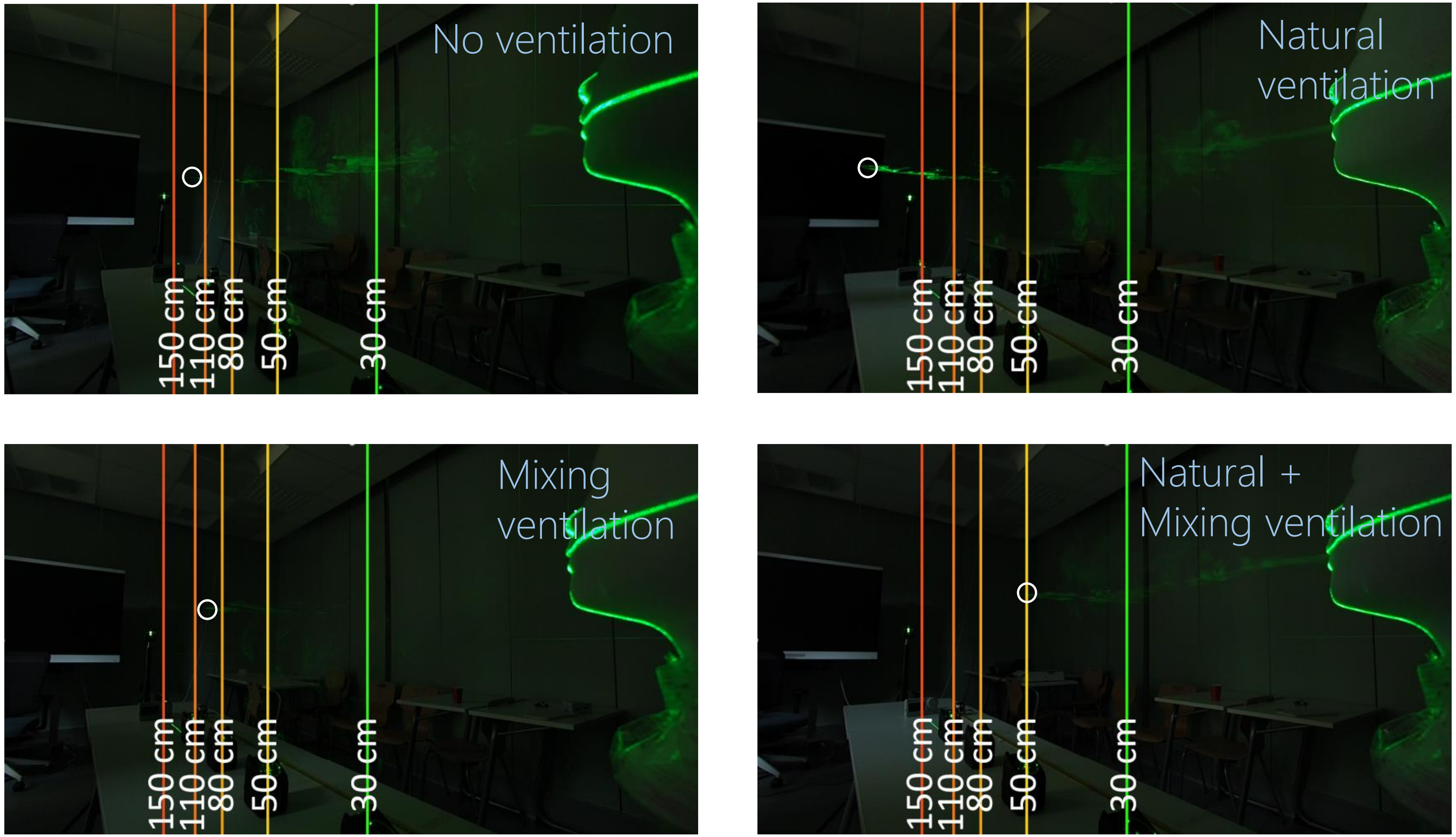
Percentage of droplets

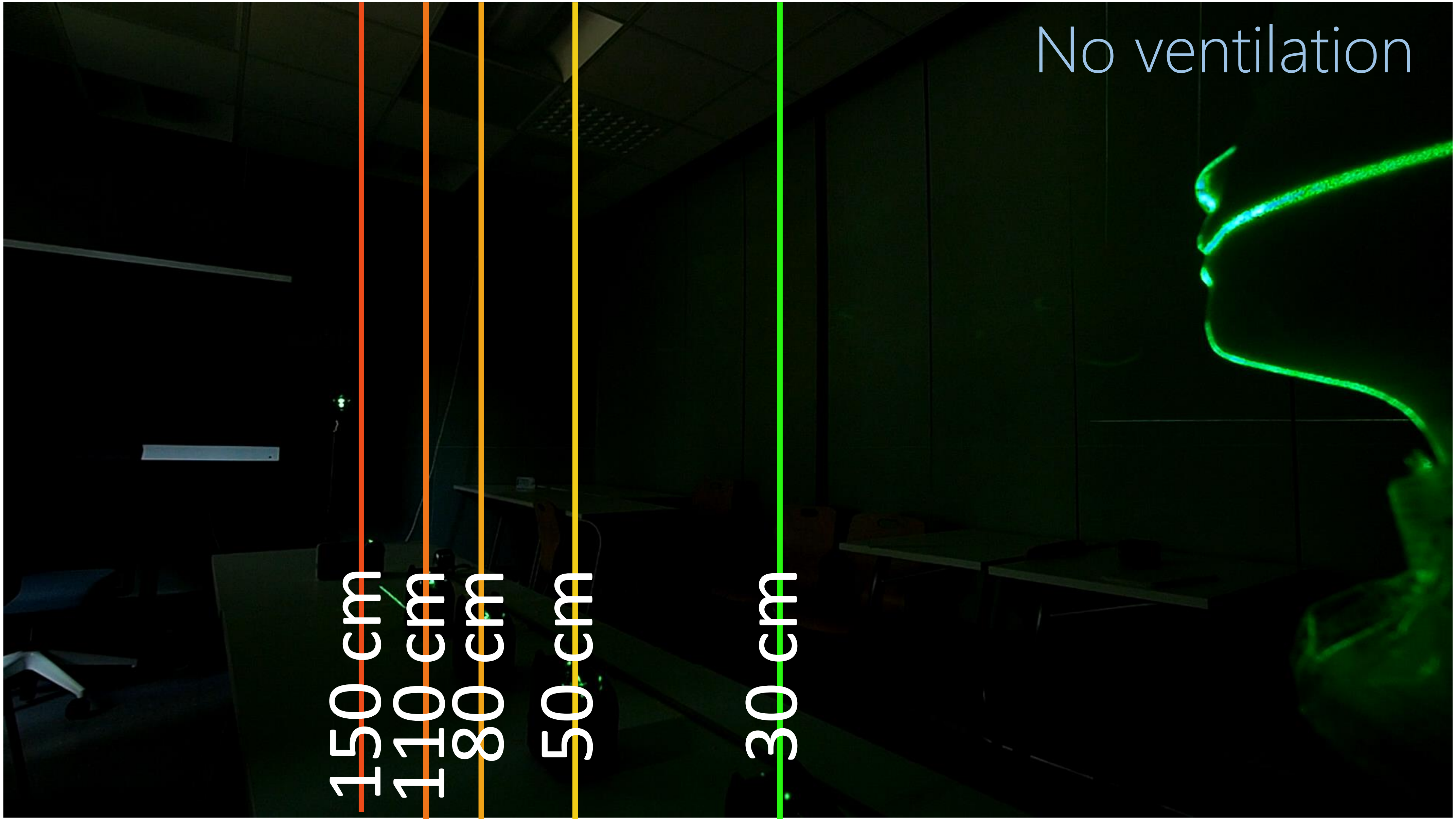
Comparison with analytical model

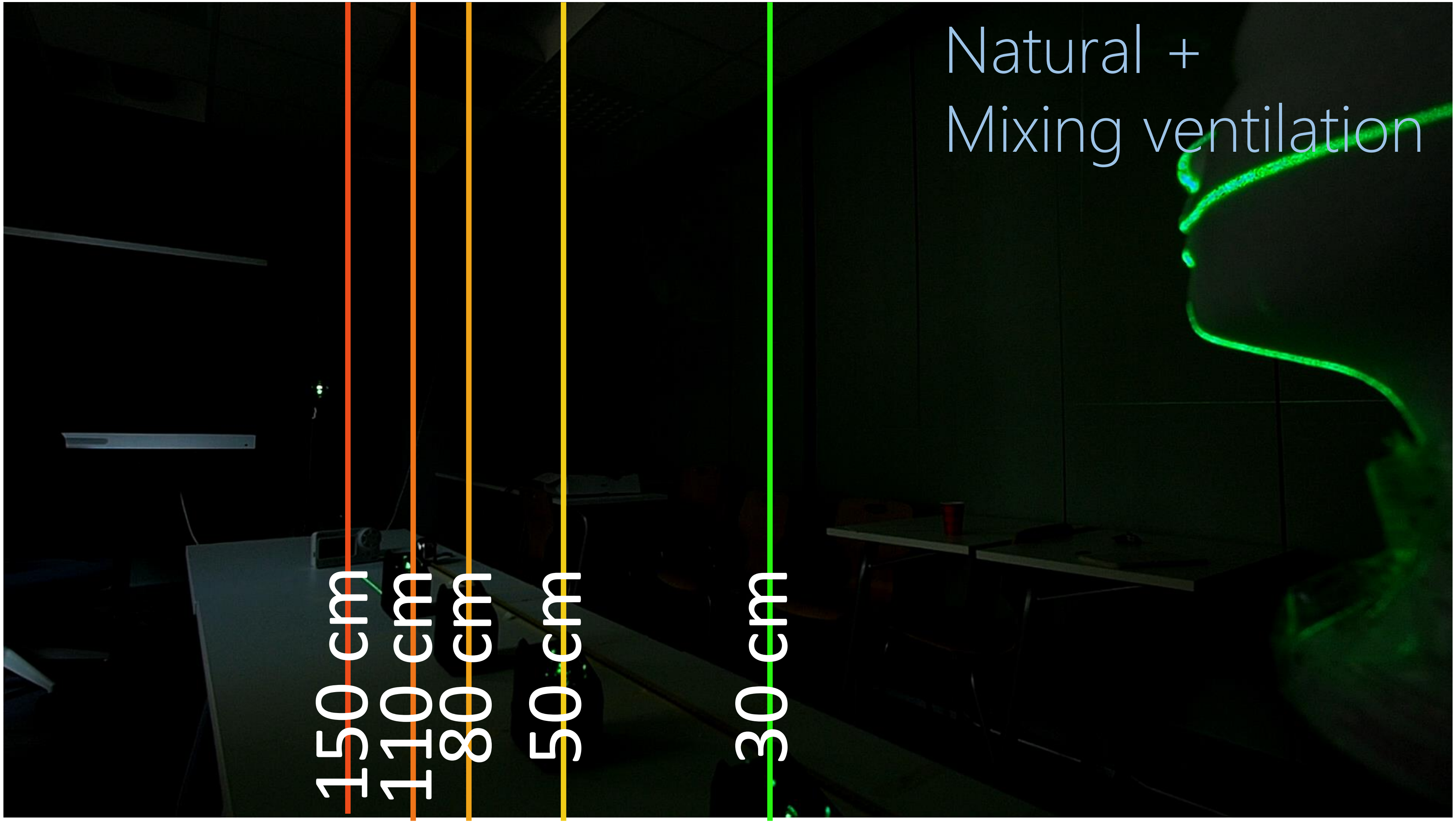
How were the results analysed?

Distance

Duration




No ventilation
150 cm
110 cm
80 cm
50 cm
30 cm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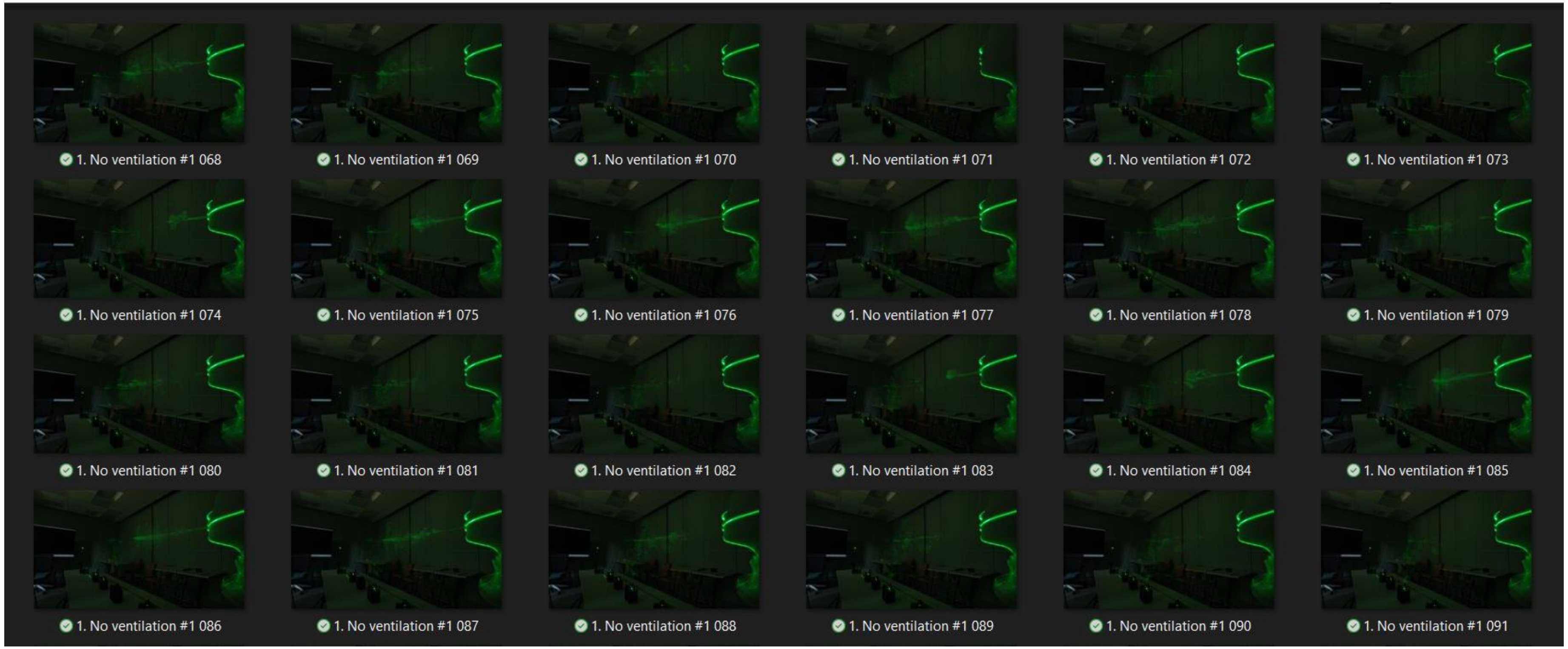
How were the results analysed?

Percentage of droplets



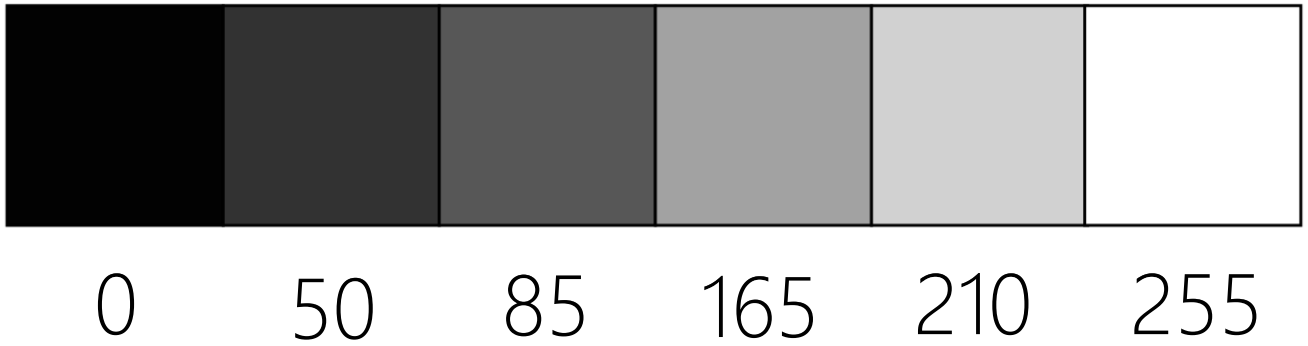
How were the results analysed?

Percentage of droplets

Substraction method

How were the results analysed?

Percentage of droplets



How were the results analysed?

Results

File Edit Font Results

	Area	Mean	Min	Max
1	2073600	1.065	0	242
2	2073600	0.697	0	244

Percentage of droplets

How were the results analysed?

Comparison with analytical model

Droplet size and time (when it will evaporate):

$$\frac{dD}{dt} = \frac{4M_L D_\infty P_a (1 + 0.276 Re^{1/2} Sc^{1/3})}{RT_\infty} \ln\left[\frac{1 - p_{sat}(T_w)/P_t}{1 - RH \cdot p_{sat}(T_\infty)/P_t}\right]$$

Newton's second law (the distance):

$$m_d \frac{du}{dt} = F_{drag} + F_{pressure} + F_{gravity}$$

Wang et al. (2020)

4. Results and discussions

Distance

Duration

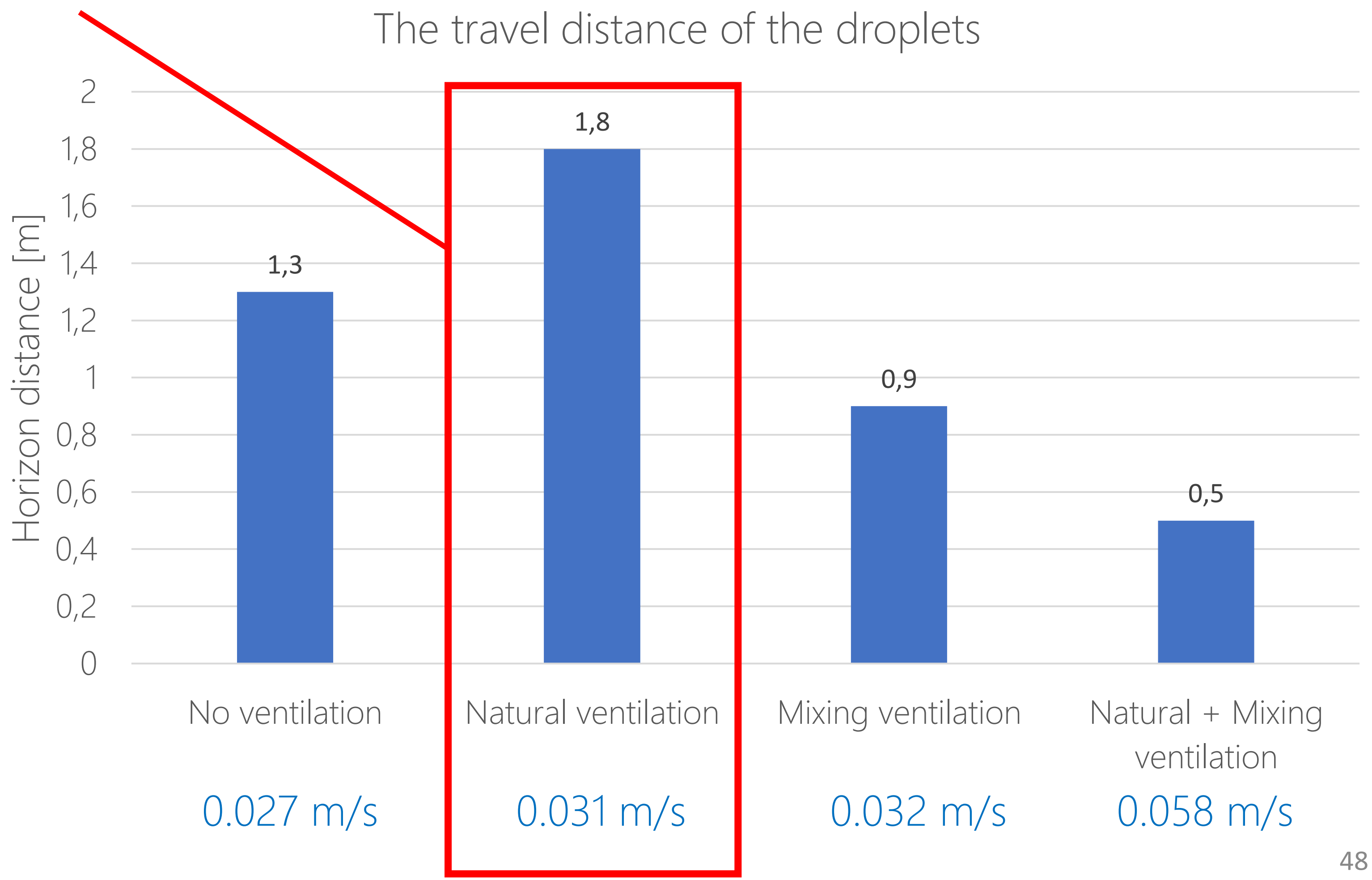
Percentage of droplets

Comparison with analytical model

Distance

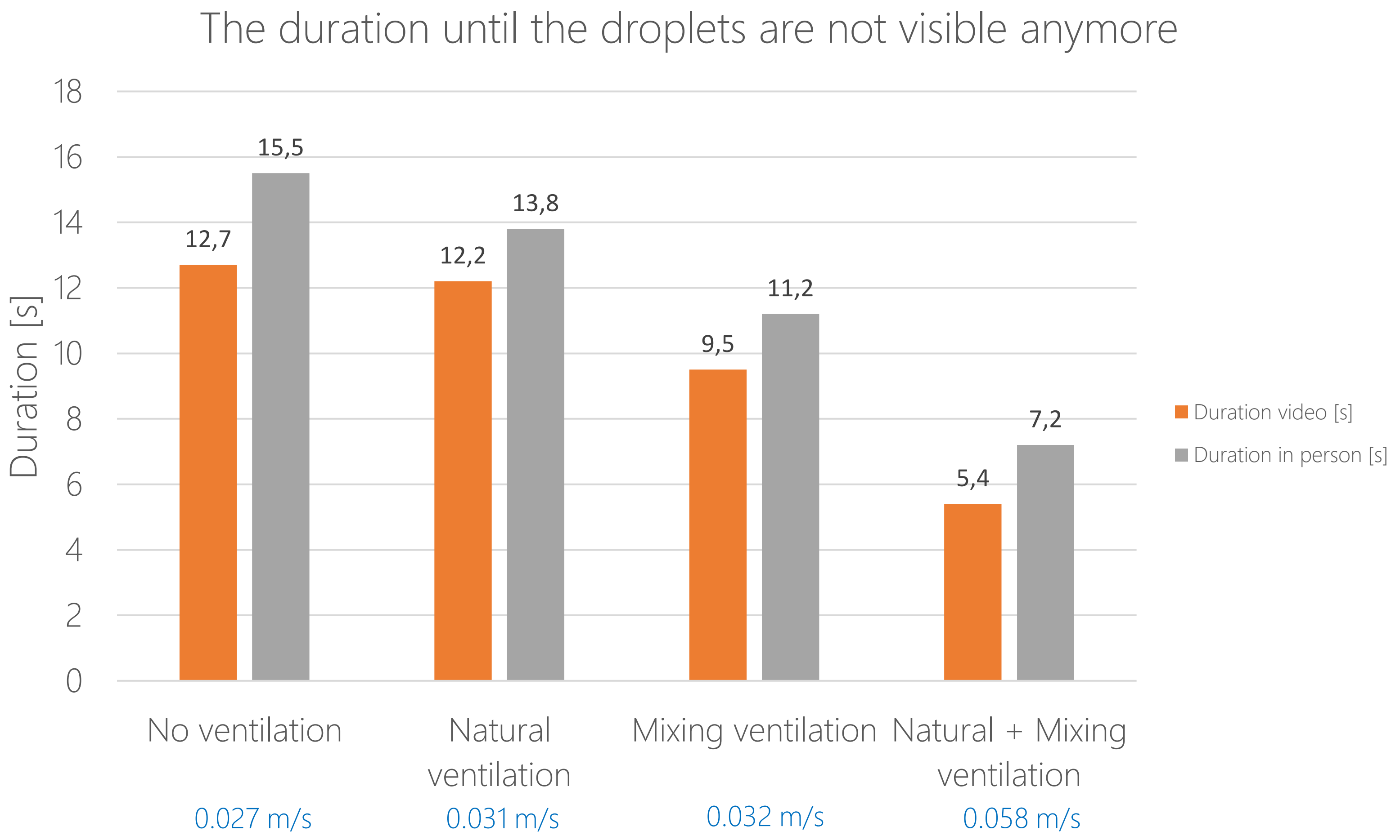
Door was open by mistake,
pushed the droplets much further?

Distance



Duration

Duration



Distance

Distance

The door was opened (by mistake)

Direction of the airflow can increase the dispersion

Layout of the windows and door

Duration

Duration

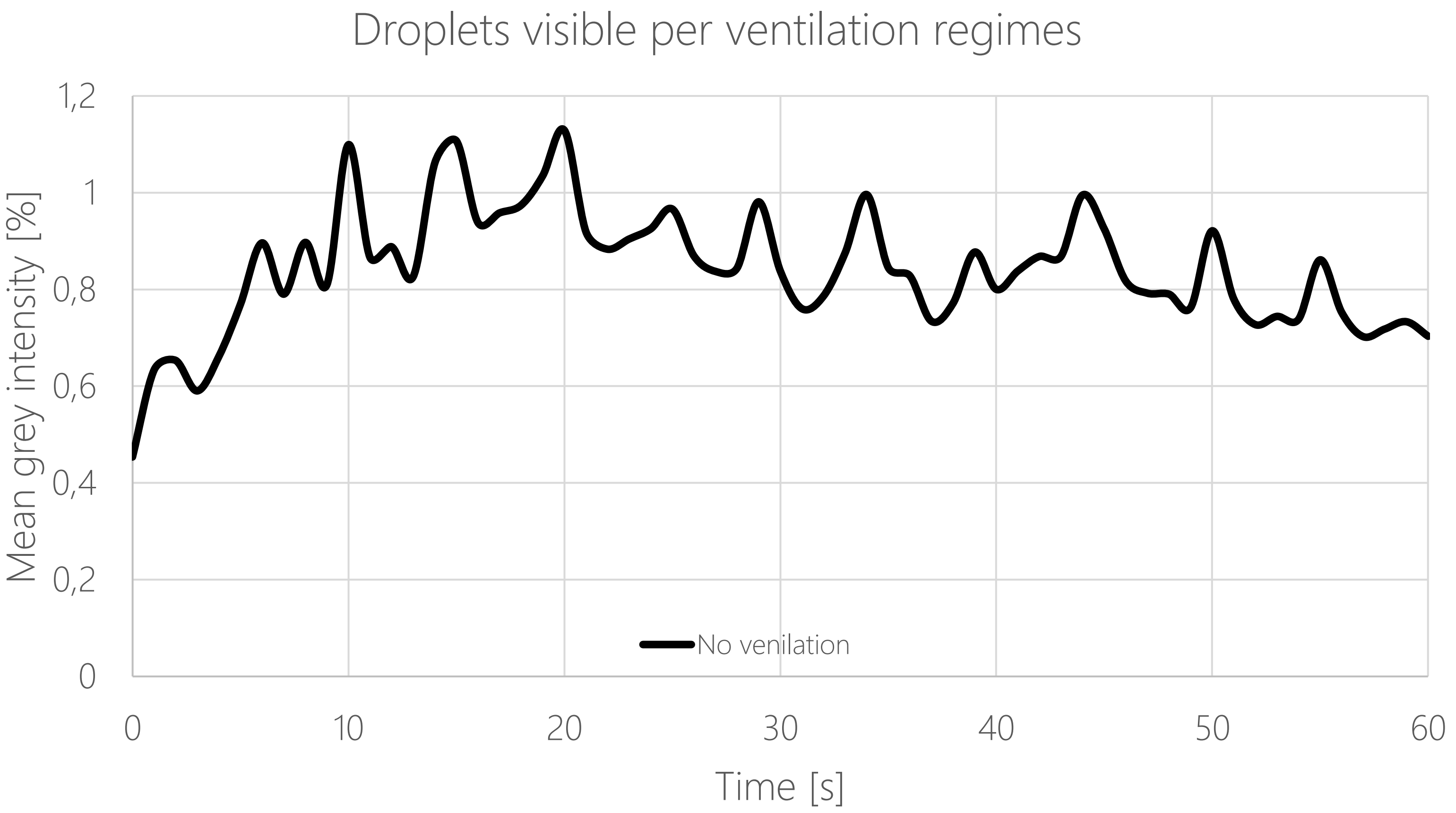
Droplets are longer visible with the human eye

Unable to see droplets <60 μm

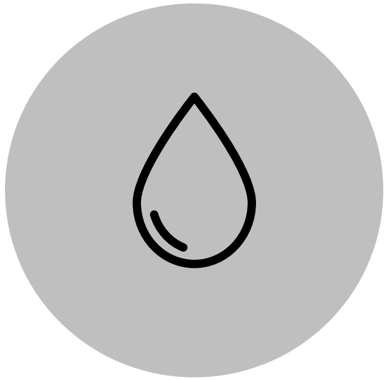
Collection of droplets

Percentage of droplets

Percentage of droplets



Percentage of droplets



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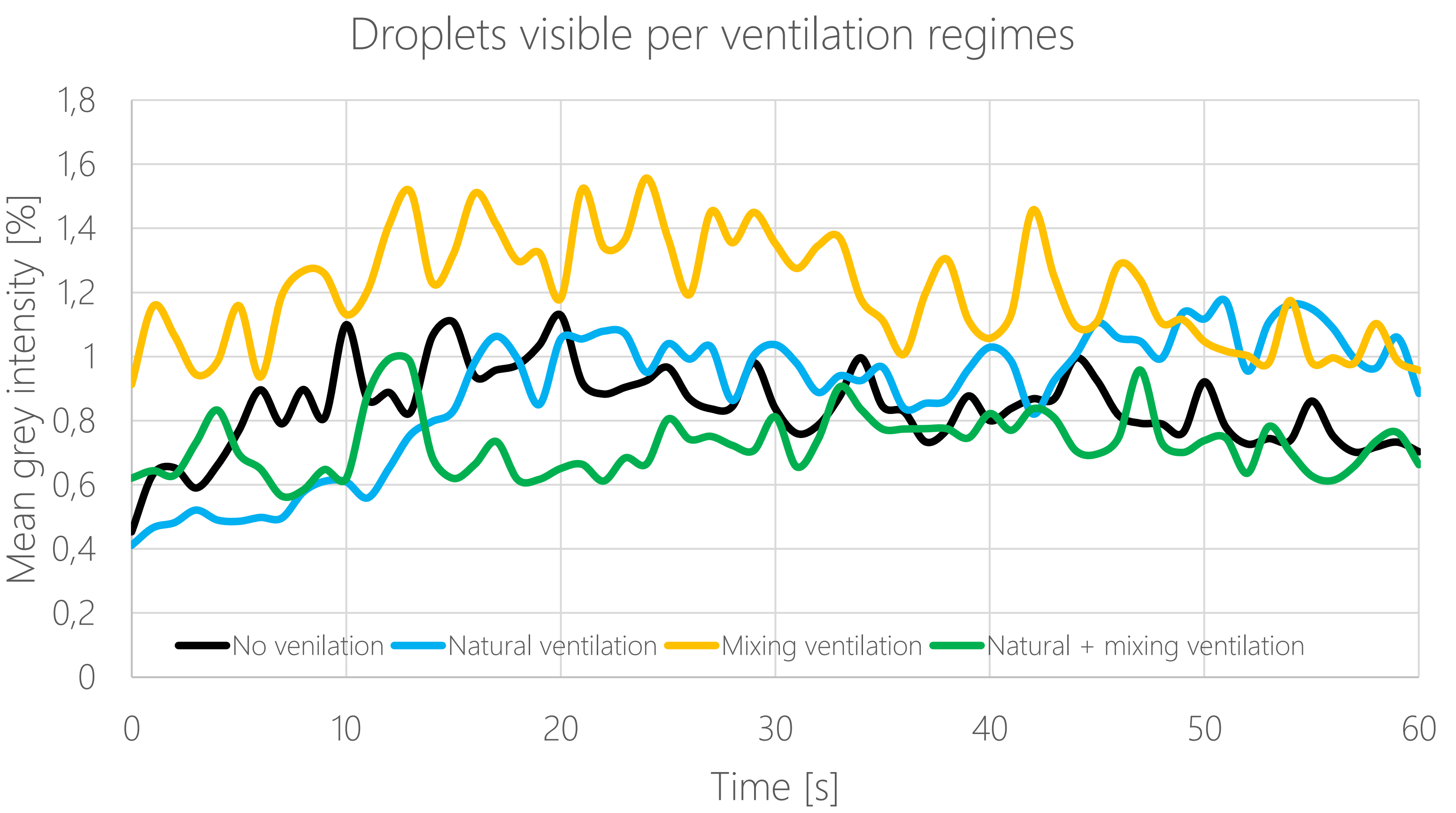

Percentage of droplets

Percentage of droplets

Mixing ventilation: constant airflow from the ceiling

Natural + mixing ventilation: droplets disperse significantly faster than other after exhalation

Comparison with analytical model

Comparison with analytical model

Droplet size and time (when it will evaporate):

$$\frac{dD}{dt} = \frac{4M_L D_\infty P_a (1 + 0.276 Re^{1/2} Sc^{1/3})}{RT_\infty} \ln \left[\frac{1 - p_{sat}(T_w)/P_t}{1 - RH \cdot p_{sat}(T_\infty)/P_t} \right]$$

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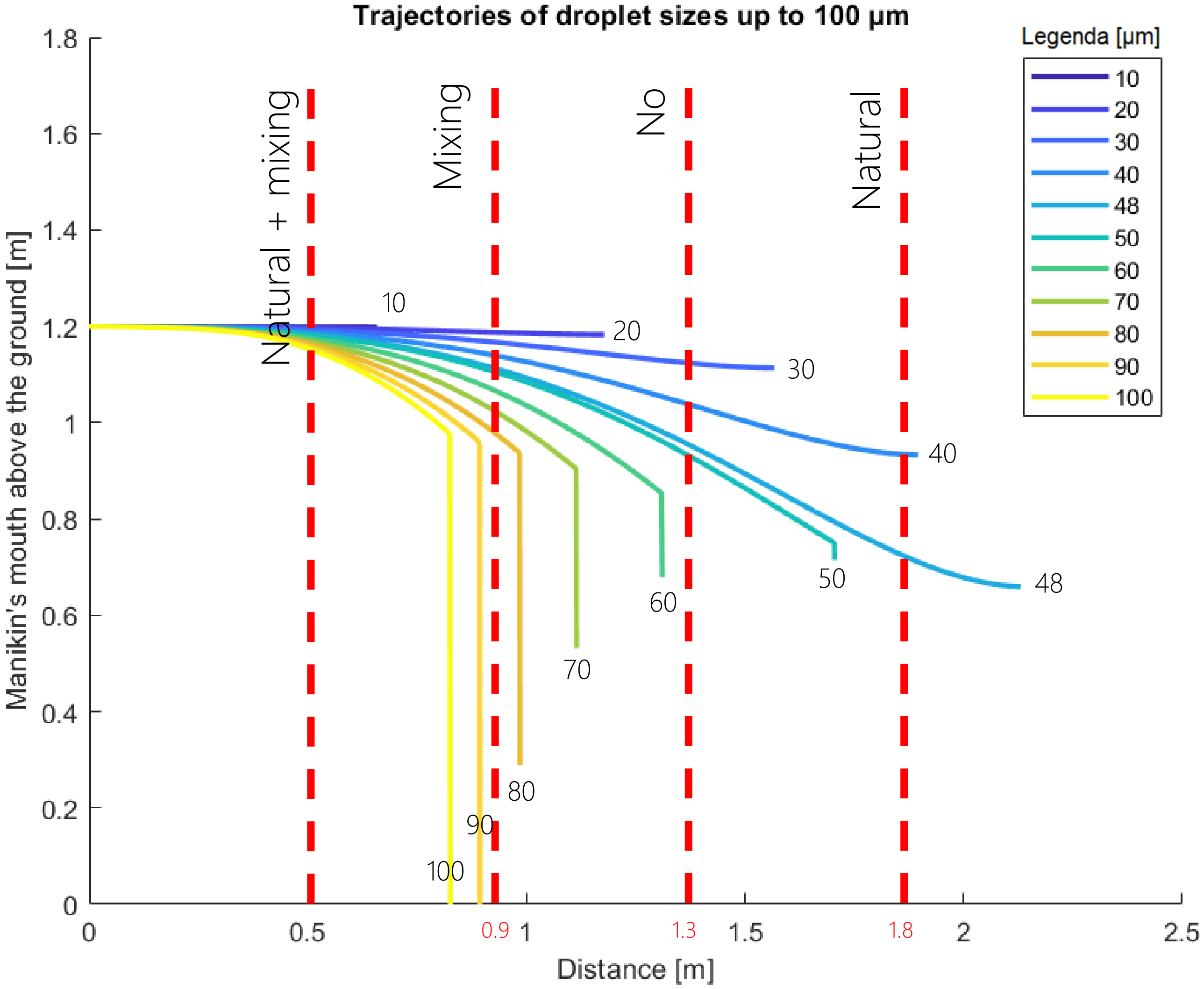


Limitations

Layout of the room

Inaccuracy with the setup

Manually operated

Unable to identify the droplet size

5. Conclusions and recommendations

Answering the research questions

Further recommendatons

Conclusions

Main research question

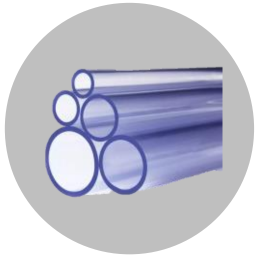
'How is the airflow pattern of 'exhaled' droplets affected in a classroom under different ventilation regimes?'

Conclusions

Which instruments are needed to assemble a portable system mimicking the human breath?

Medium
9:1 (glycol:water)

Fog generator



Pipes

Buffer (70 liter)

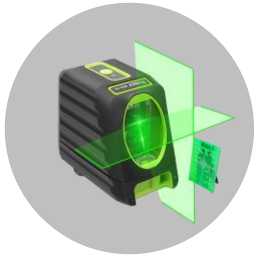
Pump (0,4 liter)

Manikin

Conclusions

How can one record and analyse the visualisation of the exhaled droplets?

Dimmed room



Laser

High-speed camera

Program: Fiji

Conclusions

How do different ventilation regimes affect the airflow pattern?

Ventilation regime	Mean air velocity [m/s]	Distance [m]	Duration [s]
No	0.027	1.3	12.7
Natural	0.031	1.8	12.2
Mixing	0.032	0.9	9.5
Natural + mixing	0.058	0.5	5.4

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No: lowest air velocity → higher concentration of droplets

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Mixing: the ceiling grilles supply constant air circulation → droplets scatters in all direction

Natural+mixing: highest air velocity → droplets disperse significantly faster after exhalation

Conclusions

What is the most efficient method to reduce the spread of aerosols in classrooms through ventilation?

If only natural ventilation can be applied → better than nothing

Natural + mixing ventilation → outdoor cooled down/heated up

Mixing ventilation is recommended → can control the climate

Conclusions

What is the added value of this portable system in airborne transmission control at educational buildings?

Visuals

Portable

Materials are accessible

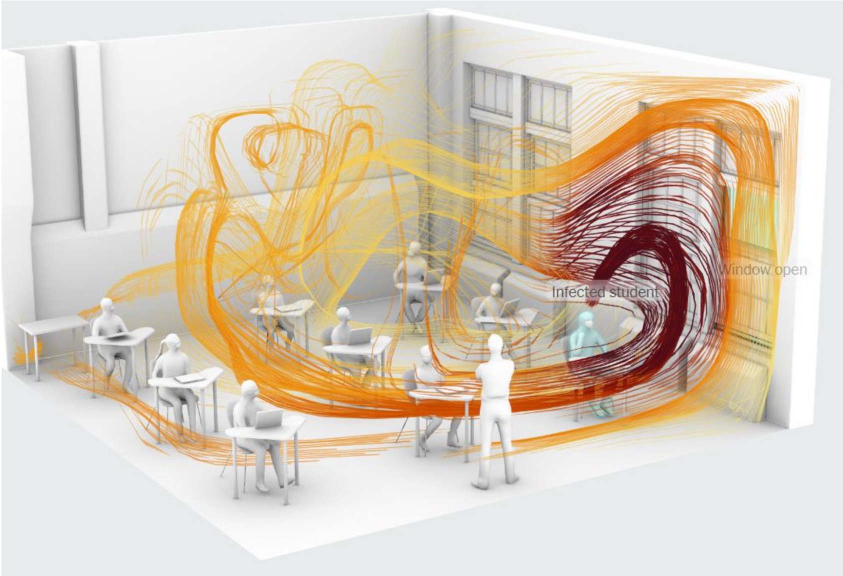
Further recommendations (Research)

Local effects

Air distribution

Apply computational fluid dynamics (CFD)

Other ventilation regimes (and combinations)



Shankara (2020)

Further recommendations (System)

Automate the process → consistent

Increase complexity → thermal manikin, 3D-printed manikin with cavity

Understand the capabilities of camera (e.g. what droplet -size it can record)

Particle Image Velocimetry (PIV) to track the trajectories of the droplets

Thank you!

Yat Long Liu
MSc Thesis – Defence
17th December 2021

TU Delft