Mitigating the risk of COVID-19 infection in closed spaces

- Operating Theatre / Treatment Room
Standard ventilation with and without wall-mounted UV filtration device
- C-19 Mobile Processing Lab
- Dentist treatment room (AGPs and fallow time)

Project Title: Opensource software simulations towards understanding, monitoring and controlling COVID-19 transmission by managing air, people distancing and adapting urban environments
Project number: 85435
Competition: UKRI Ideas to address COVID-19 – Innovate UK de minimis Aug 2020
Funding body: Innovate UK

Fred Mendonça, *fred.mendonca@esi-group.com*, ESI-OpenCFD Limited

Dec20-May21

esi-group.com

Collaborations in the COVID-19 battle

AGENDA

- **Statement of need**
  - How effective is the internal room ventilation regarding fresh/clean air circulation?
  - What happens to viral load from contamination sources?
- **Validation of underlying flow physics**
- **Useful measures for good ventilation**
- **Some case studies**
  - Operating theatre
  - Community centre
  - Restroom
  - Canteen
  - Office
  - UK C-19 Mobile Processing Unit
  - Dental treatment room AGPs and fallow time

What are the Underlying Flow Regimes?

Air movement and Aerosol Transport

- Fluid Dynamics
    - CFD (Computational Fluid Dynamics) solves the ***Navier-Stokes equations governing continuum fluid mechanics*** using a finite-volume approach and high-performance computing (HPC)
  - Turbulence
  - Buoyancy
  - Heat fluxes and Radiation
  - Transient Impulses (cough, breathing …)

- Aerosols particulates
    - CFD (Computational Fluid Dynamics) additionally solves ***discrete particle mechanics fully coupled*** with the continuum fluid mechanics
  - Droplet size distribution (sub-micron up to two-orders larger)
  - Solid (pathogen) and liquid (water, fat, mucus) content
  - Heat transfer (including ultraviolet radiation) and mass transfer
  - Turbulence collision, break-up and dispersion

What can we gain from CFD Simulation?

Air movement and Aerosol Transport

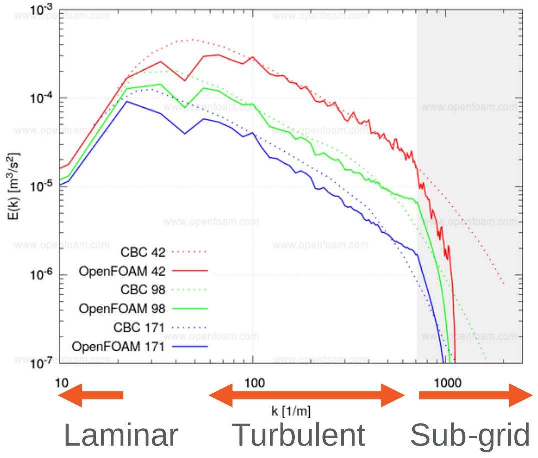
- Insights
  - Maximise fresh-air penetration and identify recirculation dead-spots
  - Understand where contamination sources could spread
  - Understand and use the concept of air-curtains
  - Design furniture placement and occupant placement to minimize transmission risk
  - Understand where particles deposit on surfaces

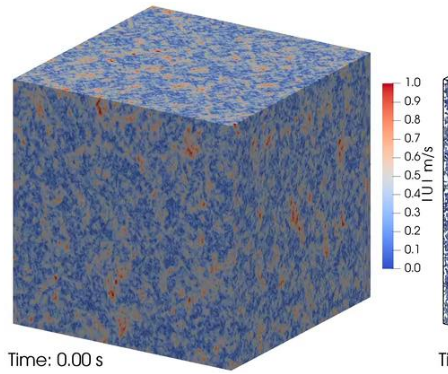
- Metrics
  - Age of the air (hrs/mins/sec) everywhere in the enclosure
  - Fresh Air Index (FAI) – a measure to compare the local air freshness versus the enclosure ventilation rating (air-changes per hour)
  - Contamination source index (CAI) – arising from super-spreaders coughing/breathing/talking
    - How CAI interacts with FAI
  - Air filtration/cleaning (UV) devices for efficient placement
    - Interaction with CAI
    - Interaction with surface contamination

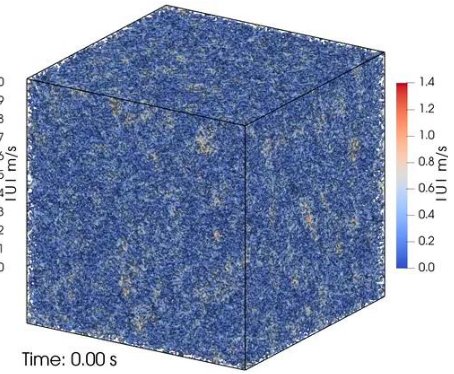
Underlying Flow Regimes: Fluid Dynamics

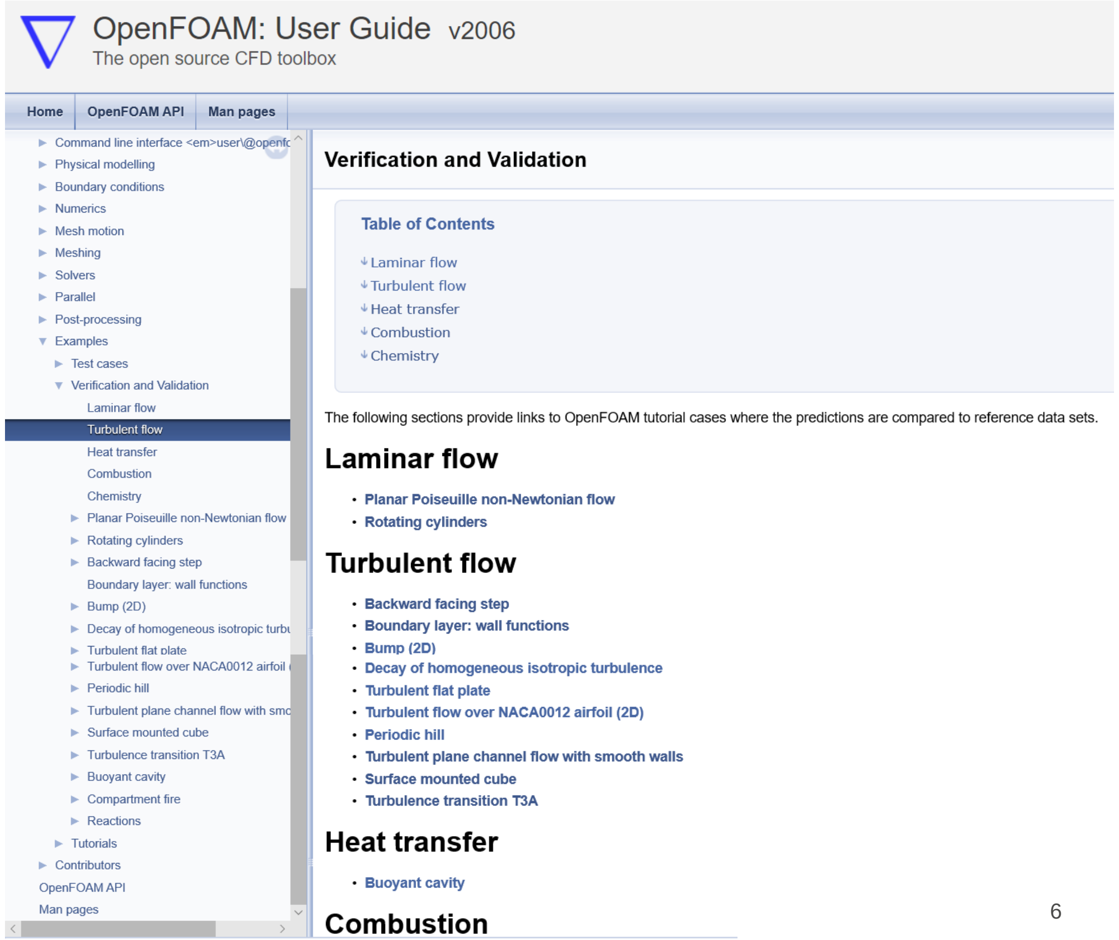
Turbulence

- Reynolds Number in the enclosure determines the turbulence regime
  - Turbulent, laminar, transitional
- OpenFOAM validations
  - RANS
  - LES-based









Underlying Flow Regimes: Fluid Dynamics

Buoyancy

- Laminar heated cavity
  - Wall heat flux
  - Buoyancy driven flow recirculation

Buoyant cavity

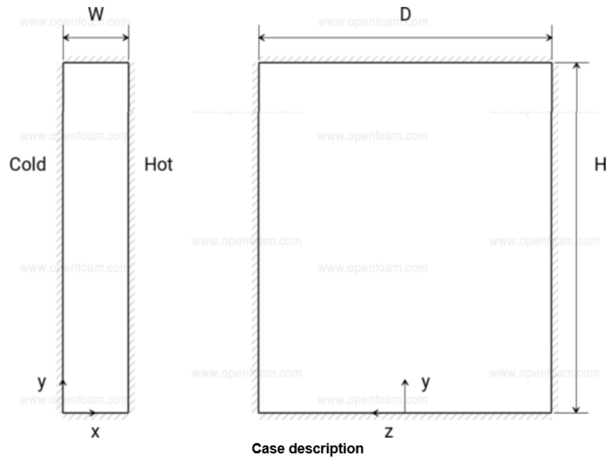
Table of Contents

- Overview
- Mesh
- Results
  - Velocity distributions
  - Temperature distributions

Overview

- Solver: buoyantSimpleFoam
- Investigation into natural convection in a heat cavity
- Experimental case described by Betts and Bokhari [5]
- $FOAM_TUTORIALS/heatTransfer/buoyantSimpleFoam/buoyantCavity

The case is described in the following figure



Case description

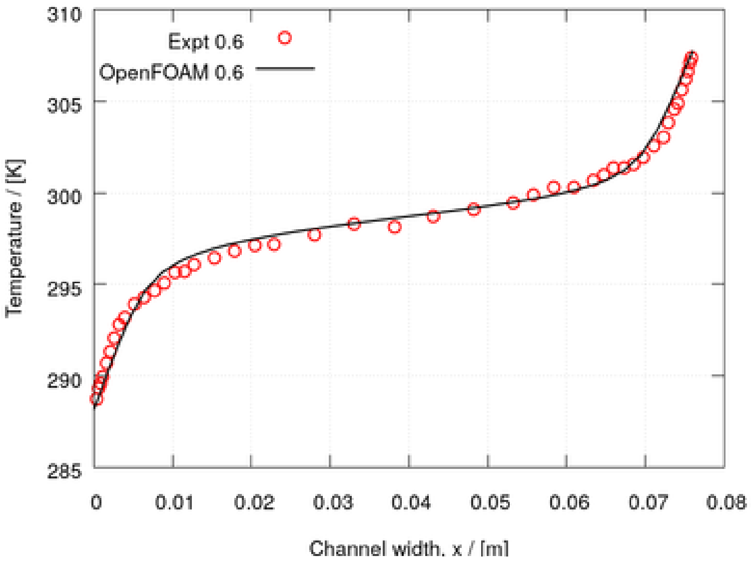
A temperature difference of 19.6K is maintained between the hot and cold; the remaining patches are treated as adiabatic.

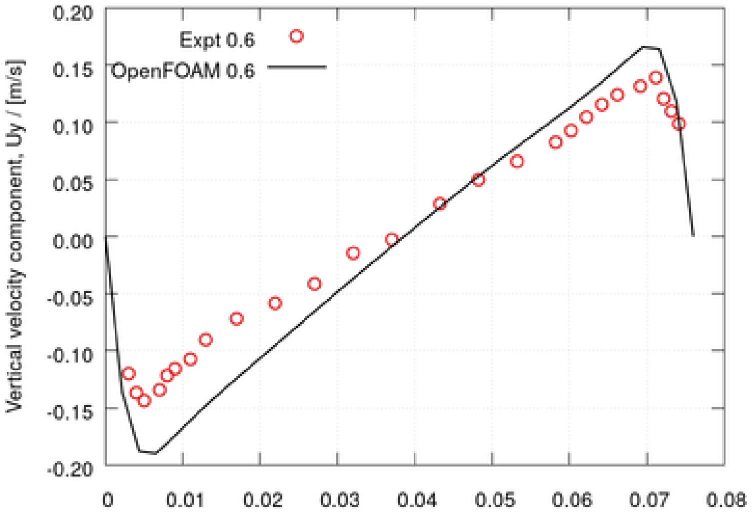
Mesh

- 3D structured mesh created using blockMesh

Results

Results are presented for a selection of y/H locations

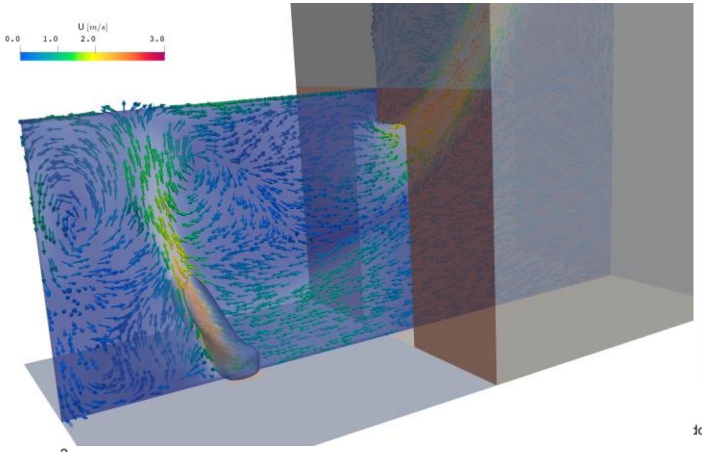


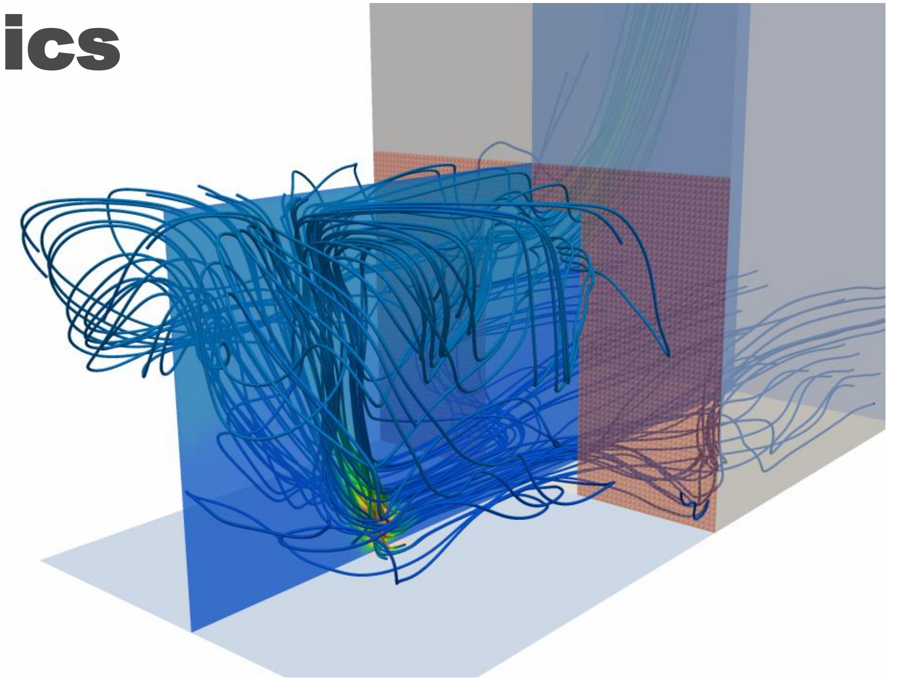


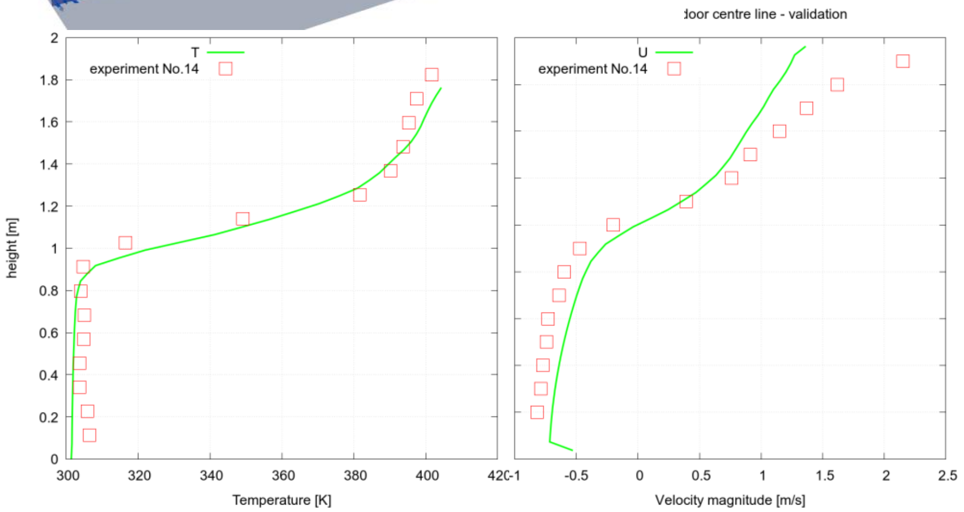
Underlying Flow Regimes: Fluid Dynamics

Heat flux and Radiation

- Steckler thermally stratified enclosure
  - Volume heat source
  - Wall heat transfer
  - Enclosure radiation exchange
  - Open door inflow/outflow
- Thermally stratified flow
- Outflow at the top of the door
- Inflow through the bottom
- Measurement stack along door centerline
  - Validated temperature profile
  - Validated velocity profile

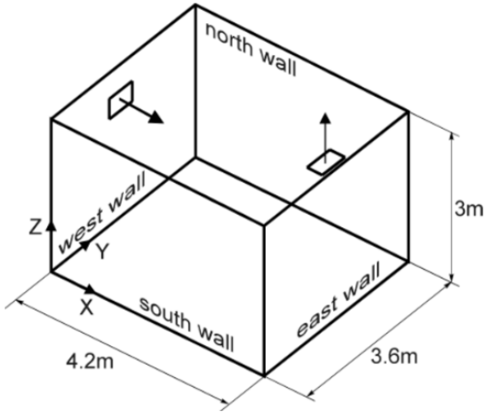






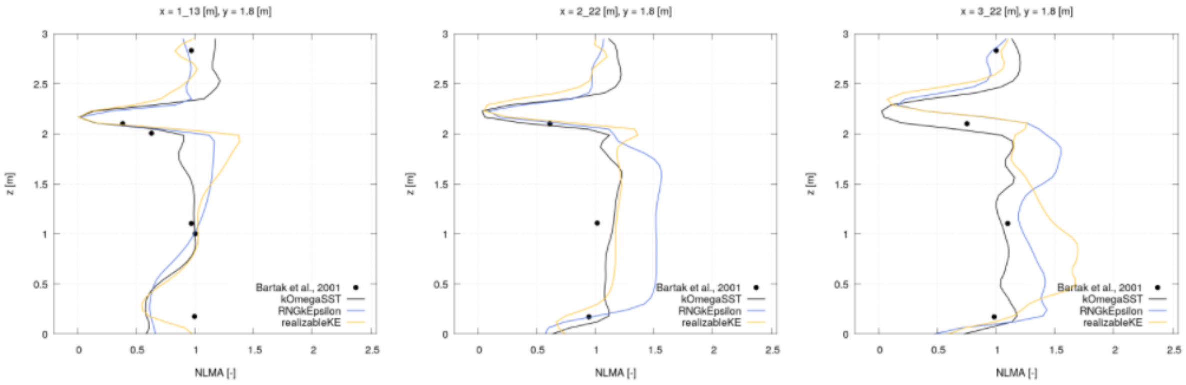
Underlying Flow Regimes: Fluid Dynamics

WP1.1 Age of Air (AoA)

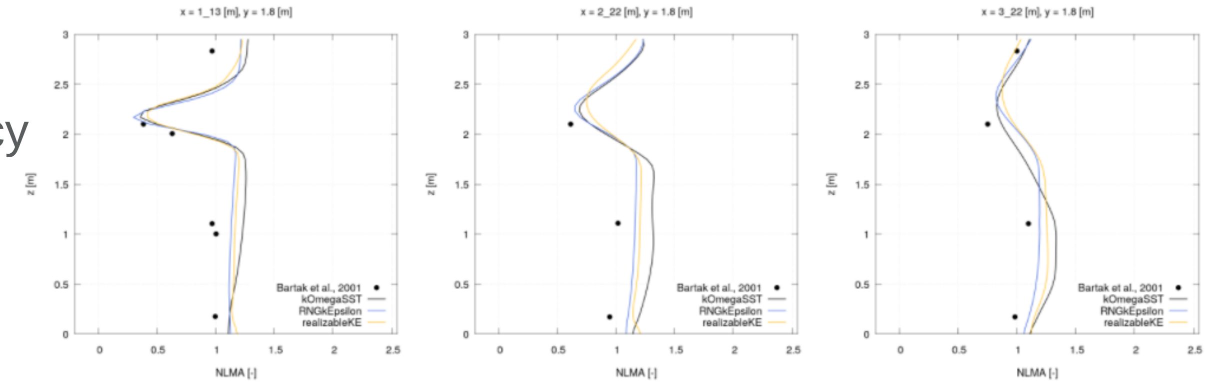


- Spread of "fresh" uncontaminated air from an external source
  - Open doors or windows
  - External source through Aircon or Heater
  - Air filtration units
  - OpenFOAM test-repository
- Passive scalar AoA (sec) solved
  - Turbulence diffusion "off" so as to maximise the convective transport physics
- Turbulence model effects are marginal
  - **k-ω-SST** selected for steady/DES consistency

Case: scalarTransport, alphaD=1, alphaDt=0, nCorr=0



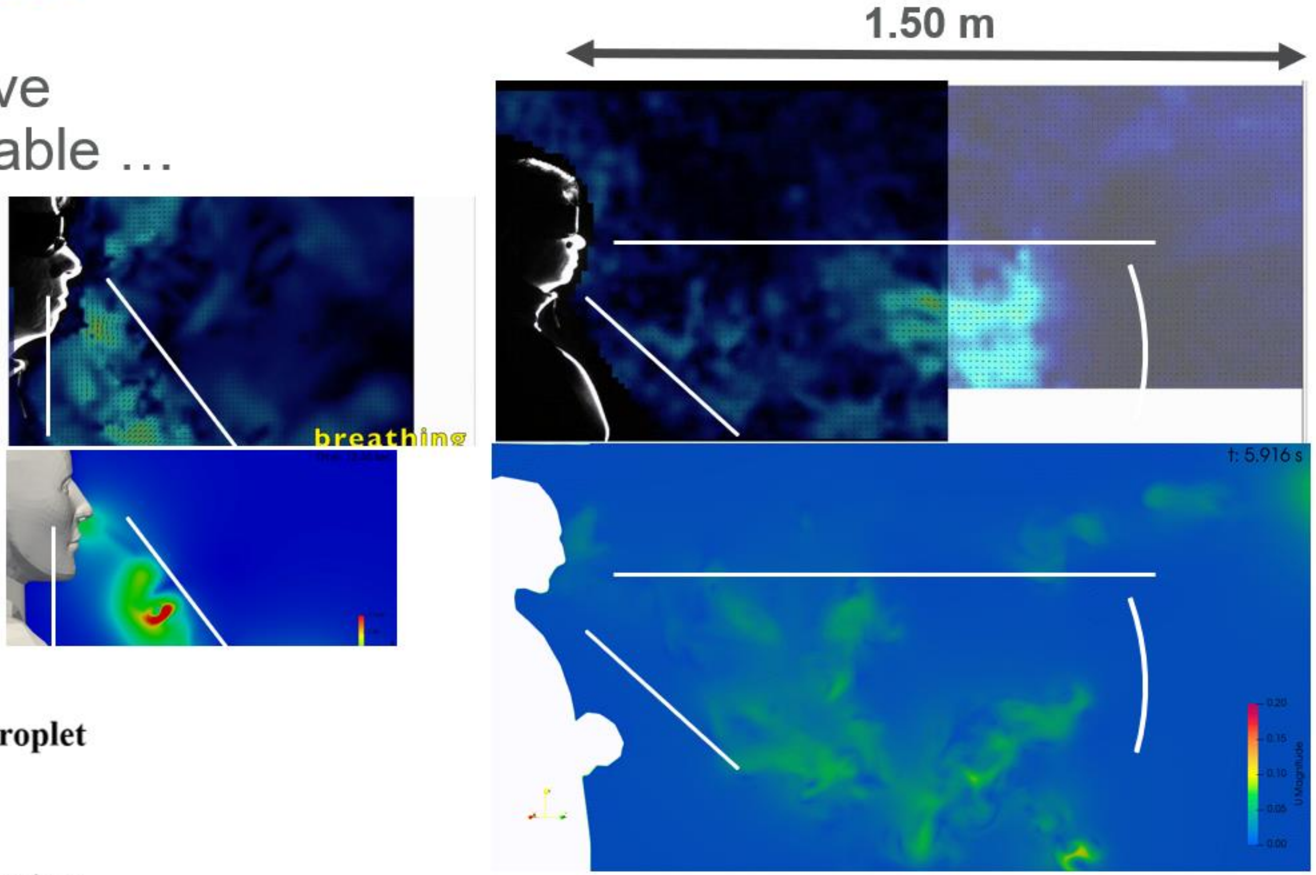
Case: scalarTransport, alphaD=0, alphaDt=1, nCorr=0



Underlying Flow Regimes: Fluid Dynamics

WP1.2 and WP2.2 Transient impulses

- Respiration impulses; verifying qualitative patterns; cycles/persons are not repeatable …
  - Spread angle and Penetration
    - Coughing (see far right >)
    - Breathing (see right, under review …)
    - Speaking (under review …)



- Reference material from:

Fundamental protective mechanisms of face masks against droplet infections

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Underlying Flow Regimes: Fluid Dynamics

WP3.1 and 3.2: Metrics

- “**Air Changes per Hour**” (ACpH) and “**Age of Air**” (AoA)
  - “Air changes per hour” ACpH
    - Time for one-exchange = Volume (m^3) / Volume flow rate (m^3 /hr)
    - ACpH = 1 hr / (Time for one exchange)
  - How long has the air “actually” been in the room?
    - Driven by
      - Convection
      - Diffusion
      - Recirculation
    - AoA steady-state solution unique our implementation in OpenFOAM

- **Fresh Air Index (FAI)** = AoA / ACpH
  - Normalised measure from steady-state
    - = 1 … Neutral rating
    - < 1 … Air is “fresh”
    - > 1 … air is “stale”

Underlying Flow Regimes: Aerosols

Droplet size distribution

- Particle trajectories
  - ILASS validation paper (2016)
  - Sprays with wide range of particle sizes
    - Particle interaction, collision, breakup and coalescence
    - Air jet and spray penetration

ILASS Americas 28th Annual Conference on Liquid Atomization and Spray Systems, Dearborn, MI, May 2016

ECN GDi Spray G: Coupled LES Jet Primary Breakup - Lagrangian Spray Simulation and Comparison with Data

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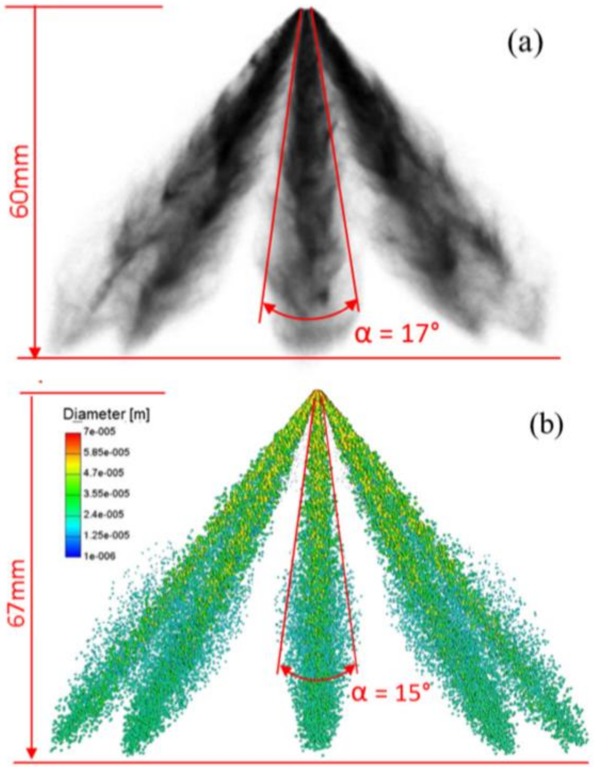
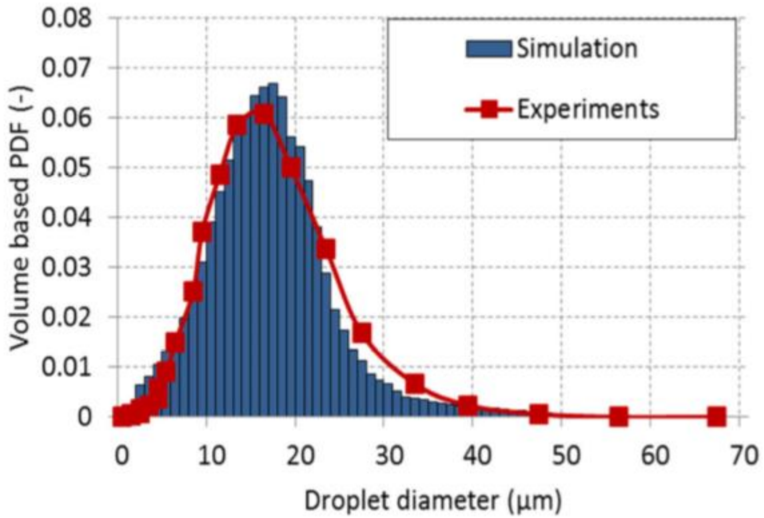
[1] Delphi Customer Technology Center, Bascharage, G.-D. Luxembourg
[2] Delphi Technical Center Rochester, Henrietta, USA

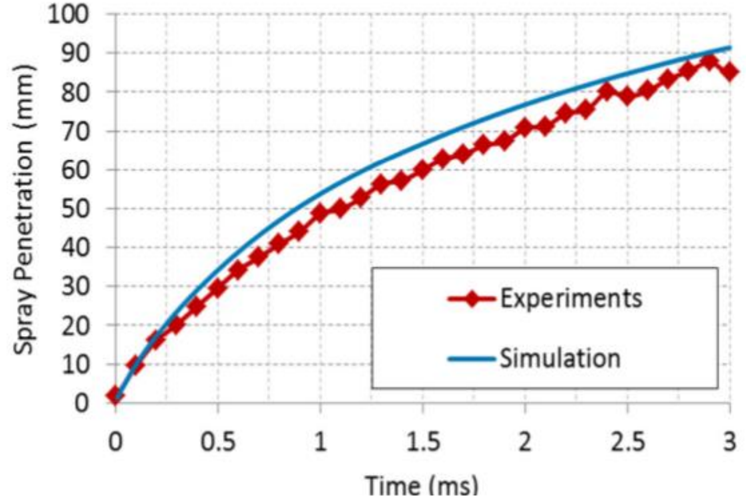
Abstract

Computational fluid dynamic (CFD) simulation of in-cylinder mixture preparation is an important component of the gasoline direct injection (GDi) engine spray pattern (or targeting) optimization process. A major area of shortcoming in CFD Lagrangian stochastic simulation of GDi spray is the proper account of the jet primary breakup (with regards to the initial droplet size - velocity distribution function) due to the substantial influence of nozzle geometry on the primary atomization process. The objective of this study is to assess the predictive capability of the volume-of-fluid large-eddy-simulation (VOF-LES) method for quantitative analysis of the spray primary breakup, so to enable a fully predictive analysis of the complete GDi spray processes. The paper presents results from a VOF-LES analysis of the ECN spray G seat flow and the near-field primary atomization coupled to a Lagrangian stochastics simulation method adopting the discrete droplet model (DDM). The analysis is carried out for a vaporizing n-Heptane spray injection into the atmospheric ambient. The distinction of this case, compared with previous application of the method, is the notable interaction of spray with the counter-bore walls. Hence, the interest is whether the VOF-LES method properly captures the interaction effects on the spray plume primary atomization.

The injector internal flow and jet primary breakup simulation is performed with the Open-FOAM software suite. The simulation of the spray processes - propagation, secondary atomization, and the droplet-air exchanges - are carried out using the AVL-FIRE commercial CFD code. The accuracy of the VOF-LES primary atomization data is inferred from the predictive accuracy of the simulated far-field spray plume trajectory, cone angle, droplet-size



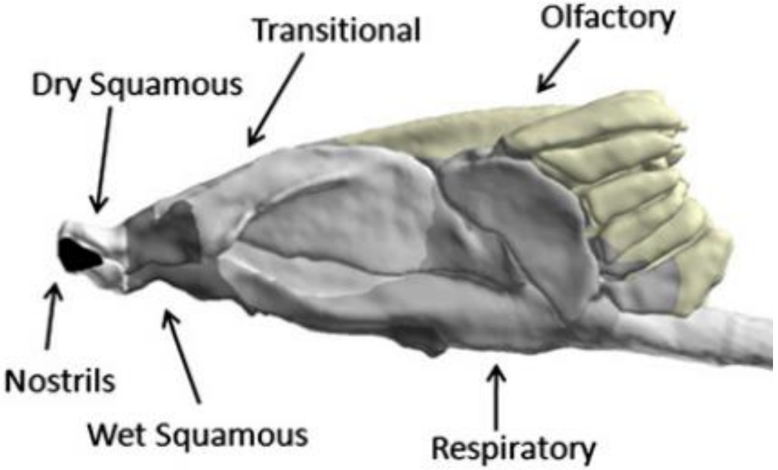




Underlying Flow Regimes: Aerosols

Aerosol penetration

- Penetration in nasal passages
- Sub-micron and micrometer particle deposition
- Joint investigation with PNNL
    - Presented at the 2017 OpenFOAM Conference



Computational fluid dynamics simulations of submicrometer and micrometer particle deposition in the nasal passages of a Sprague-Dawley rat

January 2012 · Journal of Aerosol Science 43(1):31-44
DOI: 10.1016/j.jaerosci.2011.08.008

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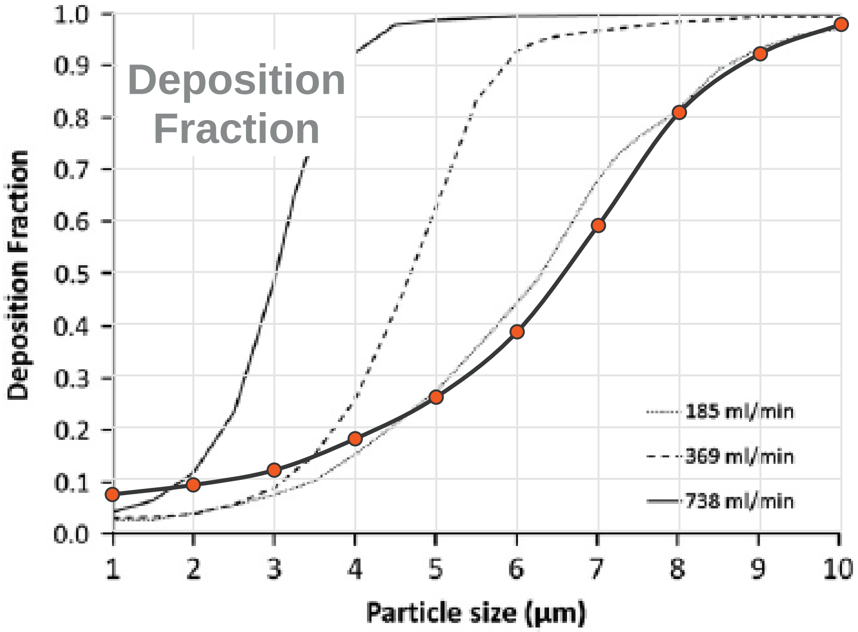
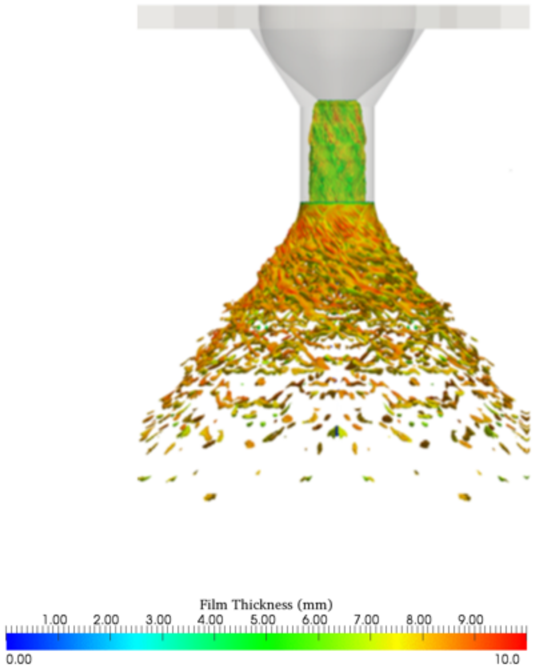
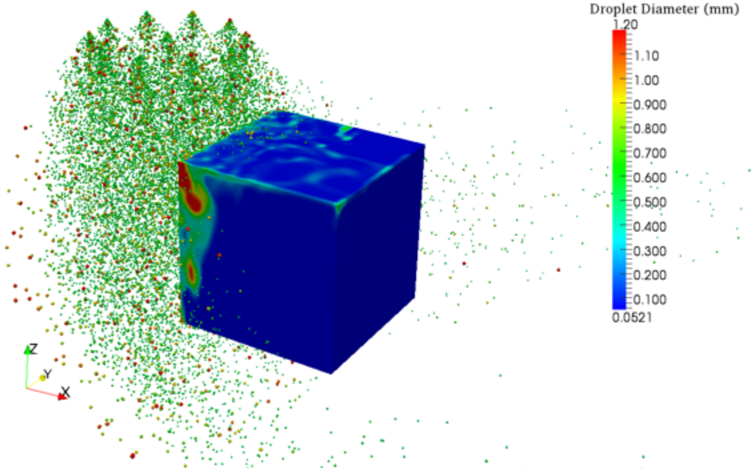


Underlying Flow Regimes: Aerosols

Aerosol, flow and heat transfer interaction

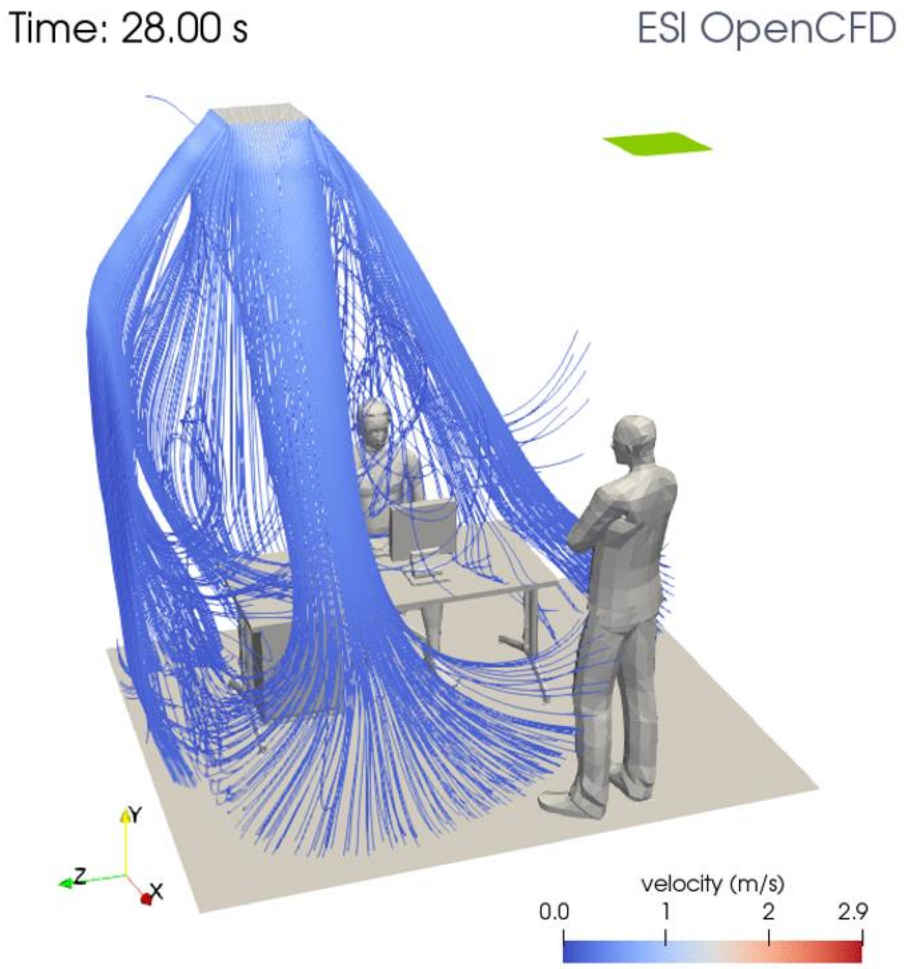
- Common in ICE and Coal fired power for which OpenFOAM has been extensively deployed
- Aerosol spray atomisation models
  - hollow/solid cone injectors, injector arrays,
  - Sauter-mean diameter/velocity/trajectory droplet distribution
- Aerosol atomisation prediction
  - VoF modelling of liquid paint injection
  - LES simulation of primary atomization of liquid paint into droplets
- Aerosol-surface interactions
  - WeberNumber-based droplet/surface interaction
    - bounce,
    - shatter
    - Stick
    - film-formation
  - Transport of resulting surface liquid film
  - Full heat and mass (species) transfer with particles and surface film

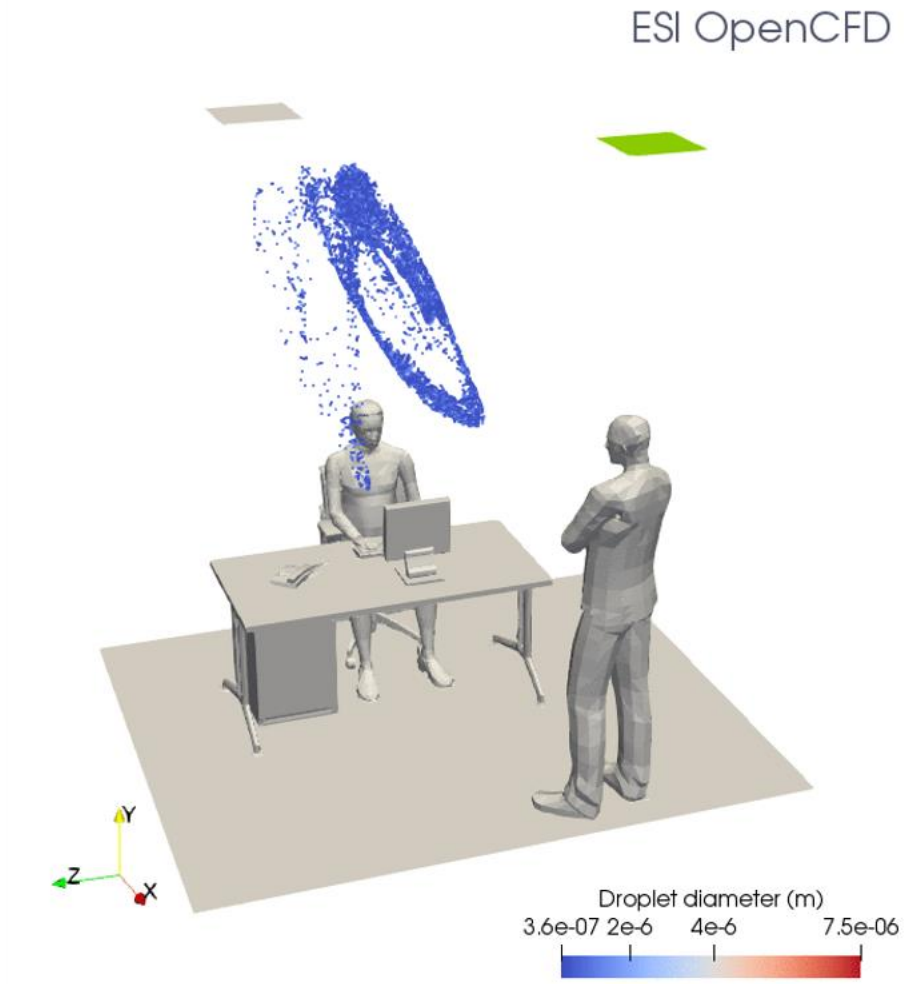




Underlying Flow Regimes: Summary

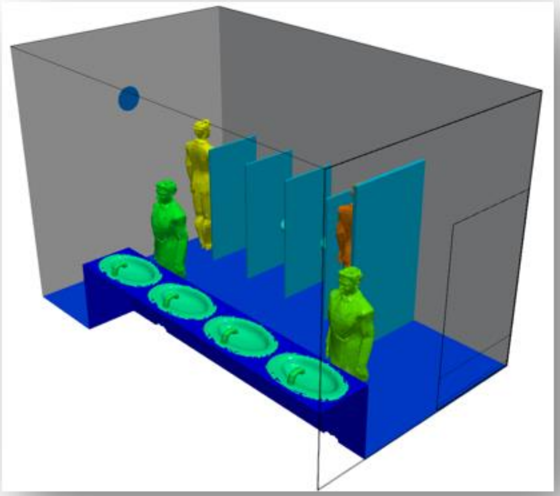
WP2.1, WP2.2 and WP5: Aerosol and Flow; all physics combined





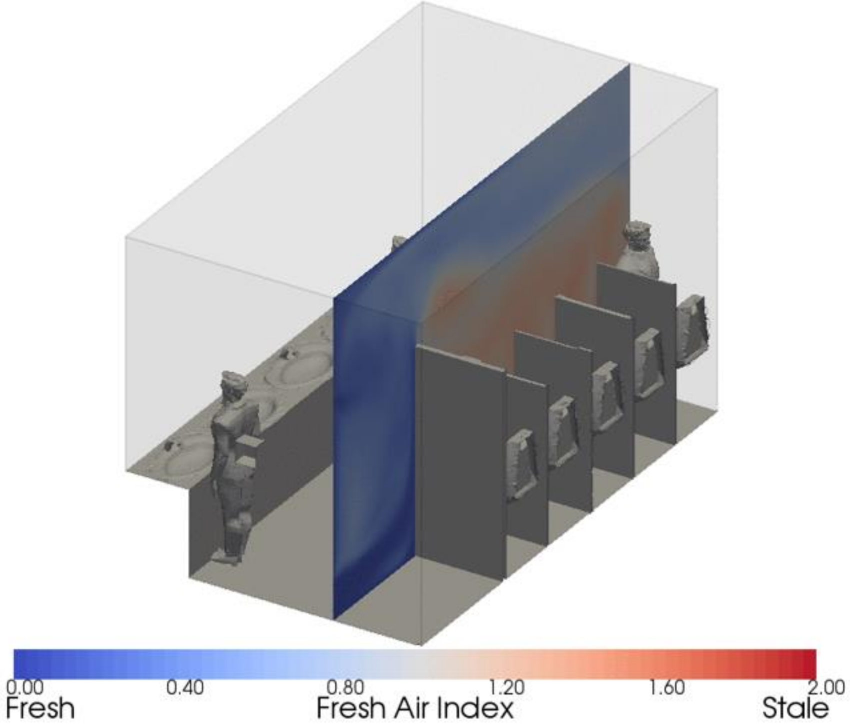
Underlying Flow Regimes: Summary

WP1.1, WP1.2 and WP5: Washroom with metrics



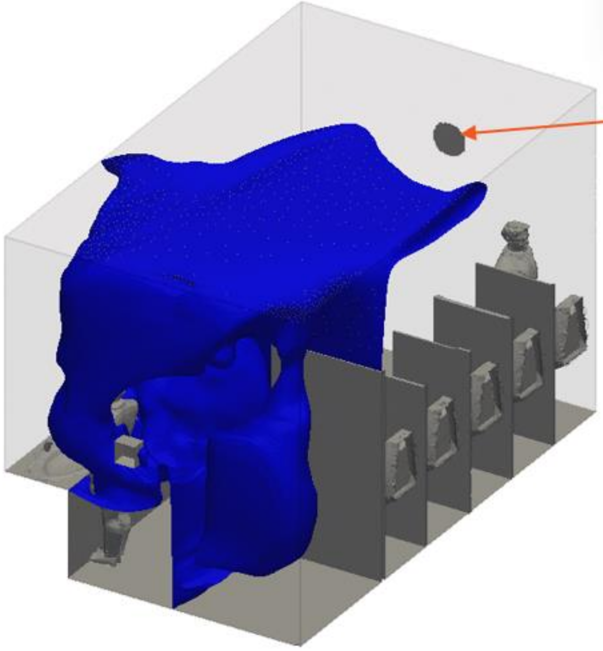
Fresh Air Index indicates stale/bad (red) air locations.
These areas have increased chances contaminant

Plane at x = 23.654 m

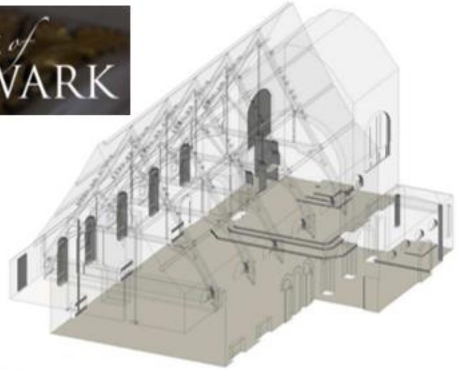


Air is exchanged every 4-5 min

Iso Surface of Age of Air at 90 secs



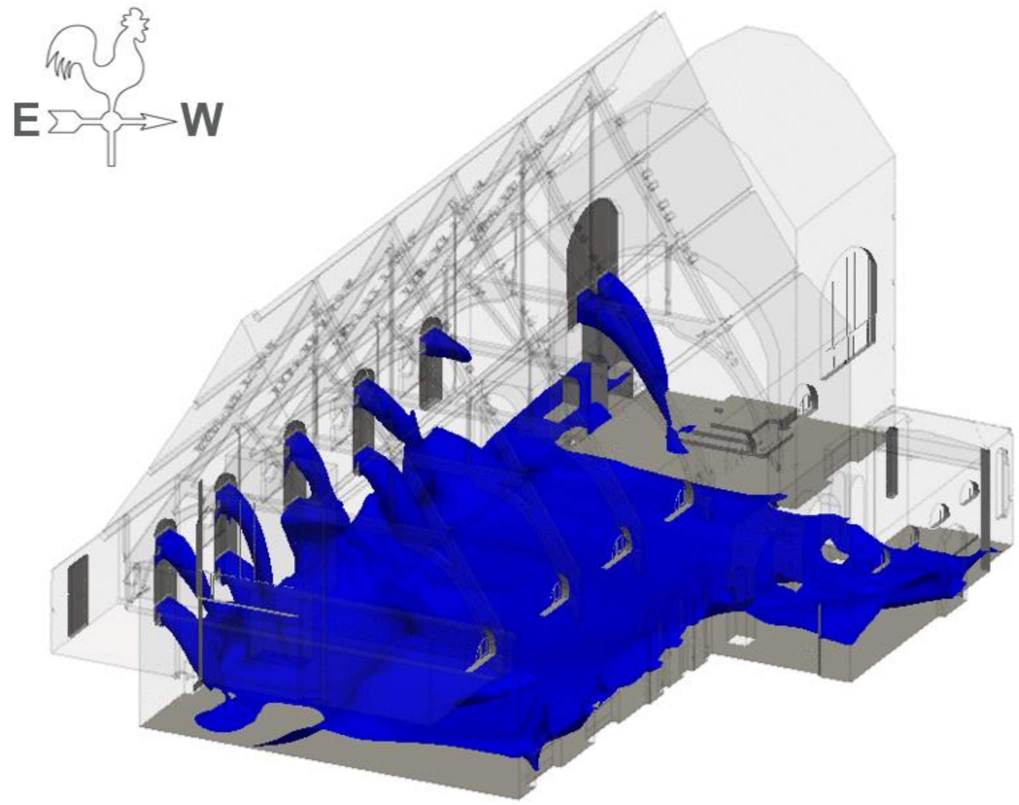
Exhaust fan extracting air at 375 CFM (2.5 m/s)



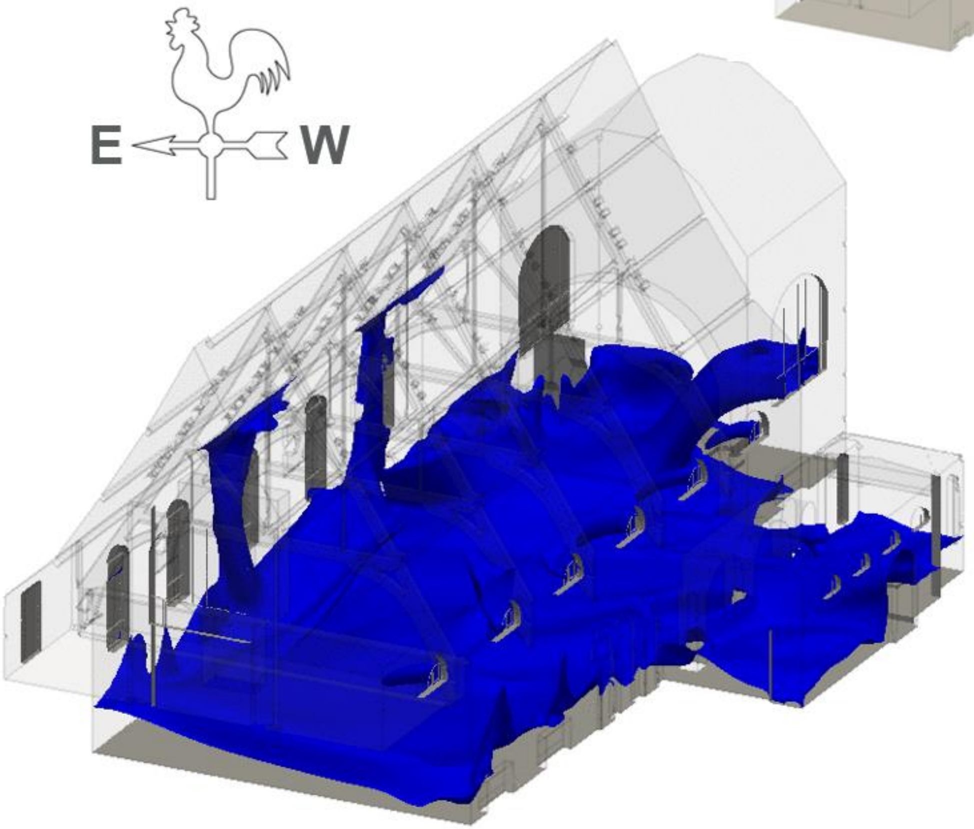
Community Centre: Church

Westerly and Easterly wind

Iso Surface of Age of Air at 440 secs



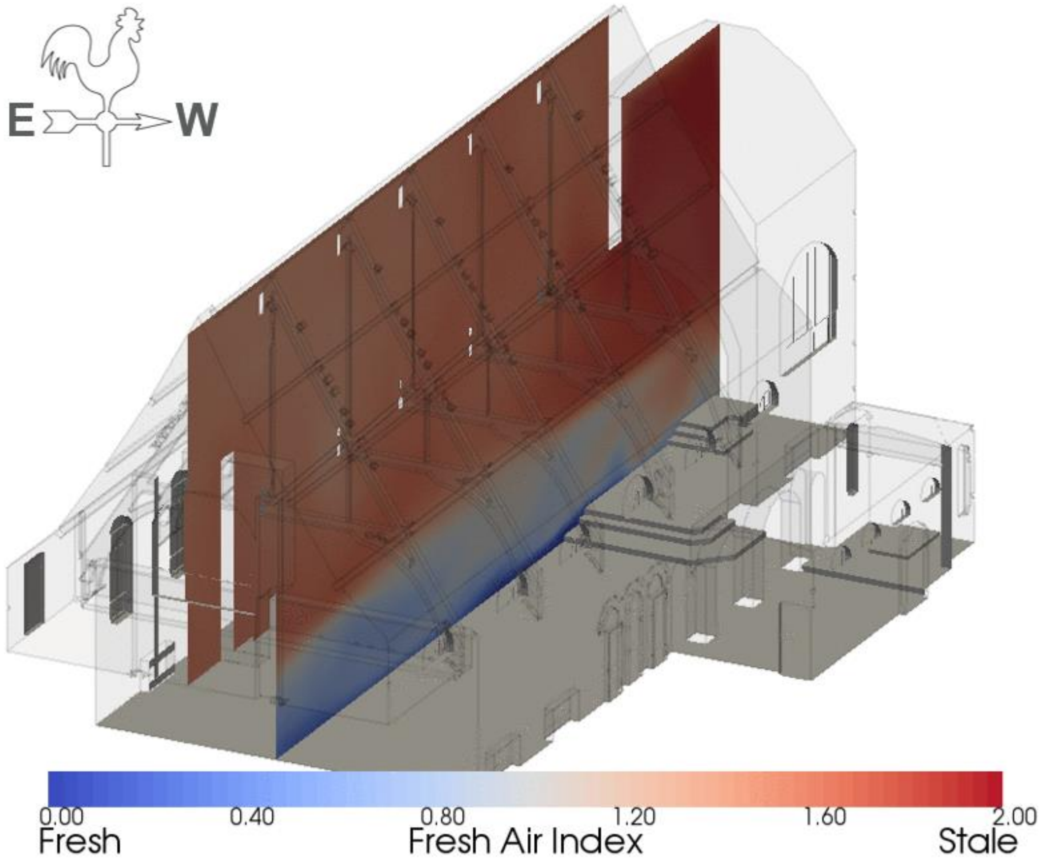
Iso Surface of Age of Air at 500 secs



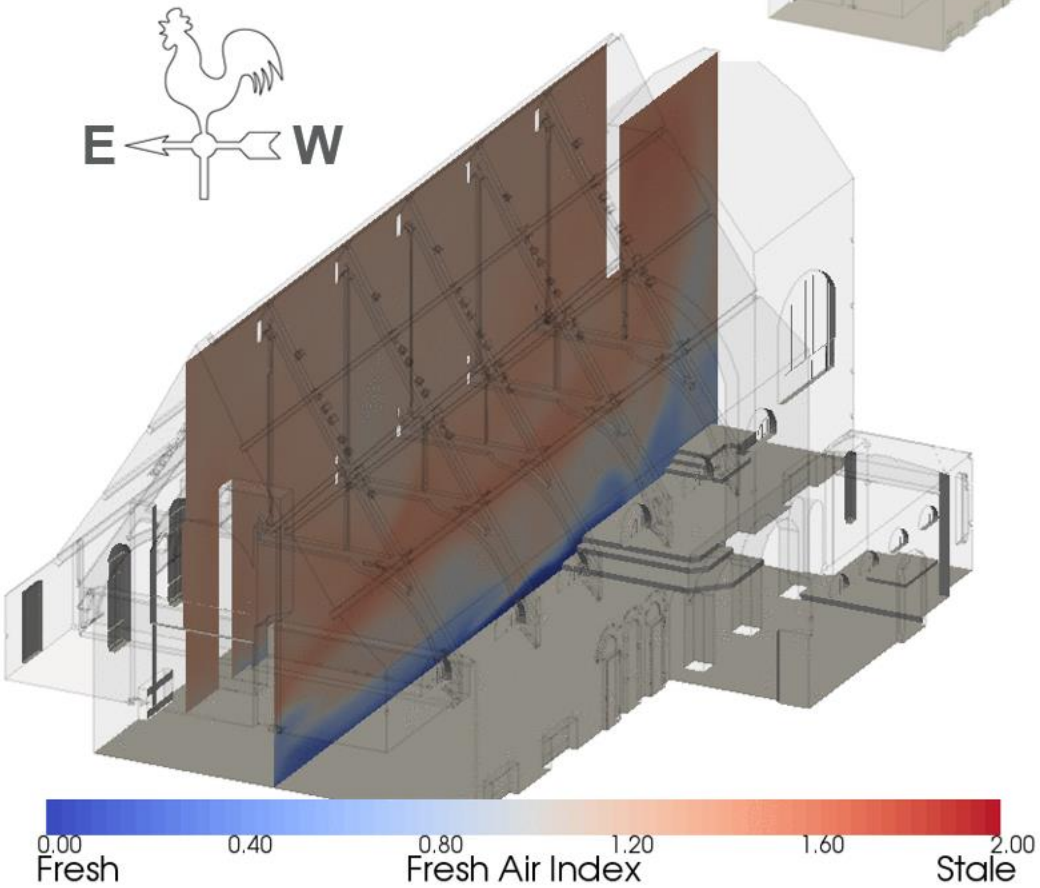
Community Centre: Church

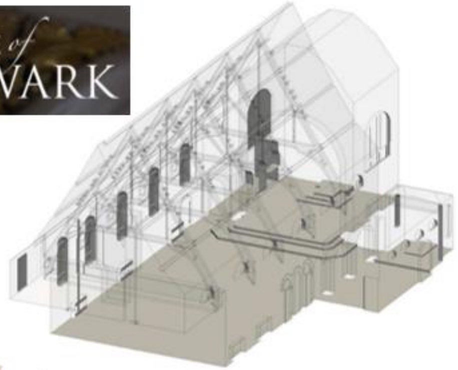
Westerly and Easterly wind

Plane at y = 20314.528 m



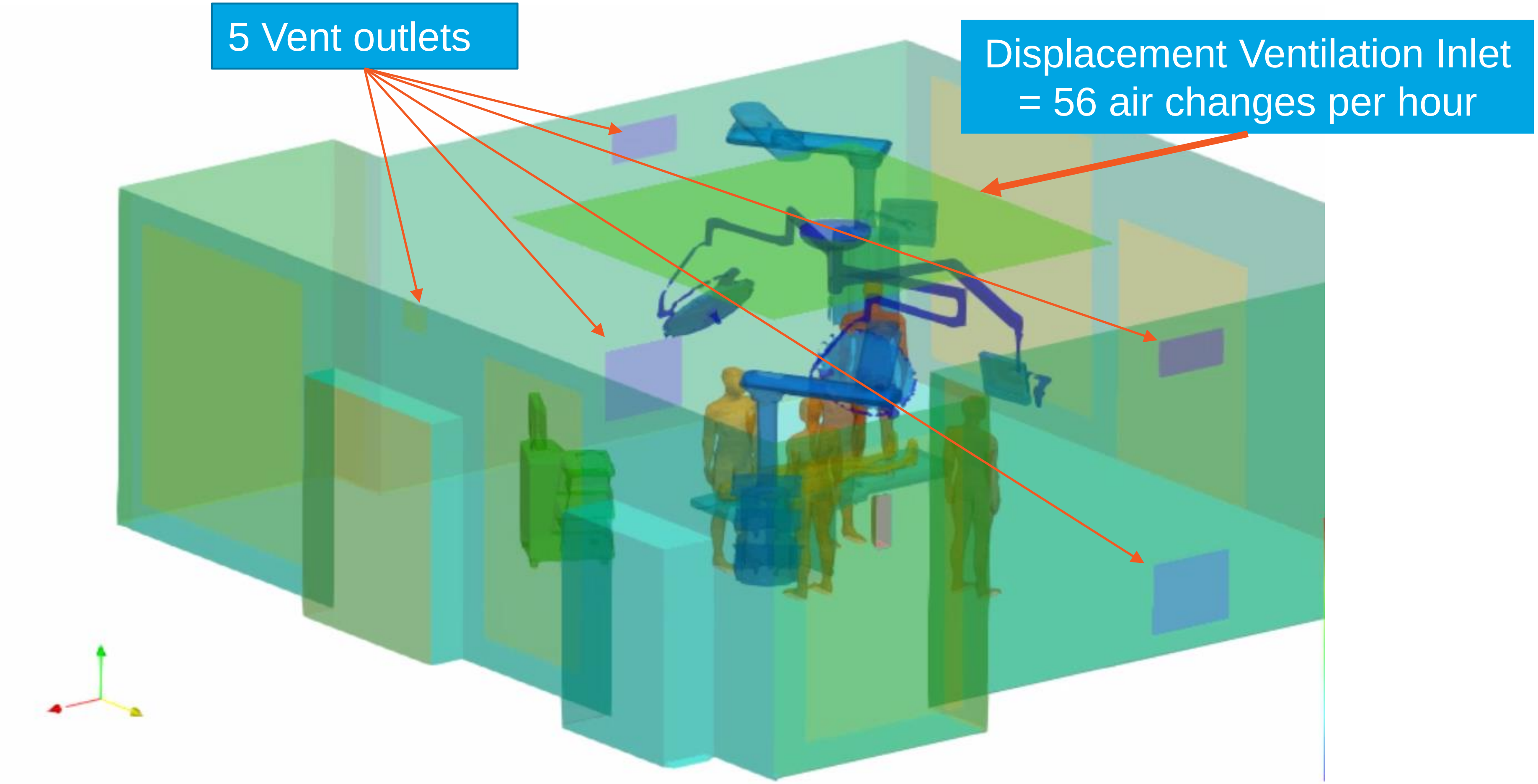
Plane at y = 20314.528 m





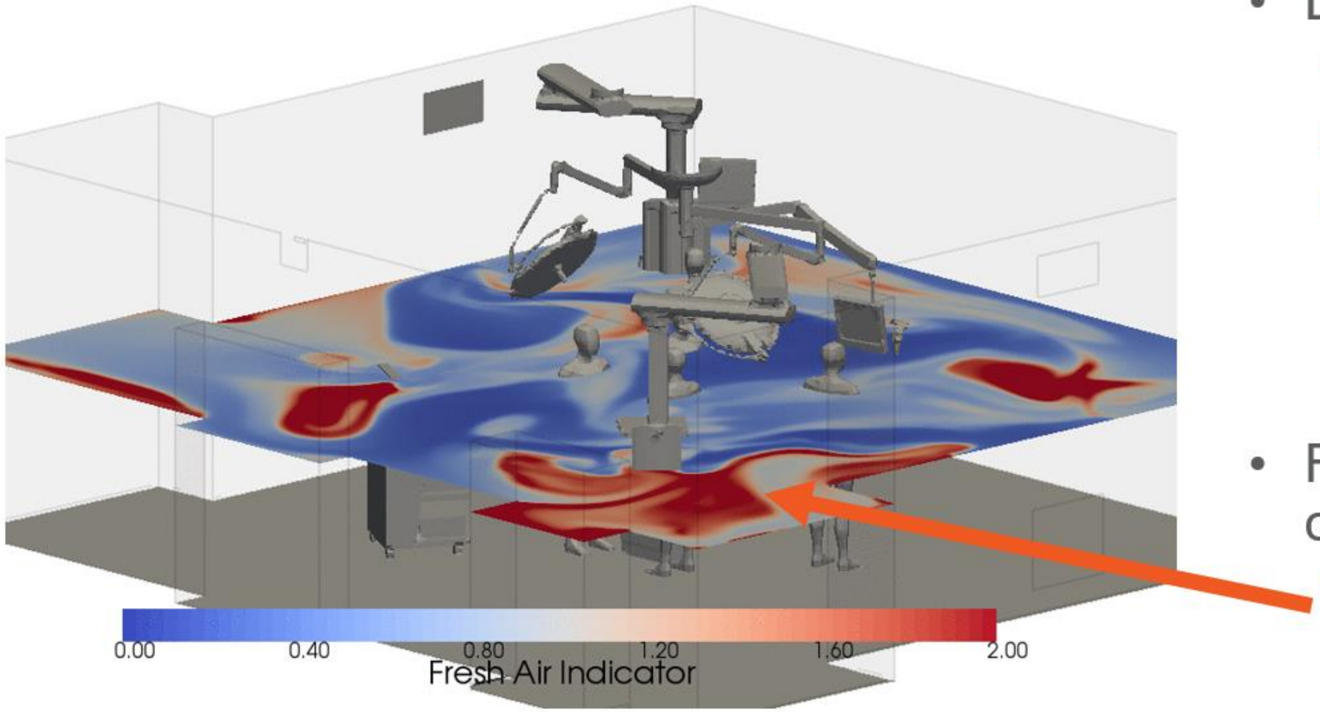
WP5: Operating Theatre Demonstrator

Layout: Theatre, staff, equipment, furniture and ventilation



WP5: Operating Theatre Demonstrator

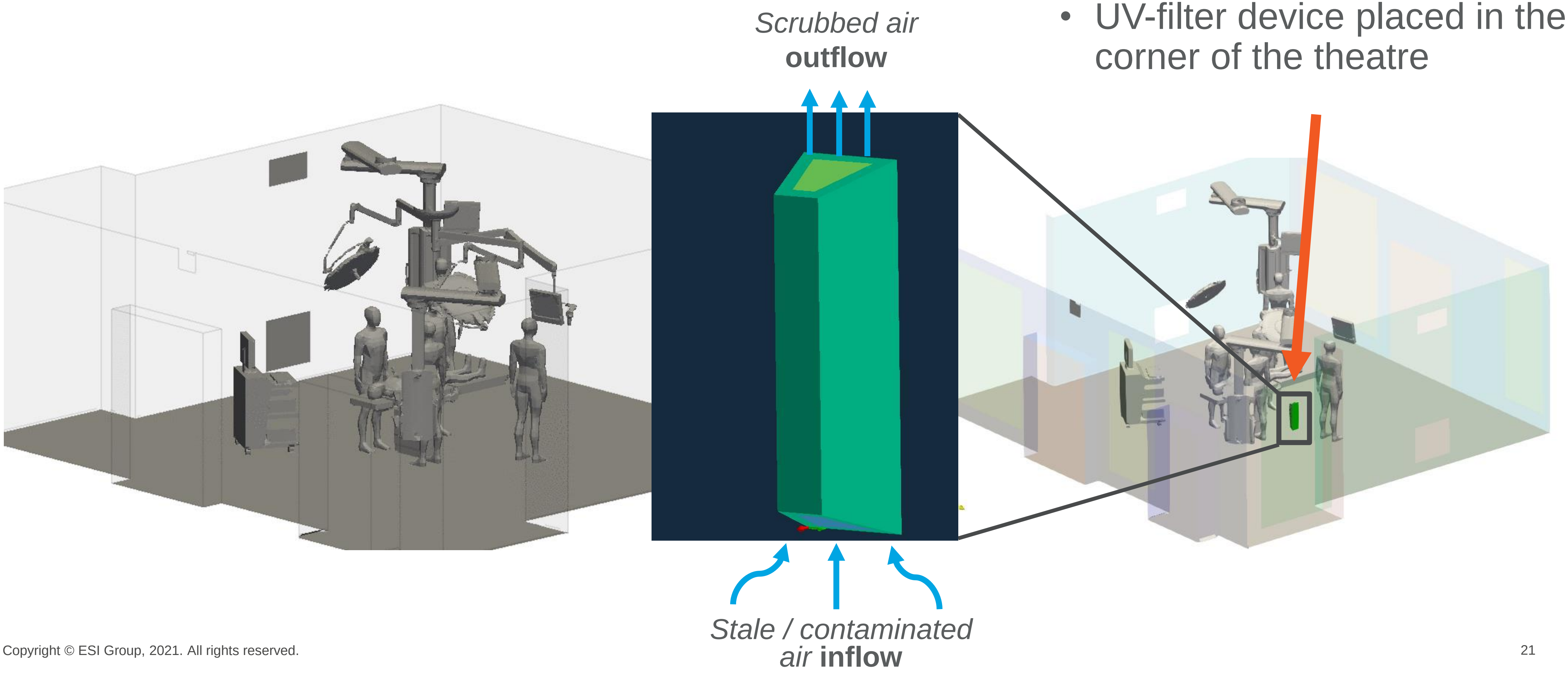
Standard layout – results of CFD Fresh Air Index (FAI)



- Design details:
  - Inflow rate = 2.4 m^3/s
  - Volume = 154 m^3
  - Design air changes per hr = 56 (one airchange every 64sec)
- FAI indicates stale air locations in the room corners (red parts in the section-sweeps)
  - This would be a good corner location for a UV-filter device

WP5: Operating Theatre Demonstrator

Modifying the layout – with filter device

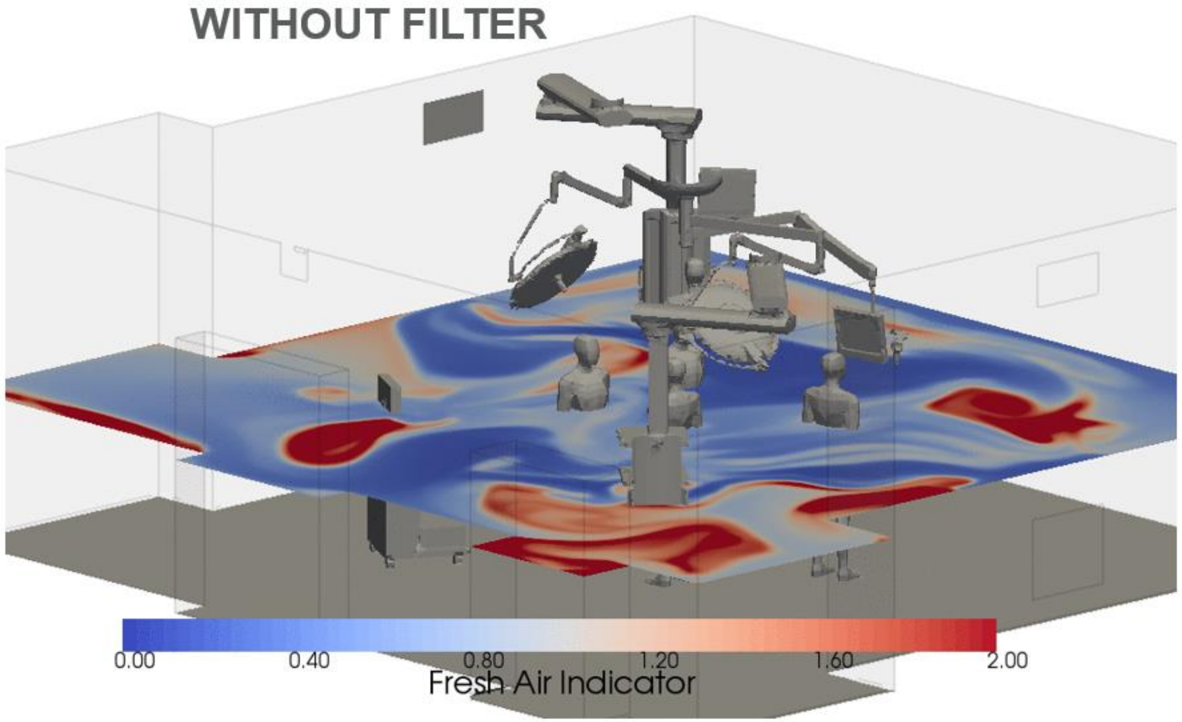


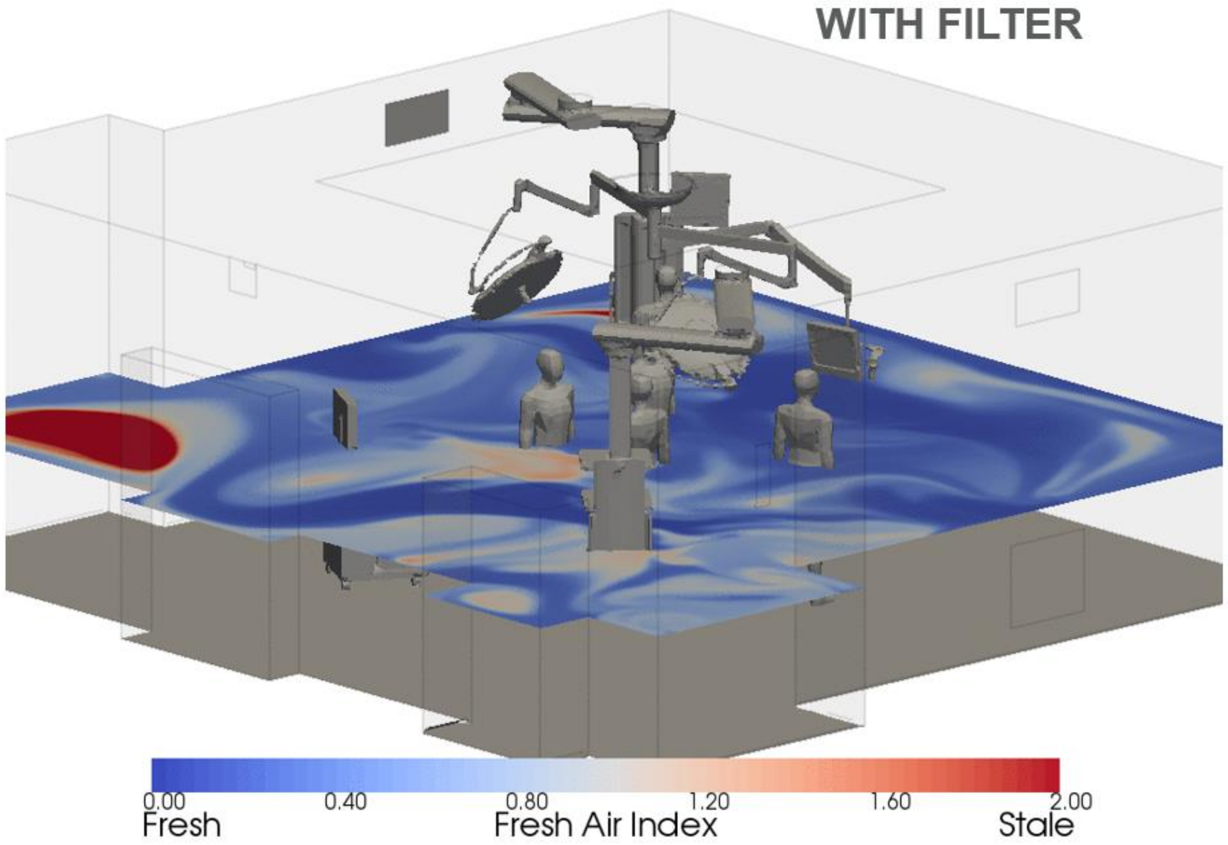
- UV-filter device placed in the corner of the theatre

WP5: Operating Theatre Demonstrator

Standard versus Modified layout – with filter device

Plane at z = -3.2 m

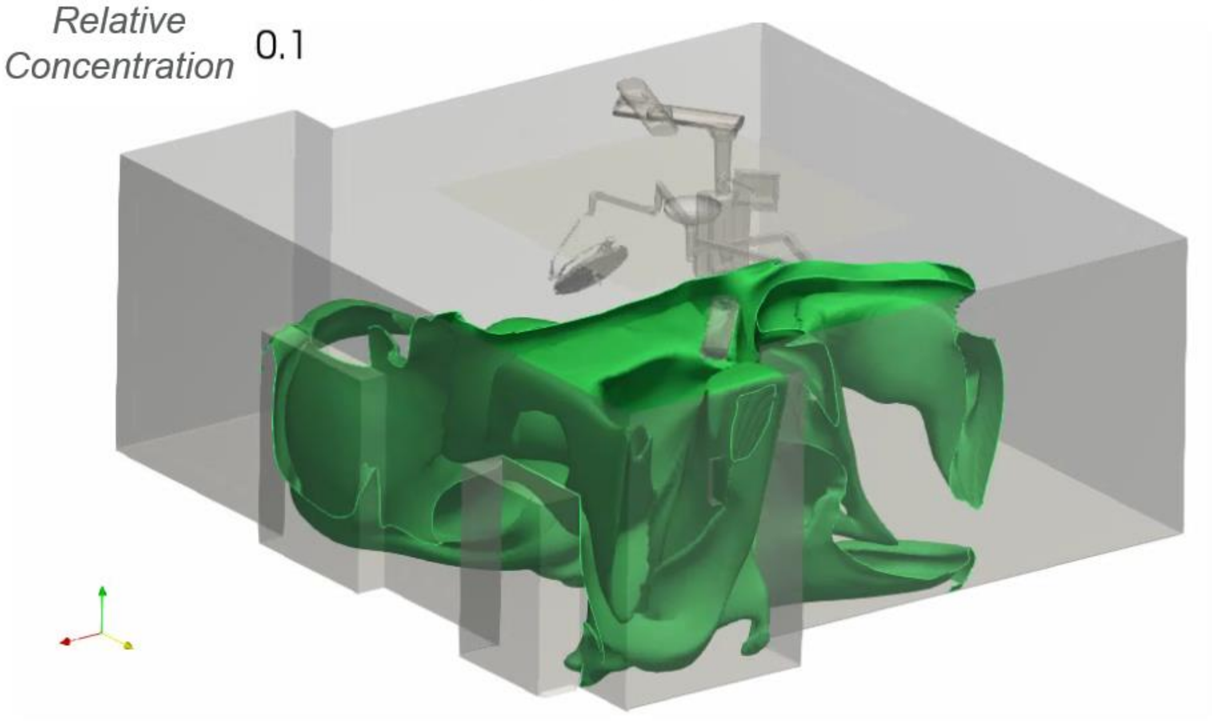


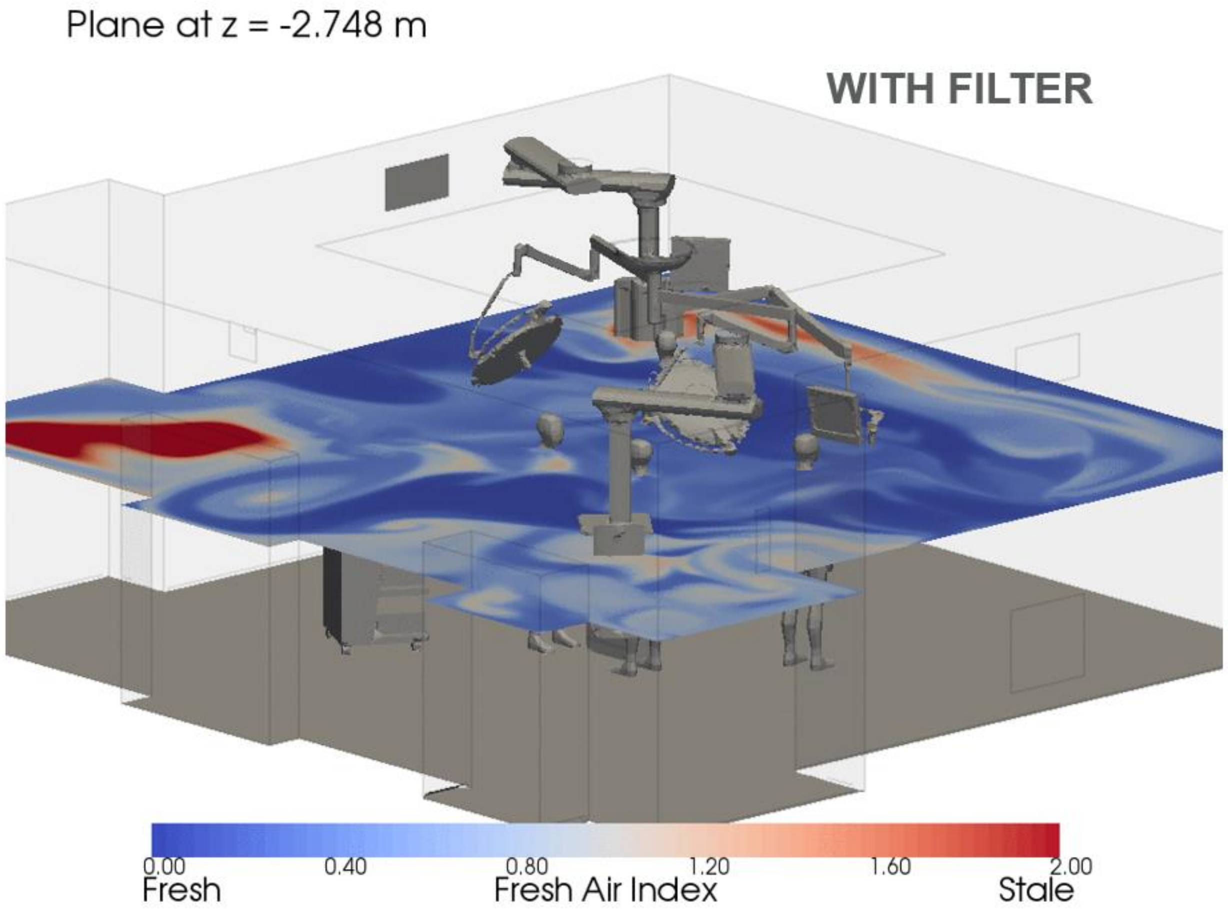


WP5: Operating Theatre Demonstrator

Modified layout – with filter device (dual purpose)

- Tracer plume (relative concentration) scrubbed air emitted from UV-device
  - Assumed passive, same properties as air
  - No further gas-phase reactions





COVID-19 Mobile Processing Units (MPU) Commissioning


OFFICIAL – COMMERCIAL

Department of Health & Social Care

Interim Engineering Evaluation of a Mobile Processing Unit (MPU) using Loop-Mediated Isothermal Amplification (LAMP) Technology

By

Captain G M McKenna REME

Lieutenant I R Campbell REME

A technical engineering evaluation report to support the engineering design of a Mobile Processing unit (Van) (MPU(V)).

British Army

Royal Electrical and Mechanical Engineers

Department for Health and Social Care

23 December 2020

OFFICIAL – COMMERCIAL

Rapid Testing Mobile Processing Units, Van(V) and Trailer(T)

Department of Health & Social Care

Funding body: Innovate UK

Project Title: Opensource software simulations towards understanding, monitoring and controlling COVID-19 transmission by managing air, people distancing and adapting urban environments

Project number: 85435

Funding Competition: UKRI Ideas to address COVID-19 – Innovate UK de minimis Aug 2020

Jan21-Feb21

esi-group.com

Customer Sign-off - Statement of value

RE: MPU(V) CFD - statement of need and value

CR Carter, Ross <Ross.Carter@[redacted]
Fri 22/01/2021 09:59
To: Fred Mendonca

To whom it may concern,

Mobile Processing Unit

An engineering team from the military were activated to support the Department of Health and Social Care (DHSC) design and build mobile processing laboratories.

These units have been designed and built in unprecedented time, learning new concepts and processes not just in COVID-19 processing but the adaptability of static laboratory testing equipment for mobile use and the interpretation of regulations and emerging technical information regarding the SAR-COVID pathogen.

This emerging technical information, left a hole in our knowledge and development, which posed a significant risk to the development of our project. As a small team we had minimal leavers of understanding the risk or more importantly articulating the possible risks.

Working with Fred and his team we have been able to break apart the possible problems posed by Air flow development within our platforms. Daily engineering decision we were making to the platform, posed a significant impacts somewhere else in the design. Working with CFD, analysing the airflow and understanding the problem has allowed us to de-risk a number of significant areas of concern and more importantly has provided the team a body of evidence to the Chief Scientific Officer, NHS and their team that these platforms are developed appropriately.

Fred and his team have been instrumental in the success of this project, their support has been 100% and I could have not asked for more.

Yours sincerely,

Major Ross Carter REME
Engineering Officer
Royal Electrical and Mechanical Engineering

Department of Health & Social Care

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The Team – assessing Fallow time and use of "Scrubbers"

UK-wide Clinical Engineering

Professor Tony Fisher *MBE MD MSc PhD FAHCS FIPEM FInstP FIET CEng CSci CPhys*
Head of Department, Dept. of Medical Physics & Clinical Engineering
Royal Liverpool University Hospital
Trust Lead Scientist
Director Merseyside Training Consortium for Medical Physics & Clinical Engineering
Head of Department, *Dept. of Medical Physics & Clinical Engineering*
Royal Liverpool University Hospital

Fred Mendonça
Director, Physics Modelling
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MD, OpenCFD Ltd

Claire Greaves
Chief Scientist & Clinical Director
Head of Medical Physics and Clinical Engineering
Nottingham University Hospitals NHS Trust

Professor Paul White
Head of Clinical Engineering
Cambridge University Hospitals NHS Foundation Trust

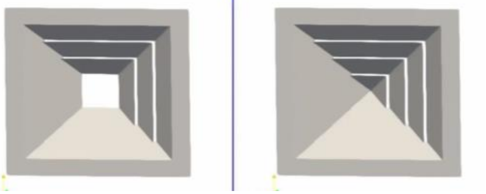
Peter Bill
Head of Neurophysiology
Regional Chief Scientist
Birmingham Women's and Children's NHS Foundation Trust

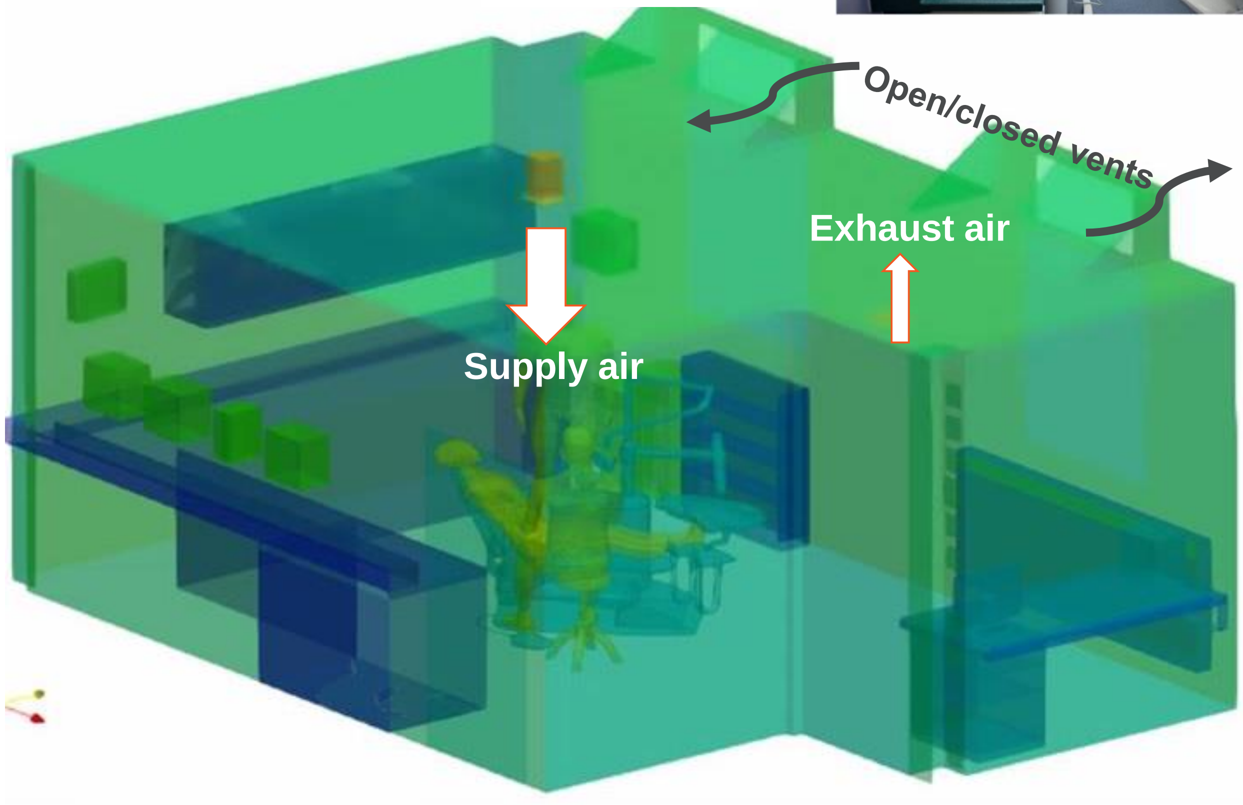
Professor Chris Hopkins
Head of Clinical Engineering
Hywel Dda University Health Board

Dental Treatment Room – Birmingham Children's Hospital

Thermally neutral operating mode

- 15th March Update – VERIFIED CFD MODEL
  - Vent air supply @ 5ACpH and extract exactly balanced
    - Treatment room volume is 44.7m^{3},
    - 3 occupants/equipment included
  - Assessing
    - Effects of Air Scrubber (location and rate)
    - Movement of Viral load from AGP
    - Dual direction
      - Roof angled
      - Central jet



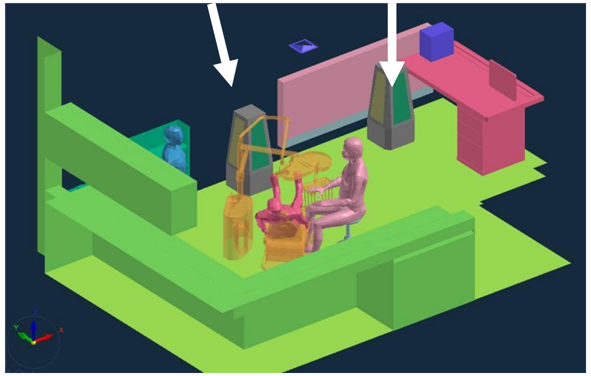


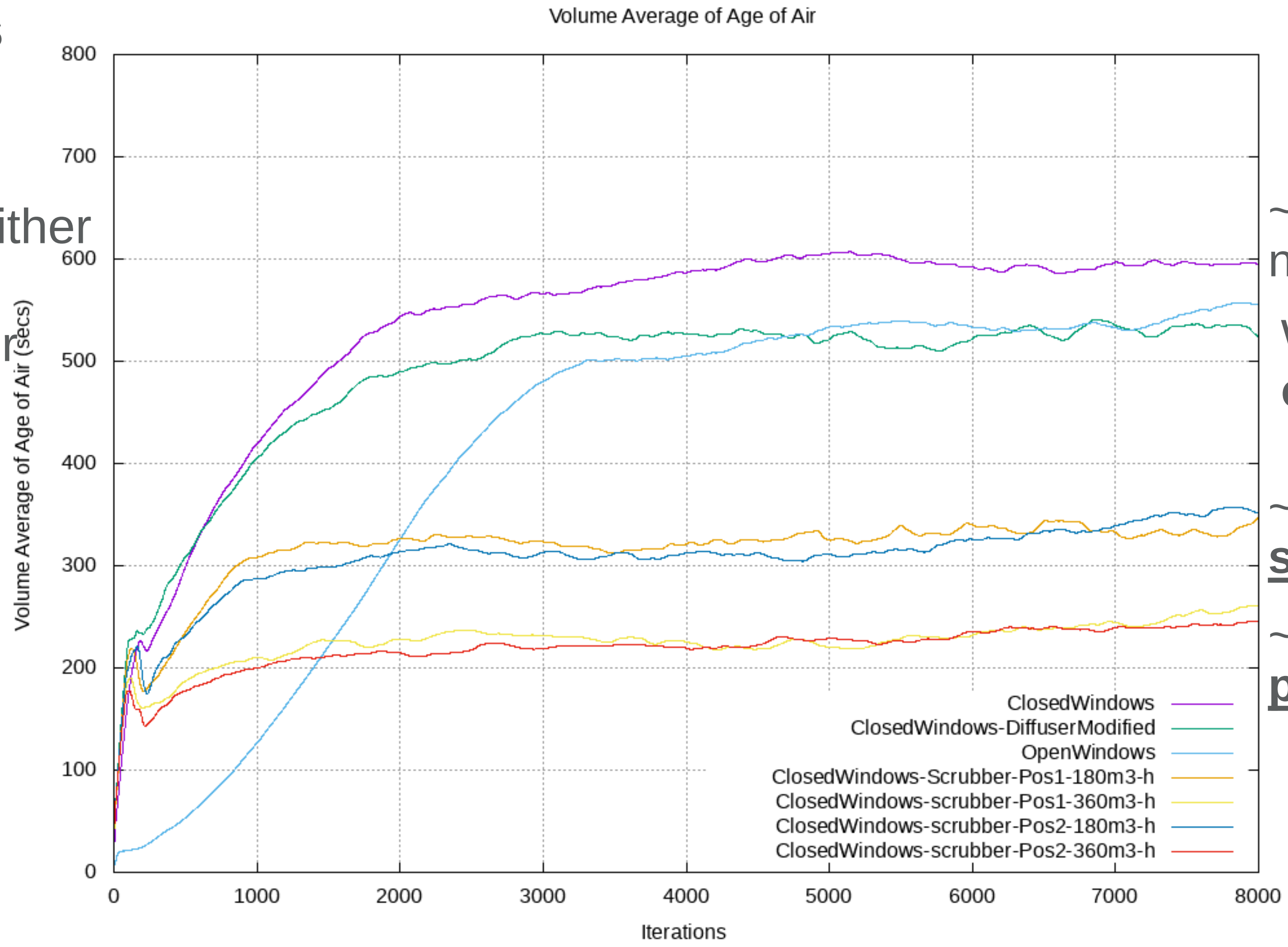
Dental Treatment Room – Birmingham Children's Hospital

Room averaged Age of Air

- No-scrubber - **10 mins**
- UV scrubber in situ
  - **Standard** flow rate (either position) ~ **6 mins**
  - **Purge** flow rate (either position) ~ **4 mins**

Pos-2 **Pos-1**





~**600**sec (original, no scrubber)

Windows **open, or, central** jet

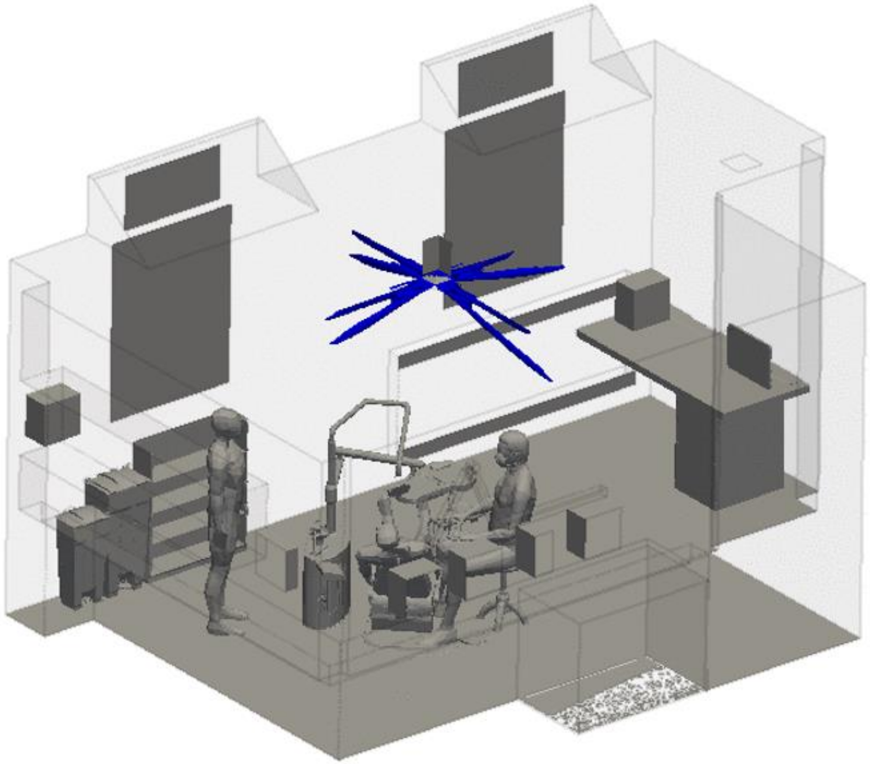
~**350**sec (UV **standard** flow rate)

~**250**sec (UV **purge** flow rate)

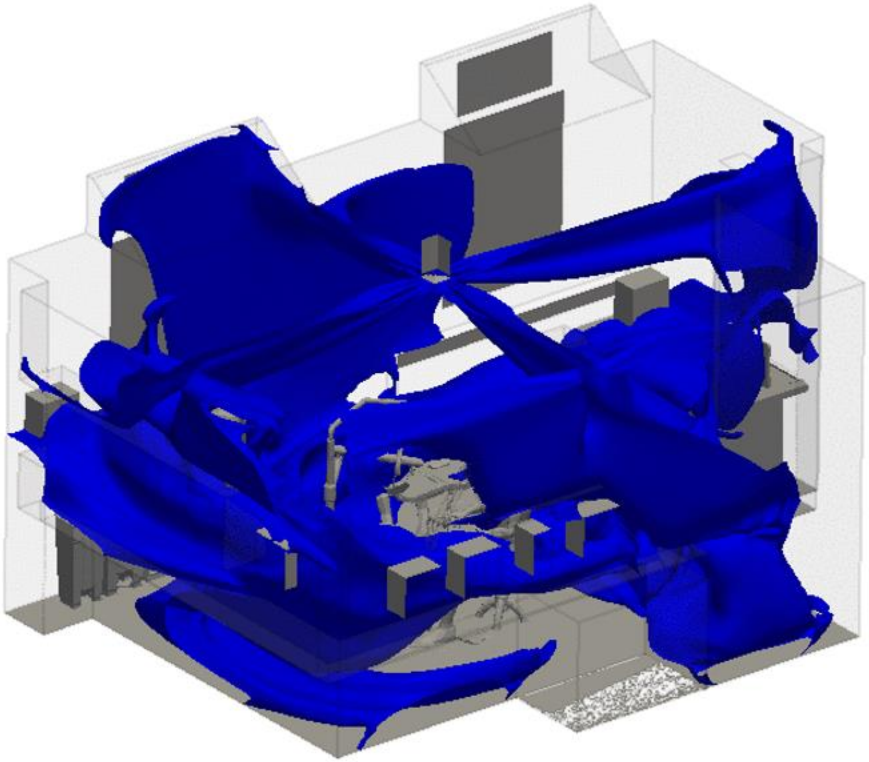
Dental Treatment Room – AgeOfAir Isosurfaces (time-advance)

NO SCRUBBER Thermally neutral operating mode **360m^3/h POS-1**

Iso Surface of Age of Air at 190 secs

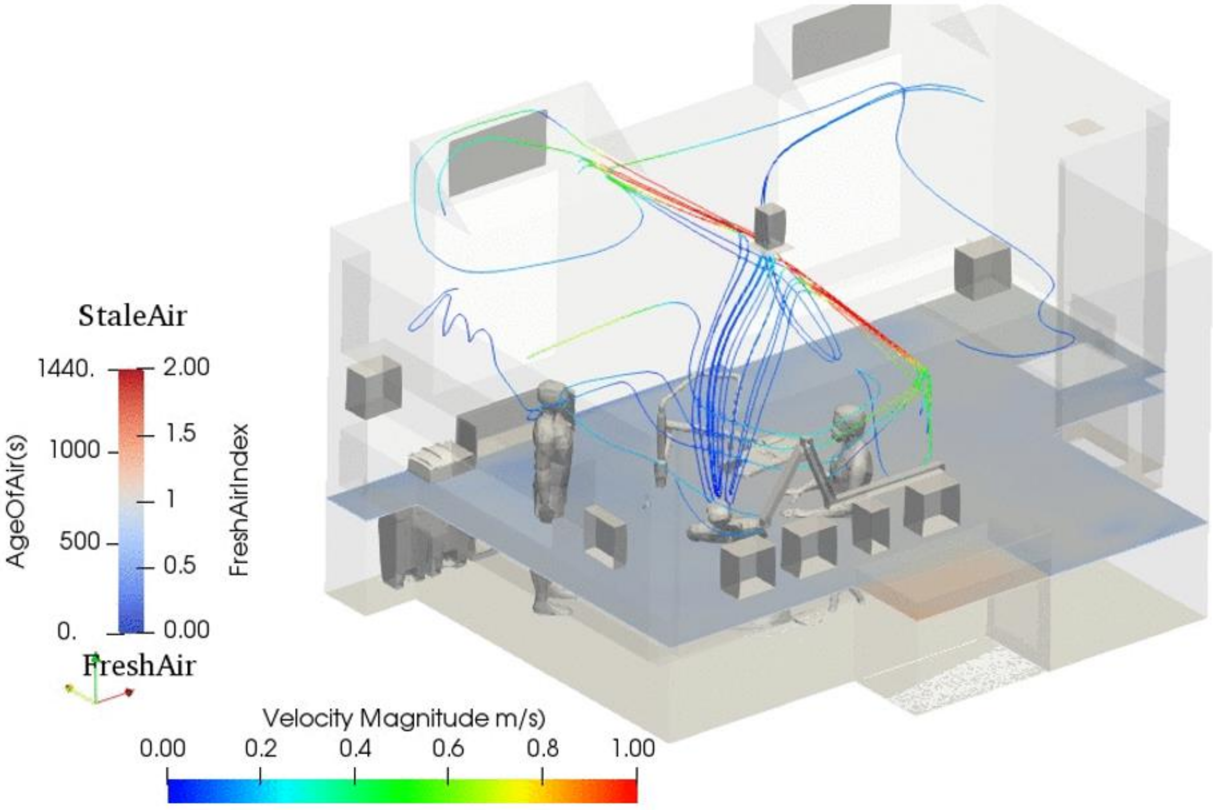


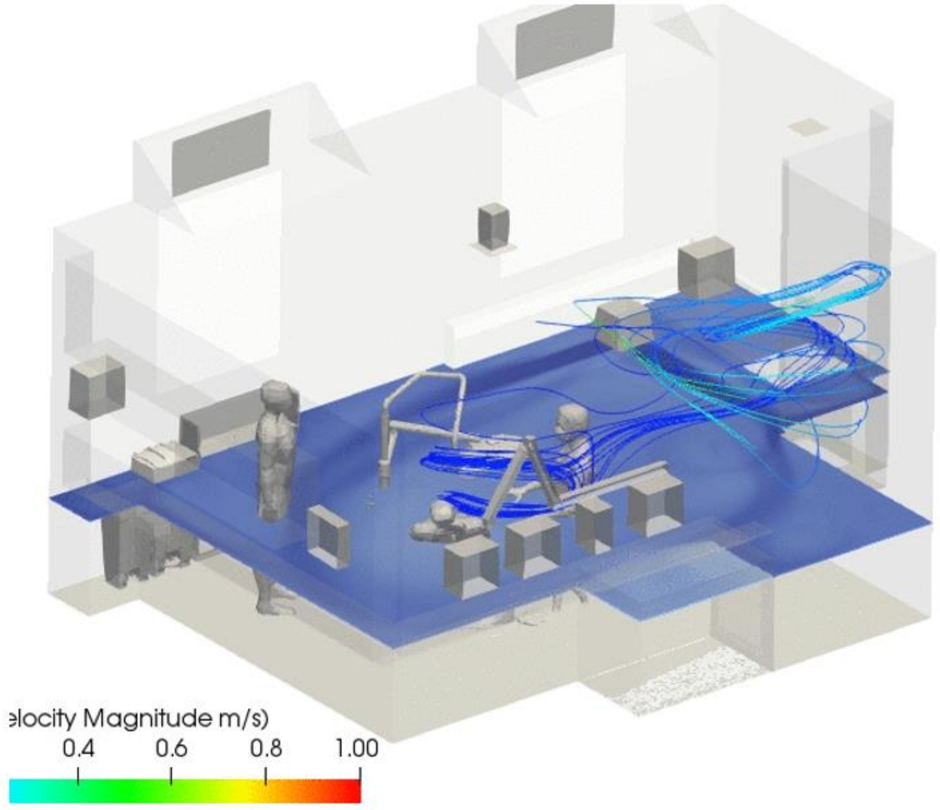
Iso Surface of Age of Air at 190 secs



Dental Treatment Room - Fresh Air Index (streams from patient)

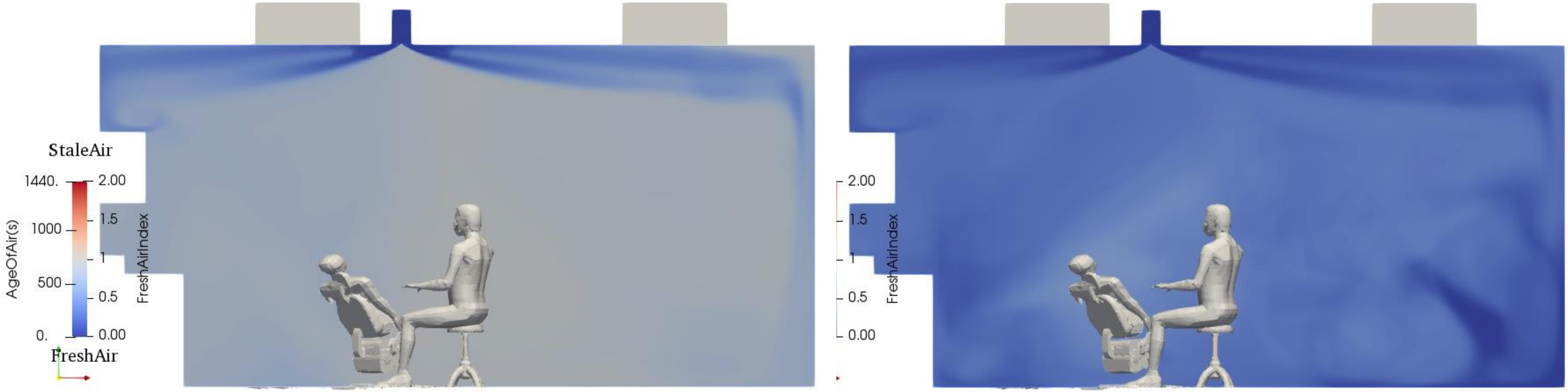
NO SCRUBBER Thermally neutral operating mode **$360 m^3/h$ POS-1**





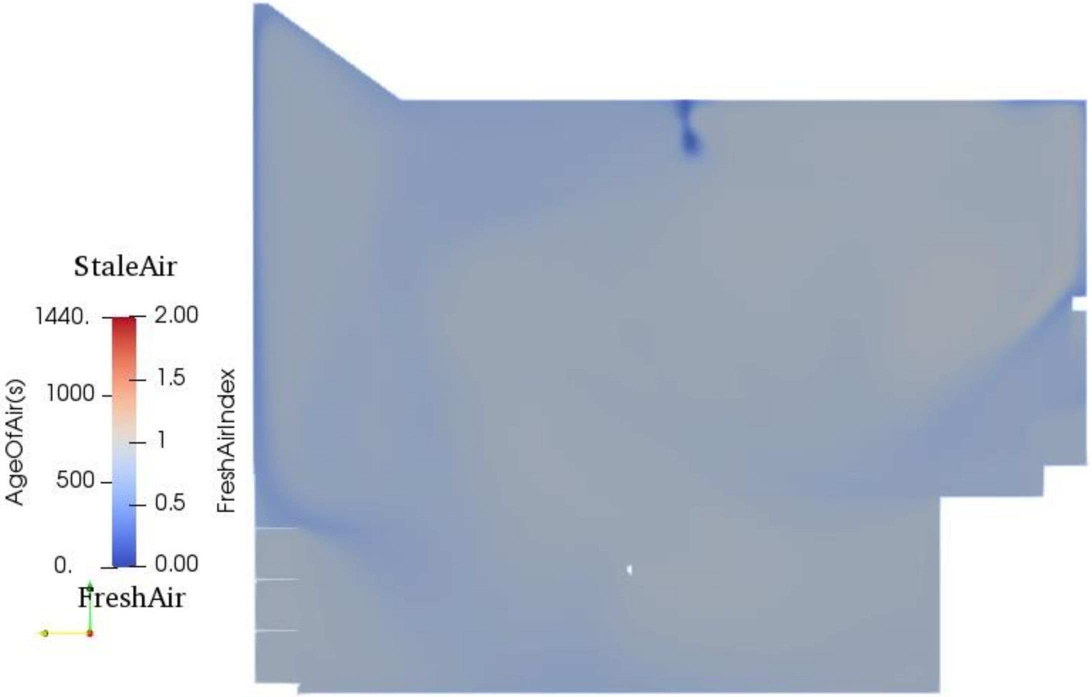
Dental Treatment Room – Fresh Air Index

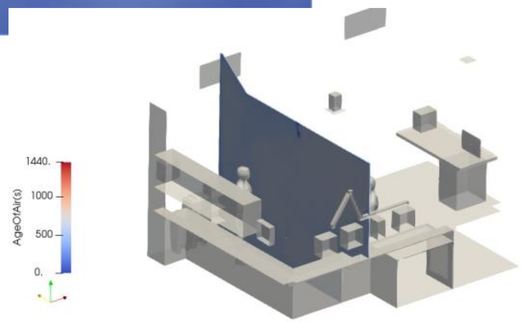
NO SCRUBBER Thermally neutral operating mode **$360m^3/h$ POS-1**



Dental Treatment Room – Fresh Air Index

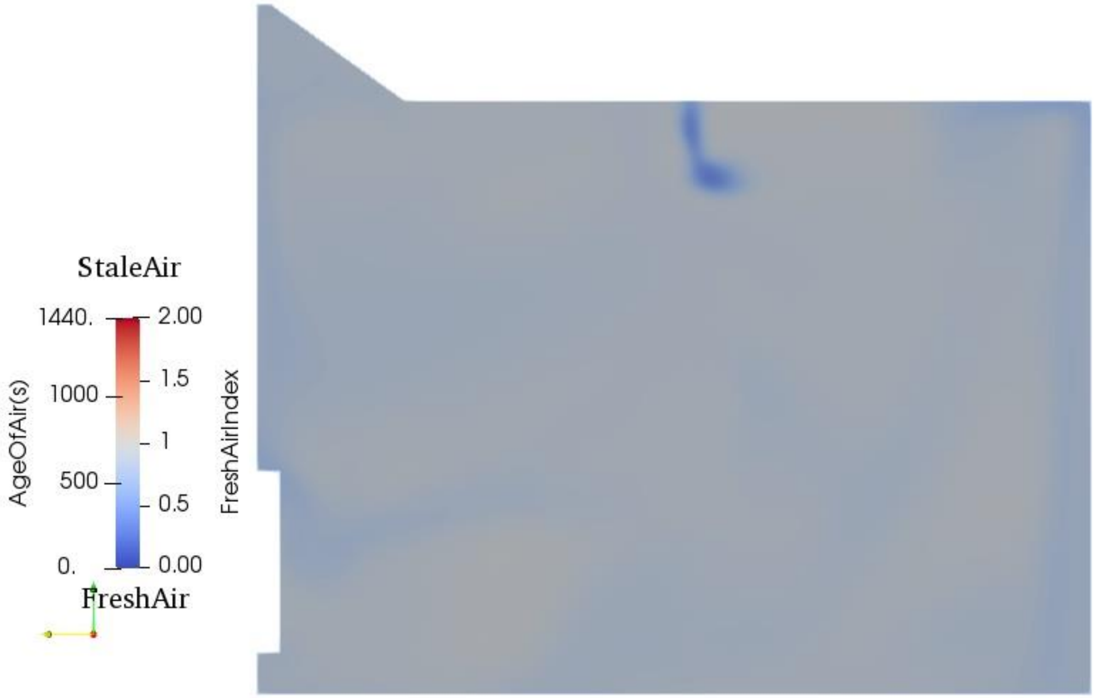
NO SCRUBBER Thermally neutral operating mode **360m³/h POS-1**

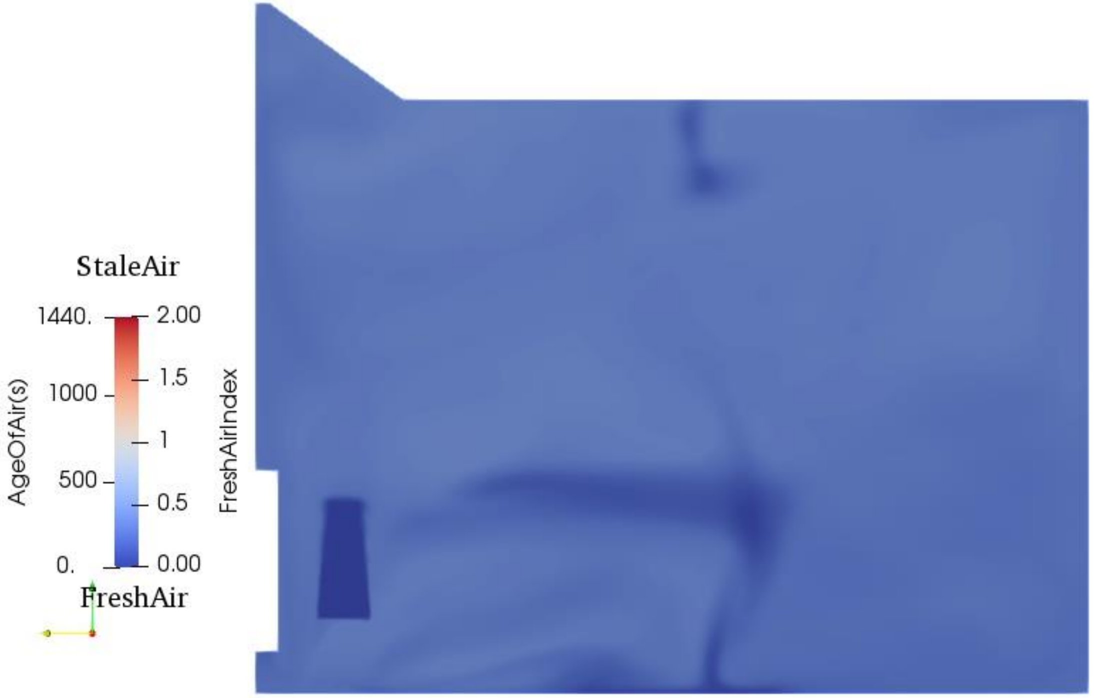


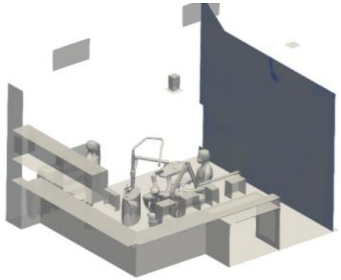


Dental Treatment Room – Fresh Air Index

NO SCRUBBER Thermally neutral operating mode $360m^3/h$ POS-1







ESI-OpenCFD collaborations in the COVID-19 battle

Closing Statements

- Making CFD accessible to facilities providers (CFD non-experts)
    - CFD has been around for more than 50 years
    - It is very deeply validated for several underlying physics and combinations of physics

- We are told that ventilation is important - learn how to
    - Measure
    - Mitigate
    - Optimise

  placements and “interventions” in enclosed environments for health, wellbeing and safety

- ***ventESI*** Vertical Application – Cloud App for non-expert CFD users
    - Available for testing now
    - Open to External partners between now and Autumn

- Innovate-UK project Nov20-Dec21 well under way
    - Several valuable stakeholder examples

- Still open to include more “stakeholder” studies – please let me know
  fred.mendonca@esi-group.com