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Research paper

An experimental investigation into the pull-down performances with different air distributions

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HIGHLIGHTS

- Pull-down (cooling a room) process for a room to reach a thermal comfort state.
- Experimental investigation to find the time and energy used for pull down.
- Stratum ventilation, mixing ventilation and displacement ventilation are tested.
- Stratum ventilation is found to use much less time and energy.

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ABSTRACT

The purpose of this study is to investigate the loads and lengths of the pull-down periods (the time used to achieve a comfortable thermal environment before a room is ready for occupation) with mixing ventilation, displacement ventilation and stratum ventilation. In a typical classroom in Hong Kong, experiments begin with the same initial hot thermal environment. Based on ASHRAE 55-2010, ISO Standard 7730 and literature, existing indices PMV, PD and ADPI, calculated from measured data, are used as the thermal comfort criteria to determine the end of the pull-down period. The results indicate that stratum ventilation outperforms the other two air distributions during the pull-down period in terms of rapidity and energy consumption. For the rapidity of the pull-down process, mixing ventilation spends a shorter time than displacement ventilation, while stratum ventilation spends less than half of the time the other two spend. The average pull-down load of stratum ventilation is only around a quarter of that of mixing ventilation or displacement ventilation, The exergy consumption of the chilled water used for the pull-down of stratum ventilation is also lower than that of the other two distributions.

1. Introduction

To minimize energy consumption by air conditioning systems, guidelines of various elevated room temperatures for summer have been issued by governments in East Asia [1–6]. The new ASHRAE Standard 55–2013 offers new provisions that allow increased air movement to broadly offset the need to cool the air in warm conditions [7]. To accommodate the elevated room temperatures, stratum ventilation was proposed for small to medium rooms [8,9]. Stratum ventilation was found to perform well in thermal comfort and IAQ through experimental and numerical investigations [10–12]. The experimental investigation also found that: (1) the CO_2 concentration in the occupied zone is typically lower than that in the upper zone; and (2) in the occupied zone, the air speed generally increases with height whereas the temperature gradient is reversed with the lowest value at the head level. The cooling effect (temperature and air movement) of the conditioned airflow is the strongest at the head level [13].

Comparison of stratum ventilation and conventional ventilations (displacement ventilation and mixing ventilation) has been conducted on different aspects. The year-round energy consumption of stratum ventilation is at least 25% lower than that of displacement ventilation or 44% lower than that of mixing ventilation [14]. The thermal neutral temperature under stratum ventilation was found to be approximately 2.5 °C higher than that under mixing ventilation and 2.0 °C higher than that under displacement ventilation [15]. The particle dispersion under stratum ventilation, displacement ventilation and mixing

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ventilation were investigated by numerical simulations. The results indicated that the particle concentrations in the breathing zone under stratum ventilation are significantly less than that under displacement ventilation or mixing ventilation. The risk of pathogen inhalation under stratum ventilation is lower than that under displacement ventilation or mixing ventilation [16,17]. The airflow characteristics of stratum ventilation in a multi-occupant room were compared with that of mixing ventilation and displacement ventilation experimentally [18].

The previous studies mainly focus on the operation of steady thermal environment, while the unsteady performances of various air distributions are largely absent. To save energy, air conditioning systems are switched off for rooms not in use (e.g. the situation at nights). As long as the capacities of the air conditioning systems are sufficient, the thermal comfort state can finally be reached (e.g., the situation in the mornings). It is of interest to know how long it takes for such a room to reach a thermal comfort state when it is ready for the occupants to stay with different air distributions. Similarly, how much energy is consumed during this transient (pull-down) period is also of interest. An air conditioning system operates under full load condition during this period for the control variable(s) to approach the set point. Thus, energy used to “cool down” a building during the pull-down processes forms a significant portion of the total energy consumption by air conditioning systems. Studies on this issue are rare. Therefore, the aim of this experimental investigation is to compare the rapidity and energy used for a hot indoor environment to reach a thermal comfort state by means of stratum ventilation, mixing ventilation and displacement ventilation respectively.

During a pull-down process, besides the heat sources, the air conditioning system needs to offset the transient heat released from the building enclosure structure (walls, ceiling, floor, etc.) and from the furniture. Massouros et al. found that this transient heat is nonlinear and time-dependent [19]. The temperature profiles, the duration of the transient state and therefore instantaneous heat release are a complicated function of the thermal and structural characteristics of the enclosure structure and furniture. Mathews et al. pointed out that it is difficult to incorporate all the complex heat transfer phenomena into an efficient building thermal analysis. It is especially true for the heat storage of a building [20]. Lacarriere et al. suggested that experimental investigation is an effective approach to cope with the heterogeneity and nonlinearity in heat transfer [21]. The focus of this study is to determine the lengths of the pull-down process, and associate energy consumption which can be calculated if lengths of the processes are found. It is required to detail the associate transient heat transfer amongst the air flowing through the room, the furniture in the room and the enclosure enveloping the room. Therefore, an experimental approach is adopted for this study.

2. Experiment setup

2.1. Test chamber

The chamber is arranged as a typical classroom in Hong Kong. The sizes are 8.8 m (L) × 6.1 m (W) × 2.4 m (H). The chamber is located at interior zone without external windows and walls. The internal heat sources are given in Table 1. The only occupant during the pull-down processes is the first author who conducts the tests. The associated air-conditioning system consists of a ceiling-mounted variable-air-volume-type air handling unit, ceiling-mounted diffusers for mixing ventilation, wall-mounted perforated-type air diffusers for displacement ventilation and stratum ventilation, motorized dampers and ductwork.

Table 1
Internal heat sources (W).

Workstation	PC	Lamps	Occupant
300	150 × 2 = 300	56 × 21 = 1176	75

For mixing ventilation, there are six ceiling supply diffusers and three return air louvers at 2.4 m above the floor level (Fig. 1). For displacement ventilation, supply air is provided from both sides of four wall-mounted perforated diffusers at 0.33 m above the floor level and returns to three ceiling inlets (Fig. 2). For stratum ventilation, air is supplied horizontally from four wall-mounted perforated diffusers installed on the front wall at 1.3 m above the floor level together with four wall-mounted return air inlets on the rear wall at the same height as supply air diffusers (Fig. 3).

2.2. Test procedure and cases studied

In order to evaluate thermal comfort in the classroom, air speed and temperature are recorded during the experiment. The measurement positions are shown in Fig. 4 for stratum ventilation and mixing ventilation and Fig. 5 for displacement ventilation. In Fig. 4, there are four measurement points (P1–P4) at the height of 0.1 m, one measurement point (P5) at 0.6 m level and five measurement points (P6–P10) at 1.1 m level. P6 and P7 face the leftist supply diffuser directly. P8 and P9 are located facing the middle of two neighboring supply diffusers. Shown in Fig. 5, for displacement ventilation, due to the importance of the 0.6 m level for sedentary occupants, there are three measurement points (P1, P3 and P5) at 0.6 m level and two measurement points (P2, P4) at 0.1 m. The actual setup of the air chamber is illustrated in Fig. 6.

The air velocity and temperature are measured by SWEMA transducer SWA 03. The velocity measuring range is 0.05–3.00 m/s; the accuracy is ±0.02 m/s for 0.07–0.05 m/s and ±0.03 for 0.5–3 m/s; and the dynamic response time is 0.2 s. The air temperature measuring range is 10 °C–40 °C with an accuracy of ±0.2 °C. The relative humidity is recorded by the BMS system.

Nine scenarios with the three air distributions at three airflow rates of 0.25, 0.358 and 0.537 m^3/s, corresponding to 7, 10, 15 air changes per hour (ACH), are studied experimentally. These airflow rates are determined based on the load variations for the building types of typical Hong Kong classrooms, offices and retail shops of the same area. In order to eliminate random error, each scenario is repeated once at least. To keep a balance between the accuracy and cost, the scenarios of stratum ventilation at 0.25 m^3/s, mixing ventilation at 0.358 m^3/s and displacement ventilation at 0.537 m^3/s are conducted three times in order to test the repeatability. Totally, there are twenty one runs as summarized in Table 2. For the run code “?V–N-n”, “SV, MV and DV” denote stratum ventilation, mixing ventilation and displacement ventilation respectively. “N” gives the air change per hour in the run. “n” is the repetitive run sequence. “DV-10-2”, e.g., means the second run of displacement ventilation at 0.358 m^3/s.

It would be meaningless to compare the lengths and energy comsumption of two pull-down processes as their starting points are significantly different one from another. To enable comparison, the initial conditions (the starting state of the pull-down process) of all the experimental runs must be as close as practically possible. For this purpose, the chamber is left without air-conditioning overnight. The initial average temperature at the levels of 0.1 m, 0.6 m and 1.1 m is shown in Fig. 7. The initial average temperatures of all runs are around 28.3 °C at 0.1 m, 29.8 °C at 0.6 m and 30.8 °C at 1.1 m. Additionally, a pull-down test is started only if its initial temperature fluctuation is within a reasonable range of ±0.4 °C for 15 min at least.

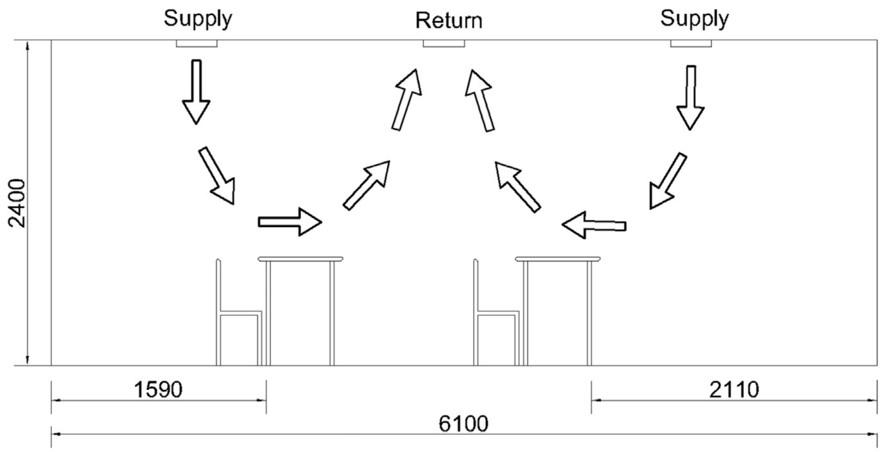

Fig. 1. Mixing ventilation with ceiling supply and return.

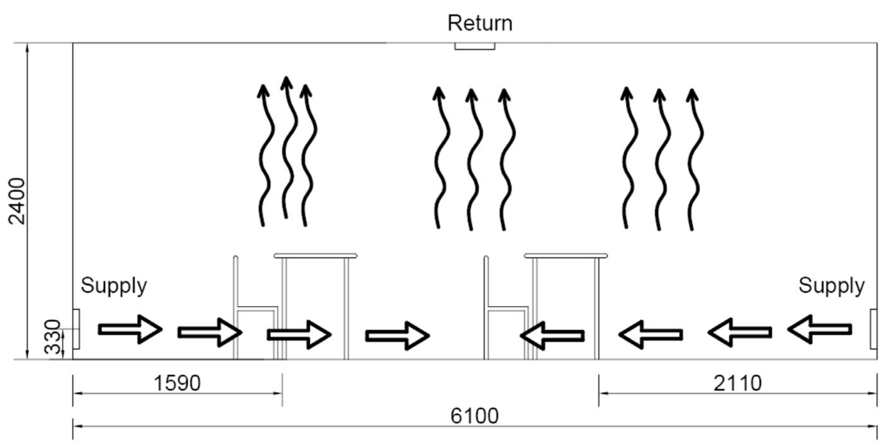

Fig. 2. Displacement ventilation with front and rear wall supply at low level and ceiling return.

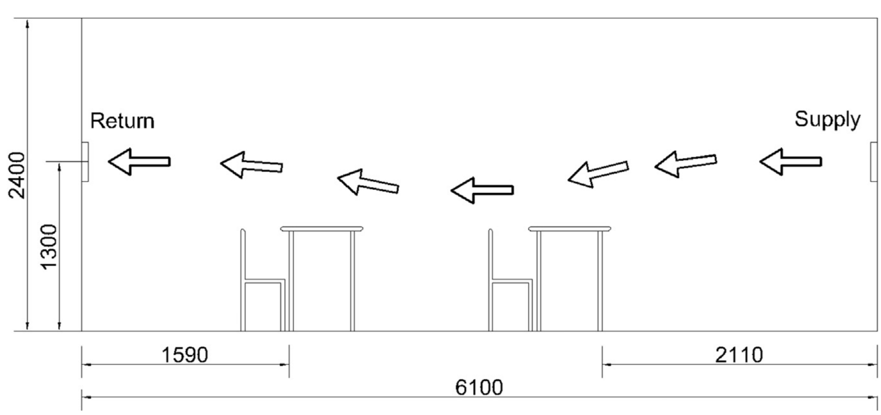

Fig. 3. Stratum ventilation with front wall supply and rear wall return at mid-height of walls.

The supply air temperature is well controlled for the experimental runs. The supply air temperatures are 21.2 ± 0.3 °C, 15.0 ± 0.3 °C and 18.1 ± 0.3 °C for the stratum ventilation runs, mixing ventilation runs and displacement ventilation runs respectively. The fresh air was supplied by a primary air handling unit with its flow rate fixed for all experimental cases. The room set point temperature of 22 °C is low enough to ensure continuous running of the air-conditioning system in its full capacity until manually switching off when it is obvious that the initial state of thermal comfort has been passed over.

3. Evaluation of performance in thermal comfort

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. ANSI/ASHRAE Standard 55–2010 [7] and ISO Standard 7730 [22] provides the method for

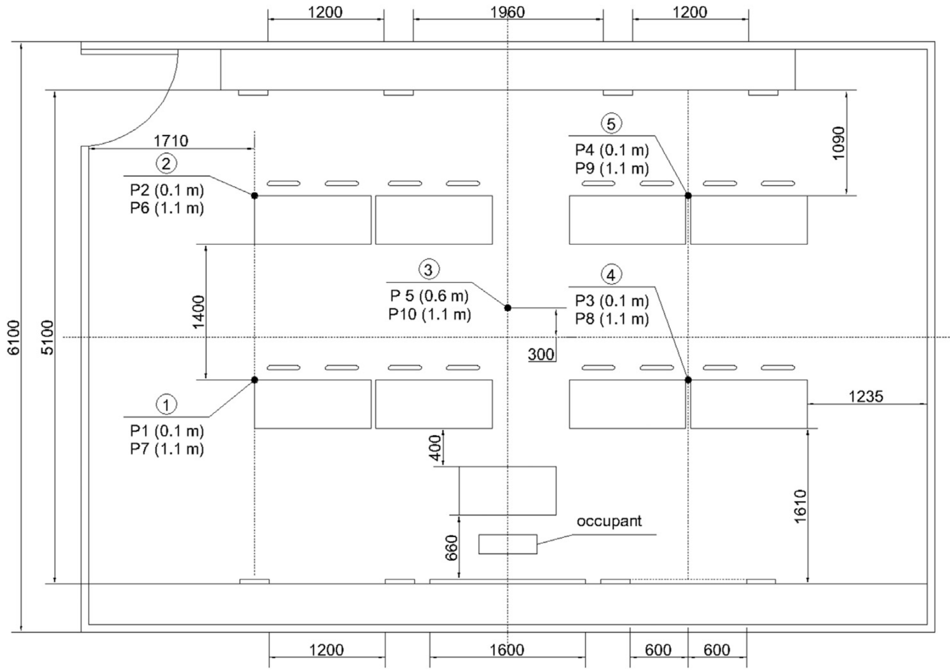

Fig. 4. Plan view of measurement positions (mm) for stratum ventilation and mixing ventilation at 0.1 m, 0.6 m and 1.1 m levels.

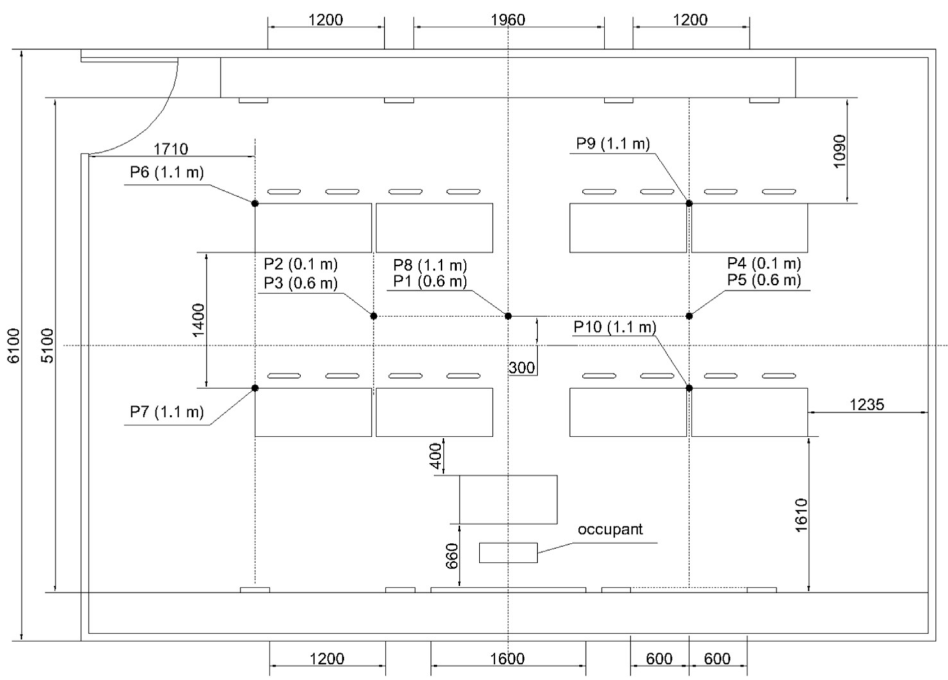

Fig. 5. Plan view of measurement positions (mm) for displacement ventilation at 0.1 m, 0.6 m and 1.1 m levels.

determining acceptable thermal comfort conditions. In order to achieve a good thermal comfort and therefore complete the pull-down operation, these requirements must be met: (1) PMV; (2) vertical air temperature difference; (3) PD due to draft. In addition, air diffusion performance index (ADPI) is also used to evaluate thermal comfort under mixing ventilation and stratum ventilation. If all these three criteria are fulfilled, a state of thermal comfort has just been reached. This state is the end of the pull-down period. Because vertical stratification is an indispensable property of displacement ventilation, the ADPI approach is not applicable to displacement ventilation.

3.1. Predicted mean vote (PMV)

The predicted mean vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort to the average response of people (Fanger, 1972). PMV model is widely accepted in thermal environment study. For this study, a metabolic

Fig. 6. Experimental setup in air chamber.

rate of 1.1 met (65 W/m^2) is used because the occupants in the classroom are sedentary. The clothing insulation factor is 0.5 (1 clo = 0.155 m^2 K/W) which corresponds to the summer dressing. The mean relative humidity of 45% is used in the calculation. Because the room is in an interior zone without solar radiation, dry-bulb temperature was used to calculate PMV. The formal of PMV-PPD could be found in ASHRAE 55-2010 [7] and ISO Standard 7730 [22].

Meanwhile, the recommended PMV range is defined in ASHRAE 55-2010 [7] and ISO Standard 7730 [22], i.e., $-0.5 < PMV < 0.5$ is considered as the acceptable thermal environment for general comfort.

Because the experimental chamber is also a typical classroom in Hong Kong, the clo-value and activity level are limited to 0.5 m^2 K/W and 1.1 met, respectively.

3.2. Percentage dissatisfied (PD) due to draft

Draft is unwanted local cooling of the body caused by air movement, which depends on the air speed, the air temperature, the activity and the clothing. According to CRR 1752 1998, the requirements of Class C indoor thermal environment for PD is less than 25% [22]. According to ASHRAE 55-2010 [7] and ISO Standard 7730 [22], the allowable PD due to draft is below 20%.

3.3. Vertical air temperature difference

Thermal discomfort may be caused by thermal stratification that temperature at the head level is much warmer than that at the

Table 2
Parameter of twenty one runs.

Run no.	Airflow rate (m^3/s)	$t_{0.1m}$ (°C)	$t_{0.6m}$ (°C)	$t_{1.1m}$ (°C)	Supply air temperature (°C)	Run parameter code
1	0.25	28.3	29.8	31.07	21.2 ± 0.3	SV- 7-1
2		28.4	29.9	30.87		SV- 7-2
3		28.2	29.7	30.73		SV- 7-3
4	0.358	28.9	30.3	31.30		SV-10-1
5		28.6	30.1	31.07		SV-10-2
6	0.537	28.6	30.1	31.10		SV-15-1
7		28.5	29.6	30.62		SV-15-2
8	0.25	28.3	29.6	30.69	15.0 ± 0.3	MV- 7-1
9		28.3	29.7	30.60		MV- 7-2
10	0.358	28.3	29.6	30.47		MV-10-1
11		28.4	29.8	30.84		MV-10-2
12		28.1	29.8	30.79		MV-10-3
13	0.537	28.1	29.4	30.33		MV-15-1
14		28.4	29.8	30.75		MV-15-2
15	0.25	28.2	29.7	30.95	18.0 ± 0.3	DV- 7-1
16		28.0	29.6	30.82		DV- 7-2
17	0.358	28.0	29.8	30.96		DV-10-1
18		27.8	29.5	30.74		DV-10-2
19	0.537	28.4	29.9	30.88		DV-15-1
20		28.6	30.0	31.04		DV-15-2
21		28.1	29.3	30.66		DV-15-3

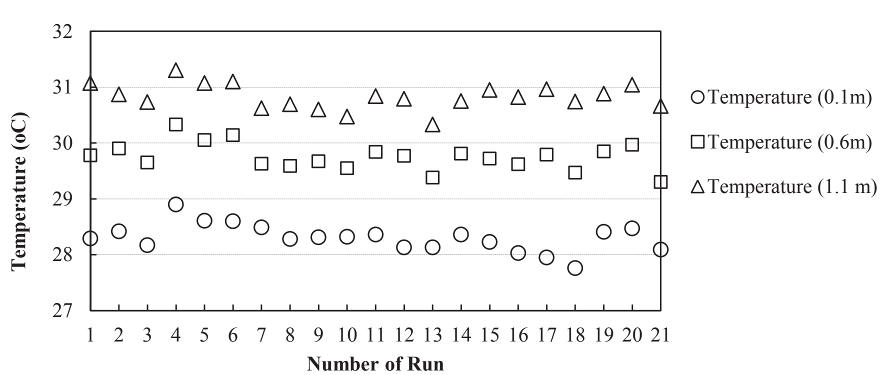

Fig. 7. Initial average temperatures at 0.1 m, 0.6 m and 1.1 m levels.

ankle level. Thus, vertical air temperature difference between the head and ankles should be considered for thermal comfort, especially for the displacement ventilation. According to ASHRAE 55-2010 [7] and ISO Standard 7730 [22], the allowable differences in air temperature is 3 °C or less.

$$t_{vt} = t_{1.1} - t_{0.1} \quad (1)$$

where

t_{vt} = vertical air temperature difference
$t_{1.1}$ = temperature at the height of 1.1 m, °C
$t_{0.1}$ = temperature at the height of 0.1 m, °C

For stratum ventilation and mixing ventilation

$$t_{vt1} = t_{p6} - t_{p2}$$

$$t_{vt2} = t_{p7} - t_{p1}$$

$$t_{vt3} = t_{p8} - t_{p3}$$

$$t_{vt4} = t_{p9} - t_{p4}$$

For displacement ventilation,

$$t_{vt1} = t_{p6} - t_{p2}$$

$$t_{vt2} = t_{p7} - t_{p2}$$

$$t_{vt3} = t_{p8} - t_{p4}$$

$$t_{vt4} = t_{p9} - t_{p4}$$

where

t_{vt} = vertical air temperature difference, °C
t_{pi} = temperature of the ith measurement point, °C

3.4. Air diffusion performance index (ADPI)

ADPI was not originally designed to evaluate stratum ventilation, but it essentially measures the degree of mixing achieved by a room air distribution system, which is determined based on the collective result of the effective draft temperature (EDT) for evenly distributed points in a occupied zone [23]. It could therefore be modified to evaluate the uniformity at the head-level plane. ADPI has been widely used to evaluate and/or predict the performance of mixing ventilation. Similarly, the new formula of effective draft temperature for stratum ventilation (EDTS) was developed for stratum ventilation [24]. For EDT, the thermal comfort range is −1.5 to +1.0 K. For EDTS, the thermal comfort range is −1.2 to + 1.2 K.

$$\theta_{ed} = (t_x - t_c) - 8(v_x - 0.15) \quad (2)$$

$$\theta_{eds} = (t_x - t_c) - (v_x - 1.1) \quad (3)$$

where

θ_{ed} = effective draft temperature, K
θ_{eds} = effective draft temperature for stratum ventilation, K
t_x = local airstream dry-bulb temperature, °C
t_c = average room dry-bulb temperature, °C
v_x = local airstream centerline speed, m/s

The ADPI can be calculated as follows [23]:

$$ADPI = n/N \times 100\ (\%) \quad (4)$$

where,

$ADPI$ = Air Diffusion Performance Index, %;
n = number of comfort points;
N = number of the total measurement points.

4. Evaluation of energy performance

In addition to the records of the time spent in each pull-down process, energy consumption of each pull-down run is also calculated. The consumption consists of fan power and cooling load. The building management system (BMS) records the data of cooling load. The total fan pressure is taken to be 750 Pa for mixing ventilation, 600 Pa for both displacement ventilation and stratum ventilation with a fan efficiency of 70% in all runs [14].

$$E = E_f + E_c = N_f \cdot t + Q_c \cdot t \quad (5)$$

The cooling load and fan power are given by Yao et al. (2007) [25]:

$$N_f = (\gamma_\alpha \cdot Q_v \cdot P)/(3600 \cdot 1000 \cdot \eta) \quad (6)$$

$$Q_c = C \cdot (T_r - T_s) \cdot q \quad (7)$$

where

E = total energy consumption, kJ
E_f = energy consumption by fan, kJ
E_c = energy consumption for cooling, kJ
N_f = fan power, kW
Q_c = cooling load, kW
γ_α = specific weight
Q_v = supply airflow rate, m^3/h
P = total pressure, pa
η = fan efficiency, %
C = specific heat capacity of water, kJ/°C kg
T_s = supply water temperature, °C
T_r = return water temperature, °C
q = water flow rate, l/s
t = time elapsed to reach the state of thermal comfort, s

5. Evaluation of exergy performance

Jiang et al. proposed an exergy analysis method for water-cooled air conditioning systems, an energy quality coefficient should be considered for energy consumption of cooling water [26]:

$$W_{ex} = E_c \cdot \lambda_{coldw} \quad (8)$$

$$\lambda_{coldw} = T_0/(T_g - T_h) \cdot \ln(T_g/T_h) - 1 \quad (9)$$

where

W_{ex} = exergy consumption, kJ
E_c = energy consumption of cooling water, kJ
λ_{coldw} = energy quality coefficient
T_0 = reference temperature, K
T_g = supply temperature of cooling water, K
T_h = return temperature of cooling water, K

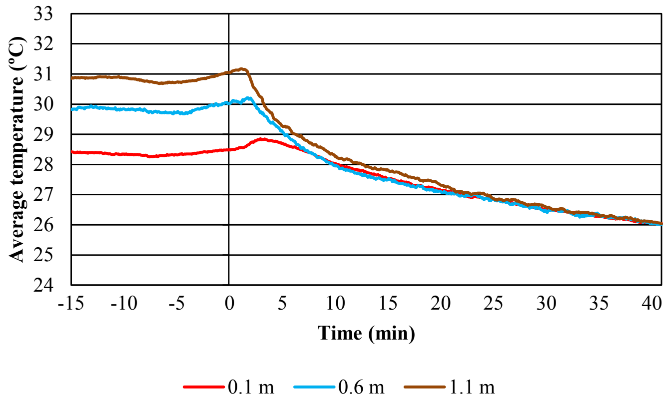

Fig. 8. Temperature history during pull-down process of Run 6 (SV-15-1).

6. Experimental results

As shown in Fig. 7, all runs begin with almost identical thermal conditions. Before the pull-down process, temperatures fluctuation is maintained within a reasonable range (±0.35 °C) for 15 min at least. Run 6 (SV-15-1) shown in Fig. 8 is used as an example to illustrate the general trend of the temperature versus time profiles during a pull-down process. At time zero, the air conditioning system is switched on. For this particular run, the number of air changes per hour is 15. During the entire process, the supply air temperature is controlled at 21.2 ± 0.3 °C. Because the test chamber is in an interior zone, the influence of weather condition is minimized.

After the air condition system is switched on, the indoor thermal parameters including temperature, air velocity and others begin to vary over time. For Run Nos. 8, 9, 15 and 16 (Table 2), i.e. runs of mixing ventilation and displacement ventilation at 0.25 m^3/s, the room cannot be cooled to reach thermal comfort due to insufficient cooling capacity. All other 17 runs reach a thermal comfort state after certain time period. This period is regarded as the pull-down process. For the state at the end of the process, thermal comfort indicators including (1) PMV, (2) PD due to draft, (3) Vertical air temperature difference, (4) EDT and EDTS are given.

6.1. PMV

As shown in Figs. 9–11, the values of PMV at more than 80% of measurement points are within in range of −0.5 to +0.5, which indicating a good thermal environment and therefore the ends of the pull-down processes. Comparing PMV under the three air distributions, it is noticed that the average thermal sensation for stratum ventilation is slightly warm, and that for mixing ventilation is slightly cool. For displacement ventilation, the average thermal sensation for the lower zone (<0.6 m) is slightly cool, but it is slightly warm for the breathing zone (1.1 m). That is mainly due to the different temperature distributions at the end of the respective pull-down processes. The average temperatures in the occupied zone at the ends of the pull-down processes are 24.59, 25.46 and 27.05 °C at 0.358 m^3/s, and 24.77, 24.66 and 27.42 °C at 0.537 m^3/s for mixing ventilation, displacement ventilation and stratum ventilation respectively. It is noteworthy a good agreement between this experimental result and a previous

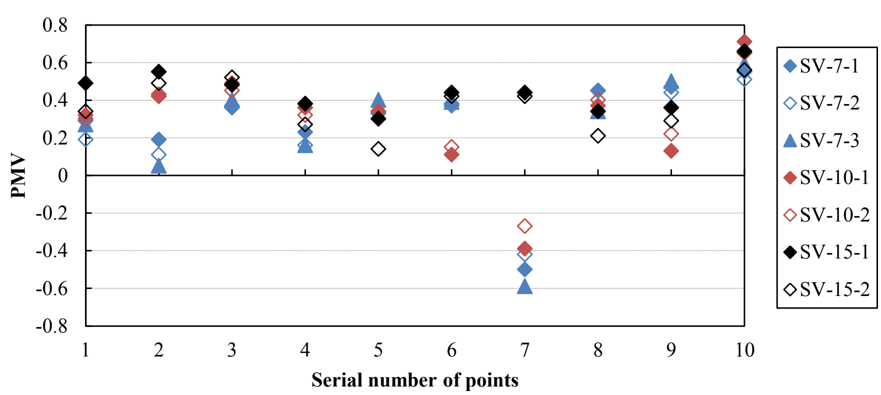

Fig. 9. PMV of stratum ventilation runs at the end of pull-down processes.

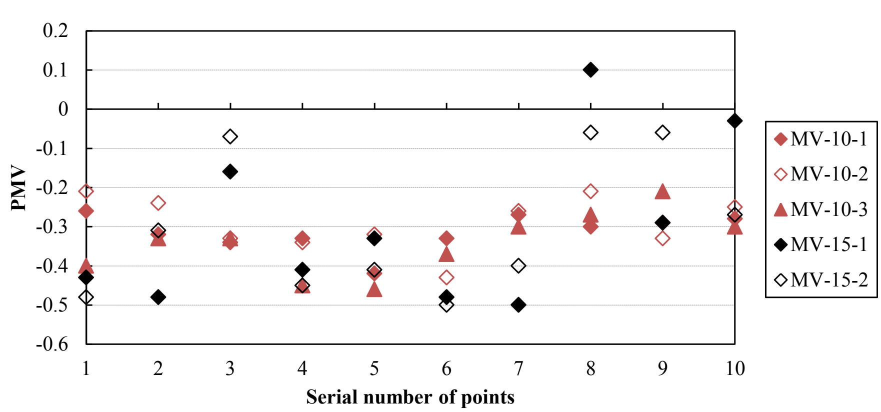

Fig. 10. PMV of mixing ventilation runs at the end of pull-down processes.

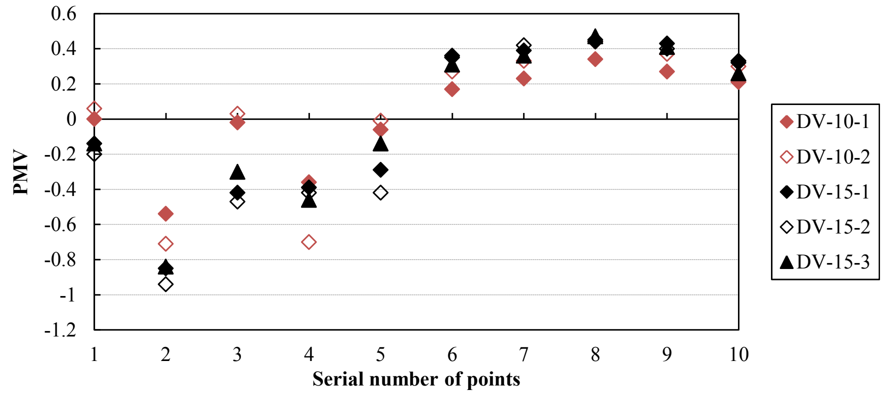

Fig. 11. PMV of displacement ventilation runs at the end of pull-down processes.

study on the thermal neutral temperatures of the three air distributions [15].

6.2. PD due to draft

The PD due to draft should be checked for mixing ventilation. To be cautious, it is better to check this index for stratum ventilation though the acceptable air velocity is up to 0.8 m/s for warm conditions ASHRAE 55-2013 [7]. As shown in Figs. 12 and 13, except the 7th measurement point for stratum ventilation, all the values of PD are below 20%, which fulfill ASHRAE 55-2013 [7] and ISO Standard 7730 [22]. Displacement is thermally driven and therefore the draft risk is low.

6.3. Vertical air temperature difference

Due to its working principle, temperature stratification under displacement ventilation is inevitable. Therefore, it is important to evaluate the vertical air temperature difference for displacement ventilation. According to Table 3, the temperature difference at the end of the pull-down period of every run conducted in this study is less than 3 °C.

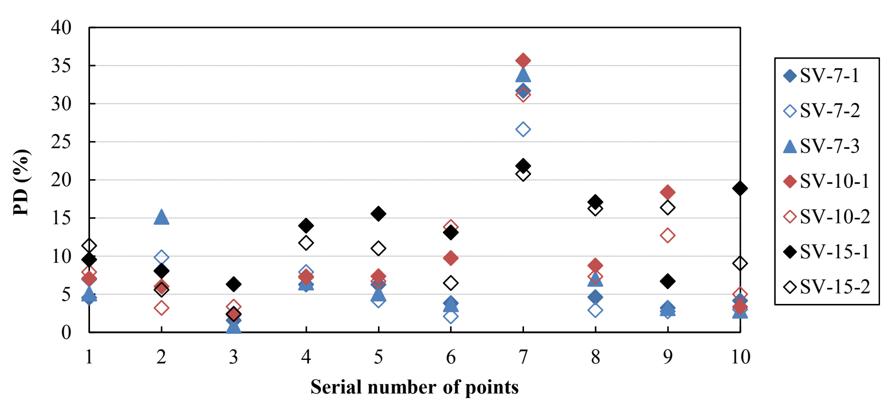

Fig. 12. PD of stratum ventilation runs at the end of pull-down processes.

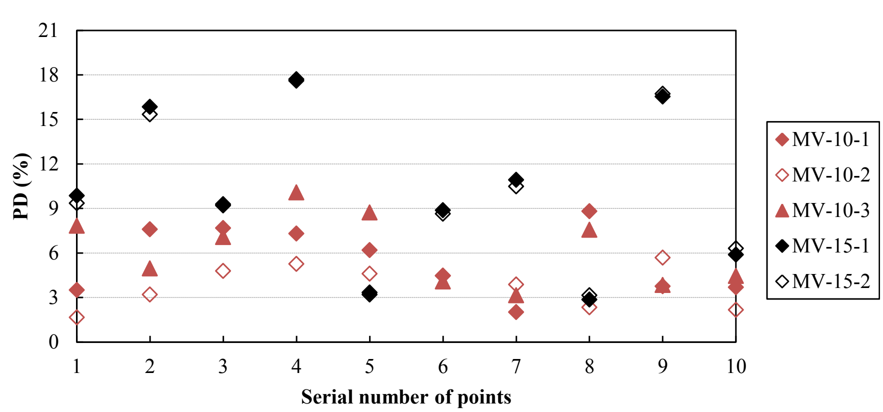

Fig. 13. PD of mixing ventilation runs at the end of pull-down processes.

Table 3
Vertical air temperature difference of displacement ventilation runs at the end of pull-down processes.

Run parameter code	t_{vt1} (°C)	t_{vt2} (°C)	t_{vt3} (°C)	t_{vt4} (°C)
DV-10-1	2.20	2.37	2.06	2.23
DV-10-2	2.31	2.51	2.42	2.65
DV-15-1	2.65	2.35	2.38	2.31
DV-15-2	2.59	2.33	2.43	2.25
DV-15-3	2.58	2.61	2.43	2.74

Table 4
ADPI of runs at the end of pull-down processes.

Airflow rate (m^3/s)	MV			SV		
	1	2	3	1	2	3
0.25	–	–	–	70%	70%	70%
0.358	100%	100%	100%	90%	90%	–
0.537	90%	90%	–	90%	90%	–

6.4. Air diffusion performance index (ADPI)

The EDT values for mixing ventilation and EDTS values for stratum ventilation are calculated based on measured data (Figs. 14 and 15). Table 4 shows the ADPI for runs of mixing ventilation and stratum ventilation. Most EDTS values for stratum ventilation are in the range of (0.5, 1.0) K. For mixing ventilation, all runs at 0.358 and 0.537 m^3/s satisfy the requirement of ADPI ≥80% [23]. For stratum ventilation, ADPI for runs at 0.25 m^3/s is 70%; this figure is 90% for runs at both 0.358 and 0.537 m^3/s. These results indicate generally uniform thermal environments at the end of the pull-down processes. As mentioned in Section 3.4, ADPI is not applicable to displacement ventilation.

7. Rapidity and energy consumption of pull-down process

For Runs 8, 9, 15 and 16, i.e. runs of mixing ventilation and displacement ventilation at0.25 m^3/s, the room cannot be cooled to reach thermal comfort due to insufficient cooling capacity. Therefore only the pull-down periods of the three air distributions at 0.358 and 0.537 m^3/s are shown for comparison. The pull-down period of stratum ventilation is the shortest, 32.5 and 16 min in average at 0.358 and 0.537 m^3/s respectively. At 0.358 m^3/s, the length of the pull-down period of stratum ventilation is approximately 1/3 of that of mixing ventilation and 1/4 of that of displacement ventilation (Table 5). Similarly at 0.537 m^3/s, the length of the pull-down period of stratum ventilation is approximately 2/5 of that of mixing ventilation and 1/5 of that of displacement ventilation (Table 5). Different from the other two air distributions, air is directly supplied into the target zone (breathing zone) under stratum ventilation. The conditions of the upper zone (height > 1.6 m) are not the focus of attention. Thus the pull-down period of stratum ventilation is the shortest. For displacement ventilation, because the cooler air stays at the floor level and there are no occupants during the pull-down period, the upward air movement (thermal plumes) is weak, which prolongs the pull-down process.

The comparison amongst the runs of stratum ventilation at 0.25, 0.358 and 0.537 m^3/s is shown in Table 6. It can be seen that the

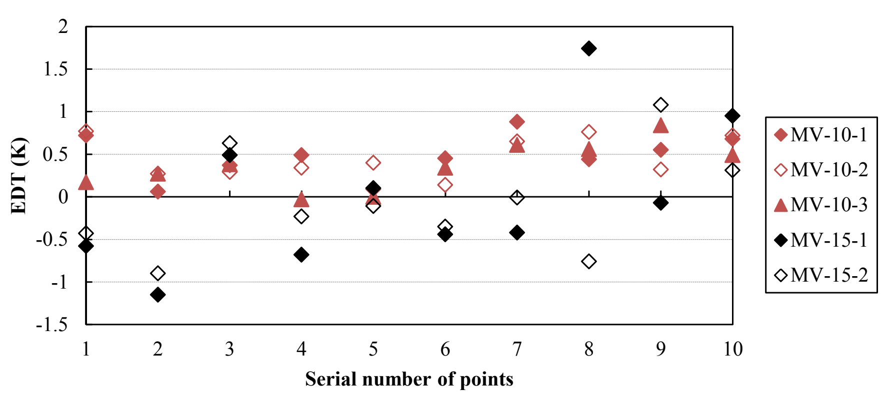

Fig. 14. EDT of mixing ventilation runs at the end of pull-down processes.

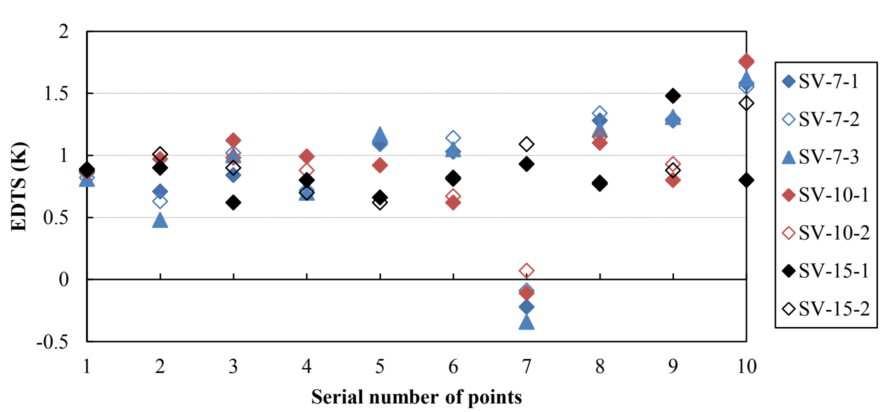

Fig. 15. EDTS of stratum ventilation runs at the end of pull-down processes.

Table 5
Pull-down period of runs at airflow rates of 0.358 and 0.537 m^3/s.

Run parameter code	Time (min)	Run parameter code	Time (min)
SV-10-1	33	SV-15-1	17
SV-10-2	32	SV-15-2	15
MV-10-1	97	MV-15-1	35
MV-10-2	97	MV-15-2	37
MV-10-3	95	DV-15-1	80
DV-10-1	129	DV-15-2	82
DV-10-2	117	DV-15-3	82

Table 6
Pull-down period of runs of stratum ventilation.

Run parameter code	Time (min)
SV-7-1	58
SV-7-2	61
SV-7-3	58
SV-10-1	33
SV-10-2	32
SV-15-1	17
SV-15-2	15

pull-down period decreases with the increase of supply airflow rate. This is because the supply air temperature is kept constant; therefore more air circulation means higher cooling capacity.

The energy consumptions of the pull-down period of the three air distributions are shown in Figs. 16 and 17. The energy consumption by stratum ventilation is approximately 1/4 of those by mixing ventilation and displacement ventilation at 0.358 m^3/s. At 0.537 m^3/s, this figure is slightly more than 1/4 of that by mixing ventilation and 1/5 of that by displacement ventilation. The reasons for lowest energy consumption by stratum ventilation are the shortest pull-down period and highest supply air temperature. Although the pull-down period of mixing ventilation is shorter than that of displacement ventilation, the supply temperature of mixing ventilation is lower than that of displacement ventilation. Coincidently, these two distributions consume nearly the same amount of energy at 0.358 m^3/s.

The comparison amid the runs of stratum ventilation at 0.25, 0.358 and 0.537 m^3/s is shown in Fig. 18. Amongst the three scenarios of stratum ventilation at 0.25, 0.358 and 0.537 m^3/s, the last performs best in energy consumption (actually in rapidity too), which indicate that the maximal airflow rate should be applied during the pull-down process when the room is unoccupied and therefore draft is not a concern.

8. Exergy analysis

The monthly mean temperature is 28.8 °C in July between 1981 and 2010 according to Hong Kong Observatory [27], which is used as the reference temperature T_0. The typical supply/return cooling water temperatures are 13/18 °C, 7/12 °C and 10/15 °C for stratum ventilation, mixing ventilation and displacement ventilation respectively. The comparison of exergy consumption of cooling water is calculated according to Jiang et al. (2004) [26]. The exergy

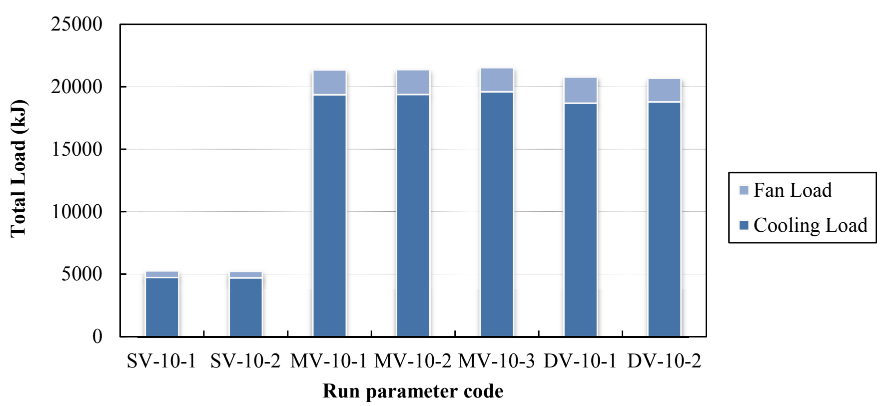

Fig. 16. Energy consumed for pull-down runs at 10ACH.

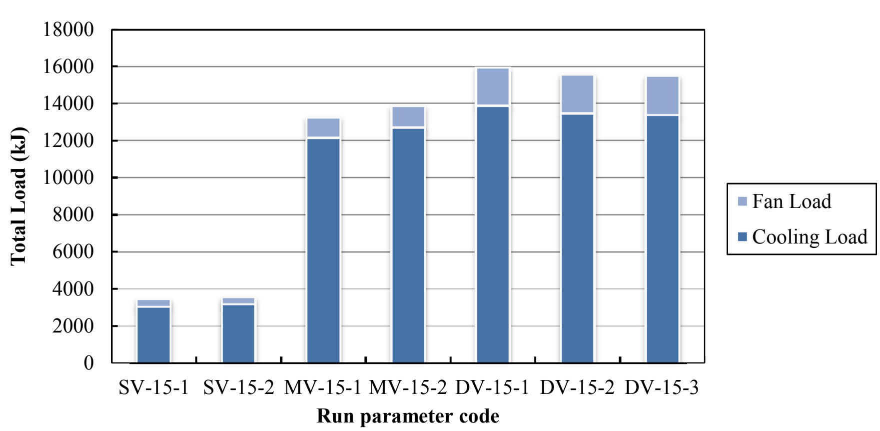

Fig. 17. Energy consumed for pull-down runs at 15ACH.

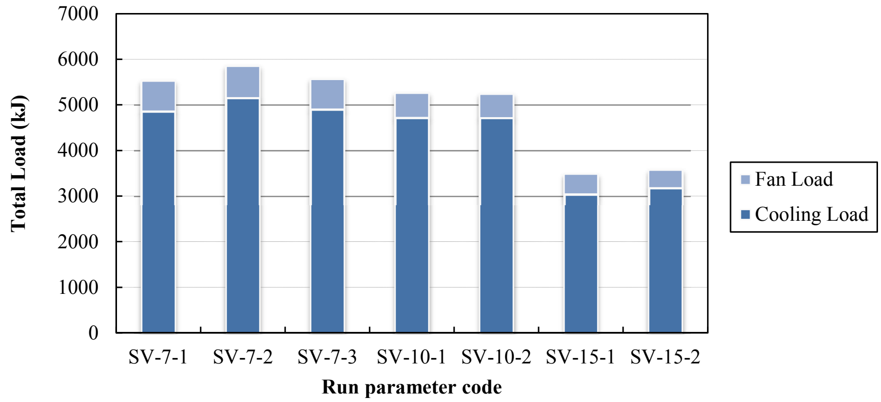

Fig. 18. Energy consumed for pull-down runs of stratum ventilation.

Table 7
Exergy of cooling water during pull-down process of runs at airflow rates of 0.358 and 0.537 m^3/s.

Run parameter code	Exergy (KJ)	Run parameter code	Exergy (KJ)
SV-10-1	217.81	SV-15-1	140.32
SV-10-2	217.53	SV-15-2	146.68
MV-10-1	1323.32	MV-15-1	830.41
MV-10-2	1324.96	MV-15-2	868.14
MV-10-3	1338.91	DV-15-1	793.05
DV-10-1	1067.57	DV-15-2	769.06
DV-10-2	1072.71	DV-15-3	764.61

consumption of the cooling water during the pull-down period of stratum ventilation is 16% of that of mixing ventilation and 20% of displacement ventilation at 0.358 m^3/s (Table 7). The exergy consumption of stratum ventilation is 17% of that of mixing ventilation and 19% of that of displacement ventilation at 0.537 m^3/s (Table 7).

9. Conclusions

The pull-down periods of the three distributions are investigated experimentally in this study. With the same initial conditions, the pull-down period is ended when the thermal comfort condition is achieved. The experimental results indicate that the pull-down period of stratum ventilation is much shorter than those of the other two air distributions. The period of displacement ventilation is slightly longer than that of mixing ventilation. Because of the shorter pull-down period and higher supply air temperature, the energy consumption by stratum ventilation during the pull-down period is much less than those of the other two air distributions. The energy consumption by displacement ventilation during the pull-down period is slightly more than that by mixing ventilation. Similarly, the exergy consumption of the cooling water during the pull-down period of stratum ventilation is also much less than those of the other two air distributions, while the energy consumption of displacement ventilation during the pull-down period is slightly less than that of mixing ventilation.

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