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ABSTRACT

Model experiments are one of the methods used for the determination of airflow in large spaces. This paper will discuss the formation of the governing dimensionless numbers. It is shown that experiments with a reduced scale often will necessitate a fully developed turbulence level of the flow. Details of the flow from supply openings are very important for the determination of room air distribution. It is in some cases possible to make a simplified supply opening for the model experiment.

INTRODUCTION

Large ventilated air spaces as shopping arcades, atria and exhibition buildings have grown popular in the last decade. The main purpose of designing the air distribution in such constructions is to obtain control of the energy flow and the temperature level. It is also very important to have a high ventilation efficiency in the occupied areas and a system which can handle this area without too large air exchange in the rest of the air volume. Smoke movements in case of a fire and necessary escape routes are other important subjects. It is also necessary to limit the air velocity in the occupied areas because people may work with restricted activity level in the shops and in open offices.

It is not possible to use full-scale experiments in the design of the air distribution system due to the large dimensions. It is also difficult to use simplified design methods as those based on throws of jets and penetration depths of non-isothermal jets. The cause of this is the complicated geometry which is present in many situations. Several sources for the air movement as for example diffusers, pressure difference around the construction, cold downdraft and thermal plumes make it also difficult to use simplified methods.

Computational Fluid Dynamics (CFD) and physical Model Experiments (ME) are two possible methods for the determination of the air distribution system and the latter will be discussed in the following.

Intensive work on air distribution in large spaces has just been initiated by the International Energy Agency Annex 26 programme "Efficient Ventilation of Large Enclosures". The programme will both contain field measurements, simplified methods, model experiments and CFD-methods (1).

GOVERNING EQUATIONS AND DIMENSIONLESS NUMBERS

The conditions for model experiments are formulated from the governing equations in a non-dimensional form (2). The governing equations consist of the continuity equation, three Navier-Stokes' equations (one in each coordinate direction x, y and z) and the energy equation. The variables in the equations are normalized by means of the supply velocity u_o, the length scale $\sqrt{a_o}$ (a_o is supply area) and the temperature difference ΔT_o between the return and supply openings. The following three dimensionless numbers will appear in the equations

$$Ar = \frac{\beta g \sqrt{a_o} \Delta T_o}{u_o^2} \quad , \quad Re = \frac{\rho_o u_o \sqrt{a_o}}{\mu_o} \quad \text{and} \quad Pr = \frac{\mu_o c_p}{\lambda} \tag{1}$$

where Ar, Re and Pr are the Archimedes number, the Reynolds number and the Prandtl number, respectively. β, g, ρ_o and μ_o are volume expansion coefficient, gravitational acceleration, density and viscosity, respectively, while c_p and λ are specific heat and thermal conductivity.

The conditions for model experiments are explained in the following way. The governing equations are made non-dimensional in full scale and in the reduced scale used in the model experiments. For example, the velocity in the room is divided by diffuser velocity in the room, and the velocity in the model is divided by the supply velocity in the model to normalize all velocities. The two sets of equations are identical and they describe the same solution provided that:

- the dimensionless boundary conditions, including geometry, are identical
- the dimensionless numbers in the equations are identical, i.e. the Archimedes number, the Reynolds number and the Prandtl number are the same for room and model
- the constants ρ_o, β, ... only have a small variation within the applied temperature and velocity areas.

Large spaces mean large Reynolds' numbers if all other variables are kept constant. Large spaces do also mean large Archimedes' numbers. The Archimedes number may be considered as a ratio between gravity and momentum forces, and it can therefore be concluded that gravity force and free convection will be increasingly important in large ventilated spaces.

SIMILARITY PRINCIPLE

It is impossible to make a model experiment in a strongly reduced scale if all the dimensionless numbers are to be kept constant. If, for example, the scale is reduced by a factor of 10, then the velocity has to be increased by a factor of 10 due to the Reynolds number which will give an increase of the temperature difference by a factor of 1000 to keep the Archimedes number. The Prandtl number is, on the other hand, unchanged when air is used as the fluid in the model experiments.

The problem can in practice be overcome if the Reynolds number is high and the flow pattern is mainly governed by fully developed turbulence. It is possible to ignore the Reynolds number and the Prandtl number because the structure of the turbulence and the flow pattern at a sufficient high level of velocity will be similar at different supply velocities and therefore independent of the Reynolds number. Likewise the transport of thermal energy by turbulent eddies will dominate the molecular diffusion and will therefore be independent of the Prandtl number.

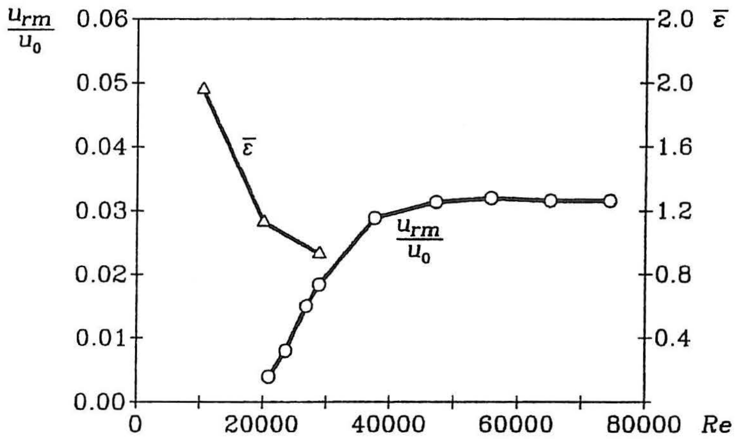

Fig. 1. Examples of normalized velocity and ventilation effectiveness versus Reynolds' number. References (3), (4) and (5).

Figure 1 shows some isothermal measurements made in a full-scale room of conventional size (H × L × W, equal to 2.4 × 5.4 × 3.6 m). The diffuser is wall-mounted and the air distribution is of the mixing ventilation type. It is seen that the normalized value of the maximum velocity in the occupied zone, u_{rm}, obtains a constant level for Reynolds' numbers larger than 45000. This corresponds to an air change rate of 5 h^{-1} and a u_{rm}-velocity of 0.2 m/s. The conclusion that the normalized flow is independent of the velocity at a high Reynolds number is also valid for non-isothermal flow. Müllejans (6) has shown how the general stream line pattern in a series of model tests is similar at different Reynolds' numbers and only a function of the Archimedes number. Measurements in (7) do also indicate fully developed flow in the case of displacement ventilation with practical temperature and velocity levels.

It is obvious from figure 1 that the ventilation effectiveness $\bar{\varepsilon}$ is a function of the Reynolds number, which also indicates undeveloped turbulence for air change rates below 5 h^{-1}. The results show that it is difficult to find the exact velocity and concentration levels everywhere in a small room by model experiments at small air change rates.

On the other hand, the general conclusion may be that it is possible to ignore the Reynolds number and the Prandtl number in large ventilated enclosures due to the fully developed turbulence in situations with large dimensions (large Re). It is therefore often possible to make model experiments with the flow in large constructions by keeping the same Archimedes number in model and full-scale measurements and by ignoring the Reynolds number and the Prandtl number, assuming it is possible to obtain sufficient velocity in the model for fully developed flow.

The presence of a fully developed turbulent flow is also necessary when the air distribution in a room is simulated by a CFD-method because turbulent models, as for example the $k-\varepsilon$ model, assume this type of flow. ME-methods and CFD-methods do therefore have the same capability in this respect.

RADIATION, CONDUCTION AND CONVECTION AT SURFACES

Radiation between surfaces and conduction through surfaces will influence the surface temperature distribution. It is difficult to formulate conditions for model experiments which include those parameters. A practical approach is to prescribe a normalized temperature distribution in the model which is equal to the normalized temperature distribution expected in full scale. The temperature difference ΔT_0 is used as reference in both cases.

Similarities will also be present in convective flow from surfaces in case of a high turbulent level. This effect can be illustrated by analysing the normalized formulas for e.g. cold downdraft and thermal plumes. It is important to notice that the high turbulent level in this case should originate from the temperature differences or from the dimensions in the free convection flow and not from the turbulence level generated by the supply flow. Large enclosures will have large surfaces with different temperatures. This will in practice ensure a high turbulent level in the flow and therefore the possibility to work with the similarity principle.

A practical approach is to simulate cold or hot surfaces with replacement jets which match the air flow in the model to the flow in the full-size room. This method is described by Nevrala and Probert (8).

MODELLING OF AIR TERMINAL DEVICES

Modelling of the Air Terminal Device is another important aspect. The air distribution in a room is strongly influenced by small details in the diffuser, and it is obvious that a reduction of the scale by a factor of e.g. 10 will make it very difficult to reproduce all the details in the diffuser design.

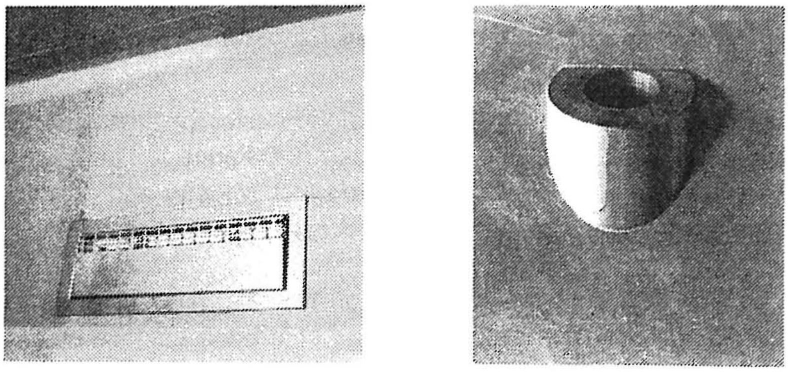

Fig. 2. a) End wall-mounted diffuser (the same device as used in figure 1). b) Nozzle directed against the ceiling in an angle of 45°.

Figure 2a shows an end wall-mounted diffuser which supplies the air through a row of small openings in an angle of 45° direction towards the ceiling. This diffuser is simulated in a model experiment by a nozzle which supplies a jet in the same direction towards the ceiling, see figure 2b. Figure 3 shows the velocity decay of centre line velocity u_x versus distance x in the two cases a) and b). The agreement between velocity decay from the diffuser and the decay in the model seems to be fair, but there are differences outside the centre plane which have some influence on the velocity level in the occupied zone.

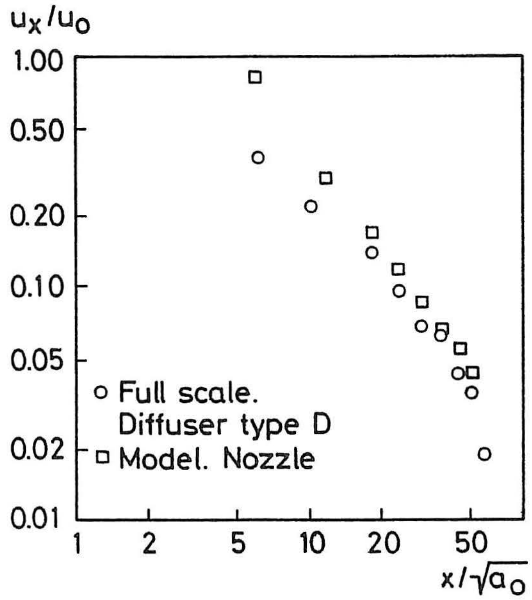

Fig. 3. Velocity decay in a wall jet along the ceiling in a room and in a model, reference (9).

It is also necessary to simplify the diffuser when the CFD-method is used because a detailed description will consume too many grid points. EM-problems with physical design of a diffuser can therefore be studied by a CFD-method. Reference (10) shows that the procedure given in figure 2 and figure 3, with a rough description of the cross section of the jet and a correct description of the momentum flow "momentum method", may give a fair description of the flow in the occupied zone. A promising method is shown in (11) where a correct face area of the merged jets from diffuser openings is used in the model combined with a correct momentum flow. The volume flow to the model will in this case be too large, but the velocity level in the main body of the recirculating flow will be correct because the velocity is proportional to the square root of the supplied momentum flow in large areas of the room at constant Archimedes' number, as for example shown by Jackman (12).

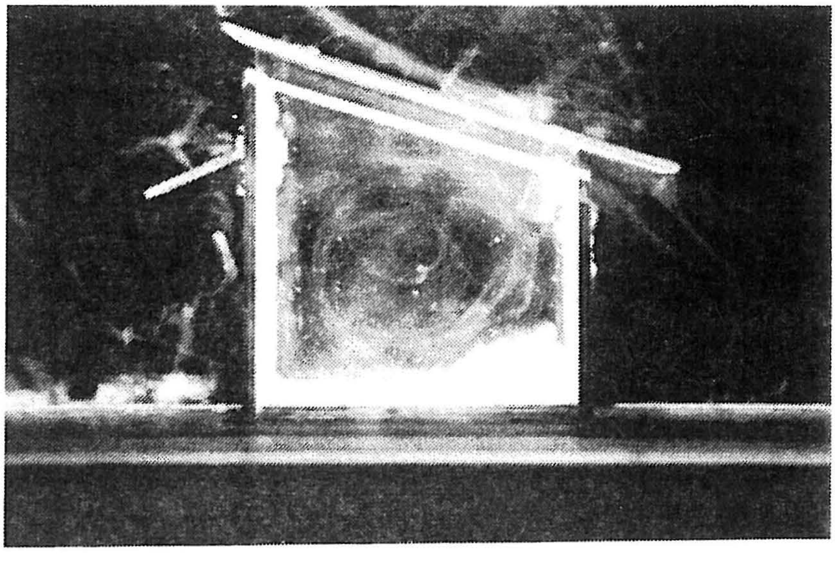

Fig. 4. Flow in a room ventilated by the wind.

The inlet boundary conditions for a model experiment may in some cases be simplified as shown in figure 2 and figure 3. It is in other cases necessary to make a detailed model of the diffusers and return openings to get conditions which are sufficiently detailed, and figure 4 shows a model experiment where the boundary conditions are located outside the building in the wind profile. This type of inlet boundary conditions can be relevant to experiments with natural ventilation of large constructions such as shopping arcades and atria where the pressure distribution is an important factor. The model experiments shown in figure 4 are made in connection with a school project in Tanzania.

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