Title

Energy-saving strategies with personalized ventilation in cold climates

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ABSTRACT

In this study the influence of the personalized supply air temperature control strategy on energy consumption and the energy-saving potentials of a personalized ventilation system have been investigated by means of simulations with IDA-ICE software. GenOpt software was used to determine the optimal supply air temperature. The simulated office room was located in a cold climate. The results reveal that the supply air temperature control strategy has a marked influence on energy consumption. The energy consumption with personalized ventilation may increase substantially (in the range: 61-268%) compared to mixing ventilation alone if energy-saving strategies are not applied. The results show that the best supply air temperature control strategy is to provide air constantly at 20°C. The most effective way of saving energy with personalized ventilation is to extend the upper room operative temperature limit (saving up to 60% compared to the reference case). However, this energy-saving strategy can be recommended only in a working environment where the occupants spend most of their time at their workstation. Reducing the airflow rate does not always imply a reduction of energy consumption. Supplying the personalized air only when the occupant is at the desk is not an effective energy-saving strategy.

KEYWORDS

Energy analysis; Energy saving; Personalized ventilation; Supply air temperature control; Ventilation; Personal Environmental Control System.

INTRODUCTION

Personalized Ventilation (PV) aims to supply clean and cool air at low velocity and turbulence direct to the breathing zone of occupants. Each occupant may be provided with control of the supplied flow rate and/or supplied air temperature. Control of the airflow direction may be available as well. Thus, beside its ability to decrease the level of pollution in inhaled air and the risk of infection transmission [1, 2], PV improves occupants' thermal comfort. PV may thus increase occupants' satisfaction, decrease Sick Building Syndrome (SBS) symptoms and sick leave, and increase work performance [3].

Little is known about energy use of personalized ventilation. Seem and Braun [4] studied the energy use characteristic of a system incorporating personal environmental control compared with convectional designs through the use of computer simulations. They simulated the desktop personal environmental control system described by Arens et al. [5]. The system incorporated an electrical radiant panel, two local air distribution fans, a noise generator, a local task lighting and a workstation occupancy sensor. Their study showed that the effect of personal environmental control ranged between a 7% saving and 15% penalty in building lighting and HVAC electrical use. Bauman et al. [6] measured the field performance of the same system described above. They reported that the energy consumption of a personal environmental control system follows the occupancy behaviour; the system switches off when occupants leave the workstation, thus allowing energy saving to be measured.

Energy-saving potential

In the literature, information is available about the energy-saving potential of personalized ventilation. The main strategies suggested in the literature to have potential for energy-saving with personalized ventilation are:

- Reducing the outdoor airflow rate due to the higher ventilation effectiveness of PV [7, 8, 9, 10, 11, 12].
- Expanding the room temperature comfort limits by taking advantage of PV's ability to create a controlled microenvironment [6, 10, 11].

- Supplying the personalized air only when the occupant is present at the desk [4, 6].

There are several definitions of ventilation effectiveness [13]; in this paper the ventilation effectiveness is defined as the ratio of the concentration of pollution in exhaust air divided by the concentration of pollution in air inhaled by occupants. According to the European standard EN 13779 [14] and report CR 1752 [15], the minimum airflow rate can be reduced by using the ventilation effectiveness (divided by the ventilation effectiveness). The ASHRAE standard 129 [16] defines the Air Change Effectiveness (ACE) as the ratio of the age of the exhaust air and the age of the air in the breathing zone. For the ASHRAE standard 62.1 [17] the minimum outdoor air supply rate could be decreased using ACE (multiplied by 1/ACE). Several studies reported high ventilation effectiveness or ACE associated with personalized ventilation. Faulkner et al. [9] studied in chamber experiments the ACE of a task ventilation system with an air supply nozzle located underneath the front edge of a desk. The personalized airflow rate per person (q_V) varied from 3.5 to 6.5 l/s. They reported that the system studied had an ACE equal to 1.5; therefore the minimum outdoor air supply rate could be decreased by one third. Sekhar et al. [11] found that in a tropical climate, for an ambient temperature of 26°C, and a PV flow rate of 7 l/s per person at a supply air temperature of 23°C or 20°C, the ventilation effectiveness was 1.42. Melikov et al. [7] studied in chamber experiments the influence of five different air terminal devices on the ventilation effectiveness with the airflow rate varying from 5 l/s up to 23 l/s. The ventilation effectiveness varied within the range 1.30- 2.38. A highly efficient air terminal device providing almost 100% clean and cool personalized air in each inhalation has been developed by Bolashikov et al. [8]. The air terminal device makes it possible to increase the ventilation effectiveness 20 times or more compared with mixing ventilation. Niu et al. [12] studied the ventilation performance of a chair-based personalized ventilation system. By comparing eight different air terminal devices it was found that up to 80% of the inhaled air could be composed of fresh personalized air (ventilation effectiveness equal to 5) with a supply flow rate of less than 3.0 l/s. Nielsen et al. [2] proposed a chair with integrated personalized ventilation discharging supply air at very low velocities and relying on the entrainment of this clean PV air from the natural convection flow around the human body. They found that more than 70-80% of the inhaled air is personalized air (ventilation effectiveness > 3.5-5) with an airflow rate in most cases equal to10 l/s.

Bauman et al. [6] reported that at a high room air temperature (25°C - 27°C), the local cooling effect of the desktop system was able to maintain average temperatures in the occupied zone of one workstation from 0.5°C to 1.5°C below the corresponding temperatures in an adjacent workstation without a desktop system. Kaczmarczyk et al. [18] in an experiment comprising 60 human subjects showed that at a room temperature of 26°C PV, supplying air at 20°C was able to keep occupants in better thermal comfort (close to neutrality instead of slightly warm) than a mixing ventilation system. Sekhar et al. [11] showed that human subjects prefer, from a thermal comfort and perceived indoor air quality point of view, an environment with a room temperature of 26°C and PV at 23°C or 20°C rather than a room at 23°C without a PV system. They stated that for a tropical climate, where the common indoor temperature for a conditioned building is 23°C, a significant reduction of energy consumption can be achieved if the room temperature is maintained at 26°C. Even if the air is supplied isothermally the personalized air is able to cool the occupant. According to the present international indoor climate standards [19, 20, 21], elevated air speed can offset the indoor temperature rise and provide occupants with thermal comfort. A relationship between the air speed and the upper operative temperature limits can be found in the above mentioned standards. The relationship is based on a theoretical calculation; however, it has been verified in human subject experiments [22]. Individual differences exist between people with regard to the preferred air speed [22, 23]. Therefore, the standards require personal control over the speed.

Depending on their activities during working time occupants may spend only a part of the time in the office and even a shorter time at the desk [18, 24, 25, 26, 27, 28, 29, 30, 31, 32]; therefore energy-saving may be achieved if the system is able to automatically switch off when occupants are not at the desk.

The purpose of this study is to analyse, by means of simulations with IDA-ICE software, the influence of the personalized supply air temperature control strategy on energy consumption and the energy-saving potentials of a personalized ventilation system in a cold climate.

METHODS

The European standard 15265-2006 [33] recommends a format for reporting the input data of an energy simulation. The following presentation of input data complies with the guidance in the standards.

Building locations and weather data

An office in a building located in Copenhagen (Denmark) was simulated. The weather is characterized by a cold climate. The ASHRAE IWEC Weather File for Copenhagen is used as input data in the simulation model.

Description of the office room

The open-space office has a floor surface area of 6 x 20 m. The room height is 3 m. The external walls are constructed with 20 mm of plaster (thermal conductivity, λ=0.6 $WK^{-1}m^{-1}$), 150 mm of glasswool (λ=0.036 $WK^{-1}m^{-1}$), 240 mm of clay brick (λ=0.57 $WK^{-1}m^{-1}$) and 10 mm of internal plaster; the overall U-value of the external wall is 0.2 $WK^{-1}m^{-2}$. The window is composed of an external glass pane (thickness 6 mm), 15 mm of argon (90%) and an internal low-emissivity glass pane (thickness 6 mm). It has an overall U-value of 1.2 $WK^{-1}m^{-2}$, a g-factor or Solar Heat Gain Coefficient equal to 0.61, and a light transmittance equal to 0.77. The window has a total area of 36 m^2 (20% of the floor area, height = 1.8 m and width = 20 m). The window faces south. There is a shading device composed of blinds between the window panes. It has a multiplier for a total shading coefficient equal to 0.39. It is activated when the incident light on the windows is higher than 200 W/m^2. The internal walls, floor and ceiling are adiabatic. The effect of thermal mass is taken into account.

Internal temperature, ventilation and infiltration rate

The thermal comfort conditions and ventilation specifications were chosen in order to comply with the values defined in EN 15251 [19] for the category I of the indoor environment in the room during occupation. From 6:00 till 17:00 the heating and cooling systems kept the indoor operative temperature within a range between 21°C (lower room operative temperature limit) and 25.5°C (upper room operative temperature limit). During weekends and night-time the temperature set-back was 12°C in winter and 40°C in summer. The upper room operative temperature limit, θ_{UP}, was expanded in the cases shown in Table 1 for studying the influence of this strategy on the energy need. The design airflow rate was supplied during occupation hours. The airflow rate is calculated according to the European standard EN 15251 [19]. The total airflow rate, q_V, is the sum of the required ventilation rate per person and per floor area. EN 15251 [19] recommends 10 l/s person as ventilation rate per person for the indoor environment category I and 1 $l/(sm^2)$ when the building is considered to be low- polluting. The floor area per occupant is 10 m^2. Therefore, the total airflow rate is equal to 20 l/s per person during occupation hours. The total airflow rate is more than double that required in the ASHRAE standard 62.1 [17]. The European standard requires a higher ventilation rate than the ASHRAE standard. At full occupancy, 12 occupants were present in the room (10 m^2 per person); thus the total outdoor airflow rate is 240 l/s. The airflow rate was reduced in the cases shown in Table 1 (cases 9-14) in order to study the influence of this strategy on the energy need. From Case 23 and Case 26 the occupancy varied according to Figure 1 and Figure 2. The standard EN 15251[19] suggests supplying a minimum value of 0.1 to 0.2 $l/(sm^2)$ during unoccupied hours. This part is not covered by the ventilation system but by the infiltration. The Equivalent Leakage Area [34] is equal to 0.0093 m^2 (0.2 $l/(sm^2)$ when the pressure difference is 4 Pa).

Internal heat gains, occupancy and description of the HVAC system

The 12 occupants contribute to both sensible and latent heat load in the room. The activity level of the occupants was 1.2 met (1 met = 58.15 W/m^2), and the total heat produced per occupant was thus around 125 W. The balance between sensible and latent heat loads is calculated by the software. The occupants were present in the room from Monday to Friday, from 8:00 to 17:00 with a break of one at noon. Saturday and Sunday were free days and no public holidays were involved. The heat load due to office equipment was 6 W/m^2. According to ASHRAE [35], this value corresponds to a "light load office". The loads follow the schedules of the occupants. The lighting load was 10 W/m^2 during working hours (8:00-17:00). Outside these hours the light was switched off.

In practice, it will be difficult to use the personalized ventilation alone to condition an entire room if the PV system supplies only outdoor air. For comfort reasons there are limitations for the maximum airflow rate and the temperature of the supplied personalized air. Therefore it is not possible to adapt the flow rate (as in the variable air volume system) or the supply temperature (as in the constant air volume system) of the personalized air to the

levels needed for heating or cooling of the whole room. In this study two independent systems were modelled. Four-pipe fan coil units were used to control the operative room temperature. The required outdoor airflow rate was conditioned in the design conditions by an AHU with a heat recovery exchanger (efficiency of 0.7). The humidity was not controlled during the simulations since this is not common practice in Denmark. A free-cooling strategy during night-time (from 18:00-6:00) from 1 May to 30 September was used. The supplied airflow was 3 l/(sm^2). The free-cooling starts when the outdoor air temperature is at least 5°C cooler then indoor air and the indoor air temperature is at least 25°C. It stops if the indoor air temperature is lower than 21°C or the difference between indoor and outdoor is less than 3°C.
The overall quality of the building (wall thermal insulation, type of windows, shading control, HVAC system, free cooling, high efficiency heat recovery) may be considered high.

Simulation software

IDA Indoor Climate and Energy (ICE) is a tool for simulation of thermal comfort, indoor air quality and energy consumption in buildings. It covers a range of advanced phenomena such as integrated airflow and thermal models, CO_2 modelling, and vertical temperature gradients. The mathematical models are described in terms of equations in a formal language named Neutral Model Format (NMF). This makes it easy to replace and upgrade program modules [36]. GenOpt is an optimization program designed for finding the values of user-selected design parameters that minimize a so-called objective function (or cost function), such as annual energy use, leading to optimal operation of a given system. The minimization of a cost function is evaluated by an external energy simulation program. GenOpt can be coupled to any simulation program (e.g. EnergyPlus, IDA-ICE, TRNSYS, etc.) that reads its input from text files and writes its output to text files [37].

SIMULATED CASES

The first purpose of the paper is to investigate the energy need of a personalized ventilation system in comparison with a convectional mixing ventilation system for several control strategies of the supply air temperature (see Table 1 from Case 1 to Case 8). The second purpose of the paper is to explore the strategies having potential for energy-saving listed in the introduction (see Table 1 from Case 9 to Case 26). A mixing ventilation system supplying the air at a constant temperature (16°C) throughout the year is the reference case. All the simulated cases are summarised in Table 1 and described below.

Table 1

Simulated cases with personalized ventilation.

Case	Control strategy of the supply air temperature	Supply air temperature profile	θ_{UP} ^{a} [°C]	Airflow rate per person q_V [l/(s person)]	Occupancy from 8:00-17:00
1	Constant	20°C	25.5	20	Full
2	Constant	23°C	25.5	20	Full
3	Constant	26°C	25.5	20	Full
4	Outdoor	Figure 3	25.5	20	Full
5	Outdoor	Figure 3	25.5	20	Full
6	Outdoor	Figure 3	25.5	20	Full
7	Indoor	Figure 4	25.5	20	Full
8	Indoor	Figure 4	25.5	20	Full
9	Constant	20°C	25.5	5	Full
10	Constant	20°C	25.5	10	Full
11	Constant	20°C	25.5	15	Full
12	Indoor	Figure 4	25.5	5	Full
13	Indoor	Figure 4	25.5	10	Full
14	Indoor	Figure 4	25.5	15	Full

15	Constant	20°C	27	20	Full
16	Constant	20°C	28	20	Full
17	Constant	20°C	29	20	Full
18	Constant	20°C	30	20	Full
19	Indoor	Figure 4	27	20	Full
20	Indoor	Figure 4	28	20	Full
21	Indoor	Figure 4	29	20	Full
22	Indoor	Figure 4	30	20	Full
23	Constant	20°C	25.5	20	Figure 1
24	Constant	20°C	25.5	Varying[b]	Figure 1
25	Constant	20°C	25.5	20	Figure 2
26	Constant	20°C	25.5	Varying[b]	Figure 2

[a] The cooling systems tried to keep the room operative temperature below the upper room operative temperature limit.

[b] The airflow varies according to the occupation reported in Figure 1 and Figure 2. At full occupation the airflow is equal to 20 l/s per person.

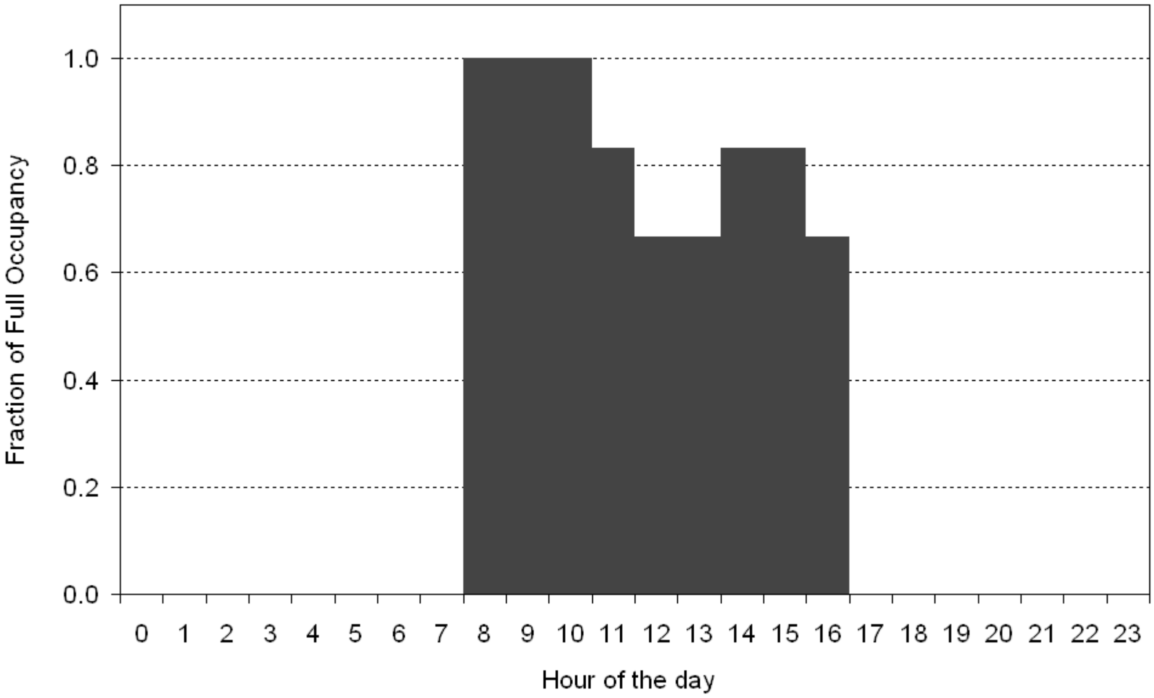

Figure 1 Occupancy profile according to the standard EN 15232 [39].

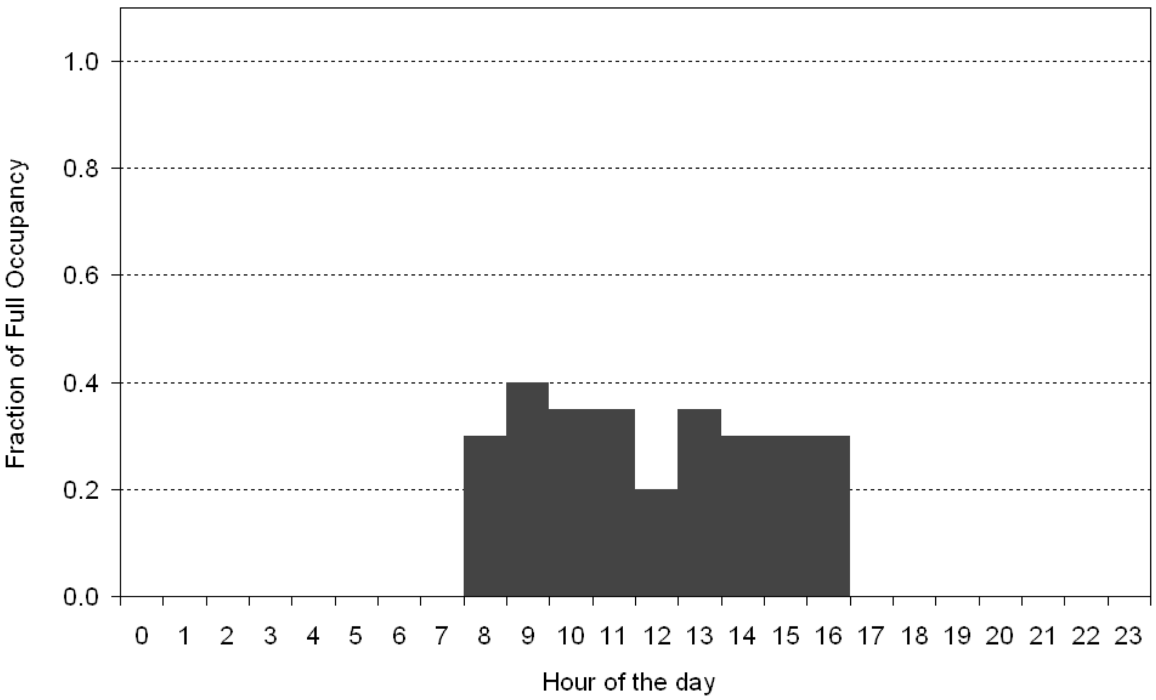

Figure 2 Occupancy profile according to the measured data by Nobe et al. [25].

Supply air temperature control (Case 1 - Case 8)

When the occupants are not provided with control over the temperature of the supplied personalized air, the building manager has to define the supply air temperature (θ_{SUP}) needed to provide the occupants with thermal comfort at a minimal level of energy consumption. In a single duct constant air volume system, θ_{SUP} set-point may be constant, or it may be reset based on the outdoor (θ_{ODA}) or indoor (θ_{IDA}) air temperature. PV supplies the air close to occupants. Therefore the lowest and highest permissible supply air temperatures are limited by thermal comfort issues. In this study it has been chosen that θ_{SUP} may vary in the range 20-26°C. All the θ_{SUP} profiles presented in the following are restricted within this range. In Case 1, 2, 3, θ_{SUP} was constant and equal to 20, 23, 26°C respectively. In Cases 4, 5, 6 (see Figure 3) the θ_{SUP} was reset according to θ_{ODA}. Two of them (Cases 4 and 5) were chosen by the authors and the other one, Case 6, was obtained using GenOpt (this software is discussed later in the paper). Cases 4 and 5 are characterized by supplying the personalized air at 20°C when the θ_{ODA}<20°C in order to minimize the heating energy that the Air Handling Unit (AHU) must provide to the supplied air. When θ_{ODA}>20°C the personalized air is supplied to the room without being conditioned. The profiles are limited in the upper part by a maximum supply air temperature equal to 22 and 26°C respectively. GenOpt software was used to find the optimal supply air temperature profile (Case 6) within the boundaries of the room air temperature given by EN 15251 [19] for category I of the indoor environment. GenOpt was set to minimize the sum of energy needed for heating and cooling of the outdoor supply airflow rate and the room (mathematically named cost function). In order to minimize the cost function, GenOpt changes the θ_{SUP} corresponding to the following fixed outdoor temperatures (-20, 10, 15, 18, 20, 21, 23, 25, 26, 27, 30, 40°C) by choosing an integer value within the range 20-26°C. In Cases 7 and 8 (see Figure 4) the θ_{SUP} was controlled by the θ_{IDA}, which is equal to the return air temperature in a mixing ventilation system. The Case 7 profile aims to maximize occupants' thermal comfort because it supplies hot air when it is chilly in the room and cool air when it is warm; the profile was named "comfort" profile. The authors expect that the "comfort" profile would probably be used by the occupants if they would have the opportunity to control the supply air temperature. In Case 8 the air is supplied isothermally within the range 20-26°C, based on recent findings indicating that elevated velocity at the breathing zone improves inhaled air quality and compensates for the negative impact of increased temperature on perceived air quality [38]. The profile was named "isothermal" profile.

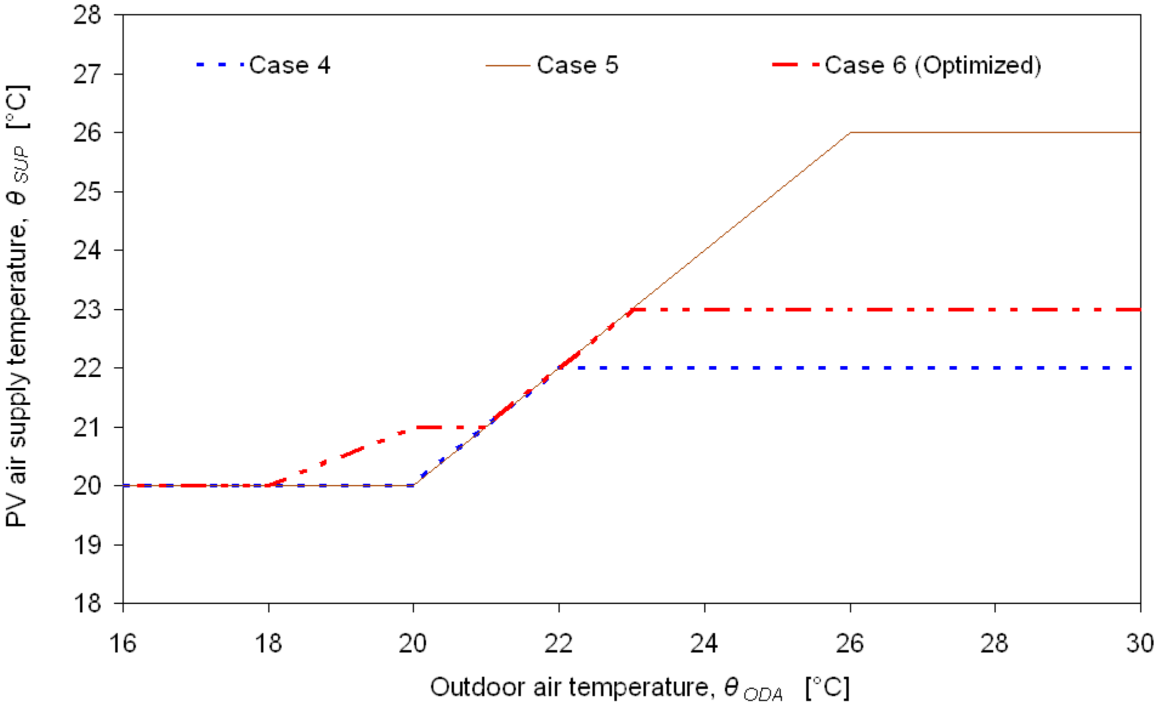

Figure 3 PV supply air temperature profiles as a function of the outdoor air temperature for Cases 4, 5 and 6 (See Table 1).

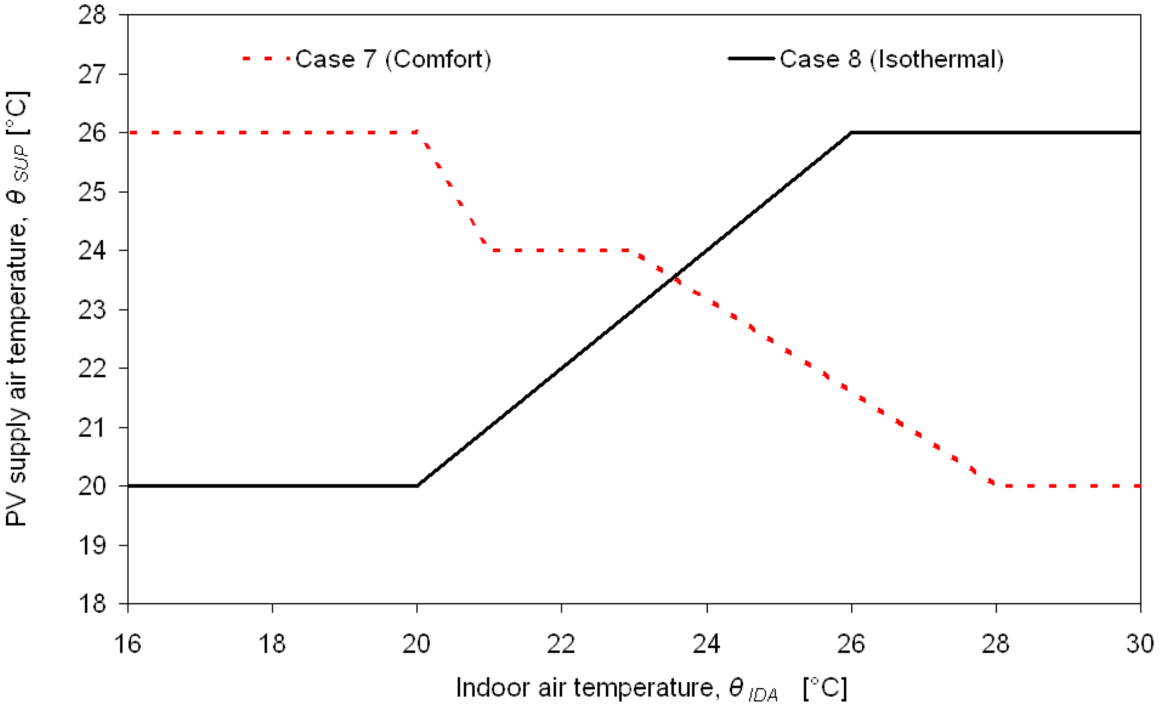

Figure 4 PV supply air temperature profiles as a function of the indoor air temperature for Case 7 and Case 8 (See Table 1).

Energy-saving strategies (Case 9 - Case 26)

The three energy-saving strategies presented in the paragraph "Energy-saving potentials" were investigated (from Case 9 to Case 26, see Table 1). Two supply air temperature strategies were used: supplying the air at 20°C constantly for the whole year (Case 1) and the "comfort" profile (see Figure 4, Case 7). The former has been chosen because from the simulation it was found that it is the strategy which minimizes the energy need.

From the Case 9 to Case 14 (see Table 1) the effectiveness of reducing the q_V was studied. q_V was reduced to 15, 10, and 5 l/s per person. These values correspond to a ventilation effectiveness of 1.34, 2 and 4 respectively. From the Case 15 to Case 22 (see Table 1) the effectiveness of expanding the θ_{UP} was studied. θ_{UP} was expanded from 25.5°C (corresponding to Category I of the indoor environment according to EN 15251 [19]) to 27, 28, 29, and 30°C. The lower room operative temperature was kept equal to 21°C because it was found (not reported in this paper) that reducing it (e.g. to 18°C) does not affect the energy need.

From the Case 23 to Case 26 (see Table 1) the effectiveness of supplying the personalized air only when the occupant is present at the desk was studied. Two occupancy behaviour profiles were used. In this paper the fraction of full occupancy is defined as the ratio between the actual number of occupants seated at the desk over the maximum number of occupants for whom the room was designed. The first occupancy behaviour profile (shown in Figure 1) has been obtained from the European standard EN 15232 [39]. The second profile (shown in Figure 2) has been extrapolated by the data measured by Nobe et al. [25] in a Japanese 52-story office building where 240 workstations were monitored for a week. The two profiles were bounded within the office hours used for previous simulations (from 8:00 to 17:00). In this study it is assumed that when the occupant is not at his/her desk he/she is out of the office. When the occupant is not at the desk the heat loads generated by him/her and his/her equipment is not taken into account, and in the Cases 24 and 26 the personalized air is switched off.

RESULTS

The "energy need" is the sum of energy for heating (AHU Heating) and cooling (AHU Cooling) of the supplied air in order to obtain the desired θ_{SUP} and for heating (Room Heating) and cooling (Room Cooling) of the conditioned space in order to maintain the indoor operative temperature within the designed range during a given period of time (from 6:00 to 17:00). The definition is in accordance with the European standard EN 15615 [40]. The energy need for several θ_{SUP} control strategies (Table 1, Cases 1 - 8) is shown in Figure 5. The energy need for the reduced outdoor airflow rates (Table 1, Cases 9 - 14) is shown in Figure 6. The energy need for the expanded upper room operative temperature limits (Table 1, Cases 15 - 22) is shown in Figure 7. The energy need for personalized air supplied only when the occupant is present at the desk (Table 1, Cases 23 - 26) is shown in Figure 8.

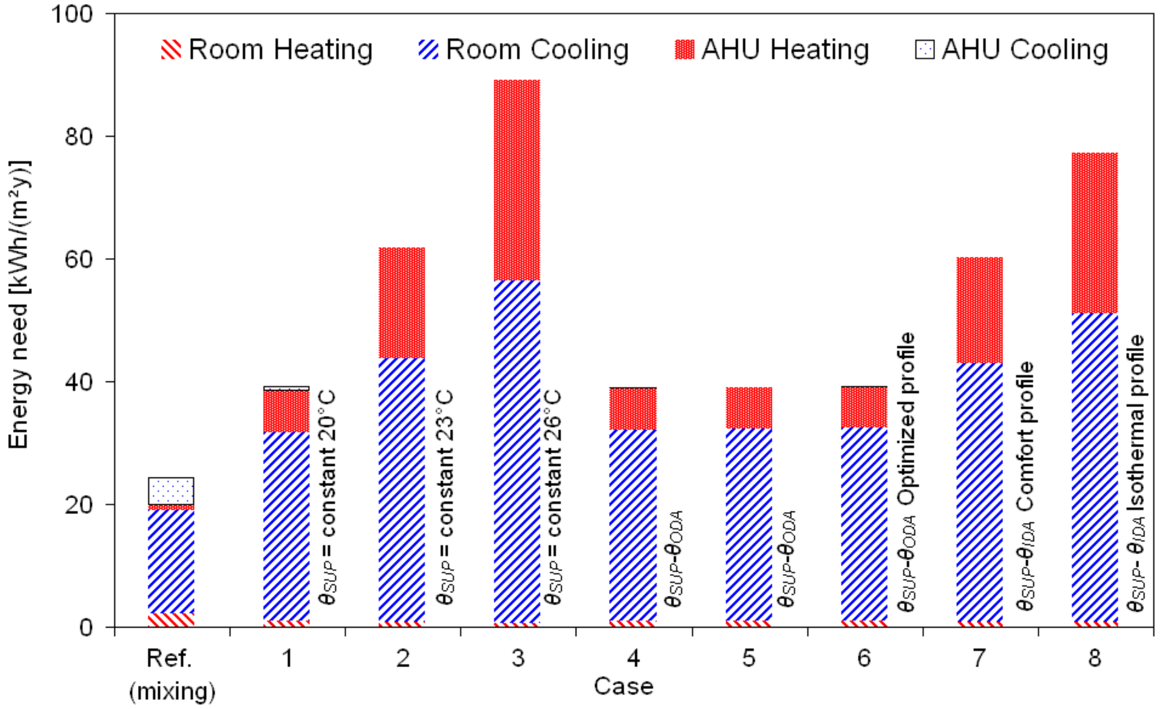

Figure 5 The energy need for several control strategies of the personalized supply air temperature, θ_{SUP} (see Table 1).

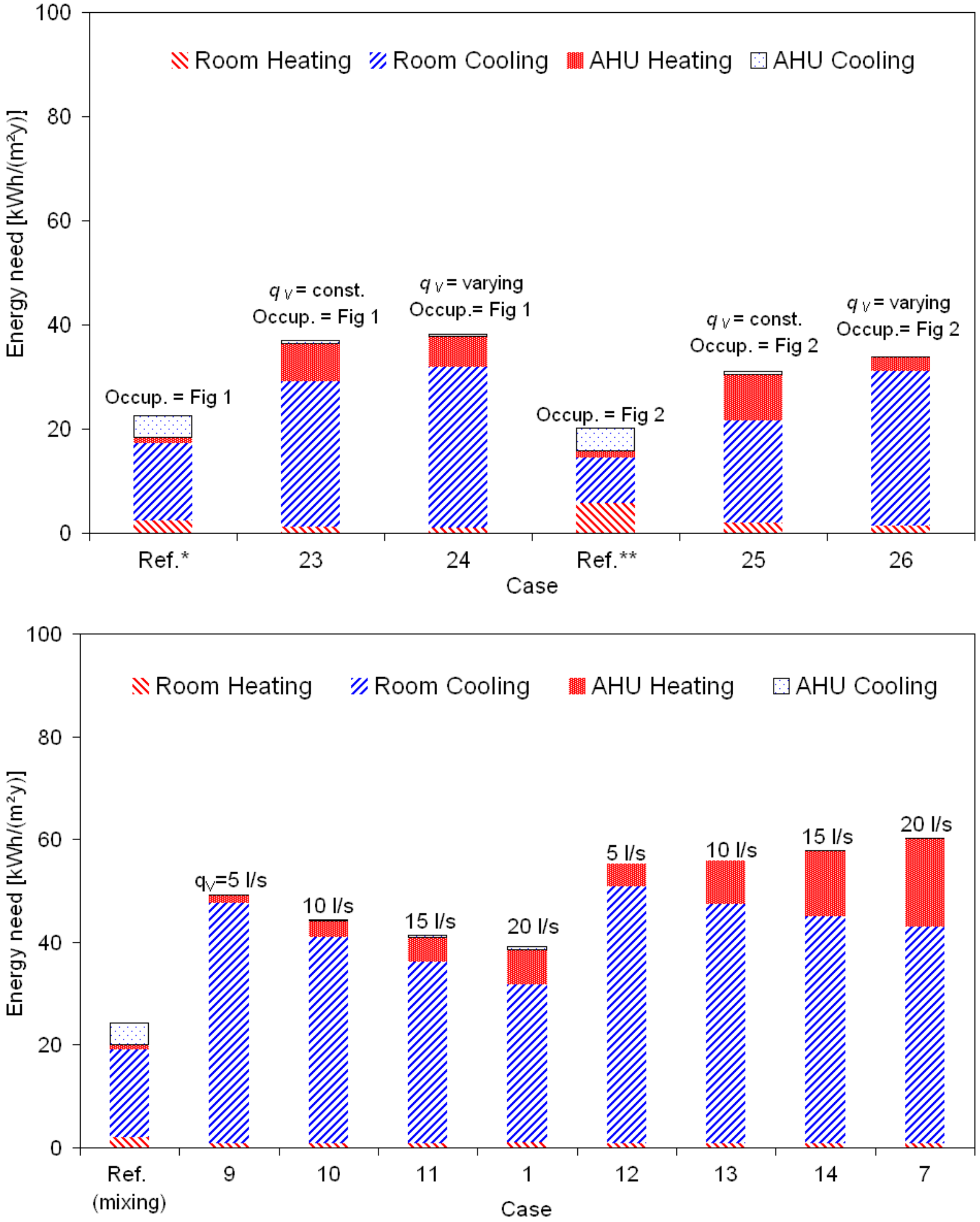

Figure 6 The energy need for the reduced outdoor airflow rates, q_V, for θ_{SUP} constant and equal to 20°C (Cases 9, 10, 11, 1) and for θ_{SUP} following the comfort profile shown in Figure 4 (Cases 12, 13, 14, 7).

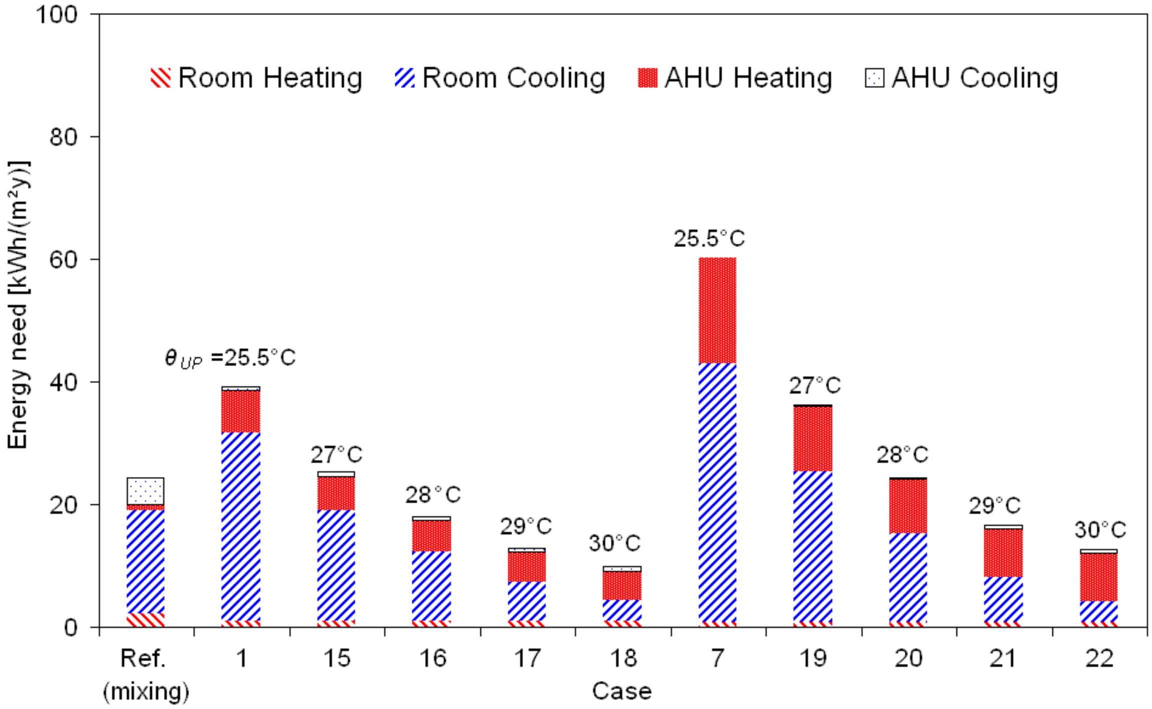

Figure 7 The energy need for the expanded room temperature comfort limits, θ_{UP}, rates for θ_{SUP} constant and equal to 20°C (Cases 1, 15, 16, 17, 18) and for θ_{SUP} following the comfort profile shown in Figure 4 (Cases 7, 19, 20, 21, 22).

Figure 8 The energy need for personalized air supplied only when the occupants are present at the desk for the occupancy profile shown in Figure 1 and for the one shown in Figure 2. The airflow rate is constant in Case 23 and 25, and it varies according to the occupancy profile in Cases 24 and 26. Ref* and Ref ** are respectively the energy need for the reference case (mixing ventilation) and when the occupancy and the relative heat loads are varied according to the profiles shown in Figure 1 and Figure 2.

DISCUSSION

Influence of the supply air temperature on energy need (Case 1 - Case 8)

The results shown in Figure 5 reveal that the simulated building needs mainly cooling. Room Heating is needed only for the reference case (mixing ventilation supplying air at 16°C). The building has a good insulation and air tightness and the internal heat gains are sufficient to maintain the required operative temperature. The supplied personalized air needs to be cooled only sporadically; in fact AHU Cooling is equal to zero except for the reference case. The supply temperature and its control strategy have a marked influence on energy consumption. The energy need for the simulated cases is in the range 39.0-89.2 kWh/(m^{2}y). The energy need for the reference case is 24.3 kWh/(m^{2}y); it means that by using PV the energy need increases from 61% to 268%. This is mainly due to the fact that the lowest supply air temperature for the PV system was limited to 20°C for comfort reasons. In the reference case the air is supplied at 16°C. The building needs mainly cooling and the need for warming the personalized supplied air up to 20°C is a heat load (AHU Heating) that later has to be removed by the cooling system (Room Cooling). This phenomenon can be seen in Figure 5 by subtracting the AHU Heating from the

Room Cooling; the remaining Room Cooling is almost constant in the range between 23.2 and 25.2 kWh/(m^2y). To supply the air at an elevated temperature of 23°C or 26°C (Cases 2 and 3) required a greater amount of energy than to supply at 20°C (Case 1). The energy needs for Cases 1, 4, 5, and 6 are almost equal, i.e. the different supply air temperature control strategies do not differ with regard to the energy need. The reason can be understood by analysing the outdoor air temperature cumulative profile. In Copenhagen the outdoor air temperature is higher than 20°C only 3.2% of the time in one year, higher than 22°C only 1.3%, higher than 24°C only 0.5%, and higher than 26°C only 0.1% of the year. Therefore, controlling the supply air temperature, θ_{SUP}, based on the outdoor temperature, θ_{ODA}, using profiles that differ only for θ_{ODA}>20°C, does not make any significant difference with regard to energy need. Controlling the θ_{SUP} by the indoor air temperature, θ_{IDA} (Case 7 and Case 8) implies high energy consumption. Case 7 has an energy need almost equal to Case 2, where $\theta_{SUP} =$ 23°C, but from a thermal comfort point of view, it would perform better. For the simulated building and for the assumptions made in this paper, the best supply air temperature control strategy is to provide air constantly at 20°C, the minimum permissible supply temperature.

The supply air temperature of a personal ventilation system has a marked influence on the energy consumption because it may become a significant heat load that needs to be removed. In a mixing ventilation system the outdoor air, after been conditioned, can be mixed with the recirculated air to reach the desired supply air temperature. This cannot be done with a PV system if its main aim is to improve significantly the inhaled air quality and to reduce the risk of spread of diseases.

Analysis of the energy-saving strategies (Case 9 - Case 26)

The energy-saving strategies with personalized ventilation were studied with Cases 9 – 26, as defined in the Method section, sub-section “Energy-saving strategies”. The results are shown in Figure 6, 7 and 8. The influence of reducing the personalized flow rate, q_V, thanks to the higher ventilation effectiveness on the energy need, is shown in Figure 6. In Cases 9, 10, 11 and 1 q_V is equal to 5, 10, 15 and 20 l/s per person respectively, and the θ_{SUP} is in all cases constant and equal to 20°C. In Cases 12, 13, 14 and 7 q_V is equal to 5, 10, 15 and 20 l/s per person respectively, and the θ_{SUP} is a function of the θ_{IDA} and varies according to the “comfort” profile (see Figure 4, Case 7). In all cases the energy need is determined mainly by the AHU Heating and the Room Cooling. From Figure 6 it can be deduced that reducing q_V implies: a reduction of AHU Heating because the amount of outdoor air that needs to be heated is reduced and an increase of the Room Cooling because the outdoor air has a free cooling effect. Therefore, reducing q_V is beneficial only when the decrement in AHU Heating is higher than the increment in the Room Cooling. This is valid for the Cases 12, 13, 14, and 7 but not for the Cases 9, 10, 11, and 1 because the supply air does not need to be warmed up more than 20°C. When the θ_{SUP} is kept constant and equal to 20°C (Cases 1, 11, 10, 9) the energy need increases from 39.2 kWh/(m^2y) to 49.3 kWh/(m^2y) with the decrease of q_V from 20 to 5 l/s per person which corresponds to 26% of energy penalty. In this case it is not an advantage to reduce the airflow because the supplied air has a free cooling effect. When θ_{SUP} follows the “comfort” profile the energy need slightly decreases from 60.2 kWh/(m^2y) to 55.2 kWh/(m^2y) with the decrease of q_V from 20 to 5 l/s per person. In this case energy is reduced by 8% and it is an advantage to reduce the airflow. In conclusion, in a cold climate, reducing the personalized airflow rate does not always lead to a reduction of energy need because the outdoor air may have a free cooling effect. PV requires more energy than the reference case (mixing ventilation) even if the temperature of the supplied personalized air follows the applied “comfort” profile. However, it is believed that reducing q_V would always lead to energy-saving in hot and humid climates.

The influence of extending the upper room operative temperature, θ_{UP}, on energy need is shown in Figure 7. In Cases 1, 15, 16, 17 and 18 θ_{UP} is equal to 25.5, 27, 28, 29, and 30°C respectively, and the personalized supply air temperature, θ_{SUP}, is constant and equal to 20°C. In Cases 7, 19, 20, 21 and 22 θ_{UP} is equal to 25.5, 27, 28, 29, and 30°C respectively, and the θ_{SUP} follows the “comfort” profile. Also in these cases the energy need is determined mainly by the AHU Heating and the Room Cooling. From Figure 7 it can be deduced that increasing θ_{UP} implies a significant decrease of the Room Cooling, but it does not affect substantially the AHU Heating. Therefore, extending the upper room operative temperature limit is always beneficial. Independently of the θ_{SUP} strategies, the extension of θ_{UP} leads to energy need reduction, and when θ_{UP} is equal or higher than 28°C, using the personal ventilation system implies less energy need than the reference case of mixing ventilation.

The results in Figure 7 show that when the θ_{SUP} is kept constant and equal to 20°C and θ_{UP} is increased from 25.5 to 30°C, the energy need decreases from 39.2 kWh/(m^{2}y) to 9.9 kWh/(m^{2}y), corresponding to 75% of energy-saving (Cases 1, 15, 16, 17, 18). When θ_{SUP} follows the "comfort" profile (Figure 4) and θ_{UP} is increased from 25.5 to 30°C the energy need decreases from 60.2 kWh/(m^{2}y) to 12.7 kWh/(m^{2}y), corresponding to 79% of energy-saving (Cases 7, 19, 20, 21, 22). This energy-saving strategy is an effective way of reducing the energy need. However, it can be recommended only in the working environment where the occupants spend most of their time at their workstation in a comfortable thermal environment achieved by personalized ventilation.

The influence of supplying the personalized air only when the occupant is at the desk is shown in Figure 8. Ref.* and Ref.** are the energy needs for the reference case (mixing ventilation) when the internal heat load generated by occupants and equipment follows the occupancy profiles reported in Figure 1 and Figure 2 and the ventilation airflow is constant. This leads to an energy decrease from 24.3 kWh/(m^{2}y) to 22.6 kWh/(m^{2}y) for the Ref.* case and to 20.2 kWh/(m^{2}y) for the Ref.** case. This means that the reduction of the internal heat load generated by occupants and equipment implies a reduction of 7% and 17% respectively for the occupancy profiles shown in Figure 1 and Figure 2. The energy need for the reference case was recalculated in order to be comparable (same internal heat load) with the energy need with the PV.

Supplying the personalized air only when the occupant is at the desk implies lower airflow rates. As in the previous cases (Cases 9-14) the reduction of the airflow rate causes two effects, a reduction of the AHU Heating (less outdoor air needs to be warmed up) and an increase of the Room Cooling (reduced free cooling). From Figure 8 it can be seen that for both occupancy profiles it is not effective to supply the airflow rate only when people are at the desk. When the airflow rate is adjusted according to the occupancy profile shown in Figure 1, the energy need slightly increases from 37 kWh/(m^{2}y) to 38.3 kWh/(m^{2}y), corresponding to 3% of energy penalty (Cases 23 and 24). When the airflow rate is adjusted according to the occupancy profile shown in Figure 2, the energy need increases slightly from 31.1 kWh/(m^{2}y) to 33.9 kWh/(m^{2}y), corresponding to 9% of energy penalty (Cases 25 and 26). This energy-saving strategy is not effective for reducing the energy need.

It has been documented that personalized ventilation may provide better inhaled air quality, thermal comfort and protection from cross-infection compared to mixing ventilation [1, 41, 42]. The results of this study reveal that in a cold climate, depending on the θ_{SUP} control strategy and on the energy-saving strategies applied, this can be achieved with higher (up to almost 4 times), equal or lower (up to 60% of energy-saving) energy consumption compared to traditional systems. In hot and humid climates where the outdoor air cannot be used for free cooling, the energy-saving strategies described may provide higher energy-saving than the one reported in this paper for a cold climate.

In this paper, only the energy-saving potential has been studied. The most important benefit in the use of personalized ventilation for the improvement of occupants' health, comfort and performance, as well as protection against cross-infection, has not been considered. It is important to note that the advantages and savings due to improvement of these factors may be much higher than the energy consumption of personalized ventilation.

CONCLUSIONS

The main conclusions of this study on energy-saving potential of personalized ventilation when used in cold climates are:

- The control strategy of the personalized air temperature supplied has a significant influence on energy consumption. In cold climates the energy consumption with personalized ventilation may increase substantially (between 61% and 268%) compared to mixing ventilation alone if energy-saving strategies are not applied.
- The best supply air temperature control strategy is to provide air constantly at 20°C, the minimum permissible supply temperature.
- The most effective way of saving energy with personalized ventilation is to increase the maximum permissible room temperature (saving up to 60% compared to the mixing ventilation may be achieved) but it can be applied only in offices where occupants spend most of their time at the desk.
- Reducing the airflow rate does not always imply a reduction of energy consumption because the outdoor air may have a free cooling effect. Supplying the personalized air only when the occupant is at the desk is not an effective energy-saving strategy.

NOMENCLATURE

ACE	air change effectiveness
AHU	air handling unit
AHU Cooling	Energy that is extract by the AHU from the outdoor airflow rate in one year (kWh/(m^2y))
AHU Heating	Energy that is supplied by AHU to the outdoor airflow rate in one year (kWh/(m^2y))
PV	personalized ventilation
q_V	personalized volume airflow rate per person (l/(s person))
Room Cooling	Energy that is extracted by the fan coil units from the room in one year (kWh/(m^2y))
Room Heating	Energy that is supplied by the fan coil units to the room in one year (kWh/(m^2y))
SBS	sick building syndrome
Greek symbols	
θ_{IDA}	indoor air temperature (°C)
θ_{ODA}	outdoor air temperature (°C)
θ_{SUP}	supply air temperature (°C)
θ_{UP}	upper room operative temperature limit (°C)

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