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A GENERAL MODEL (SEMI-EMPIRICAL) TO PREDICT TEMPERATURE EFFICIENCY OF DISPLACEMENT VENTILATION SYSTEMS

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ABSTRACT

Temperature efficiency is an important index to estimate the ventilation effectiveness. Usually ,the temperature efficiency is determined through field or model tests such as gas-tracing technology. The heat source structure(location, size, heat emission, etc) has a strong effect on the temperature efficiency. The heat sources present themselves or may be arranged in three basic models:(A)heat sources uniformly distributed in the space; (B) heat sources uniformly distributed on the floor; (C)concentrated heat sources at the bottom of a room. Based on the literature and our previous long time work by experimental and CFD technology on the indoor upward air supply systems, the ventilated space temperature distributions can be classified into several typical patterns according to different indoor heat sources conditions. Then the thermal stratification heights of the displacement ventilation are analyzed and determined. Based on the analysis and experimental data, the temperature efficiency is proven to closely correlate with the thermal stratification height Z, the room radiation transfer factor R, the room volume V as well as the ratio of source to floor area f/F. The semi-empirical equation of temperature efficiency for a ventilated room with a plate heat source is proposed. A general model to predict temperature efficiency of displacement ventilation systems is obtained. Some practical examples agree satisfactorily with experiment results.

KEYWORDS

Temperature efficiency, Thermal stratification height, Temperature distribution, Temperature gradient, Room radiation transfer factor, Displacement ventilation.

INTRODUCTION

Up to now, Temperature efficiency, an important index to estimate the effectiveness of ventilation systems, is usually determined from experimental measurements. However, referencing to available literature on the displacement ventilation systems, it is possible to deduce some essential features of the temperature efficiency: Archimedes number Ar must be involved in the efficiency function(Andlyev1955;Lian1996); the efficiency may closely correlate with the ratio of area of the source to that of the floor(Batolin and Ergilman1953) and effect of the turbulence exchange contributes a minor portion to the heat flux from the sources to the occupied zone(Shilkrot 1993).Generally, the temperature efficiency is a function of the most important variables.

$$E_T = \frac{t_E - t_O}{t_{O.Z} - t_O} = F(V, F, f, h_s, n_s, Q, G) \qquad (1)$$

where E_T =temperature efficiency, t_0=temperature of supply air, $t_{O.Z}$ =temperature of occupied zone ,t_E=temperature of extract air, V=room volume (m^3), F=floor area (m^2) ,f=area of plate heat source (m^2) , h_s=source height (m), n_s=number of sources, Q=total heat emission in room, G=airflow rate (m^3/s).

Due to the complexities of boundary conditions of ventilated room, the solution in closed form to the governing equations of momentum, heat and mass transfer of ventilation systems can not be derived and semi-empirical routines have to be chosen in practice. For the purpose of developing an expression for the temperature efficiency function, the assumptions are made as follows:

- A two-cell model is used to simulate a ventilated(Shilkrot 1993).
- On account of the low velocity air supply, the effects of configuration of air opening are negligible except the total air flow rate.
- Radiant heat transfer from sources and /or ceiling to floor is sufficient for taking into account the radiation effects.

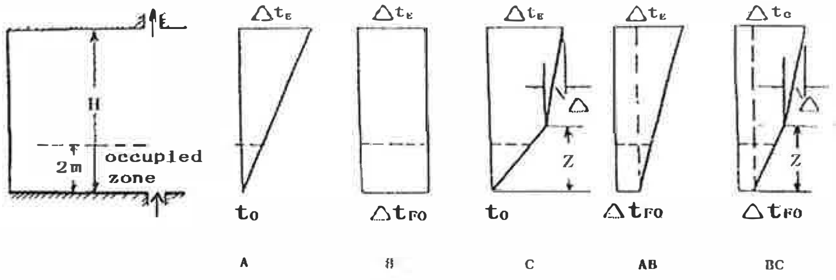

Figure 1:Temperature patterns of some typical source models

TEMPERATURE PATTERNS OF TYPICAL HEAT SOURCES MODELS AND ANALYSIS

Experience indicates that the primary factors in influencing air temperature in rooms with upward air supply are mean air velocity, distribution of heat sources and presentation of the heat exchange modes. Heat source present itself or may be arranged in three basic models: heat sources uniformly distributed in the space; heat sources uniformly distributed on the floor or concentrated heat sources at bottom of the room. Distribution of heat sources encountered in engineering may be sort of combination of the basic models as well. With the basic distribution models of heat sources on the air temperature determined individually, actual engineering problems about indoor air temperature may be solved by superimposition(Zhao and Li 1998).

Figure 1 depicts the temperature patterns of the basic models A, B, C and two combined models AB and BC. The curve for model AB is a combination of curves of A and B, and the curve for BC is a superimposition of B and C. In this way, curves for composite models such as ABC etc are available.

The characteristic elements of typical temperature patterns including the temperature gradient (dt/dh), thermal stratification height (Z), radiant heat transfer factor (R) , and the temperature difference between exhaust air and that at the stratification height (•) are listed in Table 1(Zhao and Li 1998).

TABLE 1. CHARACTERISTIC ELEMENTS OF SOME TYPICAL TEMPERATURE PATTERNS

Source model	Temperature gradient $\frac{dt}{dh}$	Z	R	•	f/F
A	$\bullet t_E/H$	H	0	0	0
B	0	0	1	0	1
C	$h < Z,\ (1 - P_r)\Delta t_E / Z$ $h > Z,\ P_r\Delta t_E /(H - Z)$	0~H	0	$P_r \bullet t_E$	0~1
AB	$(1\text{-}R)\bullet t_E/H$	H	0~1	0	0
BC	$h < Z,\ [(1 - R) - (1 - \varphi)P_r]\Delta t_E / Z$ $h > Z, (1 - \varphi)P_r\Delta t_E /(H - Z)$	0~H	0~1	$\bullet 1\text{-}\bullet \bullet P_r \bullet t_E$	0~1

where Z=thermal stratification height (m), R=room radiant transfer factor, •=temperature difference between extract and that at stratification height, H=room height (m) , P_r=percentage of radiant heat emission of heat source, • t_E=temperature difference between supply and extract air, • =configuration factor.

As the essential variables determining the space temperature patterns with specified heat source models identified, the temperature efficiency function can be written in the form (Zhao and Li):

$$E_T = F(Z, R, \Delta) \tag{2}$$

Eq. (1) is equivalent to Eq. (2) and variables V, F, f, ... are implicite in Z, R and •. To derive the expression of function *F* in Eq (2), explicit dependence of Z, R and • upon variables V, F, f, ... must be determined in advance.

For ventilated rooms with a plate heat source the thermal stratification height Z has been approximately determined(Zhao 1998, Mundt 1990).

By semi-empirical treatment or flow rate correction, the height of source location h_s or the number of source n_s may be incorporated into the expressions of Z. Considering the air temperature at floor is highly sensitive to the radiant heat transfer in a room, therefore the room radiant heat transfer factor can be defined by

$$R = \frac{t_{FO} - t_O}{t_E - t_O} \tag{3}$$

from author's previous work(Zhao and Li 1998,1999)

$$R=\frac{Q_R}{Q}+\left[\frac{1}{\frac{\rho c_p G}{F}(\frac{1}{\alpha_r}+\frac{1}{\alpha_c})+1}\right](1-\frac{Q_R}{Q}) \tag{4}$$

where t_{FO}=temperature of air at the floor, •=air density (kg/m^3), $\bullet_c$=convective heat transfer coefficient (W/m^{2}K), •=radiant heat transfer coefficient (W/m^{2}K), c_p =specific heat at constant pressure (J/kg K), Q_R= radiant heat projecting to floor from heat source (W).

Replacing $\rho, c_p, \alpha_r, \alpha_c$ with given values and using air exchange rate N times V as a substitute for air flow rate, an approximate room radiant heat transfer factor equation is given by

$$R=\frac{Q_R}{Q}+\frac{1}{0.2NH+1}(1-\frac{Q_R}{Q}) \tag{5}$$

First discussing the simplest situation, i.e. •=0 ,Eq. (2) reduces to a simpler form. As can be seen in Fig.1, the temperature pattern for source model BC is the general form of all those shown in the figure and the temperature efficiency resulted from model BC is elicited. The simplified temperature efficiency $E_{T.o}$

$$E_{T.O}=\frac{1}{1-C(1-R)} \tag{6}$$

Where C is convective factor in Eq.(6) , $\left[\begin{array}{ll} C=\frac{Z}{4} & if\ Z<2 \\ C=1-\frac{1}{Z} & if\ Z\geq 2 \end{array}\right]$

If R=1, Z=0, model BC changes to model B, and $E_{T.O}$=1.
If R=0, Z=H, H>2, model BC changes to model A and $E_{T.O}$=H.

If R>0, Z=H, H>2, model BC changes to model A and $E_{T.O}=\frac{H}{HR+(1\text{-}R)}$

Under normal conditions, •>0 and E_T>$E_{T.O}$,$E_T$is conveniently related to $E_{T.O}$ by means of a coefficient K_O.

$$E_T=K_0E_{T.O}=\frac{K_0}{1-C(1-R)} \tag{7}$$

K_O is empirical coefficient, coefficient K_O depends on the system configuration(Zhao etal 1999).

$$K_0\approx\frac{1}{1-(1-\varphi)P_r} \tag{8}$$

$$E_T=E_{T.O}K_0=\frac{1}{[1-C(1-R)][1-P_r(1-\varphi)]} \tag{9}$$

This is the final analytical solution of temperature efficiency in an upward ventilated rooms.

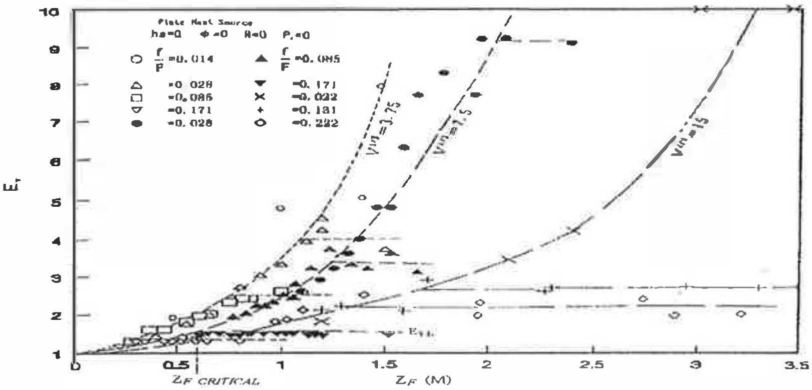

Figure 2:Temperature efficiency of upward ventilated rooms with plate heat sources

Figure 3: Check Eq.(11) against test data

EXPERIMENTS AND VERIFICATIONS

Numerical simulation and test measurement were used to check the results obtained. For simulating the upward ventilated rooms with plate heat source located at the center of the floor surface, the 3-D. Shareware PHONICS was used. Total 107 simulated results including three different values of V and ten different values of f/F are shown in Fig.2. As shown in Fig.2, the fact of all data being in an order state, proves that the temperature efficiency bears a relationship to Z_F and V. With the aid of using a correction coefficient K_V, the room volume can be integrated in Eq.(9). coefficient K_V is derived from Fig.2.

$$K_V = \frac{1}{1-(1-e^{-0.2Z^{15}})\frac{15}{V^{1/3}}} \qquad (10)$$

Combination of Eq.(9) and Eq.(10) gives the semi-empirical equation of the temperature efficiency

$$E_T = \frac{1}{[1-C(1-R)][1-P_r(1-\varphi)][1-(1-e^{-0.2Z^{15}})\frac{15}{V^{1/3}}]} \qquad (11)$$

As shown in Fig.2, for a given value of f/F temperature efficiency has a maximum value $E_{T.L.}$ This means that for a given f/F, E_T increases with increasing Z_F at the initial stage. Then at a certain value of Z_F, denoted by $Z_{F.CRITICAL}$, E_T reaches the maximum value $E_{T.L.}$ After that it keeps the value constantly. So E_F (11) is applied in the following range of stratification height: $Z_F < Z_{F\,CRITICAL}$. $Z_{F.CRITICAL}$ depends on the room volume V and area ratio f/F. Note that a special situation exists where the heat source is uniformly distributed on the floor, thus the ratio f/F takes the maximum, unity, and the temperature efficiency is the maximum, i.e. $E_T=1$ and simultaneously $Z_{F.CRITICAL}=0$.

CONCLUSION

Temperature efficiency of the upward air flow has been treated by analyzing the temperature response to various heat source distribution. The efficiency has turned out to be closely correlated with variables

$$E_T = F(Z,R,V,\frac{f}{F},P_r,\varphi)$$

The semi-empirical equations to predict temperature efficiency is given as Eq.(9). By sampling sufficient information from experiments, an empirical correction for room and source dimensions can be incorporated into Eq.(9) to complete the task of establishing the effectiveness expression for a practical system. Comparison with tests shows that the previous work is valid.

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