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An Experimental Study on Thermal Comfort Improvement For Residential Air Conditioner Applying a Wind-free Technology

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Abstract

This paper focused on the indoor thermal comfort improvement by the wind-free air conditioner. Evaluate the indoor thermal comfort and air quality to meet the growing demands of the occupants, a hybrid flow path was applied to the air conditioner. There are various parameters which are influenced thermal comfort, Especially, Air flow is the most essential parameter to achieve comfort condition. This study presents the thermal comfort improvement for wall mount type, floor-standing type and ceiling type air-conditioner, respectively. When the occupant zone reached to comfort condition, the air flow can be changed to the wind-free mode, it can be reduced cold draft and energy consumption. The air flow visualization and temperature distribution was measured compare general cooling mode with wind-free mode.

Keywords: Wind-free; Thermal comfort; Air-conditioer;

1. Introduction

With improved living standards and the increase in the desire and importance for comfortable indoor environment, the penetration rate of residential air conditioners in South Korea is increasing every year. According to the survey report on home appliance penetration rates published by the Korea Power Exchange, the penetration rate of residential air conditioners increased from 2% in 1985 to 61% in 2011 and to 75% in 2015[1]. The cause of this increase is the increase in the various desires of consumers for indoor thermal comfort. While air conditioners were recognized as summer products for reducing the indoor air temperature in the past, the development of air conditioners is being expanded from temperature-oriented air conditioning to comprehensive comfort air conditioning by reinforcing various additional functions, such as heating, dehumidification, and air cleaning.

Indoor thermal comfort not only improves personal satisfaction but also has the economic effect of increased productivity. Dorgan[2] estimated that the annual profit resulted from the productivity improvement and medical cost savings caused by indoor air quality improvement is $62.7 billion, and Fisk[3] reported that the economic effect of the reduction in diseases and the increase in work efficiency caused by the improvement of indoor environment amounts to $40.0 - $200 billion. It can be said that indoor thermal comfort is a basic and essential condition in modern society.

1.1 Principles of wind-free air conditioners

Indoor thermal comfort can be secured by controlling the four elements of air conditioning, i.e. the indoor temperature, humidity, airflow, and cleanliness. Among them, the airflow acts as a positive element by rapidly forming a comfort condition in the space during the initial operation. The airflow, however, has double-sidedness because it acts as a negative element that induces cold draft after the formation of the comfort condition. [4][5]

To maintain continuously comfortable environment for indoor occupants without the discomfort caused by the airflow, wind-free air conditioners were developed using the hybrid flow path.

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For the wind-free air conditioners, the hybrid flow path is constructed so that the indoor temperature can be rapidly reduced with the opening of wind doors during the initial operation and the internal flow path can be changed with the closing of the wind doors when the wind-free mode is selected after a comfort condition is reached in the residential space. The airflow is uniformly discharged at low speed through micro-holes to maintain the comfort of the residential space without the feeling of airflow.

In this study, the cases of residential and system air conditioners with the hybrid flow path for wind-free cooling and the effect of wind-free cooling on the improvement of indoor thermal comfort were analyzed.

2. Theories on Indoor Thermal Comfort and Their Application

2.1 PMV and PPD

To quantify human thermal sensation, Fanger (1970) presented the predicted mean vote (PMV) by combining the results of the experiment performed with 1,300 participants and the heat balance equation for the human body.

PMV is determined by six elements, including four environmental elements (room air temperature, mean radiation temperature, relative humidity, and air velocity), metabolism, and thermal resistance of clothing. It can be expressed as a function of the human body thermal load (L) calculated with the body surface temperature and sweat evaporation rate that provides neutral thermal sensation in the metabolism (M) as shown in equation (1).

$$\mathrm{PMV} = 0.303\exp(-0.036\mathrm{M}) + 0.028 \tag{1}$$

The PMV value was set based on the seven-point thermal sensation scale of ASHRAE. The predicted percentage of dissatisfied (PPD) represents the expected percentage of people who are not satisfied with the given environment. There is a correlation between PMV and PPD as shown in equation (2). The given environment is evaluated as "comfortable" if PMV is within ±0.5 and PPD is less than 10%.[6]

$$\mathrm{PPD} = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^2)] \tag{2}$$

2.2 Application of PMV and PPD

For the calculation of PMV and PPD, equations (1) and (2) were automatically calculated by programming. The input parameters required for the calculation are shown in Table 1.

Table 1. Input parameters of PMV-PPD Program

Input Parameter	Unit
Metabolism (M)	met=W/m^2
External work (W)	W/m^2
Thermal resistance of clothing (I_{clo})	clo=m^2°C/W
Room air temperature (Ta)	°C
Mean radiation temperature (Tr)	°C
Air velocity (Va)	m/s
Relative humidity (Rh)	%

The environmental elements, i.e. the room air temperature, mean radiation temperature, air velocity, and relative humidity, were automatically obtained using sensors, and the elements related to the human body that could not be measured were treated as constants as shown in Table 2.

Table 2. Constants of PMV-PPD Program

Parameter	constant
Metabolism	1.2met = 69.84 W/m^2 (Office, Home)
External work	0W/m^2 (for everyday activities)
Thermal resistance of clothing	0.5 clo = 0.078m^2°C/W(Summer)

3. Experimental Setup and Method

3.1 Experimental setup

Experiments were performed in a residential environment laboratory that simulated the actual environment. The residential environment laboratory consisted of an outdoor environment chamber for simulating various outdoor environments and a model house.

The model house simulated the living room and main room of an apartment. Fig. 1 shows the schematic diagram of the model house. Thermocouples were installed in three dimensions to measure the temperatures inside the model house, and indoor thermal environment elements were measured using relative humidity sensors, radiation thermometers, and wind speed measuring instruments.

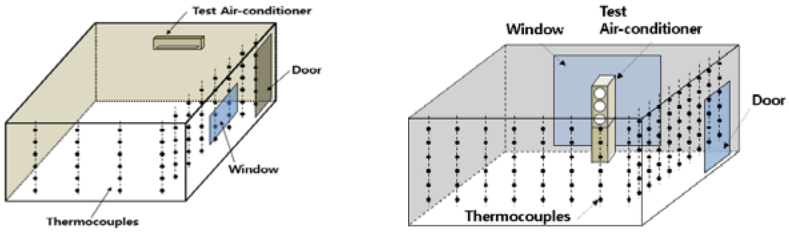


Fig. 1. Schematic diagram of model house

3.2 Experimental method

Table 3 shows the experimental test conditions in model house. The initial outdoor load conditions were a dry-bulb temperature of 35℃ and a wet-bulb temperature of 24℃ (relative humidity 39%). Tests were conducted after both the model house and the outdoor environment chamber were stabilized. The air conditioners were operated after the windows and doors had been closed to minimize the entry and exit of heat, and the indoor temperature, relative humidity, mean radiation temperature, and air velocity were measured every 20 seconds. To analyze the effect of the hybrid flow path on indoor thermal comfort, the cooling set temperature was fixed at 24℃ and the air conditioners were operated while the air volume setting was varied. In the case of residential and system air conditioners, they adopt inverters and maintain a constant indoor temperature by varying the cooling capacity through the control of the revolutions of the compressor when the indoor temperature reaches the set temperature. When the indoor temperature was stabilized at 24℃, the indoor temperature distribution, air velocity, and thermal comfort for each air volume setting were compared.

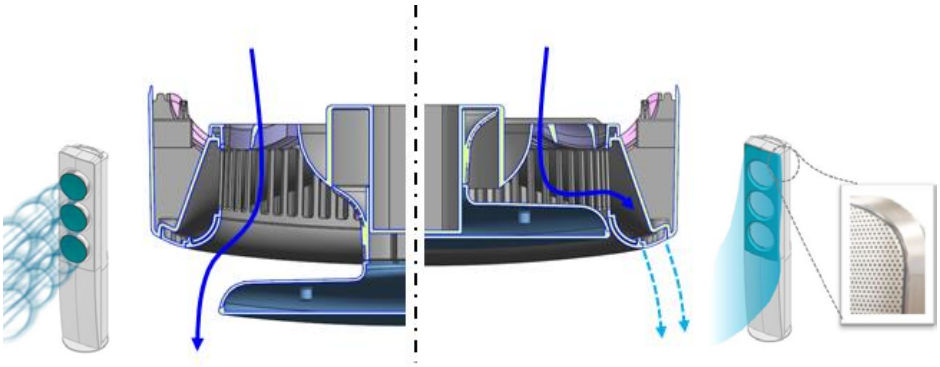
Table 3. Experiment test conditions

Parameter	Value
Initial Dry bulb temperature	35
Initial wet bulb temperature	24

Set temperature of air-conditioner 24

4. Experiment Results and Discussion

4.1 Stand-type wind-free air conditioner



(a) Cooling mode (b) Wind-Free mode

Fig. 2. Schematic of hybrid flow path

For residential air conditioners, the airflow is essential for creating comfortable conditions through the suction of hot and humid air indoors and air conditioning. Most indoor occupants, however, have the perception that direct exposure to the cold airflow from an air conditioner is harmful to their health.

Considering this double-sidedness of the airflow, the hybrid flow path was applied to stand-type air conditioners, which dominate the domestic market, to rapidly reduce the indoor temperature with powerful cooling during the initial operation and to generate comfortable environment without the feeling of airflow after the set temperature is reached.

When the hybrid flow path is applied, powerful and fast airflow is discharged from the front with wind doors opened for rapid cooling during the initial operation as shown in Fig. 2(a). When the wind-free mode is selected after the residential space reached a comfort condition, the internal flow path is changed as the wind doors are closed as shown in Fig. 2(b). In this case, the airflow is uniformly discharged at low speed through the 135,000 micro-holes in the front panel.

4.1.1 Indoor temperature and air velocity

To analyze the indoor thermal comfort of a stand-type residential air conditioner in an indoor residential space (the indoor activity range of occupants: less than 1.8m height from the floor, more than 0.3m distance from the external wall, and within 1 m from the air conditioner) [7], the air velocity and indoor temperature distributions at the cooling and wind-free modes are shown in Figs. 3 and 4, respectively.

When the air velocities at 1.5 m from the air conditioner were compared, the air velocity exceeded 0.5 m/s at all points even at the low airflow mode, resulting in non-uniform indoor temperatures. ASHRAE defines the air velocity of 0.15 m/s or less in a residential space as still air [8].

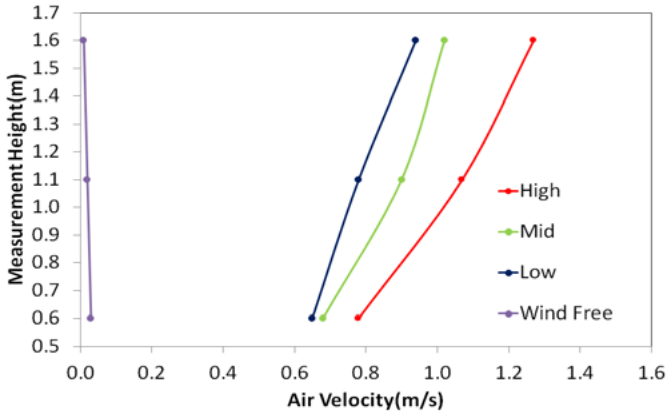
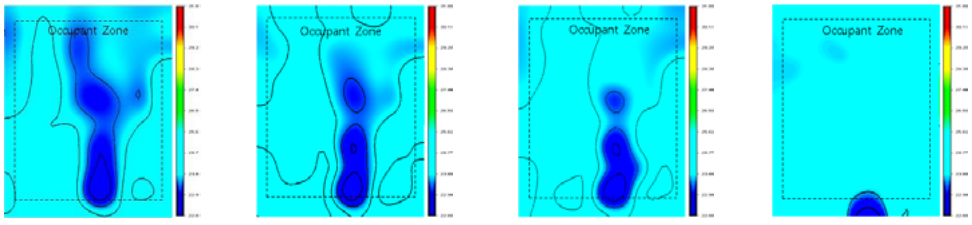


Fig. 3. Air flow velocity distribution of cooling mode and Wind-Free mode



(a) High Airflow mode (b) Mid Airflow mode (c) Low Airflow mode (d) Wind-Free mode

Fig. 4. Temperature distribution of cooling mode and Wind-Free mode

At the wind-free mode, the air velocity was 0.15 m/s or less, and thus the airflow could not be felt. As the indoor temperature was maintained while the air velocity in the residential space was 0.15 m/s or less, a uniform indoor temperature distribution was formed as shown in Fig. 4(d).

4.1.2 PMV and PPD

To compare the indoor thermal comfort of the cooling mode with that of the wind-free mode, PMV and PPD were shown in Figs. 5 and 6, respectively. In the case of the cooling mode, as the air volume setting decreased while the indoor temperature was maintained at 24℃, the air velocity decreased and the PMV and PPD values slightly increased to thermal neutrality. Even at the low airflow mode, however, it is expected that at least 30% of the occupants exposed to the discharged airflow will experience discomfort caused by the cold.

At the wind-free mode, the air velocity was 0.15 m/s or less and the influence of the airflow was minimized. As PMV approached zero, thermal neutrality was closer, and PPD was also in the comfort zone of10 or less. Uniform thermal comfort was secured in the residential space because the air velocity was no more than 0.15 m/s and the indoor temperature was uniformly maintained as shown in Fig. 4(d).

4.2 Wall-mounted wind-free air conditioner

As wind-free air conditioning is also required in personal spaces, such as bedrooms and studies, the hybrid flow path was applied to wall-mounted residential air conditioners. When the hybrid flow path is applied, the wind doors are opened and rapid cooling is performed with powerful and fast airflow as shown in Fig. 7, and

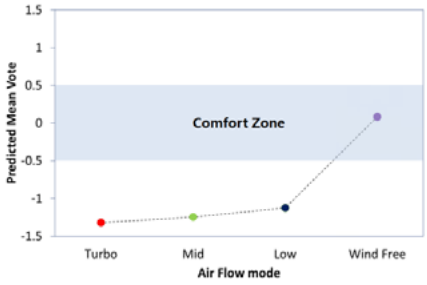


Fig. 5. Comparison of the PMV at cooling mode and Wind-Free mode

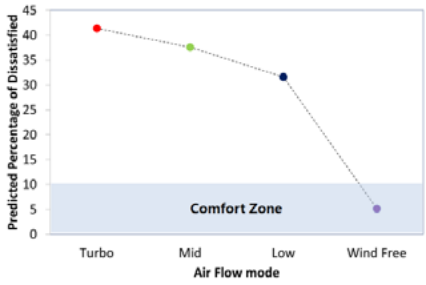
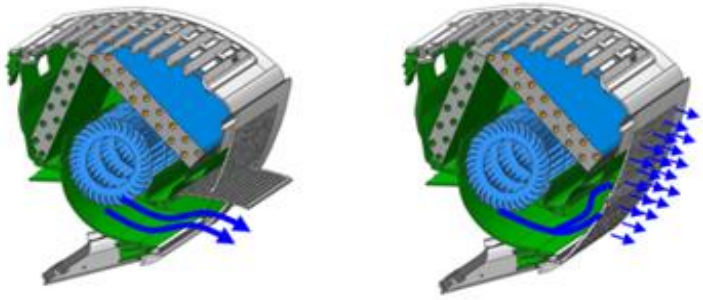


Fig. 6. Comparison of the PPD at cooling mode and Wind-Free mode

the internal flow path is changed as the wind doors are closed when comfortable cooling is required after the set temperature is reached. The residential space can remain comfortable without wind as the airflow is uniformly discharged at low speed through the micro-holes in the front panel.

To analyze the indoor thermal comfort of a wall-mounted wind-free air conditioner, it was installed in the residential environment laboratory, and the indoor temperature and air velocity were analyzed in the same manner as the stand-type wind-free air conditioner.



(a) cooling mode (b) Wind-Free mode

Fig. 7. Schematic of hybrid flow path

4.2.1 Indoor temperature and air velocity

To analyze the indoor thermal comfort of the wall-mounted air conditioner in an indoor residential space (the indoor activity range of occupants: less than 1.8m height from the floor, more than 0.3m distance from the external wall, and within 1 m from the air conditioner) [7], the air velocity and indoor temperature distributions at the cooling and wind-free modes are shown in Figs. 8 and 9, respectively.

When the air velocities at 1.5 m from the air conditioner were compared, the air velocity exceeded 1.0 m/s at the cooling modes, including the high, mid, and low airflow modes, thereby causing non-uniform indoor temperatures (Fig. 9(a), (b), (c)).

At the wind-free mode, the air velocity was 0.15 m/s or less and thus the airflow could not be felt. As the indoor temperature was maintained while the air velocity in the residential space was 0.15 m/s or less, a uniform indoor temperature distribution was formed as shown in Fig. 9(d).

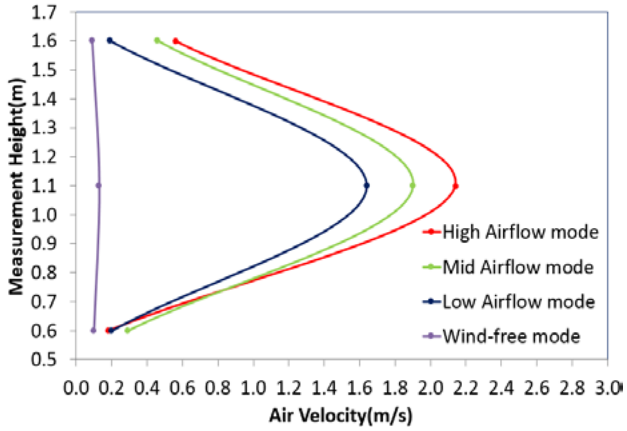
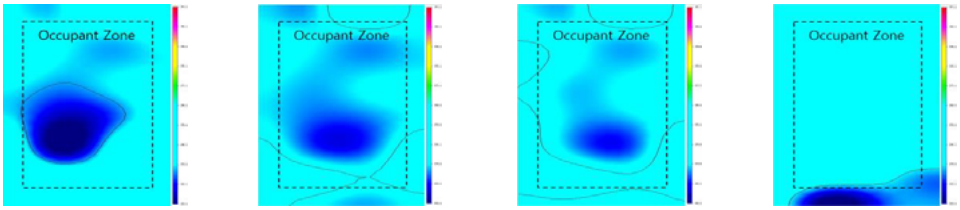


Fig. 8. Air flow velocity distribution of cooling mode and Wind-Free mode



(a) High Airflow mode (b) Mid Airflow mode (c) Low Airflow mode (d) Wind-Free mode

Fig. 9. Temperature distribution of cooling mode and Wind-Free mode

4.2.2 PMV and PPD

To compare the indoor thermal comfort of the cooling mode with that of the wind-free mode, PMV and PPD were shown in Figs. 10 and 11, respectively. In the case of the cooling mode, as the air volume setting decreased while the indoor temperature was maintained at 24℃, the air velocity decreased and the PMV and PPD values were slightly improved to thermal neutrality. Even at the low airflow mode, however, it is expected that at least 20% of the occupants will experience discomfort caused by the cold.

At the wind-free mode, the air velocity was 0.15 m/s or less and the effect of the airflow was minimized. As PMV approached zero, thermal neutrality was closer, and PPD was in the comfort zone of 10 or less. Uniform thermal comfort was secured in the residential space because the air velocity was no more than 0.15 m/s and the indoor temperature was uniformly maintained as shown in Fig. 9(d).

4.3 Ceiling-type 1-way cassette wind-free air conditioner

To expand the wind-free function from residential air conditioners to system air conditioners, the hybrid flow path was applied to 1-way cassette air conditioners, which are mostly built-in products, as shown in Fig. 12.

In the case of 1-way cassette air conditioners, the airflow arrival distance is important for uniform and fast cooling due to their installation characteristics. The conventional 1-way cassette air conditioners exhibited an approximately 40% flow loss due to the airflow resistance caused by blades when remote-distance airflow was implemented. In the case of the wind-free 1-way cassette air conditioners with the hybrid flow path, however, the air volume loss could be reduced to approximately 20% by raising the flow path by 10° compared to the

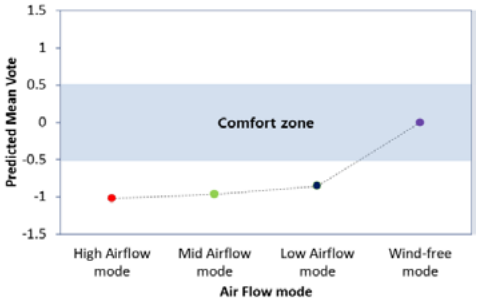


Fig. 10. Comparison of the PMV in the cooling mode and wind-free mode

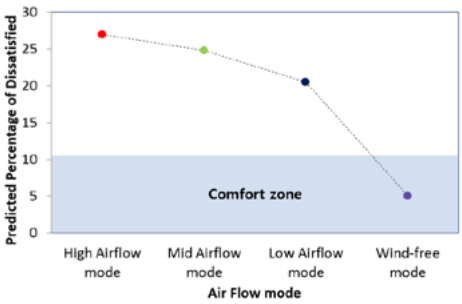
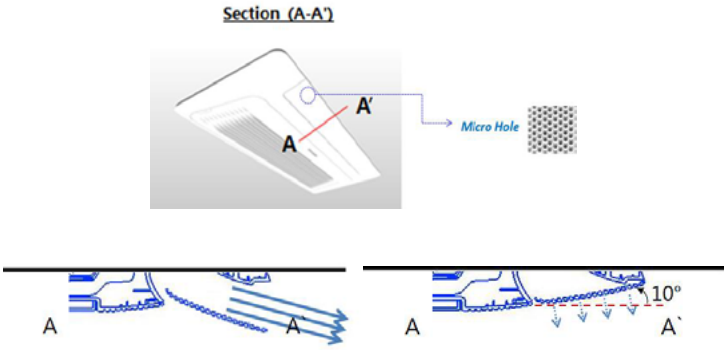


Fig. 11. Comparison of the PPD in the cooling mode and wind-free mode

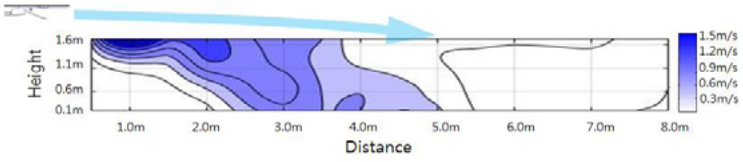
conventional flow paths. Moreover, while the geometry of the internal flow path of the conventional 1-way cassette air conditioners was almost perpendicular to the ceiling surface, that of the wind-free 1-way air conditioners was inclined according to the angle of the discharged airflow.

As a result, the remote-distance airflow of the wind-free 1-way cassette air conditioners with the hybrid flow path increased by approximately 60% compared to that of the conventional 1-way cassette air conditioners as shown in Fig. 13(b).

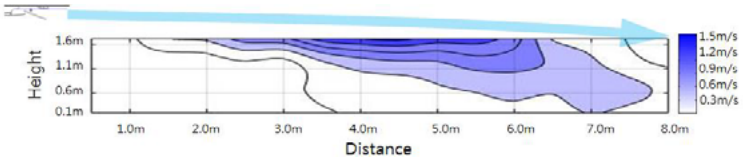


(a) Long air flow mode (b) Wind-Free air flow mode

Fig. 12. Schematic of hybrid flow path



(a) Conventional 1-way CST



(b) Wind-Free 1-way CST

Fig. 13. Air flow velocity distribution

4.3.1 Indoor temperature and air velocity distribution

To compare the thermal comfort according to the airflow when a comfort condition is formed after reaching the set temperature, the air velocity and temperature distributions under the cooling mode of a conventional 1-way cassette air conditioner and the wind-free mode of a wind-free 1-way cassette air conditioner were shown in Figs 14 and 15, respectively.

When the air velocities at 1.5 m from the air conditioner were compared, the air velocity of the conventional 1-way cassette air conditioner exceeded 0.7 m/s as shown in Fig. 13, and non-uniform indoor temperatures were maintained because the temperatures at the points through which the air flew were low as shown in Fig. 14(a). On the other hand, the air velocity of the wind-free 1-way cassette air conditioner at the wind-free mode was 0.15 m/s or less as shown in Fig. 14, and a uniform temperature distribution was maintained in the residential space as shown in Fig. 15(b).

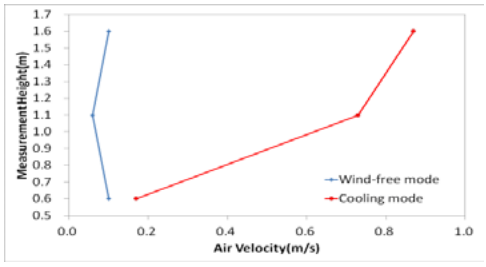
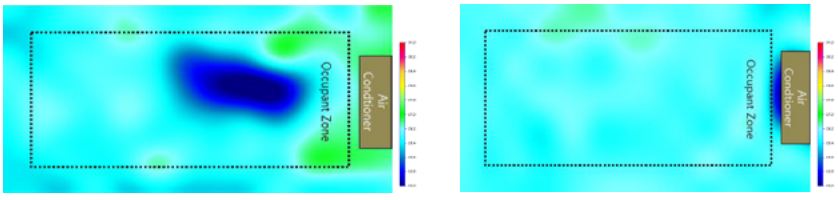


Fig. 14. Air flow velocity distribution of cooling mode and Wind-Free mode



(a) Cooling mode (b) Wind-Free mode

Fig. 15. Temperature distribution of cooling mode and Wind-Free mode

4.3.2 PMV and PPD

To compare the indoor thermal comfort of the cooling mode with that of the wind-free mode, PMV and PPD were shown in Figs. 16 and 17, respectively. In the case of the conventional 1-way cassette air conditioner, the indoor temperature was not uniform and PMV was approximately -1.49 due to the discharged airflow. Therefore, discomfort caused by the cold is predicted and it is expected that approximately 50% of the

occupants will experience discomfort when PMV is converted to PPD. In the case of the wind-free 1-way cassette air conditioner at the wind-free mode, on the other hand, the air velocity was 0.15 m/s or less in the residential space and a uniform indoor temperature distribution was formed. Therefore, it is expected that the occupants will be comfortable regardless of their positions.

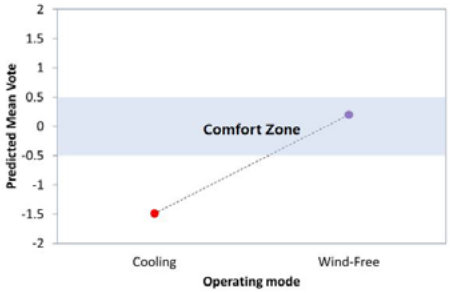


Fig. 16. Comparison of the PMV in the cooling mode and Wind-Free mode

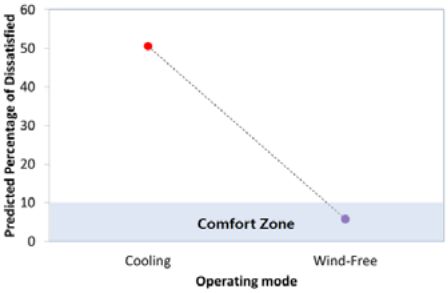


Fig. 17. Comparison of the PPD in the cooling mode and Wind-Free mode

5. Conclusion

In this study, the thermal comfort of the wind-free air conditioners that applied the hybrid flow path to residential and system air conditioners was analyzed to implement powerful cooling during the initial operation and comfortable environment without discomfort caused by the cold airflow from the air conditioner after reaching the set temperature. To this end, experiments were performed in the residential environment laboratory that simulated the actual environment, and the results of the air velocity, indoor temperature distribution, predicted mean vote (PMV), and predicted percentage of dissatisfied (PPD) at the conventional cooling mode and the wind-free mode were compared.

In the case of the stand-type wind-free air conditioner, the indoor temperature distribution was not uniform due to the discharged airflow faster than 0.5 m/s at the cooling mode when the indoor temperature was maintained at 24°C, and it is expected that at least 30% of the occupants will experience discomfort caused by the cold. At the wind-free mode, the air velocity in the residential space was no more than 0.15 m/s and a uniform indoor temperature distribution was confirmed.

In the case of the wall-mounted wind-free air conditioner, an experiment was performed under the same conditions as those of the stand-type wind-free air conditioner. At the cooling mode, the indoor temperature distribution was not uniform due to the discharged airflow of 1.0 m/s or faster, and it is expected that at least 20% of the occupants will experience discomfort caused by the cold. At the wind-free mode, the air velocity in the residential space was 0.15 m/s or less and a uniform indoor temperature distribution was confirmed.

To expand the wind-free function to system air conditioners, the hybrid flow path was applied to 1-way cassette air conditioners, which dominate the built-in market. As a result, the airflow arrival distance increased by approximately 60% compared to the conventional 1-way cassette air conditioners, making it possible to rapidly and uniformly cool a large space during the initial operation.

Under the condition of maintaining the same indoor temperature when a comfort condition is formed after reaching the set temperature, the air velocity of the conventional 1-way cassette air conditioner exceeded 0.7 m/s, resulting in non-uniform indoor temperatures. In addition, it is expected that approximately 50% of the occupants will experience discomfort due to the discharged airflow. In the case of the wind-free 1-way cassette air conditioner, still air (with an air velocity of 0.15 m/s or less) defined by ASHRAE was formed in the residential space at the wind-free mode, confirming that a uniform indoor temperature distribution was maintained.

When the hybrid flow path is applied to residential and system air conditioners and wind-free cooling is performed, it is expected that occupants can secure uniform thermal comfort in their residential spaces because discomfort and non-uniform indoor temperatures caused by the discharged airflow are removed.

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