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THE EFFECT OF LOCATION OF A CONVECTIVE HEAT SOURCE ON DISPLACEMENT VENTILATION: CFD STUDY

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ABSTRACT

Two-dimensional computational simulations are performed to examine the effect of vertical location of a convective heat source on thermal displacement ventilation systems. In this study, a heat source is modeled with seven different heights from the floor (0.5m, 0.75m, 1.0m, 1.25m, 1.5m, 1.75m, 2.0m) in a displacement ventilation environment. The flow and temperature fields in thermal displacement ventilation systems vary depending on the location of the heat source. As a heat source rises, the convective heat gain from the heat source to an occupied zone becomes less significant. This effect changes the temperature field and results in the reduction of the cooling load in the occupied zone. The stratification level is also affected by the heat source location at a given flow rate.

KEY WORDS

Air flow, CFD, Displacement ventilation, Stratification, Temperature distribution, Plume, Convection.

INTRODUCTION

A displacement ventilation system discharges air at low velocity near the floor. The supplied cool, clean air spreads and forms a pool of conditioned air over the floor. When this air meets a heat source, a convective plume is generated because of the temperature difference and resultant buoyant force. This plume acts as a channel through which warmed and polluted air goes upward up to a ceiling area where it exits through the exhaust. Due to entrainment by the surrounding air, the volumetric flow rate of the plume gets larger as plume rises. When the flow rate of the plume is equal to that of the supply air, thermal and contamination boundary levels form by which the upper level (warm and polluted) and the lower level (cool and clean) are distinguished.

This stratification is one of the most beneficial factors in the thermal displacement ventilation over conventional mixing type ventilation since, in the displacement ventilation systems, only a portion of total loads considered in the mixing ventilation systems is satisfied. More importantly, the displacement ventilation improves indoor air quality in the lower level by separating contaminated air from clean air through the stratification. This leads to the idea that energy saving as well as good indoor air quality can be efficiently controlled by the use of displacement ventilation. Many investigators have reported the advantages of displacement ventilation theoretically and experimentally for various HVAC applications (Mathisen (1989), Sandberg *et al.* (1989)). It was also reported that for 100,000 ft^2 office, the cooling load was reduced by 25 ~ 30 % using displacement ventilation. Consequently displacement ventilation reduced the supply air volumetric flow rate to 70% of what is required in conventional mixing ventilation in the same situation (Dunham Inc. (1999)).

Attention should be paid to vertical temperature distribution in the displacement ventilation. As the plume ascends, hot air in the plume warms surrounding air by convection. Due to low entrainment, very stable stratification around the plume forms. This results in a temperature gradient in a conditioned space. Since this temperature gradient is an important factor for comfort in a displacement ventilation design, the effect of the heat source location on this needs to be investigated. A temperature field is also strongly related to the cooling load calculation in the displacement ventilation (Li *et al.* (1992)).

The cooling load in the occupied zone consists of two heat gains; a primary convective portion of heat from all heat sources to the lower level and a secondary convective portion from warmed surfaces in the lower level which results from direct radiation heat exchange between heat sources and those surfaces. Each portion of heat gains is likely to alter depending on the heat source location since radiation and convection heat exchanges vary (Halton Inc. (1999), Zhivov *et al.* (1997), Chen *et al.* (1998)). Therefore, it is necessary to understand the effect of the location of the heat source to estimate cooling load effectively for the displacement ventilation. Despite numerous investigations on the effect of a supply flow rate and a supply air temperature on the displacement ventilation (Zhivov *et al.* (1997), Chen *et al.* (1998)), there are few reports (Nielsen (1993)) regarding the effect of the heat source locations on the displacement ventilation systems. In this study, the effects of a primary convective heat gain as the vertical location of the source changes on displacement ventilation systems are investigated by using computational fluid dynamics (CFD).

CFD APPROACH

Figure 1 shows the two dimensional geometry (9.0m by 3.0m) under consideration. A heat source (0.5m by 0.5m) located at the center of the geometry produces a total of 1000 watts. Its vertical location changes from 0.5m to 2.0m above the floor. Supply air enters from wall-mounted, low-velocity diffuser with mass flux of 0.17 kg/s and temperature of 18°C. A return air outlet is installed near a ceiling in the opposite wall side. The size of the modeled supply air diffuser and outlet is 1.2m by 1m and 0.3m by 1m, respectively.

A Finite Volume Method (Patankar (1980)) is used to solve the time-averaged Navier-Stokes equations with a non-uniform grid network. A revised turbulent k-ε model (Launder *et al.* (1974)) with

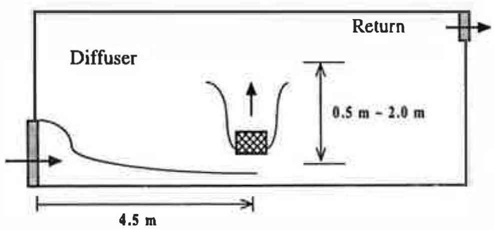

Figure 1. Geometry under consideration

an universal logarithmic variation of velocity and temperature near any solid surface is used. In this study, The Boussinesq model, that assumes constant density through the computational domain, is used for the buoyant force term in the momentum equation. Since $\beta\Delta T << 1$ in this study, the Boussinesq model is appropriate for this simulation, where β is a thermal expansion coefficient of air and ΔT is the temperature difference between air inside and outside the plume generated by the heat source. Various vertical locations of the heat source including 0.50m, 0.75m, 1.00m, 1.25m, 1.50m, 1.75m, and 2.00m are simulated to see the effect of vertical locations of the heat source. Less than 500 iterations are taken for a complete convergence for each case.

RESULTS AND DISCUSSIONS

Typical velocity fields are shown in the Fig. 2 (source height of 0.5m and 1.5m). A plume is generated by the heat source. As the plume goes upward, the volumetric flow rate of the plume is increased by entrainment of surrounding air. Finally, rising air impinges upon the ceiling, is directed to the wall and circulation flow is formed in the upper region. It is observed that while hot polluted air is circulated in the upper region, another large circulation flow is also created in the lower region. These two flow regions yield stratification (momentum based separation) between the upper and lower regions since each circulation contains properties to its region such that two flow regions have little momentum interaction. Therefore, the strength and size of those circulation flows are a main factor in characterizing the stratification level.

It is observed in Fig. 2 that as the location of a heat source changes (the cases of 0.25m, 0.75m, 1.25m, 1.75m, 2.0m are not shown here), the characteristics of the circulation flows formed in the upper region vary. This alteration results in different level of stratification. It is shown that while a larger circulation flow is generated in the upper region when the source is at a low location ((a) in Fig. 2), a smaller one is formed in the upper region when the source is at higher position ((b) in Fig. 2). This is related to plume strength. If a plume pressure, $\rho_{plume}V^2_{plume}$, which is built up as a static pressure in the upper region becomes strong enough to overcome buoyant force, $\Delta(\rho g)_{lower\ zone\ air}$, then hot air in the upper region pushes room air downward until it loses its momentum. When it looses vertical momentum, it flows horizontally making a circulation in the upper region. It is deduced that when the source is at low location and the plume develops fully, a large circulation is created yielding a lower stratification level. The reverse is applied to the case of higher locations of the heat source where a plume jet does not develop enough to build strong jet pressure. In this case momentum based stratification is formed at a higher level. It should be noted that no stratification level would be created with jet pressure that is strong enough to push buoyant air to the floor level. In this case, only one large circulation flow would be observed in whole conditioned space (Shilkrot (1993)).

Dotted lines in Fig. 2 show the flow rate based stratification level where the volumetric flow rate of the plume is equal to that of supply air. Since the volumetric flow rate of the plume is increasing as the

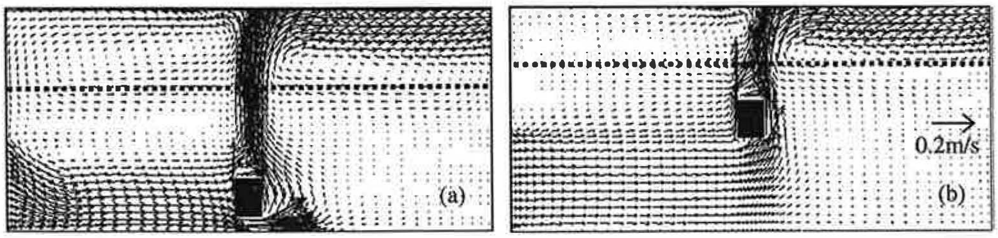

Figure 2. Velocity vector plot for the heat source at (a) 0.5m and (b) 1.5m

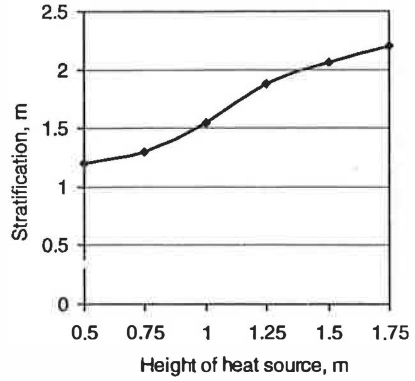

Figure 3. Stratification levels as heat source rises

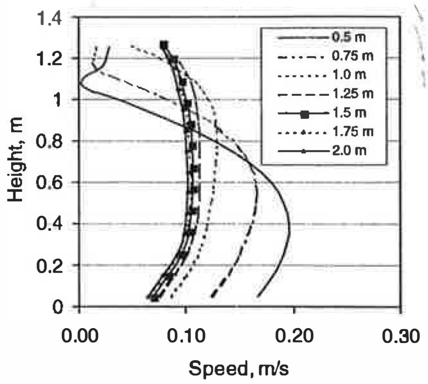

Figure 4. Velocity distribution of the flow region off the diffuser by 1m

plume rises, the higher location of the heat source yields a higher stratification level. The variation of stratification level with source locations is shown in Fig. 3. It indicates that vertical location of the convective heat source alters the stratification level linearly over the heights (0.5m~1.75m). When heat source is located at 2.0m (not seen here), no distinct stratification level is observed. This is because the rising plume is directed into the wall before it develops to a level where its flow rate equals to that of supply air. In this case it can be also observed that air from lower region enters the upper region and mixes directly with the air in the upper region.

The source height not only changes the stratification level but also flow pattern of the diffuser flow. Figure 4 shows an effect of the heat source height on the flow around the diffuser. It has known that the flow out of a low-velocity diffuser has characteristics of gravity current rather than that of a jet (Li *et al.* (1997)). One of the gravity current behaviors is the deflection of direction and spreading over an area (cascading) due to temperature difference. The result shows that when a heat source is in heights equal to or below the vertical location of a diffuser (in this case under 1.3m), the source location affects the behavior of gravity current significantly. In the case of source above diffuser height, however, the effect of source height is less consequential. It is observed that for a source height above 1.5m the cascading effect of the gravity current disappears and shows same velocity profiles even though source location changes. Low velocities below 0.2m are attributed to floor surface friction. The Archimedes number (Ar), a non-dimensional number that governs the non-isothermal gravity current, is defined as

$$Ar = \frac{Buoyance\ Force}{Inertia\ Force} = \frac{g\,\Delta T\,d}{T\,V^2}$$

Where g is gravitational acceleration, T is characteristic temperature, ΔT is the temperature difference between supply air and characteristic temperature, V is supply air velocity at the face of diffuser, and d is characteristic length which is usually taken by height of the diffuser. The higher the Ar number, the more the gravity current is deflected.

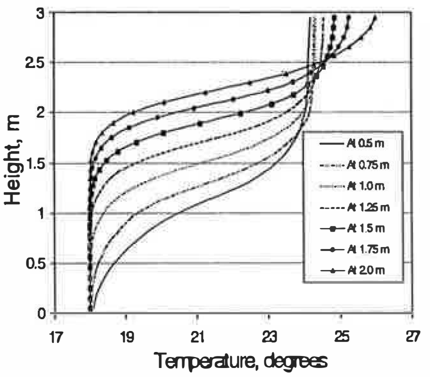

Figure 5. Vertical temperature gradient according to heat source location at x = 3m from the diffuser

Figure 5 shows how the vertical temperature distribution changes depending on the various heat source heights. It

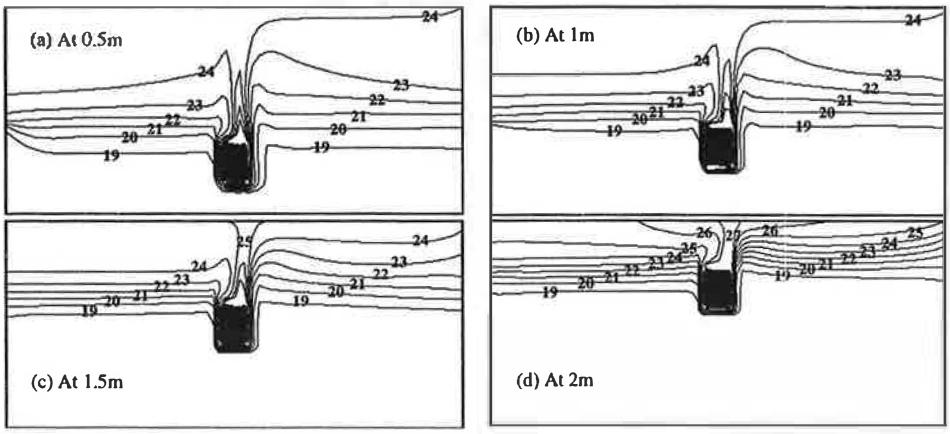

Figure 6. Temperature distribution as the heat source location changes

is shown that temperature does not change linearly over the all heights and it can be divided into three parts; lower, middle, and upper parts. The lower part is designated as the region from the floor up to the heat source height while the upper part is the region in which temperature is maintained uniformly in the upper level. While the height of the lower part is changing with the source height, the upper part is well fixed for various source locations. The temperature remains constant in the lower and the upper parts, (except the 2.0m case) but in the middle part, it changes linearly. It is interesting to note that when the location of source gets higher, a larger temperature gradient is created (compared to lower source location) in the region above the heat source. Figure 6 shows the temperature distribution with source locations (figures of 0.75m, 1.25m, 1.75m are not shown). It is clearly noted that the vertical location of the heat source affects the temperature fields both in the lower and upper levels. It is shown that the region below the source height maintains supply air temperature while in the upper region, the temperature gradients changed with the source locations. This is because most of convective heat from the heat source is carried by the plume and is transported and accumulated at the upper region. It is also interesting to note that temperature distribution in the upper region shows a similar trend as heat source rises. This leads to an idea that temperature distribution in the upper level is somewhat independent on the location of heat source unlike the lower level.

Figure 7 shows how the average temperature changes in the upper and lower regions. It should be noted that the average temperature of the lower region is taken either in a region, 0.2m to 1.8m or 0.2m to 2m regardless of the stratification level. It reveals that as the source ascends, the average temperature of the upper region is gradually increasing (about 1°C change), while in the lower region it is decreasing more rapidly (about 3°C change). It is apparent that the location of the heat source has a more significant effect in the lower level than in the upper level, which should be considered in the design of the displacement ventilation systems. It is interesting to note that as the heat source rises, the exhaust air temperature range increases. For an example, when the heat source is at 1.75m, the temperature range of exhaust air is 1.2°C while at 0.5m, it is 0.2°C. It is also shown that in all cases, there is a region of where the temperature is beyond the average exhaust temperature and it is shown in Fig. 6.

Figure 8 shows how the cooling load in the occupied zone, that is defined as $Q=Cp*\text{mass flow rate}*\Delta T$, is reduced with source height. ΔT is the temperature difference between supply and occupied zone temperature. The cooling load is normalized based on the cooling load at source height of 0.5m. It is shown that the cooling load decreases significantly with the source height. It indicates that if the height of the heat source is higher than the stratification level, practically all its convective heat

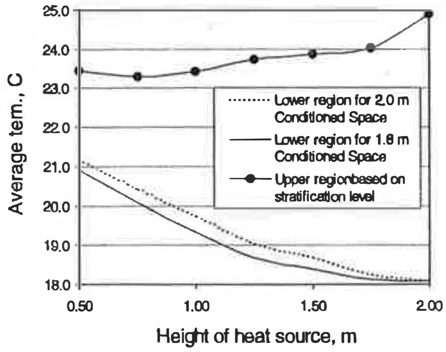

Figure 7. Average temperature of lower and upper region as heat source rises

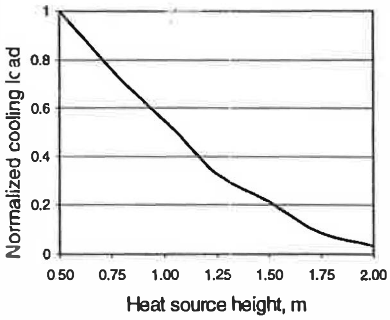

Figure 8. Normalized cooling load

contribution into the lower zone can be neglected for cooling load calculations unlike the conventional ventilation (mixing type). In this case radiation heat gain into lower level is more important in calculating the cooling load of the displacement ventilation.

SUMMARIES AND CONCLUSIONS

The effect of source location on convective heat gain into the lower region of displacement ventilation systems is investigated by using CFD simulation. When a location of the heat source is higher, a convective heat gain from the heat source to the lower level decreases significantly, which results in change of temperature field and in a reduction of the cooling load in that region. The results also show that the level of stratification is altered depending on the source location, because the characteristics of circulation flows generated in the upper region changes with source heights. The source location also significantly affects the behavior of the gravity current produced by a low velocity diffuser when the heat source is in a location lower than a diffuser height. A larger temperature gradient is created in the region above the heat source as the heat source ascends.

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