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Research paper

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

Xiao Wang, Zhang Lin*

Building Energy & Environmental Technology Research Unit, Division of Building Science and Technology, City University of Hong Kong, Hong Kong SAR, China

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

* Corresponding author.
E-mail address: bsjzl@cityu.edu.hk (Z. Lin).

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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.