Huonetilailmavirtausten simulointi

Kokemuksia ja esimerkkejä pandemia-ajalta

Aku Karvinen, erikoistutkija, projektipäällikkö

13/06/2024 **VTT – beyond the obvious**

Laskennallinen virtausmekaniikka (CFD)

“Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows.

Computers are used to perform the calculations required to simulate the free-stream flow of the fluid, and the interaction of the fluid (liquids and gases) with surfaces defined by boundary conditions.

With high-speed supercomputers, better solutions can be achieved, and are often required to solve the largest and most complex problems.”

Source: Wikipedia

Laskennallinen virtausmekaniikka (CFD)

Navierin ja Stokesin yhtälöt:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \, \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}(\rho \, \mathbf{u}) + \nabla \cdot (\rho \, \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \mu \, \nabla^2 \mathbf{u} + \tfrac{1}{3} \mu \, \nabla (\nabla \cdot \mathbf{u}) + \rho \mathbf{g}.$$

Source: Wikipedia

Laskennallinen virtausmekaniikka (CFD)

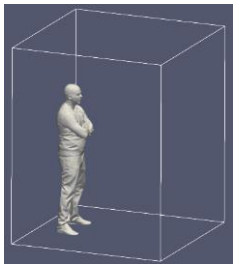
- Finite volume Method (FVM)
- Finite Element Method (FEM)
- Lattice Boltzmann method (LBM)

Suurimmat haasteet sisäilmavirtausten simuloinnissa

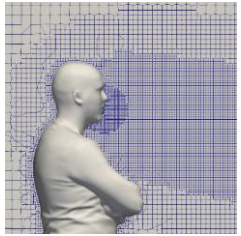
- Turbulenssi
- Suuret skaalaerot (tuloilmaelimet)
- Lämpölähteiden huomioiminen
- Hiukkasten depositio
- Suodattimien simulointi

Laskennallinen virtausmekaniikka (CFD)

Laskenta-alue



Diskretointi



Ilmavirtaus

Partikkelit

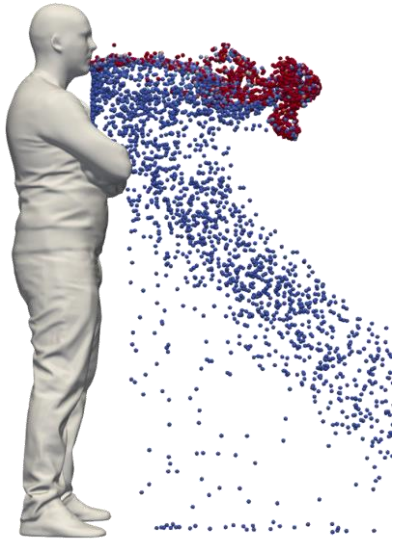
Voimat:

- Vastusvoima
- Noste
- Virtuaalinen massa
- Historia
- Jne.

HPC*

Satoja tai tuhansia ytimiä

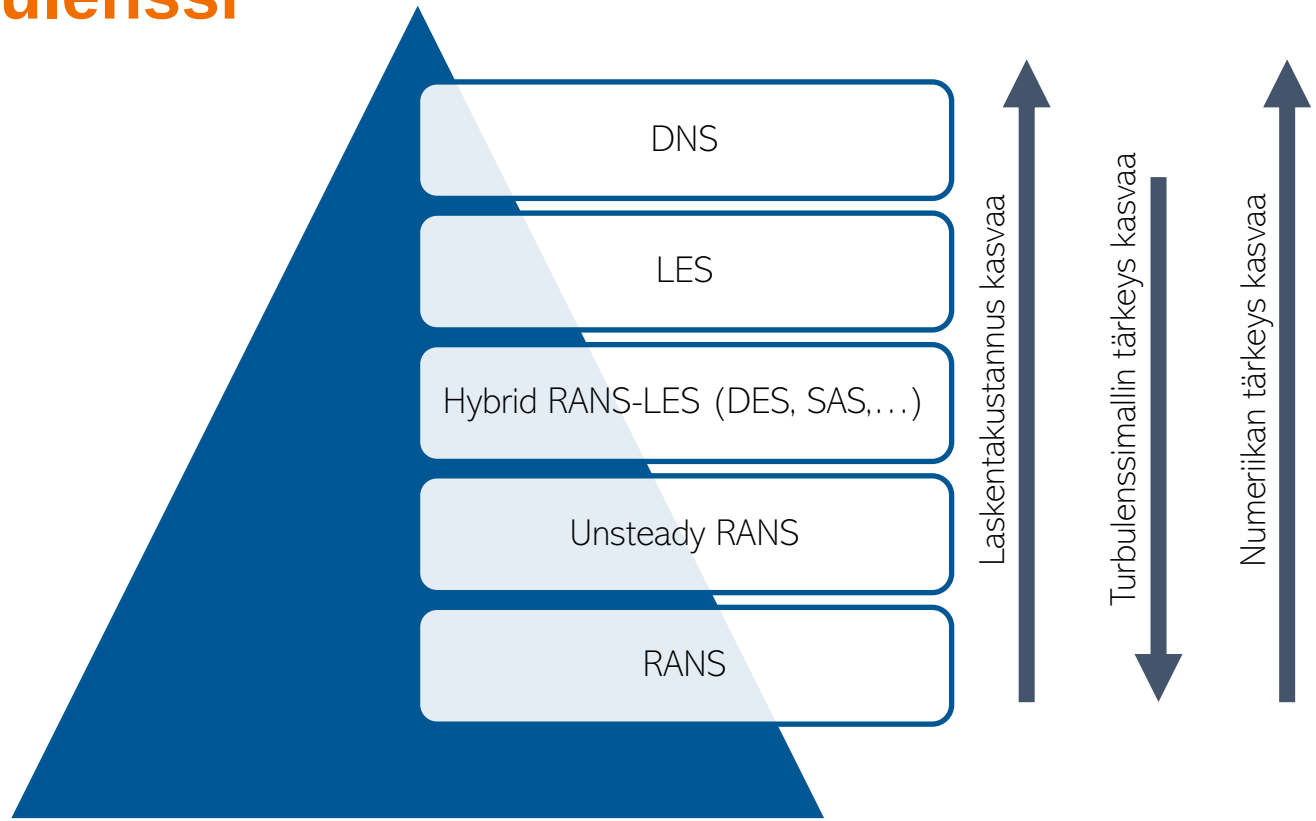
Päiviä tai viikkoja



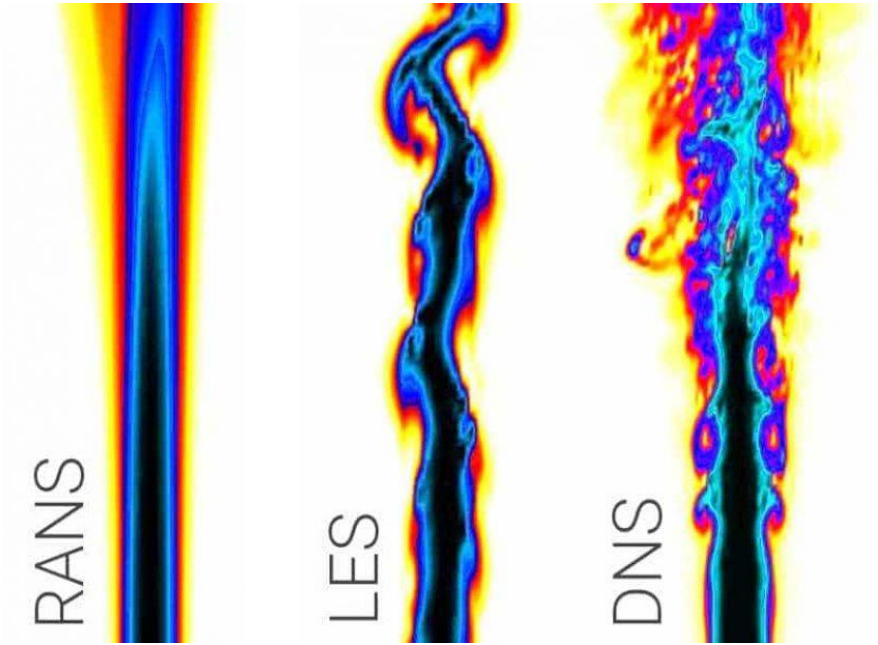
*High Performance Computing

Turbulenssi

Turbulenssi

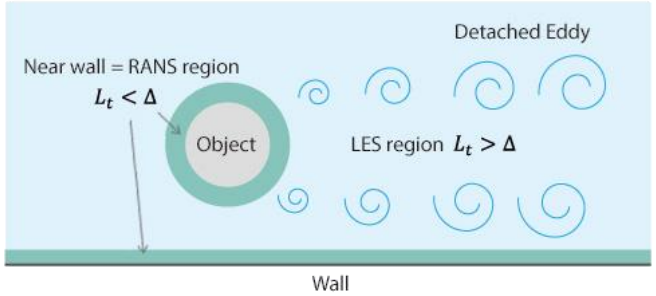


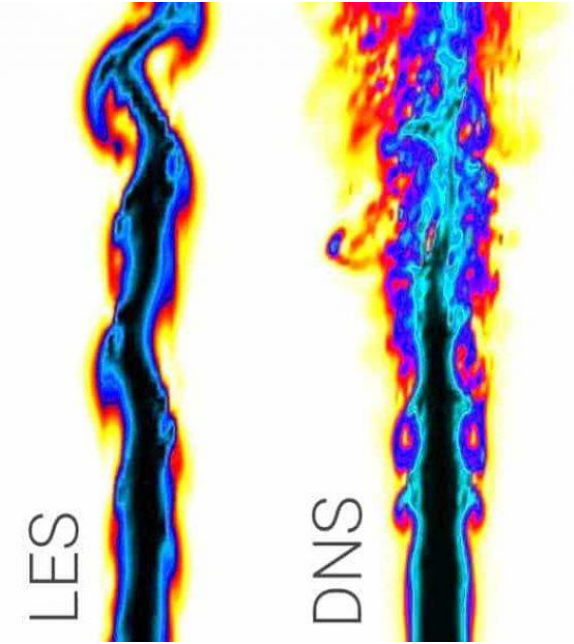
Turbulenssi



Turbulenssi

DES





Partikkeli-kaasu –virtaukset

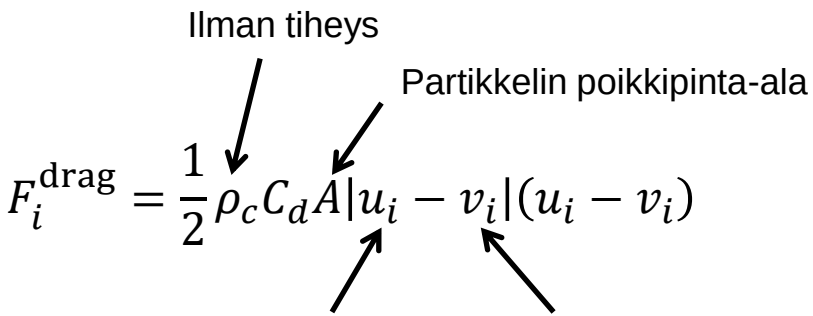
Partikkeli-kaasu –virtaukset

- Kaksi vaihtoehtoista menetelmää:
  - Eulerian-Eulerian -menetelmä
  - Eulerian-Lagrangian -menetelmä
- "*A dilute flow… information, such as particle velocity, size and temperature, travels along particle trajectories. This condition is unlike the flow of a continuous substance in which information travels in all direction (subsonic flows). The cloud of particles in a dilute flow cannot be treated as a continuous fluid so the* ***Lagrangian approach is the only approach suitable for a dilute flow***."

C. T. Crowe, J. D. Schwarzkopf, M. Sommerfeld and Y. Tsuji: Multiphase Flows with Droplets and Particles, Second Edition, 2012

Vastusvoima

- Vastusvoima:



  missä

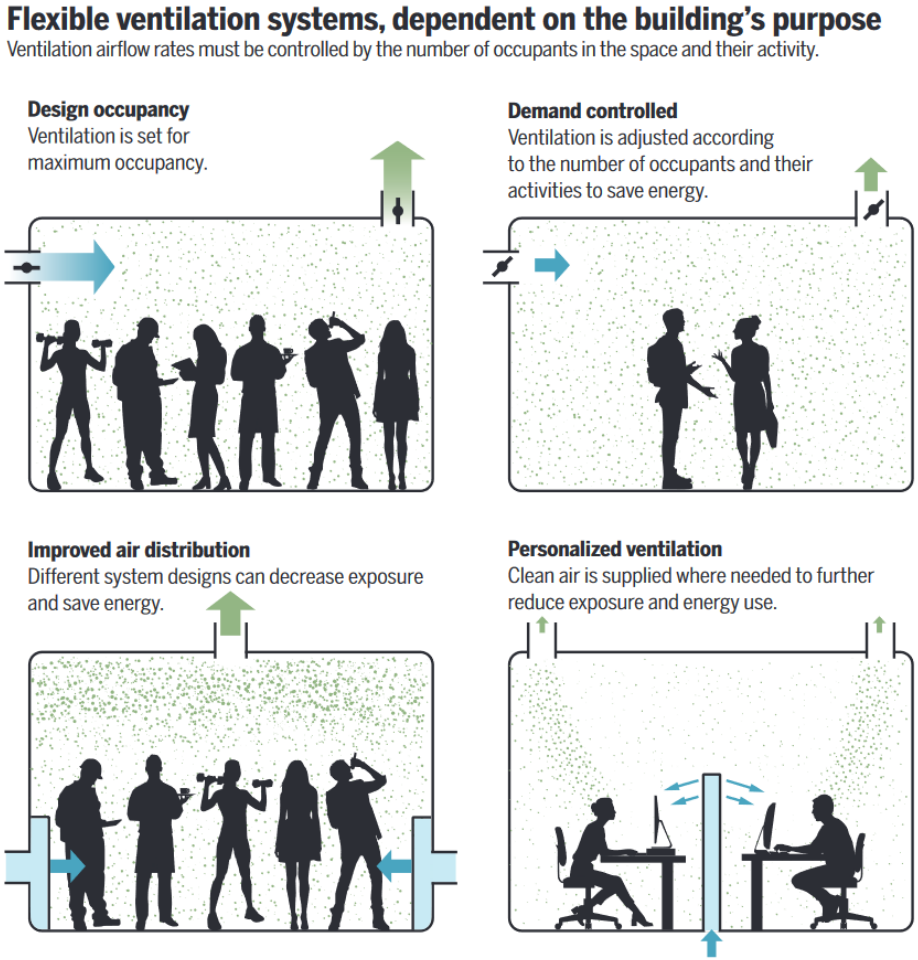
  $C_d = \frac{24}{Re_p}$

  Stokesin virtaukselle, eli pienten nopeuserojen tapaukselle, eli kun $Re_p << 1$

- Monimutkaisempi muoto suurille nopeuseroille
- Vain tämä voima otettu yleensä huomioon – muut voimat merkityksettömän pieniä

Ilmanvaihto

Ilmanvaihto



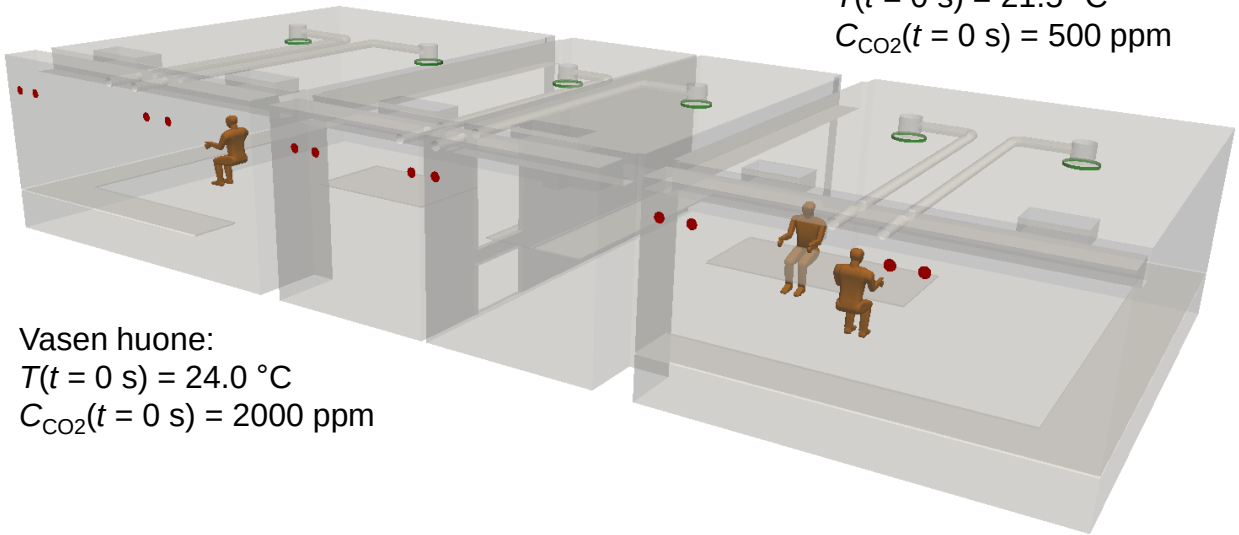
Morawska, Lidia, Joseph Allen, William Bahnfleth, Philomena M. Bluyssen, Atze Boerstra, Giorgio Buonanno, Junji Cao, et al. 'A Paradigm Shift to Combat Indoor Respiratory Infection'. *Science* 372, no. 6543 (14 May 2021): 689–91.

Esimerkkejä

Siirtoilma luokkahuoneen tuuletuksen apuna

Luokkahuone

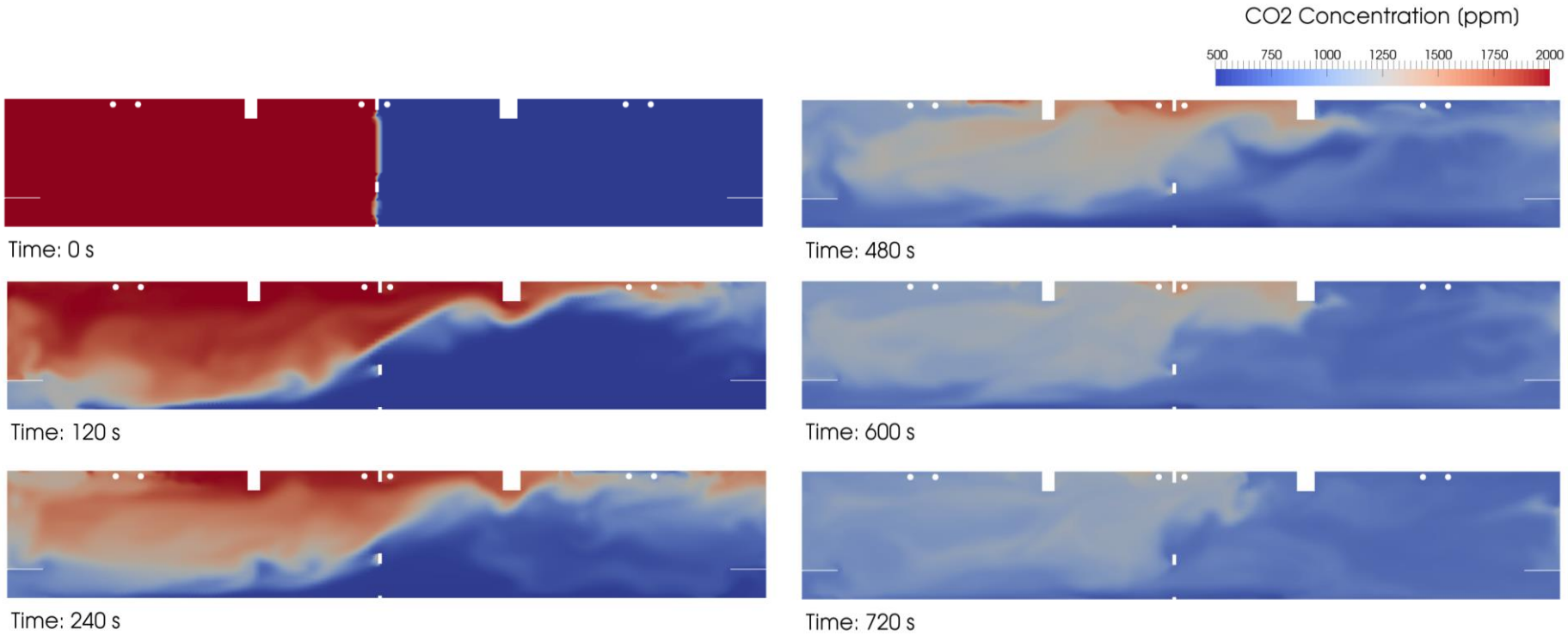
- Vasen huone aluksi täynnä ihmisiä, oikea tyhjä
- Ovi huoneiden välillä avataan ajanhetkellä t = 0 s
- Vihreät ovat tuloilmaelimiä, punaiset poistoja



Oikea huone:
$T(t = 0\ \text{s}) = 21.5\ °\text{C}$
$C_{CO2}(t = 0\ \text{s}) = 500\ \text{ppm}$

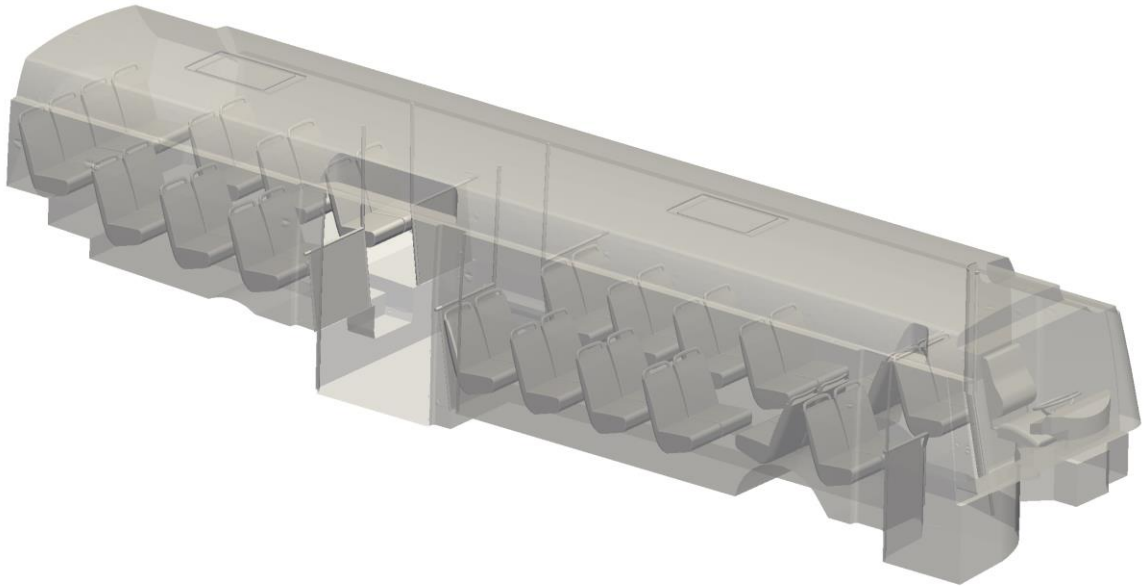
Vasen huone:
$T(t = 0\ \text{s}) = 24.0\ °\text{C}$
$C_{CO2}(t = 0\ \text{s}) = 2000\ \text{ppm}$

Tulokset

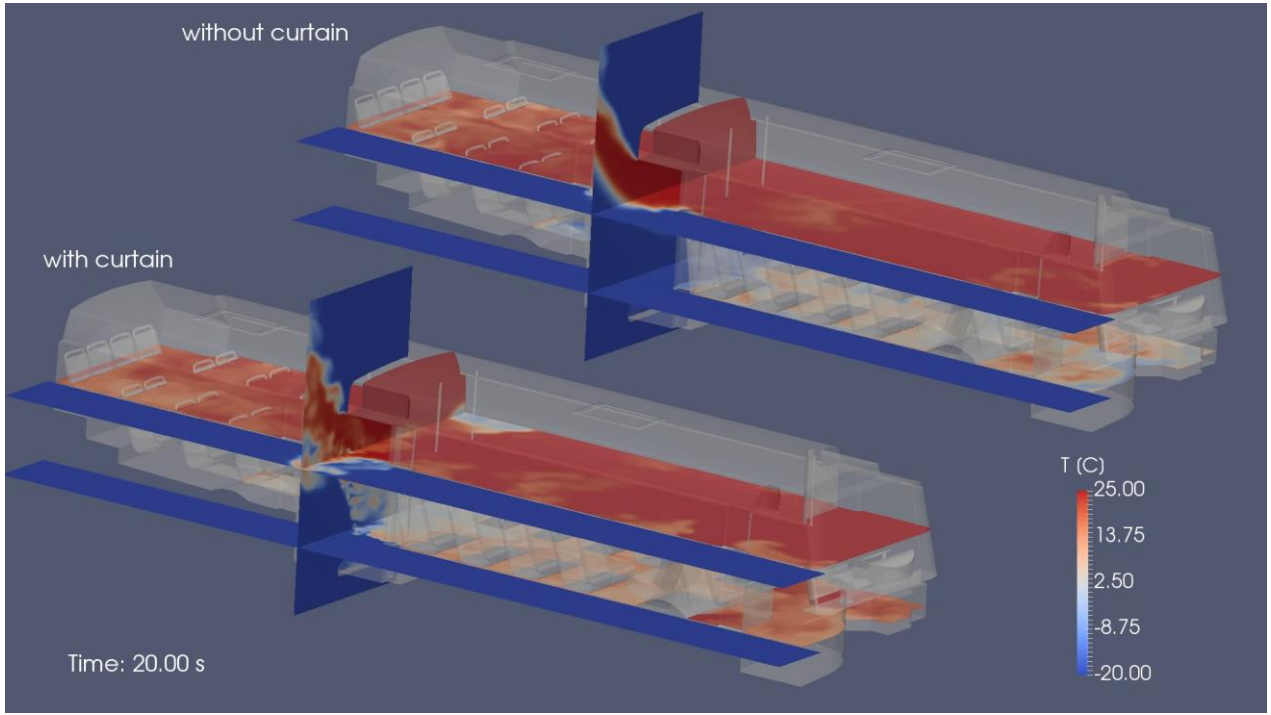

CO2 Concentration (ppm)
500
750
1000
1250
1500
1750
2000
Time: 0 s
Time: 480 s
Time: 120 s
Time: 600 s
Time: 240 s
Time: 720 s

Sähköbussi

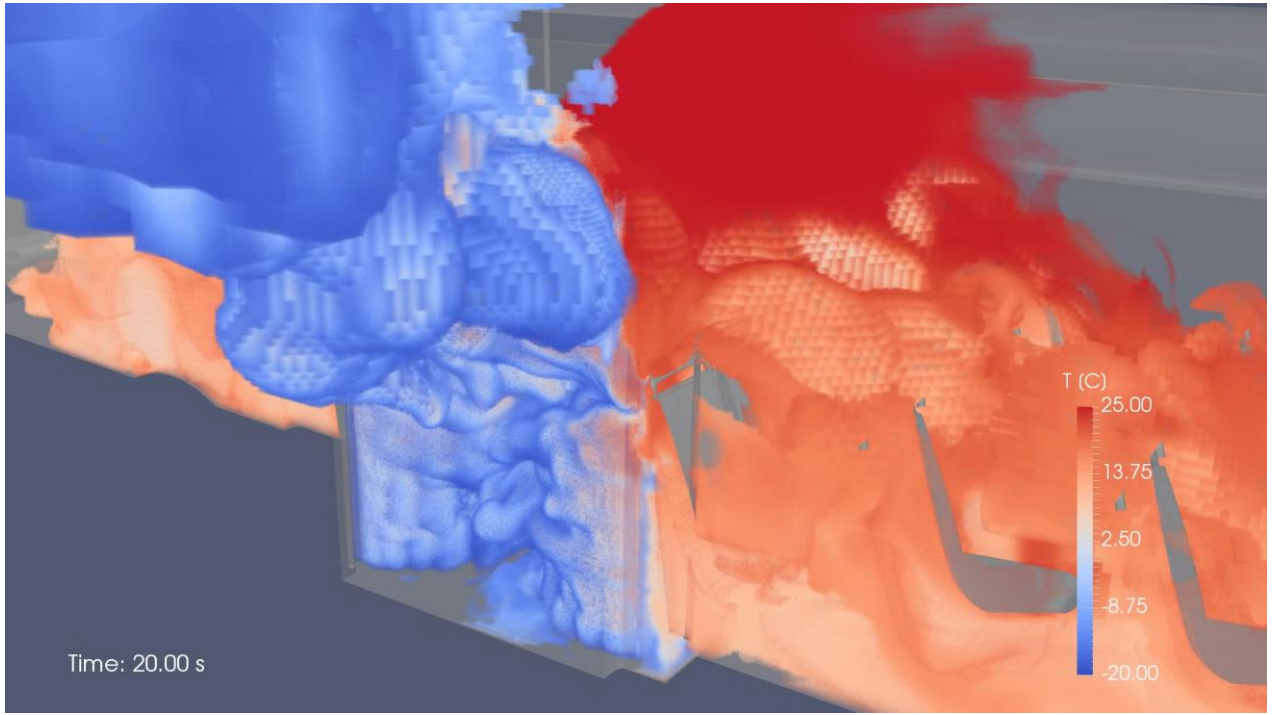
Sähköbussi



Sähköbussi

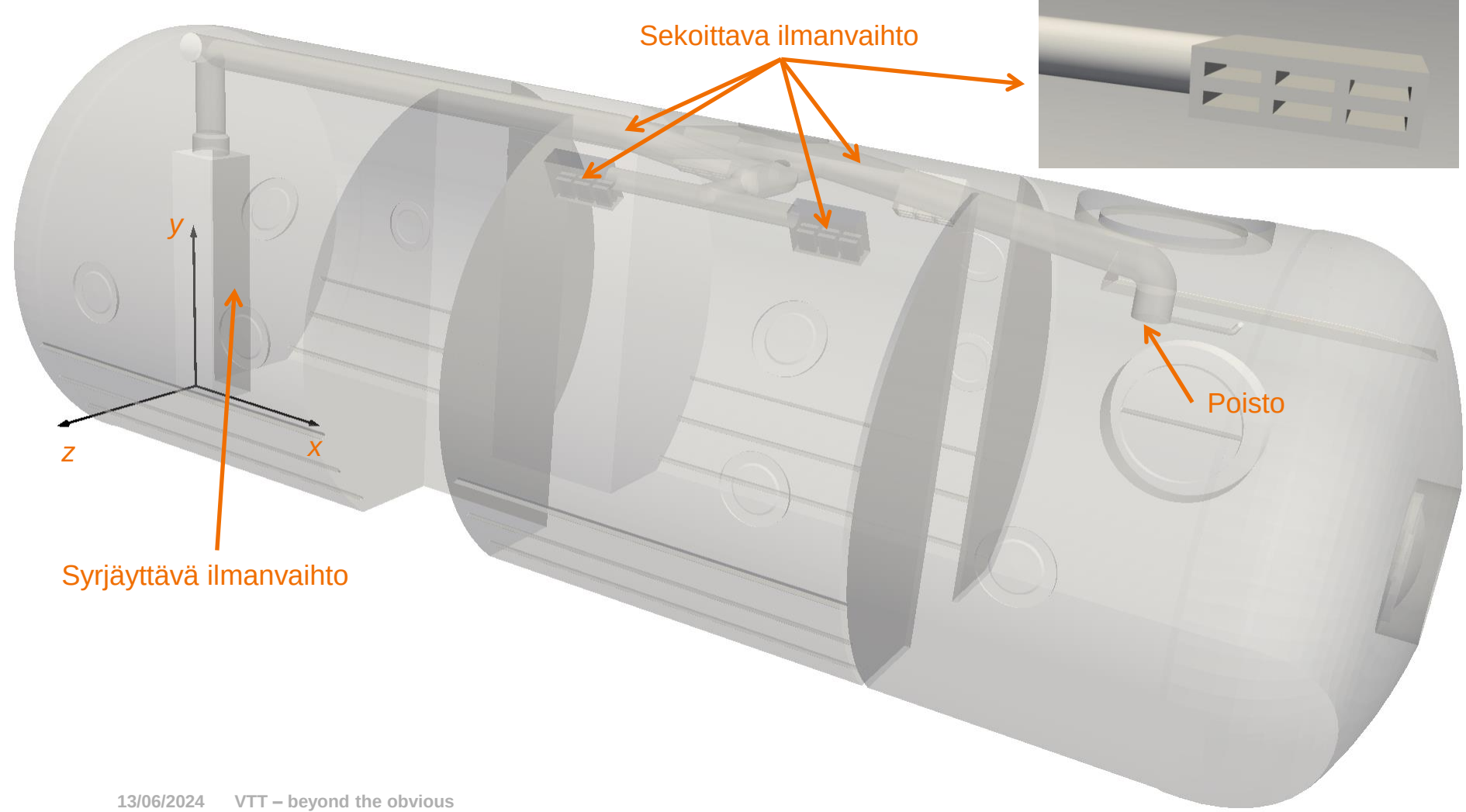

without curtain
with curtain
T (C)
25.00
13.75
2.50
-8.75
-20.00
Time: 20.00 s

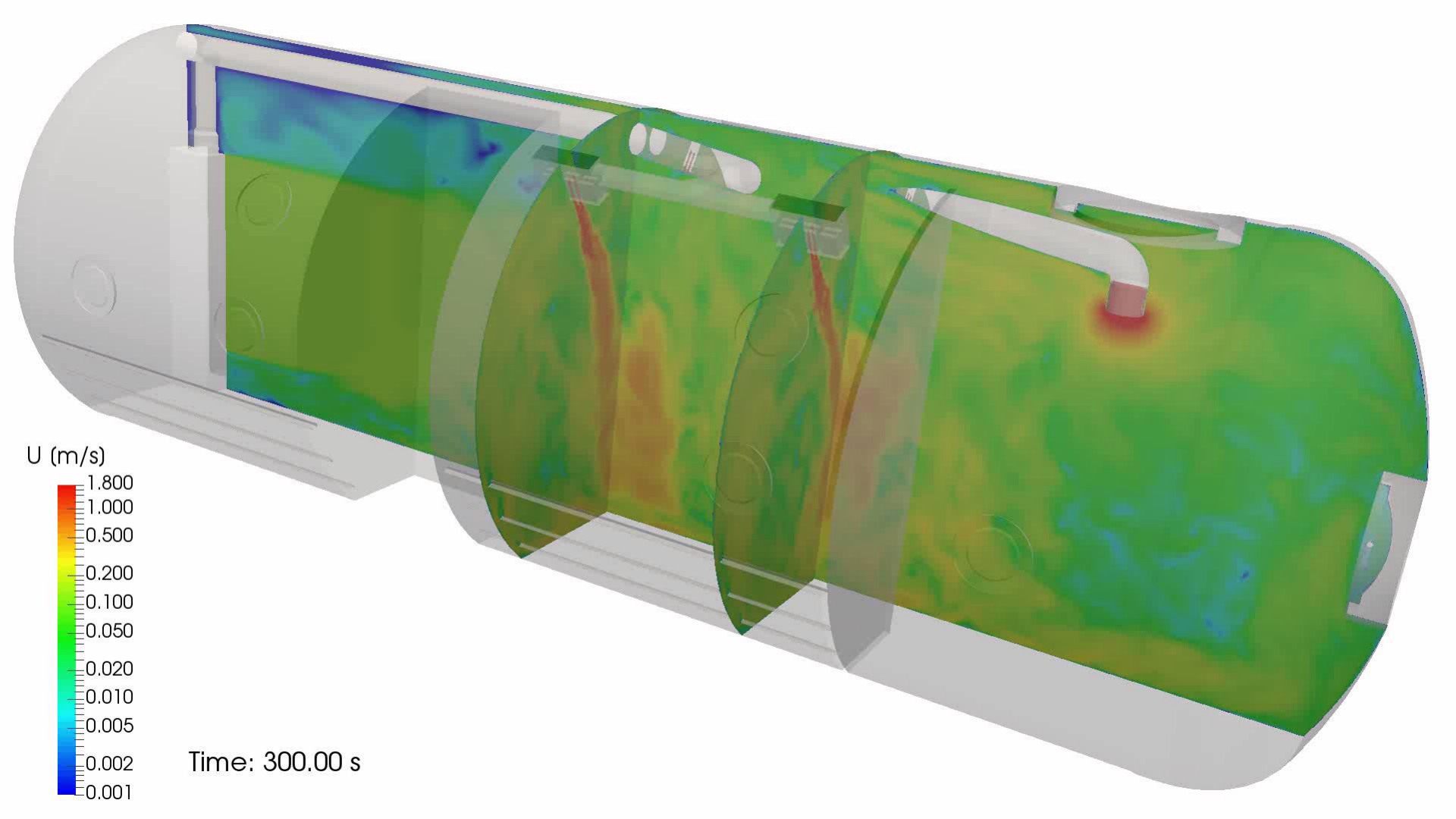
Sähköbussi



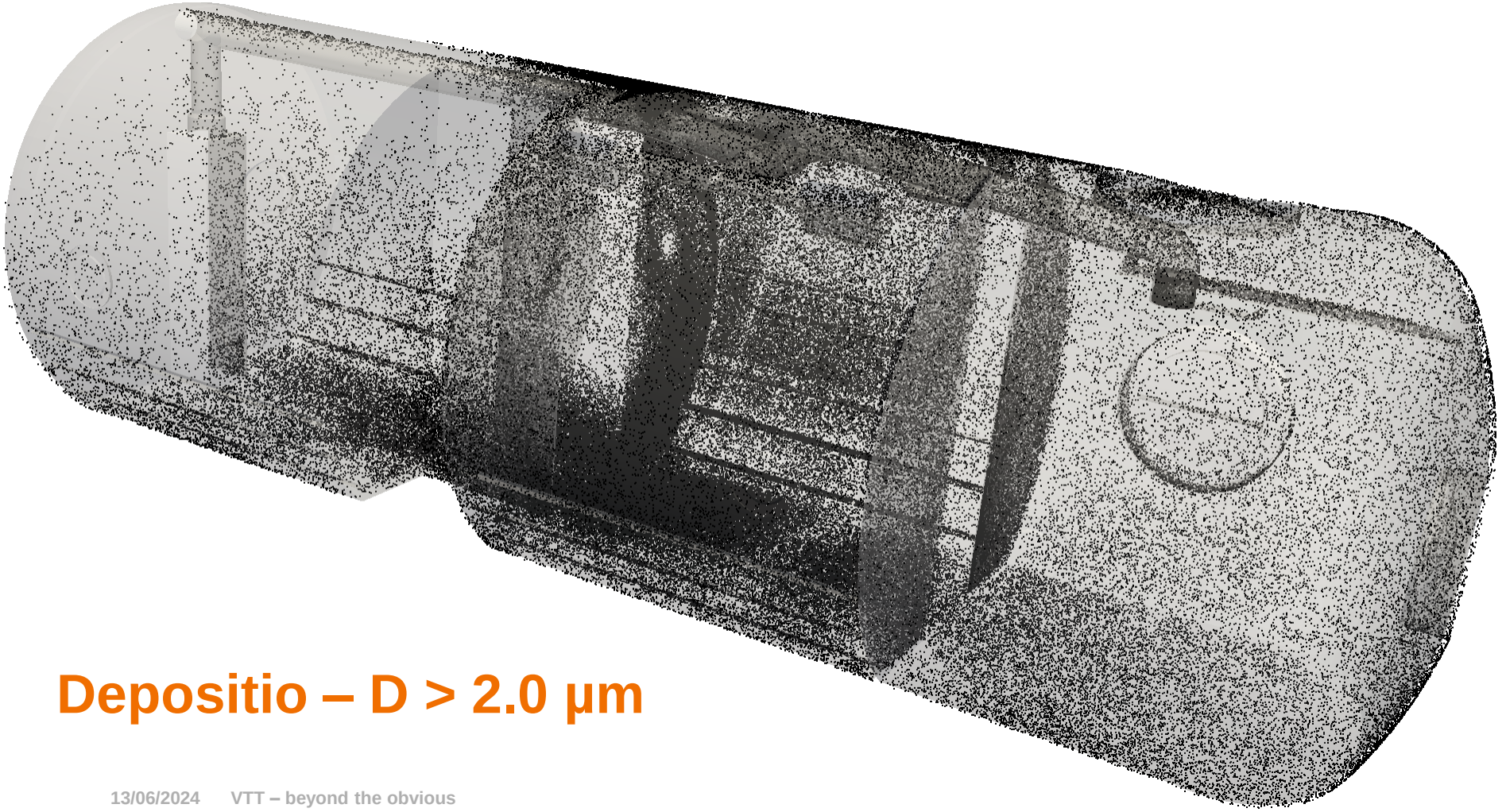
Depositio kansainvälisellä avaruusasemalla

Comex HH


Sekoittava ilmanvaihto
y
z
x
Poisto
Syrjäyttävä ilmanvaihto


U (m/s)
1.800
1.000
0.500
0.200
0.100
0.050
0.020
0.010
0.005
0.002
0.001
Time: 300.00 s

Depositio – Kaikki hiukkaset



Depositio – D > 2.0 µm

Koronapandemia

700 000 000 tapausta

7 000 000 kuolemaa

Jopa

14 000 000 000 000 $

vuoden 2023 loppuun mennessä pelkästään USA:ssa

CFD pandemiantorjunnassa

- Ilmavirtaus
- Konvektiovirtaukset
  - Ihmisten lämpötila
  - Lämmitys
  - Ikkunat
- Ihmisten emittoimat pisarat ja aerosolihiukkaset
  - Evaporaatio
- Lämpötila, suhteellinen kosteus, jne.

Ihmisen emittoimien hiukkasten simulointi

THE RELATIVE SIZE OF PARTICLES

From the COVID-19 pandemic to the U.S. West Coast wildfires, some of the biggest threats now are also the most microscopic.

A particle needs to be 10 microns (μm) or less before it can be inhaled into your respiratory tract. But just how small are these specks?

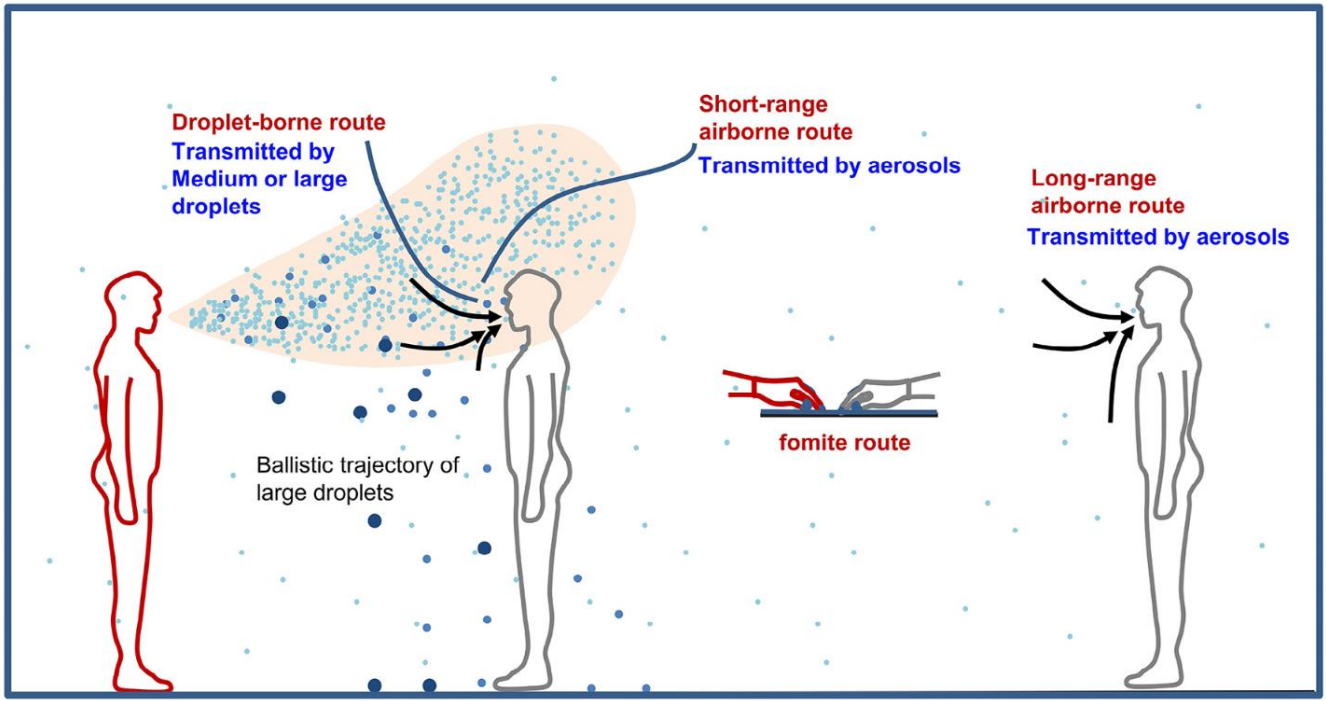
Here's a look at the relative sizes of some familiar particles ↘

SOURCES Clearstream, Daniel Loverbey, EPA, Financial Times, News Medical, Science Direct, SCMP, Susan Sokolowski, Petroclear, U.S. Dept. of Energy
COLLABORATORS **RESEARCH + WRITING** Carmen Ang, Iman Ghosh | **DESIGN + ART DIRECTION** Harrison Schell

VISUAL CAPITALIST

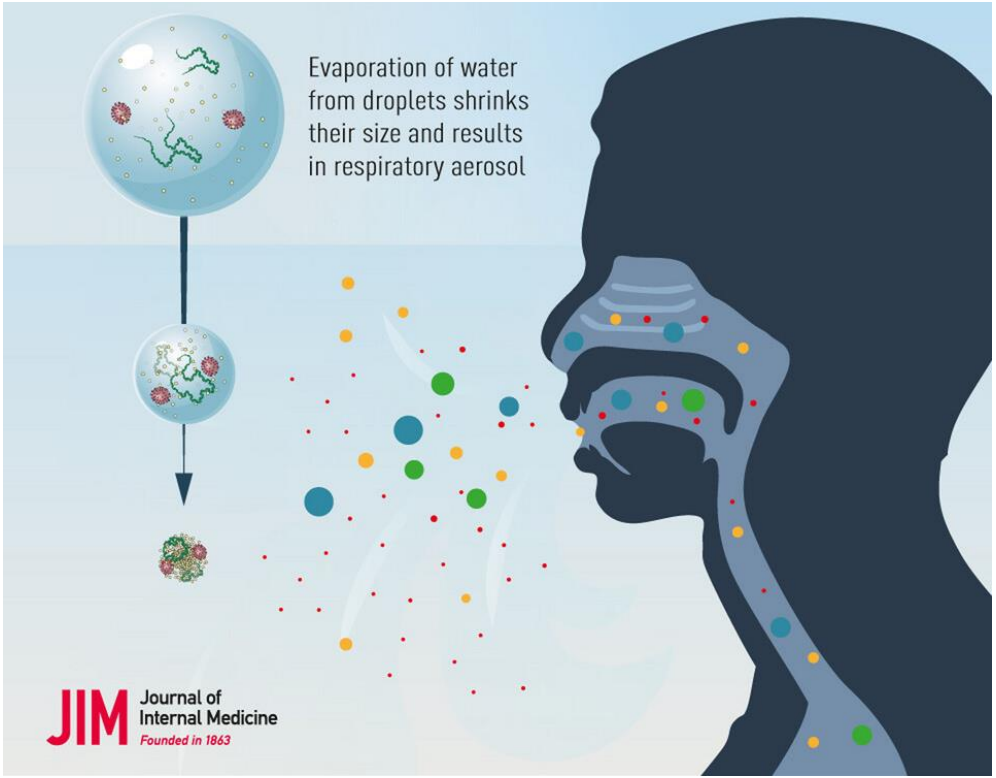
/visualcapitalist @visualcap visualcapitalist.com

Siirtoreitit

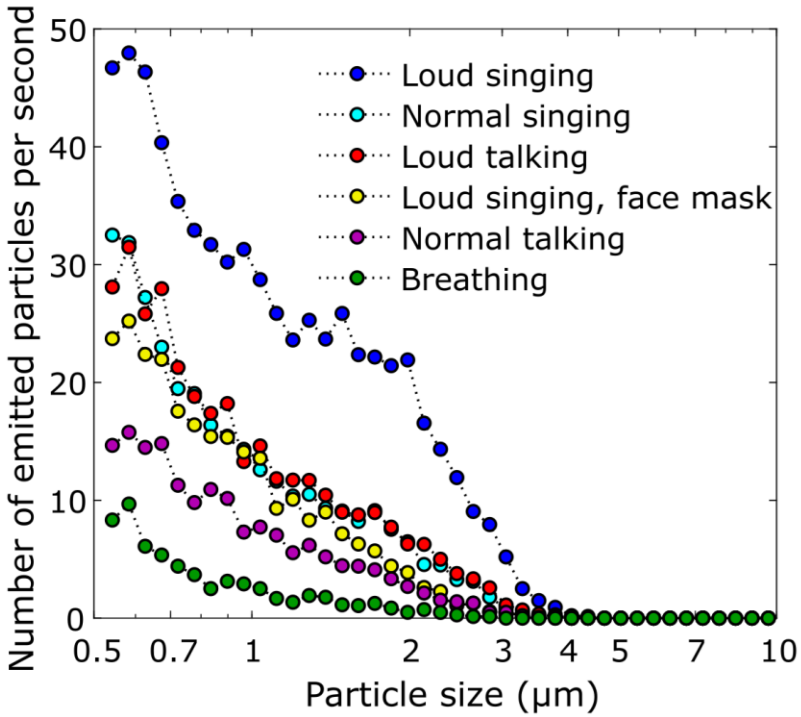


Wei, Jianjian, and Yuguo Li. 'Airborne Spread of Infectious Agents in the Indoor Environment'. *American Journal of Infection Control*, Indoor Air as a Vehicle for Human Pathogens, 44, no. 9, Supplement (2 September 2016): S102–8.

Evaporaatio



Hiukkasten kokojakauma



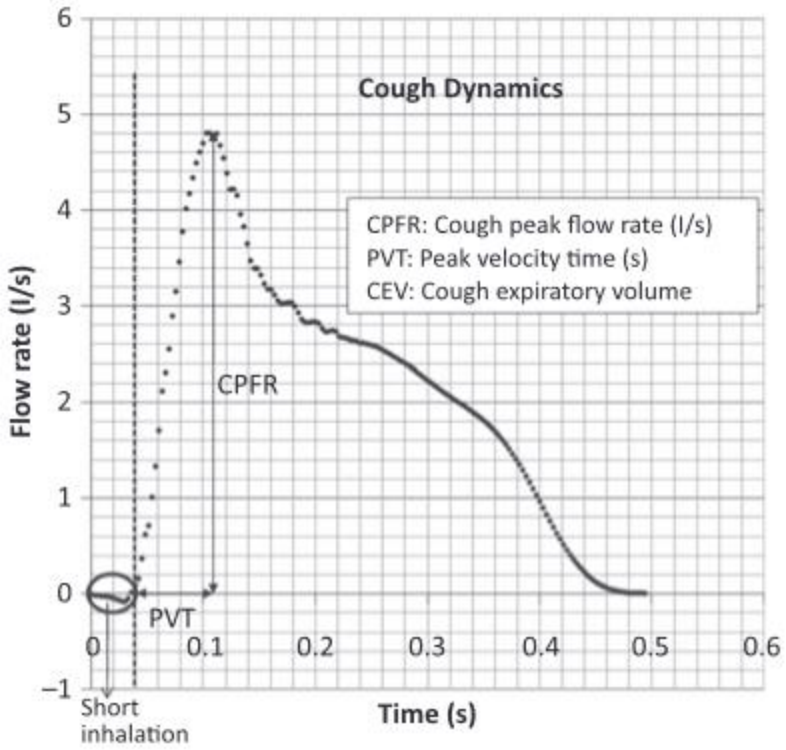
M. Alsved *et al.*, 'Exhaled respiratory particles during singing and talking', *Aerosol Science and Technology*, vol. 54, no. 11, pp. 1245–1248, Nov. 2020.

Paljonko hiukkasia emittoituu?

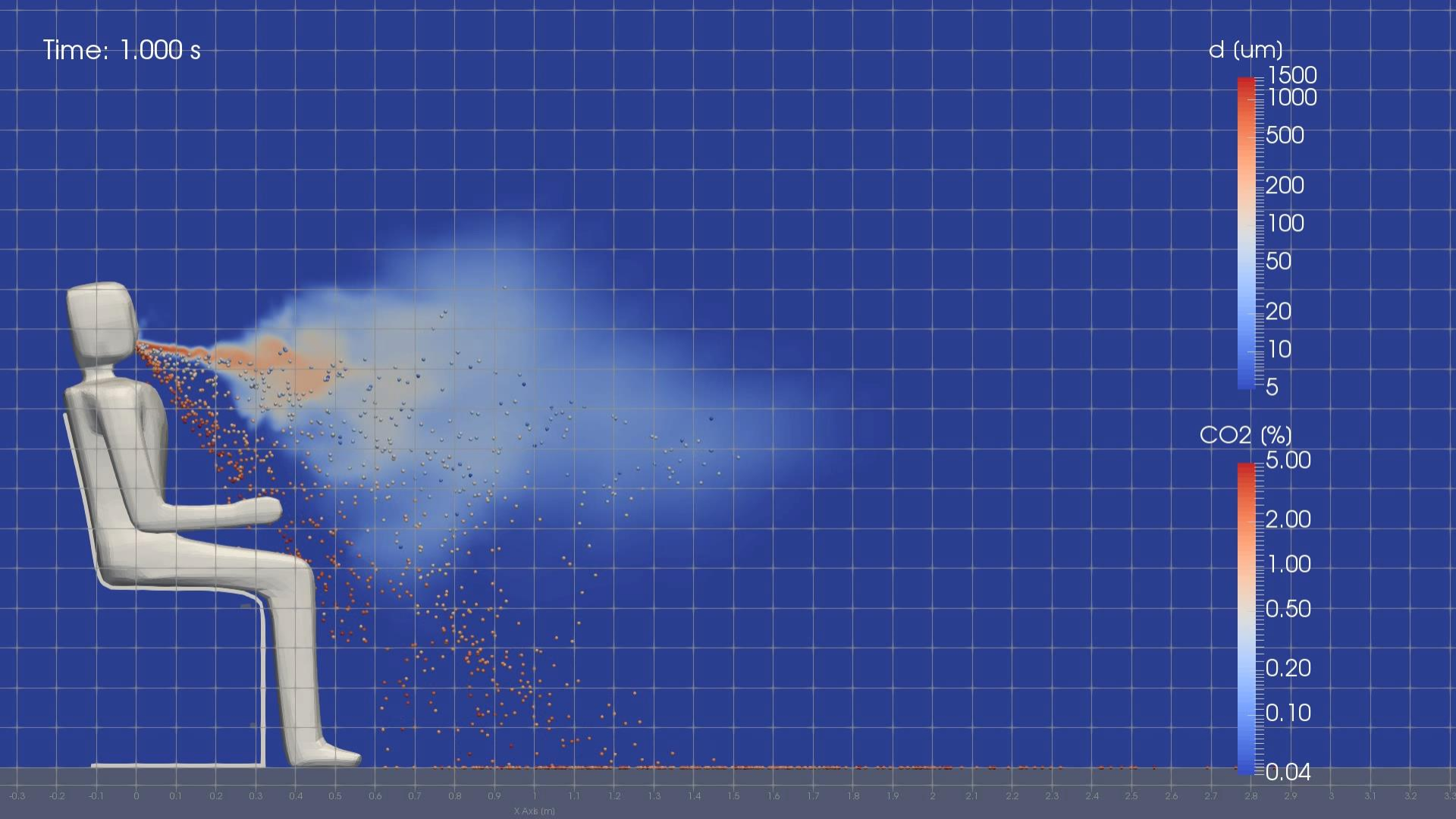
- Yskäisy: noin 5000 partikkelia
- Aivastus: kymmeniä tuhansia partikkeleita
- Muut aktiviteetit:
  - Hengitys: 135 partikkelia/s
  - Puhe: 270 partikkelia/s
  - Äänekäs puhe: 570 partikkelia/s
  - Laulu: 690 partikkelia/s
  - Äänekäs laulu: 980 partikkelia/s
  - Äänekäs laulu maskin kanssa: 410 partikkelia/s

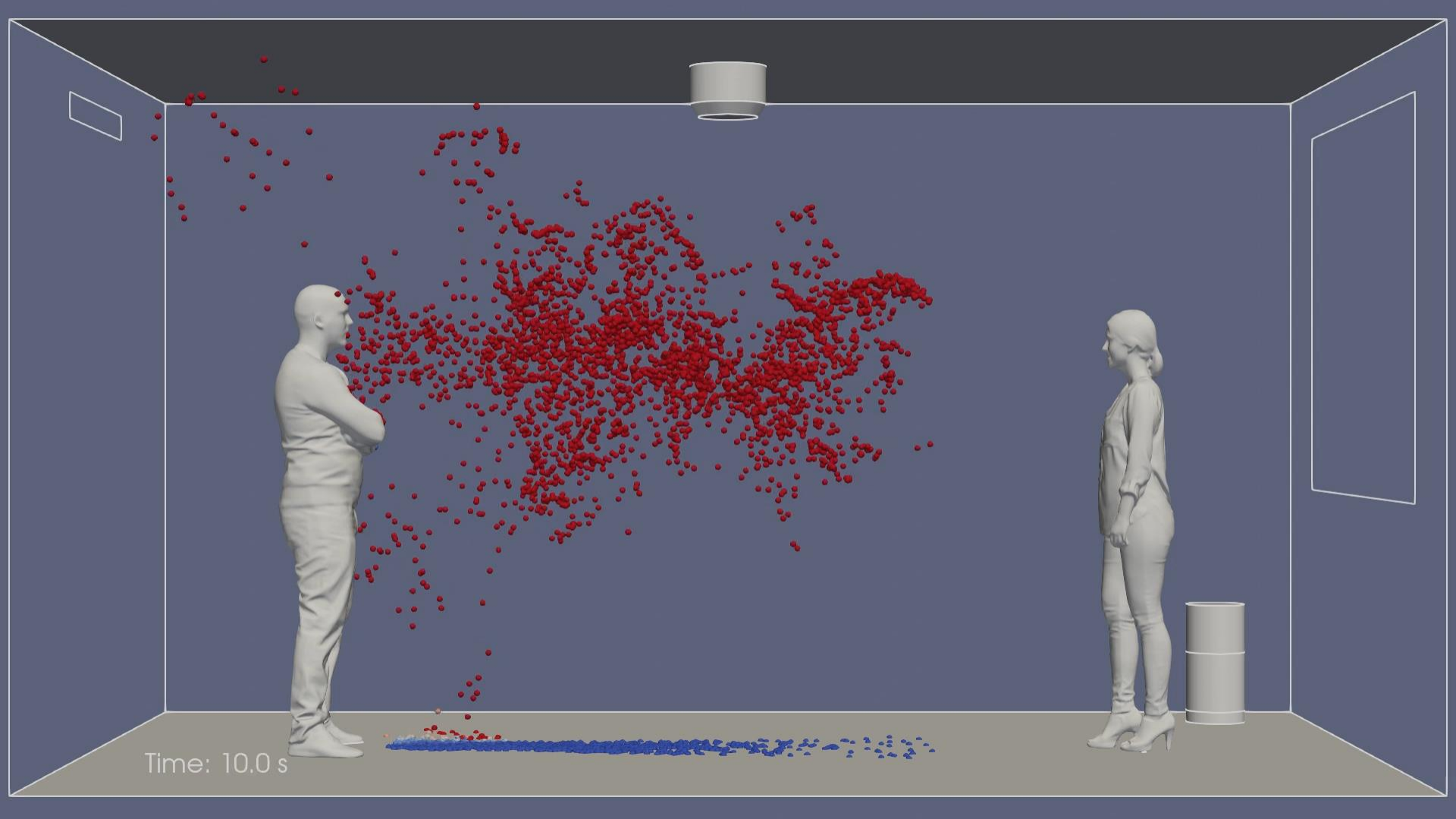
Muiden aktiviteettien lähde: M. Alsved *et al.*, ‘Exhaled respiratory particles during singing and talking’, *Aerosol Science and Technology*, vol. 54, no. 11, pp. 1245–1248, Nov. 2020.

Yskäisyn dynamiikka

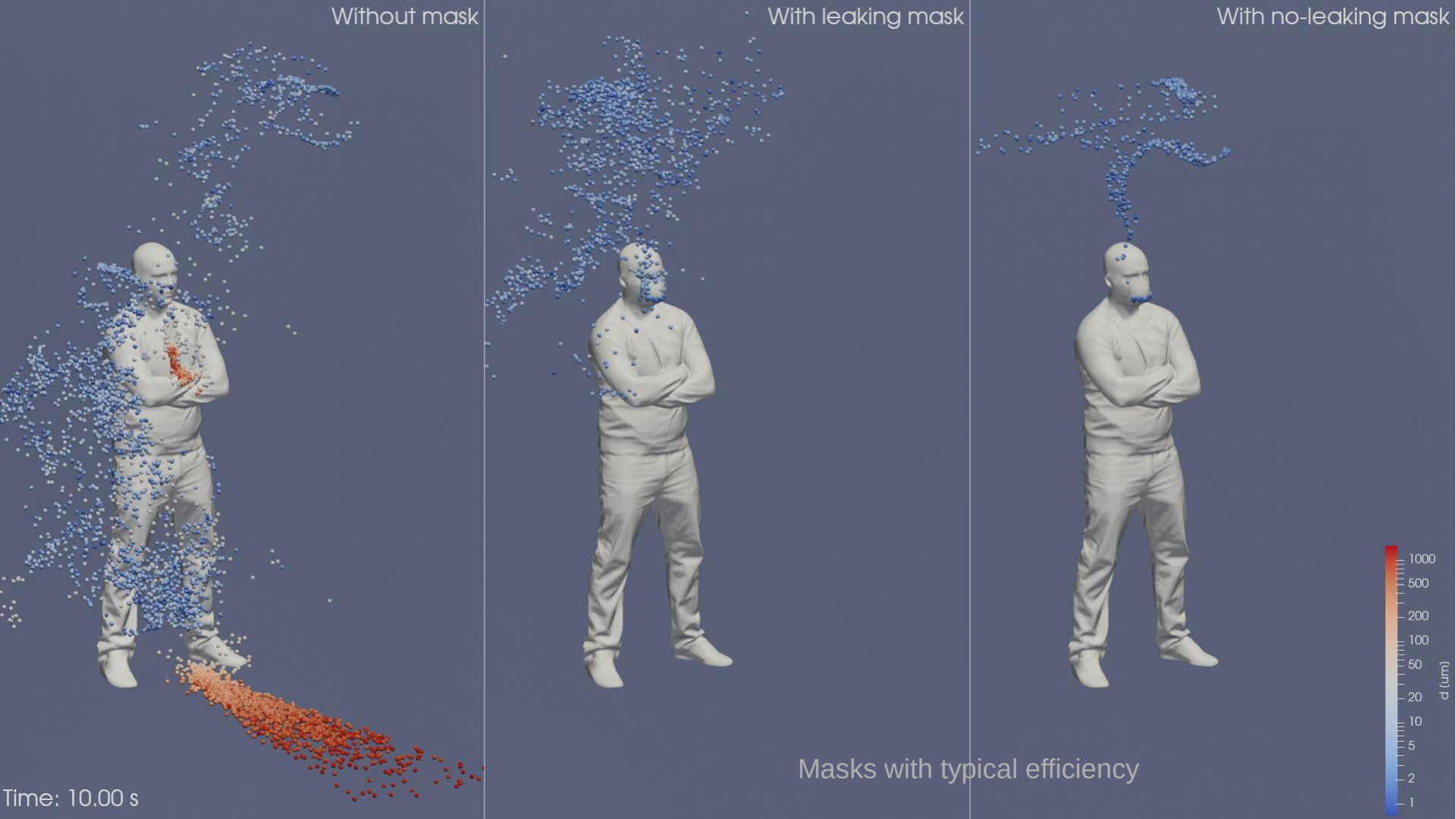


Gupta, J. K., C.-H. Lin, and Q. Chen. 2009. 'Flow Dynamics and Characterization of a Cough'. *Indoor Air* 19 (6): 517–25.


Time: 1.000 s
d (um)
1500
1000
500
200
100
50
20
10
5
CO2 (%)
5.00
2.00
1.00
0.50
0.20
0.10
0.04
-0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3 3.1 3.2 3.3
X Axis (m)


Time: 10.0 s

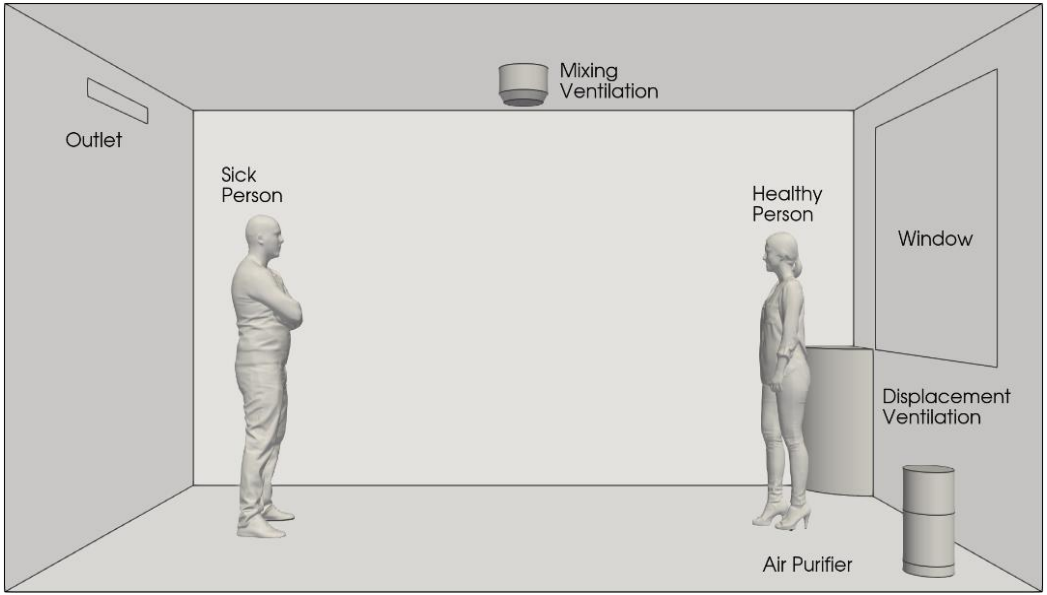
Maskin vaikutus hengitystieinfektion lähdekontrollissa

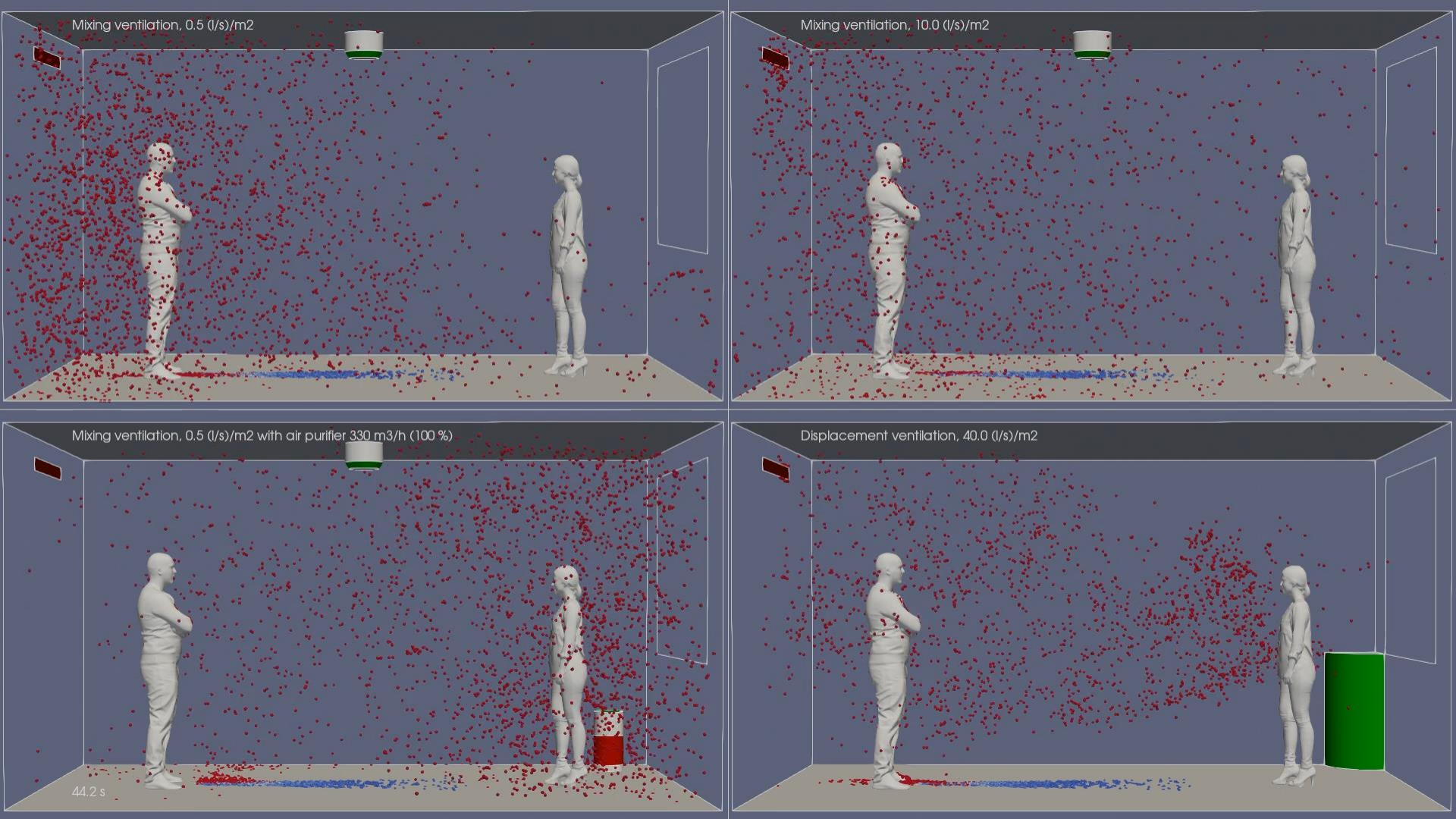

Without mask
With leaking mask
With no-leaking mask
Masks with typical efficiency
Time: 10.00 s
1000
500
200
100
50
20
10
5
2
1
d (um)

Ilmanvaihdon ja –puhdistuksen merkitys

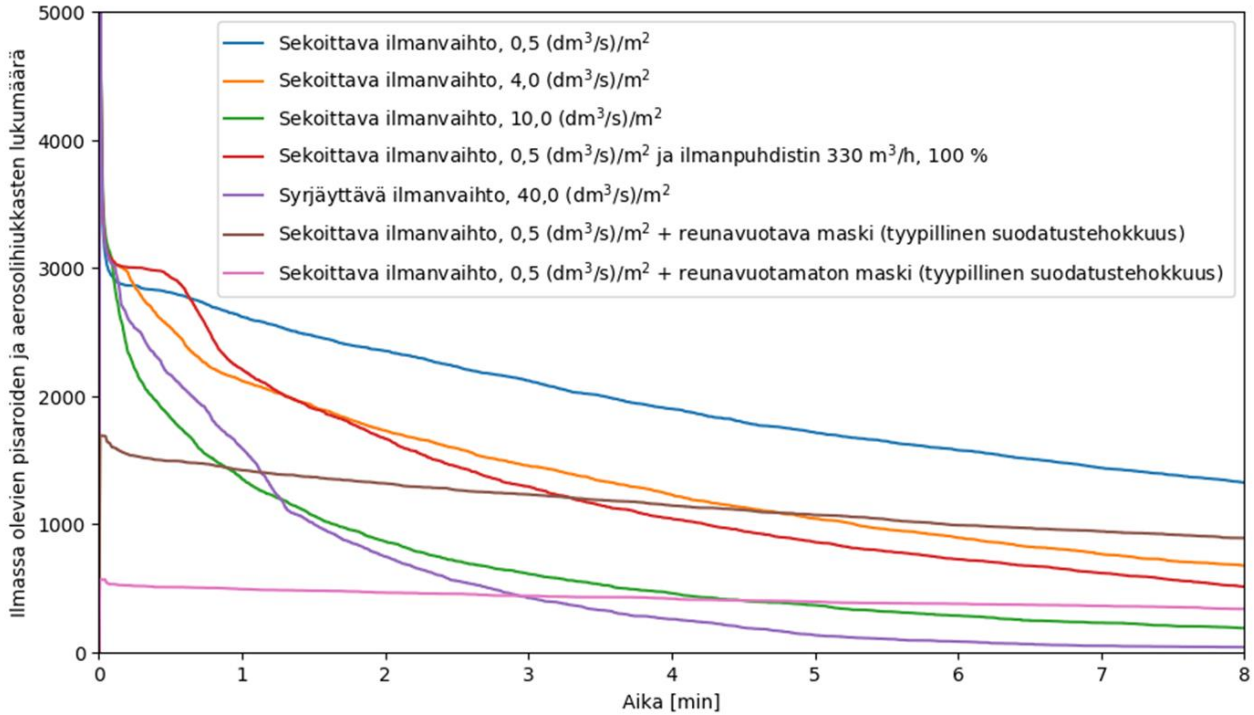
Ilmanvaihto ja –puhdistus

Sairas ihminen yskäisee




Mixing ventilation, 0.5 (l/s)/m2
Mixing ventilation, 10.0 (l/s)/m2
Mixing ventilation, 0.5 (l/s)/m2 with air purifier 330 m3/h (100 %)
Displacement ventilation, 40.0 (l/s)/m2
44.2 s

Ilmassa olevien hiukkasten lukumäärä



Johtopäätös

Virtauslaskenta on hyödyllistä, mutta haastavaa huonetilavirtausten laskennassa

VTT

beyond

the obvious

Thank you!

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