EXTENSION OF THE KINETIC ENERGY MODEL FOR CALCULATION OF THE ZONE AVERAGE AIR VELOCITY

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Summary

A kinetic energy model for calculation of the average room velocity was developed in earlier stage of the research. The model was found to have a very good correlation with the experimental in most cases. However, with vertical, downward projected air supply the calculated velocities were only 54 percent of the measured occupied zone average velocities, though a linear correlation was found as well. This was concluded to be due to the fact that in this case the occupied zone was partly within the main zone of the vertical supply jet, which caused that the occupied zone kinetic energy level exceeded the room average.
The purpose of the present work was to further develop the kinetic energy model to account for the zonal phenomenon as well.
A new calculation method for the calculation of the zonal average air velocity in the ventilated room was developed and verified with laboratory and field measurements.
The verification showed a very good correlation between the method and the experimental data. The method can be used to estimation of a zonal air velocity in ventilated room during design stage.

Introduction

A kinetic energy model for calculation of the average room velocity has been presented in (Hagström 2000). The model takes into account, except the supply air jet, also the influence of the other kinetic energy sources, such as thermal plumes, on the room velocity, The introduced kinetic energy flux can be calculated from equation:

$$e = \frac{1}{2}\rho u^3 A = \frac{1}{2}\rho u^2 q = \frac{1}{2}\rho \frac{q^3}{A^2}, \qquad (1)$$

where, *A* (m^2) is the outlet area and, *u* (m/s) is an initial velocity and, *q* (m^3/s) is volume flow rate from the source. Application of the equation to different sources is presented in (Hagström 2000).

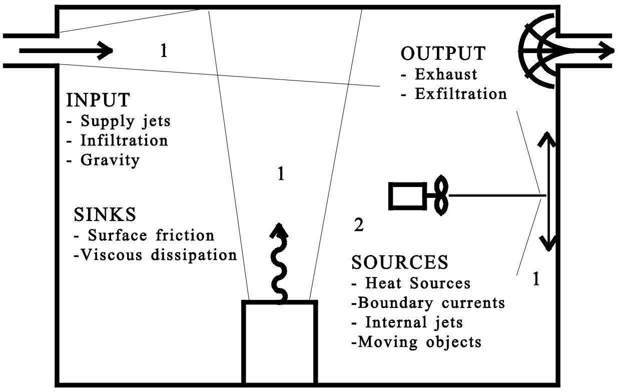

Figure 1. Kinetic energy components and zones in a room space; 1 the jet (supply or thermal) main zone, 2 room bulk flow.

Based on the theoretical analysis and experimental validation, a method for the room average velocity calculation was presented. The average velocity quantifies the velocity level in the room bulk flow, thus, excluding areas of primary flows of air jets or plumes. An equation developed for the average velocity calculation is (Hagström 2000):

$$u_r = \left(\frac{C_x^{1/2}}{\rho} \frac{e_{input} + e_{sources}}{0.664\, A_s} \right)^{1/2} \left(\frac{V_r}{A_s} \right)^{\frac{1}{6}}, \qquad (2)$$

where C_x= 1.40 [m$^{11/3}$/s$^{5/3}$] is an empirical coefficient, ρ is air density, [kg/m^3], e_{input} and $e_{sources}$, [W], are kinetic energy fluxes from external and internal sources, A_s,[m^2], is an area of the room surfaces and V_r, [m^3], is a room volume. The ratio $C_x^{1/2}/\rho$ can be neglected in the normal range of room temperatures because the influence on the velocity is only ±2 %.

The calculation method was found to have excellent correlation with the experimental data from both isothermal and non-isothermal experiments for cases were the supply air jet was diffused before entering the occupied zone (Hagström 2000). Similar results were received from additional verification with different types of diffusers (Hagström 2002). However, with vertical, downward projected air supply the calculated velocity levels were only 54 percent of the measured occupied zone average velocities, though a linear correlation was found as well. This was concluded to be due to the fact that in this case the occupied zone was partly within the main zone of the vertical supply jet. Thus, the additional kinetic energy that was introduced directly by the supply jet into the occupied zone increased the zonal velocity in the occupied zone above the room average. The objectives of the current research was to find a solution in order to take into account this remaining "excess" kinetic energy of a jet that is directed into the room zone under consideration.

Zonal average velocity

As the equation (2) resulted in a linear correlation for the vertical supply too, it was selected as a base for further development of the zonal approach. The zonal approach is illustrated in Figure 2.

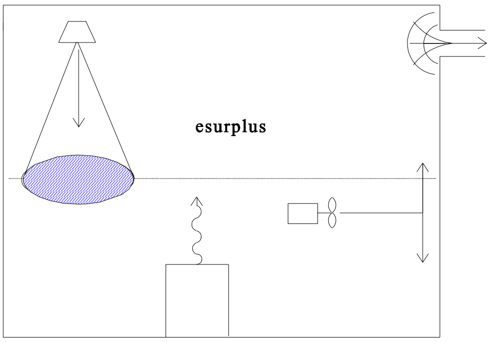

Figure 2. Kinetic energy balance, the zonal approach. The ruled surface illustrates the surplus kinetic energy to the occupied zone in the vertical air supply case.

A method for the calculation of an average velocity within a room zone is based on the following ideas:

- The average kinetic energy level within the room affects the air velocity in all parts of the room volume.
- In certain zone the zonal average velocity level can exceed the room average velocity level, if surplus kinetic energy is supplied into the zone by primary flow, such as an air jet.
- The zonal velocity level is a function of both the average kinetic energy level and the surplus kinetic energy to the zone under consideration.
- As the zonal average velocity exceeds the room average velocity also the surface friction within the zone is above the average.

Zonal average velocity equation

Following the above-presented ideas, a straightforward empirical assumption was made that the zonal mean average velocity can be calculated as a summary of the velocity components from the average and the zonal kinetic energies:

$$u_z = \left(1.50\,\frac{e_{input} + e_{sources}}{V_r}\right)^{1/2} \left(\frac{V_r}{A_s}\right)^{\frac{2}{3}} + \left(1.50\,\frac{e_{surplus}}{V_z}\right)^{1/2} \left(\frac{V_z}{A_{s,z}}\right)^{\frac{2}{3}}, \tag{3}$$

where the first part of the equation is the same as equation (2) and the latter part represents the zonal part, $e_{surplus}$ is the surplus kinetic energy supplied into the zone by a jet, V_z is the free room volume of the zone and $A_{s,z}$ is the area of the room surfaces within the zone. The zonal volume and surface area can be calculated easily, when the room layout is known. Thus, the only new parameter that needs to be specified is the surplus kinetic energy.

Calculation of the surplus kinetic energy

The initial kinetic energy flux introduced by the jet can simply be calculated by equation (1) using mean velocity and the area of the jet opening. The surplus kinetic energy flux that is supplied into the zone under consideration is the amount of the kinetic energy flux still remaining in the jet at the point of its entrance to the zone. The volume flow rate of the fully developed turbulent air jet at the entrance to the zone can be calculated using jet theory (Grimitlyn 1994) :

$$q_x = \frac{2}{K_1} \frac{X}{\sqrt{A_o}}\, q_o\,, \tag{4}$$

where q_x is the jet volume flow rate at a distance X from the origin and q_o is the initial volume flow rate, K_1 is the velocity decay coefficient in the third zone of the air jet, and A_o is the area of the supply air outlet. The centreline maximum velocity of the jet can be calculated as:

$$u_x = K_1 \frac{\sqrt{A_o}}{X}\, u_o\,, \tag{5}$$

The effective average velocity of the air jet can be calculated using information of the cross-sectional jet profile. For compact round jets, the velocity profile can be characterized using Gauss error-function by (Reichard 1942). A practical modification of the profile is presented by (Shepelev 1961):

$$u(y) = u_x \exp\left[-\tfrac{1}{2}\left(\frac{y}{0.082X}\right)^2\right], \qquad (6)$$

where y [m] is perpendicular distance from the jet centreline. Ninety-eight percent of the remaining jet kinetic energy is included, when calculating effective average velocity in such a way that the velocity in the outer edge, y_e, is fifty percent of the centreline velocity. In such case the effective average velocity becomes:

$$u_a = C_a u_x = 0.75\, u_x, \qquad (7)$$

where Ca is the coefficient describing the ratio of the jet average and maximum velocity.
For other than circular jets the average velocity needs to be specified based on the measured jet profile. As an example for a grille, which was used with the vertical, downward projected air supply (Hagström 2000), the effective average velocity using the same velocity criteria was 0.9 times the centreline velocity. The surplus kinetic energy into the zone of consideration can then be calculated as:

$$e_{surplus} = \frac{1}{2}\rho u_a^2 q_x = \rho C_a^2 K_1 \frac{(u_o\sqrt{A_o})^3}{X}. \qquad (8)$$

Experimental verification of the zonal approach

Experimental data
Measurement data from both laboratory and field experiments was used for verification of the equation (3). Data from vertical, downward projected air supply reported in (Hagström 2000) was collected in reduced scale laboratory experiments of an industrial hall. During the experiments influence of an air change rate, room obstructions and the cooling load on the occupied zone conditions were studied. Thus, the room flow situations were varied in a large range during the experiments.

Additional verification was made with the data from the field measurements in sheet metal workshops, with three different air distribution methods. The measurements were repeated both during and outside the working hours. During the working hours the cooling loads and processes were on and the number of disturbances, such as opening and closing doors and movement of workers, machines and equipment, was higher. The air distribution methods in different factories were:

- F1. Horizontal air supply above the occupied zone from the grilles (h=3m).
- F2. Inclined air supply within a forty-five degrees angle from the multi-nozzles with a concentric insert located close to ceiling.
- F3. Displacement air distribution with low impulse units located on the floor.

In factory F1 it was also possible to adjust supply air temperature and the vane position of the grilles. Experiment F1.1 was made with the straight vanes and experiments F1.2 and F1.3 with the vertical vanes in a ninety degrees angle. Experiment F1.3 was isothermal and the jet was not introduced directly into the occupied zone, thus equation (2) was used in calculation. For all other field experiments equation (3) was used for calculation of the occupied zone average velocity. In displacement air distribution case the whole initial kinetic energy was regarded also as surplus energy, because the air supply units were located within the occupied zone.

Verification results
The results of the verification with the laboratory experiments of vertical grilles are presented in Figure 3, where the predicted room average velocities are drawn as a function of measured average velocities in the occupied zone.
The results showed a very good correlation with relatively high reliability between predicted and measured velocities of twenty-two experiments.

The over all correlation from the verification with eleven field experiments is shown in Figure 4. Despite the possible disturbances present in the field conditions, the correlation between predicted and measured occupied zone average velocities was outstanding.

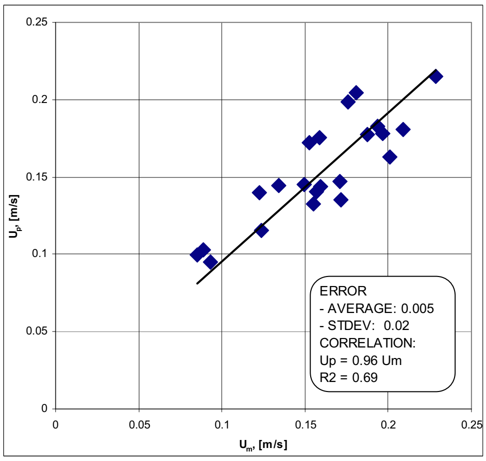

Figure 3. Vertical grilles, correlation of measured and predicted occupied zone

velocities, 22 experiments

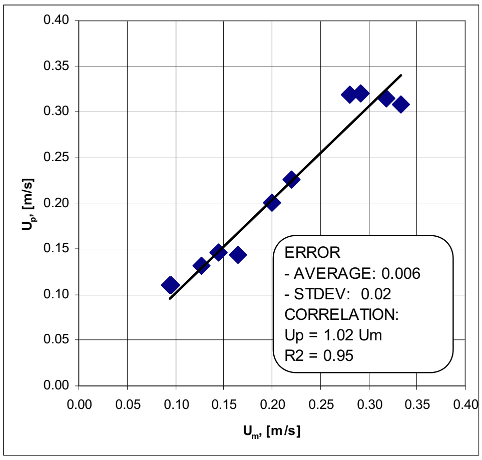

Figure 4. Field measurements, comparison of measured and predicted occupied zone average velocities, 11 experiments.

The detailed comparison of field experiments is shown in Table 1.The relative differences of single cases were within ten to fifteen percent of the measured value, which can be regarded as a good accuracy for design purpose.

Table 1. Detailed comparison of field experiments.

CASE	Working	Average velocity		Up/Um
	Hours	Um	Up	[%]
F1.1	Yes	0.22	0.23	103%
F1.2	Yes	0.20	0.20	100%
F1.3	Yes	0.16	0.14	87%
F2.1	Yes	0.29	0.32	109%
F2.2	Yes	0.28	0.32	114%
F2.3	No	0.33	0.31	92%
F2.4	Yes	0.32	0.32	99%
F3.1	No	0.09	0.11	118%
F3.2	No	0.10	0.11	116%
F3.3	1/2	0.13	0.13	104%
F3.4	Yes	0.15	0.15	101%

Conclusions

A new method for the calculation of the zonal average air velocity in the ventilated room was developed. Also a method to calculate the kinetic energy input from different diffuser types was developed to extend the applicability of the average velocity method.

Results from laboratory and field measurements were used to verify the method. The verification showed a very good correlation between the method and the experimental data.

The method can be used to extend the applicability of the kinetic energy model for estimation of a zonal air velocity in cases, when supply air is blown directly into the zone of consideration. It can be utilized by the designer to estimate the room air velocity level and comfort conditions already at an early stage of the design process.

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