International High Performance Buildings Conference
School of Mechanical Engineering

2014

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Ting Yao
Division of Building Science and Technology, City University of Hong Kong, Hong Kong S.A.R. (China), tingyao-c@my.cityu.edu.hk

Zhang Lin
Division of Building Science and Technology, City University of Hong Kong, Hong Kong S.A.R. (China), bsjzl@cityu.edu.hk

Numerical Study of the Effect of Air Terminal Layouts on the Performance of Stratum Ventilation System

Ting YAO[1]*, Zhang LIN[2]

[1]Civil and Architectural Engineering, City University of Hong Kong,
Hong Kong SAR, China
Tel: +852 3442 5271, Fax: +852 3442 0586, E-mail: tingyao-c@my.cityu.edu.hk

[2]Division of Building Science and Technology, City University of Hong Kong,
Hong Kong SAR, China
Tel: +852 3442 9805, Fax: +852 3442 9716, E-mail: bsjzl@cityu.edu.hk

* Corresponding Author

ABSTRACT

It has been found that air terminal layouts could affect ventilation performance in a room. As a new air distribution system, stratum ventilation was proposed to accommodate elevated room temperatures. Its performance with various air terminal layouts was investigated by numerical method in this research. Totally four different exhausts locations were studied to determine the optimal exhaust locations. Exhausts were located at (a) middle level of the wall opposite to the supplies; (b) low level of the same wall of the supplies; (c) low level of the wall opposite to the supplies and (d) the ceiling level, respectively. Ventilation performances were evaluated by airflow pattern, temperature distribution, percentage of dissatisfied (PD) people due to draft, effective draft temperature (EDTs) and local mean age of air. The computational predictions were validated by experimental results. From the results, similar performance with exhausts located at middle or low level of the wall opposite to the supplies was observed. In case with exhausts located at the ceiling level, temperature and EDTs in occupied zone is relatively low. However, with this arrangement more fresh air could be supplied to the breathing zone. Better performance is found in case with exhausts located at low level of the same wall with supplies. Indoor environment could achieve thermal comfort and good air quality. This arrangement also helps to save the space for system installation. It is therefore a better choice for stratum ventilation design if performance requirements are met.

1. INTRODUCTION

A high-quality indoor environment is expected by more and more people in recent years, which is largely determined by the air distribution system. Stratum ventilation as a new air distribution system was proposed to accommodate the elevated room temperatures recommended by the governments. It was realized by positioning supply terminals at the side-walls slightly above the height of occupants. Fresh air is directly supplied to the occupied zone. It was found to perform well in providing good indoor air quality, maintaining thermal comfort and year-round energy saving (Tian *et al*., 2008; Tian *et al*., 2010; Lin *et al*., 2011).

Researchers have found that the layout of air terminals could affect the design and performance of air distribution system (Lin *et al*., 2005; Khan *et al*., 2006; Lau and Chen, 2007). For stratum ventilation system, there is no research focused on this issue. This study therefore aims to investigate the performance of stratum ventilation with various air terminal layouts.

2. METHODOLOGY

2.1 Computational Fluid Dynamics (CFD) Method

In this research, CFD method was applied to study stratum ventilation performances with various terminal layouts. Figure 1 shows the classroom configuration for simulation. The classroom is 8.8 m (L) × 5.75 m (W) × 2.4 m (H). Four different air terminal layouts were considered. Information of supplies and exhausts location is list in Table 1. In the classroom, there are seventeen sedentary occupants, one workstation and twenty-eight lamps. Total cooling load is 2,756 W. Indoor design temperature is 300 K. Supply airflow rate is 10 ach, and supply temperature is 293.65 K.

After grid-independence tests, grid with hexahedral cells of four case is 1,026,821, 1,022,425, 1,051,595 and 1,058,902 respectively. RNG k-ε model based on the commercial program FLUENT is used to perform the simulation. In this study, the model was validated by experimental data. The governing equations are discretized with second order accuracy. The discrete ordinates radiation model is used to take radiative heat transfer into account. SIMPLE algorithm is used to couple pressure and velocity. Buoyancy effect is considered by Boussinesq model. Velocity-inlet and outflow boundary conditions were used for supplies and exhausts respectively. Heat sources such as lamps, workstation and occupants were set with constant heat flux.

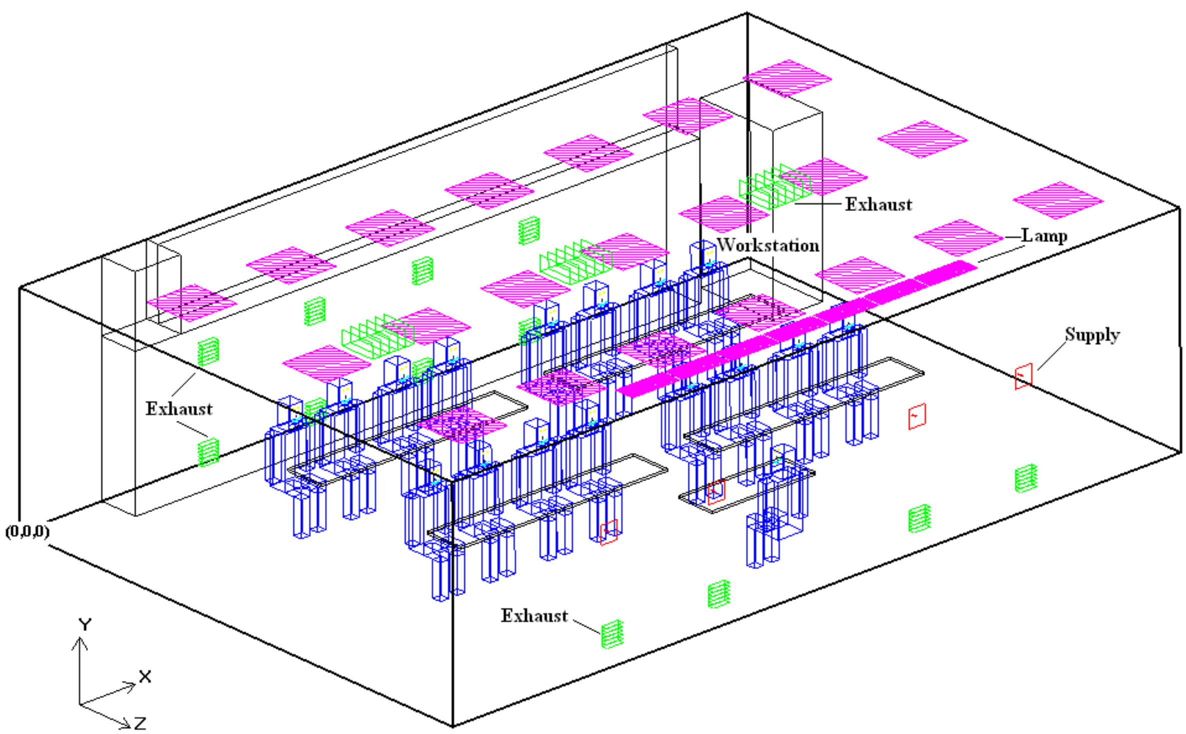


Figure 1: Layout of the classroom

Table 1: Supply and exhaust location

Layout	Supply Location	Exhaust Location
a	1.3 m height (front wall)	1.3 m height (back wall)
b		0.33 m height (front wall)
c		0.33 m height (back wall)
d		Ceiling

2.2 Evaluation Criteria

An important objective of an air distribution is to create an environment of thermal comfort and good air quality. In this study, performances of stratum ventilation with various air terminal layouts are evaluated on the aspects of thermal comfort and air quality by the following parameters:

1. Airflow pattern
2. Temperature distribution
3. Effective draft temperature (EDTs)
4. Percentage of dissatisfied people due to draft (PD)
5. Local mean age of air

Effective draft temperature for stratum ventilation has been modified by Lin (2011) given by the following equation:

$$\theta_{\mathrm{eds}} = \left(T_x - T_c\right) - \left(V_x - 1.1\right) \tag{1}$$

For stratum ventilation, the thermal comfort condition is good if -0.6 K < θ_{eds} < 0.6 K, and is satisfactory if -1.2 K < θ_{eds} < 1.2 K when the velocity is less than 0.8 m/s. EDTs, PD and local mean age of air is calculated by user-defined functions incorporated into the CFD program of FLUENT. PD was calculated by the formulae developed by Fanger et al. (1989) in ISO 7730: 1994(E) (1994). The mean local air age is defined as the average lifetime of air at a particular location and gives an indication of the "freshness" of the air. It can be solved as an additional transport scalar (Abanto et al., 2004).

3. RESULTS AND DISCUSSION

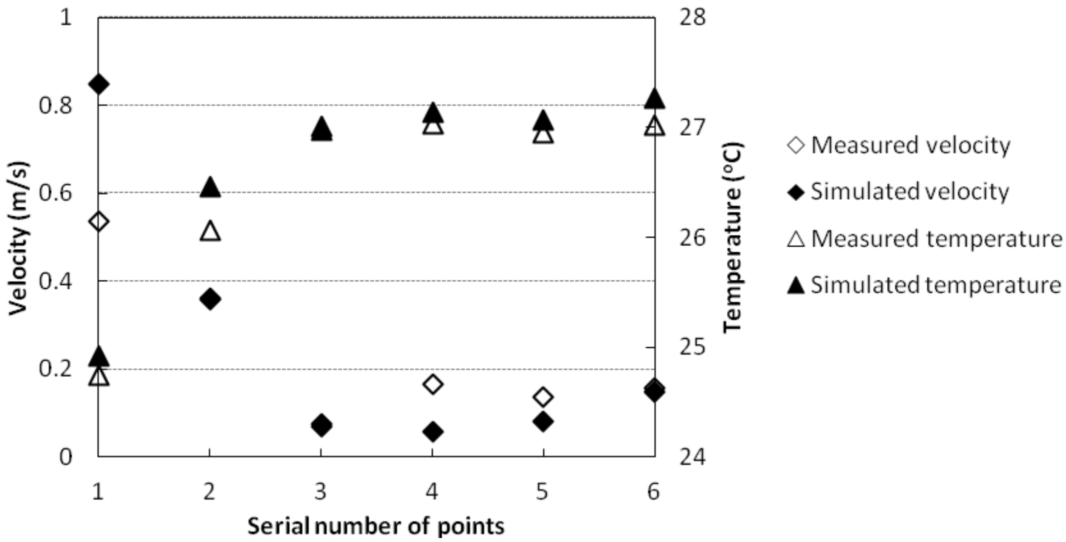
3.1 Model Validation

Experiments were conducted to validate the simulated model. The temperature and velocity of six points at 1.1 m height were measured. The locations of measured points are list in Table 2. The actual room conditions were determined using an INNOVA professional measuring tool set with data logger to ensure that the room condition was steady throughout the measurement. The air velocity and temperature of points were measured by SWEMA transducer SWA 03 and LUMASENSE transducers MM0038 and MM0034.

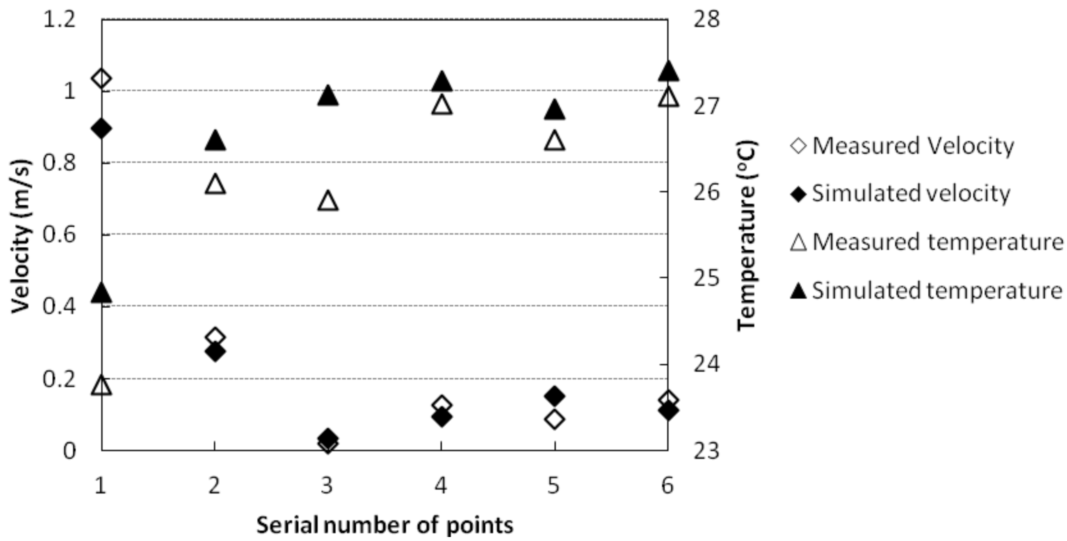
The predicted temperature and velocity of Points L1 to L6 was compared with the measured values. Limited by the space, results of only two cases with Layouts (a) and (c) are shown in Figure 2. From the figure, it can be concluded the simulated values agreed well with the measured ones. Thus the model can be applied to predict performance of stratum ventilation with various air terminal layouts.

Table 2: Positions of measured points

Point	L1	L2	L3	L4	L5	L6
x, z (m)	1.83, 4.10	1.82, 2.75	1.83, 1.05	6.30, 4.10	6.30, 1.05	4.40, 3.10



(1)



(2)

Figure 2: Measured and simulated values for two cases: (1) case with Layout (a) and (2) case with Layout (c)

3.2 Simulated results

Figure 3 shows the air flow pattern at 1.1 m level. Although with different air terminal layouts, similar air flow pattern is found at this level. In the air jet region, air velocity is significantly higher than that outside the region. Air velocity decays with the distance from the supplies. When the air jets reach the first row occupants, it decreases to 0.8 m/s. Occupants sitting in the vicinity of supplies may experience draft. For the occupants sitting in the second row, velocity is relatively lower which is around 0.3 m/s.

Different from air flow pattern, Figure 4 shows the various temperature distributions at the same level. Temperature with air terminal Layout (d) is obviously lower than that with other three layouts. Temperature of most areas in the classroom is in the range of 299 to 299.5 K. That is because warm air flows upwards and is exhausted from ceiling. Temperature difference between air supplied and indoor is relatively small, which leads to air jets from supplies flow downwards slowly. Thus, more fresh air is supplied to this zone. Compared with other three cases, temperature distribution with Layout (b) is more uniform except for region near supplies.

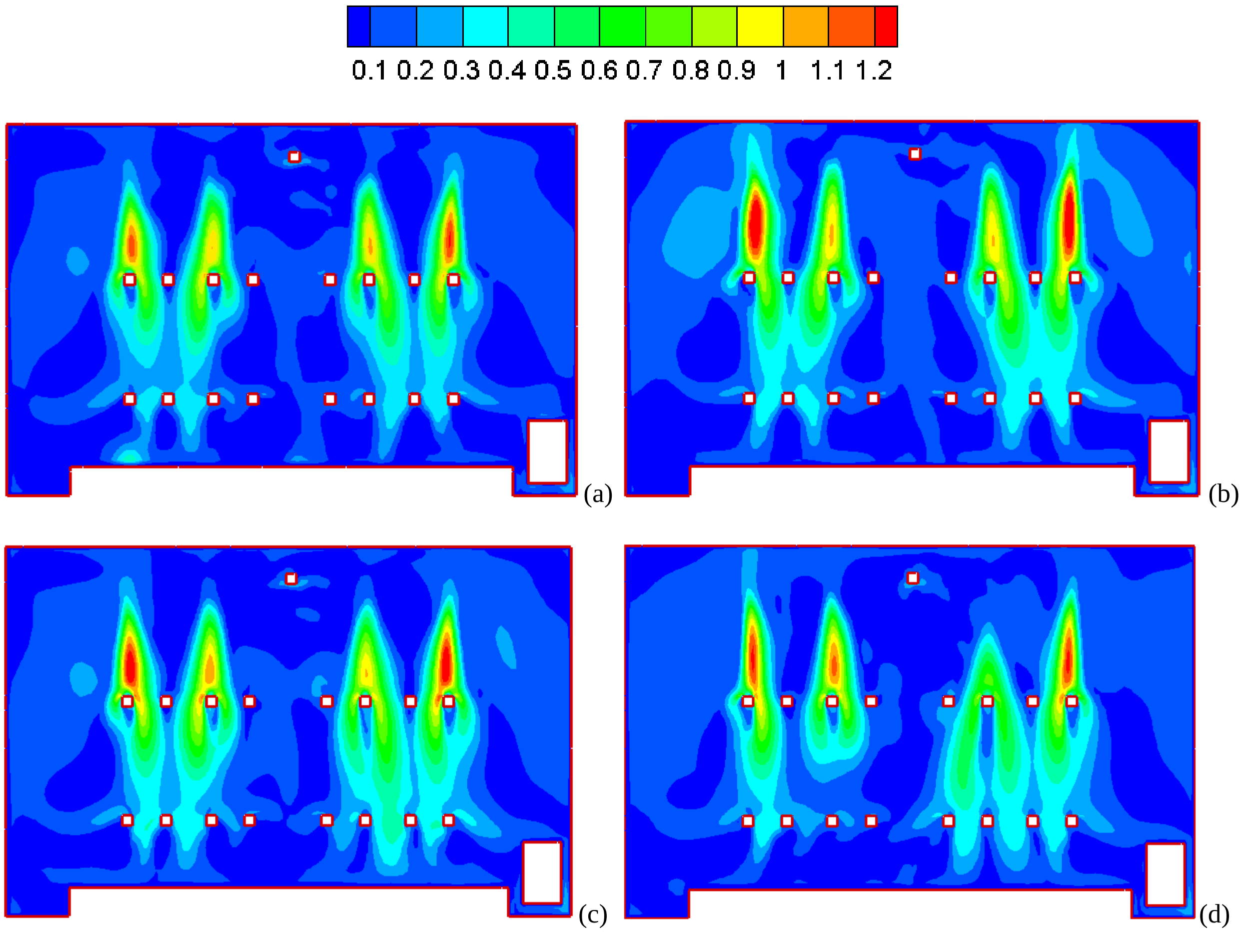
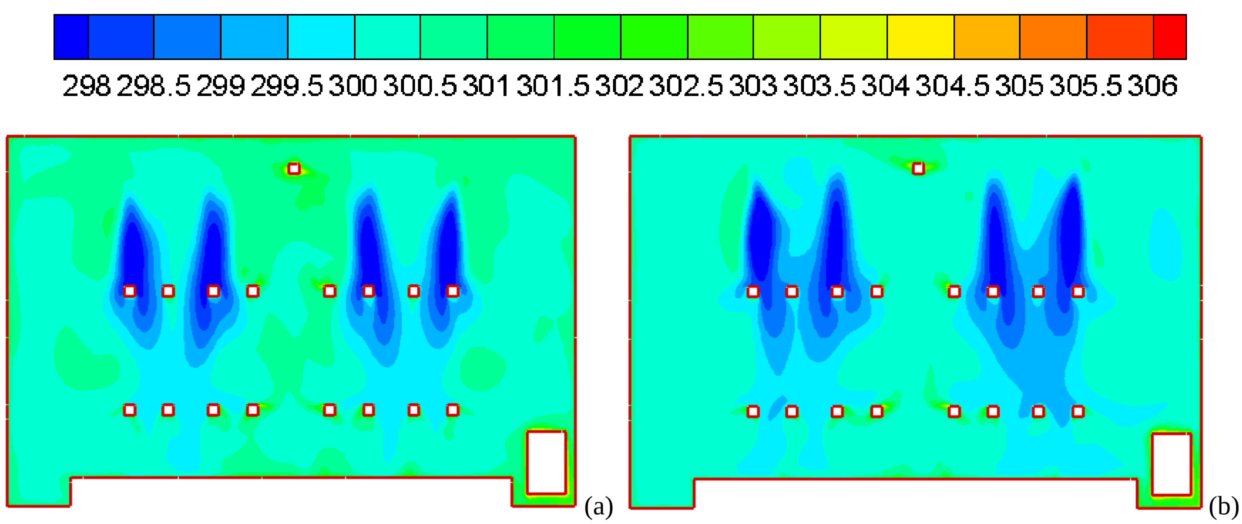


Figure 3: Airflow pattern (m/s) at 1.1 m plane with Layouts (a), (b), (c) and (d)



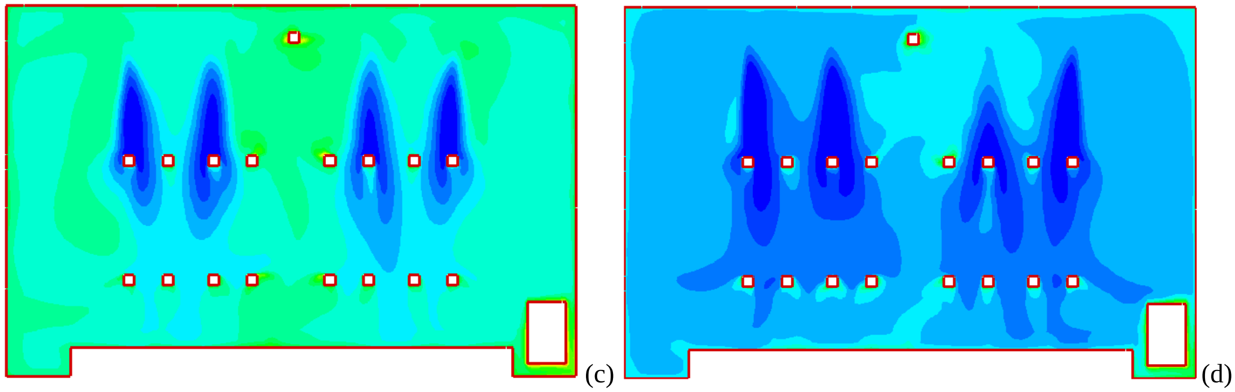


Figure 4: Temperature (K) distribution at 1.1 m plane with Layouts (a), (b), (c) and (d)

EDTs calculated by Equation (1) at 1.1 m level with various air terminal layouts are shown in Figure 5. The satisfactory thermal comfort range for EDTs is from -1.2 K to 1.2 K. From the figure, it can be seen that EDTs of cases with Layouts (a) (b) and (c) have similar distribution. EDTs of area where teacher sitting is obviously higher. Among the four scenarios, EDTs distribution of Layout (b) is more uniform. EDTs for most areas are within the satisfactory range of 0 – 1 K. For air jet regions, because of higher velocity and lower temperature, EDTs are significantly lower and out of the satisfactory range. Compared with other three cases, EDTs of occupied zone with Layout (d) is relatively low. EDTs for the second row is around -1 K.

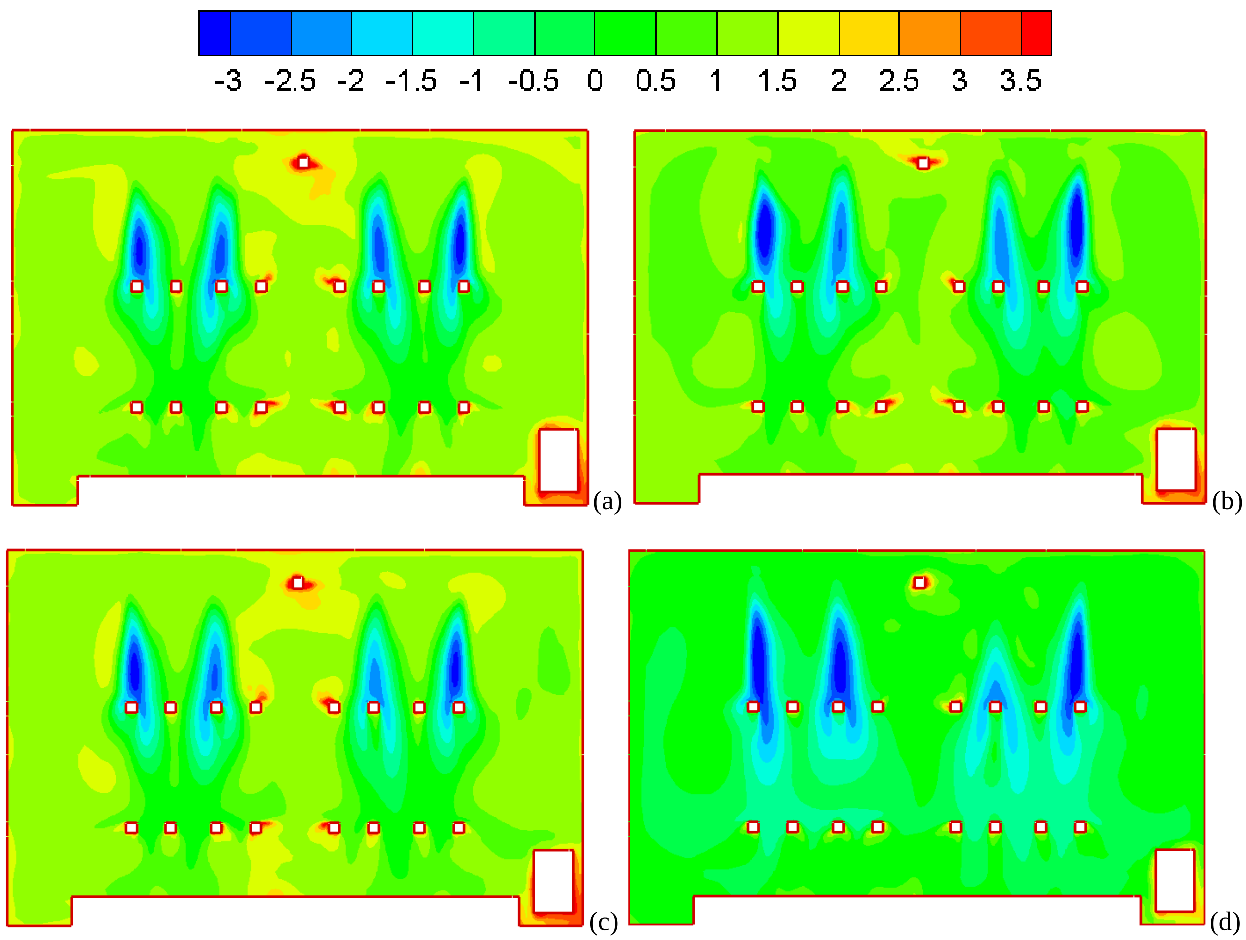


Figure 5: EDTs (K) at 1.1 m plane with Layouts (a), (b), (c) and (d)

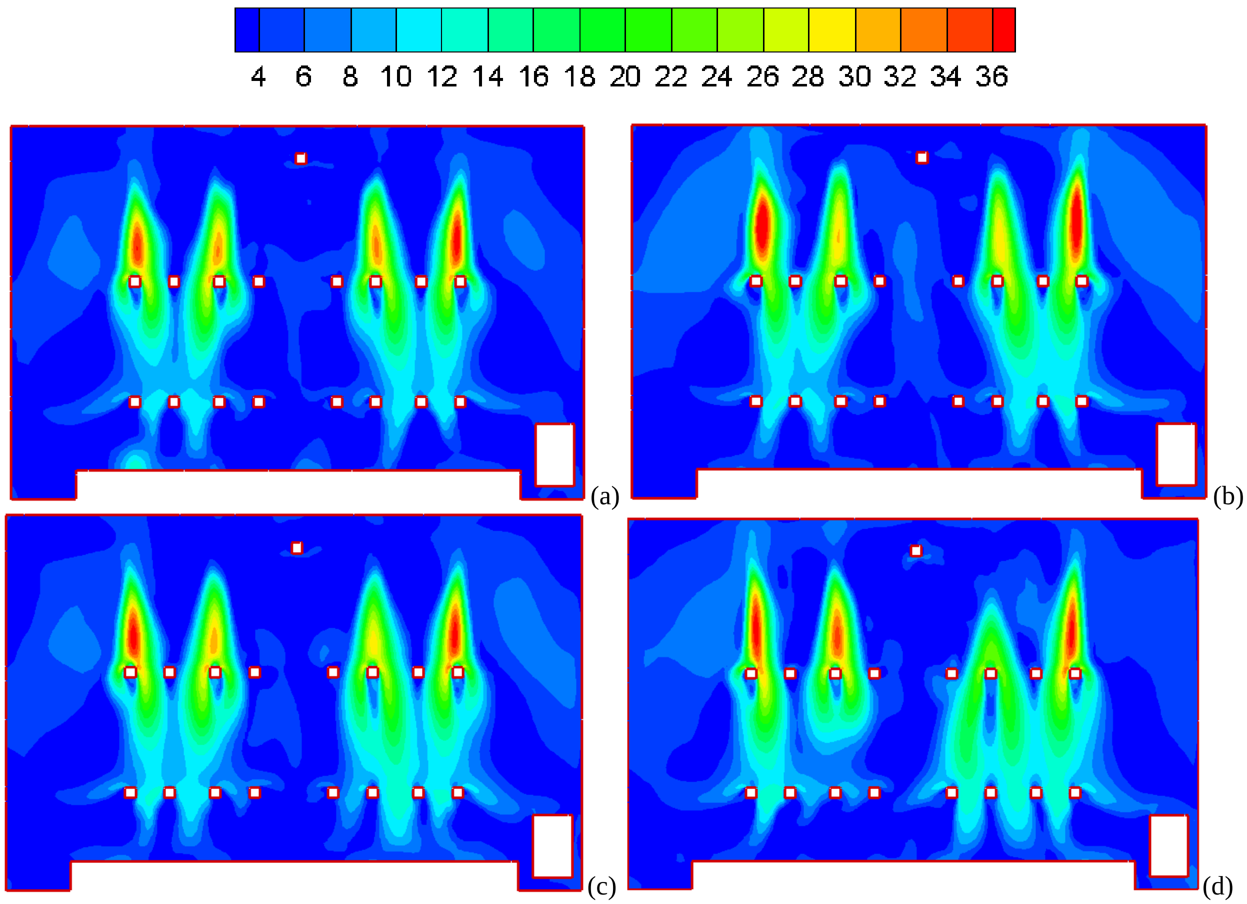


Figure 6: PD (%) at 1.1 m plane with Layouts (a), (b), (c) and (d)

In terms of PD at 1.1 m level of four cases, similar distribution is found in Figure 6. Requirement of Class C indoor thermal environment for PD is 25% according to CR 1752 1998 (Fanger et al., 1989). In the vicinity of supplies, the PD values are in the range of 20 – 36%. Occupants sitting in this region may experience draft. Away from the supplies, PD values are below 14%. Thermal comfort for most areas in the classroom is acceptable.

Air quality in the classroom was evaluated by local mean age of air (Figure 7). Older age of air can be found at left side of classroom with Layouts (a) and (c) because of air circulation. Relatively uniform air age distribution is found in case with Layout (b). The air age for most areas at this level is between 230 – 330 s. Younger air age in occupied zone can be observed in case with Layout (d), especially for the second row. As mentioned above, that is because air jets flow downwards slowly results in more fresh air supplied to occupied zone at this level.

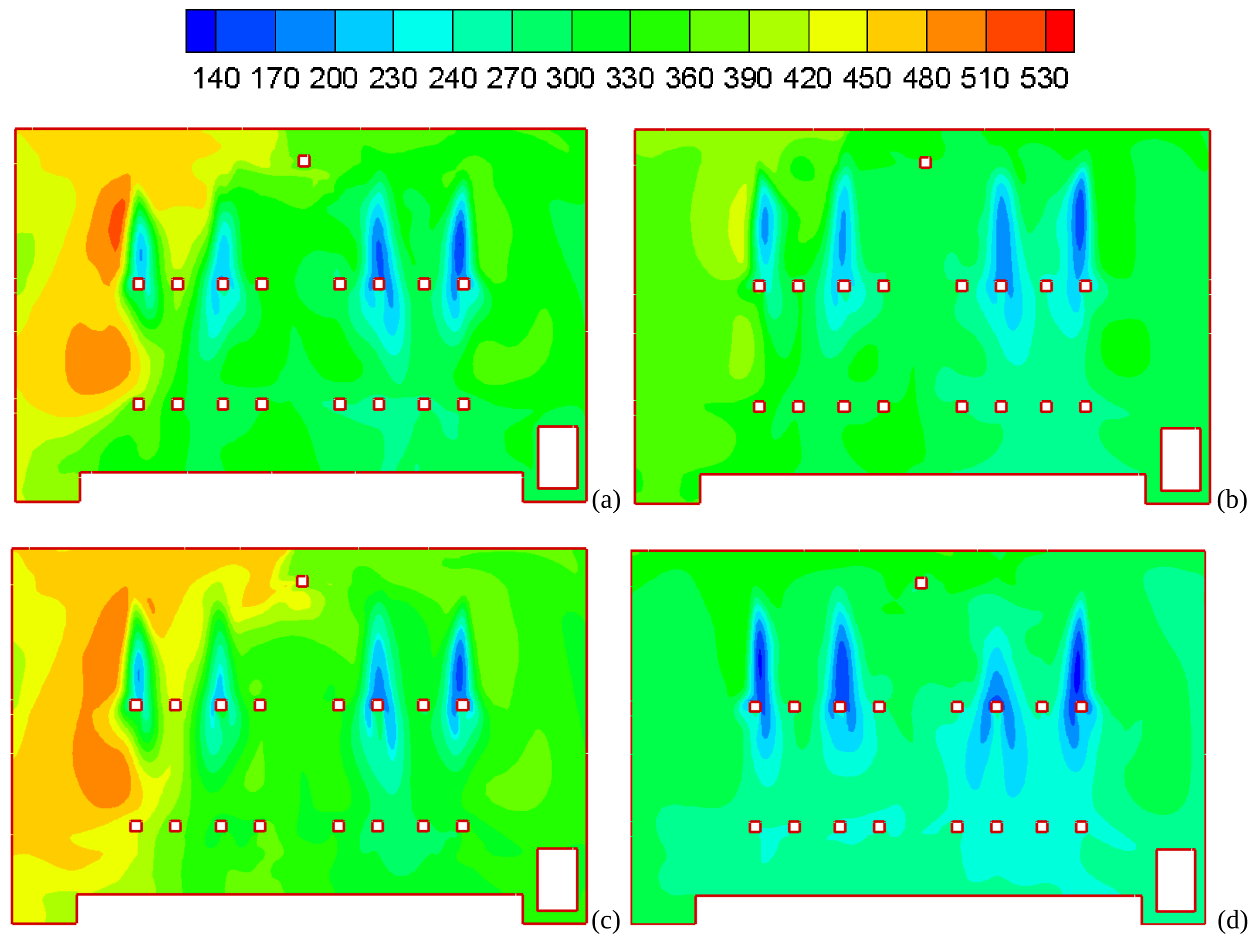


Figure 7: Local mean age of air (s) at 1.1 m plane with Layouts (a), (b), (c) and (d)

4. CONCLUSIONS

This study aims to investigate the effect of air terminal layouts on the stratum ventilation performance. Totally four different air terminal layouts were studied. A CFD model validated by experimental data was applied. Similar ventilation performance is found with exhausts located at middle or low level of the wall opposite to the supplies. In the case with exhausted located at ceiling level, lower temperature distribution of occupied zone was observed, which leads to relative low EDTs. However, with this arrangement, more fresh air could be supplied to the occupants' breathing zone. Compared with other cases, performance of case with exhausts located at the same wall of supplies is better. Relative uniform temperature and EDTs distribution, acceptable thermal comfort and good air quality could be achieved. It also helps to save system installation space. Therefore, it is a better choice for stratum ventilation design if performance requirement are met.

NOMENCLATURE

T_c	average room dry-bulb temperature	K
T_x	local airstream dry-bulb temperature	K
V_x	local airstream centerline speed	m/s
θ_{eds}	effective draft temperature for stratum ventilation	K

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ACKNOWLEDGEMENT

The work described in this paper is supported by a General Research Grant from the National Natural Science Foundation of China (Project No. 51178407).