Mathematical modelling of airflow and temperature distribution in living rooms

Stanislavs Gendelis, Andris Jakovics
Laboratory for mathematical modelling of environmental and technological processes, Faculty of Physics and Mathematics, University of Latvia
Riga, Zellu Street 8, Latvia, LV-1002

Summary
The paper deals with the distributions of temperature and averaged turbulent airflows in living rooms in a 3D approximations using Ansys/CFX software. The distributions are calculated depending on the placement of the heater and the windowsill and ventilation conditions. The authors analyse the influence of these factors on the air circulation and the related heat flows through building structures. The thermal balance of a room and its dependence on various external factors is also considered. As a parameter of thermal comfort conditions, the airflow velocities and indoor temperatures with its gradients are analysed. It is shown that it is possible to save heating consumption, at the same time maintaining the conditions of thermal comfort in the room.

1. Introduction

Person's feeling of comfort is fundamental impressed by velocity of airflows, absolute temperature and amplitude of the vertical temperature gradient in the room. The optimal arrangement of heaters, accordant packing of window-frames and installation of controllable venting system allows maintenance of thermal comfort in the living room with reduced heat consumption. Influence of above mentioned factors is detailed analysed by use of mathematical modelling approach. Physical model of heat balance for a living room with various physical conditions and geometry is used, which allows analysing the distributions of the airflows and temperature. The mathematical model enables to choose an optimal placement of building elements in order to decrease heat losses and improve conditions of thermal comfort.

2. Methods

The room with different boundary conditions (convection, surface temperature, air openings) is modelled that helps to understand the peculiarities of heat transfer process in the room as well as distribution of various characteristic quantities and their dependence on the different conditions. Multiple parameters are varied in 3D calculations and their influence on the distributions of temperature and velocity fields is analysed, which characterises the conditions of the thermal comfort. For numerical calculations software Ansys/CFX is used.

The calculations have been performed for the room shown in Fig. 1 filled with an air. The window and the wall to the exterior air are modelled using different materials with heat transfer coefficient *U* for the window 2,5 W/m^{2}K and for the wall – 0,35 W/m^{2}K. On other rooms' boundaries convection boundary conditions are set with according surface heat transfer coefficients. There is conditionally assumed that the surrounding rooms (upstairs, downstairs and side rooms) have the comfortable temperature of 20 °C, but that the end wall is contiguous with a corridor or a staircase where the temperature is lower (15 °C). The outdoor temperature is chosen corresponding to the winter conditions (-10 °C). The surface temperature of the heater is set to constant 50 °C. On the surfaces of crannies in window-frame and ventilation system's opening boundary conditions with constant pressure and accordant temperature of -10 °C and 15 °C are defined. Pressure difference between opposite walls is set to ±1 or 0 Pa (see Table 1). For all surfaces, except openings, non-slip boundary conditions are used. The airflow in the room depends both on the convection created by the temperature difference and on the air exchange between openings in the structures.

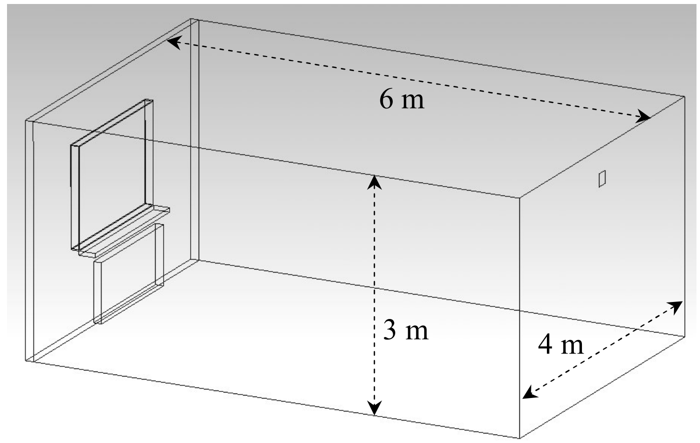

Fig. 1. Layout of a modelled room

To describe the quasi-stationary behaviour of temperature and averaged turbulent flows, traditional differential equations are employed [1]:

- Reynolds averaged momentum equation;
- continuity equation;
- equations for specific turbulence energy k and dissipation rate of this energy ε;
- energy conservation equation.

The turbulent viscosity is calculated by using the k-ε turbulence model under traditional boundary conditions [2].

The discretisation was performed with tetrahedral elements of varying size; boundary layers are discretised with smaller prismatic elements. The characteristic size of finite elements is from 10 cm in the middle of the room till 0,3 mm in the vicinity of the heater and the openings in the walls. Therefore, the total number of elements depending on geometry reaches $6 \cdot 10^6$. The boundary conditions of the third type (convection from walls to the outside) and the low viscosity of air essentially worse the convergence of iteration process. The time required for calculations with a 3 GHz computer is about 3 days. The difference between the heat amount from the heater and the heat losses from the outer surfaces and openings decreases below 7%.

3. Results

Five typical situations selected for modelling the temperature distribution and air flows in a dwelling house (see Table 1):

- along the window-frame a slot exists through which, depending on the pressure difference with the ventilation opening by the opposite wall, the cold air from outside can flow indoors or the hot air from inside – outdoors (variants 1, 2, 3);
- under the window there is/there is no sill (variant 3, 4);
- the heater is placed under the window (which is traditional) or by the inner wall opposite to the window (variants 3, 5).

Since the convective heat transfer from the heater is essentially dependent on the air flow intensity near its surface, it is obvious that, despite its constant temperature, the maximum heat will be taken off when along it a vigorous air motion occurs (variant 1), whereas at placing the heater by an inner wall (variant 5) the released heat amount will be only 57% of the above mentioned. The highest average temperature in the room is calculated in variant 4 (without windowsill) and the lowest – in variant 1 with a cold air inflow (see Table 1).

Table 1. Physical and geometrical properties for different modelling variants and the calculation results

Variant	Pressure difference Δp (Pa)	Windowsill	Placement of the heater	Total heat amount Q (W)	Average velocity v (m/s)	Average temperature T (°C)	Vertical temperature difference ΔT (°C)	Horizontal temperature difference ΔT (°C)	Air exchange rate n (1/h)
1	1	+	A	253	0,06	13,7	4,1	9,2	1,50
2	-1	+	A	167	0,06	18,5	0,7	2,8	1,50
3	0	+	A	176	0,05	17,6	0,7	6,4	0,86
4	0	-	A	199	0,04	19,6	1,4	2,3	0,21
5	0	+	B	145	0,02	18,3	2,0	4,6	0,34

A – near window, B – near opposite wall (to the corridor)

From the viewpoint of thermal comfort it is important that the temperature difference in the vertical and in the horizontal directions is as small as possible. It is seen that in variant 5 (with a heater near the inner wall) air stratification with the vertical temperature difference more than 2 °C is observed (Fig. 2d). An especially cold zone is formed near the floor by the window, since this zone is considerably cooled by the downstream cold air that enters along the window glass and through slots in the window joints. Therefore for people it is uncomfortable to be in a zone closer than 0,5 m from the window, since there is an air temperature below 10 °C and there is a strongly felt flow of cold air (up to 0,35 m/s), which in everyday life is known as "a draught blowing over one's feet".

Even more disadvantageous conditions in every aspect are formed in variant 1, where owing to the pressure difference from outside through the window slots cold air actively enters (Fig. 2a), causing very significant heat losses. The heat amount received from the heater in this variant is maximum, but the temperature in the middle of the room falls down to 14 °C. The velocity of cold air flow near the window exceeds 0,5 m/s, and the intensity of this flow is retained high also in the middle of a room (0,2 m/s). It is clear that to feel comfortably under such conditions is hardly possible. For comparison, in variant 4 (Fig. 2c), which could be considered the most optimal of all, the characteristic room temperature reaches 19,6 °C.

In variant 3 (no pressure difference between the window slot and the ventilation opening) the temperature distribution in height is very uneven (Fig. 2b). This is caused by active cold and hot air flows, which are partially separated by a windowsill and directed horizontally. When the air warmed by a heater is moving along its surface upward, it meets an obstacle – a windowsill, as a result of which the direction of a hot air stream is changed. But at the opposite wall of the room there exist downward inflow of cooler air through the ventilation opening.

From the viewpoint of ensuring the thermal comfort the most advantageous situation in such a room will be created when the outdoor pressure difference is zero (Δp=0 Pa) and the heater is not closed by a windowsill (variant 4). In this case the temperature difference in height in a larger part of the room are smaller than 1,5 °C (Fig. 2c), but the temperature in the room is the highest as compared with those in other variants, i.e. it is the closest to the temperature in the contiguous rooms (20 °C). The intensity of air flow is low (< 5 cm/s) practically throughout the room. In variant 4 (without windowsill) the warm air flow is heating the inner surface of the window thus fully eliminating the risk of condensate appearance on this surface since in this case the temperature near the window surface is even greater than in the middle of a room. In this variant the heat inflow from the contiguous rooms where the temperature is conditionally assumed to be 20 °C is practically eliminated. In all other cases a significant heat inflow from contiguous rooms is observed.

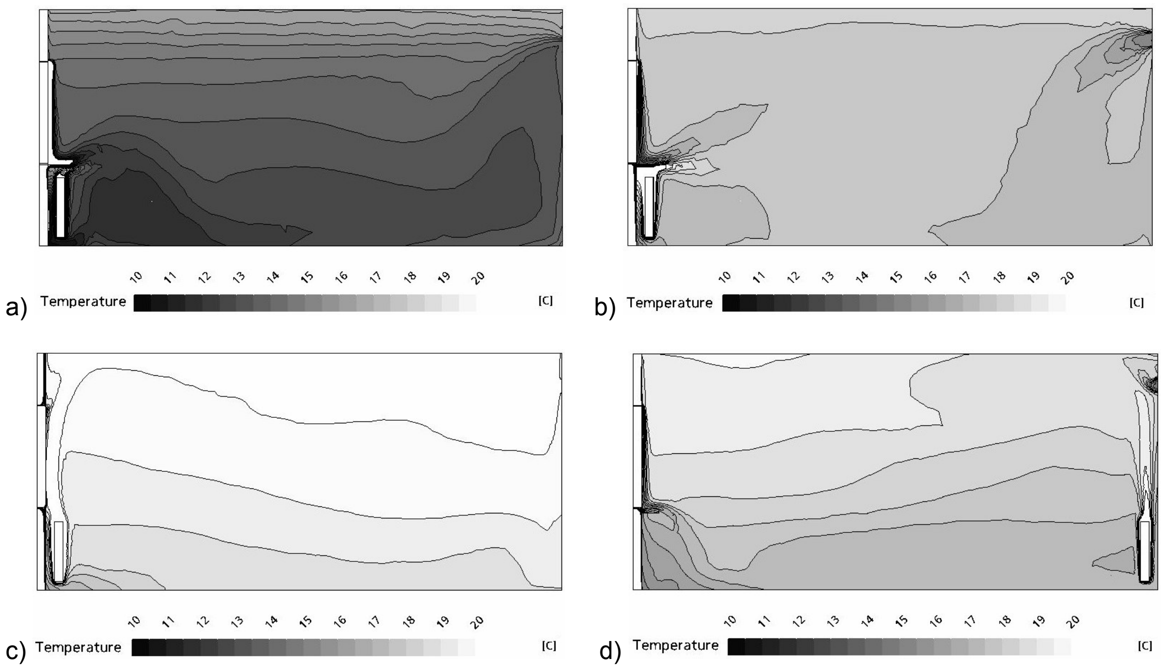

Fig. 2. Temperature contours form 10 to 20 °C for variants 1 (a), 3 (b), 4 (c), 5 (d)

Especially high risk of condensate appearance exists for the outside building structures that have a high permeability of heat. In this aspect the most critical construction is the window (U=2,5 W/m^{2}K). Such a risk is increasing with the difference between the characteristic temperature of the room and the temperature of the window surface: in variant 3 (Δp=0 Pa and the windowsill limits the warm air flow) the characteristic room temperature exceeds 18 °C, while at the upper edge of the window the temperature falls down to 10 °C. As a result, the condensation on the window surface is highly probable; since, if the relative air humidity in the room is 60%, the condensation will begin at a temperature below 11 °C. It should however be noted that through the slots in window joints there is inflow of cold air whose absolute moisture content is lower. Therefore the condensation may take place in the bottom part of the window where the air from outside when flowing over this surface has already been mixed up with the more humid room air.

Somewhat unexpected has been the result that the risk of condensation on the window surface is practically absent in the case when the heater is placed by the wall opposite to the window (variant 5). This is determined by the warm air flow along ceilings in the direction to the outer wall and relatively immobile warm air masses in the upper part of this wall above the window (Fig. 2c). In this case the risk of condensation could increase in the bottom part of the outer wall if its heat permeability is increasing. Since in all variants the heat insulation of the outer wall is relatively good (U=0,35 W/m^{2}K), the probability of condensation near it is low.

Another significant condition for attaining comfort is air exchange in the room, which is necessary for maintaining the content of oxygen inhaled by people. As the normal value characterizing air exchange intensity in the rooms without forced ventilation the air exchange rate n=0,7 1/h is accepted. Taking into account the air inflows and outflows through slots in the window-frame and through the ventilation opening it is obvious that in variants 1, 2 and 3 the air exchange is sufficient (see Table 1). In turn, an air exchange above the normal would cause considerable heat energy losses (especially in variants 1 and 2), at the same time not making people feel better, since it decreases the room temperature and increases velocities of air flows.

Formation of the low temperature zones is illustrative demonstrated by isosurfaces shown on Fig 3. In case when heater is installed below windowsill and no pressure difference is defined (variant 3) the cold air zones are formed only in small areas near the outside wall except for air inflow through slots in window-frame (Fig. 3a), at the same time adverse lower temperature conditions are observed near the upper part of the opposite wall (Fig. 3b). This cold zone near the wall to the corridor is formed due to an air inflow with temperature of 15 °C from the ventilation opening. However, in case when heater is located by the wall opposite to the window (variant 5), cold air inflow is observed not only close to the slots in the window-frame, but also in the wide area near the floor and side walls (Fig. 3c). The reason for this temperature distribution is a convective airflow of cold exterior air, which moves to the opposite wall (Fig. 3d) where heater is installed, thereby in this modelling variant stratification is very notable (see also Fig. 2d) and the temperature difference reaches 2 °C.

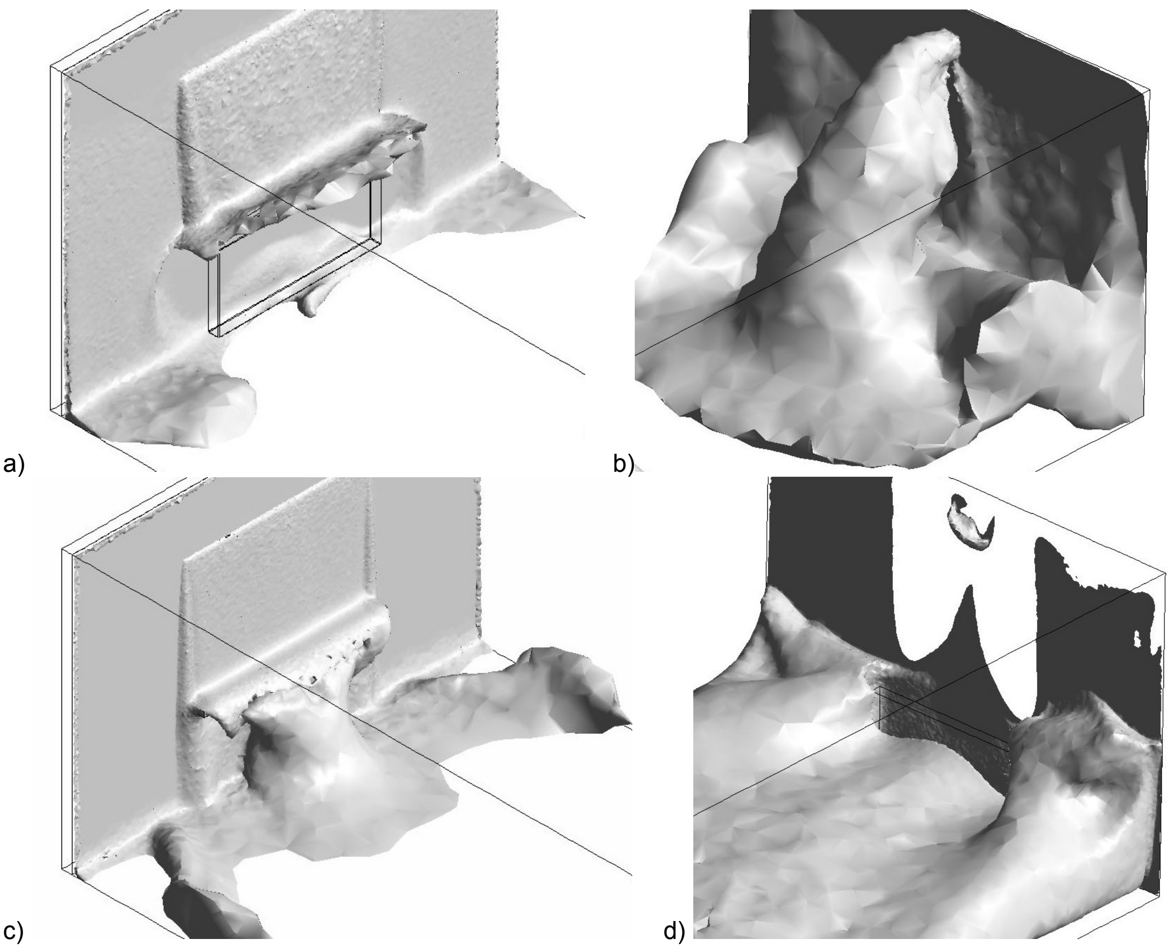

Fig. 3. Temperature isosurfaces for variant 3 (a, b) and variant 5 (c, d)

To summarize, among all the considered modelling variants the least advantageous from the viewpoints of thermal comfort conditions is variant 1, and the most advantageous – variant 4 (see Fig. 4). Detailed analysis of modelling results for living rooms with different boundary constructions' heat transfer coefficients, varying heater surface temperature, geometry configurations and corresponding comparison of heat balances is analyzed in publication [3].

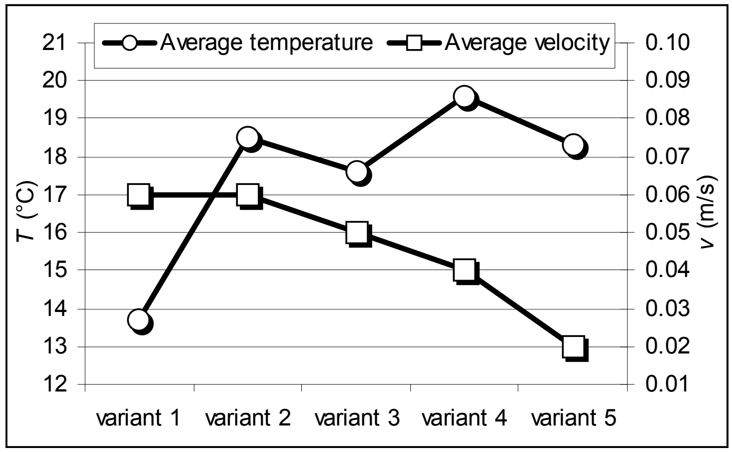

Fig. 4. Characteristic average temperature and airflow velocity in the middle of the room for different modelling variants

2. Conclusions

3D numerical calculations of temperature and airflow distribution in a living room with opening for air exchange show the essential influence of windowsill and heater dislocation on thermal comfort conditions in the room as well as on heat transfer form the heater with constant surface temperature. It is established that the most advantageous situation are observed with no pressure difference between exterior air and ventilation opening and no windowsill is exist. However, in case of 1 Pa over-pressure on outer wall opening, low temperature regions is developed in the room with marked temperature stratification and thee exist relatively high air velocities, which mean heightened heat transfer form the heater. Obtained temperature distributions help to forecast critical places near boundary constructions where high risk of condensation exists.

The model of a separated room shows the influence of various kinds of factors on the resulting distributions of thermo-physical parameters in the room that are directly related to the conditions of thermal comfort. At the same time, the heat consumption can be reduced and this helps to reduce energy production and the related pollution.

References

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