Distribution of Particulate Matter Concentration and Temperature Stratification Examined by Zonal Model and Experimental Measurements in Room with A Novel Portable Displacement Ventilation Cooling Unit

Toshio Yamanaka[*1], Choi Narae[2], Tomohiro Kobayashi[3], Aya Essa[3], Noriaki Kobayashi[3], Miharu Komori[4], Nobuki Matsui[5], Tetsuya Okamoto[5], Takeshi Arakawa[5], Yuki Yamoto[5], and Shogo Otaka[5]

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

2 Toyo University
2100 Kujirai
Kawagoe-shi, Saitama, Japan

3 Osaka University
2-1 Yamadaoka
Suita-shi, Osaka, Japan

4 Nihon Sekkei
1-23-1 Toranomon
Minato-ku, Tokyo, Japan

5 Daikin Industries, Ltd.
1-1 Nishihitotsuya
Settsu-shi, Osaka, Japan

ABSTRACT

This study introduces a novel conceptual design of a mobile DV cooling unit that is aimed to support the ventilation and reinforce the thermal stratification in DV rooms. Supplying filtered chilled air from at low height, the portable DV unit (PDV unit) functions as if it is a typical DV diffuser. Moreover, the PDV unit employs heat exhausted from the heat pump to reinforce the temperature gradient by injecting the hot air flow in the upper zone of the room. Utilizing the exhaust air makes the PDV unit entirely ductless which adds to its flexibility placed in to balance the airflow. In this study, the vertical distribution of particulate matter and temperature stratification were examined by zonal model and experimental measurements in room with this novel portable displacement ventilation cooling unit. As a conclusion, from the experiment, DV capacity of PDV unit was turned out, and the effects of airflow rates of DV and PDV unit on the performance were made clear.

KEYWORDS

displacement ventilation, portable displacement ventilation cooling unit (PDV unit), zonal model, full-scale experiment, droplet nuclei

1 INTRODUCTION

Displacement Ventilation (DV) system (Nielsen, 1993) is an energy efficient ventilation system that can achieve a cleaner occupied zone compared to the regular Mixing Ventilation(MV). DV depends mainly on temperature stratification to clarify the lower occupied zone from contaminants, thus, increasing the temperature gradient results in a more efficient system. However, since DV relies on buoyancy and low velocity supply, any disturbance in the slow air flow reduces its efficiency. For example, obstacles blocking the flow can cause dead-zones of low-quality unchanged air. Another issue that can affect the local air quality of certain zones in the room is the unbalanced heat load. These problems hinder DV system from being adopted widely despite its advantages.

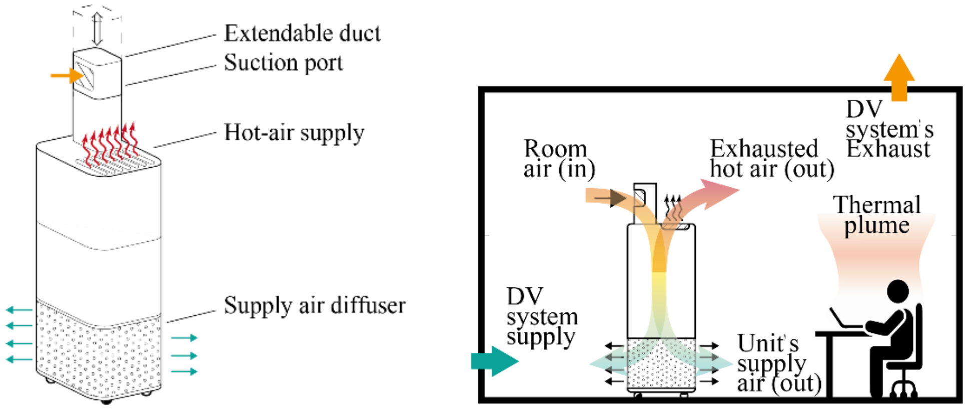
In this study, the effectivity of the novel PDV unit was assessed in terms of temperature and PM distribution. Zonal model calculation and experimental measurements were carried out for this purpose. First, in the zonal model, only the thermal effect of the PDV unit was formulated. A parametric study exploring the effect of multiple variables was carried out. Secondly, field measurement was performed in which a prototype model of the PDV unit was built and operated. In the experimental measurements, the effect of various parameters was assessed by monitoring both temperature and particulate matter concentration distribution. Based on the zonal model calculations, the PDV unit's settings in the experiment were set.

2 CONCEPT OF PDV UNIT

To enhance the performance of DV system, this study addresses three points discussed by the aforementioned literature: 1- Diffusers positioning, to overcome unbalanced supply due to room shape, size or occupants seating pattern. 2- Strengthening the temperature stratification to improve the air quality and comfort of the occupied zone. 3- Integrating portable air purifiers.

To tackle the potential enhancement points, a novel air purifier unit that functions as a portable DV system is proposed. Although close ideas of merging portable air-conditioning units and air purifiers have investigated in some studies (Zhang, 2010), no similar one unit has been proposed so far, especially in DV system. The proposed machine should function as a mobile DV diffuser. It consists of a heat pump with no ducts to be connected to outdoor. Being ductless, the exhaust heat is discharged in the room to act as an additional heat source to enhance the temperature vertical stratification. Mimicking a typical DV system, supply diffuser is in the lower section of the unit while the suction port in the top section as shown in Fig. 1a. The suction port provides air for both function, cooling and exhaust heat. Moreover, to function as standalone DV system, air filters such HEPA filters function should be added to purify the return air. Placement and functioning method of the portable DV unit (PDV unit) are illustrated in Fig. 1b.

The concept of the PDV unit is examined using zonal model calculations and experimental measurements. In the following sections both methods' details and results are discussed.



(a) Prototype of PDV unit (b) Layout of PDV unit in room

Figure 1: Outline of PDV unit

3 ZONAL MODEL

3.1 Outline of zonal model of the room with DV and PDV unit

Zonal model calculations were used in various studies to predict the thermal as well as contaminant environment in DV and other ventilation systems.

In this calculation, the basic two-layer model illustrated in Fig. 2 was adopted and the PDV unit effect was formulated in the adapted zonal model. The model assumes stratification in two layers and neglects radiation from the different surfaces as shown in Fig. 2. The thermal balance for the upper and lower zones is given by equations (1)-(2).

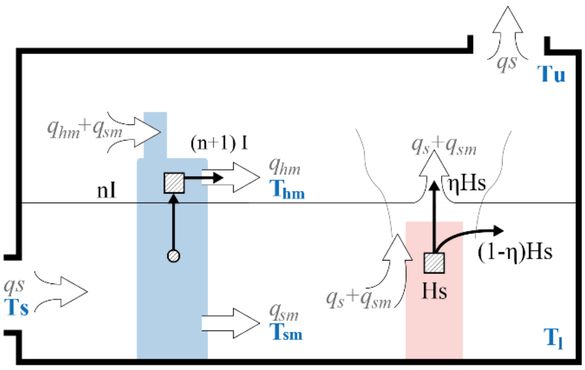


Figure 2: Zonal Model of DV room with PDV unit

For upper zone, the following balance equation of the heat can be written :

$$(n+1)\, I + \eta H_s + C_p\rho\ (q_s+q_{sm})\ T_l - C_p\rho q_s T_u - C_p\rho q_{sm} T_u = 0 \qquad (1)$$

For lower zone, the following equation can be written :

$$C_p\rho q_{sm} T_u - nI + (1-\eta)\ H_s + C_p\rho q_s T_s - C_p\rho\ (q_s+q_{sm})\ T_l = 0 \qquad (2)$$

PDV unit's cooling capacity and exhaust heat generation are shown in equations (3) and (4) respectively.

$$nI - C_p\rho q_{sm}\ (T_u\text{-}T_{sm}) = 0 \qquad (3)$$

$$(n+1)\ I - C_p\rho q_{hm}\ (T_{hm}\text{-}T_u) = 0 \qquad (4)$$

where for the DV system, q_s is the supply flowrate and T_s is the supply temperature. For the room, T_u and T_l are the air temperature of upper and lower sections respectively. C_p stands for specific heat of air (1004 J/K.kg) while ρ is the air density (1.2 kg/m^3). Representing heat sources in the room, human and computer devices, H_s is the heat load generated and η is the ratio of the heat that ascends to the upper part of the room assumed to be 1. Regarding the PDV unit, n is the unit's coefficient of performance (COP), I is the input power (W), q_{sm} and q_{hm} are the machine's supply flowrate and hot air flow rate respectively. T_{sm} and T_{hm} are the supply temperature and hot-air temperature respectively.

3.2 Parametric analysis

In this single-factor analysis, some of the DV system and PDV unit specifications were changed to study the effect of each variable on the unit's performance and the room temperatures. In all cases, the assumed values are input to equations (1)-(3) to be solved simultaneously, then the resultants were used to calculate the hot air temperature using equation (4). Table 1 summarizes the set of values used in the study. The factors studied in this section are:

Cases-A: PDV unit's COP, varying from 3.0 to 4.0,

Cases-B: PDV unit supply flowrate, varying from 100 m^3/h to 300 m^3/h, at fixed DV flowrate,
Cases-C: DV supply flowrate, varying from 100 m^3/h to 300 m^3/h, at a fixed PDV unit flowrate,
Cases-D: PDV unit hot air flowrate, varying from 100 m^3/h to 300 m^3/h.

Table 1: Cases of parametric study by zonal model

		Cases-A	Cases-B	Cases-C	Cases-D
DV	q_s (m^3/h)	200	200	**300 -100**	200
	T_s (°C)	20			
PDV unit	COP, n	**3.0 – 4.0**	3.5	3.5	3.5
	I (W)	Dependant			
	q_{sm} (m^3/h)	200	**100 – 300**	200	200
	q_{hm}(m^3/h)	$=q_{sm}$	$=q_{sm}$	$=q_{sm}$	**100 – 300**
	T_{sm} (°C)	20			
	T_{hm} (°C)	Dependant			

The results of the zonal model calculation of Cases A-D are plotted in this section. It should be noted that in all cases, since the idea situation of η =1 is assumed, the occupied zone temperature, T_l, is constant at 20 ° C, equal to the supply temperature.

1) PDV unit Coefficient of performance

Calculations of increasing the unit's COP from 3 to 4 at constant supply flowrate and temperature were carried out, Cases-A. From Fig. 3a, the increase in COP is seen to enhance the performance by decreasing the exhausted heat as can be. Increasing the COP from 3 to 4 reduces the required input power by a third to provide a fixed flow rate at a fixed supply temperature, as shown in Fig. 3b.

2) PDV unit supply flowrate at fixed DV flowrate

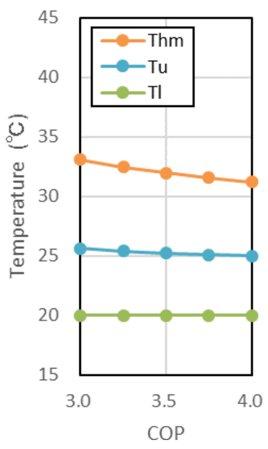
As shown in Fig. 3c and Fig. 3d, calculations with q_{sm} varying from 100 m^3/h to 300 m^3/h were performed, Cases-B. The 100 m^3/h case requires a relatively small wattage of around 20 W. It can be observed as well that increasing the flow volume requires a steep increase in the input power of the machine. Increasing I, thus, results in exhausting air at higher temperature (T_{hm}).

3) DV flowrate at fixed PDV unit supply flowrate

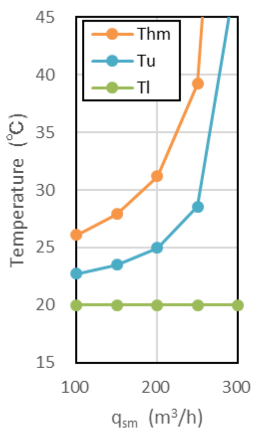
Decreasing the DV supply flowrate is intended to investigate the PDV unit input power needed to compensate. As shown in Fig. 3e, the relation is exponential. At q_s 100 m^3/h where the DV supply flowrate was lowest, the input power required for the PDV unit to compensate was more than 3 times that of q_s 200 m^3/h. This increase in I was reflected in the hot air temperature and upper zone temperature as shown in Fig. 3f. Since T_u increased to 40 ° C making the difference between the upper and lower zone temperatures 20 ° C, this shows that the PDV unit compensation capacity is bound by the temperature difference comfort between head and feet height. However, the PDV unit location, although not represented in the zonal model, might be a major factor in this aspect.

4) PDV unit hot air exhaust flow rate

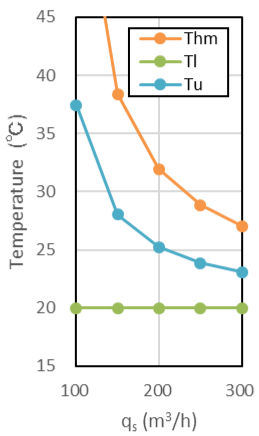
The relation between hot air flow rate and temperature is given by equation (4). For a fixed case-D, q_{hm} varying were used to calculate the hot air temperature. Fig. 3g shows that increasing the flow rate from 100 to 300 m^3/h can decrease the temperature by 10 ° C. However, the effect of this variable especially, needs to be investigated using CFD analysis or experiment measurements as the flowrate of hot air can highly affect the temperature horizontal distribution and generally the DV induced stratification.



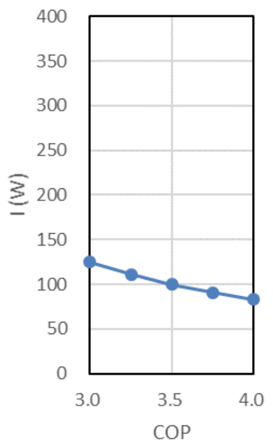
a. Cases-A: COP vs temperatures



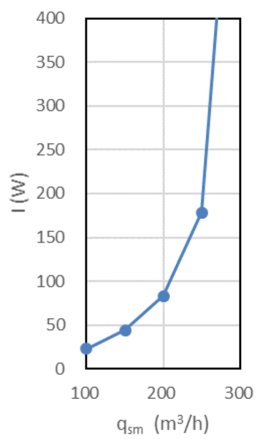
c. Cases-B: PDV unit supply flowrate vs temperatures



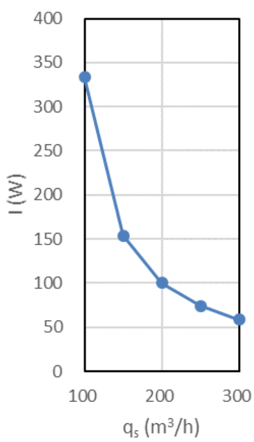
e. Cases-C: DV supply flowrate vs temperature



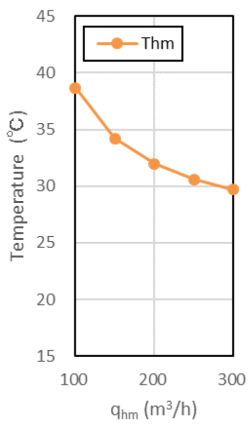
b. Cases-A: COP vs required input power



d. Cases-B: PDV unit supply flowrate vs required input power



f. Cases-C: DV supply flowrate vs PDV unit required input power



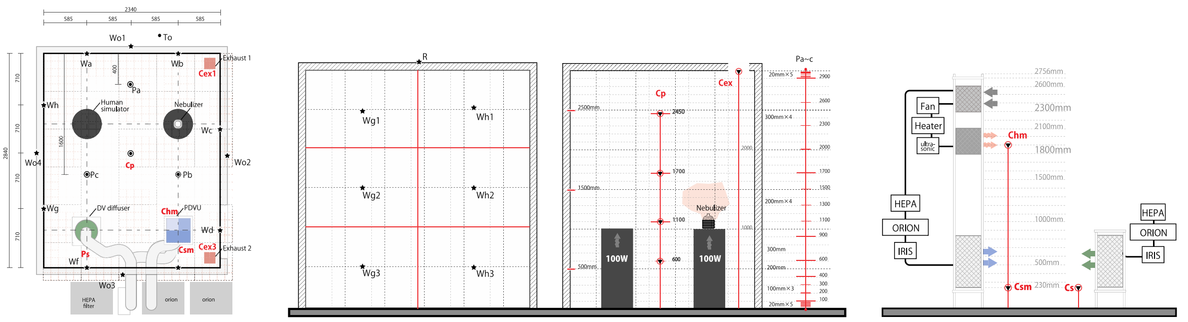
g. Cases-D: PDV unit hot air flowrate vs hot air temperature

Figure 3: Relationship between PDV unit parameters (COP, PDV unit supply airflow rate, DV supply airflow rate, PDV unit hor airflow rate) and temperatures, required input power etc.

4 EXPERIMENT

4.1 Experiment room

The measurements were carried out in the period of January 26 – February 7, 2023 in a full-scaled experimental chamber made in Osaka University. This experimental room was built of insulated wooden boards. As annotated in Fig. 4, the room dimensions are 2.84 mm * 2.34 m * 3.00 m, which is relatively small.



a. Plan b. Longitudinal section c. Cross section d. System components

Figure 4: Experiment room and measurement points

4.2 Equipment

The PDV unit was not built as an intact one unit as designed, but broken down into its basic components with the same function as PDV unit as shown in Fig. 4d. All equipment was placed outside the room, only the diffusers, suction port, and hot-air inlet were placed inside the room.

The PDV unit components were fixed into a 2.7 m high metal frame. The suction port is 0.3 m size cube intaking air from three sides, top and bottom sides are solid while the remaining face is where the ducts were connected. The suction port is connected by 12.5 cm wide ducts to two paths; cooling and heating. The cooling and filtration function was achieved using air processor (AP-750M-C, Orion Machinery Co., Ltd.) connected to HEPA filter. Chilled and filtered air flow through the inlet duct was connected to a fabric duct to act as a circular diffuser for DV, 0.6 m high and 0.3 m in diameter. A similar arrangement was used for the room's DV system. As for the heating function, duct fan (FY-23DZ4, Panasonic) and duct heater (DM-11N, Nippon Heater Co., Ltd.) were used. The heated air flows through a 0.3 m * 0.3 m cylindrical fabric duct. The supply air flow from both DV and PDV unit are controlled by Iris dampers and monitored by low differential pressure transducer (DP-45, Validyne Engineering). The hot-air flow was monitored by ultrasonic flow meter (TRZ150D-C, Aichi Tokei Denki) connected to current data logger (RTR-505, T&D Co., Ltd.). All ducts of the system were glass fibre insulated, and the openings in the walls were tightly sealed.

Representing seated occupants as heat source, two cylindrical person simulators were operated at 100 W each, controlled by voltage regulators and monitored by watt meters. Each person simulators is 1.00 m high and of a diameter of 0.40 m. They were placed over an insulative-5 cm-foam disc in locations indicated in Fig. 4a.

Temperature was measured using T-type thermal couples connected to CADAC-3 data logger (Eto Electric Co.). The measurement points are indicated in Fig. 4a and Fig. 4b. For surface temperature, Wa1~Wh3 stand for walls inner surface points, Wo1~4 stand for the outer surface points, and R stands for the roof surface point. To measure the vertical temperature distribution in the experiment room, 22 points at each pole, Pa-c were measured. The floor and ceiling surface temperature was measured at the same poles. The surface temperature of one heat simulator was measured as well. In addition, the air temperature of the PDV unit's supply diffuser, hot air diffuser, and suction port were measured as well as the DV supply and the exhaust temperatures. The temperature outside the experimental chamber and inside the experiment building was monitored at point To.

The contaminant simulated in this experiment was coughing droplets. Artificial saliva was prepared with 12 g salt (NaCl) and 76 g glycerine for 1 litre of distilled water. The droplets were produced by nebulizer (NE-C801, OMRON Healthcare, Inc.) and the emission rate was controlled by setting the gas flow to 2 NL/min. N_2 gas was chosen as its density is almost the same as that of air. In order to have a distributed emission, rather than a stream of droplets, the nebulizer was covered by a plastic bottle made of PET that has many holes with 0.5 mm diameter in its upper part. The bottle was heated by a bottle warmer (12.3 W) wrapped around it in order to prevent condensation and to raise the temperature of the droplet emission.

The droplets were measured using handheld particle counters (RION and Kanomax) fixed at Pd at heights 0.9 m, 1.1 m, and 1.7 m. In addition to 2.45 m which matches the suction port height. Measurements of the exhaust opening were taken as well. In addition, to confirm the supply air filters, particles count at both supply diffusers and hot-air supply were monitored.

4.3 Cases and parameters

The parameters investigated in this study were the supply flowrate of DV and PDV unit. The supply flowrate of both DV and PDV unit was tried with three variations 200 m^3/h, which is 100 m^3/h for one person, and one lower and one higher flowrate, 100 m^3/h and 300 m^3/h. The hot air flowrate was set constant to 200 m3/h regardless of the supply flowrate.

A total of 7 cases carried out are summarized in Table 2. The cases can be divided into 3 groups according to the comparative parameter. Group 1 shows the effect of changing PDV unit supply flowrate at a constant DV unit flowrate. Group 2 is a comparison between different DV supply flowrate at a constant PDV unit supply of 200 m^3/h. Viewing the PDV unit as a complementary ventilation system, Group 3 compares all cases with a total supply flow rate of 200 m^3/h.

As shown in Table 2, the case naming includes the system running, DV for the displacement ventilation supply, and PU is short for the PDV unit. Each system abbreviation is followed by the supply flowrate value. Here Ex1 is the name of exhaust position on the ceiling as shown in Fig.4a as Exhaust 1. (Ex2 is not listed.)

Table 2: Experiment cases

Case number	Case name*	DV supply flow rate q_s [m^3/s]	PDV unit supply flow rate q_{sm} [m^3/s]	DV supply flow rate q_s [m^3/s]
1	DV200	200	0	200
2	DV200_PU100	200	100	200
3	DV200_PU200	200	200	200
4	DV200_PU300	200	300	200
5	DV100_PU200	100	200	100
6	DV100_PU100	100	100	100
7	PU200_EX1	0 (No ventilation)	200	0 (No ventilation)

*DV means Displacement Ventilation and PU means PDV unit

4.4 Measurement method

Data recordings were taken at a one-minute interval. The timeline of the measurement is illustrated in Fig. 5. The ventilation system was switched on and the temperature recordings were continued until steady state was reached, which took about 2.5 hours. Afterwards, the nebulizer was turned on for one hour. After stopping the emission, the particles count at the exhaust was monitored until it decreased back to the background count. The emission stage was run for 2 rounds with the particle counters fixed at different heights. Finally, the ventilation system was switched off. A sample of 30 minutes in which both temperature and particles distribution were at steady state was taken for data analysis. Variation in the rounds particle count is shown in Fig.5 in the case 2 (DV200_PU200). The count variation of the exhaust air shows the unstable emission rate of nebulizer. It can be said that the absolute value of the concentration data could have deviation due to time variation of emission rate of the nebulizer.

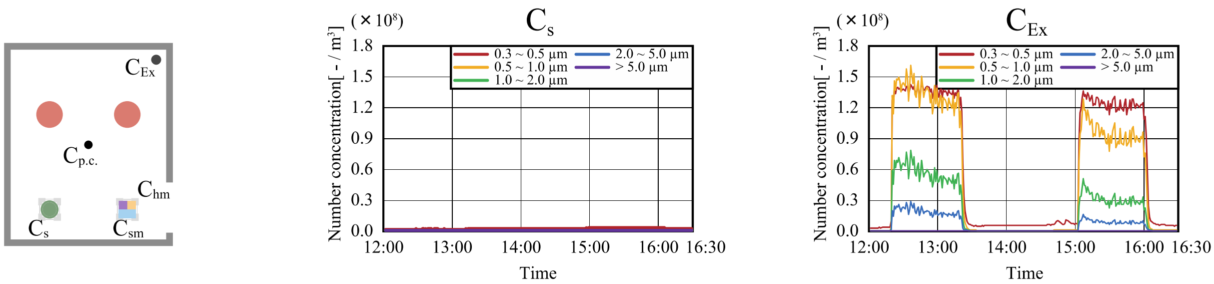


Figure 5: Variation of droplet count (Case 2 : DV200 - PU200)

5 RESULTS AND DISCUSSION

5.1 Temperature stratification

Group 1: Varying PDV unit's supply flowrate (q_{sm})(Fig.6a)

To investigate the effect of operating the PDV unit in the room, cases of varying PDV unit supply flowrate 0 ~ 300 m^3/h at constant DV flowrate are compared in Fig.6a. Comparing the cases, it can be observed that cases with PDV unit have a stronger temperature stratification. The larger PDV unit flowrate is the lower the overall temperature and especially the upper temperature peak becomes.

Group 2: Varying DV supply flow rate (q_s) (Fig.6b)

Decreasing the DV supply flowrate from 200 m^3/h to 100 m^3/h did not cause a major shift in the temperature curve. However, since these cases had the PDV unit in operation, it can be assumed that the PDV unit mitigated the decrease effect. Turning the DV off on the other hand, caused an increase in temperature ranging from 1 to 2°C with a stronger temperature stratification.

Group 3 Varying total flowrate (q_s+ q_{sm})(Fig.6c)

DV200 case displayed the lowest temperature in the upper zone. PU200 case and DV100_PU100 case showed very close results.

5.2 Particles distribution

The vertical distributions of particle concentrations in each case are shown in Fig.7. The data connected by lines are at the point of Cp in Fig.4a, and the isolated plot at the height of 1.9 m shows the concentration at the hot air supply port. This hot air is originaly extracted at 2.45m+FL and heated but not filtered by HEPA. In the case of DV only (Case 1), data is not plotted, as this PDV unit is not operating.

Group 1: Varying PDV unit's supply flowrate (qsm)(Fig.7a)

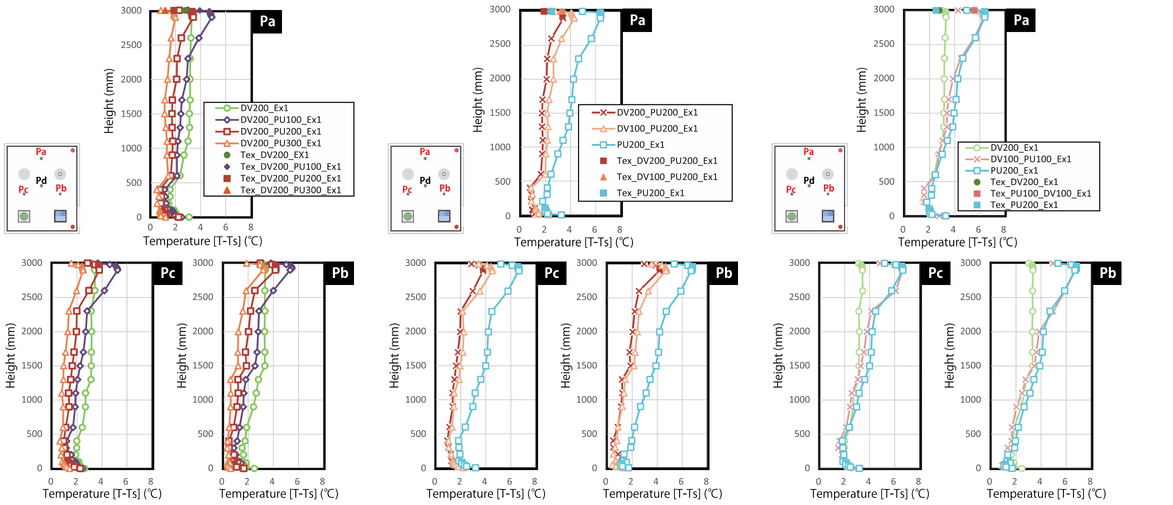
Although increasing the unit's flowrate from 100-200 m^3/h caused a matching reduction of the particle count, but increasing the supply airflow rate of PUV unit has no essential effect on the particulate concentrations.

Group 2: Varying DV supply flow rate (qs) (Fig.7b)

Decreasing the DV airflow rate had the foreseen effect of increasing the particle count and volume concentration. The increase was not confined to the higher heights and extended to the 1700 mm height. Lower heights had almost no particles even with the DV turned off, so the PDV unit has the distinct effect on the cleaning air in occupant zone and advantage of stability caused by the strong temperature stratification.

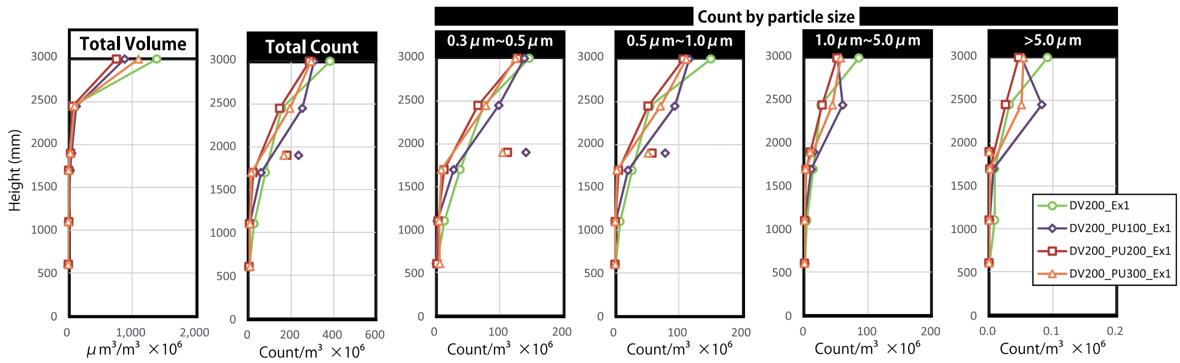
Group 3: Varying total flowrate (qs+ qsm)(Fig.7c)

Agreeing with the temperature profiles, the effect of compensating the reduction in DV airflow rate by the PDV unit airflow rate was dependent on the total airflow rate value. As shown in Fig. 7c, reducing DV airflow rate at the q_{total}=200 m^3/h causes an increase in the top zone particle count and volume. It can be said that DV is more effective than the PDV unit if the airflow rate is the same, but PDV unit has high capacity of air purification of the air in the occupancy zone.

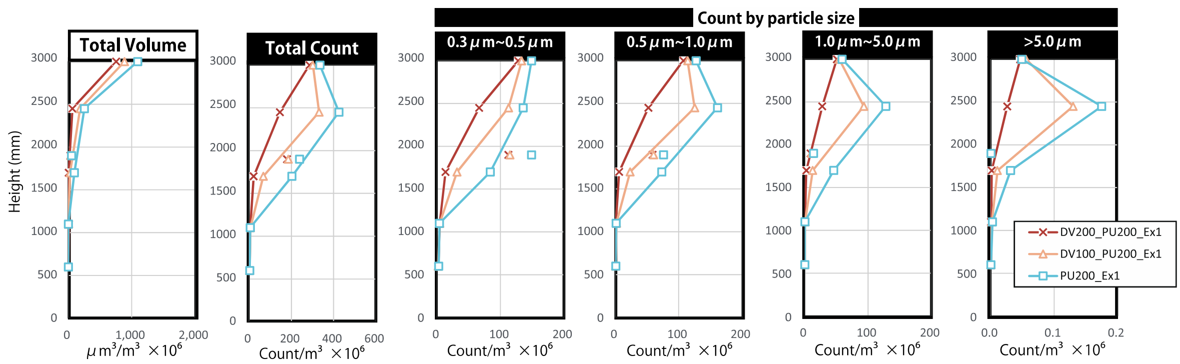


a.Group-1 (varied PDV unit supply) b.Group-2 (varied DV supply) c. Group-3 (varied supply combination)

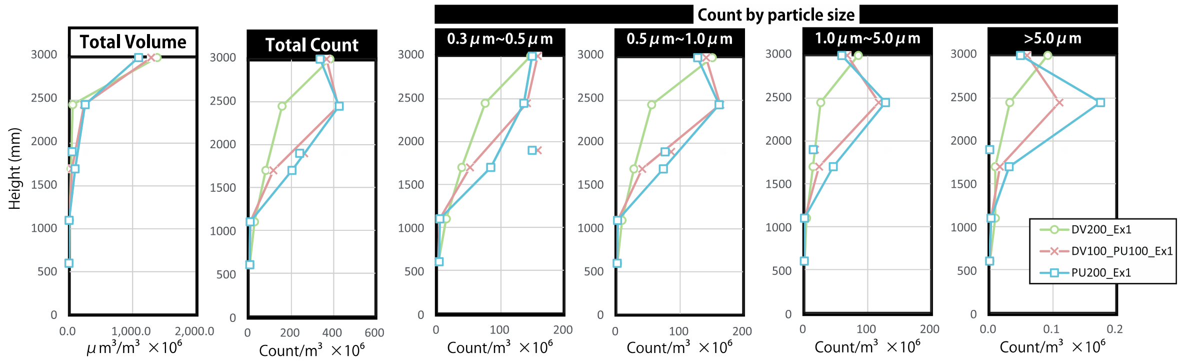
Figure 6: Temperature Stratifications in each Group of cases



a. Group-1 (varied PDV unit supply)



b. Group-2 (varied DV supply)



c. Group-3 (varied supply combination)

Figure 7: Vertical distributions of particle concentration (Total Volume, Total Count, Count of each particle size)

5.3 PDV unit capacity

Since the PDV unit was operated using separate systems, the heating and cooling capacities at each case were calculated using equations (3) and (4). The results are in Table 3. Q_{sm} is the cooling capacity, and Q_{hm} is the heating capacity.

The calculation shows that despite setting the heater's power Q_{hm} to 450W and monitoring it using the watt meter, the actual heat gain was not constant in all cases. Most of the cases had a lower heating capacity. Reviewing the temperature readings in Table 3, it can be noticed that the outside temperature T_o was below the supply air temperature which means that given the long ducts connections, heat seems to have been lost before arriving at the hot air supply port.

Table 3: Temperature, flowrates and PDV unit capacity by case (unit: [°C], [m³/h], [W])

Cases	T_o	T_s	T_{sm}	T_{hm}	T_u	T_{ex}	T_{Hs}	T_l	q_s	q_{sm}	q_{hm}	Q_{sm}	Q_{hm}
												equation (3)	equation(4)
DV200_	-1.05	0	-	-	2.89	2.77	9.66	2.68	198	0	0		
DV300_	0.34	0	-	-	2.89	2.77	9.3	2.54	309	0	0		
DV200_ PU100	-1.08	0	-0.21	12.19	6.03	3.94	9.37	2.13	194	104	200	217	411
DV200_ PU200	-3.37	0	-0.46	10.3	5.4	1.88	8.95	1.75	193	193	201	379	329
DV200_ PU300	-1.97	0	-0.54	10.07	3.9	1.18	8.35	1.31	189	288	197	428	407
DV100_ PU200	-0.76	0	-0.56	11.05	4.15	3.35	9.13	2.04	119	200	196	316	454
DV100_ PU100	-1.43	0	-0.35	12.83	6.62	5.54	9.38	2.73	108	98	201	228	417
PU200	2.02	-	0	13.36	7.63	-	9.86	3	0	199	201	507	385

6 CONCLUSION

From the experiment, DV capacity of PDV unit was turned out, and the effects of airflow rates of DV and PDV unit on the performance were made clear, and the zonal model is quite useful to know the mutual effect of various parameters.

7 REFERENCES

Nielsen, P. V.(1993). *Displacement Ventilation.* Dept. of Building Technology and Structural Engineering, Indoor Environmental Engineering, No. 15

Zhang, T. (Tim), Wang, S. , Sun, G., Xu, L., Takaoka, D. (2010). Flow impact of an air conditioner to portable air cleaning, Building Environment, 45, 2047–2056. doi:10.1016/j.buildenv.2009.11.006