Space heating and ventilation 3D-simulation for an office room

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Abstract

In order to study thermal conditions and air flows in a 4 m x 5 m x 3.5 m (height) size office room, 3D FEM simulation model was created. The room is enclosed by walls, floor and ceiling which thermal characteristics are specified by typical heat transfer coefficients and specific heat capacities. Space heating is generated by an electric heater which control is based on on/off-controller and a temperature sensor. Air ventilation is based on constant air flow which volumetric speed is set by the requirements of the national building code. Non-uniformity of room temperature and air conditioning cause discomfort of occupants and loose of energy efficiency. Multiphysics simulation combining thermal and CFD simulations may reveal possible thermal imbalance and undesirable air flows in the room.

Introduction

Occupant's comfort in a room is mainly affected by air temperature, air humidity, air flows and air quality (impurity particles and VOC). There is a large range, up to 6 °C, in the optimal temperature which occupants feel the most pleasant one. There is a known difference between women and men. Women generally prefer higher room temperature than men. The thermal perception depends on the other physical conditions, clothing of a person and is also time varying, changing from day to day. Air flows caused by ventilation are considered pleasant or unpleasant depending on the thermal conditions as well as personal factors. All these observations lead to a conclusion that a specific optimal temperature and ventilation level do not exist but varies between persons and in time as well as depends on other conditions.

Optimal thermal conditions for an occupant are reached when metabolic heat generated by the occupant transfers to ambient without increasing temperature of occupant internal organs and tissues. Thermal conditions are affected by air temperature, moisture and air flow velocities. The level of metabolic heat generation depends on the physical activity of an occupant. Therefore, optimal conditions for office workers differs from optimal conditions for industrial workers.

Air flows caused by ventilation can be perceived neutral, uncomfortable or comfortable depending on the other conditions and the occupant. Heat is generated more in hard physical than in light sedentary activity. For those who feel temperature of 22-23 °C neutral or cool in sedentary activity are sensitive to feel draught even at low air velocities. Those occupants who feel warm at this temperature sustain air velocities up to 0.4 m/s without feeling draught. At temperature of 30 °C higher air velocities, up to and around 1.6 m/s are acceptable [1].

Review on previous studies

There are several previous studies and presentations which are based on simulations done with Comsol Multiphysics software:

The blog of [2] presented the rich set of features Comsol Multiphysics can provide for simulating thermal flows related to a house. Despite title the paper focused mainly on external thermal transfer and heat convection caused by external weather conditions like ambient temperature and wind. The inside of the house was defined as an isothermic domain. By this way inside temperature is constant and no temperature differences exist.

Authors of [3] conducted 2D-simulations for air flows inside rooms. They used k-ε turbulence model, unstructured meshing and segregated solution set for the solver. Simulation results were compared to anemometric measurements of equivalent room space. Simulations systematically resulted in slightly lower (3-10%) flow speeds than measurement, but practically the same results.

Authors of [4] studied thermal and air flows in and between interior rooms. The simulation studied a case of two adjacent rooms having a separating glass wall. Comsol Multiphysics with its thermal transfer and CFD modules were used. Fluid flow was modelled with a laminar flow interface. According the authors pipe flow remains laminar until Reynolds number exceeds 2000. Time dependent simulation results included temperature and air flow distributions and heat flux through the separating wall.

Air flows in a kitchen and in a chimney was simulated by [5]. They simulated natural air flow caused by buoyancy forces and compared that to forced air flow generated by a fan. Simulations show how air flow increase by increasing height of a chimney.

Simulation model

Equ. 1. describes the thermal balance. Q_{hvac} is the heating power generated by the space heaters, C_{am} is specific heat capacity of the medium composed of air and materials inside the room, H_i is thermal conductance of wall i, T_a is inside temperature, T_i is temperature exterior to wall I, H_v is thermal conductance of ai, T_v is ventilation air temperature.

$$Q_{hvac} = C_{am}\frac{dT_a}{dt} + \sum_i H_i(T_a - T_i) + H_v(T_a - T_v) \quad (1)$$

3D simulation model for a small office room was created. The room has dimensions of 4 m x 5 m x 3.5 m (height) and is designed for two persons. The model combines heat transfer, air flow (CFD) and events interfaces. Space heating will be done using two electrical heaters with radiators. Heating power is set according practical rules which are normally followed. Required heating power depends on various parameters like the use of the room. Air ventilation will be done with two inlets and two outlets. Air flow is modelled as a laminar flow using incompressible flow and gravity set. Air flow volume speed [l/m^3] is set according the national building code regulations. Using laminar flow model for typically low volume speeds is a justified choice. Thermal modelling uses heat transfer in solids and fluids physics. Heat fluxes through the walls, the roof, the floor, the windows and the door has been modelled with the heat transfer coefficients [$W/m^2 \cdot K$] given in the national building code regulations. Space outside windows is expected to be exterior and space outside other boundaries is expected to be interior of the building. The model uses symmetry both for the heat transfer in solids and fluids as well as the laminar flow physics.

The model has its counterpart in a real building. Taking advantage of symmetry, slight modifications had to be done. The Fig. 1 shows half of the model with typical furniture, an office table, a chair, a bookshelf and a cabinet. However, the simulations were executed for an empty room for the sake of simplicity.

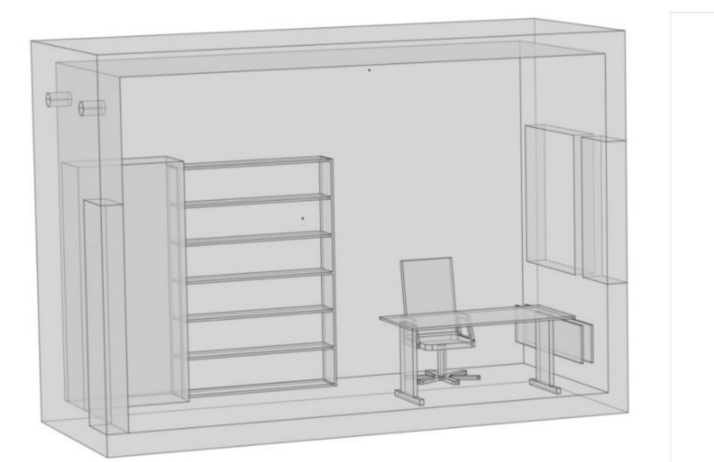

Figure. 1. Half of the office room is shown here with typical furniture. Ventilation air inlet (left) and outlet (right). Heating radiators are in a typical location under the windows.

Heating control is based on on/off-switching. In these simulations room temperature is set to 23 °C, the set range to 22-24 °C. Event interface is used for the control. Temperature sensors are located to four locations: side by the door, one in the middle of the back wall, in the middle of the ceilings/roof and near the radiator. One option is also to use the average temperature of the room.

Model parameters

Table 1. Parameters used in the simulations.

Air flow per person (2	0.006-0.012 m^3/s
Inlet air temperature	18, 20, 22 °C
Heat transfer coefficient for windows (1	1 W/m^2K
Heat transfer coefficient for the internal walls, roof, floor (1	2.5 W/m^2K
Heat transfer coefficient for the exterior wall (1	0.17 W/m^2K
Heat transfer coefficient for the door	3 W/m^2K
Outside temperature	10 °C
Corridor temperature	18, 20 °C
Radiator heating power (max)	2 x 1000 W
Room temperature set	23 °C
Room temperature range	22-24 °C

1) Set according the national building code of Finland [6].
2) Set according the national building code of Finland [7].

Meshing

Total volume of the model is 35 m^3. Physics-controlled mesh was generated automatically with element size set to normal. This results in 54601 vertices, 232912 tetrahedras, 1200 pyramids, 27446 prisms, 21726 triangles, 282 quads, 1421 edge elements, 103 vertex elements and 261558 domain elements.

Simulations

The main targets of these simulations were to solve temperatures and air flows inside the room during a time period of 24 hours. Air speed in the air ducts and in the room are assumed to be low. Simulations are simplified by assuming air flows to be laminar.

Time dependent simulation

Time dependent simulation for 24 hours (1440 minutes) with 10 minutes timesteps was defined. The simulation couples heat transfer in solids and fluids, laminar flow and events physics. The default solver was selected.

Simulation were executed using a computing cluster which provides sockets composed of Intel Xeon Gold 6248 or E5-2680 CPU's running at 2.5 GHz. For these simulations the cluster provides up to 40 cores and up to 200 GB memory. The used cluster may not provide much higher speed compared to the best PC's, but it allows to run multiple simulations parallel with a huge memory. By this way all simulations could be done by parallel simulations approximately in 20 hours. Output files were in size of 1.5 GB each.

Results

Fig. 2. shows temperature in the room after 24 h (1440 s). It's obvious that in front of the radiators the temperature is the highest. The lowest temperatures are found in the corners of the room. In front of the room, seeing from the door, air is cooler than the average. All these can be explained by examining the air flows. Fig. 3 shows the air flows. Naturally the highest air speeds are found near the ventilation air inlets and outlets. Air flow proceeds near the roof and meets the opposite wall and windows. The air flow is higher that the air flow that without the ventilation would direct upwards from the radiators caused by the heating of the air. The air flow causes the heat to spread in the front of the radiator. Air flow itself continues now near the floor towards the door and starts rising upwards. For ventilation level 6 liter/s per person max air flow speed at the inlet is 0.38 m/s, on middle of the roof 0.1 m/s, front of the windows < 0.1 m/s and above the floor < 0.05 m/s. Air flows are so slow that occupants of the room hardly feel any draught. However, temperature differences in the room are sensible. The two persons at their workstations might feel excessive heat specially on their foots.

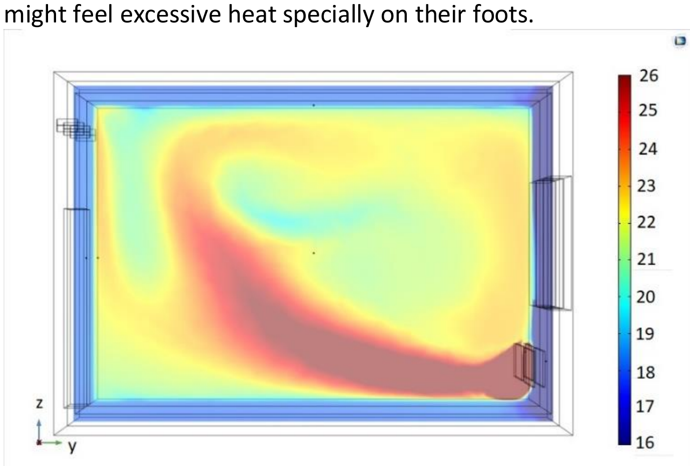

Figure 2. Temperature (°C) in the room at t = 24 h. Slice on the zy-plane at x = room width/4. Temperature is set to 23 °C. Ventilation air is 18 °C, 6 l/s per person.

Fig. 4-7 show the average room temperature and the heater state during the 24 hours period. These results cover the two most common cases for temperature sensor location. In Fig. 4 the sensor locates beside the door at height of 1.5 meters. This is the case also for the actual room which has been modelled. Ventilation air flow is set by level 6 l/s per person. This is the minimum air flow specified in the national building code of Finland. In Fig. 5 the air flow has been increased to level 12 l/s per person. Typical location for a sensor is beside the radiator. Although this is a common case, it is for many reasons also the worst location. Fig. 6 shows this case with air flow set to 6 l/s per person and Fig. 7 is the same case with air flow set to 12 l/s per person.

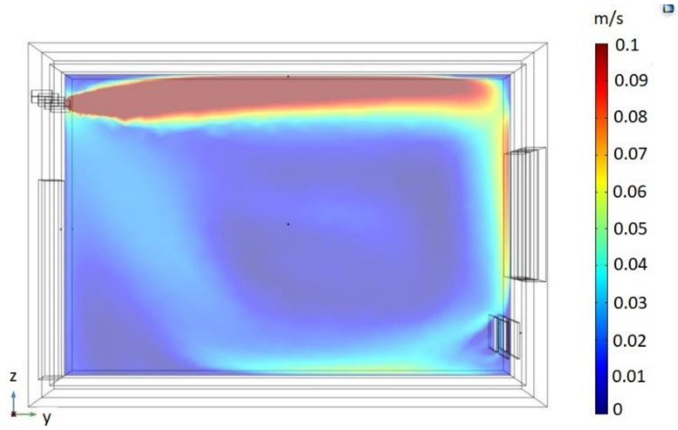

Figure 3. Air flows in the room at time = 24 h. Slice on zy-plane at the center of the air inlet. Temperature is set to 23 °C. Ventilation air is 18 °C, 6 l/s per person.

The simulation result shows an offset error, over- and undershooting and a settling time. In Fig. 4 the offset error is about -1 °C, over and undershooting around 1.5 °C. Temperature reaches the final lever quite quickly after heater has switched off. Fig.5 shows that increasing ventilation level, the offset error is higher, -1.5 °C. In case the temperature sensor is beside the radiator, the offset error is approximately -3 °C. Fig. 6 also shows that average temperature responses slowly the heater state. In this case increasing air ventilation level reduces the offset error magnitude. In both cases increasing ventilation level increases the number of heater state changes. Simulations were executed for the other sensor locations also. Simulations indicate that these would be better locations for a temperature sensor.

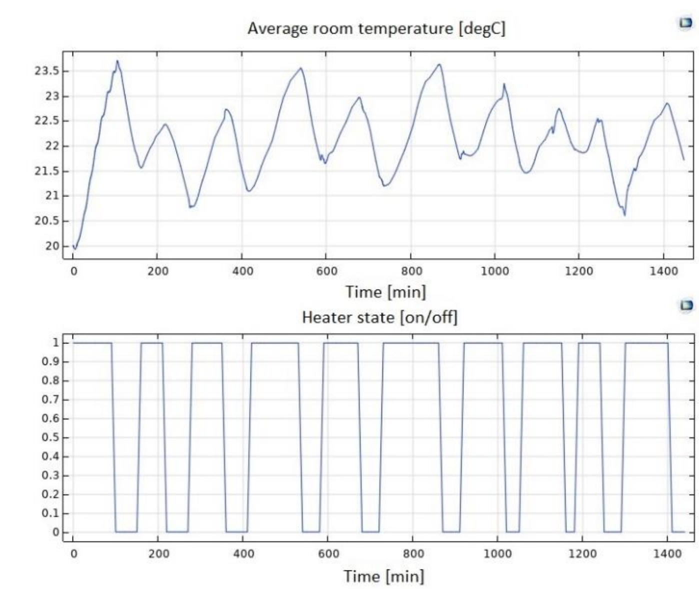

Figure 4. Temperature sensor beside the door. Average room temperature and the heater state. Ventilation flow is 18 °C, 6 l/s per person (total 12 l/s).

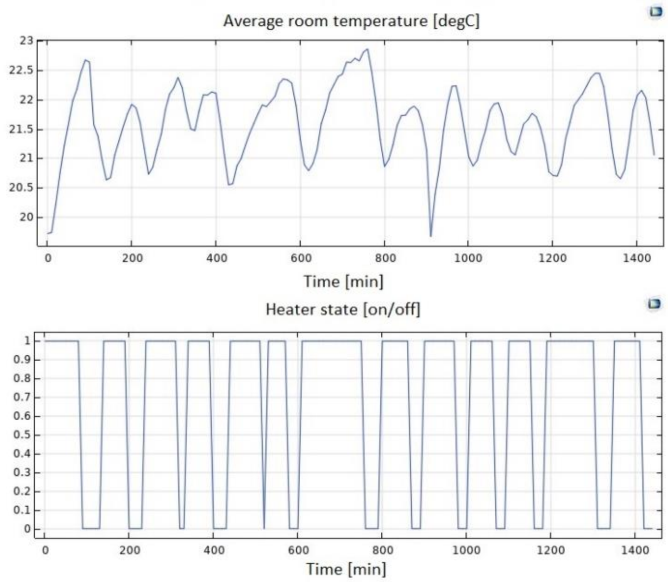

Figure 5. Temperature sensor is beside the door. Average room temperature and the heater state. Ventilation flow is 18 °C, 12 l/s per person (total 24 l/s).

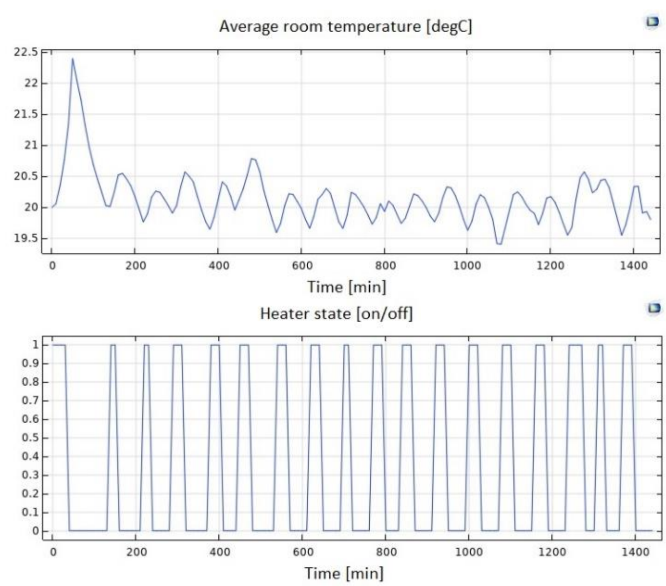

Figure 6. Temperature sensor is beside the radiator. Average room temperature and the heater state. Ventilation flow is 18 °C, 6 l/s per person (total 12 l/s).

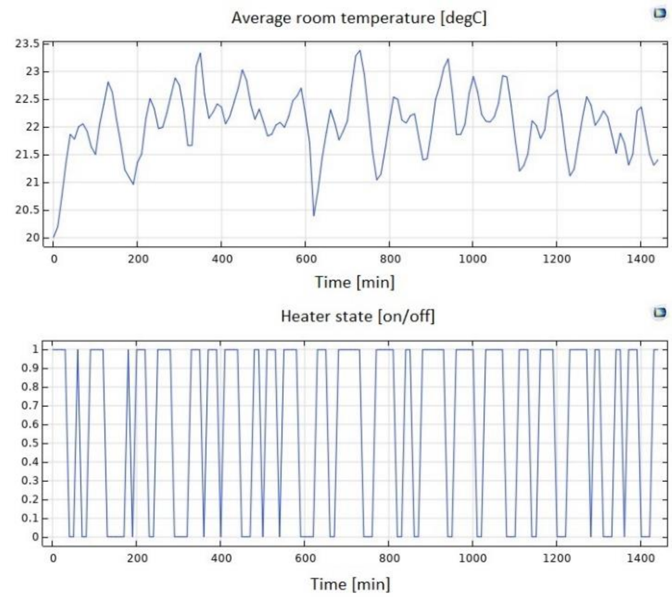

Figure 7. Temperature sensor beside the radiator. Average room temperature and the heater state. Ventilation flow is 18 °C, 12 l/s per person (total 24 l/s).

Results shown in Fig. 2-7 are for the case ventilation air temperature is 18 °C, 5 °C cooler than the set temperature for the room. In this extreme case the electrical heaters are driven with the highest duty cycle D and the energy consumption is also the highest. Reducing the temperature difference between set room temperature and ventilation air temperature, the duty cycle and energy consumption will be reduced. This is shown in Table. 2.

Table 2. The duty cycle of electrical heaters for the cases ventilation air temperature is 18, 20 and 22 °C and the flow 6 l/s per person (total 12 l/s). Temperature sensor is beside the door. Room temperature is set to 23 °C.

T [°C]	D [%]
18	64.9
20	35.4
22	30.7

Ventilation air temperature has a drastic effect on the duty cycle of the heaters. In these simulations the heat generated by occupants has not been included. Typical heat generation of a person working in physically light duties is around 130 W. This could have been included in to the simulation model.

Conclusions

Simulations indicate that ventilation air flow speeds near occupants with normal and double ventilation levels stay at relatively slow values, below 0.1 m/s. In normal room temperature occupants hardly feel any draught. Temperature differences exist in the room. With the given locations for workstations occupants might feel excessive heat in foots due the proximity of heating radiators. Occasionally there has been workstation for a third person near the door of the room. The third person in this position has complained about cool temperature sensations. Simulations provide some understanding for these claims. In this particular room temperature sensor locates near the door. In this case simulations show the offset error in the average room temperature is -1℃ with ventilation level 6 l/s per person and -1.5 ℃ with ventilation level 12 l/s per person. In case the temperature sensor locates near the radiators the offset error is -3℃. But in this case increasing the ventilation level improves situation and the offset error is -1℃ for ventilation level 12 l/s per person. In both cases on/off transitions of the heaters increase as the ventilation level increases. These simulations were executed for an empty room. Furnitures and people would change air flows to some extent. Air flows were simulated with laminar flow models. This was considered adequate for low air speeds.

References

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