Cooling Performance of Air-Conditioning System with Ceiling Suspended Packaged Air Conditioning Unit over Divided-Type Membrane Ceilings in Large Classroom

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ABSTRACT

The mainstream of air-conditioning system for medium and small sized buildings is conditionally air mixing ventilation with ceiling cassette unit of packaged air conditioner (PAC), however, it may bring a high cold-draught risk to occupants, due to the direct drop of the supply air jet. To solve this problem, the air mixing ventilation system can be improved into an air based radiant air-conditioning system by stretching the non-flammable membrane under the ceiling with PAC, thus the cold-draught of PAC could be substantially eliminated and the indoor environment could be improved easily. This air-conditioning system is named Membrane Ceiling Air-Conditioning System Using Ceiling Suspended PAC in this study. Many advantages of the system are (1) draught-less environment by inhibiting air velocity in occupation zone; (2) combination of the convective cooling by supplying micro airflow through a membrane ceiling and the radiative cooling from the cooled membrane ceiling; (3) the occupants' safety in case of the ceiling is collapsing because of its lightweight compared with the conventional ceiling materials; (4) the effect to avoid glare by diffusing illumination light. In addition, by dividing the membrane and making slits between them, that is divided-type, the convective airflow between the spaces across the membrane can be increased.
However, it isn’t clear how the indoor environment will be affected by divided-type membrane ceiling air-conditioning system under various conditions. The aim of this study is to investigate the performance of this membrane ceiling air-conditioning system, and to conduct a Computational Fluid Dynamics (CFD) analysis on the airflows in the lecture room with this improved membrane ceiling air-conditioning system. The parameter in the CFD analysis is the membrane laying ratio, which is the ratio of membrane ceiling area to floor area.-Furthermore, room air temperature, air flow pattern and two evaluation indices (DR and ADPI), and exchange air velocity were evaluated by CFD analysis.
The result of this study shows that the improved membrane ceiling air-conditioning system can largely reduce the air velocity and thermal discomfort in occupied zone, compared with the traditional PAC. In addition, it is also shown that the membrane laying ratio would give a large effect on the indoor thermal environment, cooling efficiency and indoor air quality in the occupied zone.

KEYWORDS

Membrane, CFD Analysis, Draught, DR, ADPI

1 INTRODUCTION

In Japan, the mainstream of air-conditioning system for medium and small sized buildings is air mixing ventilation with ceiling cassette unit of packaged air conditioner (PAC). However, in cooling mode, there is a risk of cold draught due to the fall of supply air, and it may cause discomfort of the occupants. In order to solve this problem, the radiant air conditioning systems have attracted many people's interest. There are two types of radiant air-conditioning systems, water-based type or air-based type. It is usual to use water as refrigerant, because of due to the high capabilities of energy saving. Although, it is difficult to install this system and maintain system performance. Thus, the number of introductions example using air-based type has been increasing recently.

In addition, the new air-conditioning system, how non-flammable membrane has been installed underneath the ceiling at rooms with PAC, has been proposed. By installing the membrane, ventilation system of rooms with PAC can be easily changed to the air-based radiant air-conditioning system, which will improve the indoor environment by preventing draught risks in the occupied zone.

Here in this paper, the air-conditioning system shall be called membrane ceiling air-conditioning system. The characteristics of the system are; (1) draught-less environment by inhibiting air velocity in occupied zone; (2) combination of the convective cooling by the micro airflow through a membrane ceiling and the radiative cooling from cooled membrane ceiling *[1]*; (3) occupants are kept safe due to the lightweight of the membrane compared to the other materials, in case of collapsing of the radiant ceiling; (4) the effect to avoid glare by diffusing illumination light at the membrane *[2]*. As shown in Figure 1, in order to increase the amount of convective heat transmission and exchange flowrate, the membrane was divided, thus the airflow can go through the slit between the membrane.

However, the indoor environment of a room with divided-type membrane air-conditioning system has not yet been sufficiently studied. The aim of this study is to investigate the performance and to provide the design date of the membrane ceiling air-conditioning system. CFD analysis was conducted at the room with this new membrane ceiling air-conditioning system. DR and ADPI as indices of draught risk, exchange airflow rate as the index of indoor air quality (IAQ), and cooling effect, are evaluated by CFD and reported in this paper. Membrane laying ratio, which is defined as the ratio of membrane ceiling area to floor area, was changed as the parameter in this study.

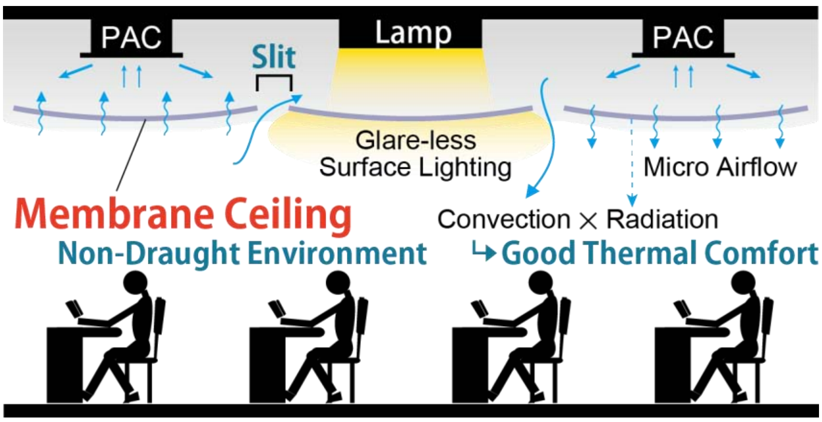


Figure 1: Outline of Divided Membrane Ceiling Air Conditioning System with PAC

Nomenclature	
k	Turbulence kinetic energy [m^2/s^2]
Q_{ex}	Exchange airflow rate between attic to indoor space [m^3/s]
Q_{mem}	Exchange airflow rate through membrane [m^3/s]
Q_{op}	Exchange airflow rate through opening (not membrane) [m^3/s]
V_{ex}	Exchange air velocity between attic to indoor space [m/s]
n_{cell}	Number of cells [-]
A_{cell}	Area of a cell on the CFD analysis (= 0.5 ×0.5 = 0.25) [m^2]
t_{ed}	Effective draught temperature [°C]
t_o	Mean air temperature of occupied zone [°C]
t_r	Mean air temperature of room [°C]
t_{PAC}	Supply air temperature from PAC [°C]
t_p	Air temperature at a point P [°C]
Tu	Turbulent intensity [%]
$\overline{U_e}$	Estimated mean velocity [m/s]
$\overline{U_o}$	Estimated mean air velocity of occupied zone [m/s]
$\overline{U_p}$	Estimated mean air velocity at a point P [m/s]
$\overline{V}$	Mean velocity [m/s]
V_z	Velocity in z direction [m/s]
u_e^*	Estimated velocity standard deviation [m/s]

2 SIMULATION MODEL FOR CFD ANALYSIS

In order to investigate the applicability of the new membrane ceiling air-conditioning system to air-conditioned classroom in summer, the CFD analysis was conducted in this study. Cradle STREAM V14.1 *[3]* which is a CFD software was used. The outdoor condition and CFD settings are shown in Table 1 and Table 2, respectively. All of the cells are 50mm × 50mm× 50mm cubes. Table 3 summarises the boundary conditions, and the analysis domain and methods of modelling are shown in Figure 2 - 4.

Table 1: Outdoor Condition

Outdoor Temp. [°C]	35
Hallway Temp. [°C]	30
Solar Radiation [W/m^2]	160
Effective Temp. Difference [°C]	West : + 6

Table 2: Summary of CFD setting

Turbulence Model	Standard k-ε model
Algorithm	SIMPLER
Discretization Scheme	QUICK
Total Number of Cells	1,289,376

Table 3 : Boundary Conditions

a. Boundary Surface

Boundary Surface		Heat Transfer Condition	Wall Function
Ceiling		Log-law	Log-law
Wall	N･S	Symmetry	
	E･W	Log-law	
	W	Log-law	Log-law
Floor		Log-law	Log-law

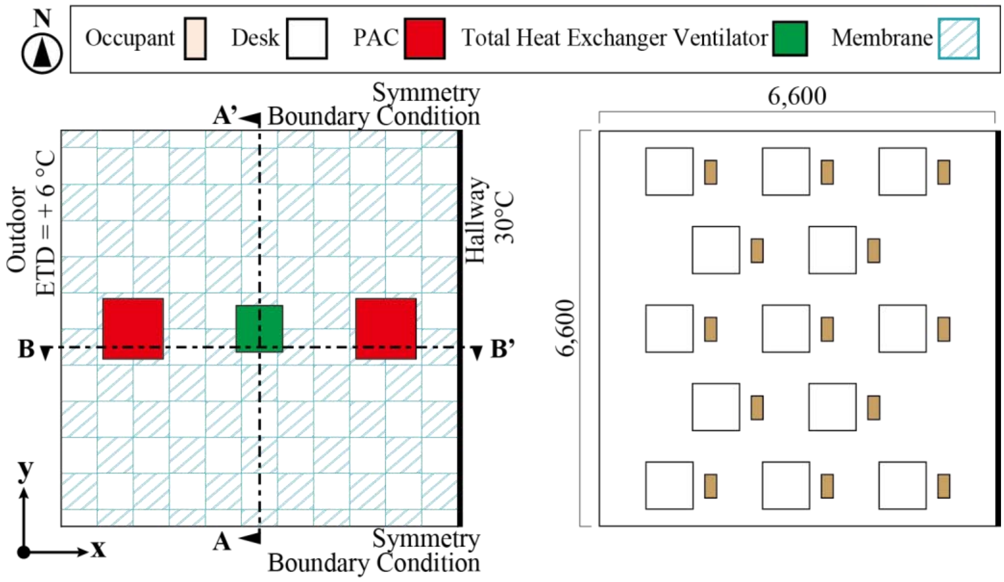
b. Heat Load

Occupant		60 W×40 people
Window		83.627 W/m^2 × 11.88m^2
Wall	East	Heat Transfer
	West	4.10 W/m^2 × 39.6m^2

c. Flow

System		Airflow Rate [m^3/h]	Supply Temp.
PAC	Inlet	65.625 × 4	P Control Sensing Temp. : Return Air of PAC
	Outlet	262.5	
Total Heat Exchanger Ventilator	Inlet	500.0	Heat Exchange Efficiency 77 %
	Outlet	500.0	

The heat transmission through the east interior wall, whose opposite side is the hallway, and the slab of ceiling and floor, were calculated by setting the equivalent heat conductivity and air temperature outside each wall and slab. On the other hand, the heat load through the west exterior wall was simulated by setting the heat flux condition and was calculated, using effective temperature difference (ETD) of summer in Japan *[4]*. The heat load at the window was obtained by adding the heat transfer and the solar radiation heat, with consideration of the heat loss through the window, and was set on the room side window position.



a. Air Conditioners and Membrane b. Occupants and Desks

Figure 2: Plan of Analysis domain of classroom

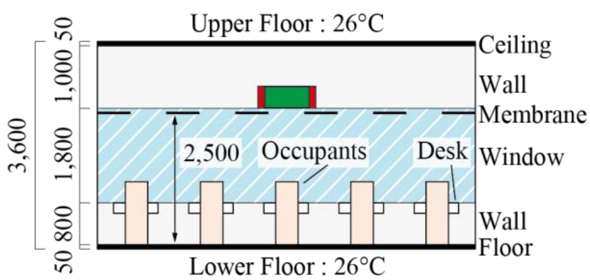


Figure 3: Cross Section at A-A'

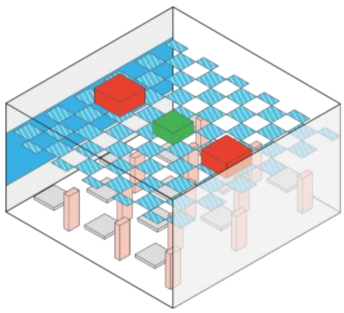


Figure 4: Isometric Drawing

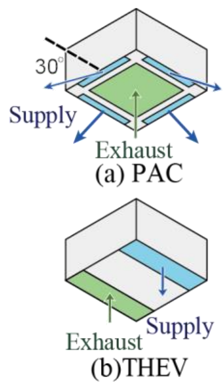


Figure 5: Model of Systems

As shown in Figure 5, two PACs and a total heat exchanger ventilator (THEV), which are introducing fresh air, were installed in the room as air conditioning system. It was assumed that PACs have the thermostats and can regulate the supply temperature to fix the exhaust temperature at 26°C and supply the cold air in the direction of depression angles formed with the ceiling surfaces of 30° from the size 50mm × 600mm inlet to the room. The THEV whose heat exchange effectiveness, which represents the ratio of exchange heat quantity between outdoor air and the room air returned, is 77% supplies the flesh air vertically downward and exhausts upward.

The characteristics of the membrane are shown in Table 4. This analysis took two steps; the first step is the investigation of membrane modelling in CFD analysis. Actually, one of the characteristics of membrane is air permeability. However detailed consideration in CFD analysis is so difficult due to too high calculation load that two simple membrane CFD models were used in the study; (1) Panel model (PM), (2) Pressure-Loss model (PLM). The former one is the PM where a membrane is simulated by non-thickness panel with the thermal conductance, and its air permeability hasn't been simulated. The radiation heat exchange between the membrane panels and others is simulated. On the other hand, using the PLM, the membrane is simulated by the condition domain through which the air momentum is reduced, equal to the membrane with 20% aperture rate, and the simulation of air permeability is conducted, though it is the fault if the membrane is ignored in radiation analysis. From the above, it is examined which one would be better from the two methods. The first step of analysis was conducted by the case detailed in Table 5. The emissivity is set to 0.9 when radiation analysis is turned on.

Table 4 : Characteristics of the Membrane

Thermal Conductance	Aperture Rate
0.054 W/m	20 %

Table 5 : Examination Case of Memb. Modeling

Case	Membrane Model	Radiation Analysis
i	Panel	-
ii	Panel	X
iii	Pressure-Loss	-
iv	Pressure-Loss	X

The second step of the analysis is aimed to grasp the thermal comfort with different pattern of membrane laying ratios as shown in Figure 6. The 60mm square membrane panels installed in Case iv model due to above consideration were set at 2.5m height of the room.

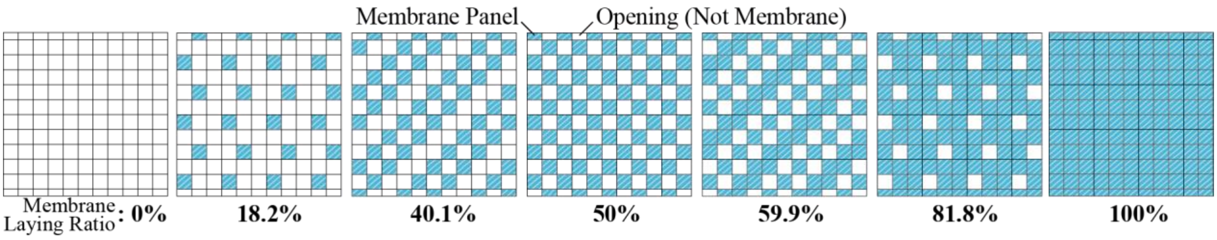


Figure 6: Layout of Membrane Panels of Analysis Case

3 EVALUATION OF THERMAL COMFORT IN THE ROOM

3.1 Equation to convert to scalar mean air velocity

To calculate thermal comfort indices used in the study, scalar mean air velocity and turbulent intensity as measured by low velocity thermal anemometers incorporating an omnidirectional velocity sensor should be applied, as the mean velocity field predicted by CFD simulation on the basis of RANS equation differs *[5]*. Thus, to quantify the improvement in determination of the indices when the air velocity field was estimated by CFD analysis, the following equations were used in the study.

$$\overline{U_e} = \begin{cases} \overline{V}(1 - 0.044Tu + 1.195Tu^2 - 0.329Tu^3),\ Tu \leq 1.3 \\ \overline{V}(0.287 + 1.502Tu),\ Tu \geq 1.3 \end{cases} \tag{1}$$

$$\mathrm{u_e^*} = \sqrt{(\overline{V}^2 + 2k - \overline{U_e}^2} \tag{2}$$

where

$$\mathrm{Tu} = \frac{\sqrt{\frac{2k}{3}}}{\overline{V}} \tag{3}$$

Thus, estimated velocity field was used to evaluate the draught environment by two indices.

3.2 DR

Fanger et al. (1989) investigated the effect of turbulent intensity on sensation of draught *[6]*. In order to evaluate the draught risk (DR) i.e., the percentage of dissatisfied people due to draught in the occupied zone, the following equation can be used.

$$\mathrm{DR} = (34 - \mathrm{t_p})(\overline{U_p} - 0.05)^{0.62}(0.37\overline{U_p}Tu + 3.14) \qquad (4)$$

Here, the part of the room up to 1.8m above the floor was assumed as the occupied zone.

3.3 ADPI

The air distribution performance index (ADPI) was developed as a way to quantify the comfort level in a space conditioned by a mixed air system in cooling *[7]*. It originally represents the volume ratio of the occupied zone where the following (a) and (b) conditions in Equation (5) were simultaneously verified, however the conditions were altered (a) and (b) conditions to (a) and (b)' conditions in order to consider the influence of the cold draught only.

- $\overline{\mathrm{U}_p} < 0.35$ (a)
- $-1.5 < t_{ed} < 1.0$ (b) → $-1.5 < t_{ed}$ (b)'

Where t_{ed} (effective draught temperature) can be calculated using the next equation:

$$\mathrm{t_{ed}} = (t_p - t_r) - 7.73(\overline{U_p} - 0.15) \qquad (5)$$

4 RESULT AND DISCUSSION

4.1 Investigation of membrane modelling in CFD analysis

The air temperature and velocity distributions at the height of 1.3m on A-A' and B-B' cross sections depicted in Figure 2 for Case i-iv (detailed in Table 4), are shown in Figure 7 respectively. As for the air temperature distribution, by comparing Case i-iv, ~~in~~ under PM and PLM conditions, the temperature field in the room with PLM membrane was all cooler than that with PM membrane. It is considered that more amount of cold supply air from PACs reached the occupied zone by going through the PLM membrane, compared to PM membrane. Furthermore, when radiation analysis was conducted in CFD analysis, the temperature both in PM and PLM conditions got lower than that without consideration of radiation. On the other hand, it was indicated that there is almost no great difference for the velocity distribution regardless of radiant analysis. However, it was shown that the velocity in the room with PLM was higher than that with PM when ~~to~~ comparing the two modelling methods, and the maximum difference between them was approximately 0.2m/s, because the airflow goes through the membrane similarly. From the above, we can see that the temperature and velocity distributions is influenced by the permeability of the membrane substantially. Thus, the analysis method of Case iv was used in the study. However, it must be noted that the most appropriate radiation heat exchange between the membrane and the room was not able to simulate, because the PLM membrane is ignored in radiation analysis.

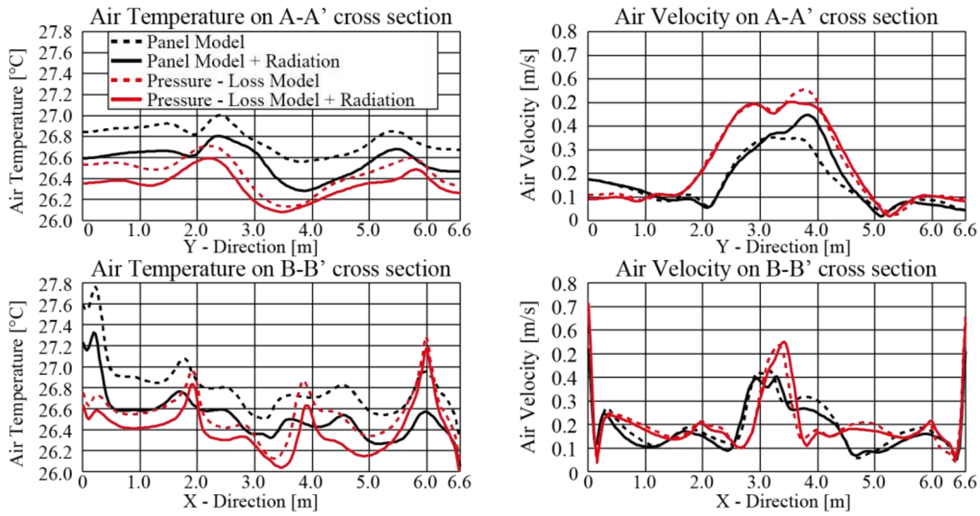


Figure 7: Compare of air temperature and velocity on A-A' and B-B' cross section at 1.3m height

4.2 Comparison of the indoor environment under various membrane laying ratio cases

4.2.1 Distribution of temperature, velocity, DR and ADPI

The average result for each case is shown in Table 6. The vertical distribution of air velocity and horizontal distribution of air temperature, velocity, DR and ADPI are respectively shown in Figure 8 and Figure 9. It is shown that the horizontal air temperature distribution became almost uniform in each case, and–the larger membrane laying ratio gets, the higher the temperature in occupied zone becomes. The reason is considered as that supply temperature from the PAC which includes the thermostat could not be appropriately controlled with high membrane laying ratio. Thus, the control system of PAC with a membrane ceiling may need to be considered in other ways.

On the other hand, when membrane laying ratio becomes higher and higher, the air velocity in occupied zone becomes much slower, and the DR and ADPI was evaluated to be a better result. Since the supply air jetting from the PAC lost momentum due to passing through the membrane. Therefore, we can conclude that the indoor environment can be improved by preventing draught risks as increasing the membrane laying ratio.

Table 6 : Average result value of air temperature, air velocity and indices

Case	Membrane Laying Ratio [%]	T_r [°C]	T_o [°C]	T_{pac} [°C]	U_o [m/s]	T_{ed} [°C]	DR [%]	ADPI [%]
1	0	26.3	26.2	23.7	0.311	-1.31	10.2	69.6
2	18.2	26.4	26.2	23.6	0.282	-1.15	9.4	76.6
3	40.1	26.4	26.3	23.6	0.240	-0.78	8.3	84.4
4	50.0	26.5	26.4	23.6	0.210	-0.57	7.4	90.1
5	59.9	26.6	26.4	23.6	0.197	-0.52	7.0	91.8
6	81.8	26.7	26.6	23.6	0.174	-0.24	6.1	94.5
7	100	26.8	26.8	23.6	0.164	-0.10	5.6	94.9

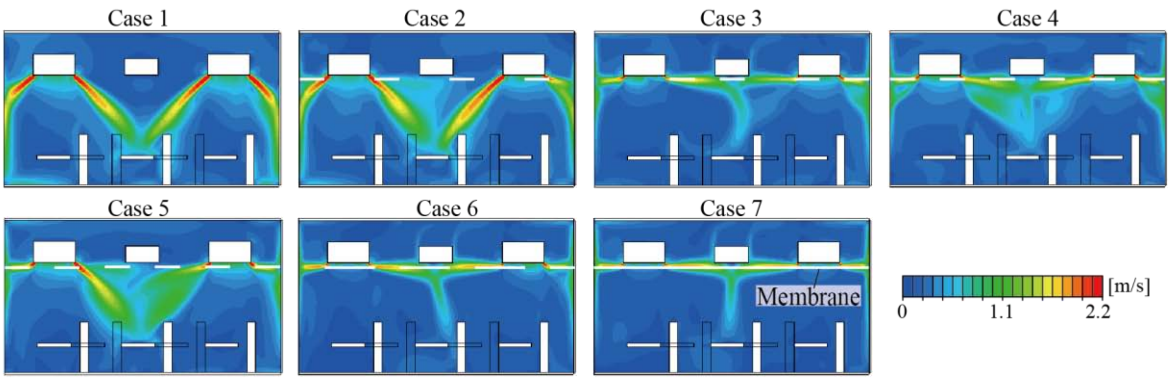


Figure 8: Vertical distribution of air velocity on B-B' cross section

4.2.2 Comparison between Exchange air velocity, DR and ADPI

To find an appropriate membrane laying ratio, the exchange air velocity, in other words, the amount of airflow rate exchanged from attic (space between ceiling and membrane) to indoor space divided by the floor area in the room, was used as an index. It is because increasing of exchange air velocity means increasing of convection flow and make a good effect for IAQ and cooling efficiency. The exchange air velocity can be estimated based on the following equations.

$$v_{ex} = \frac{Q_{ex}}{A_{floor}} \tag{6}$$

where

$$Q_{ex} = Q_{mem} + Q_{op} \tag{7}$$

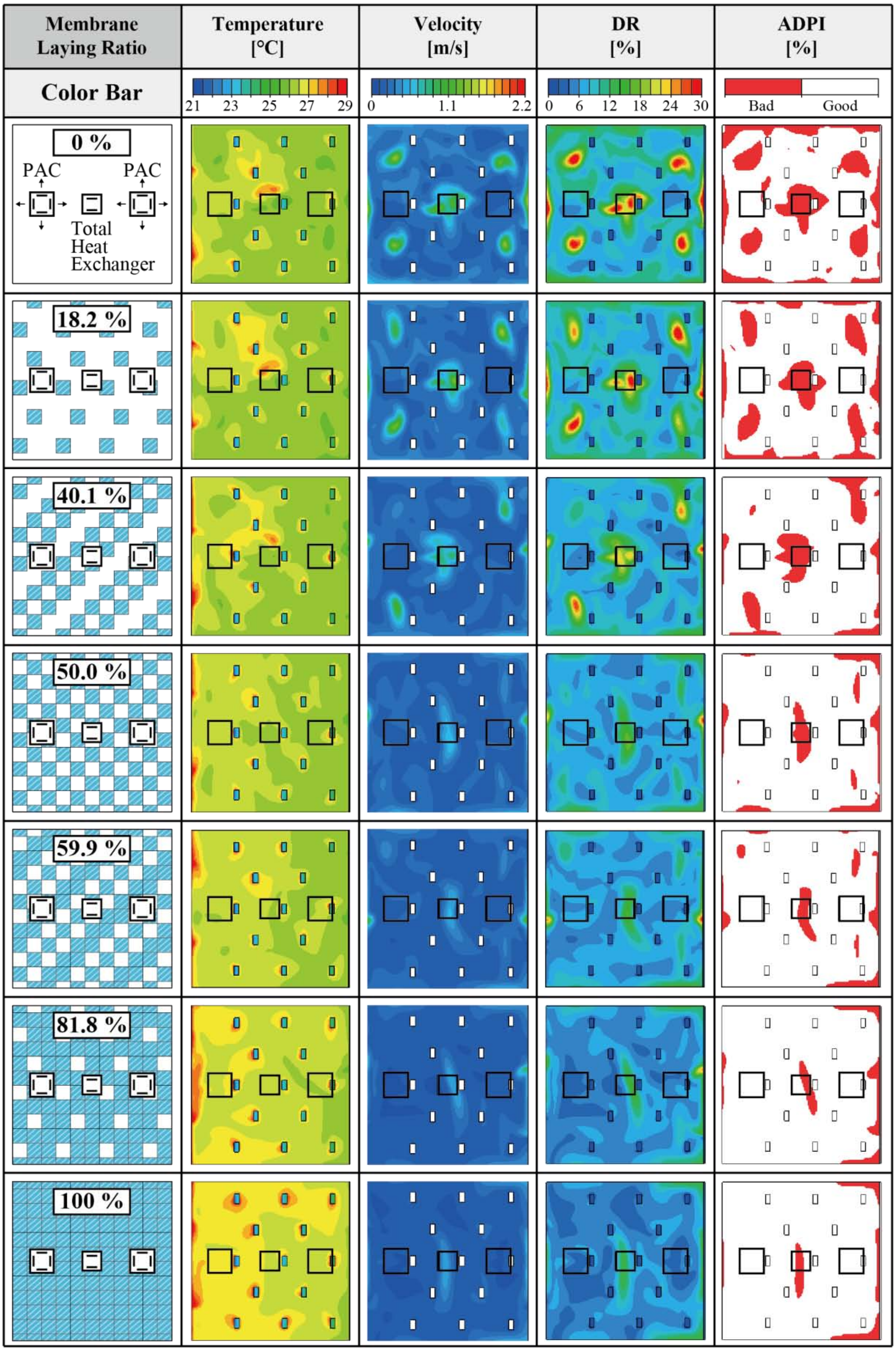


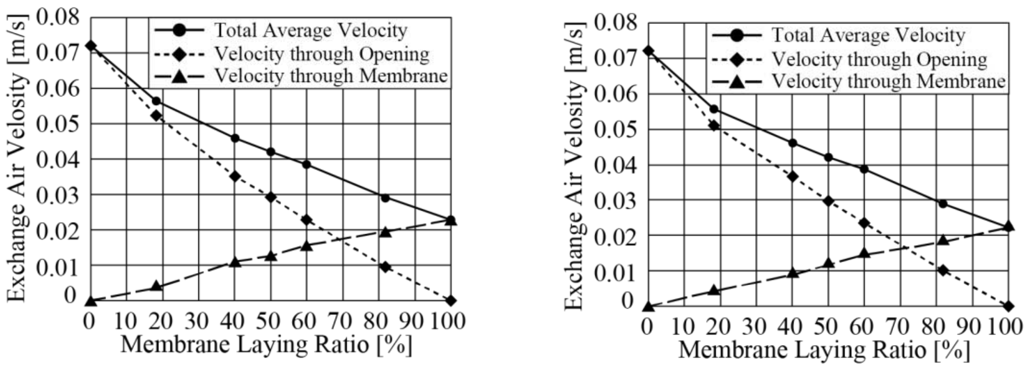
Figure 9: Horizontal distribution of air temperature, air velocity, DR and ADPI at 1.1m height

Furthermore, Q_{mem} and Q_{op} are calculated by the following equation.

$$Q_{mem}\ (\text{or}\ Q_{op}) = n_{cell} \cdot A_{cell} \times \mathrm{V_z} \tag{8}$$

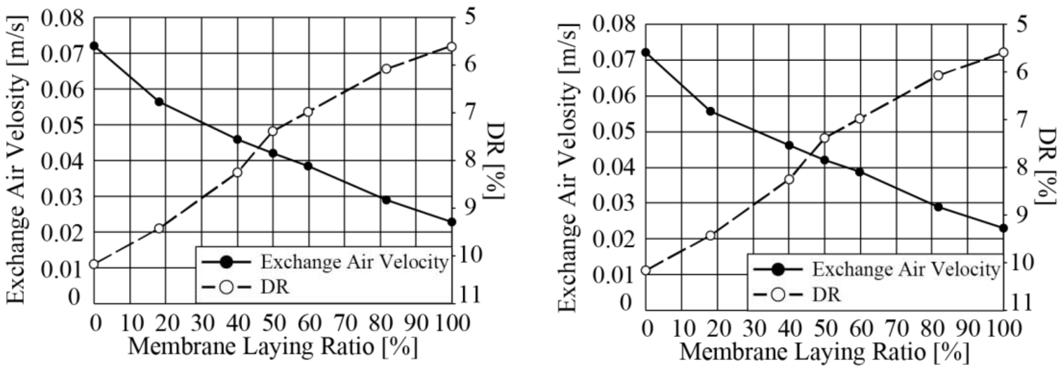
Where, n_{cell} is the number of cells which are passed by exchange air. Therefore, when Q_{mem} is calculated, the number of the membrane and the velocity through the membrane is used.

The breakdown of exchange air velocity is shown in Figure 10. When the membrane laying ratio is about 70%, the velocity through the opening and the membrane may be same. The comparison between exchange air velocity, DR and ADPI are shown in Figures 11-12. It is shown that there was not much difference between upward and downward exchange velocity. On the other hand, we can also see that the exchange air velocity was decreased by increasing the membrane laying ratio. As mentioned in the preceding section, the draft risk could be prevented. Therefore, it is noted that the membrane laying ratio should be carefully decided because it will give large impact on the indoor environment.



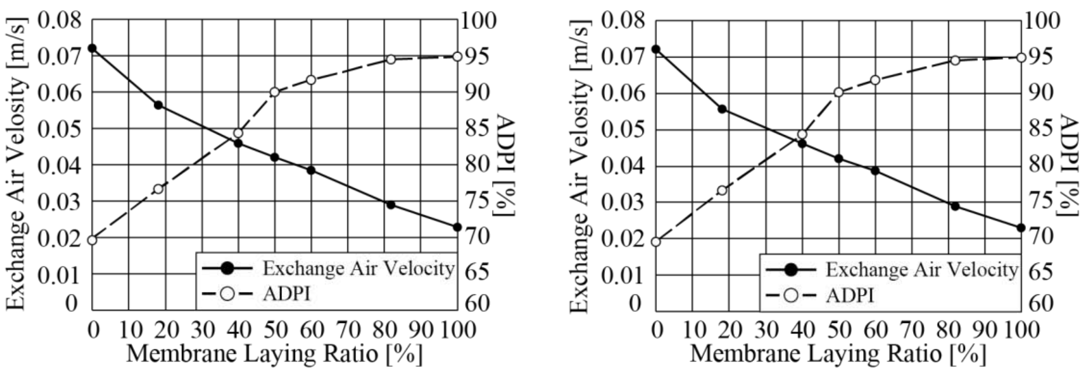
(a) Upward (b) Downward

Figure 10: Breakdown of Exchange Air Velocity



(a) Upward (b) Downward

Figure 11: Exchange Air Velocity vs. DR



(a) Upward (b) Downward

Figure 12: Exchange Air Velocity vs. ADPI

5 CONCLUSIONS

In this study, the evaluation on the impact of membrane ceiling air-conditioning system using ceiling suspended PAC on the indoor environment is carried out by CFD analysis.

The main remarks obtained in this study is summarized as follows:

- In order to simulate a membrane in CFD analysis, it is examined that the pressure-less model may be better than the panel model, because the indoor environment is much influenced by the airflow through the membrane. However, further studies are need to be done in order to simulate high-accuracy for the system, because radiative heat transfer between the wall and membrane is ignored in the pressure model.

- By increasing the membrane laying ratio, the exchange air velocity was decreased, so that the draught risk was prevented. Therefore, it is noted that the membrane laying ratio should be carefully decided because it has an essential impact on the indoor environment.

As future prospects, we intend to conduct a full-scare experiment in order to grasp the actual phenomenon and confirm the consistency between the result of CFD analysis and the experiment. In addition, the effects of the amount of exchange velocity on the indoor air quality and the efficiency of the performance of air-conditioning system will also be evaluated in the next work.

6 ACKNOWLEDGEMENTS

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