Influence of the Heating and Ventilation Systems Cooperation, in the Dwelling, on Energy Demand and Occupants Thermal Comfort

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Abstract

This paper refers to conceptual design of the dwelling using performance simulation software. TRNSYS and TRNFlow are used to create models of the building, respectively: thermal and multizone airflow model. The dynamic simulation, with changing boundary conditions during hourly, daily, weekly and yearly simulation cycles, is possible using these computational tools. Interactions between heating and ventilation systems are investigated in detail. Two ventilation concepts are considered: natural and mechanical. Two heating system variants are taken into account: convection and radiative. Advance occupancy profile is included in order to properly model internal heat gains.

Simulations are performed, using validated model, for different combinations of heating and ventilation systems to analyze the influence of their cooperation on the dwelling energy demand and inside thermal comfort. Control strategy is developed to provide efficient collaboration of building, system and occupants.

The natural ventilation calculation are based on CLIMA 2005 paper and thermal comfort standards EN 15251:2012 is used as background for results analysis.

TRNSYS, validation, floor heating, convection heating, natural and mechanical ventilation, thermal comfort, energy demand

1. Introduction

For the purposes of building energy and their internal thermal comfort analysis a wide range of simulation tools, which vary in terms of detail processing level, can be used [1]. On one hand a study of usable space-time in terms of air velocity, temperature distribution or the asymmetry of radiation with the use of sophisticated CFD methods is necessary. On the other, using balance calculations in steady state conditions one can quickly assess energy consumption of a building for a given indoor room temperature. Henceforth this article uses a middle approach, called the multi-zone building model. It enables a detailed analysis of a building's energy consumption as well as an observation of the following thermal comfort parameters: room operative temperature, air moisture content and air flow, as well as approximate calculations of PMV and PPD parameters. For both the calculations (energy and thermal comfort) TRNSYS program was used.

The aim of the following simulation analysis is comparing how different heating systems and ventilation systems work together in terms of energy consumption and thermal comfort. Calculations were done based on a multi-family residential building. The model was validated.

2. The Building

The building under analysis is a real structure located in Poznań (Poland). It is a multi-family building with four residential stories and a cellar (Fig. 1). Cellars in the vast majority are not heated and they are used as technical rooms. The shape factor of the building is at the level A/V=0,37 m^{-1}, the floor area of space is 753.8 m^2 and the air space 2223.0 m^3. All building envelope comply with the relevant standards in that regard. The building is a part of a bigger housing estate located on the suburbs, built in years 2000-2001. The first three floors are identical, whereas the 4th floor is slightly smaller. Each floor consists of four apartments with a living area of about 55 and 46 m^2. An apartment on the 2nd floor was used for the modeling purposes with walls directed roughly towards west and south. The apartment consists of two bedrooms (**L** and **BE**), a kitchen (**K**), bathroom and toilet (**BA**) as well as a hallway (**H**) (Fig. 1).

A construction model of the building was made based on the project documentation. The following boundary conditions have been established:

- For the partitions adjacent to other apartments an adiabatic boundary condition was adopted, excluding the bathroom wall, for which a temperature of a bedroom's inside wall from the previous time step was set as an outside temperature,
- For the walls adjacent to the staircase a staircase temperature function of outside temperature variable was adopted. The linear correlation between staircase temperature and outside temperature was assessed based on measurements done in the staircase during the previous academic year [2].
- For the outside walls, climate conditions partly based on measurements of a nearby (around 6 km from the building) weather station and partly derived from a mathematical model were adopted.
- The model also incorporates the influence of shadows cast by the body of the building as well as other nearby buildings.

In order to consider heat and moisture buffering of the rooms and their contents (i.e. furniture) it was posited that the heat capacity of an area is five times that of the heat capacity of the air inside the area, and the moisture holding capacity is twice that number.

For the purpose of this simulation a weekly usage profile of a deterministic character was posited, with the resolution of 10 min. A week was divided into four types of days: Sundays, Saturdays, even and odd working days. The amount of time the residents stayed inside the building, with regards to the area and activities was defined base on [3]. A heat and moisture gain from the residents was adopted based on the data from [4] (function of air temperature and activity variables). In reality the apartment is occupied by one adult and one teenager, which was considered during validation of the model when determining heat gains, however for the simulation analysis it was posited that the apartment is occupied by a family of three (parents and one child). Average internal gains for the above usage profile are 4.94 W/m^2.

The simulations were carried out with a 5 minute time-step.

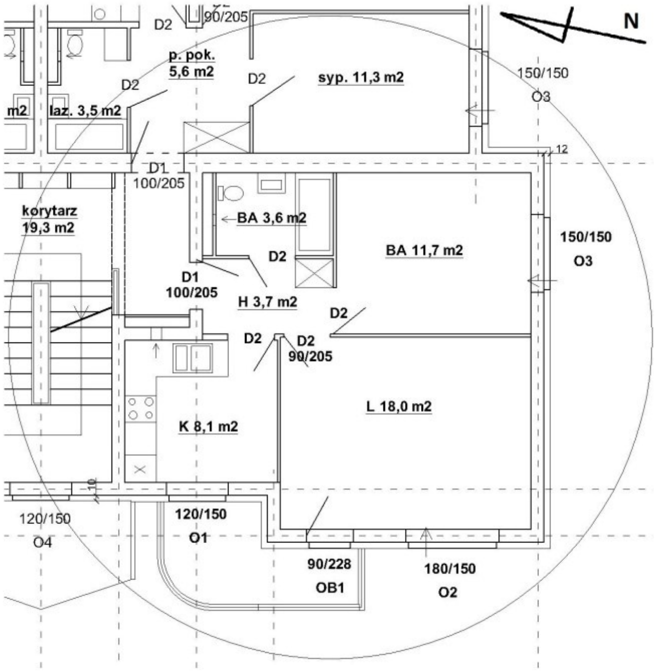

Fig. 1 A photo of the building

3. Validation

3.1 Simplified Model

The analyzed building has been metered. Based on the weekly measurements of heat consumption of specific apartments validation has been made for a simplified apartment model:

- construction of the building together with cold bridges (windows and balcony);
- constant heat gains 3 W/m^2 (1 adult, 1 teenager);

- set heating temperature in **L**, **K** and **BE** 22 °C, as well as **BA** 25 °C;
- constant infiltration of 0.57 h^{-1} – determined based on the use of degree–days in the dynamic assume method.

3.2 Infiltration Calculation Method [5]

Currently, we have no simple methods in real conditions to describe the amount of air infiltration. We can use the fan pressurization method but for existing buildings this method is very troublesome [6]. Alternative to fan pressurization method is a comparing based method, using degree-days in dynamic assume method, theoretical characteristics and operating characteristics [7].

Taking into consideration variation of degree-days in dynamic assume method in the function of the amount of infiltration air to the building we achieve two curves on a graph. One of them for theoretical characteristic grows with increasing ventilation intensity share, the second one decreases for operating characteristic.

The crossing point of two curves gives monthly average values of air infiltration to the building and accounting number degree-days in dynamic assume.

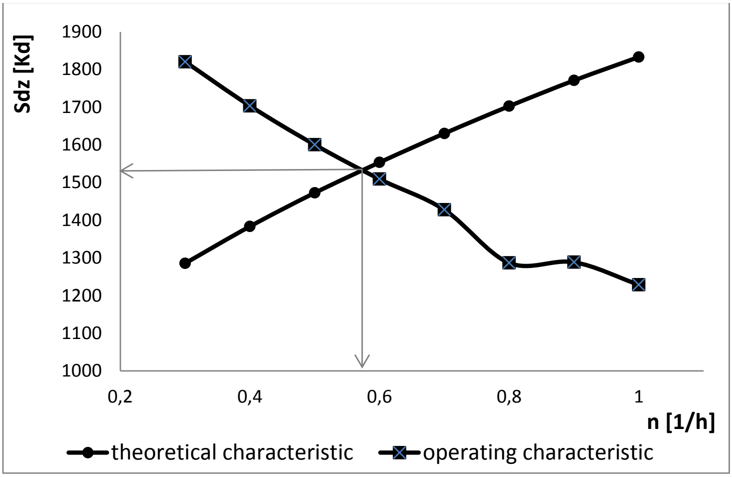

Fig. 2 Comparison of theoretical and operating characteristic

For analyzed building's average values of air infiltration for operational period are equal to n=0,57 h-1 (Fig. 2).

3.3 Comparison of the Presented Model with Measurements

Figure (Fig. 3) shows the comparison between measurements and simulation results. Measuring was carried out in weekly intervals between October 26th 2011 and June 26th 2012 (34 weeks). The largest discrepancies between presented results are noticeable during transitional periods (autumn and spring), since it is difficult to assess the influence of each particular heat loss factor. For the analysis a period of highest similarity between measurements and simulation was chosen as well as a period of highest heat consumption: from December 21st 2011 to March 7th 2012 (weeks 9-19).

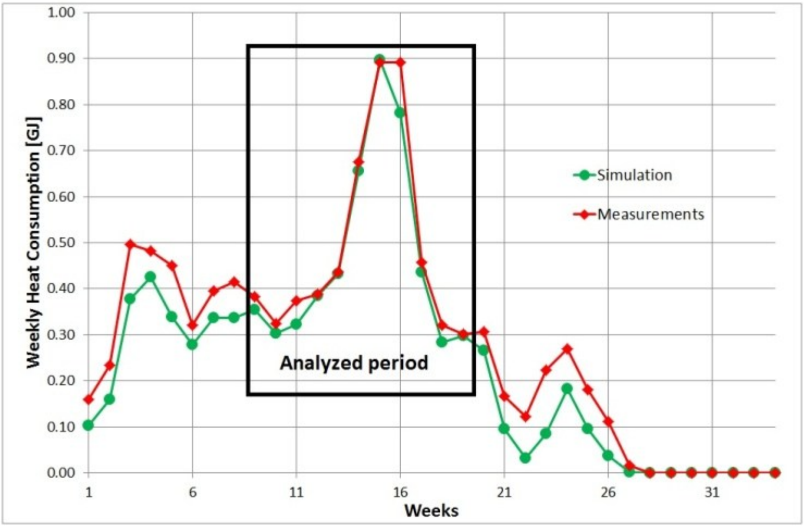

Fig. 3 Comparison of theoretical and operating characteristic

4. Comparable Heating and Ventilation Systems

Convection heaters. In each room (excluding the hallway) it is assumed heaters of default power are present. The power supply temperature of the heaters varied, the minimal value was equal to 50 °C, any higher values are assumed depending on the outside air temperature, the function of that correlation was drawn up based on measurements done inside the building. Each heater is equipped with a thermostatic valve of proportionality range of 2 K (**L, K**, **BE**: 20 - 22 °C, and **BA**: 22 – 24 °C). It was posited that the thermostatic valve is characterized by a time constant equal to 23 min.

Underfloor heating. In each room (excluding the hallway) underfloor heating is present. The water supply temperature is related to the average outside temperature for the last 24 h. The function describing this correlation was worked out [8]. Quantity regulation was established besides quality regulation – the flow is regulated in each heating circuits controlled by off valves. The hysteresis range is as follows: (**L**, **K**, **BE**: 21.25-21.50 °C, and **BA**: 23.75 – 24.00 °C).

Natural ventilation. A constant flow of infiltrating air was assumed, equal to the infiltration calculated for the validation model (0.57 h^{-1}).

Secondly it was assumed that the air from **K** is transported directly to the ventilation duct and the air from **L** and **BE** also goes to **BA** through the hallway

Mechanical ventilation. The inflow of fresh air takes place mainly (minimal infiltration) through the inflow-outflow ventilation system, operated by the air handling unit with a cross-flow recuperator of 70% effectiveness, heating coil. The amount of inflown air is 63 m3/h (38 m^3/h to **L** and 25 m^3/h to **BE**), the stream of outflown air is 60 m^3/h (42 m^3/h from **K** and 18 m^3/h from **BA**). The inflown air temperature is set to 18 °C.

The power of ventilators was assumed based on guidelines from Polish government regulations.

5. Simulation Results

During the simulation energy demand was observed in terms of: heating, ventilation (mechanical) and heating coil. The operative temperature (T_{op}) of the room was taken into account with regard to thermal comfort. Following is a simulation result analysis consisting of a comparison between energy demand of both variants as well as a comparison of comfort parameters between the variants in terms of the regulations in force.

Figs. 4-7 show the operative temperature of each room as a continuous function of external average temperature (T_{rm}) [9] for four analyzed variants. Additionally the graphs show a range various categories of comfort according to [9, 10]. Categories linked with mechanical ventilation have been described in Table 1.

Table 1. Range of optimal operative temperature values in order to keep the PMV parameter between -0.5 and 0.5 (category II in [9]), assuming no change in other parameters.

T_{rm}		**Attire**	**T_{op}**			
<	>		**Met=1**		**Met=1.2**	
[°C]	*[°C]*	*[clo]*	*PMV=-0.5*	*PMV=0.5*	*PMV=-0.5*	*PMV=0.5*
5	14	0.75	23.48	26.58	21.62	25.46
-10	5	1	21.86	25.43	19.77	24.18

Closer attention should be given to the nature of the graphs: the dots form columns, which show the range of T_{op} over a span of one day, since T_{rm} (abscissa) is constant for a given day. Another common observation for every correlation is a visible characteristic of each of the rooms. The most stabile T_{op} is in the bedroom **BE**, because it is adjacent to the least amount of walls forming the building envelope and cold bridges. Larger diurnal variations of T_{op} take place in bedroom **L**, which is a bigger room and has a much higher heat exchange with the external environment. However, the largest amplitude is visible in the kitchen, because of large short-term heat gains that are natural to this room.

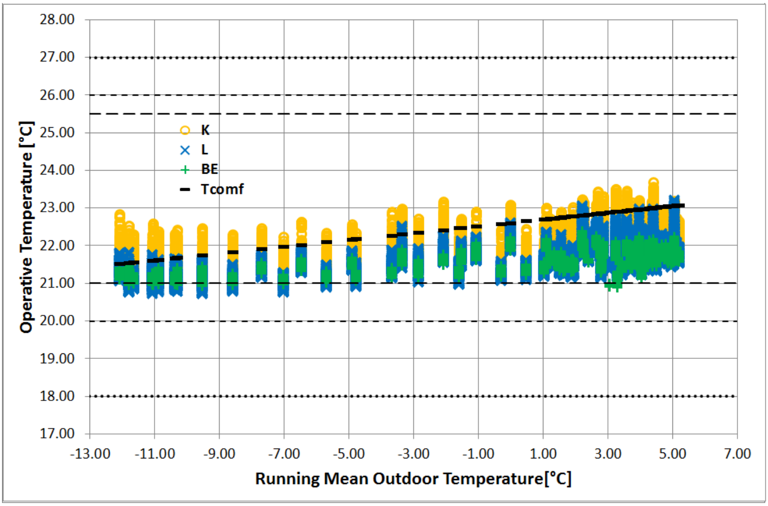

Fig. 4. The operative temperature of areas **L**, **K** and **BE** together with the calculated value of comfort temperature based on T_{rm}, as a function of T_{rm} using natural ventilation andconvection heating. The broken lines represent ranges of T_{op} for each category: long line – I (high level of expectations), short line – II (standard level of expectations), dot – III (acceptable level of expectations).

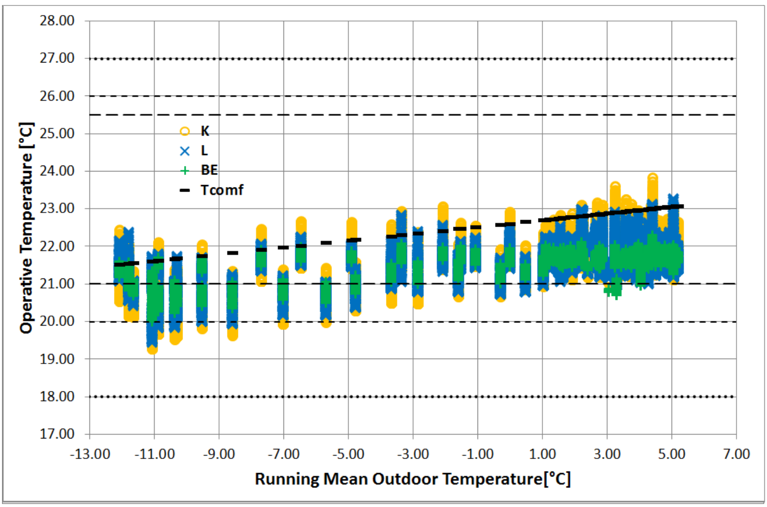

Fig. 5. The operative temperature of areas **L**, **K** and **BE** together with the calculated value of comfort temperature based on T_{rm}, as a function of T_{rm} using natural ventilation and underfloor heating. The broken lines represent ranges of Top for each category: long line – I (high level of expectations), short line – II (standard level of expectations), dot – III (acceptable level of expectations).

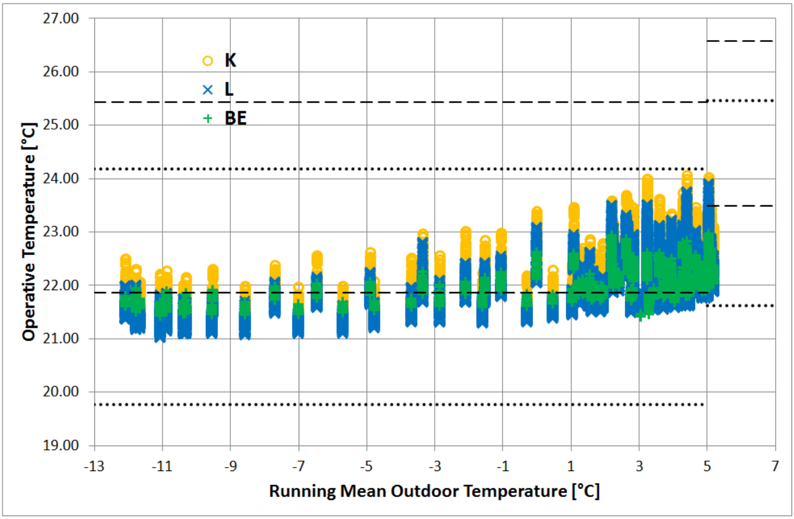

Fig. 6. Operative temperature of areas **L**, **K** and **BE** as a function of running mean outdoor temperature in terms of mechanical ventilation and convection heating. The broken and dotted line represent the T_{op} values ensuring that PMV is between -0.5 a 0.5 (category II in [9]) for physical activity of 1 and 1.2 met respectively.

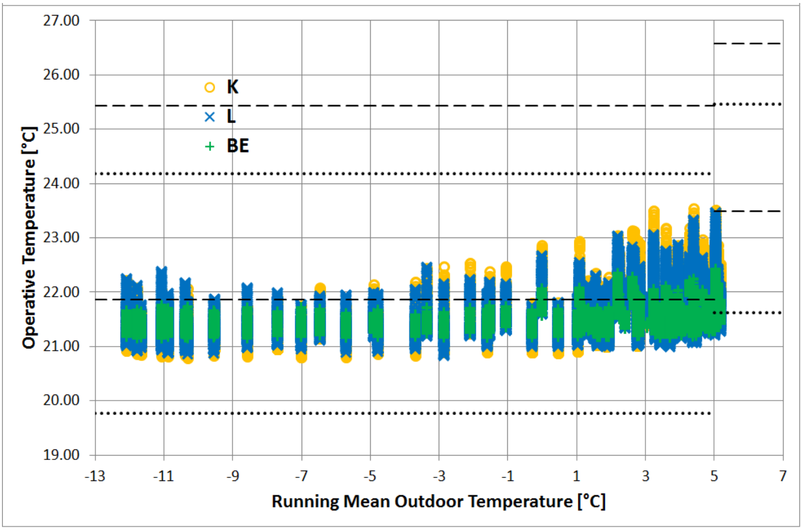

Fig. 7. Operative temperature of areas **L**, **K** and **BE** as a function of running mean outdoor temperature in terms of mechanical ventilation and underfloor heating. The broken and dotted line represent the T_{op} values ensuring that PMV is between -0.5 a 0.5 (category II in [9]) for physical activity of 1 and 1.2 met respectively.

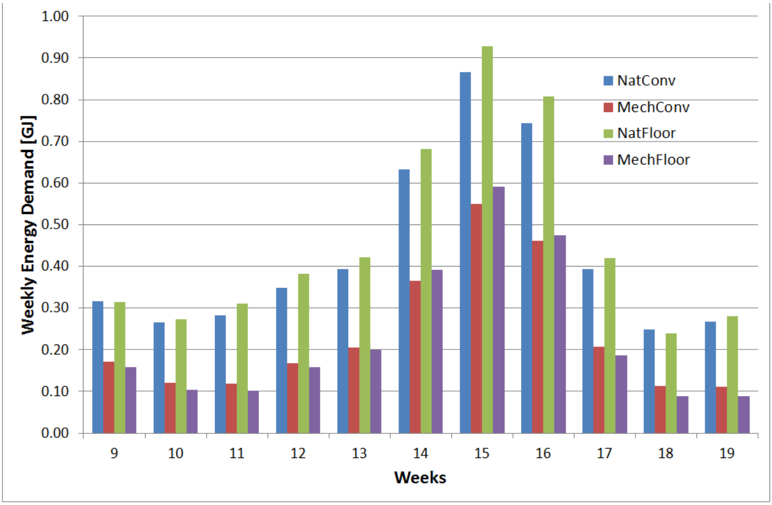

Fig. 8. Comparison of weekly energy demand for the building using different variants.

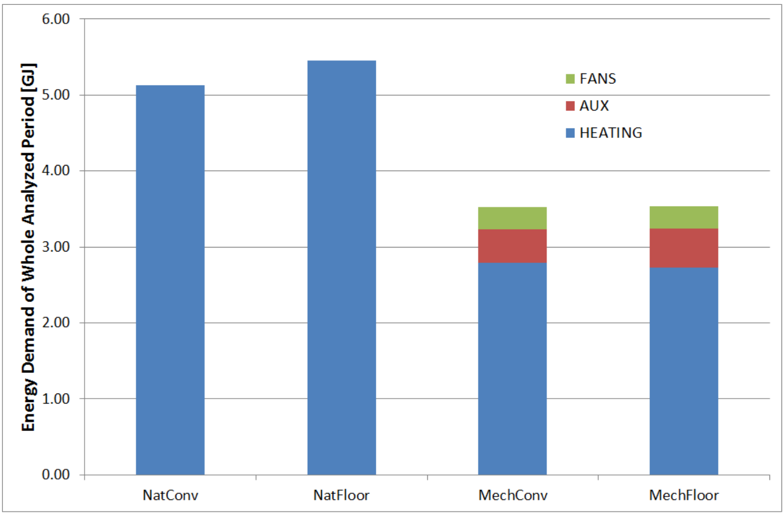

Fig. 9. The share of heating and energy for appliances in the total energy demand of the apartment in the analyzed period.

6. Discussion

Comparing the two types of heating systems using natural ventilation (Fig. 4 and 5) it is clearly visible that underfloor heating is a less stabile solution, with a higher thermal inertia and is simply less effective (lower

T_{op}). It is due to the fact that the heating factor has a visibly lower temperature, which effects in the heat transfer being much less intensive. Secondly, the active surface – floor – is relatively smaller compared to passive (cooling) surfaces – walls and ceilings. The situation in the kitchen is most evident of this problem, where the active surface has been deducted because of the use of kitchen appliances. In the case of radiator heating systems the heating surface is less of a factor because the radiation heat transfer has a smaller share in the overall balance. That is why T_{op} of rooms derived from a simulation of such a solution is largely focused on the comfort temperature (determined according to CEN guidelines) and almost completely matches the criteria of the most rigorous category. Moreover it needs to be reminded that natural ventilation has been modeled in a simplified way, which evenly spreads the flow of infiltrating air in time. In reality this flow varies throughout the day and is largely dependent on regulating it with opening and closing of windows. Inclusion of this fact would probably result in a higher variance of T_{op} in rooms during the day, which in turn would widen the difference between the comfort between surface and radiator heating systems. It is due to the fact that underfloor heating has a large thermal inertia, so when challenged with a varying infiltration flow it would lower its effectiveness even more.

The situation differs when we replace natural ventilation with mechanical ventilation. It can be assumed that in general the flow of fresh air flow will not change in terms of amount but a big quality change will occur – the inflow of air has a much higher temperature. In the case of underfloor heating the operative temperature in the analyzed period does not fall below 20.7 °C (Fig. 7). However, during days of highest T_{rm} (of the period under observation) the operative temperature is too low (after adjusting it to the assumed change in clothing). There is no such situation in the case of radiator heating with mechanical ventilation systems: T_{op} gently rises together with the rise of T_{rm} and thus, does not exceed the boundaries of PMV equal to ±0.5 (Fig. 6). In the case of surface heating improvement could be seen after surface heating was complemented with convection heating that mechanical ventilation enables. However this combination still has a lower thermal potential, which results in lower T_{op}, and subsequent worse thermal comfort.

For the calculations a multi-zone building model was used, each room is modeled as a perfectly mixed volume of air together with the surrounding walls, thus we do not have full information on the distribution of temperature in the room, so any temperatures are mean values. However it is clear [8] that underfloor heating provides a better vertical temperature gradient and is different from the radiator heating systems which employ a point heating system. That is why a spatial analysis of both discussed systems, e.g. using the CFD model, could show a higher temperature differentiation in a given zone for the radiator heating system, which would be strongly perceptible in case of a bigger space. The results will also rely on the character and distribution of inlet and outlet elements of ventilation system, both in case of natural and mechanical ventilation.

For the presented assumptions, it appears that radiator heating system ensures a higher comfort, regardless of the ventilation system in place. However the joint use of surface heating and mechanical ventilation has a visible potential and by adjusting the parameters and/or a small support from a radiator it can prove to be a better solution, especially because of the possibility of using high-effectiveness, low-temperature sources of heat. Incorporating another variable – air moisture content – would greatly enhance the real-life value of the above mentioned comparison.

Analyzing the presented solutions from energy-consuming standpoint (Fig. 8 and 9) mechanical ventilation proves to be the most advantageous (with heat recovery). Between the two types of heating there is no major difference, however a tendency can be seen that during colder periods, underfloor heating has higher energy-consumption than radiator heating, warmer periods being the opposite, which is a result of a higher thermal inertia of underfloor heating systems. It is necessary to point out that energy demand of the system was analyzed, which can differ from energy consumption after including all the aspects of how heating systems work.

7. Conclusion and future works

Thermal comfort in different variants varies in terms of quality; however it never falls below category II [9]. Installation of heat radiator system ensures better thermal comfort conditions, but using underfloor heating and mechanical ventilation jointly shows potential, which can be beneficial after modifying certain parameters or supporting it with small radiators. From the energy consumption perspective it can be stated that using mechanical ventilation with heat recovery systems during cold periods is a solution worth further analysis.

Subsequent steps of this analysis should include:

- Air moisture content as a factor of thermal comfort,
- Energy demand and thermal comfort responsiveness in terms of particular parameters of the system,
- Model validation in terms of thermal comfort parameters,
- Elaboration of the infiltration model,
- Energy demand vs. energy consumption analysis,
- Analysis of linking the system with the heat source and its interoperability,
- Developing the systems automation interoperability.

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