Parametric study and energy analysis of a personalized ventilation system

I. Cruceanu, C. Maalouf, I. Colda, M. Lachi

Abstract: The personalized ventilation system aims to improve the quality of the inhaled air, to decrease the risk of transmission of the infectious agents and to improve the thermal comfort of the occupants.

In this work, a classical ventilation system is compared to a personalized ventilation system from the energy consumption and the thermal comfort point of view. The analysis is made with a nodal model, using the numerical simulations in the SPARK simulation environment. The object of the simulations is a classroom in Bucharest, Romania. Our results suggest that personalized ventilation can reduce the energy consumption of about 60%. Results are completed with a parametric study that shows that system performance is mainly affected by outdoor temperature variations and glazing solar heat gain coefficients which affects entering solar radiation creating internal heat loads.

Keywords: Personalized Ventilation, Classical Ventilation; Energy Consumption; thermal comfort, simulation; SPARK.

NOMENCLATURE

Symbol	Definition	Unit
ρ_l	Mass density of air	$kg.m^{-3}$
c_p	Specific heat capacity	$J/.Kg^{-1}\ K^{-1}$
I	Room Inertia	
Φ_{South}	Heat flux	W
T_m	Mean radiant temperature	K
h_r	Linearized radiative coefficient	$W\ m^{-2}K^{-1}$
σ_0	Stephan Boltzmann Constant	$W\ m^2\ K^{-4}$
T	Temperature	°C
S	Surface	m^2

I INTRODUCTION

The concept of personalized ventilation was first introduced by Fanger [1] who said that “we would hesitate to drink water from a swimming pool polluted by human bio effluents. Still we accept consuming indoor air that has previously been in the lungs of other persons and is polluted by human bio effluents and other contaminants”. Besides the above mentioned disadvantage, a total volume ventilation system is not offering individual control on the system, and the possibility of energy saving. Personalized ventilation concept is applicable for places where people spend most of their time sitting on a desk. The goal of this type of ventilation is to bring fresh air to the user and in doing so, to improve the thermal comfort of the occupants [2-4]. It also can give the user the possibility to adjust the direction and air flow rate. The system uses supply grilles located close to the breathing area of the user [5], so that the occupant inhales the air from the unpolluted core of the supply jet (Fig 1). This means that the quality of the inhaled air is increased [6], the risk of transmission of the infectious agents diminishes [7-9] and the efficiency increases. Niu [10] found that over 80% of the inhaled air could be composed of fresh personalized air. The increase of the ventilation efficiency implies reduced outdoor supply air rates and reduced energy consumption [11]. There are two more strategies used to reduce energy consumption [12-16]: supplying fresh air only when the user is on his desk and the increase of the interior air temperature due to the fact that the personalized ventilation concept is based on the creation of a microclimate. Studies have shown that a personalized

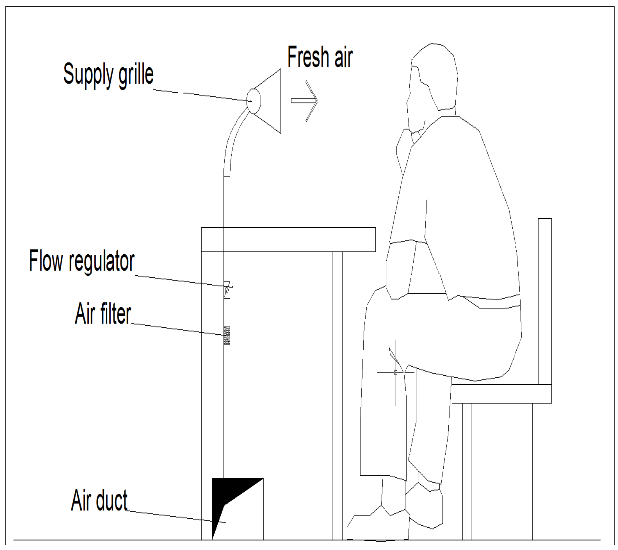

Fig. 1: Principle of desk mounted personalized ventilation system.

ventilation system can offer comfortable conditions even if the indoor temperature in the room is higher than the acceptable temperature. This is due to the fact that the most sensitive part on heat is the head. Sometimes with the classical ventilation systems due to the stratification, in the head zone the temperature could rise and become outside of the comfort zone. In alternative the PV system offers

I. Cruceanu, is with the Civil Engineering, UTCB, Bd. Lacul Tei nr. 122 – 124, Romania (Corresponding author: iunia.gligor@yahoo.com)

I. Colda is with the Technical University of Civil Engineering Bucharest, Blvd Pache Protopopescu 66, Romania

C. Maalouf, M. Lachi are with Laboratoire Thermomécanique- GRESPI, Faculté des Sciences, University of Reims Champagne Ardenne, BP1039, 51687, Reims, France (Corresponding author: chadi.maalouf@univ-reims.fr).

sufficient air movement around the head and the face to give the occupant a comfort sensation [17-21].

The purpose of this study is to analyse the energy consumption of a personalized ventilation system and compare it to a traditional ventilation system in the case of a classroom situated in the city of Bucharest Romania, using the simulation environment SPARK [22-26] suited to complex problems. We compared both cases for different supply air flow rates and temperatures. Energy performance and thermal comfort conditions are estimated using the heating and cooling energy consumption as well as the cumulated temperature frequency for each case. Finally, a parametric study is run in order to assess the effect of some problem physical parameters such as glazing solar heat gain coefficient, roof insulation thickness, room surface area, occupants number, internal and external heat transfer convection coefficients…

II METHODS

A Description of the classroom

The building is a classroom of 6.4x8.1 (51.84 m^2) and 3.5m height. It is located in Bucharest, Romania. Weather file is provided from the ASHRAE data base. The study period is for three monthes from April till June. The Western wall is an external wall and the southern façade is made of a double glazing with a solar heat gain coefficient of 40%. The other walls are considered as partitions and are in contact with conditioned spaces at 24°C.

The floor is composed of an 18 cm concrete slab, 10 cm polystyrene and 7 cm concrete. The ceiling is composed of 10 cm of polystyrene, 18 cm concrete and 2 cm plaster. The west wall is made of 18 cm bricks with an external insulation of 7 cm of polystyrene.

The partition walls are made of 15 cm of brick in sandwich between two layers of plaster, 2 cm each.

B. Occupancy and internal heat gains

We considered that the room is occupied by 31 persons from 8.00 to 18.00, five days a week. Each hour has a break of 8 minutes during which only 15 occupants remain in the class (monthes of April and May) and 8 persons in June. The infiltration rate depends on the internal pressure and is considered equal to 0.8 V/h when the ventilation system is off and 0.4 V/h when the system is on.

The lighting is on from 8h to 10h for the monthes of April and May (15 W/m^2). Fig..2 presents the sensible heat load of the room due to lighting and occupants (monthes of April and May).

C Description of the ventilation system

Two ventilation systems are compared:

- A classical ventilation system for which the air flow rate is considered 7 l/s/occupant respecting the Romanian standard. This system is on from 8h till 19h in the evening apart from the week-end.
- A personalized ventilation system for which the air is treated by an air-conditioning unit that regulates the supply air temperature and is adjusting the air flow according to the room's occupancy. There is no mechanical ventilation and the air is evacuated through room leakage.

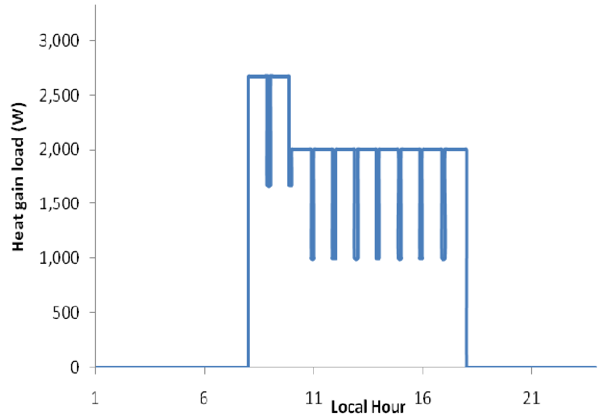

Fig 2: Heat load in the classroom due to light and occupancy for the monthes of April and May.

In both cases, room internal temperature varies freely without any regulation system.

D The simulation software and room model

Simulations are run within the Simulation Problem Analysis and Research Kernel (SPARK) [22-26], an equation based modeling environment developed by the Simulation Research Group at Lawrence Berkeley National Laboratory. The advantages of this environment are its modularity and its syntax which is suited to parametric studies.

Room is modelled using a nodal method which considers the room as a perfectly mixed zone characterized by a pressure, a temperature and a moisture concentration. It involves equations for air and moisture mass balance, heat balance for ambiance and equations describing heat transfer through the walls, additional convection between inside wall surfaces and room balance. The energy balance equation for the air zone can be written as:

$$(\rho_i c_p V + I)\frac{\partial T}{\partial \tau} = \Phi_{West} - \Phi_{East} + \Phi_{South} - \Phi_{North} + \Phi_{Bottom} - \Phi_{Top} + \Phi_{Source} \quad (1)$$

where I is room thermal inertia . This equation involves heat fluxes through the envelope (from walls and openings) and internal heat sources. Energy balance is also applied to walls and is solved using a finite difference method in which wall is discretized into 5 nodes [27].

External heat transfer convection coefficient is taken equal to 16 W/m^2°C and internal heat transfer coefficient is equal to 5 W/m^2°C.

Concerning radiation heat exchange between room walls it was computed using the mean radiant temperature method in which the radiative flow between a wall and all the other walls of the room is written as:

$$\Phi^{int}_{rad,LW} = h_r S(T - T_m) \quad (2)$$

The value of h_r is expressed by:

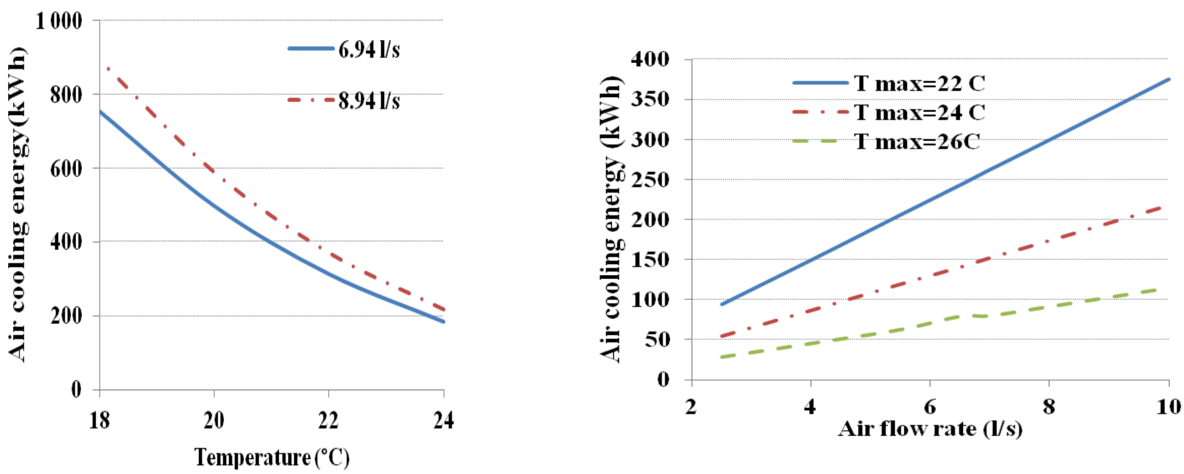

Fig3: Variation of the energy consumption needed to cool the inlet air as a function of air flow rate and maximum supply temperature for both the personalized ventilation case (right) and the classical ventilation case (left).

$$h_r = 4\varepsilon\sigma_0 T_m^3 \tag{3}$$

σ_0=5,67*10^{-8} W m^{-2} K^{-4} – Stephan Boltzmann Constant Where T_m is the mean radiant temperature of the walls and is given by:

$$T_m = \frac{\Sigma S_j T_{Sj}}{\Sigma S_j} \tag{4}$$

E. Simulated cases

We compared the two ventilation systems from both energy consumption and thermal comfort sides. For the conventional ventilation system (VC), the inlet air flow rate was calculated according to the Romanian Standard. Two values are considered of 840 m^3/h and 995 m^3/h. The supply temperature may vary in the range of 18°C (minimal) and a maximal value that could be 18, 20, 22 and 24°C. We have analyzed a total of 8 cases.

For the personalized ventilation system (VP) several supply air flow rates are simulated - 2,5 l/s; 4 l/s; 5,5l/s; 6,5 l/s; 7 l/s; 8 l/s and 10 l/s for occupant. Due to the fact that the system supplies the air to the breathing zone of the occupant, some restrictions must be imposed regarding the supply air temperature. The temperature will vary between a minimum of 20°C and an imposed maximum of 22, 24 or 26°C (the fresh air will be heated or chilled). We've studied a total of 21 cases.

For each case, 3 parameters were taken into consideration:

- The energy consumption HC needed to heat up the fresh air to reach its imposed minimum temperature.
- The energy consumption CC needed to cool external air to its requested maximal temperature.
- The cumulated frequency that characterizes the interior comfort and is defined by the following relation :

$$\text{FC}=\sum_t \left(T_i(t) - T_{ref}\right)\delta(T_i) \tag{5}$$

T_{ref} is the reference temperature taken to be 28°C for the classic ventilation and 30°C for the personalized ventilation. $\delta(T_i)$ is the symbol of Kronecker and is equal to 1 if T_i is superior to T_{ref}, otherwise it is equal to 0. This frequency accounts for the degree-hours of thermal discomfort. The smaller it is, the greater thermal comfort is expected. The simulations are carried for April, May and June however, in order to initialize the calculations and to avoid the influence of the initial conditions, only the results of May and June are taken into consideration.

III RESULTS

Figure 3 shows the cooling energy consumption (CC) for both cases, personalized and classic ventilation, as a function of air flow rate and for different maximal air supply temperatures. As we can see in both cases, energy consumption increases with air flow rate and decreases with the growth of maximal air supply temperature. For the classic ventilation system and an air flow of 25 m^3/h/person, the energy consumption varies from 182.9 kWh to 755.8 kWh when the maximum supply temperature is lowered from 24 to 18°C. Increasing the air flow from 25 to 30 m^3/h/person brings an 18% increase in the energy consumption. For the case of the personalized ventilation and the same airflow rates, the consumption varies between 80.3 kWh and 262.7 kWh for a maximum temperature of 26 to 22°C. Due to the fact that the air, in this case, is introduced near the user, an inlet temperature of 18°C cannot be used. With a growth of 2°C, cooling energy consumption decreases about 50%.

Figure 4, presents the heating energy consumption variation (HC) needed for both the classical and personalized ventilation systems to heat up the fresh air to a minimum supply temperature of 18°C (for the CV) and 20°C (for the PV). We notice that for both cases this consumption is not function of maximum supply temperature. It increases with supply airflow rate and it is higher for the personalized ventilation system. For 7 L/s/person it is 134 kWh for the (PV) whereas it is 89 kWh for the (CV).

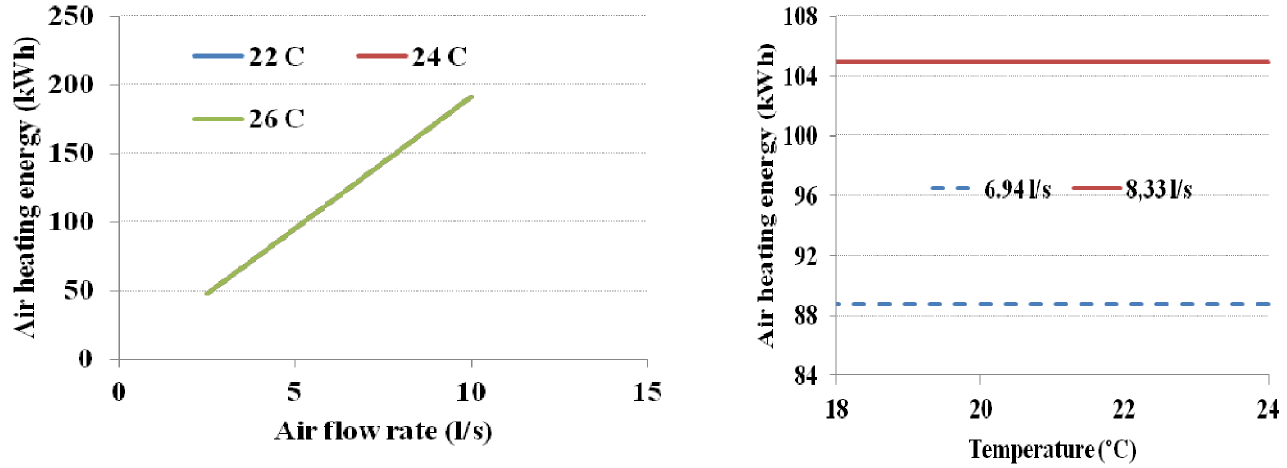

Fig 4: The energy consumption needed to heat the inlet air for both PV (left) and CV (right) cases.

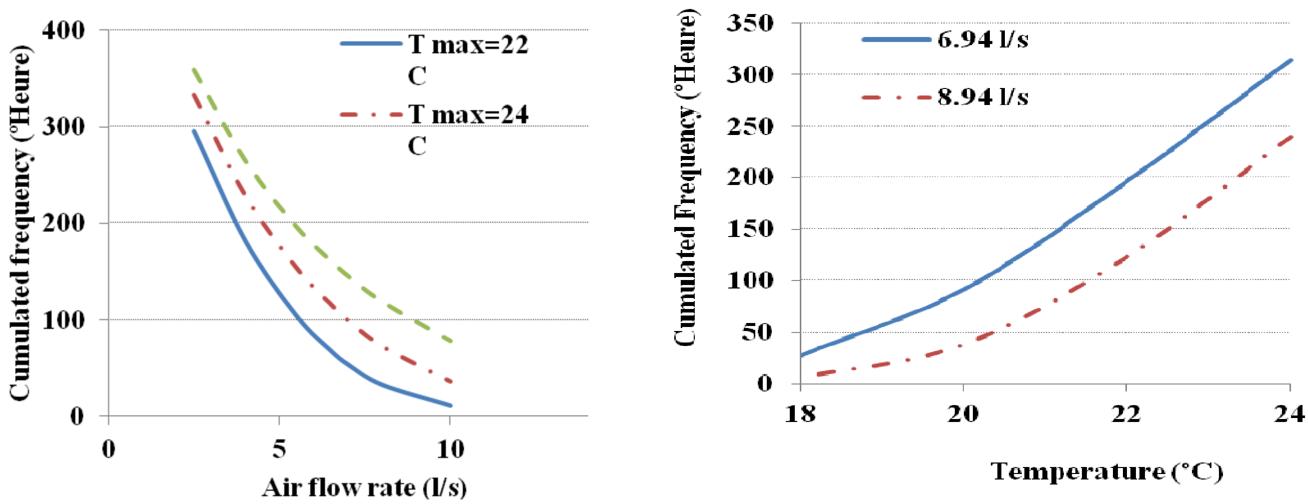

Fig 5: The variation of the cumulated frequency (FC) for both cases PV (top) and CV (bottom) cases.

Figure 5 shows the variation of the cumulated frequency for both cases and for different air flow rates and maximum air supply temperatures. Higher air flow rates or lower supply air temperatures lead to a decrease of the cumulated frequency indicating that the internal temperature is lowered and the thermal comfort is improved.

For the classical ventilation case, the FC value is very high and it has satisfying values only for an inlet temperature of 18°C (both air flow rates) or a 20°C and an air flow of 30 m^3/h/person. In the case of personalized ventilation the smaller values are for a maximal temperature of 22°C and for air flows larger than 6 l/s/person.

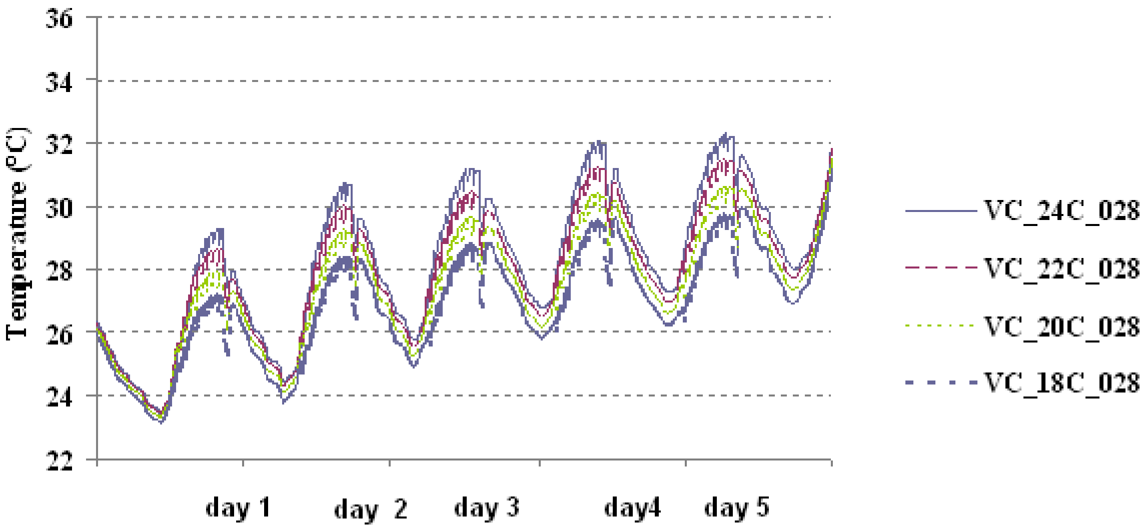

Fig 6: The variation of the interior temperature for different air flows in classical ventilation case during the month of june for the hottest week of the month

Fig 6 shows the variation of the interior temperature during the hottest week of June in the case of classical ventilation with different air flows. For 24°C the interior temperature is higher than 28°C for the whole week and even reaches 32.2°C. The cumulated frequency is, in this case, 315 (° hours). When the inlet temperature is 18°C, the maximum interior temperature is 29.4°C and the frequency 27.5 (°hours). The energy consumption for cooling varies from 183 kWh to 755.8 kWh. To these values, 88.8 kWh (HC) must be added to take into account the energy needed for the air when its temperature is below 18°C.

When comparing energy consumption for the same air flow and the same maximal supply temperature for both systems, we notice that cooling energy is very higher for the classical case than the personalized ventilation case and that heating energy is lower for the classical case. The difference comes from the fact that in the personalized ventilation system the minimum supply air temperature is 20°C while for the traditional system it is 18°C. These results confirm Schiavon results [27,28] that personalized ventilation is suited to hot climates and not to cold climates where heating energy consumption is higher than the classical ventilation system case.

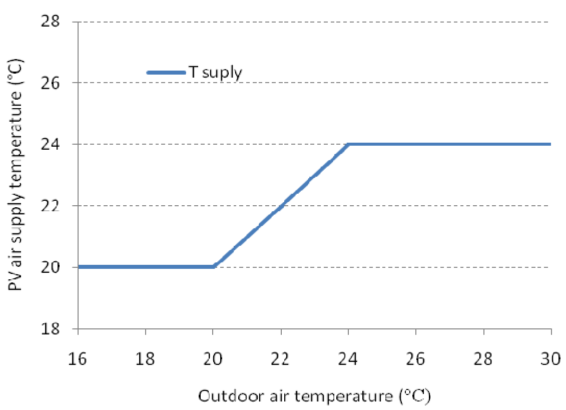

Fig 7. PV air temperature as a function of the outdoor temperature (case when T supply is between 18°C and 24°C)

In our case, as the system is used for cooling, total energy consumption is reduced from 844.6 kWh to 400 kWh when using personalized ventilation system with a supply temperature of 22°C and an air flow rate of 7 l/s/person, with about 52% of reduction (FC=50°hrs). For a supply temperature of 24 °C and an air flow rate of 8 l/s/person, the energy consumption is about 327 kWh and the FC is about 64.5 °hrs which is also acceptable.

IV SENSITIVITY ANALYSIS

In this part we have decided to realize a sensitivity analysis to be able to see the influence of different parameters of the model on our results. The analysis will be made by comparison to the reference case (Fig 8) –PV air flow rate 8 l/s, maximum supply air temperature of 24°C, minimum air supply temperature 20°C (Fig 7) and an occupancy of 31 persons.

The first parameter that we decided to analyze is the number of occupants in the classroom.

A. Number of occupants in the classroom

Because we are talking about the ventilation system, the number of occupants present in the classroom will have an immediate impact on the energy consumption. We have varied the number of occupants of ± 20 % from the reference case number. The values of the results are presented in Table1.

As we can see if the number of people present in the classroom increases from 31 to 37 persons, the energy consumption will also rise about 18.36%. If the number decreases to 24, the consumption will decrease about 18%. It is also important to see the influence on the cumulated frequency which gives us an idea about the conditions inside the classroom. The value of the cumulated frequency diminishes when the number of occupants increases and has a small increase when the occupation number decreases.

TABLE 1- THE IMPACT OF THE VARIATION OF THE OCCUPANTS NUMBER, SOLAR HEAT GAIN COEFFICIENT AND ROOF'S INSULATION THICKNESS RELATIVE TO THE REFERENCE CASE

Parameters	Heating capacity (kWh)	Cooling capacity (kWh)	Cumulated frequency (° Hours)
Reference case 24°C, 8l/s	153.1	174	64.5
Ocupants +20%	181.1	205.95	63.193
Occupants -20%	125	141.88	69.33
SHGC +20%	153.1	174	175.84
SHGC -20%	153.1	174	12.2
Insulation thickness +20%	153.1	174	67.5
Insulation thickness -20%	153.1	174	60.6
Ext. conv. coefficient + 20%	153.1	174	61.34
Ext. conv. coefficient - 20%	153.1	174	69
Interior convection coefficient +20%	153.1	174	58.9
Interior convection coefficient -20%	153.1	174	64.9
Outdoor air temperature +10%	103.5	356	148
Outdoor air temperature -10%	230.46	64.8	16.6

This is due to the fact that when occupancy increases, more fresh air is supplied to the room and its mean temperature slightly decreases, so the cumulated frequency will diminish about 2%. For the case with 25 persons we can observe that the increase for the cumulated frequency does not follow the same pattern as the cooling or heating consumption. The percent of increase is around 7.5%.

B .Solar heat gain coefficient

The second parameter we choose to vary is the solar heat gain coefficient (SHGC) for the south facing glazing. Again we selected the same interval of variation ±20 %.
The values presented in Table 1 show that for the same airflow rate the SHGC has a great influence on the cumulated frequency and in consequence on the interior air temperature. An increase of the SHGC of 20% gives a value of the cumulated frequency of 12.2 (°hours) which represents a decrease of 81%.
A decrease of 20% of SHGC gives us a value of FC of 175.84. This means that the cumulated frequency almost tripled its value (x2.72). So we can say that even if the SHGC does not affect the energy consumption, it has a direct impact on the internal thermal comfort conditions.

C.Roof insulation thickness

As we can see in the table below the insulation thickness of the roof is of little importance for the cumulated frequency. The variation is small compared to the reference case (4.89% for -20% insulation thickness and 6.99% for + 20% insulation thickness). As insulation thickness increases, internal heat is kept inside the room and evacuated slowly through the roof and thus the indoor temperature increases slightly

D.Exterior convection coefficient

Another parameter we decided to vary, is the value of the exterior convection coefficient. An increase of the exterior convection coefficient of 20% will slightly improve the interior comfort. Heat is evacuated faster to the outdoor ambiance and room temperature decreases. Cumulated frequency decreases about 4.9%. Decreasing the external convective heat transfer coefficient 20% of its value, leads to an increase of the interior temperature and a growth of 7% in the cumulated frequency value.

E. Interior convection coefficient

When varying the internal convection coefficient, the cumulated frequency follows the same pattern as for the external convection case. When the internal heat convection coefficient increases about 20%, the cumulated frequency diminishes. An increase of 20% of internal heat convection coefficient leads to a decrease of about 8.7% of the cumulated frequency because heat is evacuated fastly from the room. We notice that a decrease in the convection coefficient will slightly impact the cumulated frequency because indoor temperature won't increase any more. It only decreases slowly.

F. Outdoor air temperature

Table 1 shows the effect of variating outdoor temperature of ±10%.

We notice that an increase of 10% of the outdoor air temperature has a great impact on the energy consumption. For the heat energy consumption it is reduced about 32.3% compared to the reference case. For the cooling energy consumption it increases and the difference is more important. The cooling consumption has almost doubled. Total energy consumption (the sum of HC and CC) increases 40% compared to the reference case. In what concerns the cumulated frequency, its value will increase from 64.5 to 148 (°hours). Decreasing the outdoor temperature about 10% will raise the heating energy consumption more than 50%, and reduce the cooling energy consumption of about 60%. The total energy consumption is reduced about 10%. The cumulated frequency also decreases to 17 (°hours) meaning that internal comfort is improved.

TABLE 2- THE IMPACT OF THE VARIATION OF THE DIMENSIONS OF THE ROOM RELATIVE TO THE REFERENCE CASE

Parameters	Heating capacity (kWh)	Cooling capacity (kWh)	Cumulated frequency (° Hours)
Reference case 24°C, 8l/s	153.1	174	64.5
Width +10%	153.1	174	71.52
Width -10%	153.1	174	52.23
Length +10%	153.1	174	76.95
Length -10%	153.1	174	48.75

G. Classroom dimensions

We were also interested to see the influence of the dimensions of the room on interior classroom temperature. For this case we decided to vary both the length and the width of the classroom due to the fact that one of the exterior walls is a glass wall. In this case the influence on the cumulated frequency will be greater, as we can see in the Table 2 above.

We can see that an increase of the window surface of 10 % raises the value of the cumulated frequency about 19 %, and increasing the width of 10% will increase cumulated frequency of almost 11% because no more solar energy will enter as in the case of the length.

V. CONCLUSIONS AND PERPECTIVES

In this paper, energy consumption of two ventilation systems was analyzed and compared: classical ventilation system and a personalized ventilation system. The system is used to cool a classroom in Bucharest, Romania. Both systems were modelled using the simulation environment SPARK. Simulations are used to evaluate energy consumption and thermal comfort conditions. Our results suggest that when compared to classical ventilation system, personalized ventilation can provide comfortable conditions and reduce energy consumption of about 60%.

A sensitivity analysis was made in order to see the influence of different physical parameters on the energy consumption and on the interior air temperature. As we could see, the variation of the occupants number had an influence on the energy consumption but it did not had a major influence on the cumulated frequency – consequently on the interior air temperature.

The parameter that has a great influence on the interior temperature is the solar heat gain coefficient

Energy consumption is mainly affected by outdoor temperature variations. Simulations have shown that when temperature increases (weather becomes hotter) energy consumption will increase drastically and also thermal conditions will get worse.

These results should be taken carefully as more analysis is to be done for the personalized system in order to analyze air flow around occupants.

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