A statistical approach to the evaluation of the maximum velocity within the occupied zone

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ABSTRACT
Currently, a design of the maximum velocity stress in the occupied zone is based on application of the jet theory equations or on the data from the manufacturers' catalogue. However, these methods are based on the idealized test conditions in empty rooms and do not necessarily predict the conditions existing in realistic rooms with heat sources and sinks. Furthermore, little data is available of the distributions inside the occupied zone. A new statistical method for occupied zone maximum velocity prediction is introduced and verified using experimental data. The method was found to result in better correlation with the experimental data than air jet theory equations.

INDEX TERMS
Air distribution; Air velocity; Modelling; Design

INTRODUCTION
The design of room air distribution is presently based on the evaluation of the maximum stress within the occupied zone. Usually, it is considered that the velocity is for the most part a function of the supply air jet. Thus, the design is made using jet theory equations or based on the throw pattern data provided by the diffuser manufacturers. However, these methods are typically based on the idealized test conditions in empty rooms and do not necessarily predict well the conditions existing in realistic rooms with obstructions and heat sources. In addition, such methods give only little or no data of the velocity distributions inside the occupied zone and do not allow analyse or optimisation of the occupied zone conditions in general.

Computational fluid dynamics (CFD) codes predict temperature, velocity and contaminant distributions. The use of CFD models is widespread in research community and some attempts to use it in design of room air conditioning are also presented. It has been recognized to have a great potential but it has not evolved into a principal design tool. The most common arguments why the use CFD has not expanded in ventilation design are: CFD is too time-consuming and expensive tool for normal design, its use requires a special expertise that the designers do not have, finally its reliability as stand alone tool is still questionable. Thus, the use of CFD in ventilation design will still be limited to special applications for some period of time.

Another approach that has not much been used is the knowledge of statistical distributions of velocity conditions within the ventilated spaces. The existence of the similarity in distributions is demonstrated by some researchers. Fissore *et al.* (1991) studied air velocity distribution in a space ventilated by slot-type diffusers and found that the velocity distribution matched well with the Gaussian assumption. Studies of air distribution in rooms with air supply through ceiling mounted diffusers and sidewall grilles were conducted at the All-Union Research Institute for Labour Protection in Leningrad (Grimitlyn *et al.*, 1982, 1986). It was suggested that the velocities in the occupied zone can be described by evaluating the air jet maximum velocity at the point within the room where the jet enters the occupied zone from the air jet theory. Using the experimental deviation will provide a confidence that 95% of the averaged occupied zone velocities will be within the predicted range.

The focus of the current work was to study whether it is possible to establish general rules from the velocity distributions within the occupied zone. A simple design tool is presented based on the kinetic energy method (Hagström, 2000) for occupied zone average velocity and on the generalized standard deviation data from the experiments. It is also demonstrated that the new method can predict the maximum velocity better than jet theory.

METHODS

Experimental data was collected in full and reduced scale laboratory experiments. The size of the smaller room was 7.2 m by 3.6 m by 2.4 m and the full-scale room was 25 m by 12 m by 8 m. During experiments the influence of an air change rate, a level of room obstruction room area and room height and the cooling load on the occupied zone conditions were studied. The air diffusion method studied was horizontally attached to the ceiling air supply from nozzle diffusers with the occupied zone ventilated by reverse flow, see schemes given in Figure 1. From now on reduced scale experiments are referred as **Nozzle** and full scale as **Full scale**.

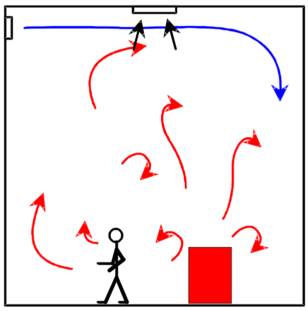

Figure 1 The air diffusion method studied.

During each test the local average velocity and turbulent intensity were measured altogether from 90 points, in 30 locations and at three different heights, 45, 330 and 520 mm (150 mm, 1.1 m and 1.7 m in full-scale experiments, respectively).

Based on the measurement following global values were defined:

- *Occupied zone average velocity* (V_{ave}) was calculated as a spatial average of the measured average velocities in 90 measurement points inside the occupied zone.
- *Occupied zone velocity standard deviation* (V_{std}) was calculated as a spatial standard deviation based on the measured average velocities in 90 measurement points inside the ventilated room. It describes the uniformity of the velocity conditions throughout the occupied zone.
- *Occupied zone maximum velocity* (V_{max}) is the maximum value out of the measured average velocities in 90 measurement points.

RESULTS

In the following, the relationship between occupied zone average velocity, velocity standard deviation and maximum velocity in experimental data is analysed. First, the comparison is made to each case separately and finally all the cases are handled together in order to study whether a more generalized relationship can be found.

A clear correlation was found between the average velocity and both maximum velocity and velocity standard deviation during the measurements. For nozzle the maximum velocity was found to be two times the average velocity with the correlation coefficient R^2-value 0.91 and velocity standard deviation 0.41 times the average velocity with R^2-value 0.51. Thus, the difference of the measured maximum and average velocities was 2.5 times the velocity standard deviation. For full-scale, the maximum velocity was found to be 2.4 times the average velocity with the correlation coefficient R^2-value 0.68 and velocity standard deviation 0.51 times the average velocity with R^2-value 0.84. Thus, the difference of the measured maximum and average velocities was for nozzle 2.4 and for full-scale 2.7 times the velocity standard deviation.

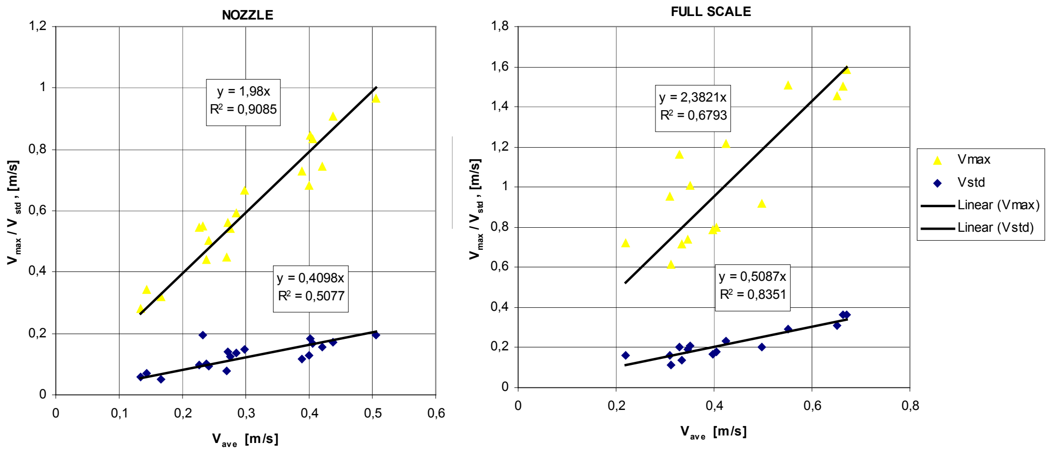

Figure 2 Correlation of the measured occupied zone maximum velocity/velocity standard deviation and the average velocity.

The overall correlation of the combined results from all experiments between the average velocity and both maximum velocity and velocity standard deviation is good. The maximum velocity is 2.2 times the average velocity with the correlation coefficient R^2-value 0.84 and velocity standard deviation 0.46 times the average velocity with R^2-value 0.84. The difference of the measured maximum and average velocities was 2.6 times the velocity standard deviation, which agrees well with a gaussian assumption presented by Grimitlyn.

DESIGN OF THE MAXIMUM VELOCITY

Statistical Approach

From the experimental data above it was seen that the maximum velocity and the velocity standard deviation could be expressed as a function of the occupied zone average velocity with a relatively good accuracy. Based on this dependency, the following simple approach for the room air velocity evaluation is applied:

- Distribution of air velocities in the room bulk flow follows the normal distribution with sufficient accuracy.
- The relative standard deviation in the room flow is a constant value: 0.5. Thus, the velocity standard deviation is a linear function of the average room velocity.

From this it follows that, as the maximum value in normal distribution is the average plus three times the standard deviation, the maximum velocity is 2.5 times the occupied zone average velocity. The properties of the normal distribution can be utilized also in more thorough analysis. It allows one to choose the used design criteria: To be below the absolute maximum velocity in every location of the space may be in many cases a too stringent criterion. Instead, one may like to specify the comfort criteria in such a way that it is met in a specified percentage of the occupied zone. This can be expressed as:

$$V_{cr} = V_{ave} + C_{cr}V_{std} = V_{ave}(1 + \tfrac{1}{2}C_{cr}) \qquad (1)$$

where V_{cr} is the velocity design criteria and C_{cr} is the coefficient describing the reliability that the specified percentage of the occupied zone will meet the selected criteria. For example, if 95% of the room should be below the selected maximum velocity C_{cr} gets value 1.65.

The average velocity is needed for the evaluation. It can be calculated based on the room kinetic energy balance (Hagström, 2000). An equation for the average velocity calculation for the air diffusion method used is:

$$v_{ave} = \left(1.5\frac{e_{input} + e_{sources}}{A_s}\right)^{1/2}\left(\frac{V_r}{A_s}\right)^{1/6} \qquad (2)$$

where, e_{input} and $e_{sources}$ (W) are kinetic energy fluxes from external and internal sources, respectively, A_s (m^2) is the area of the room surfaces and V_r, (m^3) is the room volume.

Air Jet Theory

The equations developed for room air distribution design based on the air jet theory are summarized in Hagström (1999). When attached to the ceiling jets the maximum velocity may exist in two points; at the jet intercept to the occupied zone or in the reverse airflow within the occupied zone. During the prediction, the higher value was chosen as the maximum velocity for comparison. Maximum air velocity V_s at the point of the jet intercept with the occupied zone can be evaluated from the following equations (Grimitlyn, 1986):

$$V_s = \sqrt{2}\, K_1 K_c v_o \frac{\sqrt{A_o}}{L + H_r - h_{o.z.}} \qquad (3)$$

where K_1 is the velocity decay coefficient, K_c is the jet confinement coefficient, v_o and A_o are the jet initial velocity and opening area, L is the distance from the supply opening to the point of jet separation from the ceiling, H_r is the room height, and h_{oz} is the height of the occupied zone.

The maximum air velocity $V_{o.z.}^{rev}$ in the reverse air flow ventilating the occupied zone can be evaluated from the following equation (Grimitlyn, 1975):

$$V_{o.z.}^{rev} = \frac{0.73\, v_o \sqrt{A_o}}{\sqrt{B\, x\, H_r}}, \qquad (4)$$

where B is the room width.

COMPARISON OF DESIGN APPROACHES

The maximum velocity was predicted for each measurement set-up using both jet theory and statistical approach. For statistical values, the occupied zone average velocity used was calculated from Eqn (2) and the maximum velocity was calculate adding three times the standard deviation. The results from both methods were compared to measurements separately.

- *Nozzle* (see Figure 3).
  - *Jet theory*. No correlation was found between the measured and calculated maximum velocities. The calculated maximum velocity was on average half of the measured.
  - *Statistical approach***.** A clear correlation was found between the measured and calculated maximum velocities. The calculated maximum velocities were on average a little higher than measured. The slope of the correlation line was 1.26 with R^2-value 0.81.

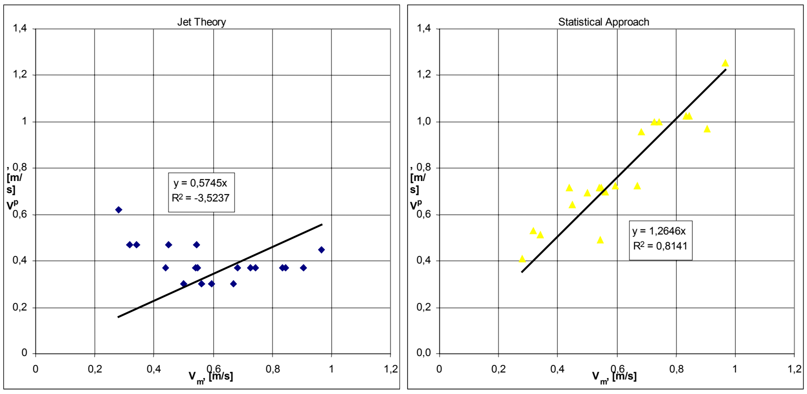

Figure 3 Nozzle, comparison of predicted maximum velocities by jet theory and statistical approach with the measured maximum velocity.

- *Full scale* (see Figure 4).
  - *Jet theory*. No correlation was found between the measured and calculated maximum velocities. The calculated maximum velocity was on average half of the measured.
  - *Statistical approach*. A relatively good correlation was found between the measured and calculated maximum velocities. The slope of the correlation line was 1.03 with R^2-value 0.59.

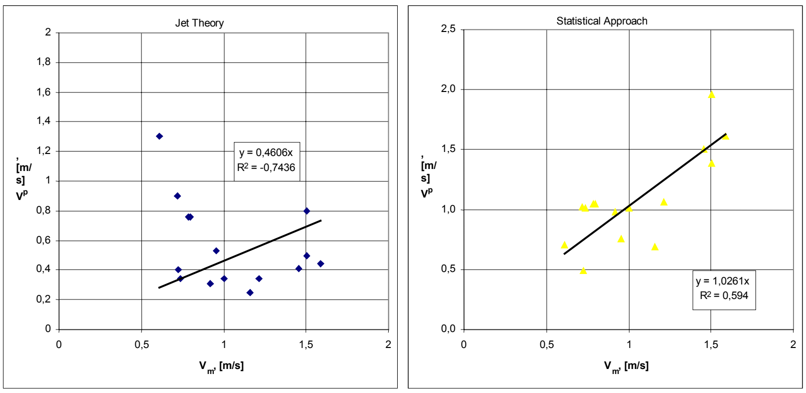

Figure 4 Full scale, comparison of predicted maximum velocities by jet theory and statistical approach with the measured maximum velocity.

DISCUSSION

The jet theory was found to predict very poorly the maximum velocity in complex room situations. In most cases, the results very scattered with no correlation to measurements. In statistical approach case a correlation between measured values was found. Some difference between measured and calculated maximum velocities still existed. There are two possible reasons for this; first, the validity of the normal distribution assumption need to be analysed more carefully, and second, though the number of the velocity measurement was statistically reasonable, 90, it is possible that the absolute maximum velocity was not found in all studies. Utilizing normal distribution as it was presented in Eqn (1), would avoid the latter source of error. However, for the practical purposes, it must be noted, that the absolute error in the maximum velocity due to simplification is relatively small in most cases.

CONCLUSION AND IMPLICATIONS

Currently, a design of the maximum velocity stress in the occupied zone is based on application of the jet theory equations or on the data from the manufacturers' catalogue. These methods are based on the idealized test conditions in empty rooms and can be used to evaluate the draft risk from jet. However, they do not necessarily predict the conditions existing in realistic rooms.

A new method for occupied zone maximum velocity prediction is introduced. The method is based on the evaluation of the room average velocity using kinetic energy balance and on statistical information of the room velocity deviation. The results look promising for practical purposes. However, further studies with additional air diffusion methods should still be made before generalization can be made.

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