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CFD Modeling for Ventilation System of a Hospital Room

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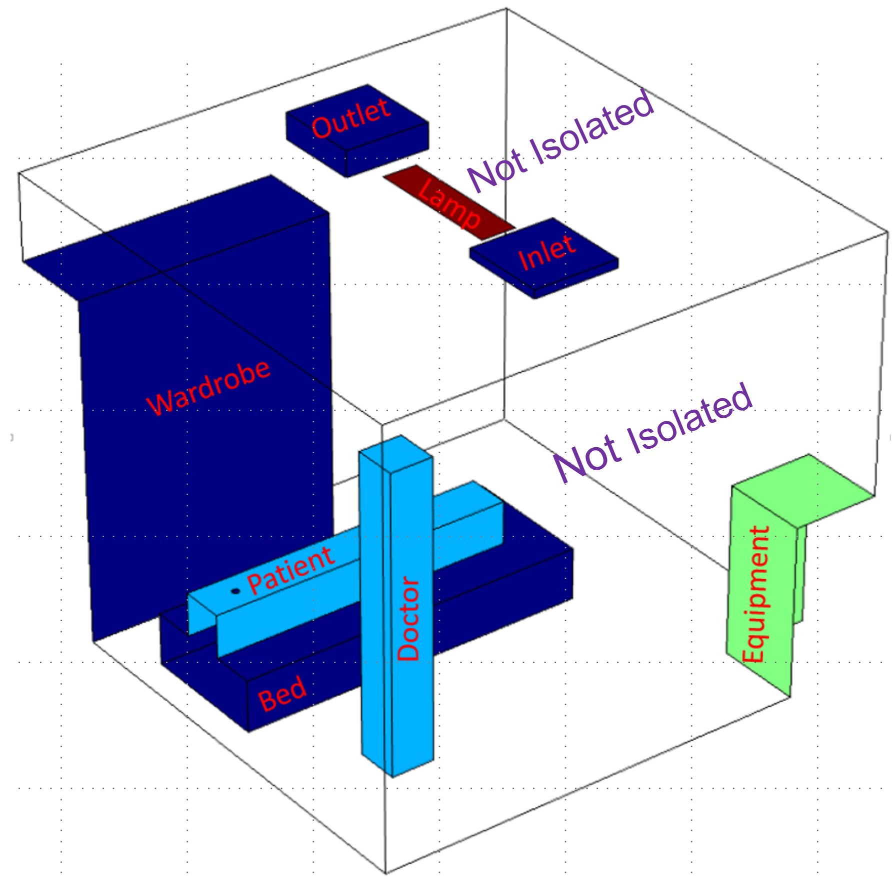
Introduction

- Efficient ventilation can contribute to
  - Reducing the cooling and heating energy consumption of buildings
  - Increasing comfort level of residence
  - Minimizing the risk of airborne infection in hospital rooms.
    - More than two million people in Europe are infected due to Health-care Associated Infection (HAI) (Pittet et al., 2005).
    - Although it is believed that transfer of infection via contact is the main cause for HAI, there are evidences that airborne bacteria may also cause infection due to inhalation of infectious bacteria (Hathway, 2008, Brachman, 1970).

Problem Description

- Ventilation rate is 6 ACH (Air Change per Hour) for health care facilities per ASHRAE standard 170.
- The room is thermally isolated on three sides and its base.
- Heat exchange between the room and outside occurs through the ceiling and the fourth side of the room

Heat Sources	
Body heat flux for doctor and patient	60 W/m^2
Equipment heat flux	100 W/m^2
Lamp heat Flux	200 W/m^2
Inlet temperature	20 °C
Outside temperature	5 °C



Flow Type

- Convection of heat can be either forced or free. Free convection occurs if

$$\frac{g\alpha\Delta T}{U^2/L} = \frac{Gr}{Re^2} \gg 1$$

- If it is free (natural) convection then flow field character is described by the Grashof number

$$Gr = \frac{g\alpha\Delta T l^3}{\vartheta^2}$$

Grashof number indicates ratio of the buoyancy force to the viscous force

Use of COMSOL Multiphysics

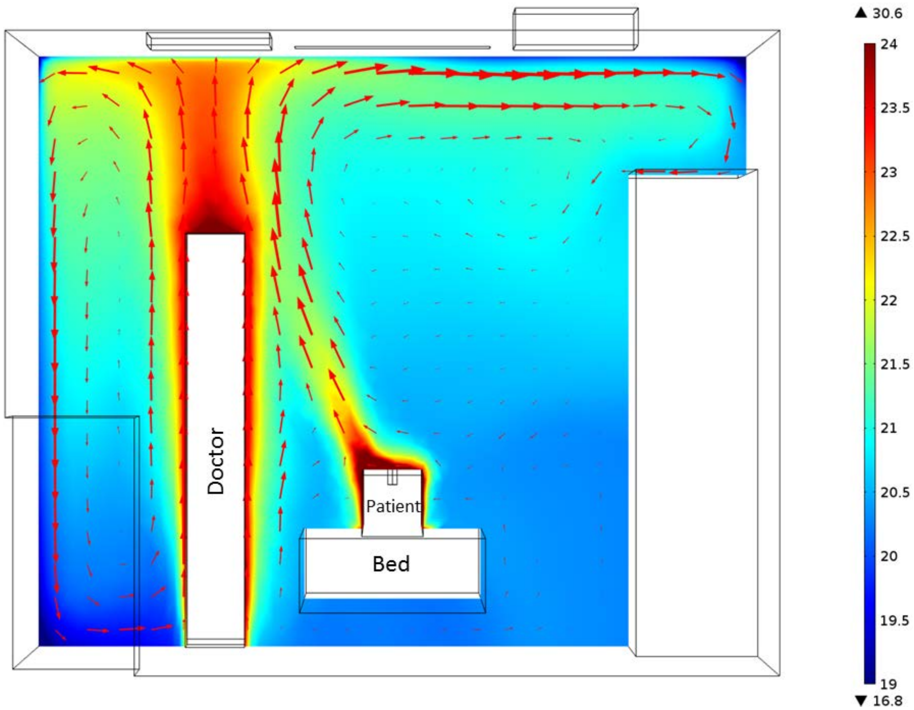
- Coupled Navier–Stokes and continuity equations for air as well as the convection-diffusion equation for heat
- “Turbulent Flow” and “Heat Transfer in Fluids” physics in COMSOL 5.1
- The k–omega (k–ω) turbulence model with consistent stabilization for turbulent airflow
- Variation of density with temperature “Multiphysics/Non-Isothermal Flow”
- Boundary layer mesh, 1.4 million degrees of freedom

Solution Strategy

- Turbulent air flow is solved in three steps:
  - Step 1: we used a coarse mesh and higher viscosity for air
  - Step 2: we used the developed flow from the first step as an initial condition for the second step which has a fine mesh
  - Step 3: the air viscosity is gradually reduced to its true value using a parametric sweep in COMSOL
- To simulate release of bacteria due to coughing we used “Particle Tracing for Fluid Flow” physic
  - Two hundred and fifty bacteria particles are released during coughing time
  - Percentage of bacteria that are leaving the hospital room through the exhaust of the ventilation system is quantified

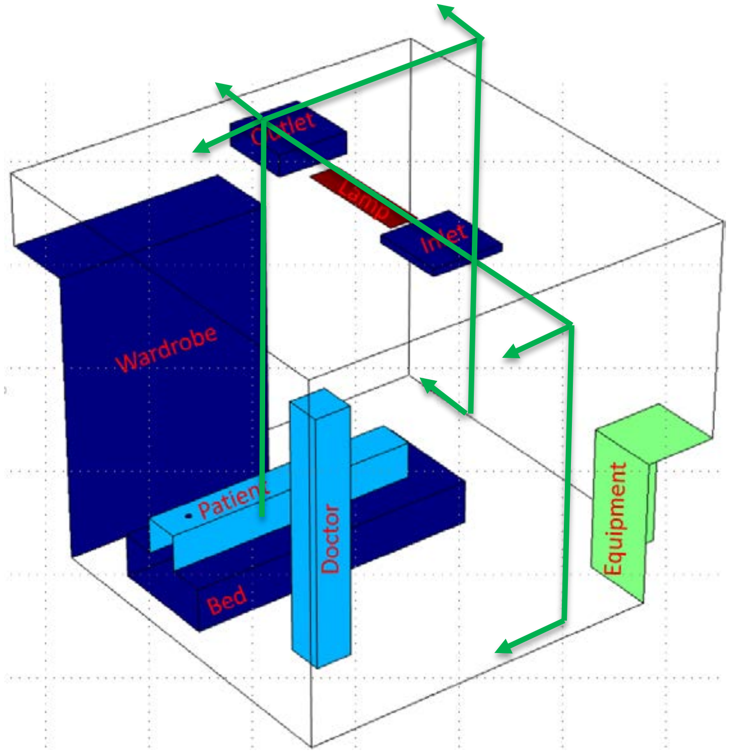
Flow Field and Temperature Distribution

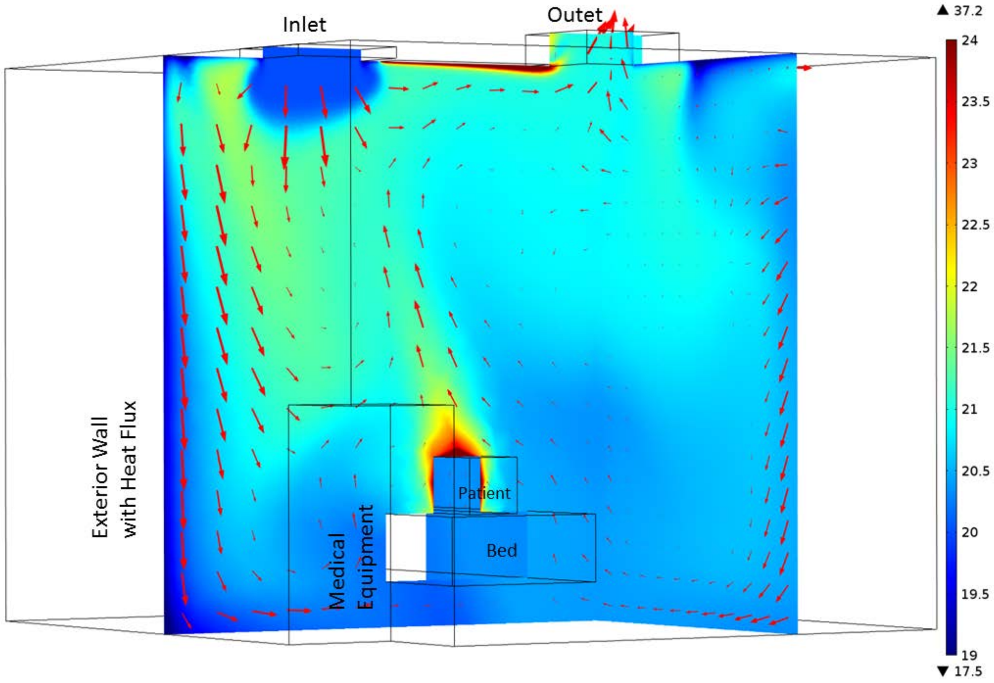
- Upward air movement next to the doctor and patient
- Downward air movement next to the wall
- Flow of air from the patient toward the doctor
- Two recirculation zones above the wardrobe and next to the doctor



Temperature distribution and velocity vector. The color legend corresponds to temperature (°C)

Flow Field and Temperature Distribution





Temperature distribution and velocity vector. The color legend corresponds to temperature (°C)

- Upward air movement next to the patient
- Downward air movement next to the wall

Thermal Comfort

- Thermal comfort is the **state of mind** that expresses satisfaction with the thermal environment. Thermal comfort is not related to the equations for heat and mass transfer and energy balance; it is assessed by subjective evaluation (ASHRAE Standard 55).
- The main factors that influence thermal comfort are those that affect heat and mass transfer in energy balance models, namely metabolic rate, clothing insulation, air temperature, mean radiant temperature, air speed and relative humidity
- The common approach to characterizing thermal comfort is to correlate the results of psychological experiments to thermal analysis variables

Predicted Mean Vote

- The average thermal sensation response of a large number of subjects using ASHRAE thermal sensation scale is called the Predicted Mean Vote (*PMV*)
- ASHRAE 55 recommends the acceptable PMV range for thermal comfort to be between -0.5 and +0.5 for an interior space.
- Predicted Percentage of Dissatisfied (*PPD*) predicts percentage of occupants that will be dissatisfied with thermal conditions as PMV moves from 0 or neutral.
- ASHRAE 55 requires that at least 80% of the occupants be satisfied.

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

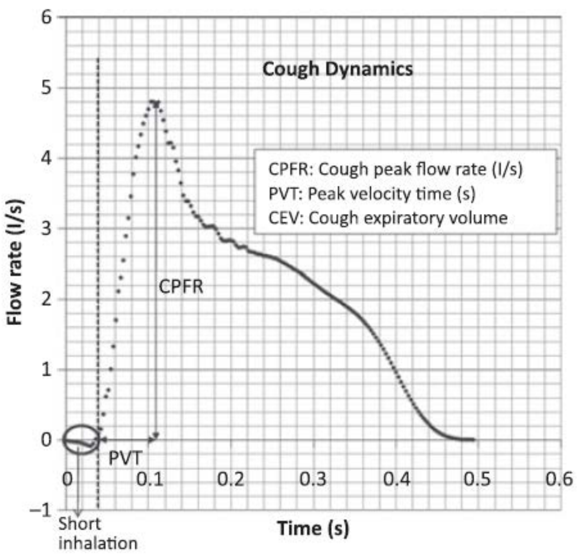
ASHRAE Thermal sensation scale

Thermal Comfort

- Average temperature is 20.8°C
- Average air speed experienced by the patient is 0.06 (m/s)
- We assumed that the patient is wearing trousers and a long-sleeve shirt and therefore his clothing level is 0.61 (clo)
- The metabolic rate of a patient who is sleeping is 1 (Met)
- Humidity is assumed to be 50%
- Mean radiant temperature is assumed to be 21°C
- PMV is -1.59 and PPD is 56%. The probability of the patient being dissatisfied with the room temperature is 56%, with a sensation of being cool.

Coughing

- Coughing is a transient phenomenon
- The airflow rate from coughing and its momentum are negligible compared to the airflow rate inside the room
- We used a constant airflow rate at the mouth of the patient equivalent to the coughing flow rate

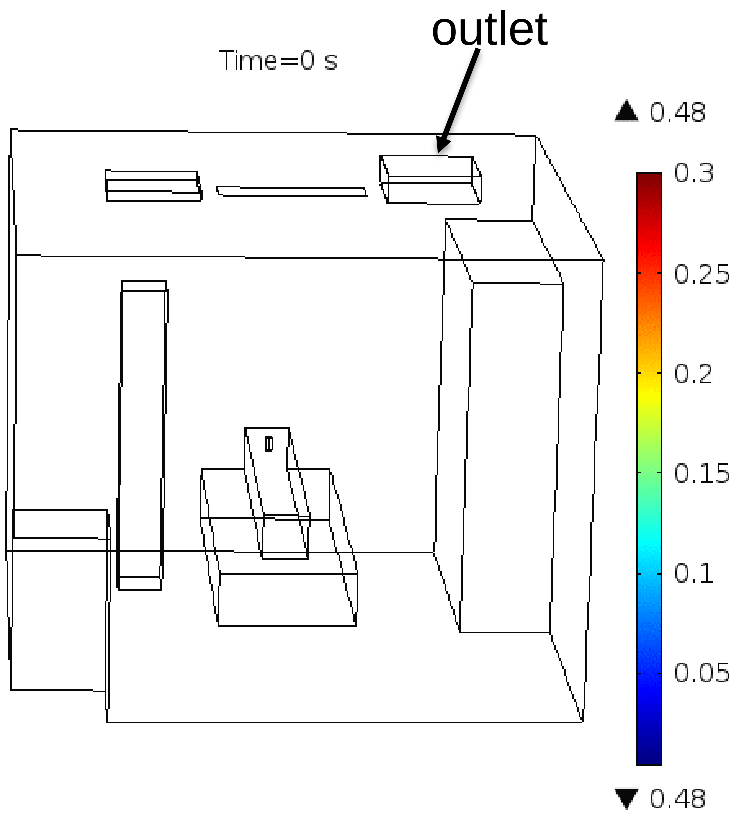


Cough flow rate variations with time

J. K. Gupta, C. H. Lin, Q. Chen, “Flow dynamics and characterization of a cough”, Indoor Air 19: 517-525 (2009)

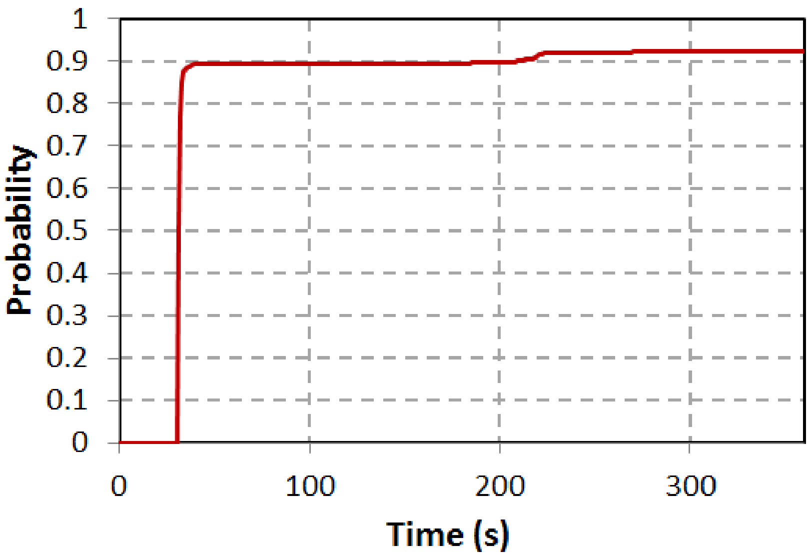
Bacteria Distribution due to Coughing

- Bacteria particles are released for a typical coughing duration, which is 0.5 seconds.
- The majority of bacteria leave the room through exhaust 30 seconds after coughing.



Bacteria Distribution due to Coughing

- None of the bacteria leaves the room in less than 30 seconds after coughing.
- After 300 seconds 8% of the bacteria are still remaining
- The remaining bacteria may contaminate the entire room and increase the risk of airborne infections



Transmission probability of bacteria at the exhaust versus time

Conclusion

- Computational fluid dynamics can be used to increase the comfort level and improve ventilation design and energy efficiency of buildings.
- With computational fluid dynamics we can obtain better insight into aerosol contamination dispersion characteristics to optimize airflow pattern in hospital clean rooms.