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Energy analysis of the personalized ventilation system in hot and humid climates

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ABSTRACT

Personalized ventilation (PV) is an individually controlled air distribution system aimed at improving the quality of inhaled air and the thermal comfort of each occupant. Numerous studies have shown that PV in comparison with traditional mechanical ventilation systems may improve occupants' health, inhaled air quality, thermal comfort, and self-estimated productivity. Little is known about its energy performance.

In this study, the energy consumption of a personalized ventilation system introduced in an office building located in a hot and humid climate (Singapore) has been investigated by means of simulations with the empirically tested IDA-ICE software. The results reveal that the use of PV may reduce the energy consumption substantially (up to 51%) compared to mixing ventilation when the following control strategies are applied: a) reducing the airflow rate due to the higher ventilation effectiveness of PV; b) increasing the maximum allowed room air temperature due to PV capacity to control the microclimate; c) supplying the outdoor air only when the occupant is at the desk. The strategy to control the supply air temperature does not affect the energy consumption in a hot and humid climate.

KEYWORDS

Personalized ventilation
Personal environmental control system
Hot and humid climate
Energy saving
Occupants' comfort
Control strategy

INTRODUCTION

Personalized ventilation (PV) aims to supply clean and cool air direct to the breathing zone of each occupant. Each occupant is provided with control of the supplied PV flow rate and/or supplied PV air temperature. Control of the airflow direction may be available as well. Thus, besides its ability to decrease the level of pollution in inhaled air and the risk of infection transmission [1, 2], PV improves occupants' thermal comfort and perceived air quality. PV may thus increase occupants' satisfaction, decrease sick building syndrome (SBS) symptoms and increase self-estimated productivity [3, 4, 5, 6]. It has been reported that the temperature and flow rate of personalized air are more critical than the ambient temperature for occupants' thermal comfort and inhaled air quality. Large individual differences with regard to preferred air movement have been identified in human subject experiments on personalized ventilation performed in hot and humid climates [5, 6].

Little is known about the energy use of personalized ventilation. Seem and Braun [7] studied the energy use characteristics of a system incorporating personal environmental control compared with conventional designs by

using computer simulations. They simulated the desktop personal environmental control system described by Arens et al. [8]. 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. [9] studied the performance of the system described above when implemented in a building. They suggested that using the system only when an occupant is present at the workplace may lead to energy saving.
Sekhar et al. [5], based on the thermal comfort response of subjects exposed to numerous environmental conditions achieved with personalized ventilation in conjunction with a secondary air-conditioning system, estimated 15-30% less energy use with personalized ventilation than with mixing ventilation when the room temperature was kept at the higher end of the comfort temperature range recommended in the present standards.

Schiavon and Melikov [10] studied, by means of energy simulation, the influence of the personalized supply air temperature control strategy on energy consumption and the energy-saving potential of personalized ventilation installed in a high quality Scandinavian building located in a cold climate. They reported that 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. Their results reveal that temperature control of the supplied personalized air has a marked influence on energy consumption and 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 to 30°C (saving up to 60% compared to the reference case of mixing ventilation alone). However, this energy-saving strategy can be recommended only in a working environment where the occupants spend most of their time at their workstation. The energy simulations are extremely sensitive to the climate and to building characteristics and the results obtained in specific boundary conditions cannot be extrapolated and applied to different scenarios. The authors suggested that the energy saving could be much greater in a hot and humid climate (e.g. Singapore).

Schiavon and Melikov [10], based on a literature review, summarized the control strategies of a PV system that may have energy-saving potential in building applications:

- Reducing the outdoor airflow rate due to the higher ventilation effectiveness of PV [5, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20];
- Expanding the room temperature comfort limits by taking advantage of PV's ability to create a controlled thermal microenvironment [5, 9, 14, 20, 21];
- Supplying the personalized air only when the occupant is present at the desk [7, 9].

They reported feasible ranges of airflow rate reductions, ventilation effectiveness, and increments of room air temperature [10].

The purpose of this study is to analyze, by means of simulations with IDA-ICE software, the energy consumption and the energy-saving potential of personalized ventilation applied in a hot and humid climate.

METHODS

The European standard 15265-2006 [22] 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 location and weather data

An office in a building located in Singapore was simulated. The weather is characterized by a hot and humid climate. The ASHRAE IWEC Weather File for Singapore 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 m x 20 m. The floor to floor height is 3.7 m and the floor to suspended ceiling height is 2.7 m. The external walls are constructed with 280 mm of medium-weight concrete (λ=0.66 $WK^{-1}m^{-1}$), 19 mm air layer and 8 mm spandrel glass; the overall U-value of the external wall is 1.4 $WK^{-1}m^{-2}$. The window is composed of an external sun protection glass pane (thickness 6 mm), 22 mm of air and an internal glass pane (thickness 4 mm). It has an overall U-value of 2.6 $WK^{-1}m^{-2}$, a g-factor or Solar Heat Gain Coefficient equal to 0.37, and a light transmittance equal to 0.44. The window has a total area of 30 m^2 (40% of the envelope area, height = 1.5 m and width = 20 m). The window faces south. There is a shading device in the form 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 100 W/m^2. The internal walls, floor and ceiling are adiabatic. The effect of thermal mass is taken into account.

Description of the HVAC system

The scheme of the HVAC system modelled is shown in Figure 1. The personalized air is conditioned by an air-handling unit (AHU) that adapts the airflow rate according to the occupancy (discussed later) and controls the personalized air supply temperature. There is no mechanical exhaust; thus air is exhausted through leaks and holes on the external walls. A second system, a two-pipe overhead fan coil unit, is used to keep the room air temperature within the specified temperature limits, no outdoor air being provided to the room through the fan coil unit. There is no heating system. For comfort reasons, the use of a PV system involves limitations on the maximum airflow rate and on the supply air temperature. Therefore, it is not possible to adapt the airflow rate (as in the variable air volume system) or the supply air temperature (as in the constant air volume system) to the required latent and sensible cooling load. Therefore, two independent systems have been used to ensure the design of thermal comfort and indoor air quality levels.

The reference system (mixing ventilation) is composed of a constant air volume system and an overhead fan coil unit. The building may be considered representative of a standard Singapore office building.

Internal temperature, ventilation and infiltration rate

The thermal comfort conditions and ventilation specifications were chosen in order to comply with the values defined in Singapore Standard CP 13-1999 [23]. From 6:00 till 22:00 an overhead two-pipe fan coil system keeps the indoor air temperature within a range between 22.5°C (minimum allowed room air temperature) and 24°C (maximum allowed room air temperature, θ_{UP}). The Standard allows 25.5°C as upper room temperature limit but this is seldom used in Singapore. During weekends and night-time the temperature set-back was 37°C. The maximum allowed room air temperature, θ_{UP}, was expanded to 26°C and 28°C in order to study the influence of this energy-saving strategy on the energy need. The design airflow rate was supplied during occupied hours and it was governed by occupancy profiles discussed in the following. The personalized airflow rate, q_V, was equal to 6.5 l/s per person during occupied hours (6:00 till 22:00) as required by the Singapore Standard CP 13-1999 [23]. At full occupancy, 12 occupants were present in the room (10 m^2 per person), and the total outdoor airflow rate was thus 78 l/s. The airflow rate was reduced to 5.5, 4 and 2.5 l/s per person in order to study the influence of this energy-saving strategy on the energy need. The constant air volume system used in the reference case supplied 6.5 l/s per person at 16°C during the operation hours according to occupancy of the room. The infiltration was taken into account by inserting in the model an Equivalent Leakage [24] equal to 0.025 m^2. This value implies 0.52 ACH when the HVAC system is not working and the pressure difference between inside and outside is 4 Pa and 0.37 ACH when the pressure difference is 2 Pa.

Table 1 Lighting load during weekdays.

Time	% Lighting
01:00-5:59	5
06:00-7:59	10
08:00-8:59	30
09:00-12:59	100
13:00-13:59	80
14:00-17:59	100
18:00-18:59	50
19:00-20:59	30
21:00-22:59	20
23:00-0:59	10

Internal heat gains and occupancy

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 is calculated by the software. The occupants' presence in the room from Monday to Friday varied according to Figure 2. In this paper, the fraction of full occupancy is defined as the ratio between the actual number of occupants present at their desks over the maximum number of occupants for whom room is designed. A second occupancy profile, as shown in Figure 3, was used for studying the influence of supplying the personalized air only when the occupant is present at the desk on the energy need. The first occupancy behaviour profile (shown in Figure 2) has been obtained from the European standard EN 15232 [25]. The second profile (shown in Figure 3) has been extrapolated by the data measured by Nobe et al. [26] in a Japanese 52-story office building where 240 workstations were monitored for a week. The fractions of full occupancy reported in [25] and [26] were slightly increased for the hours after 18:00 in order to better describe the typical working time in Singapore. 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 [27], this value corresponds to a "light load office". The equipment loads follow the schedules of the occupants. The occupancy (and thus the heat load from the equipment) was reduced to the profile shown in Figure 2 in order to study the effectiveness of the PV system in adapting the airflow rate to the occupancy. The lighting load was 10 W/m^2 and it follows the load shown in Table 1. Singapore Standard SS 530 [28] states that the maximum lighting power budget (including ballast losses) should be 15 W/m^2 for offices. 10 W/m^2 is commonly used for "energy efficient" building designs. During weekends the lights are switched off.

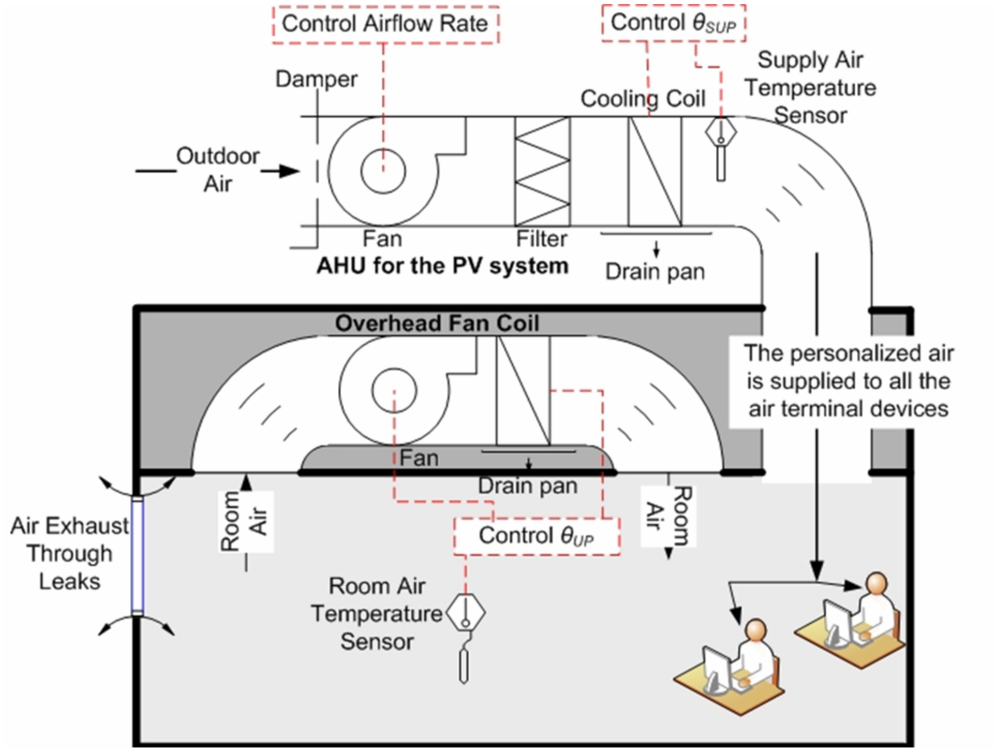

Figure 1. The simulated HVAC system consisting of an AHU dedicated to the personalized ventilation system and an overhead fan coil dedicated to control the room air temperature. The AHU controls the PV supply airflow rate and air temperature. The drawing is not to scale.

Simulation software

IDA Indoor Climate and Energy (ICE) is a tool for simulating 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 [29]. The accuracy of the IDA ICE was assessed through the IEA solar heating and cooling programme, Task 22, subtask C [30]. IDA ICE 3.0 has been chosen as one of the major 20 building energy simulation programs that were subjected to analysis and comparison [31].

Simulated cases

The energy need of a personalized ventilation system compared to a conventional mixing ventilation system was studied for three control strategies of the supply personalized air temperature. The energy-saving potential of the three strategies listed in the introduction was examined as well. Thus 74 cases comprising 3 personalized air supply temperature strategies (namely constant at 20°C, constant at 24°C, variable according to Figure 4), 4 personalized airflow rates (6.5, 5.5, 4, 2.5 l/s per person), 3 maximum allowed room air temperatures (24°C, 26°C, 28°C) and 2 heat load and occupancy profiles (see Figure 2 and Figure 3) were simulated. All the simulated cases are summarized in Table 2. To identify each simulation a denomination code composed of four short codes is applied. The personalized air supply temperature is identified with the following abbreviation: c20, c24 and v. After identifying the supply air temperature, the airflow rate is defined (6.5, 5.5, 4, 2.5), and then the maximum allowed room air temperature (24, 26, 28), reaching finally an indication of the heat load and occupancy profiles ("A" for the profile shown in Figure 2 and "B" for the profile shown in Figure 3). For example, the case c24-5.5-26-A means that the personalized air is supplied constantly at 24°C, the supply airflow rate is equal to 5.5 l/s per person, the maximum allowed room air temperature is equal to 26°C and the heat and occupancy profile follows the profile shown in Figure 2. Two reference conditions (namely Ref. 1 and Ref. 2) were simulated. They differed on the occupancy profiles, therefore on the heat load released in the room. In Ref. 1 the equipment and human heat loads followed the occupancy profile shown in Figure 2, and in Ref. 2 the profile shown in Figure 3. In the two reference cases the airflow rate varied in accordance with the occupancy profile. Two reference cases were evaluated because the comparisons between the mixing ventilation system and the PV system had to be made with the same internal heat loads. The simulated cases are described below.

Table 2 Simulated cases.

Case	θ_{SUP} [a]	θ_{UP} [b] [°C]	q_V [c] [l/(s person)]	Case	θ_{SUP} [a]	θ_{UP} [b] [°C]	q_V [c] [l/(s person)]
Ref.1	16	24	6.5	Ref. 2	16	24	6.5
c20-6.5-24-A[d]	20	24	6.5	c20-6.5-24-B[d]	20	24	6.5
c24-6.5-24-A	24	24	6.5	c24-6.5-24-B	24	24	6.5
v-6.5-24-A	variable	24	6.5	v-6.5-24-B	variable	24	6.5
c20-5.5-24-A	20	24	5.5	c20-5.5-24-B	20	24	5.5
c24-5.5-24-A	24	24	5.5	c24-5.5-24-B	24	24	5.5
v-5.5-24-A	variable	24	5.5	v-5.5-24-B	variable	24	5.5
c20-4-24-A	20	24	4	c20-4-24-B	20	24	4
c24-4-24-A	24	24	4	c24-4-24-B	24	24	4
v-4-24-A	variable	24	4	v-4-24-B	variable	24	4
c20-2.5-24-A	20	24	2.5	c20-2.5-24-B	20	24	2.5
c24-2.5-24-A	24	24	2.5	c24-2.5-24-B	24	24	2.5
v-2.5-24-A	variable	24	2.5	v-2.5-24-B	variable	24	2.5
c20-6.5-26-A	20	26	6.5	c20-6.5-26-B	20	26	6.5

c24-6.5-26-A	24	26	6.5	c24-6.5-26-B	24	26	6.5
v-6.5-26-A	variable	26	6.5	v-6.5-26-B	variable	26	6.5
c20-5.5-26-A	20	26	5.5	c20-5.5-26-B	20	26	5.5
c24-5.5-26-A	24	26	5.5	c24-5.5-26-B	24	26	5.5
v-5.5-26-A	variable	26	5.5	v-5.5-26-B	variable	26	5.5
c20-4-26-A	20	26	4	c20-4-26-B	20	26	4
c24-4-26-A	24	26	4	c24-4-26-B	24	26	4
v-4-26-A	variable	26	4	v-4-26-B	variable	26	4
c20-2.5-26-A	20	26	2.5	c20-2.5-26-B	20	26	2.5
c24-2.5-26-A	24	26	2.5	c24-2.5-26-B	24	26	2.5
v-2.5-26-A	variable	26	2.5	v-2.5-26-B	variable	26	2.5
c20-6.5-28-A	20	28	6.5	c20-6.5-28-B	20	28	6.5
c24-6.5-28-A	24	28	6.5	c24-6.5-28-B	24	28	6.5
v-6.5-28-A	variable	28	6.5	v-6.5-28-B	variable	28	6.5
c20-5.5-28-A	20	28	5.5	c20-5.5-28-B	20	28	5.5
c24-5.5-28-A	24	28	5.5	c24-5.5-28-B	24	28	5.5
v-5.5-28-A	variable	28	5.5	v-5.5-28-B	variable	28	5.5
c20-4-28-A	20	28	4	c20-4-28-B	20	28	4
c24-4-28-A	24	28	4	c24-4-28-B	24	28	4
v-4-28-A	variable	28	4	v-4-28-B	variable	28	4
c20-2.5-28-A	20	28	2.5	c20-2.5-28-B	20	28	2.5
c24-2.5-28-A	24	28	2.5	c24-2.5-28-B	24	28	2.5
v-2.5-28-A	variable	28	2.5	v-2.5-28-B	variable	28	2.5

[a] The personalized air supply temperature can be supplied constantly at 16, 20 or 24°C or varying according to the profile "variable" shown in Figure 4.

[b] The overhead fan coil units tries to keep the room air temperature from 06:00 to 22:00 below the upper room operative temperature limit, θ_{UP}.

[c] At full occupation (fractional of full occupancy =1) the airflow per person, q_V, is equal to the value reported in this column.

[d] The last letter of the simulation identification code indicates the occupancy and equipment profile. "A" is for the profile shown in Figure 2 and "B" for the one shown in Figure 3.

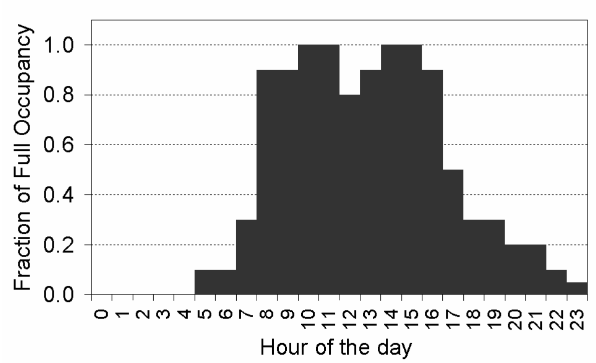

Figure 2. Occupancy profile.

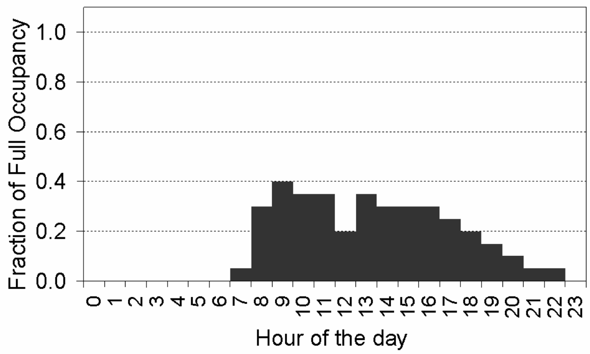

Figure 3. Occupancy profile according to the measured data by Nobe et al. [26].

Supply air temperature control

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 for occupants' thermal comfort. In a single duct constant air volume system, θ_{SUP} set-point may be constant, or it may be reset based on the outdoor or indoor (θ_{IDA}) air temperature. In Singapore, it is meaningless to reset θ_{SUP} based on the outdoor air temperature because its variability is limited. PV supplies the air close to occupants. Therefore, the lowest and highest permissible supply air temperatures are restricted by thermal comfort issues. In this study, it has been chosen that θ_{SUP} may vary in the range 20-24°C, these values being considered acceptable by tropically acclimatized subjects [6]. The profiles simulated are restricted within this range. The PV supply air temperature strategies studied are shown in Figure 4. For the profiles named "Constant at 20°C" and "Constant at 24°C" the air is always supplied at the same temperature, i.e. 20°C and 24°C, respectively. For the profile "Variable" θ_{SUP} is reset based on θ_{IDA}. It is expected that the "Variable" profile would probably be used by the occupants if they would have the opportunity to control the supply air temperature because it supplies warm air when the room is slightly cool and cool air when the room air is warmer than 24°C. A recently reported study by Kaczmarczyk et al. [32] identified that facially applied personalized flow at a temperature only several degrees higher than room air temperature improves the thermal comfort of people who feel slightly cool and does not affect significantly perceived air quality.

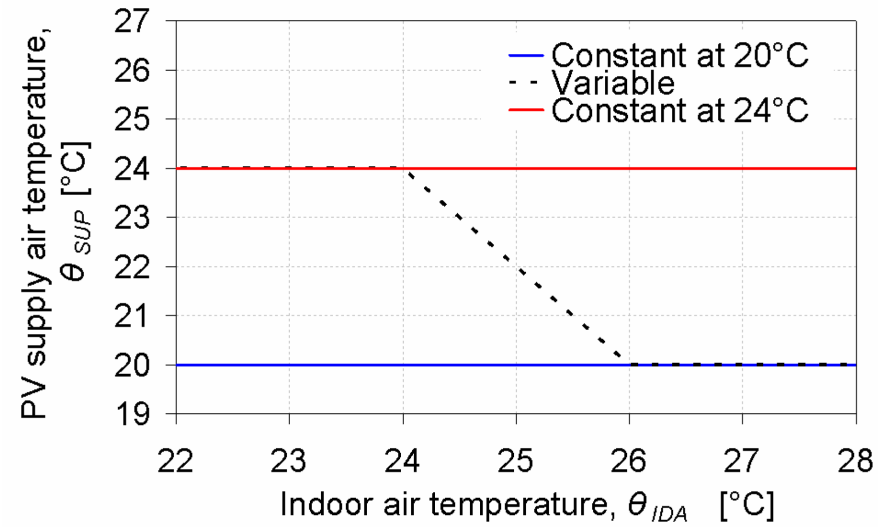

Figure 4. PV supply air temperature profiles as a function of the indoor air temperature.

Energy-saving strategies

The three energy-saving strategies presented in the introduction were investigated. The impact of reducing the outdoor airflow rate due to the higher ventilation effectiveness of the personalized ventilation system was studied. In general, decrease of the personalized airflow rate will cause a reduction of the ventilation effectiveness when personalized ventilation with the same air terminal device is used. For the purpose of the present energy-saving analyses, simulations were performed for four combinations of airflow rate and ventilation effectiveness achieved by four personal ventilation systems of different design. The combinations studied were: airflow rate of 6.5, 5.5, 4, and 2.5 l/s per person with corresponding ventilation effectiveness of 1, 1.2, 1.6 and 2.6, respectively. The personalized ventilation systems that can achieve the reported combination of airflow rate and ventilation effectiveness are described in Schiavon and Melikov [10]. Increase of the ventilation effectiveness up to 5 at small flow rate of 0.3-0.4 L/s by incorporating a small nozzle around the microphone of a headset worn by seated occupant is possible to achieve [12,33]. Recently Khalifa et al. [20] reported on a novel low-mixing PV co-flow nozzle (based on inner circular jet of clean air surrounded by an outer jet of room air) able to achieve ventilation effectiveness close to 4 with an airflow of 2.4 l/s. Improvement of ventilation effectiveness at a reduced supply of PV flow rate through a control of the free convection flow around human body by modification of furniture design has been achieved as well [17]. Supply of the personalized air from nozzles installed on the two sides of chair headrest has shown an increase in ventilation rate as well [18].

The importance of the second energy-saving strategy of expanding the maximum allowed room air temperature, θ_{UP}, was studied; θ_{UP} was expanded from 24°C to 26 and 28°C. The third energy-saving strategy of supplying the personalized air only when the occupant is present at the desk was studied based on the two occupancy profiles shown in Figure 2 and Figure 3. In this study, it is assumed that when the occupant is not at his/her desk he/she is out of the office. Therefore the heat loads generated by him/her and his/her equipment are not taken into account and the personalized air is switched off.

RESULTS

The "energy need" is the sum of energy for cooling (AHU Cooling) of the supplied air in order to obtain the desired θ_{SUP} and for cooling (Room Cooling) of the conditioned space in order to maintain the indoor air temperature within the designed range during a given period of time (from 6:00 to 22:00). The definition is in accordance with the European standard EN 15615 [34]. The AHU Cooling and the Room Cooling energy need is shown in Figure 5 for the cases with the occupancy according to the profile shown in Figure 2 and in Figure 6 for the cases with the occupancy according to the profile shown in Figure 3.

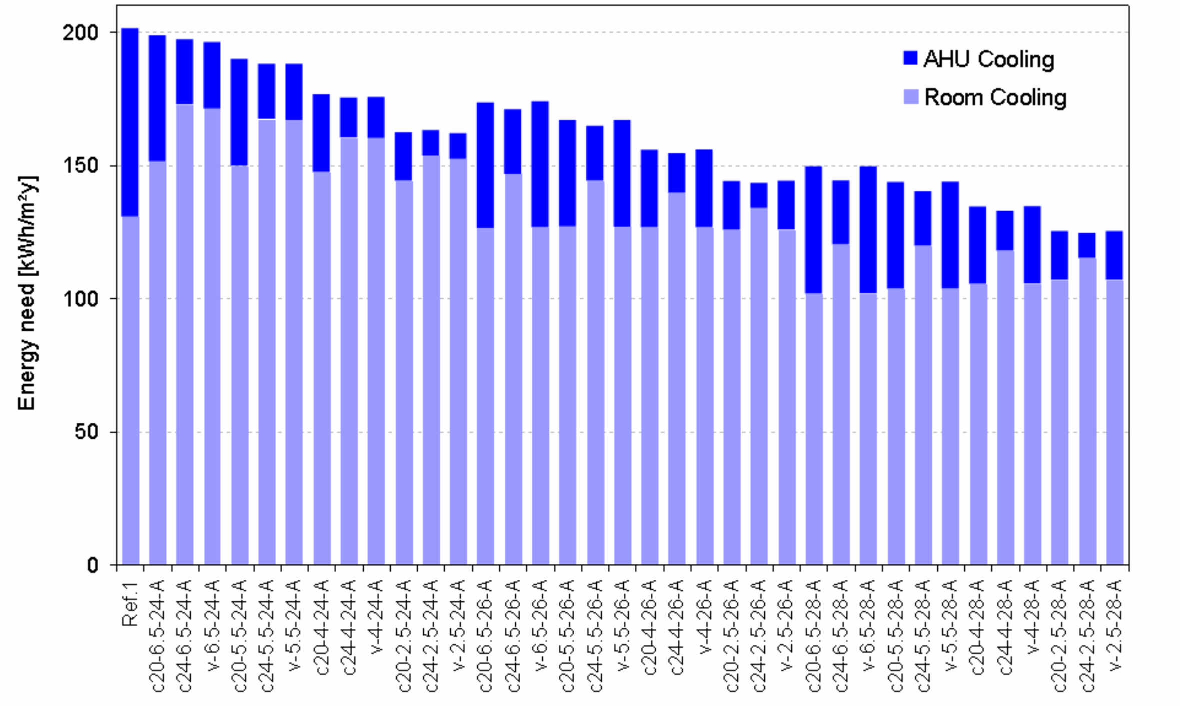

Figure 5. Energy need (sum of the AHU Cooling and Room Cooling) for the reference case Ref. 1 and for the cases with the occupancy varying according to the profile shown in Figure 2 (see Table 2).

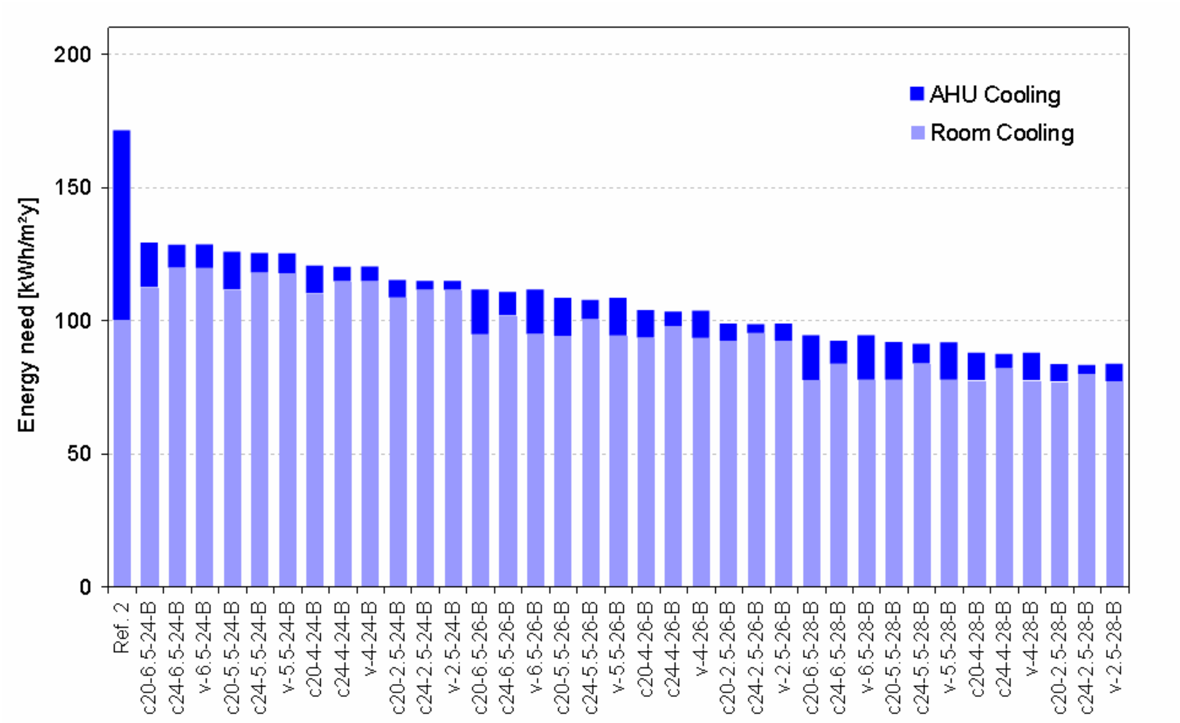

Figure 6. Energy need (sum of the AHU Cooling and Room Cooling) for the reference case Ref. 2 and for the cases with the occupancy varying according to the profile shown in Figure 3 (see Table 2).

The effect of the personalized air supply temperature control strategy on the AHU Cooling and the Room Cooling energy need is shown in Figure 7. The values reported are the average for all the simulated cases, i.e. the energy need is the average value for all the simulations with the same PV air supply strategy. The simulation design allows this kind of analysis because the simulated cases are balanced. The average effect of reducing the personalized airflow rate on the energy need is shown in Figure 8. In Figure 9 the average effect of increasing the maximum allowed room air temperature is shown, and in Figure 10, the average effect of adapting the personalized airflow rate to the occupancy level (Figure 2 and Figure 3) on the energy need is shown.

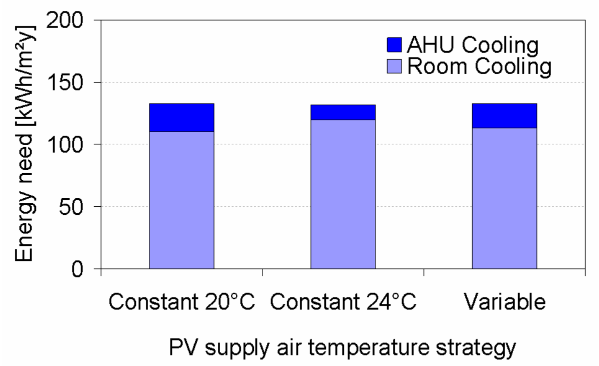

Figure 7. Average effect of the personalized supply air temperature control strategies on energy need.

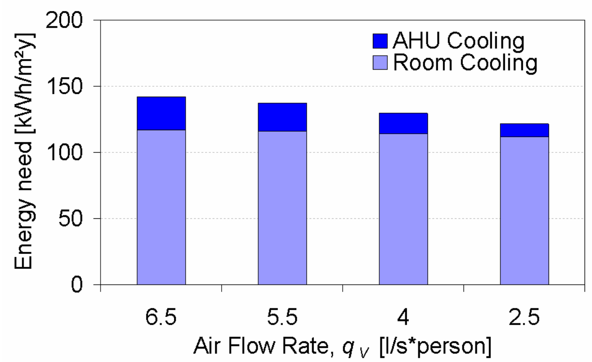

Figure 8. Average effect of reducing the airflow rates on energy need.

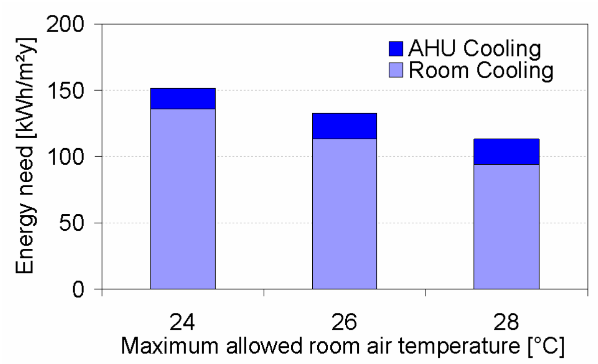

Figure 9. Average effect of increasing the maxim allowed room air temperature on energy need.

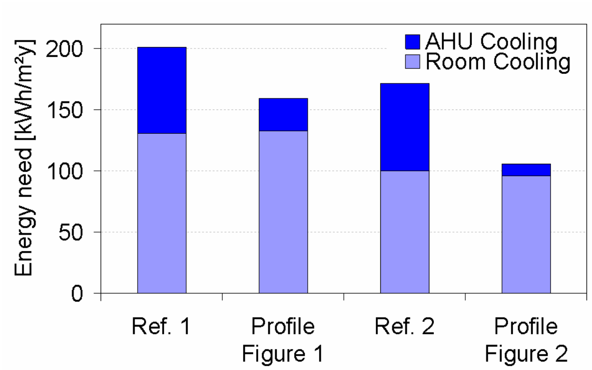

Figure 10. Average effect of the ability of a PV system to adapt the airflow rate to the occupancy level for two occupancy profiles on energy need.

DISCUSSION

The energy need for the reference cases is 201 kWh/(m^2year) for Ref. 1 and 171 kWh/(m^2year) for Ref. 2. Ref. 1 has a higher energy need than Ref. 2 because its internal load is higher (high occupancy). The AHU cooling energy needed for cooling the outdoor air is the same for the two reference cases, 71 kWh/(m^2year), because the conditioned outdoor air is supplied at the same flow rate.

The energy consumption of the personalized ventilation system varied between 199 kWh/(m^2year) and 125 kWh/(m^2year) for the cases where the occupancy and the equipment heat load followed, the profile shown in Figure 2. The use of PV compared to the reference condition Ref. 1, implies a reduction of the energy need from 1% to 36%. When the occupancy and the equipment heat load follow the profile shown in Figure 3, the energy need varied between 129 and 83 kWh/(m^2year). A comparison of these values with the reference condition, Ref. 2, implies a reduction of the energy need from 25% to 51%. Comparison of the simulated results reveals that substantial energy savings can be obtained with personalized ventilation when implemented in buildings in a hot and humid climate compared to a traditional ventilation system (mixing ventilation).
The results of the present study (Figure 7) reveal that the control strategy of the temperature of the supplied personalized air (studied at four airflow rates, three levels of the maximum allowed room air temperature and two occupancy profiles) does not affect the energy consumption. Therefore, it is not an issue for the HVAC designer and the energy building manager in hot and humid climates. This result is exactly opposite to the findings of similar simulations performed for a building in a cold climate [10]. In a cold climate, control of the temperature of the supplied personalized air is of major importance for the energy consumption and may be a problem for implementation of personalized ventilation in buildings because heating and cooling were, in some conditions, concurrent. For example, during a mild season the outdoor air needed to be heated before being supplied to the room, while the room heated by internal heat sources needed to be cooled. Thus, the outdoor air could not be used for its free cooling effect, and it became an additional heat load. This does not happen in hot and humid climates such as in Singapore, where the room and the supply air always need to be cooled. The importance of the supply air temperature control strategy depends on the outdoor climate; in a cold climate it significantly affects the energy consumption, while in hot and humid climate it is not an important issue. The configuration of the system in the cold climate simulation was similar to the system simulated in the present study, i.e. fan-coil unit for control of the room air temperature and AHU for supply of outdoor air. However, other system designs may prove to be energy-efficient when personalized ventilation is implemented. For example, personalized ventilation when used with re-circulated air or "ductless" personalized ventilation in conjunction with displacement ventilation [35]. The energy need of the three control strategies, for the same conditions, is the same, but the subdivision between Room Cooling and AHU Cooling varied. The subdivision is always different for the control strategy named "constant at 20°C" and the one named "constant at 24°C" (see Figure 5). "Constant at 20°C" requires more AHU Cooling than "constant at 24°C" because it has to cool the airflow to a lower value, and it requires less Room Cooling than "constant at 24°C" because part of the cooling load is offset

by the PV supplied air. The control strategy “variable” (see Figure 4) behaves as the strategy “constant at 24°C” when the maximum allowed room air temperature, θ_{UP}, is equal to 24°C, and as the strategy “constant at 20°C” when θ_{UP} is equal to 26 and 28°C. This is due to the temperature profile: when the room air temperature is lower or equal to 24°C the personalized air is supplied at 24°C and when the room air temperature is equal or higher than 26°C the personalized air is supplied at 20°C.

The energy-saving with personalized ventilation at reduced ventilation flow rate and increased ventilation effectiveness was studied at three levels of the maximum allowed room air temperature and two occupancy profiles. The reference personalized airflow rate was equal to 6.5 l/s per person (value required by the Singapore Standard CP 13-1999 [23]). The reference airflow rate was reduced when the ventilation effectiveness was increased according to values reported in the literature. The average effect of reducing the airflow rates on the energy need is shown in Figure 8. The reduction of the airflow rate implies a reduction of the energy need. From Figure 8 it can be seen that the airflow rate reduction causes a reduction of the AHU Cooling but it does not alter the Room Cooling. The reduction of the airflow rate would also imply a decrement of the electrical consumption of the fan and of the size of the duct system; these reductions have not been quantified in this work. Reducing the airflow rate due to the higher ventilation effectiveness of the personalized ventilation system is an effective strategy for reducing the energy consumption in hot and humid climates. In a cold climate, reducing the airflow rate does not always imply a reduction of the energy consumption because the outdoor air has a free cooling effect in a building that mainly needs cooling [10]. Thus, the benefit of decreasing the energy consumption by this strategy depends also on the outdoor climate. In a hot and humid climate the use of personalized ventilation will aim for improvement of inhaled air quality and thermal comfort. Personalized ventilation systems with high ventilation effectiveness, such as head-set and chair-incorporated air supply devices, able to provide almost 100% clean air for breathing have been reported [12, 15, 32]. However, these designs are not aimed at improving occupants’ thermal comfort. Supply of outdoor air at a reduced flow rate and increased ventilation effectiveness from relatively large air terminal devices may not be effective in cooling occupants, especially in a warm environment, because the velocity of the personalized flow generated will be low and insufficient for cooling the body. Nevertheless, the energy-saving strategies based on decreased outdoor air supply at increased ventilation effectiveness and increased maximum room temperature can be applied simultaneously: outdoor air at a reduced flow rate can be supplied from large air terminal devices with high ventilation effectiveness, e.g. the device reported in [12, 33], after it is mixed with re-circulated room air. The mixing of the clean outdoor air with the room air will decrease to some extent the inhaled air quality but will increase the supply flow rate, i.e. the velocity of the personalized flow, and thus will be able to improve occupants’ thermal comfort. Other solutions can also be implemented in practice in order to achieve energy-saving based on reduced outdoor airflow and increased ventilation effectiveness.

Previous studies have documented that PV can provide occupants with thermal comfort at room air temperature of 26 and 28 °C [5, 9, 14, 20, 21]. The importance of the level of the maximum allowed room air temperature, θ_{UP}, was studied for four airflow rates, three personalized air supply temperature control strategies, and two occupancy profiles. θ_{UP} was increased from 24°C (common value used in Singapore) to 26 and 28°C. The average effect of increasing the maximum allowed room air temperature is shown in Figure 9. Increasing θ_{UP} implies a reduction of the energy need. As expected, an increase of θ_{UP} causes a reduction of the Room Cooling but it does not significantly alter the AHU Cooling. The results reveal that increasing the maximum allowed room air temperature in a hot and humid climate is an effective way of saving energy. This finding agrees with conclusions in previous studies focused on hot and humid climates [5, 14] as well as a cold climate [10]. However, this energy-saving strategy can be recommended only in spaces with high occupant density, i.e. when occupants spend most of their time at their workstations in a comfortable thermal environment achieved by personalized ventilation.

Present standards [25, 36] recommend to take into account the occupant density during the design of HVAC systems. The occupancy level influences the heat generation in the room (equipment and humans), the moisture generation, and the airflow rate of the PV system. Simulations on energy need with the reference system and the PV system were performed at two different occupancy profiles. The results reveal that considering the occupancy level has a significant impact on the energy need (Figure 10). The ability of the system to adapt according to the occupancy in the room, especially the supply of personalized air only when the occupant is at the desk (the strategy used in the present study) was shown to be an important strategy for decreasing the energy need. Similar results can also be obtained with total volume ventilation systems such as mixing or displacement ventilation. These systems may adapt the airflow rate to the occupancy by using movement sensors or carbon dioxide sensors. There is, however, a difference between the demand ventilation in total volume systems such as mixing or displacement and personalized ventilation systems. In the total volume ventilation the outdoor airflow is controlled by the number of people in the ventilated space; in personalized ventilation the outdoor airflow is controlled by the number of people seated at the desks. This may generate a low indoor air quality when many occupants are in the room but not at their desks. This option should therefore be considered with caution.

The relative humidity for all the simulated cases was within the range 30-60%, and there are therefore no problems related to the water content in the air. As intended, the increase in the maximum allowed room air temperature implies a reduction of the relative humidity.

In this paper, the “energy need” has been reported and not the “energy delivered”. The “energy need” has been defined in the Results section. The “energy delivered” is, according to European standard EN 15615 [34], the total energy that has to be supplied to the building in order to satisfy all the users needs, it includes heating, cooling, ventilation, domestic hot water, lighting, fans, pumps, appliance, etc. The “energy need” is reported in this paper instead of the “energy delivered” in order to make the predicted results independent of the specific characteristic of the HVAC system, e.g. boiler performances, chiller part load curves or duct pressure lost, etc. The influence of the PV strategies investigated on the HVAC system behavior has not been analyzed. Such analyzes may change the reported results, for example, the ducting system for delivering the personalized air will increase the pressure losses which will lead to a higher energy consumption of the PV system.”

The results of this energy simulation based study reveal that in hot and humid climates, depending on the energy-saving strategies applied, energy saving up to 51% can be achieved with personalized ventilation in comparison with traditional total volume systems typically used today. Research on measured energy consumption of personalized ventilation applied in practice is needed. The energy-saving strategies studied are effective when the occupants are at the desk. Nevertheless, the implementation of personalized ventilation in buildings may still be advantageous to the total volume ventilation and justified because apart from the energy-saving potential the use of personalized ventilation will decrease the number of dissatisfied occupants, will improve occupants’ health (fewer SBS symptom complaints and reduced risk of cross-infection) and will improve occupants’ thermal comfort and perceived air quality, thus leading to improved work performance.

CONCLUSIONS

The main conclusions of this energy simulation based study on energy-saving potential of personalized ventilation when used in hot and humid climates are:

- The use of personalized ventilation may reduce the energy consumption substantially (up to 51%) compared to mixing ventilation when proper energy-saving strategies are applied;
- The control strategy of the supply air temperature does not affect the energy consumption; therefore it is not an issue for the HVAC designer and the building energy manager as it is in a cold climate;.
- Reducing the airflow rate due to the higher ventilation effectiveness of the personalized ventilation system is an effective strategy for reducing the energy consumption;
- Increasing the maximum allowed room air temperature is an effective energy-saving strategy;
- The ability of personalized ventilation to supply air only when the occupant is at the desk implies a reduction of the energy consumption.

NOMENCLATURE

ACH	air change per hour (h^{-1})
AHU	air handling unit
AHU Cooling	energy that is extract by the AHU from the outdoor airflow rate in 1 year (kWh/(m^2year))
PV	personalized ventilation
q_V	personalized volume airflow rate per person (l/(s per person))

SBS	sick building syndrome
Room Cooling	Energy that is extracted by the fan coil units from the room in 1 year (kWh/(m^2year))
Greek symbols	
θ_{IDA}	indoor air temperature (°C)
θ_{SUP}	supply air temperature (°C)
θ_{UP}	maximum allowed room air temperature (°C)

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