The Influence of a Moving Object on Air Distribution in Displacement Ventilated Rooms

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Abstract
As is well known, a moving person affects the stratification of indoor air and enhances the mixing in ventilated rooms with a displacement ventilation system. This paper describes the effect of moving object on the performance evaluation of displacement ventilation, by means of an experiment using a movable heated human model in a full scale room model. Distributions of air temperature and tracer gas concentration were measured to investigate the effect of the moving object's direction, mode and speed on distribution of air in the room, and ventilation effectiveness. As a result of experiment, the moving object mode and speed showed a significant effect on the air temperature distribution and ventilation effectiveness.

Keywords: displacement ventilation; moving object; full-scale experiment

1. Introduction
To keep thermal stratification is one of the most important factors in controlling and maintaining good air quality and high efficiency ventilation performance in displacement ventilated rooms. However, physical activity, like a moving person in the actual room has been found to influence the stratification of indoor air and the performance of the ventilation system. This paper describes the effect of a moving object on the performance evaluation of displacement ventilation, through an experiment using a movable heated human model, designed to go back and forth on a straight line by means of an electrical slider and a motion controller in a full scale room model. Distributions of air temperature and tracer gas concentration were measured to investigate the effect of the object's direction of movement, mode and speed on the room air distribution and ventilation effectiveness.

Physical activity in a displacement ventilated room has been found to influence the performance of the ventilation system (Mattsson & Sandberg, 1994). The measurements of these studies were performed in a full scale test room, with a person simulator of cylindrical shape as the moving object (Mattsson et al, 1996) and also thermal mannequins (Mattson et al, 1997). Furthermore full scale experiments were made in a displacement ventilated room with breathing thermal mannequins to study the effects of movements and breathing on the vertical contaminant distribution, and on the personal exposure of occupants (Bjorn et al, 1997).

The above studies are not necessarily enough to resolve the mechanism and ventilation effectiveness of displacement ventilation as affected by human activity. Therefore the objective of this paper is to obtain fundamental data by experimentation to clarify the mechanism of displacement ventilation in conjunction with a moving object such as human activity in rooms. In this study the measurements were carried out using a movable heated object controlled by an electrical slider and a motion controller in a full scale room model (Nguyen et al, 2002, Matsumoto et al, 2002). The distributions of air temperature, velocity and tracer gas concentration were measured for conventional systems and displacement ventilation. The retest similar to the experiment done by Mattsson (1996, 1997) itself is seen to be of value to the resolution of the moving object's effect. The originality of this study can be considered as to investigate the influence of the object's moving direction and to develop an control system of an object movement accurately to be compared with the results by the computational fluid dynamics (CFD) simulation (Nguyen and Matsumoto, 2001).

2. Experimental Methods
A full scale room model was used, along with a moving cylindrical object made of paper which was 1.2m high and had a diameter of 0.3m. The room has a diffuser with the dimensions, 0.3m high and 0.5m wide and an outlet, a hole with a diameter of 0.1m, located at 0.2m below the ceiling. The measurement points for temperature and concentration are shown in Figure 1.
The room was set up inside the laboratory of the Natural Energy Building at the Toyohashi University of Technology, and was constructed with panels composed of 9mm plywood and 30mm insulation material on three sides and one side wall was made of 5mm acrylic glass.

The room was ventilated by a displacement ventilation system, and the moving object was designed to go back and forth on a straight line by a programmable controller and driver. The object was heated to simulate the heat flux of a human body, using a 100-watt bulb inside.

The temperature and tracer gas concentration, carbon dioxide, were measured by C-C thermo couples and a multi gas monitor (B&K) respectively, to investigate the temperature field and the ventilation effectiveness. The speeds of the object used were 0.0, i.e. standing still, 0.4, 0.6, 0.8 and 1.0m/s. The moving modes were controlled at a constant rate of acceleration or deceleration for the short time before and after the stationary points and the constant speed in the middle as shown in Figure 2.

Local air exchange index $\varepsilon_p$ defined by the following equation was used to evaluate the ventilation effectiveness as follows:

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \times 100 \quad \%$$

(1)

$$\tau_p = \frac{\int_0^\infty C(t)dt}{C(0)}$$

(2)

where $\tau_n$ is the nominal time constant, $\tau_p$ is the local mean age of air, $C(t)$ is the normalized concentration, i.e. the actual value minus the supply air concentration, in time $\tau_n$ and $C(0)$ is the normalized initial concentration.

The air change efficiency, $\varepsilon_a$, which evaluates the ventilation efficiency in a room, is defined by the following equations.

$$\varepsilon_a = \frac{\tau_n}{2 < \tau >}$$

(3)

$$\frac{\int_0^\infty C_e(t) \cdot t dt}{\int_0^\infty C_e(t) dt}$$

(4)

where $C_e(t)$ is the concentration of the exhaust air at time $\tau$, and $<\tau>$ is the room mean age of air.

The conditions measured here are shown in Table 1. Two types of object movement were considered to investigate the effect of different moving speeds on the air distribution: perpendicular to the supply air flow and along the supply air flow. The supply air flow rates for the former set of experiments (cases 1 to 5) were 35.7 and 40m$^3$/h, and those for the latter set (cases 6 to 8) were 212.4 to 237.6m$^3$/h. The Archimedes numbers of the two sets were about 120 and 3 respectively. The supply air temperature was set to be 18 to 20 deg C during the experiments.

3. Measurement Results
3.1 Movement perpendicular to the supply air flow

Figure 3 shows the measured carbon dioxide tracer gas concentration trends for the points ch1 to ch6 at 0.1m, 0.69m, 0.69m, and 0.69m above the floor, supply air and exhaust air respectively, using the step down method. Ch1, ch2, ch3 and ch4 correspond to No.11, No.10, No.9 and No.8 respectively. The positions were used as the representative points to examine temperature, concentration and local mean age of air in Figures 3 to 10. After the concentration was almost constant, the tracer gas injection was stopped, and the temperatures and concentrations of the measurement points shown in Figure 1 were measured for about one hour. In the meantime the ambient temperature outside of the test room had been kept constant by an air conditioner.

Figures 4 shows the vertical air temperature distribution normalized by the supply air temperature near the object, which moved at speeds from 0.0 to 0.8m/s, perpendicular to the perpendicular to the supply air
flow. The temperature distributions for the case of speed 0.4m/s was larger than that for the case of standing still, and the temperature distribution was small for the case of 0.8m/s.

The air temperature distribution at the different height above the floor for the cases of the different speeds, 0.0 to 0.8m/s, moving perpendicular to the supply air flow is shown in Figure 5. The vertical temperature difference was about 5 deg C when the speed was 0.4m/s.

However for the case of the moving speed 0.8m/s, the temperature difference was only about 1 deg C. As the moving object speed was increased, the thermal stratification was gradually broken, and the room air temperature distribution became uniform.

Figure 6 shows the distribution of the local mean age of air obtained from Equation 2 by the tracer decay method for the case of the object’s speeds 0.0 to 0.8m/s. For the case of 0.0m/s, i.e. standing still, the distribution of the local mean age of air was about 7 minutes. When the speed was 0.2m/s, the local mean age of air was almost same as the standing still case in the occupied zone, but the age increased at about 10 minutes in the upper zone of the room. For speeds over 0.6m/s the local mean age of air became larger than in the standing still case in all the zones.

Figure 7 shows the vertical distribution of the local air change index, defined by Equation 1, near the object, measurement points 8 to 11, moving perpendicular to the supply air flow. The local air change index while standing still was about 340% in the occupied zone and 290% in the upper zone. For speeds over 0.6m/s the local
The local air change index was about 200% in all the zones. These indices were larger than 100% for the ideal perfect mixing case. These results might have been caused by the horizontal distribution of the local mean age of air near the object. The local air change index in the occupied zone for all the cases, except for moving speed 0.2m/s, was less than in the case of the standing still case, as shown in Figure 7.

Figure 8 shows the local air change index vs. the model moving speed. The local air change index in the occupied zone, 0.1 to 0.75m above floor level, was about 350% when the object’s speed was lower than 0.2m/s. The highest index was obtained for the moving speed 0.2m/s. But no such peak was noticed in the upper zone, 1.4 to 2.05m above floor level.

As confirmed by Mattsson (1999), the best ventilation efficiency was attained at the moving speed 0.1-0.3m/s, but the mechanism has not been clearly resolved so far. He suggested that the current caused by the moving object might be spread horizontally at the different levels in the room, instead of being convected to the upper zone where it contributes to the recirculation process. He also inferred that the mechanism cleaned up the air in the poorly ventilated zones when there was no human activity in a room, and parts of the free convection current along the moving object were swept away from the body. Nevertheless, more detailed experiments such as the flow visualization and CFD approach will likely be required to resolve the mechanism.

3.2 Movement parallel to the supply air flow

Figure 9 shows the air temperature distribution when the object moved along the supply air flow. The difference between the air temperature and the supply air temperature was increased as the model’s moving speed was increased.

Figure 10 shows the local air change index profiles. The more the speed increased, the smaller the distribution of the local air change index became.
3.3 Air change efficiency

Finally the air change efficiency, defined by Equation 3, vs. the object’s speed while moving perpendicularly, were investigated as shown in Figure 11. The air efficiencies for both standing still and 0.2m/s were about 60% and around 50% for the case of speeds over 0.4m/s. The room air distribution for the latter case can be considered nearly perfect mixing.

4. Conclusions

The effect of a moving object on the performance evaluation of displacement ventilation was investigated by means of an experiment, using a movable heated human model designed to go back and forth on a straight line using an electrical slider and motion controller, in a full scale room model. According to the results, the more the moving speed increased, the smaller the temperature distribution and the local air exchange index in the occupied zone became in all the moving directions. When the speed of the human model was set to 1.0m/s, the local air exchange index in the occupied zone was 20 to 80% less than when it was standing still. The most significant effect on the air temperature distribution and ventilation effectiveness was shown the object moved perpendicular to the supply air flow.

It is difficult to compare the difference in air distribution and ventilation performance caused by both perpendicular and parallel movement. The air distribution and ventilation efficiency were significantly affected by both of the moving modes. The general tendencies of distributions of vertical air temperature, age of air, local mean age of air and the air change efficiency for the different moving speeds were all obtained from these experiments.

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