

Numerical Study on a Hybrid System by Using a Portable Air Conditioner

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SUMMARY

This paper presents a new design concept of hybrid air conditioning system by using a portable air conditioner to achieve a better personal control of indoor environment without sacrificing the responsibility to a sustainable environment. The results of the detailed computational flow dynamics (CFD) simulation in this study, through a systematic analysis on the parameters of wall opening, outdoor wind speed and temperature, show that with an appropriate design of wall openings, this hybrid system can sustain a comfortable environment until affected by strong wind blast. At that moment, a suitable control of the sizes of these openings is suggested to extend the proper functioning of this hybrid system to achieve the dual benefits of comfort and energy conservation.

INTRODUCTION

In recent years, personalized cooling systems are under research and development to reduce CO₂ emission and achieve energy conservation. Most of the research focused on commercial HVAC systems to improve the energy performance, air quality and productivity of indoor environment. Akimoto et al. [1] and Sasaki et al. [2] developed a task air conditioning system and conducted a subjective field study on the thermal comfort and productivity. Furthermore, Chiang et al. [3, 4, 5] designed a new partition-type fan-coil unit (PFCU) system to provide the users with greater flexibility and convenience for dedicated local environment control. According to their results, as compared with a conventional air-conditioning system using ceiling diffusers, this personalized cooling system can reduce about 45% of cooling energy consumption.

The same concept can also be applied to the residential dwelling or small office buildings. However, at these places, portable air conditioner is more flexible to be implemented than the task or PFCU air-conditioning systems. Actually it has been used as a spot cooler for a long time to provide occupants cooling without wasting energy to cool the entire room. The cooling capacity can be largely reduced to as little as 500 W in comparison to several kW for the one using a conventional window or split-type room air conditioner. However, the need of a hose to ventilate the hot air discharged from the condenser to the outdoor often prohibits this appliance from being widely used. In this regard, this paper intends to develop a hybrid air-conditioning system to create an environment with natural but comfortable room air circulation that combines the buoyancy-induced airflow formed by the direct hot air discharged from this machine and the ventilation air flowing through some wall openings.

Aiming at the hybrid air-conditioning system in an office building, Chang et al. [6] studied a natural ventilation system for a model office building where air flows in through the opening on one wall, removes the heat and contaminants generated at the task zone and exhausts to the outdoor through another opening on the opposite wall adjacent to a courtyard. Mechanical

cooling system with underfloor air distribution is used as assisted cooling only when the natural ventilation is unachievable to meet the demand. Their work and Axley et al. [7] both indicate that the outdoor conditions and the designs of wall openings are the crucial parameters which affect the performance of the hybrid air-conditioning system. For residential buildings, the circumstances may be different because of the limitations of building structures and the use of a portable air conditioner. Therefore, the objective of this study is to achieve the following conditions so that the hybrid ventilation system can perform its ideal design functions in a residential building as well,

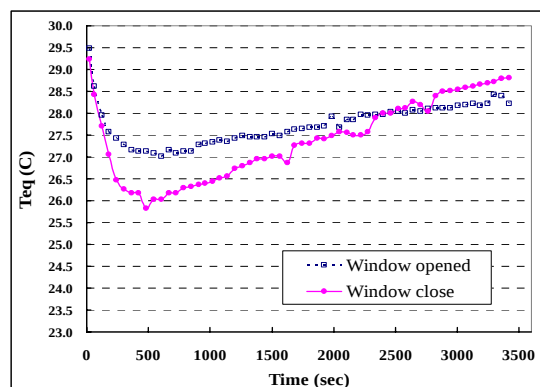
1. The hot air discharged from the condenser must rise as a thermal plume [8] to the upper portion in the room and, in the process, avoid any mixing with room air.
2. Thermal stratification must be established such that hot air can be exhausted from the upper opening on the wall.
3. Sufficient outdoor air must be introduced to make up the air being exhausted.

METHODS

The concept of designing this hybrid system was first proved by conducting a simple experiment. As shown in Figure 1(a), a spot cooler supplied cool air to a test room and a manikin sat inside the room to measure the comfort level. Initially, the temperature of the test room was set at 28°C and the outdoor chamber was controlled at 30°C. After the machine was turned on, the equivalent temperature perceived by the manikin dropped to the lowest values in 10 minutes and then gradually increased because of the accumulation of heat discharged by the condenser in the room. The variations of equivalent temperature were compared for two test conditions: one with a window opened on the wall and the other with the window close. For both cases, the equivalent temperatures eventually rose to an uncomfortable circumstance because heat was not efficiently removed from the space. However, when the window was opened, the indoor temperature increased in a slower rate. But, due to a large amount of hot air continually moved into the room from outdoor without any control mechanism, the perceived temperature of the manikin was finally not in the acceptable range. This experiment implies that we can avoid the accumulation of heat in the room by having an opening but, to achieve this hybrid system correctly functioning, a proper design of the opening is the prerequisite.



(a) Pictures of the experiment room



(b) Equivalent temperature perceived by a thermal manikin

Figure 1. Experimental set-up for testing a portable air conditioner and its test results

Although it is not difficult to study the proper wall openings in a climatic chamber, simulating the outdoor wind effect is not easy at this moment. Therefore, this paper uses computational

flow dynamics (CFD) method to complete a systematic analysis on the influential parameters such as wall opening, outdoor wind speed and temperature. Moreover, the use of CFD method can reveal detailed phenomena of flow fields and temperature distributions in such a closely interacting system.

In this study, a model room, as shown in Figure 2, has the size of 4m x 3m x 5m. The heat gains from the ceiling and through the floor are assumed to be 12 W/m² and 18 W/m², respectively. The influence of outdoor temperatures is studied by adopting two temperatures of 28°C and 25 °C, corresponding to a severe and a mild outdoor condition. The impact of outdoor wind blowing toward this building is analyzed under the conditions from the static wind (namely, completely calm) to a maximum wind speed of 0.75 m/s. Inside the model room, a portable air conditioner is placed on a short stool of 0.6m height and about 2m away from the left wall. An occupant in sitting position faces toward the portable air conditioner and is subject to the cool air supplied by this machine. Cool air leaving the evaporator with the air flow volume of 100CFM (air speed 0.84m/s) and temperature of 20°C. The hot air discharged by the condenser has the air volume of 80CFM (air speed 0.63m/s) and temperature of 40°C. It should be noted that we have slightly increased the hot air discharge ports on the machine so that the air speed is reduced so as to be able to form a thermal plume flow rising from the machine. This modification avoids the mixing of the discharged hot air with the room air and ensures an acceptable thermal stratification in the room.

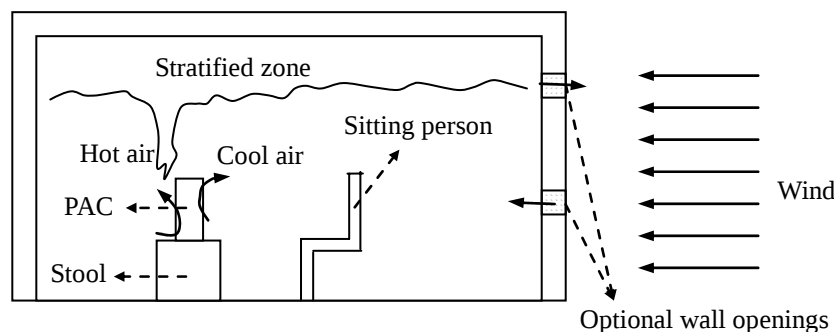
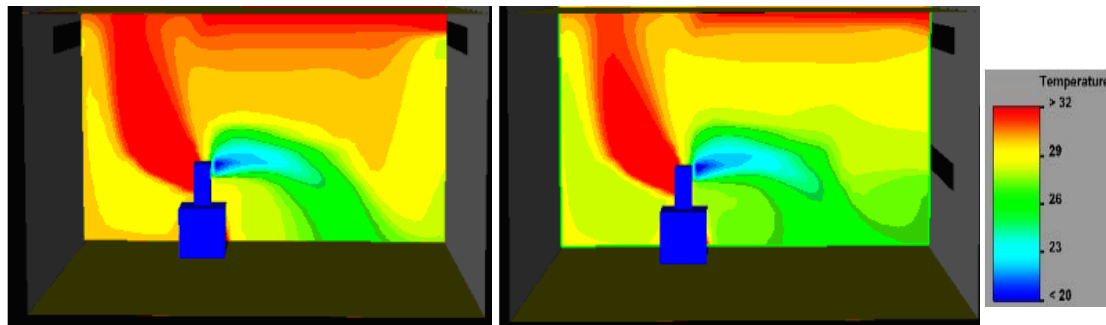


Figure 2. Sketch of the model room for CFD simulation

RESULTS

From the preliminary experimental test results, as demonstrated in Figure 1, we have found that although hot air discharged from the portable air conditioner can be exhausted to outdoor through the opened window. However, proper design of the openings is very important to form proper natural ventilation, including the processes of introducing cooler air into the room, removing interior heat loads and exhausting hot air outside. Chang et al. [6] investigated the hybrid ventilation in the intermediate seasons for an office room with large depth. There are openings on the opposite two side-walls in their model room. Low temperature outdoor air flows in through the opening on the exterior wall and rejects from another opening on the wall adjacent to a courtyard. The air flow in their model room is in a unilateral direction. The implementation of the similar design in this study, however, is found inferior to the design with two opening on the same wall. As depicted in Figure 3(a), under the circumstance that the wind speeds is zero, high temperature air tends to accumulate in the upper portion of the room and air movement is almost blocked. In contrast, for the design with two openings on the same wall, as indicated in Figure 3(b), the outdoor air can easily flow through the lower opening to the room and discharge from the upper opening. This hybrid system demonstrates a smooth air circulation and a favored thermal stratification.

Hence, the follow-up discussion of this paper will focus on this kind of openings design to explore the effect of opening size, outdoor temperature and wind speed.



(a) openings on two opposite walls (b) openings on the same wall
Figure 3. Influence of openings design on the room temperature distribution

After adopting the design of two openings on the same wall, openings with the sizes of 2m x 0.3m and 2m x 0.15m were investigated. Because achieving a comfortable local environment surrounding the occupant is the main goal of this study, a mean perceived temperature is defined to justify the comfort level of the sitting occupant by averaging the air temperatures at the selected positions of 1.1m, 0.6m, 0.1m heights, corresponding to the temperatures experienced by the head, waist and legs of the occupant. The perceived temperature calculated from the CFD simulation results are shown in Figure 4 for different openings and outdoor conditions. It is found that when the outdoor wind speed is below 0.4 m/s, the perceived temperature can be kept at less than 26.5°C, which satisfies the general requirement of a comfortable environment. Also with larger openings, the perceived temperatures are comparatively lower than those of the small openings. It must be due to the fact that the discharged hot air can be more smoothly vented outdoor. However, a reversed situation occurred as the outdoor wind speed is increased to over 0.5 m/s. The occupant might feel a sharp increase of the perceived temperature. To improve this drawback, using a small opening (eq. 2m x 0.15m) can completely suppress this problem.

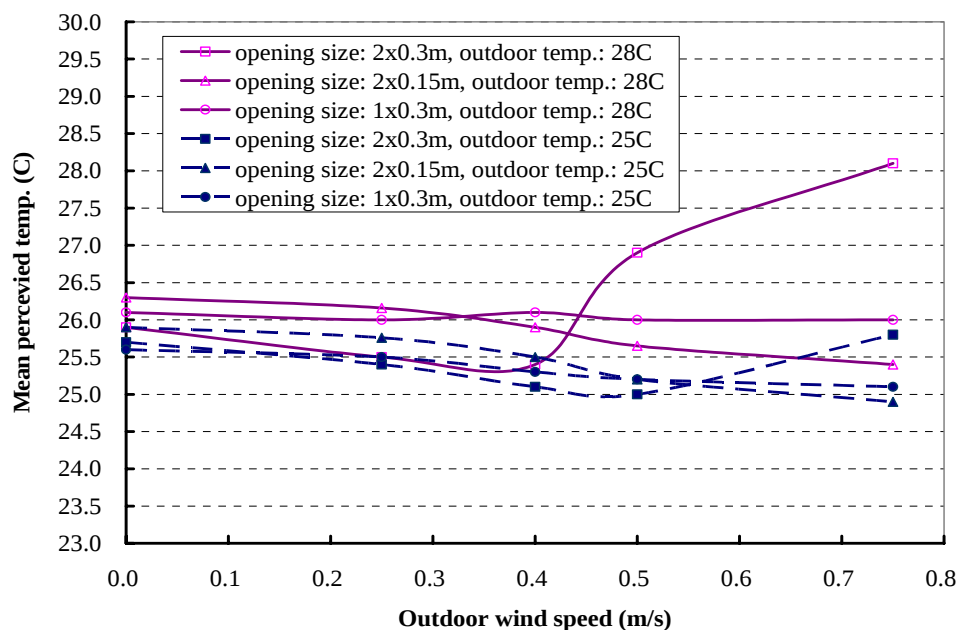
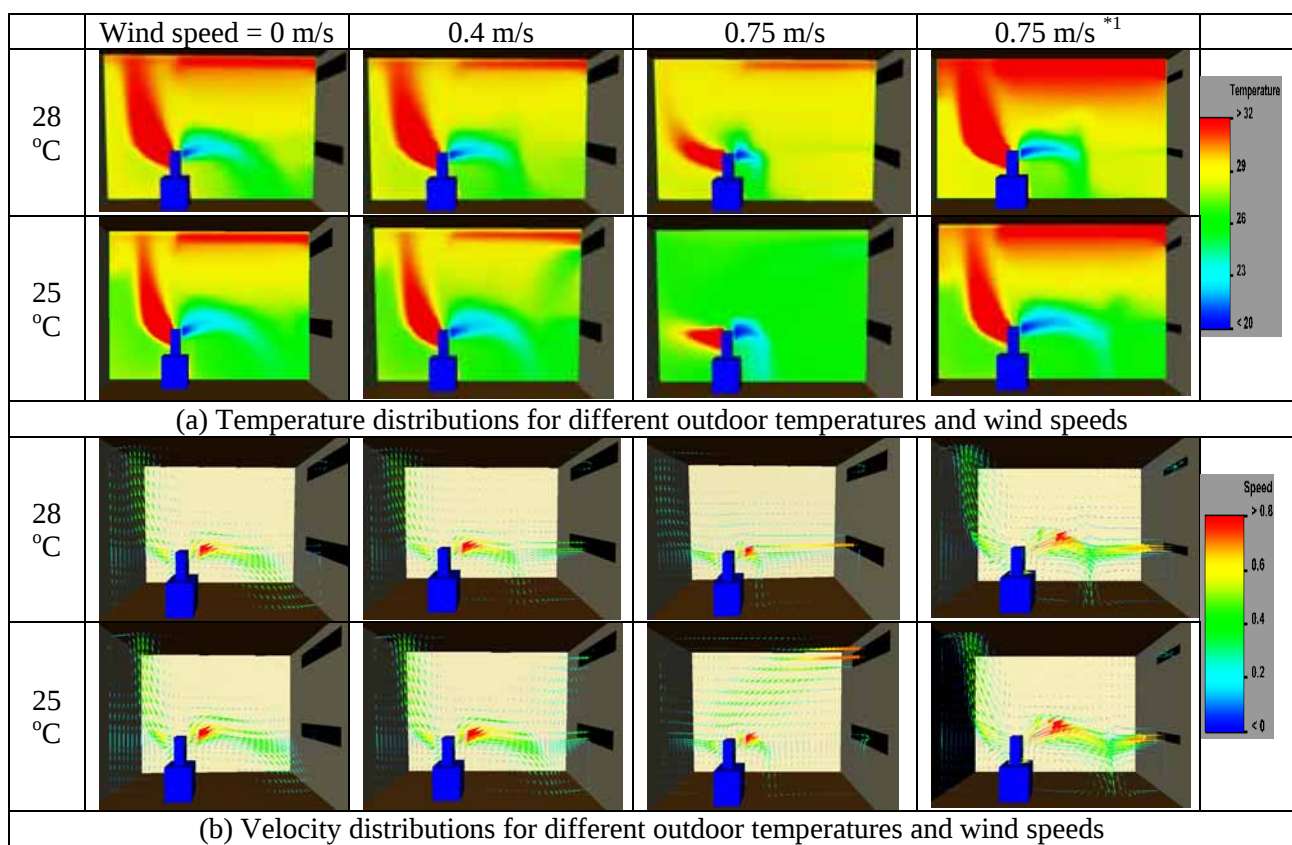


Figure 4. Variations of outdoor conditions vs. mean perceived temperature

Figure 5 summarizes the detailed air flow patterns created by the interactions of the portable air conditioner and the natural ventilation system. For the high outdoor air temperature (*i.e.* $T_o=28^\circ\text{C}$) cases, the ventilation air always flows in from the lower opening and flows out from the upper opening. As outdoor wind speed is slow, the stratification of temperature distribution is well established in the room. With the movability of this air conditioner, comfortable cooling can be provided to any portion of the space with less energy consumption. The hot air discharged by the machine moves quickly upward without disturbing the occupied zone. Nevertheless, ventilation air flow starts to hold back the cool air supplied from the machine by the increasing outdoor wind speed. The cool air is not able to reach the occupant when the wind speed is higher than 0.75 m/s. In this circumstance, the occupant is subject to complete outdoor conditions. With a reduced opening (*i.e.* 2m x 0.15m), the machine can regain its control of the living environment, but the upper stratification layer dramatically increases. For the low outdoor air temperature (*i.e.* $T_o=25^\circ\text{C}$) cases, the flow patterns present an interesting different feature. Without the assisting of the strong buoyancy force, the cold ventilation air is found to flow in from both openings as the outdoor wind speed increases.



Note: *1 flow fields with reduced openings (*i.e.* 2m x 0.15m)

Figure 5. Air flow distributions of the hybrid system formed by the portable air conditioner and natural ventilation system

Although, reducing the opening sizes from 2m x 0.3m to 2m x 0.15m can mediate the disturbance caused by the high speed air flows through the lower opening, a large stratified zone containing a lot of hot air is formed in the upper portion of the model room. To overcome this deficiency, an improved design by shifting the openings to one corner in the room can successfully avoid the confrontation of two air streams formed by the portable air conditioner and the natural ventilation. As shown in Figure 6, although the inflow through

lower opening is of high velocity, the air stream can keep off the cool air supplied from the machine. Hence, the comfortable level of the occupant can be held in a better condition. This finding implies that if these openings mounted with some adjustable louvers to divert the air flow direction, the portable air conditioner can always perform very well with natural ventilation.

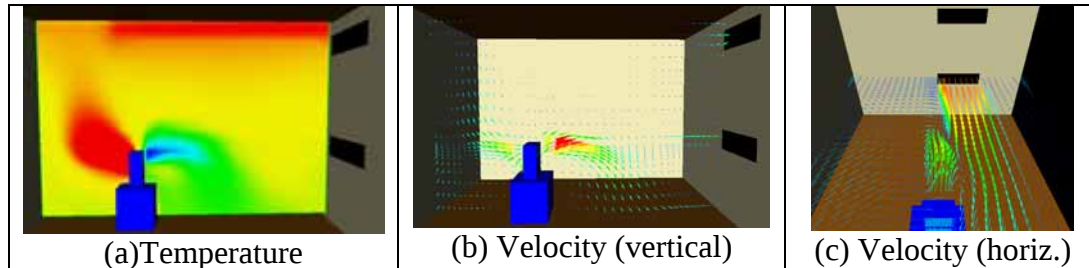


Figure 6. Flow fields for the cases where the openings are shifted to the right corner (opening size: 1m x 0.3m, wind speed: 0.7 m/s, T_o :28°C)

DISCUSSION

A thorough research on a new hybrid air-conditioning system is accomplished. With the room air circulation that combines the buoyancy-induced airflow formed by the direct hot air discharged from a portable air conditioner and the ventilation air flowing through some wall openings, a comfortable environment is achieved while consuming much less cooling energy. The detailed CFD simulation results reveal the detailed flow fields influenced by the major parameters of wall opening, outdoor wind speed and temperature. As manipulating the wall openings design, this hybrid system can sustain a comfortable environment until affected by strong outdoor wind blast. To avoid this circumstance, two additional designs, one with narrow openings and the other with swapped openings, are found to be able to extend the proper functioning of this hybrid system. In practices, mounting these openings with adjustable louvers to divert air flow direction, the portable air conditioner can always perform very well with natural ventilation. Expected flow phenomena at the beginning of this study are all satisfied including the formation of a thermal plume and a thermal stratification in the room and the induced natural ventilation flow through the openings on the walls.

ACKNOWLEDGEMENT

This research is made possible by the financial support from the Bureau of Energy, the Ministry of Economic Affairs, Taiwan, ROC.

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