Energy Efficiency Potential of Personalized Ventilation System in the Tropics

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ABSTRACT

A Personalised Ventilation system provides occupants with means of adjusting their individual thermal environment and of achieving good indoor air quality. The individual control of environmental variables makes it possible to compensate for the differences between people with regard to their requirements. In most tropical designs, the air-conditioning and mechanical ventilation system maintains the indoor spaces at cold temperatures in the vicinity of 21° C. The PV system can be seen as a system capable of achieving significant energy conservation due to the inherent possibility of maintaining the ambient space temperature warmer while supplying the PV air at a preferred cold temperature. Recent studies in Singapore have shown that the use of a PV system in conjunction with a secondary air-conditioning system not only enhances thermal comfort and IAQ acceptability but has the potential to reduce energy consumption. This is observed through an analysis of breathing zone temperatures, ventilation effectiveness and thermal comfort acceptability.

INDEX TERMS

Personal control, Ventilation system, Energy efficiency, Thermal comfort, Tropics

INTRODUCTION

The Personalized Ventilation (PV) system offers a new method of providing fresh air to each occupant's breathing zone to enhance thermal comfort and IAQ acceptability while reducing ventilation-related energy consumption. The energy saving potential of a PV system has been attributed to its high ventilation efficiency (Faulkner et. al.1999) and the possibility of raising ambient air temperature (Bauman et al 1993). Seem and Braun (1992) have investigated the impact of Personal Environment Control (PEC) on energy use. Most of the studies have been conducted in temperate climates and this paper presents findings from a tropical study in Singapore.

METHODS

The experiments were conducted in a controlled environment Indoor Air Quality (IAQ) chamber, situated in the Department of Building at the National University of Singapore. The IAQ chamber, as shown in Figure 1, is equipped to function with 6 work stations provided with 6 independent PV air terminal devices. The indoor environmental conditions of the chamber are

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controlled by two dedicated air-conditioning systems – a primary system consisting of the PV air, which is 100% outside fresh air and a secondary system consisting of a conventional ceiling-supply air-conditioning system, which supplies between 90 and 100% recirculated air.

The experimental design consisted of 17 different environmental conditions, characterised by a combination of room ambient temperature (23 °C and 26 °C), PV air temperature (20 °C, 23 °C and 26 °C) and the PV air flow rate (7, 11 and 15 lps/person). The conditions are designated by these values, listed in this order, e.g. 23-20-15 designates an ambient temperature of 23 °C with 15 L/s of PV air at 20 °C. The experimental design also included a reference condition with just the secondary system operating under the same conditions, without PV air.

The experimental protocol included the measurement of ambient and PV air temperatures, thermal comfort parameters within the occupied zone, breathing temperature in the occupant breathing zone (Figure 2) and concentration levels of various indoor pollutants (including SF_6 as a tracer gas for evaluating ventilation effectiveness). SF_6 was used to simulate a pollutant and dosed in the secondary air-conditioning system. A detailed questionnaire was employed to solicit the subjective responses of the subjects during all the experiments. Standard statistical methods were used to test for the significance level of observed differences between conditions in terms of subjective response, at 5% level of significance.

In this study ventilation effectiveness was defined as:

$$\varepsilon_V = \frac{C_R - C_S}{C_P - C_S} \qquad (1)$$

where, C_R is pollutant concentration in exhaust air, C_S is pollutant concentration in supply air, C_P is pollutant concentration in the inhalation zone.

RESULTS AND DISCUSSION

Breathing temperatures

Several comparisons of the breathing temperature between the secondary ambient system and a configuration consisting of a secondary system with a PV system are presented in Figures 2 and 3. These plots represent measurement periods after equilibrium conditions have been reached. It is seen that a PV system could effectively reduce breathing temperature by between 2° C and 5° C.

In the case of a secondary system integrated with a PV system, it is apparent that a warmer space temperature, such as 26° C, accompanied by a PV air temperature of 23° C or 20° C, achieves an overall breathing temperature that is significantly lower. Such an environmental condition in the microclimate is perceived to have a better acceptability (Fang et.al. 1998). This provides an opportunity to operate the air-conditioning system in an energy efficient manner, demonstrating the energy saving potential of PV systems.

Ventilation effectiveness

The ventilation effectiveness observed in the PV experiments ranged between 1.42 and 1.90 and were significantly higher than can be achieved with mixing ventilation, which is around 1. Higher ventilation effectiveness means less fresh air is needed to maintain a given degree of air quality, leading to reduced energy consumption for cooling and distribution. Besides the cooling energy consumption, it is also observed that the absolute quantity of fresh air provided by a PV system can be lower due to the higher ventilation effectiveness values, which contributes to additional energy savings. For a given ambient temperature of 26 °C, a PV flow rate of 7 lps per person at a PV supply air temperature of 23 °C has a ventilation effectiveness value of 1.42, which is about 50% higher than the mixing ventilation with a fresh air flow of 15 lps per person.

Subjective responses

The mean responses of thermal comfort acceptability for various environmental conditions are presented in Figure 4. It is quite common for tropical buildings to be designed and operated at cold indoor temperatures, such as 23° C or lower, in order to achieve sufficiently low levels of humidity. The enhanced acceptability of the PV system represents an opportunity for achieving improved energy conservation.

The energy saving potential was also assessed by deriving a multiple linear regression analysis relating thermal comfort and PAQ to the PV parameters:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \qquad (2)$$

where, Y- subjects evaluation of tc (thermal comfort) or paq (perceived air quality) under all experimental conditions, X_1- ambient temperature (°C), X_2- PV temperature (°C), and X_3- PV air flowrate (l/s)

The R^2 value of the linear regression is low for thermal comfort and perceived air quality (the highest R^2 is 0.43) and the regression coefficients hypothesis $\beta_s=0$ is further tested in Table 1.

The P-values in Table 1 suggest that there is an energy saving potential for PV systems, since PV temperature and PV flow rate are more critical than ambient temperature for occupants' thermal comfort and inhaled air quality. To save energy, ambient temperature could be higher, while at the same time a suitable PV temperature and small amount PV air could meet occupants' thermal comfort and perceived air quality requirement.

ANOVA was used to investigate the variation patterns of PAQ, thermal comfort and PV System (PVS) assessment in terms of PV air temperature and flow rate. At an ambient temperature of 26°C, consistent trends are observed for PAQ, thermal comfort and PVS assessment. Their values generally increase as the airflow rate increases, and decrease as PV temperature increases as shown in Table 2. The highest PAQ, thermal comfort and PVS values occur at the lowest PV temperature (20°C) and highest airflow rate (15 l/s).

At an ambient temperature of 23°C some statistically consistent trends (P-value less than 0.05) were also observed for thermal comfort assessment: thermal comfort is perceived as better with increasing PV air flow rate (although the P-value is 0.55 when PV air temperature is 23°C), or with the decrease of PV air temperature. However, there is no such trend for PAQ and PVS assessment at an ambient temperature of 23°C.

CONCLUSIONS

The potential to save energy with a PV system in the tropics is evaluated in this paper. The following advantages were documented:

- Ability of the PV system to maintain temperatures of the air in the breathing zone significantly lower than a system with mixing ventilation.
- Significantly higher ventilation effectiveness values of the PV system (1.42 – 1.90)
- Enhanced thermal comfort acceptability of the PV system in conjunction with a secondary air-conditioning system as compared to a mixing ventilation system operated alone.

Finally, it is shown that PV temperature and PV flow rate are more critical than ambient temperature for occupants' thermal comfort and inhaled air quality. For energy conservation, a higher ambient temperature with a suitable PV temperature and a small amount of PV air could meet occupants' thermal comfort and perceived air quality requirements.

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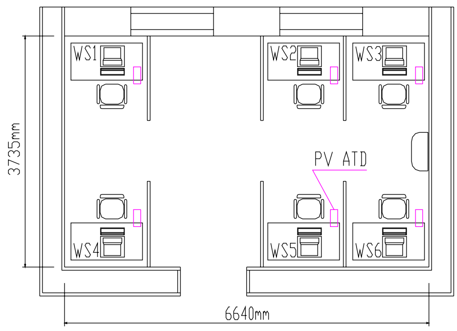

Figure 1 : Indoor Air Quality chamber

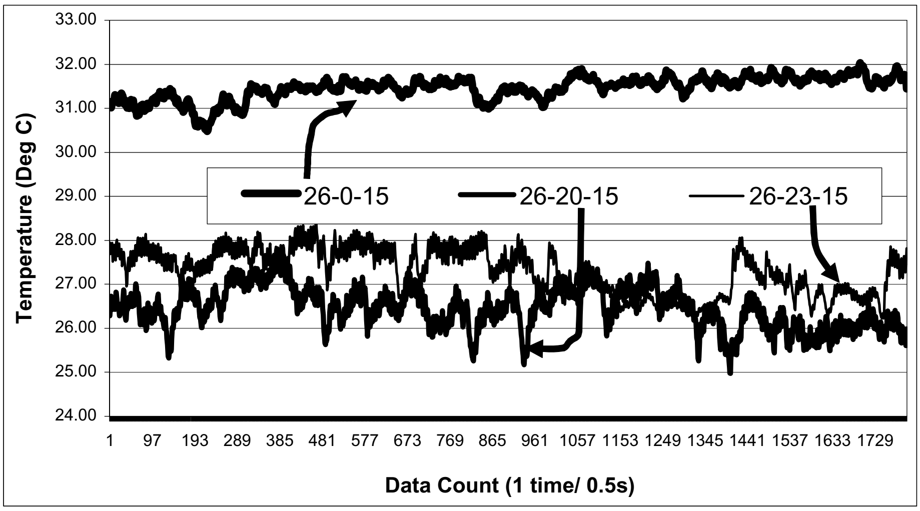

Figure 2 : A comparison of breathing temperatures at different indoor environmental conditions

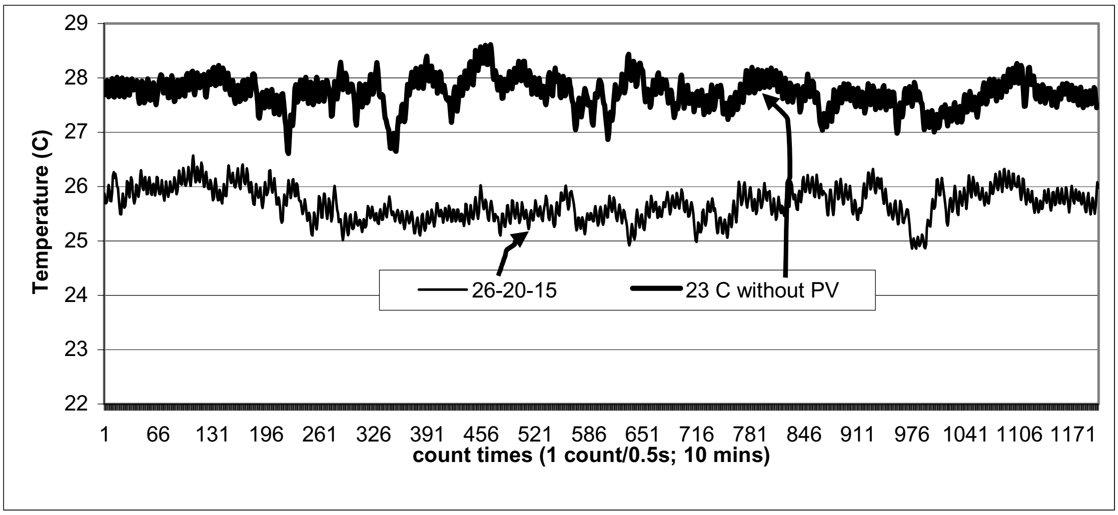

Figure 3 : A comparison of breathing temperatures at 23 °C and 26 °C ambient temperature

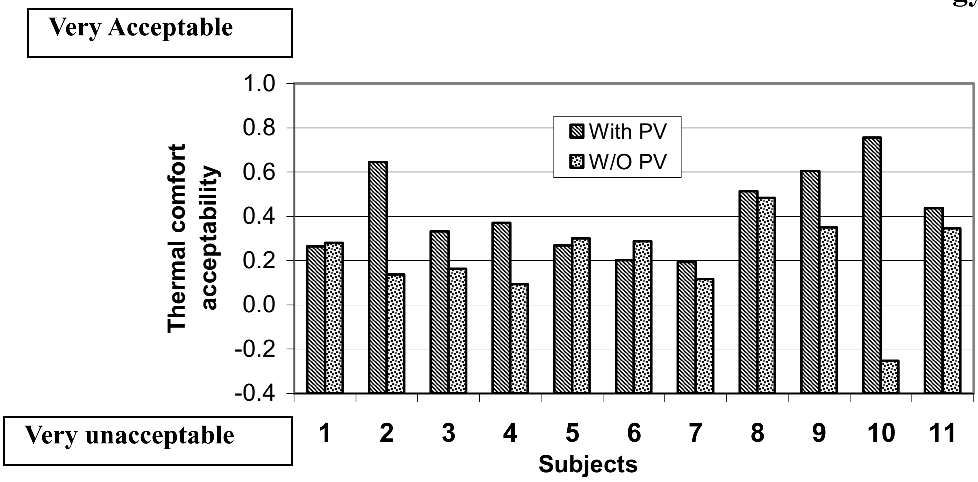

Figure 4 : Mean responses of Thermal Comfort acceptability for energy saving potential

Table 1 P value for regression coefficients

P value	tc pv	paq pv
β_0	<0.001	<0.001
β_1	0.0024	0.909749
β_2	<0.001	<0.001
β_3	<0.001	<0.001

Table 2 : PV perception trends in terms of PV air temperature and flow rate

	T_{pv} (^{0}C)	Outdoor air (L/s)			P-value
PAQ		7	11	15	
	Trend				
value at	20	0.38818	0.47909	0.59909	**0.00096**
	23	0.26455	0.33182	0.45091	**0.02269**
Ta = 26 C	26	0.12091	0.25	0.36364	**0.01086**
	P-value	**0.00002**	**0.0069**	**0.01169**	
	T_{pv} (^{0}C)	Outdoor air (L/s)			P-value
Thermal	Trend	7	11	15	
comfort					
	20	0.3482	0.4642	0.5773	**0.0151**
value at	23	0.2206	0.3306	0.3767	**0.0585**
	26	0.0879	0.2255	0.3206	**0.0177**
Ta = 26 C	**P-value**	**0.0013**	**0.0084**	**0.0076**	
	T_{pv} (^{0}C)	Outdoor air (L/s)			P-value
PVS	Trend	7	11	15	
value at	20	0.202727	0.313636	0.419091	**0.057**
	23	0.114545	0.249091	0.393636	**0.001**
Ta = 26 C	26	0.03	0.243636	0.379091	**0.002**
	P-value	**0.181679**	**0.421659**	**0.896264**	