Improvement Method of Thermal Environmental Near Windows During Heating Period -Thermal and Air Flow Characteristics of Two-Dimensional Jet from Breeze Line Diffuser in Free Field

Shaoyu Sheng*[1], Toshio Yamanaka[1], Tomohiro Kobayashi[1], Jihui Yuan [1], Masahiro Katou[2] and Saori Yumino[2]

1 Osaka University
2-1 Yamadaoka
Suita, Osaka, Japan
Sheng_shaoyu@arch.eng.osaka-u.ac.jp

2 KAJIMA Technical Research institute
2-19-1 Tobitakyu
Chofu, Tokyo, Japan

ABSTRACT

The perimeter space near windows usually has some problems with the thermal environment which is easily affected by heat transfer and radiation from windows. Compared to interior space of the room, the airflow in this area usually has different characteristics due to the effect of buoyancy, thus it may reduce thermal comfort of perimeter space. To improve the thermal environment in perimeters, breeze line diffusers are widely used in Japan as the terminal equipment of air conditioning and ventilation systems. This diffuser is the same as so-called ceiling slot diffuser. In this research, the authors analysed the performance of breeze line diffuser for heating usage by experiment. The airflow rate and temperature around the breeze line diffuser was also obtained to define boundary conditions of CFD (Computational Fluid Dynamics) model of breeze line diffuser, which will be simulated in our future work.

For the full-scale experiment, the breeze line diffuser is set up in a free field. The air supply temperature under isothermal and non-isothermal conditions, and the length of the outlet of the diffuser are adjusted as parameters. Temperature and wind velocity distribution not only around the diffuser but also the other part of the free field were measured by hot wire anemometer, ultrasonic anemometer, and thermocouple in this study.

The results of the experiment are compared. The breeze line diffuser has a limited heating effect in the occupant zone (height below 1.7m) due to the effect of buoyancy, but heating effect can be decreased if the outlet velocity is fast enough. Install some deflection plane inside the breeze line diffuser to adjust the outlet area can help to enhance diffuser's heating effect. And the authors will use these data to decide the location of P.V. Method's boundary. The airflow rate and temperature distribution will also be used as comparison data to examine the accuracy of the CFD model in further study.

KEYWORDS

Perimeter environment, Breeze line diffuser, Free field, Airflow distribution

1 INTRODUCTION

Breeze line diffusers are widely used in Japan as the terminal equipment of air conditioning and ventilation systems to improve the thermal environment of the perimeter area near the window. This diffuser is the same as so-called ceiling slot diffuser. With the buoyancy's effect, warm air outflow has very different characteristics while compared to the condition of cooling air, and the research on efficiency of the diffuser for heating usage is limited [1]. Furthermore, in recent years, designs like glass curtain wall make the glazing ratio much larger, and the equipment with higher efficiency contributes to less heat generation than before, thus these problems like temperature distribution and cold draft in perimeter area during heating period are arising. It is important to examine the performance of breeze line diffuser and improve its efficiency for heating usage.

According to the user's feedback and the results of some simple smoke test, the perimeter performance of breeze line diffuser in winter is occasionally poor because warm airflow jetting from the breeze line diffuser cannot reach the occupancy zone below 1.7m height when the outlet velocity is not high enough. Although raising the air volume can increase the outlet velocity, and the outlet temperature should also be balanced with the heat load, it may complicate the operation and decrease the total efficiency of the air conditioning system. Thus, without replacing the breeze line diffuser to a new type, two deflection panels are installed inside the diffuser to change the area of outlet. Under the same air volume condition, the velocity of outlet airflow can be varied by adjusting the panel angle of diffuser.

CFD simulation is considered as the most efficient way to examine the efficiency of breeze line diffuser with deflection panels in different outlet temperatures and operational environment, because the parameter conditions can be changed easily. As the first step of a CFD simulation, it is necessary to obtain enough data through experiment to precisely reproduce the diffuser's property in CFD simulation.

With the full-scale experiment carried out in the free field, the authors had meant to use the vector velocity and temperature data respectively measured by ultrasonic anemometer and thermocouples at the surface area of the diffuser as the boundary condition of CFD simulation. However, the frequency of ultrasonic anemometer (max 10Hz) cannot provide enough data to calculate the turbulence kinetic energy and turbulence eddy dissipation accurately. Additionally, the probe size of the ultrasonic anemometer (3cm) is larger than the diffuser's size (2.55cm wide), thus the vector velocity at the surface area of diffuser can't be well measured. These will decrease the reliability of the CFD model, and may even give incorrect prediction in further research.

The shape of the diffuser is always oversimplified in CFD though the actual breeze line diffuser has complex geometry. It is considered that simple CFD diffusers will lead to inaccurate predication. On the contrary, establishing a complex geometry model of breeze line diffuser may increase the accuracy of prediction, however huge computer capacity and long calculation time are required. Fortunately, it is generally acknowledged that using P.V. Method (Prescribed Velocity Method) to displace the model into some layer's boundary condition to reproduce the diffuser's outlet airflow has satisfactory accuracy in CFD simulation [2], [3] and fewer numbers of meshes is needed to help reduce the computational load.

The aim of this study is to obtain the data of airflow and temperature distributions both near the diffuser and whole outlet space by experiment. Based on the experimental data obtained in this study, the authors will decide the measurement layer's location of X-type probe hotwire anemometer. Furthermore, the velocity and temperature data of outlet space will be used to examine the accuracy of the CFD simulation in the future.

2. FULL SCALE EXPERIMENT

2.1 Experiment facilities

■ Breeze line diffuser

The breeze line diffuser used for experiment in this study is shown in Fig.1 and Fig.2. Two deflection panels are installed inside the diffuser to change the outlet area of diffuser with 1/1 outlet or 1/2 outlet by adjusting the panel angle. Thus, the velocity of outlet airflow can be varied under the same air volume condition.

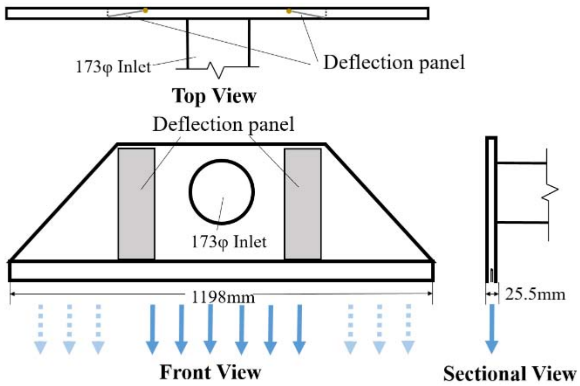


Fig.1 Detail view of the breeze line diffuser

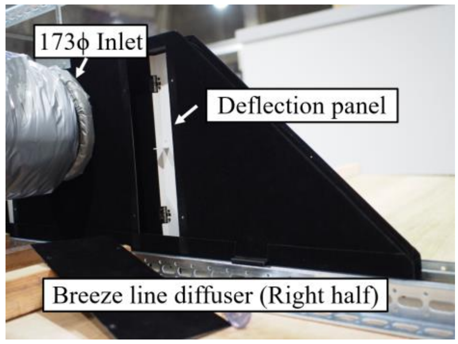


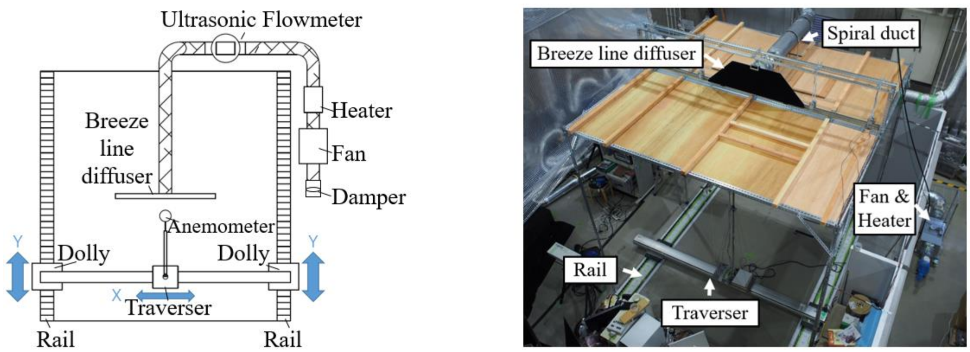
Fig.2 Photograph of the breeze line diffuser

■ Experiment space

The experiment was conducted in the Laboratory of Building Environment (hereinafter abbreviated as LBE) at Osaka University in February 2019. The experiment space with a dimension of 3 m (L) x 3 m (W) x 3 m (H), is a free field with ceiling but no surrounding exterior walls structure. The detailed are shown in Fig.3 and Fig.4. In addition, the LBE can provide enough experiment space without obvious disturbance like natural convection or heating element, and it can be regarded as a free field.

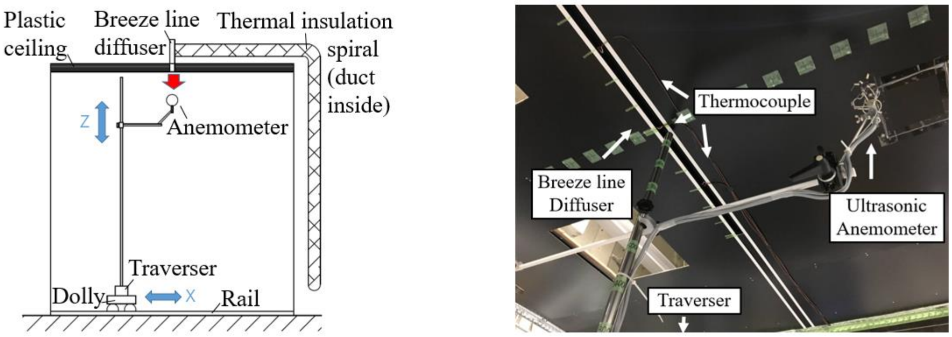
■ Air-conditioning and ventilation system

As shown in Figs.3 and 4, a breeze line diffuser is connected to a duct fan and electronic heater by spiral duct. A volume damper is set in the inlet area to control the airflow volume, and an ultrasonic flowmeter is set between fan and diffuser to measure the airflow volume. In order to control the temperature difference between inlet and outlet of air-conditioning and ventilation system, the thermocouples are fixed both on the inlet area of duct near the damper and diffuser's outlet surface. The temperature difference between inlet and outlet can be controlled by adjusting the output efficiency of electronic heater. In addition, all the spiral ducts are thermal insulated by using glass wool.



Sketch Photograph

Fig.3 Top view of outlet and measurement system



Sketch Photograph

Fig.4 Side view of outlet and measurement system

2.2 Measurement method & measurement point

■ Temperature and wind speed of diffuser's outlet surface

To measure the outlet temperature continuously, three thermocouples were stacked on diffuser's outlet surface in equal divided area. Measurement points of these thermocouples were adjusted (40cm intervals when 1/1 outlet, 20cm intervals when 1/2 outlet), depending on the length of the main flow outlet (120cm or 60 cm).
The scalar wind speed of the outlet surface (5mm below the diffuser) was measured by hot wire anemometer. All the diffuser's outlet surface was measured regardless of the location of the jet airflow. The locations of measurement points are shown in Fig.5, with 100 mm intervals in the horizontal direction and 8.5 mm intervals in vertical direction. A total of 60 data was taken for 1 minute for 1 measurement point.

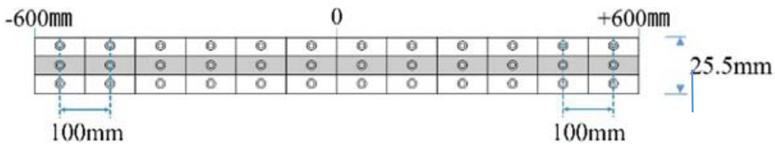


Fig.5 Overview of measurement points of scalar wind speed in outlet surface of the diffuser

■ Temperature and vector velocity of outlet space

Ultrasonic anemometer (10 Hz) and thermocouples of Type-T (1Hz) were respectively used to movement measure the vector velocity and temperature distribution in outlet space. Locations of the measurement points are shown in Fig.6.

■ Vertical temperature distribution

The vertical temperature distribution in the LBE was measured by eight thermocouples, at the height of 0.1m, 0.6m, 1.1m, 1.7m, 2.2m, 2.5m, 2.7m, and 2.9m. Measurement location is near the experiment space (thermocouples are stuck on the vertical flame of experiment space).

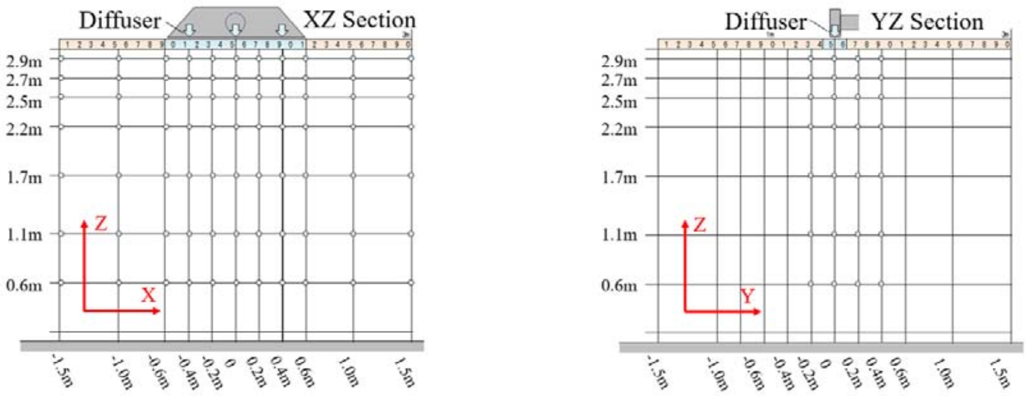


Fig.6 Overview of measurement point in outlet space

2.3 Temporal temperature change & correction method

The temperature measurement of the outlet area in this research is in order from the height near the diffuser to the ground. Including preparation time, it took at least 8 hours for each case to finish all the measurement points. Because the indoor temperature of LBE is susceptible to outdoor temperature, the indoor air temperature varied about 2~3℃ for each measurement height during measurement time (as shown in Fig.7).

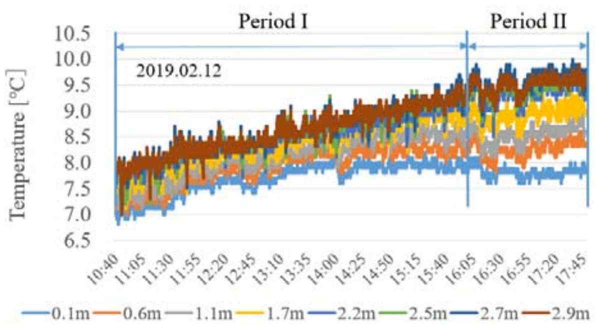


Fig.7 temperature distribution in laboratory

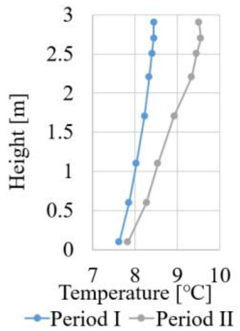


Fig.8 Average temperature distribution

The movement measurement time was divided into two periods to correct temporal errors. During Period I (10:30~16:00), the temperature of measurement points at the height of 1.7m~2.9m was measured. As shown in Fig.7, the temporal temperature change during this period can be regarded as a process of constant speed raise (about Δ1.5°C for this case). Thus, the time when measurement started of every point was recorded and temperature correction was accrued in proportion to time. The time-based correction formula is as follows (1).

$$\theta_P^* = \theta_P + \frac{t_{16} - t}{t_{16} - t_0} \times (\theta_{Pr16} - \theta_{Pr0}) \quad (1)$$

θ_P^* : corrected temperature at point P [°C]
θ_{Pr} : the temperature of reference point at the same height as measurement point P [°C]
t : elapsed time from the start of section I[s]
16 : 16:00pm (data is corrected when they was measurement before 16:00pm)
0 : start time of measurement

The temperature for measurement points at the height of 0.6m and 1.1m was measured during Period II (16:00~17:40). Compared to Period I, the temporal temperature change during Period II is less, thus the temperature data of Period II was recorded without correction.

2.4 Experiment case and parameter

The experiment cases and parameters are shown in Table 1. As shown in Fig.9 and Fig.10, the airflow rate and temperature difference between inlet and outlet are well maintained around 200 m^3/h and Δ8°C respectively. In addition, using the result of measured scalar velocity of diffuser outlet surface (as shown in Fig.11), the airflow rate was also calculated by average scalar wind speed measured at diffuser's outlet surface by hotwire anemometer. It is shown that the calculated result (1/1 outlet: $2.04 m/s \times 0.0305 m^2 = 223\ m^3/h$; 1/2 outlet: $1.99 m/s \times 0.0305 m^2 = 218\ m^3/h$) is generally consistent with the measurement value of ultrasonic flowmeter.

Table 1: Experiment case & parameter

Case	Outlet area	Thermal condition	Δ°C	Air volume
Case 1	1/1 outlet	Isothermal	-	200Nm³/h
Case 2	1/1 outlet	Heating supply	Δ8°C	200Nm³/h
Case 3	1/2 outlet	Heating supply	Δ8°C	200Nm³/h
Case 4	1/2 outlet	Isothermal	-	200Nm³/h

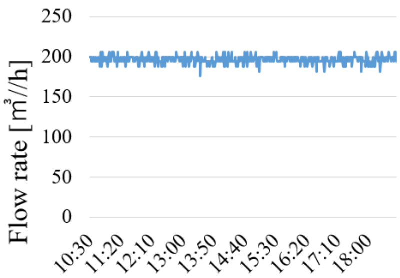


Fig.9 Airflow rate measured by flowmeter

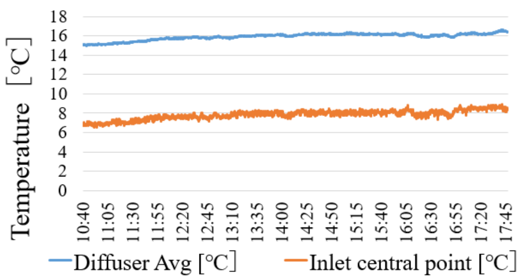


Fig.10 Inlet (Damper) & outlet (Diffuser) temperature

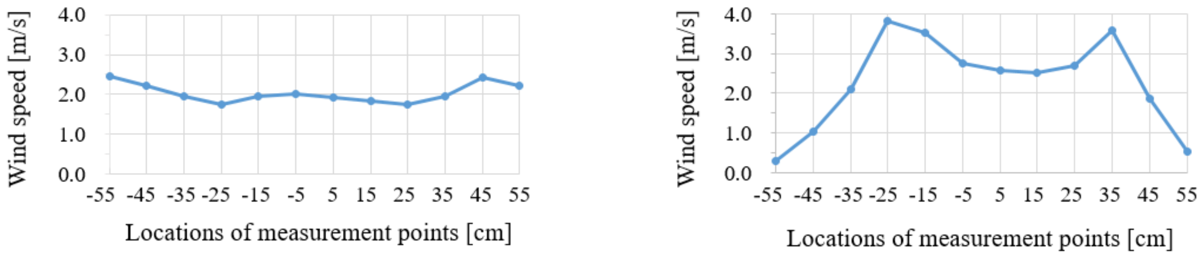
3. RESULTS AND DISCUSSION

3.1 Wind velocity distribution

Fig.11 shows the scalar wind speed of outlet surface for 1/1 outlet and 1/2 outlet conditions. The number (1~12) of X-axis represents the position of measurement in the long side, and the wind speed is averaged by 3 measurement points in the wide side of the diffuser (see Fig.5).
In order to make the airflow velocity distribution in the outlet space easier to understand, the alphabetic symbols (X_n and Y_n) was used to represent the position of measurement in horizontal and longitudinal directions. For example, X_0 and Y_0 mean the horizontal and longitudinal sections passing through the central point of the outlet. Scalar wind speed and vector velocity in X_n and Y_n sections are shown in Fig.12~Fig.19.

■ Scalar wind speed distribution of diffuser's outlet surface

All the scalar wind speed was measured in the isothermal condition.Fig.11(1) shows the outlet wind speed when the deflection panels inside the diffuser were opened (1/1 outlet). It is shown that the airflow is jetting from the whole surface of the diffuser at the average speed of 2.04m/s. Due to the geometry of the breeze line diffuser, outlet wind speed in the two sides area is about 0.5m/s faster than the central area of the diffuser.



(1) Outlet wind speed (1/1 outlet) (2) Outlet wind speed (1/2 outlet)

Fig.11 Scalar wind speed of diffuser's outlet surface

For the case when the deflection panels were closed (1/2 outlet), as shown in Fig.11(2), the vast major of airflow is jetting from the central area of the diffuser (60cm in range with the total length of the diffuser is 120cm), at an-average wind speed of 3.57m/s which is about 1.7 times faster than the case when deflection panels were opened (1/1 outlet). In the area outside of the deflection panels (above 30cm away from the center of diffuser, outside the dotted line in Fig.1), some airflow was observed as the result of air leak. Similar to Fig.11(1), outlet wind speed in the two sides of the mainstream is about 1.3m/s faster than that in central area.

■ **Airflow velocity distribution of section Y**

Fig.12 and Fig.14 respectively show the scalar wind speed and vector velocity in section Y_0 for Case 1 (isothermal & 1/1 outlet) and Case 2 (heating supply & 1/1 outlet). Fig.13 and Fig.15 respectively show the scalar wind speed and vector velocity in section Y_0 for Case 3 (isothermal & 1/2 outlet) and Case 4 (heating supply & 1/2 outlet).

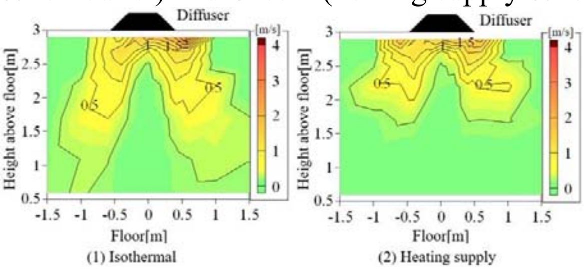


Fig.12 Scalar wind speed of section Y_0 (1/1 outlet)

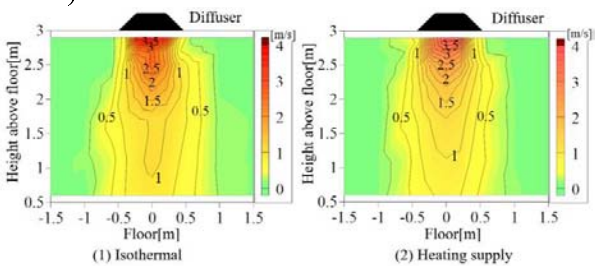


Fig.13 Scalar wind speed of section Y_0 (1/2 outlet)

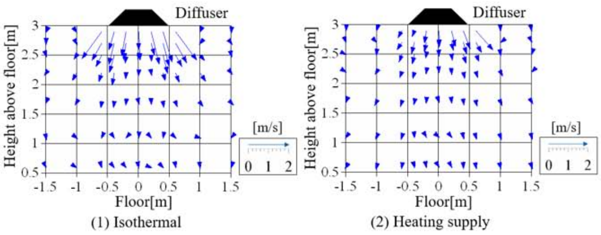


Fig.14 Vector velocity of section Y_0 (1/1 outlet)

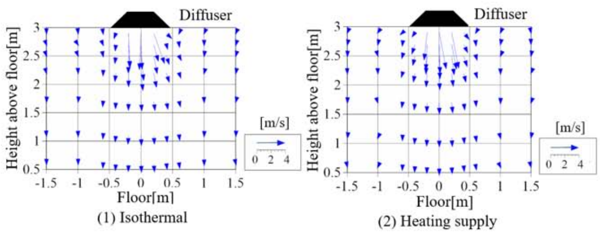


Fig.15 Vector velocity of section Y_0 (1/2 outlet)

When the outlet airflow is jetting from the whole outlet surface, it has a reversed "V" shape (see Fig.12) that the arrival ranges in the side of diffuser are much vaster than that in the center, which is similar to the outlet wind speed's distribution at the outlet surface of diffuser (Fig.11). For the isothermal case, outlet airflow can reach the occupancy zone (below 1.7m height) at wind speed of around 0.3m/s. For heating supply case, heating airflow can't reach the space below 1.7m height mainly due to the effect of buoyancy. However, heating airflow has larger diffusion ranges than isothermal airflow near the ceiling (above 2m height). When the outlet airflow is jetting under the case of 1/2 outlet, it can see that outlet airflow goes straight down to the floor without spreading around whether it's under isothermal or heated conditions from Fig.13 and Fig.15. The airflow on center of diffuser has the fastest wind speed, and reached the occupancy zone at speed of above 1m/s. The difference between the case of isothermal and heating supply outlet is the range of 1m/s speed in the heating supply case is smaller due to the buoyancy.

■ **Airflow velocity distribution of section X**

Figs.16 and 17 show the scalar wind speed of section X (3 sections: X_0, $X_{-0.4}$, $X_{-0.6}$) respectively under the cases of 1/1 outlet and 1/2 outlet. Figs.18 and 19 show the vector velocity of section X (3 sections: X_0, $X_{-0.4}$, $X_{-0.6}$) respectively under the cases of 1/1 outlet and 1/2 outlet.

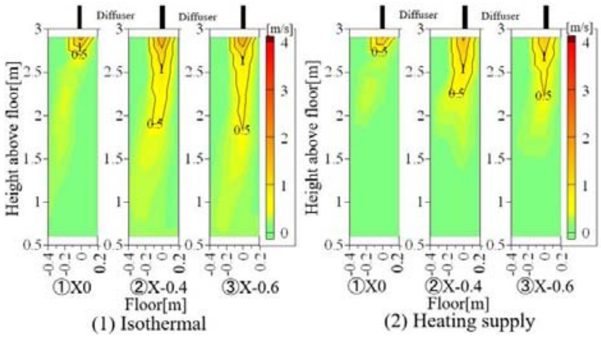


Fig.16 Scalar wind speed of section X (1/1 outlet)

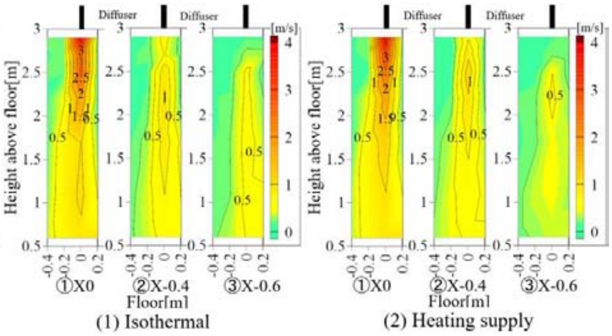


Fig.17 Scalar wind speed of section X (1/2 outlet)

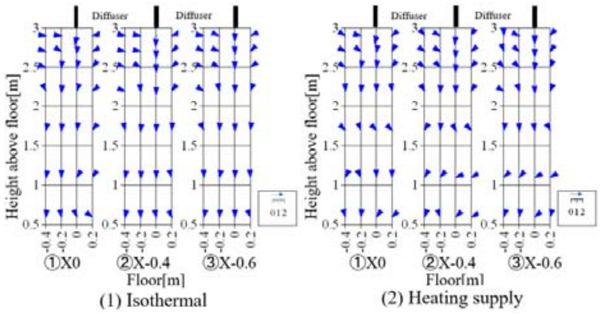


Fig.18 Vector velocity of section X (1/1 outlet)

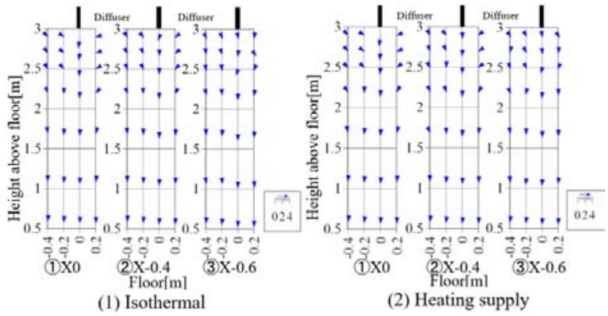


Fig.19Vector velocity of section X (1/2 outlet)

For the case of 1/1 outlet, the airflow from diffuser has the tendency of deviating aside under isothermal condition, and the deviation range becomes farther when under heating supply condition. For the case of 1/2 outlet, it is shown that the airflow is going straight from the diffuser to the floor with relatively higher wind speed, in comparison with to the case of 1/1 outlet.

Regardless of the outlet temperature condition (ΔT=8°C and ΔT=0°C) or outlet area condition (1/1 outlet and 1/2 outlet), wind direction near the ceiling is aimed at the center part of airflow (Fig.18 & Fig. 19, 2.5m~2.9m height) due to the reason of induction.

3.2 Temperature distribution

As shown in Fig.20, for the case of 1/1 outlet, when the airflow is jetting from the diffuser with 16°C, the outlet airflow temperature dropped to about 11°C at 0.5m away from diffuser, then the outlet airflow dropped to 9°C at about 2.5m away from diffuser. In addition, the result of Fig.20 also showed that the temperature stratification has been observed obviously for above Δ2°C in the occupancy zone, however very limited heating effect (less than 1°C) can be seen in this study.

The result of temperature distribution under the case of 1/2 outlet is shown in Fig.21. It is seen that the warm airflow is jetting from the diffuser with 23°C, and is reaching to the occupancy zone by much higher outlet speed, compared with the case of 1/1 outlet. The temperature in the occupancy zone just below the diffuser is about 17°C without stratification. Furthermore, an obvious heating effect (above Δ2°C) has been observed at the range of 2m in long below the diffuser.

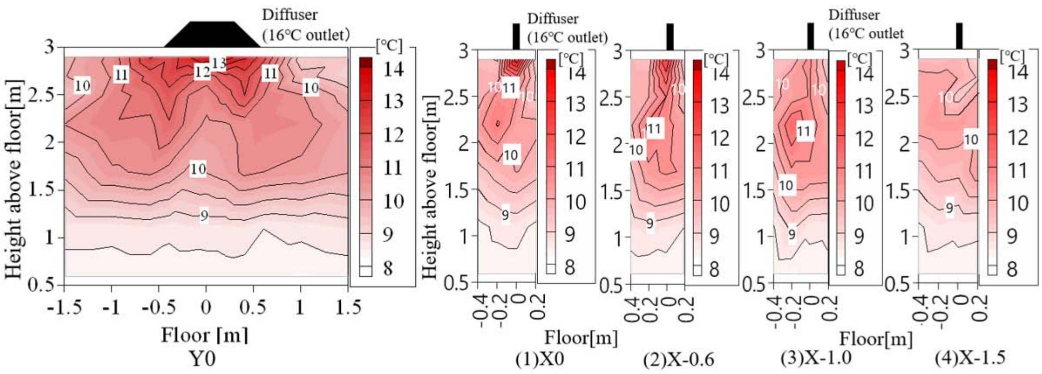


Fig.20 Temperature distribution in section (1/1 outlet)

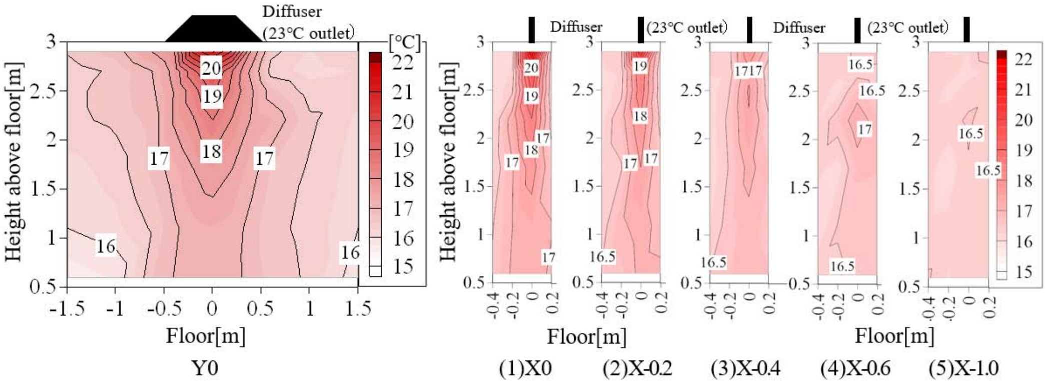


Fig.21 Temperature distribution in section (1/2 outlet)

Seeing from the side of the diffuser, from the result for the case of 1/1 outlet (Fig.20), it can see that the temperature distribution at the height of around 2.2m is higher than that closer to celling. The reason is considered to be the influence of warm air buoyancy. From the farthest section X ($X_{-1.5}$), it can see that very limited airflow arrived in this area, however there is about Δ1.5°C temperature stratification in this area.

From the result for the case of 1/2 outlet (Fig.21), it can see that the temperature distribution of the section $X_{-1.0}$ (1.0m away from the diffuser centre in X direction) has almost no stratification, about 17°C, and almost the same as the indoor temperature of LBE. The reason is considered as that the airflow can't reach to this area.

3.3 Effect of buoyancy on airflow velocity

The CFD simulation analysis on the breeze line diffuser will be planned in our future work. To decide the location of boundary conditions for the P.V. method of CFD, the scalar wind speed and wind direction angle in isothermal and heating supply conditions for both the 1/1 outlet and 1/2 outlet cases, have been measured and compared. The results are detailed in Figs.22-25.

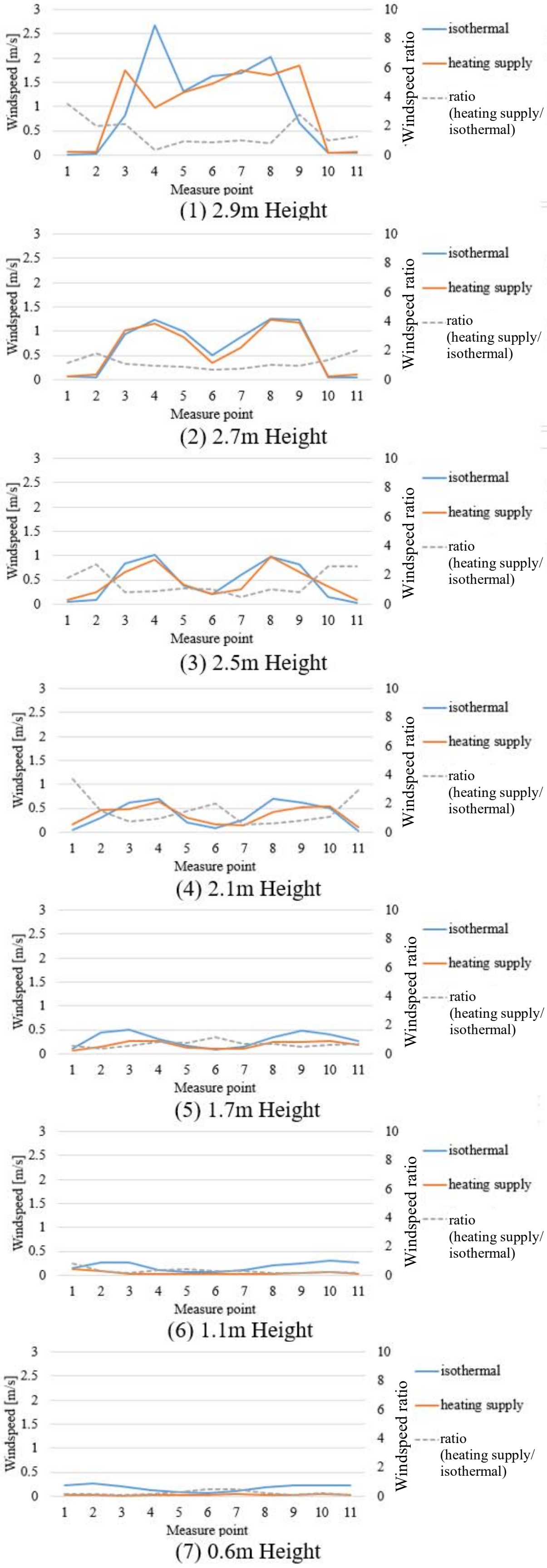


Fig.22 Wind speed ratio
(Heating supply/isothermal, Section Y 1/1 outlet)

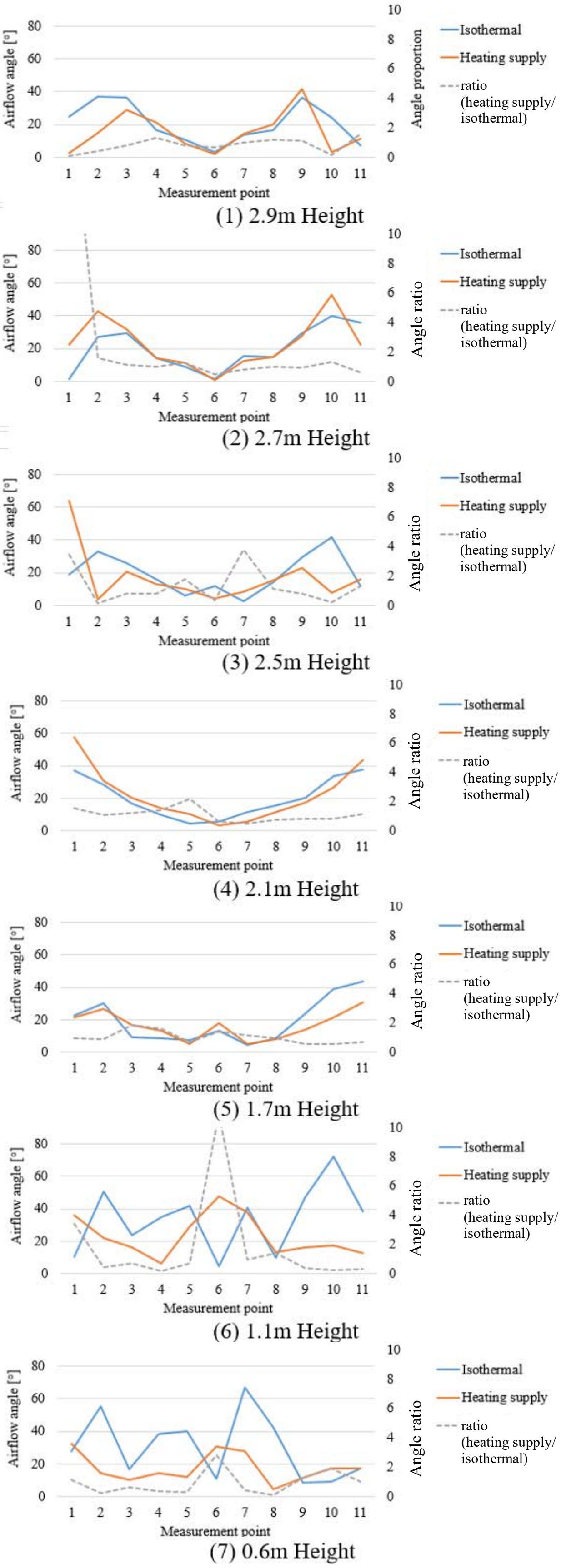


Fig.23 Airflow angle ratio
(Heating supply/isothermal, Section Y 1/1 outlet)

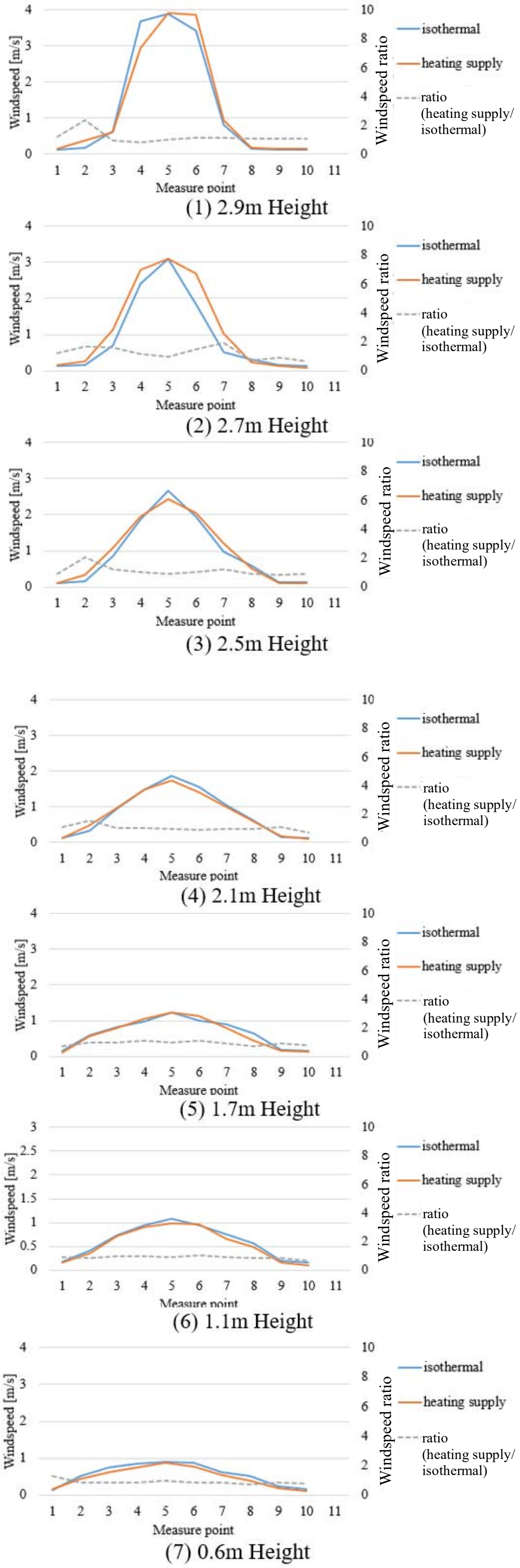


Fig.24 Wind speed ratio
(Heating supply/isothermal, Section Y 1/2 outlet)

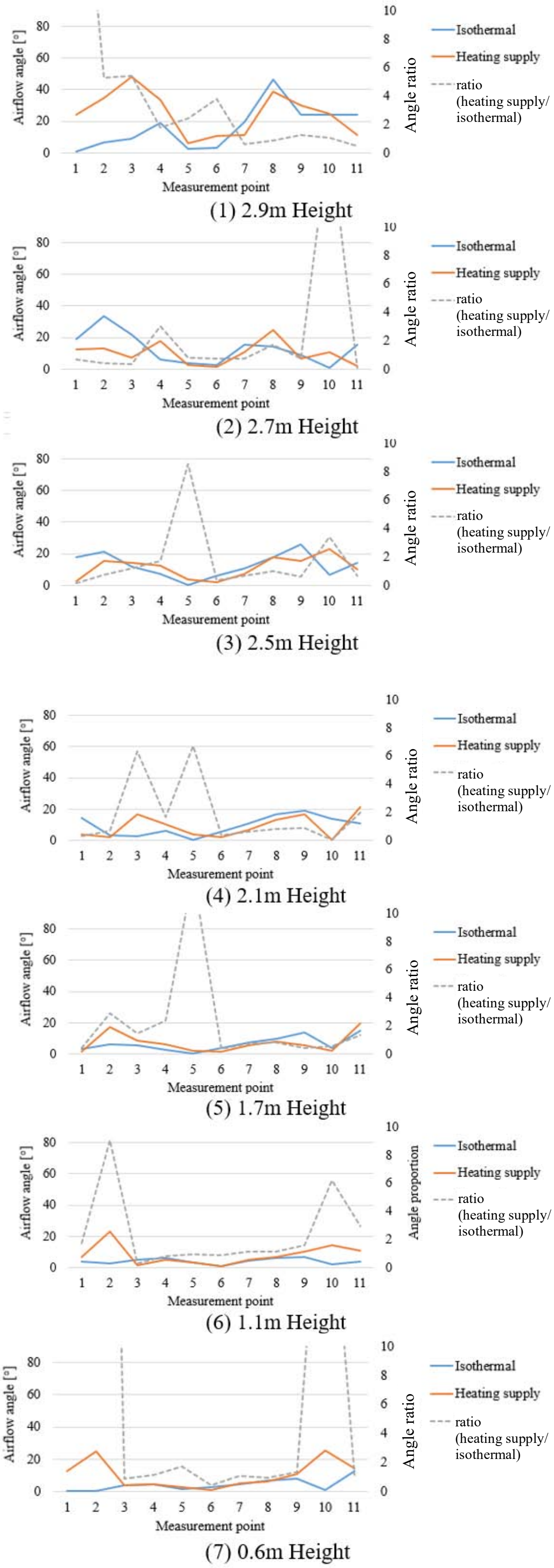


Fig.25 Airflow angle ratio
(Heating supply/isothermal, Section Y 1/2 outlet

4 CONCLUSIONS

In this research, the full-scale experiment of breeze line diffuser was carried out. The size of the outlet surface was changed by adjusting the deflection panel inside the diffuser. The knowledge obtained in this study are shown as follows.

- Buoyancy can affect the arrival area of outlet airflow (case of 1/1 outlet), however, when the outlet velocity is fast enough (case of 1/2 outlet), this influence is limited.
- The breeze line diffuser has limited heating effect in the occupancy zone (below 1.7m) when the warm air is jetting from the whole outlet surface (1/1 outlet) at a common outlet volume of about $200m^3/h$.
- Without increasing the outlet volume, to adjust the deflection plane inside of the diffuser can make the heated airflow reach the occupancy zone at a certain speed (case of 1/2 outlet).
- It is indicated that there is almost no temperature stratification, but heating effect has been observed in the occupancy zone near the diffuser under case of 1/2 outlet.
- It is worth looking forward to enhancing the heating effect of breeze line diffuser by set deflection panels inside it.

For the future work, the figure of the ratio of wind speed and airflow angle will be used to decide the location of the boundary condition for the P.V. method. A vector velocity measurement by X-type probe hotwires anemometer will be carried out at these boundary layers, and all the data obtained from this experiment will be used to examine the accuracy of the CFD model in further study.

5 ACKNOWLEDGEMENTS

The authors are sincerely grateful to the KUKEN KOGYO. Co. Ltd for providing the breeze line diffuser used in this study.

6 REFERENCES

[1] M. KATOH, T. SHINOZUKA, Y. ARAI Y, S. YUMINO, T. YAMANAKA, T. KOBAYASHI: Prediction Method of Thermal Environment during Heating in Winter for Spaces with Large-Area Window(Part 1)Measurement Results and Simplified Evaluation method for Vertical Temperature Difference in Office buildings, Transactions of the Society of Heating, Air-conditioning and Sanitary Engineers of Japan (266), 11-21, 2019.05 [in Japanese]

[2] Chen Q and Srebric J: Simplified Numerical Models for Complex Air Supply Diffusers, HVAC&R RESEARCH Volume 8, pp.277-294,2002

[3] P.V. Neilsen: DESCRIPTION OF SUPPLY OPENINGS INUMERICAL MODELS FOR ROOM AIR DISTRIBUTION, ASHRAE Transactions Part1, pp.963-971, 1992.2.