FIELD STUDY ON THE VENTILATION EFFECTIVENESS AND THERMAL COMFORT IN A CONCERT HALL WITH DISPLACEMENT VENTILATION SYSTEM

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ABSTRACT

The purpose of this study is to identify the ventilation effectiveness of a displacement ventilation system in a concert hall with 501 seats, where a large amount of outside air is required for ventilation. Displacement ventilation was considered appropriate to reduce the amount of outside air. Light bulbs were placed on all the seats to simulate the heat source from the audience. From the measured concentrations, the local mean age of air at the breathing point with the displacement ventilation system was found around one third of that of the fully mixed condition. No significant difference was found in local mean age of air on horizontal distribution in the occupied zone. The measured results of horizontal temperature distribution were almost uniform, while those of vertical temperature distribution were within an acceptable range in the occupied zone and quite high above it. The experimental findings suggest that the displacement ventilation system can be adequately operated with a relatively high cooling load to provide acceptable conditions of indoor air quality.

KEYWORDS

Air change efficiency, Displacement ventilation, Full-scale experiments, Thermal comfort

1. INTRODUCTION

A displacement ventilation (DV) system provides a high ventilation efficiency and is often installed in concert halls and conference rooms(Mathisen 1995; Fitzner 1993). DV is generally achieved by three methods: (1) supplying air from openings in all chairs(Brzeski et al. 1994), (2) supplying air through permeable carpets (Floor-supply DV system) and (3) supplying gentle air streams through low momentum air diffusers in the walls. The third system was applied to the concert hall of this building.

Few reports have been published on the measurement of ventilation efficiency in concert halls or similar buildings using tracer gases. Mathisen(1995) determined the ventilation indices based on the concentration of carbon dioxide exhaled by the occupants in the room.

This paper reports the results of the measurement on the ventilation effectiveness expressed in the forms of age of air and air change index using tracer gas as well as thermal comfort in the concert hall. To simulate the cooling load, we placed light bulbs emitting the heat equivalent to the one from a human body on each seat in the main floor (Guthrie 1996). Using this method, the plumes driving the air of DV system could be generated in the correct location with the correct volume so that measurement accuracy in temperature distribution in the room and thermal environment around the DV air diffusers could be achieved.

2. DESCRIPTION OF BUILDING

The concert hall was constructed as a

part of public institution building including a fitness studio, swimming pool, and library, which aims to improve mental and physical health of residents in the city in Hyogo prefecture, Japan (lat.34°50N. long. 135°04E) . A concept of the institution was focussed to coexistence with culture and nature, utilizing the technologies of natural energy utilization and energy conservation. DV system was adopted with expectation of the following advantageous functions:

1) Reduction in power consumption of supply and exhaust fans because of a large temperature difference between supply and exhaust air due to a favorable temperature stratification

2) Reduction in cooling operation period by using a high supply air temperature such as 20°C ~ 22°C

3) Reduction in outside air intake volume with a higher ventilation efficiency than the case of ordinary systems mixing the room air.

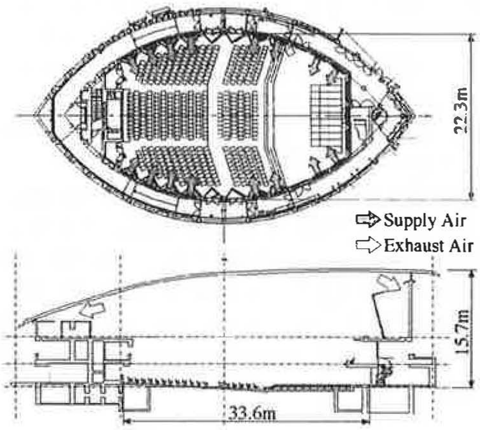
There are 501 seats on the main floor of a football shape and 60 seats in the gallery on the sides of the second floor. The floor area of the main floor and the stage is 600m^2 and the volume is 9000m^3 as shown in Figure 1. There are large glass windows surrounding the gallery. The windows can be covered by black curtains.

Two air handling units (AHU) are installed for this concert hall. The main AHU supplies fresh air together with recirculated air to the main floor and stage from DV air diffusers. Another AHU supplies air to the gallery from slot diffusers installed in the lower parts of the surrounding windows. The main AHU has both cooling and heating coils to control the humidity in the room by reheating in the dehumidification and cooling phases during the summer season. Thirty-two DV air diffusers are installed in a semi cylindrical shape of 2.1m high and 0.6m wide along the surrounding walls. The exhaust air is returned through the two openings located 9m and 12.5m above floor level. A constant supply air temperature and variable supply air volume is used to control the air temperature in the room with the air temperature sensors dispersedly located on three seats.

3. MEASUREMENT METHOD

3-1. Thermal comfort

The measurement instruments are illustrated in Figure 2. Two sets of measurement poles fitted with thermocouple temperature sensors at 0, 0.1, 0.6, 1.1, 1.6, 2.1, 3.1, 4.1, 5.1, 6.1, 7.1, and 8.1m above floor level were used. The horizontal distribution of air temperature in the room was measured consecutively at the twenty-two points as shown in Figure 3 by moving the aforementioned measurement poles. The time difference between the first measurement point and the last was



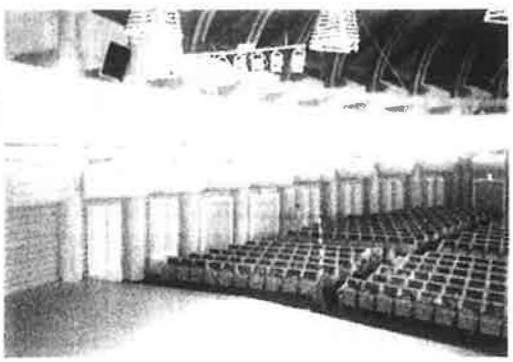


Figure 1: Experimental concert hall

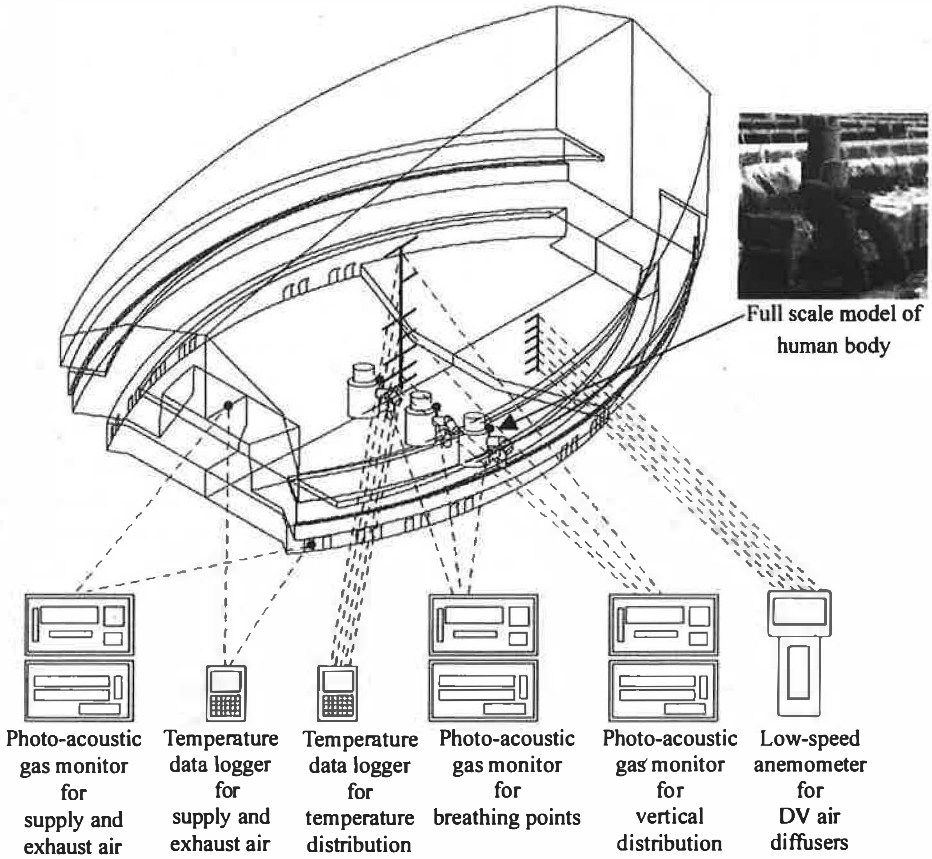


Figure 2: Measuring instruments

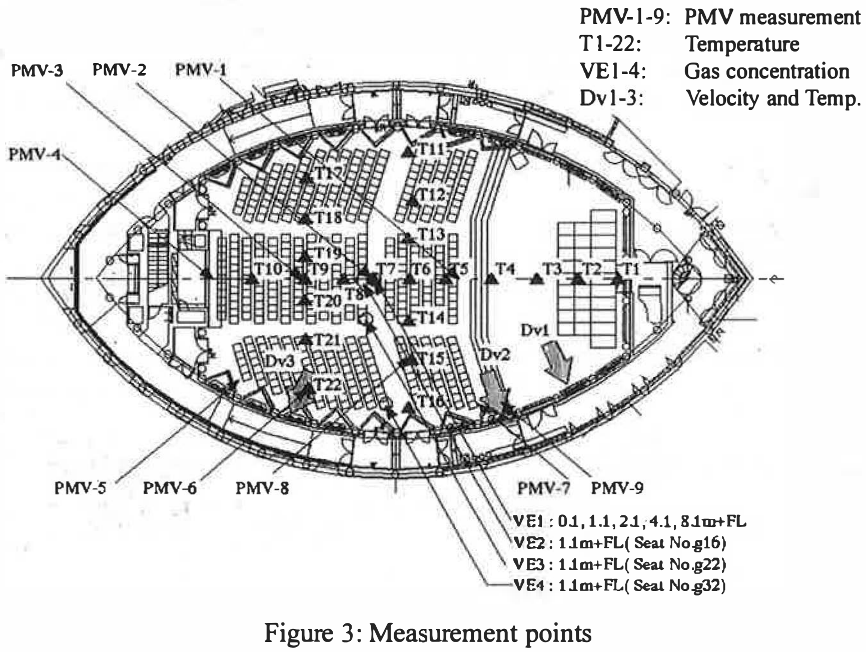


Figure 3: Measurement points

less than 17 minutes. The supply and exhaust air temperatures were measured during the room air temperature distribution measurement to confirm the stabilization of the HVAC system. Low speed anemometers were used to measure air velocities in the occupied zone close to the DV air diffusers at 0.1, 0.6, 1.1, 1.6, and 2.1m height above floor level. Measurements of the room air temperature, humidity, air velocity and radiant temperature at 1.1m above the floor level for 9 typical points were taken to calculate the values of PMV.

3-2. Ventilation effectiveness

To obtain the local mean age of air and air change index to represent the ventilation effectiveness, decay method was applied with SF6 tracer gas (Sutcliffe 1990). Three sets of photo-acoustic gas monitors were used. The concentration of SF6 was continuously measured at supply air, exhaust air, 0.1, 1.1, 4.1, and 8.1m above the floor in the center of the hall. In addition to these six points, three more points were monitored at the breathing points of three simulated human bodies at 2, 8, and 11m from the side wall. The vertical temperature distribution was also measured.

3-3. Supply air volume

The supply air volume was obtained from the air velocities at the outlet of the water spray eliminator in the AHU. A low speed anemometer was used to measure the air velocity.

3-4. Heat sources

Five hundred and one(501) light bulbs were placed on the seats to simulate the heat generation from audience. Each light bulb emitted 60W of sensitive heat. Three seats were occupied by full scale models of human body with sensors of tracer gas concentration at mouth location. During the measurement, ceiling lights were turned on to the appropriate illumination level.

4. MEASUREMENT CONDITIONS

4-1. Thermal comfort

Thermal conditions were measured on August 20, 1997 with the main AHU for the main floor switched on and the AHU for the gallery off. The air supply temperature and air volume were fixed at 22°C and 26000m^3/h respectively. The humidity control was switched off. The electrical input of the light bulbs was a total of 30.6kW, and the ceiling lights a total of 46.0kW. The windows surrounding the gallery were covered by the blackout curtains. The main AHU was switched on at 10:00 and measurements were taken between 13:00-13:40.

4-2. Ventilation effectiveness

The local mean age of air and local air change index were calculated from the measured results of tracer gas concentrations on August 21, 1997. The operating conditions of the HVAC system were identical to the case of the thermal comfort measurements. To avoid air leakage from the recirculated chamber to the supply air duct, the rotary heat exchanger was switched off and the return air damper in the AHU was closed and sealed.

A complete mixed condition was produced by using temporarily installed agitate fans with the HVAC system switch off. SF6 (1.5kg) was released into the room of 9000m^3 air volume for each measurement, which would be equivalent to a concentration of 25ppm. After the concentrations at nine points were assured to be equal, the HVAC system was started. To simulate complete mixing conditions, the agitate fans were operated continu-

Table 1: Operating conditions of components

Components / Period	Sup. air flow 26000m^3/h	Light bulbs 30.6kW	Ceiling lights 46.0kW	Agitate fans 6.4kW
DV dosing period	OFF	OFF	ON	ON
DV decay period	ON	ON	ON	OFF
Mixing dosing period	OFF	OFF	ON	ON
Mixing decay period	ON	OFF	ON	ON

ously. Not only the DV but also the complete mixing ventilation system were simulated to verify a time constant in the room. Table 1 shows the operating conditions of the components and the agitate fans during four different periods of the measurements.

4-3. Evaluation method

The local mean age of air and local air change index for the tracer decay method was applied for evaluation. These are defined as follows:

$$\bar{\tau}_p = \int_0^\infty \frac{C_p(t)}{C_p(0)} dt \quad \text{---(1)}$$

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \quad \text{---(2)}$$

ε_p = local air change index(-)
τ_n = nominal time constant(min)
τ_p = local mean age of air(min)
$Cp(t)$ = concentration of tracer gas at point p at time t(m^3/m^3)
$Cp(0)$= initial concentration of tracer gas for tracer decay method(m^3/m^3)

5. RESULTS

5-1. Thermal environment in a hall

The results of the thermal measurements are shown in Table 2. Heat extraction calculated from the temperature difference between supply and exhaust air and supply air volume was 67.2kW, namely 112W/m^2, compared with heat generation for the thermal comfort measurement. Vertical air temperature distribution in Figure 4 were drawn from measured data points by interpolation. The upper part of the room shows a stable temperature field, while the lower part shows a slight disturbance.

Vertical air temperature distribution during the ventilation effectiveness measurement is presented in Figure 5. In the mixed condition, room air temperature shows quite an even distribution. However the lower part of the room below 1.0m height indicates a somewhat lower temperature suggesting that the dilution of the tracer gas was not perfect in the lower part of the room.

Horizontal temperature distribution in the room was quite uniform. Near the DV air diffusers and the seats closest to the stage, however, the temperature was lower than at other sites. Specifically the temperature at 0.1m was likely to be lower, i.e. the temperature gradient was steeper in this layer.

5-2. Thermal comfort in occupied zone

Thermal conditions including PMV are shown in Table 3. In the center area of the main floor, PMV values slightly exceeding 0.5 were observed. The effect of radiation caused by the ceiling lights for stage is considered obvious.

Air velocity and temperature in the neighborhood of the DV air diffusers are shown in Table 4. The closest seat position to the diffuser is 1.5m apart from "Dv3" terminal. The temperature difference between 0.1 and 1.1m at this point is 2.8°C. Slightly high air velocity of 0.27m/s was observed at 0.1m above floor. These measured values except at this point were within recommendations of ISO standard 7730(1994) and ASHRAE 55-92(1992).

A large plume was observed in the center of the room with overall air distribution by flow visualization. The plume seems to be produced as a result of a slow collision of the supply airflow from the air diffusers on the both sides of the room.

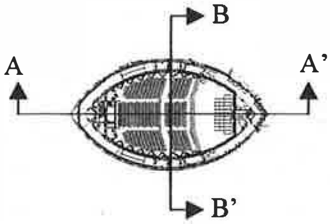
5-3. Ventilation effectiveness

A concentration decay curves of SF6 are shown in Figure 6 for DV and Figure 7 for

Table 2: Results of thermal measurements

System	Measurement conditions	Sup. air temp. °C	Exh. air temp. °C	Sup. air volume m^3/h	Heat extraction kW	Heat generation kW
DV	Thermal comfort	21.6	29.4	26000	67.2	76.6
DV	Ventilation effectiveness	21.7	30.8	26000	78.1	76.6
Mixing	Ventilation effectiveness	21.5	29.0	26000	64.4	52.4

Date:	Aug.20,1997
Floor Area:	600m^2
Supply Air Flow:	26000m^3/h
Supply Air Temp.:	22°C
Heat Load:	Person Sim. 60W×501Qty. Lighting 46kW
Outside Temp.:	30°C, Clear sky



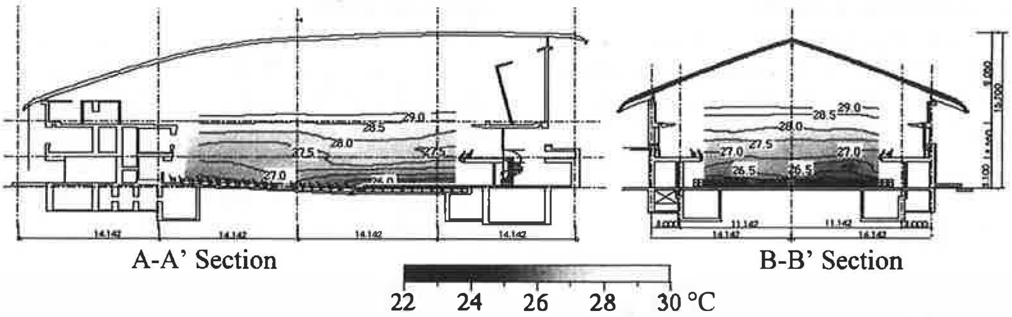


Figure 4: Air temperature distribution

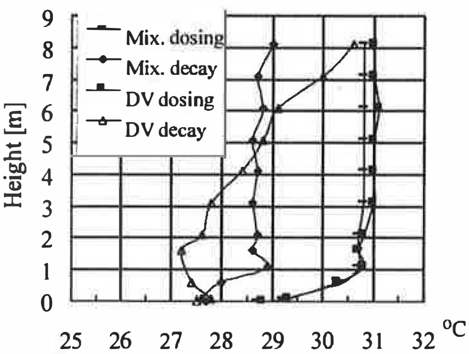


Figure 5: Vertical temperature distribution during the ventilation effectiveness measurement

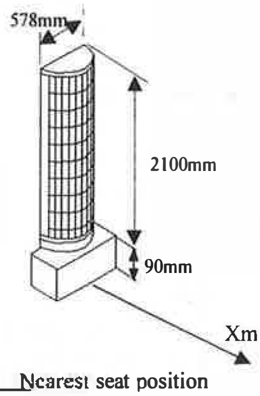
Table 3: Air temperature, mean radiant temperature, air velocity, and calculated PMV

Point	Air Temp. °C	Rad.Temp. °C	Vel. m/s	PMV*)
PMV-1	25.8	29.9	0.24	0.39
PMV-2	26.5	28.5	0.13	0.58
PMV-3	26.6	28.1	0.07	0.69
PMV-4	25.8	28.0	0.10	0.47
PMV-5	23.5	28.2	0.18	-0.24
PMV-6	24.8	25.5	0.07	-0.09
PMV-7	25.1	26.7	0.27	-0.33
PMV-8	26.3	26.5	0.08	0.37
PMV-9	25.3	27.6	0.09	0.35

*)Assuming RH=50%, Clo=0.6, Met=1.0

Table 4: Air velocity and temperature in the neighborhood of the DV air diffuser at Dv3

Height m			Xm 0.3m	0.6m	0.9m	1.5m
2.1	Air Vel.	m/s	0.02	0.02	0.02	0.02
	Air Temp.	°C	28.2	28.4	28.4	28.4
1.6	Air Vel.	m/s	0.03	0.02	0.01	0.02
	Air Temp.	°C	27.2	27.4	27.7	27.8
1.1	Air Vel.	m/s	0.33	0.03	0.11	0.08
	Air Temp.	°C	24.8	25.7	26.5	26.6
0.6	Air Vel.	m/s	0.11	0.36	0.28	0.16
	Air Temp.	°C	23.6	23.8	24.2	24.6
0.1	Air Vel.	m/s	0.15	0.08	0.13	0.27
	Air Temp.	°C	23.7	24.0	24.2	23.8
0	Air Vel.	m/s	-	-	-	-
	Surf.Temp	°C	26.1	26.1	26.1	25.9



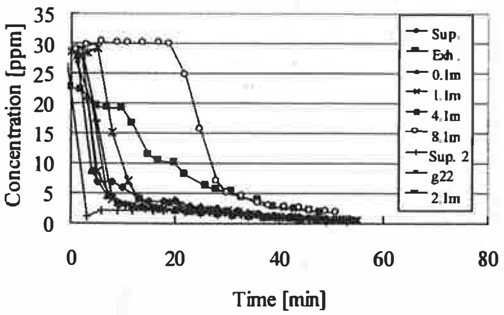


Figure 6: Tracer gas decay curve (DV)

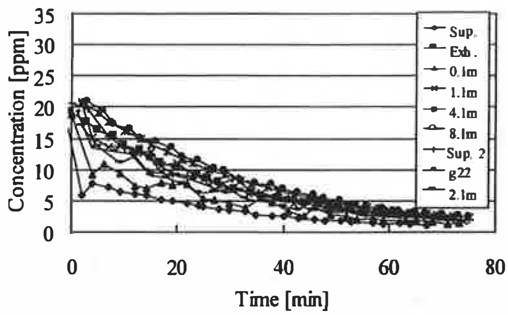


Figure 7: Tracer gas decay curve (Mixing)

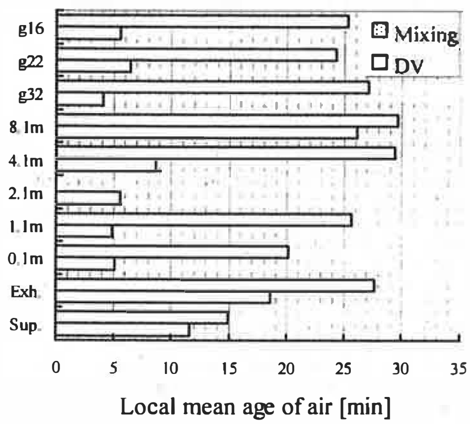


Figure 8: Local mean age of air

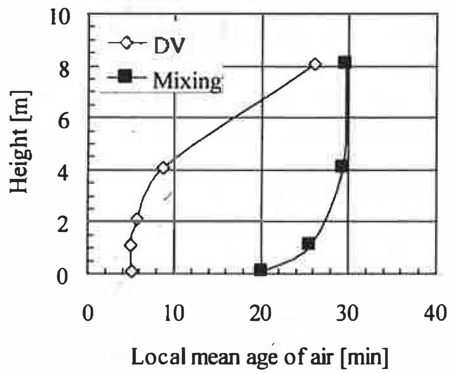


Figure 9: Local mean age of air

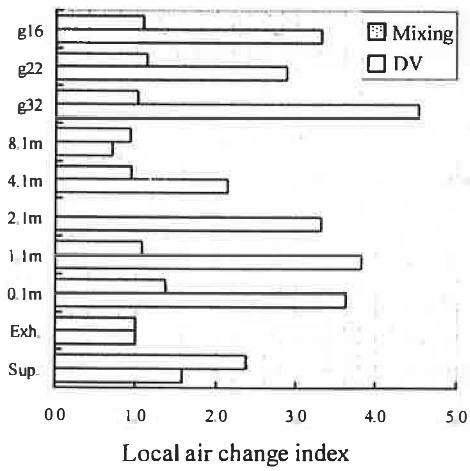


Figure 10: Local air change index

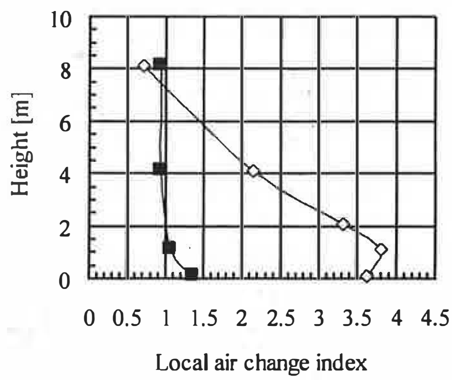


Figure 11: Local air change index

mixing condition at different heights. The decay curves under the mixing condition were found more or less the same for all measurement points in the room. The decay curves of the DV system show a significant delay depending on the height.

Local mean age of air is presented in Figures 8 and 9. Local air change index is presented in Figures 10 and 11. A nominal time constant was obtained from the local mean age of air at the exhaust openings.

The DV system showed that local mean age of air in the occupied zone was 4.1 to 6.4 [min.] and the local air change index was 2.8 to 4.5 at the breathing points. In contrast, the mixing system showed 24.2 to 27.1 [min.] and 1.0 to 1.1 respectively. It was proved that the DV system had a great advantage in providing the fresh air to the occupied zone. No significant differences in the local air change indices were recorded among the three seat locations in the case of DV system.

6. CONCLUSION

The field investigation to evaluate ventilation effectiveness in terms of local mean age of air and local air change index in a medium sized concert hall were conducted with the following conclusions.

1) In the case of the displacement ventilation system, the ventilation effectiveness was found much higher than the mixed condition.

2) On the other hand, slightly high air velocity was observed close to the displacement ventilation diffusers. A guideline to determine the appropriate distance of the seats from displacement ventilation air diffuser may be required from the thermal comfort point of view.

3) Vertical temperature difference was found to be just within acceptable range with the PMV value slightly above zero within the occupied zone.

7. ACKNOWLEDGMENT

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