

Buoyancy-driven Displacement Natural Ventilation in a Single-zone Building with Two-level and Three-level Openings

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Abstract: Displacement natural ventilation, dense ambient air is entrained at low-level openings by thermal buoyancy sources (generally, heating elements) and displaces the lighter air in the building out through high-level openings. Since the incoming air is essentially at the low level, a thermal stratification develops between the fresh air and the air previously in the building. Theoretical solutions for thermal stratification and airflow rates were obtained for buoyancy-driven displacement natural ventilation in a single-zone building with two-level openings and three-level openings. The effects of openings sizes on stratification interface level and volume flux were studied using Newton iterative Method. It was found that for a given ventilation mode, the location of the stratification interface is a function of the geometrical parameters only and independent of the strength of buoyancy sources.

Keywords: displacement natural ventilation, two-level openings, three-level openings, stratification interface level, volume flux

1. INTRODUCTION

In recent years, different questions appeared while using air conditioner, such as the syndrome Sick building (SBA)^[1]. On the other hand, building energy consumption accounts for about 25% of total energy consumption of national economy^[2], and with the improvement of the living standards of the people and popularization of the air conditioner, building energy consumption has the tendency to increase constantly. Natural ventilation, this old technology, because of its comfort, health and zero energy consumption, has become a new trend in building design in the architectural community^[3,4].

Displacement natural ventilation, dense ambient air is entrained at low-level openings by thermal buoyancy sources (generally, heating elements) and displaces the lighter air in the building out through high-level openings. Since the incoming air is essentially at the low level, a thermal stratification develops between the fresh air and the air previously in the building^[5].

For the proper design of a displacement natural ventilation system, it is essential to ensure a sufficient and comfortable level of air exchange rate and maintain the stratification interface above the level of human breathing zone. Therefore, a good understanding is necessary for the optimization of the design and operation of natural ventilation systems.

In this work, displacement ventilation for a single-zone building with two-level openings and three-level openings is investigated theoretically. The effect of opening sizes on stratification interface level and airflow rate in two models (two-level openings and three-level openings) is studied. In the present analysis,

the influence of the surface thermal radiation has not been included.

2. DISPLACEMENT NATURAL VENTILATION MODELS

2.1 Displacement ventilation in a single-zone building with two-level openings

For displacement ventilation in a single-zone building with two-level openings, as shown in Fig. 1, a buoyancy plume entrains the air around it and rises towards the ceiling^[7]. The lighter air in the plume, upon reaching the ceiling, will spread towards the sidewalls and descend between the sidewalls and the plume. This produces an upper layer of light air in the building. The pressure differences between the air in the building and that outside induce air exchange through the bottom and the top openings. Light air in the upper region flows out through the top opening and dense ambient air is entrained into the building via the bottom opening. When a steady state is reached, a constant level of stratification will be established between the dense ambient air and the light upper layer, as shown in Fig.1.

To simplify the analysis, it is assumed that:

- The density variation throughout the building is much smaller compared to the inflow air density.
- There are no changes in volume during the mixing between fluids with different densities.
- There is no fluid exchange across the stratification interface outside the plume.
- Fluid in the upper layer is fully mixed.

Consequently, for such a two-layer stratification system, the conservation of volume flux can be

expressed by the following equation:

$$Q = u_1 a_1 + u_3 a_3 \quad (1)$$

And Bernoulli's theorem can be expressed by the equation:

$$\frac{(\rho - \Delta\rho)u_1^2}{2c_1} + \frac{\rho u_3^2}{2c_3} = \Delta\rho g(H - h) \quad (2)$$

Where c_1 and c_3 are the corresponding discharge coefficients. And u_1 and u_3 are the flow velocity through the top and the bottom opening, respectively. Considering that, in practice, the density variation in the upper layer $\Delta\rho$ is much smaller than the density of the ambient air, the volume flux driven through the openings can be obtained:

$$Q = A^* [g'(H - h)]^{1/2} \quad (3)$$

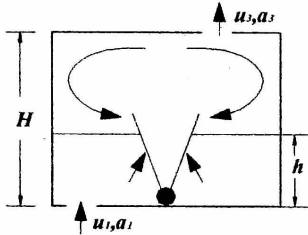


Fig.1 Schematic view of displacement natural ventilation in a single-zone building with two-level openings

Here, $g' = \Delta\rho g / \rho$ is the reduced gravity for

the fluid in the upper layer. A^* is the effective opening area, an important index to fix natural ventilation opening size, which obtained by the conservation of volume flux and Bernoulli's theorem. By assuming complete mixing in the upper layer, Linden et al. [6] gave the following turbulent entrainment flux and reduced gravity in the upper layer for a point source:

$$M = C(Bh^5)^{1/3} \quad (4)$$

$$g' = C^{-1}(B^2 h^{-5})^{1/3} \quad (5)$$

Where $C = (6\pi\alpha/5)(9\alpha/10\pi)^{1/3}$ and α is the turbulent entrainment constant. M is turbulent entrainment flux due to a buoyancy source, m^3/s . Similarly, for a line source:

$$M_L = DB_L^{1/3} h \quad (6)$$

$$g' = D^{-1}B_L^{2/3} / h \quad (7)$$

Where B_L is the buoyancy flux per unit length of the line source, and $D = (2\alpha)^{2/3}$. M_L is the turbulent entrainment flux per unit length due to a buoyancy source, m^2/s .

By matching the flow rates in the turbulent plume

and through the openings due to the upper light layer, Linden et al. [6] obtained the following expressions for the stratification interface height induced by a point and a line buoyancy source, respectively:

$$\frac{A^*}{H^2} = C^{3/2} \left(\frac{\xi^5}{1-\xi} \right)^{1/2} \quad (8)$$

$$\frac{A_L^*}{H} = D^{3/2} \left(\frac{\xi^3}{1-\xi} \right)^{1/2} \quad (9)$$

Here, A^* is the effective opening area $A^* = a_1 a_3 / [(\frac{1}{2}(a_1^2 / c_3 + a_3^2 / c_1))]^{1/2}$; A_L^* is the effective opening area per unit length; and ξ is the non-dimensional interface height.

From Eqs.8 and Eqs.9, it is seen that the interface level is exclusively determined by the geometrical parameters of the building and independent of the strength of the buoyancy source. By using a brine-water modeling system, Linden et al. [6] reported that their experimental results for the interface level were in good agreement with the theoretical predictions of Eqs.8 and Eqs.9. The model building used by Linden et al. [6] was 0.3m (long), 0.2m (wide), 0.25m (high). They used c_1 , c_3 and α values of 1.0, 1.0 and 0.102, respectively. It should be noted that, in practice, c_1 and c_3 are both possibly close to 0.61, which will be used for the data analysis in this work.

2.2 Displacement ventilation in a single-zone building with three-level openings

For the middle opening (MO), the flow direction is dependent on the relative position of MO and the neutral pressure level, where the interior pressure is equal to the exterior pressure [6].

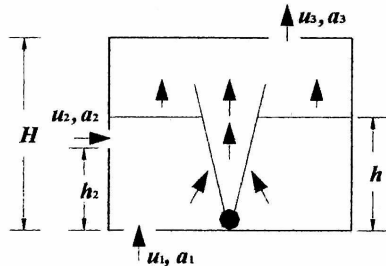


Fig.2 Schematic view of displacement natural ventilation in a single-zone building with three-level openings

Consequently, there are three possible flow modes for a single-zone building with three-level openings: (a) the stratification interface is above MO with inflow through MO; (b) MO is between the interface and the neutral pressure level with inflow through MO; and (c) MO is above the neutral pressure level with outflow through MO. Here, model (a) will be analyzed theoretically. Fig.2 is the schematic view of displacement natural ventilation in a single-zone

building with three-level openings.

Like the model of two-level openings, to simplify the analysis, it is assumed that:

- The density variation throughout the building is much smaller compared to the inflow air density.
- There are no changes in volume during the mixing between fluids with different densities.
- There is no fluid exchange across the stratification interface outside the plume.
- All the openings have negligible heights. It is noted that for openings with large vertical extension, especially MO, the analysis of this work may be not applicable.
- Fluid in the upper layer is fully mixed.

The first assumption ensures volume conservation during mixing. Thus, for a stable stratification, the vertical volume flow rate at a certain horizontal level should be equal to the total inflows through all the openings below it. For flow mode (a), we have

$$u_3 a_3 = u_1 a_1 + u_2 a_2 \quad (10)$$

Where a_1 , a_2 , a_3 are the area for the bottom, middle and top openings, and u_1 , u_2 , u_3 are the flow velocity for the bottom, middle and top openings, respectively. Considering the pressure loss across a sharp-edged opening, Bernoulli's theorem can be expressed by the following two equations:

$$\frac{\rho u_1^2}{2c_1} + \frac{(\rho - \Delta\rho)u_3^2}{2c_3} = \Delta\rho g(H - h) \quad (11)$$

$$\frac{\rho u_2^2}{2c_2} + \frac{(\rho - \Delta\rho)u_3^2}{2c_3} = \Delta\rho g(H - h) \quad (12)$$

Where c_1 , c_2 , c_3 are the pressure loss coefficients for the bottom, middle and top openings, respectively. And u_2 in Eqs.10 can be eliminated by the use of Eqs.11 and Eqs.12

$$u_3 a_3 = u_1 (a_1 + a_2 \sqrt{\frac{c_1}{c_2}}) = u_1 a_1^* \quad (13)$$

Here, $a_1^* = a_1 + a_2 \sqrt{c_1/c_2}$ is the effective bottom opening size. Considering Eqs.11 and Eqs.13, the three-level opening problem is effectively reduced to a two-level opening problem.

Consequently, expressions obtained by Linden et al. [6] for a single-zone building with two-level openings can be applied by substituting the bottom opening area with the effective bottom opening area, a_1^* .

From Linden et al. [6] for displacement natural ventilation induced by a point source, we have:

$$\frac{A^*}{H^2} = C^{2/3} \left(\frac{\xi^5}{1 - \xi} \right)^{1/2} \quad (14)$$

$$u_3 a_3 = C(Bh^5)^{1/3} \quad (15)$$

$$g' = C^{-1}(B^2 h^{-5})^{1/3} \quad (16)$$

Where, $C = (6\pi\alpha/5)(9\alpha/10\pi)^{1/3}$, α is the turbulent entrainment constant and $\xi = h/H$. E is the heat flux produced by the heating element (W). $B = (E/C_p \rho T_0)g$ is the buoyancy flux, which describes the strength of the buoyancy source. And $g' = (\Delta\rho/\rho)g = ((T_u - T_0)/T_0)g$ is the reduced gravity in the upper layer. According to Eqs.16, the temperature in the upper layer, T_u , can be determined by the reduced gravity and the ambient air temperature, T_0 . The volume flux through the bottom and middle opening can be obtained with the use of Eqs.11 and Eqs.12, respectively. A^* is the effective opening area defined as

$$A^* = \frac{a_1^* a_2}{[\frac{1}{2}(a_1^*/c_2 + a_2^2/c_1)]^{1/2}} \quad (17)$$

3 CALCULATION OF DISPLACEMENT NATURAL VENTILATION MODELS

The stratification interface level and volume flux through openings and the reduced gravity in the building were obtained if opening sizes and H have known. In this work, the simple Newton iterative method was used to calculate the stratification interface level h , reduced gravity g' and the temperature at the upper layer, T_u of the two different natural ventilation models (Model (I): two-level openings; model (II): three-level openings). The calculated results of two models were compared to analyze the influence of geometrical parameters and the difference of the two different models.

Condition of calculation:

Set c_1 , c_2 , c_3 and α values to 0.61, 0.61, 0.61 and 0.102, respectively. $H=3\sim 18m$, $T_0=303.15K$, $\rho=1.164Kg/m^3$, $g=9.8m/s^2$, $C_p=1005J/(Kg \cdot K)$, $a_1 = 0.3\sim 1.5m^2$, $a_2=0.3\sim 1.5m^2$, $a_3=0.5\sim 1.5m^2$, $E=1000W$.

3.1 Volume flux

Fig.3 shows a typical example of the volume flux for a fixed set of middle and top opening sizes, i.e. $a_2=0.4m^2$, $a_3=1m^2$. The constants c_1 , c_2 , c_3 and α used here are 0.61, 0.61, 0.61 and 0.102, respectively. It is seen that volume flux increases with increased H in two models. For model (I), the volume flux increases obviously with an increase in the bottom opening size and H . However, the volume flux increases little with increased a_1 and H in model (II). The value of V got in model (I) is larger than the value got in model (II) under the condition of Fig.3.

Fig.4 shows the relationship between volume flux and H , and the influence of different a_2 for fixed bottom and top openings of $a_1=0.5m^2$, $a_3=1m^2$ in model (II). The volume flux increases along with the increase of H , the same as in Fig.3. The larger the a_2 is the higher volume flux is got, as showed in Fig.4, which embodies the importance of middle opening size in natural

ventilation design.

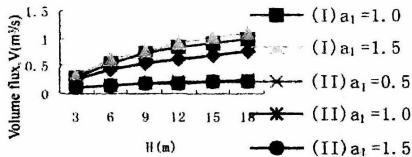


Fig.3 Volume flux for fixed middle and top openings of $a_2=0.4\text{m}^2$, $a_3=1\text{m}^2$

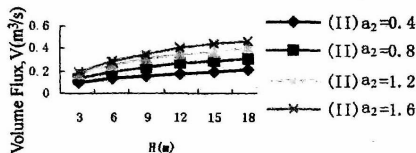


Fig.4 Volume flux for fixed bottom and top openings of $a_1=0.5\text{m}^2$, $a_3=1\text{m}^2$

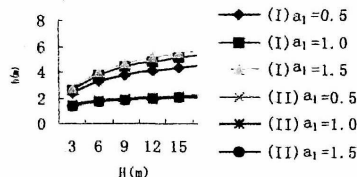


Fig.5 Interface level for fixed middle and top openings of $a_2=0.4\text{m}^2$, $a_3=1\text{m}^2$

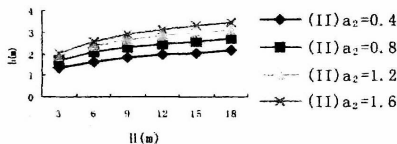


Fig.6 Interface level for fixed bottom and top openings of $a_1=0.5\text{m}^2$, $a_3=1\text{m}^2$

3.2 Stratification interface level

Fig.5 shows a typical example of the stratification interface level for a fixed set of middle and top opening sizes, i.e. $a_2=0.4\text{m}^2$, $a_3=1\text{m}^2$. It is seen that interface level increases with increased H in two models. For model (I), the interface level increases obviously with an increase in the bottom opening size and H . However, the interface level increases little with increased a_1 and H in model (II). The value of interface level, h got in model (I) is larger than the value got in model (II) under the condition of Fig.5. All the results are consistent with

the results shown in Fig.3 and Fig.4.

Fig.6 shows the relationship between stratification interface level and H , and the influence of different a_2 for fixed bottom and top openings of $a_1=0.5\text{m}^2$, $a_3=1\text{m}^2$ in model (II). The interface level increases with the increase of H , the same as in Fig.5. The larger the a_2 is the higher interface level is got. The size of middle opening plays an important part in getting proper stratification interface level.

4. CONCLUSION

Buoyancy-driven displacement natural ventilation in a single-zone building with two-level openings and three-level openings is investigated. For each of the two modes, theoretical expressions of the stratification interface level, volume flux through openings and the reduced gravity in the building are obtained.

The simple Newton iterative method was used to get the solutions of the stratification interface level h , reduced gravity g' and the temperature at the upper layer, T_u of the two different natural ventilation models.

From the calculation we found obviously that the stratification interface level is dependent of opening sizes but independent of the strength of source. It was also found that the volume flux and the temperature of upper layer do depend on the source strength.

For two-level opening model, the volume flux and interface level increase obviously with an increase in the bottom opening size. For three-level opening model, the bottom opening size has little function of the volume flux and stratification level, while larger middle opening size makes higher stratification level and volume flux.

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