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SCALE EFFECT IN ROOM AIR MOVEMENT MODELLING

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ABSTRACT
In this paper, a numerical procedure is applied for solving the two-dimensional Navier-Stoke's equations describing the flow in an air conditioned room using the finite volume method. The effect of turbulence is described by the K-ε turbulence model. The range of influence of Archimedes and Reynolds numbers on the air velocity and temperature distribution in the room is investigated using the numerical solution. Comparison of the numerical prediction is made with experimental data. The results of the numerical solutions can be used as a guide for the physical modelling of air movement under more complex thermal conditions.

INTRODUCTION
The expected performance of an air distribution system in some cases can be predicted from past experience and established design procedure. However, in other cases and particularly when non-conventional methods of air distribution are employed, physical modelling and or mathematical modelling must be used to evaluate the room environment. Where the size of the building precludes a full-scale physical model (eg. atria, indoor stadiums, theatres etc), tests are carried out on a reduced scale model. In practice, although a large scale factor (a length ratio of model to building) is preferable, this may not be realised due to the high cost of constructing large models.

For the results from reduced scale model tests to be applicable to the prototype, geometric, kinematic and thermal similarity between model and prototype must be achieved (1 to 5). Geometric similarity is a pre-requisite for any modelling investigation. For isothermal flows, geometric and kinematic similarity must be present and these can be usually achieved without too much difficulty. However, for non-isothermal flows all three similarity requirements should theoretically be present before a complete simulation of the flow in the building can be achieved. In practice, it is not possible to provide a complete similarity for non-isothermal flow and as a result difficulty in interpreting the model results may be experienced. Such problems are naturally irrelevent in mathematical modelling, however, most available mathematical models have recently been developed and require validation.

In this paper, the influence of kinematic and thermal similarities on the air velocity and temperature distribution in a room are investigated numerically using a finite volume computer program. The predicted results are compared with measurements obtained in a full-scale test room.

PHYSICAL MODELLING
To use the test data from a scaled model of a room or a building for the air distribution design of the prototype, similarity of the flow pattern, velocity distribution and temperature distribution should be achieved in the model. Previous investigators (3, 5) have shown that such similarity can only be achieved if geometric, kinematic and thermal similarity between the model and prototype exist. With the help of dimensional analysis, it can be shown, eg. Rolloos (3), that complete similarity can only be attained if the Prandtl number, Pr, the Reynolds number, Re, and the Archimedes number, Ar, are equal for both model and protoype and, in addition, geometric similarity and

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(1) for Re equality:

$$Re = \left(\frac{U\,L}{\upsilon}\right)_p = \left(\frac{U\,L}{\upsilon}\right)_m \qquad (1)$$

with the same fluid (air) used in model and prototype:

$$\frac{U_m}{U_p} = \frac{L_p}{L_m} = \frac{1}{S} \qquad (2)$$

where S is the scale factor, U is the supply velocity and L is the characteristic length.

Equation 2 indicates that the velocity in the model must be higher than that in the prototype by the factor 1/S

(2) for Ar equality:

$$Ar = \left[\frac{g\,\beta\,L\,\Delta\theta o}{U^2}\right]_p = \left[\frac{g\,\beta\,L\,\Delta\theta o}{U^2}\right]_m$$

where β = cubic expansion coefficient, 1/K

$\Delta\theta o$ = temperature difference between supply and room, K

Assuming similar thermal conditions between the model and the prototype and using the same fluid:

$$\frac{U_m}{U_p} = \sqrt{\frac{L_m}{L_p}} = \sqrt{S} \qquad (3)$$

From equations (2) and (3), it is clear that the requirements for the equality of Re is quite different from the requirements for the equality of Ar and the two equalities can never be achieved concurrently in a model study. In the case of isothermal flows similarity can be achieved with constant Re. However, for non-isothermal flows complete similarity cannot be achieved in practice. In this case the ranges of Re and Ar over which the air distribution system in the prototype is required to operate can provide an insight into deciding whether equality of Re or Ar is most relevant for model investigation.

NUMERICAL SOLUTION

The general equations describing the steady incompressible flow in a room are solved in a finite difference form. The fluctuating velocities and temperature terms are represented by an equivalent time-average terms using the K-ε turbulence model. The effect of buoyancy on the vertical component of velocity and the kinetic energy of turbulence, K, and its dissipation rate, ε, is also included in the solution procedure, see Awbi (7, 9) for further details.

TEST ROOM

The room being investigated for this purpose has a square floor of length, L = 4.2m and ceiling height, H = 2.8m. The air is supplied from a continuous slot in the ceiling spanning the width of the room and at a distance 1.2m from the wall. The room load was produced by electrically heated tapes laid over the floor area to produce a uniform load distribution. The air velocities were measured with TSI 1610 low velocity anemometers which give the magnitude of the velocity at the measuring point. The thermocouples were provided with a radiation shield to reduce the effect of radiant temperature. The measurements were carried out using square grids of 1.0 and 0.5m at distances of 0.15, 0.6, 1.2 and 1.8m above the floor.

RESULTS AND DISCUSSION

(a) Effect of Reynolds number (isothermal flow)

Figure 1a shows resultant velocity profiles in the occupied zone of the room for different air flow rates ie. different Re. These profiles represent the ratio of the mean velocities in horizontal planes of the occupied zone to the inlet velocity. As can be seen from Fig. 1a the predicted velocity profiles are close to the experimental values, except near the floor where the predicted values are higher in some cases. This can be attributed, especially in the low Reynolds number cases, to the directional sensitivity of the anemometers. The anemometer had a cylindrical sensor which measures the component of velocity normal to the cylinder axis. The sensor is normally set with its axis parallel to the floor of the room. The measuring plane at 150mm above the floor is within the boundary layer region of the reverse flow and unless the axis of the anemometer is perpendicular to the direction of the flow, a low velocity reading will be obtained at this height. At higher levels above the floor the anemometer will be measuring flow in the shear layer and the vortex regions where the flow has no defined direction. Indeed measurements at higher levels produced good correlation with predictions. Another cause of discrepancy at low levels may be attributed to the K - ε model's failure in not describing the effect of wall proximity accurately and also the effect of low Re flows near the wall. The wall effect has been included in the present computation using Launder and Spalding (6) wall function expression, however, Nagano and Hishida (10) have reported an improvement to the $K - \varepsilon$ model by the inclusion of both effects and have attained better results. The present authors anticipate the use of improved forms of the $K - \varepsilon$ model in the near future.

As shown in Fig. 1a the effect of increasing Re on the velocity profile is most prominent near the floor. Fig. 1b shows this effect extended to include higher Re and by increasing Re the maximum recirculating flow velocity near the floor also increases. The range of Re considered here covers most ranges used in model investigation.

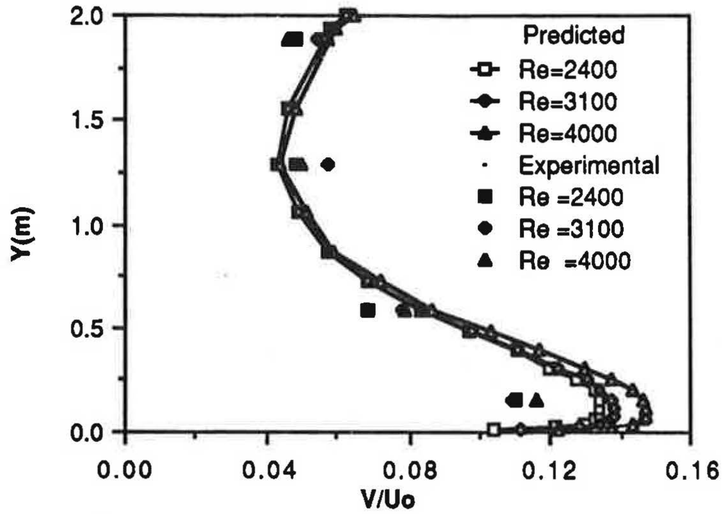

Fig.1a Computed and measured isothermal velocity profiles

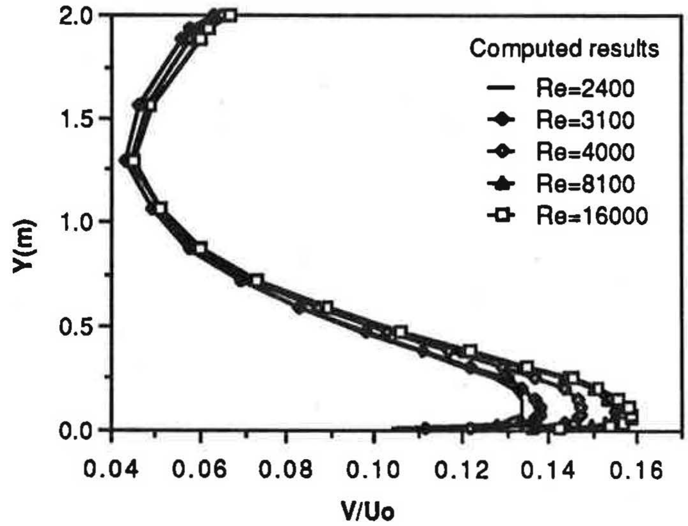

Fig 1b Computed isothermal velocity profiles

(b) Effect of Archimdes number (non-isothermal flows)

Figure 2 shows the effect of Archimedes number on the mean velocity in the occupied zone. As Ar (ie cooling load) increases the room velocity increases as a result of the downward buoyancy acting on a cool jet. The agreement between the predicted results and measurement is close for most practical pruposes. This indicates that especially for higher Ar values, modelling at reduced scale should be based on the equality of Ar between model and prototype.

Figure 3 shows the non-dimensional temperature distribution $\Delta\theta/\Delta\theta_0$ in the occupied zone for different values of Ar. $\Delta\theta$ represents the difference in the average temperature in a horizontal plane and air supply temperature and $\Delta\theta_0$ is the difference between the average temperature in the occupied zone and the supply temperature. As can be seen from this figure the effect of Ar on the temperature gradient is very small which indicates a good mixing of the flow. Since the room load was situated on the floor, the temperature ratio increases towards the floor with $\Delta\theta/\Delta\theta_0 > 1$.

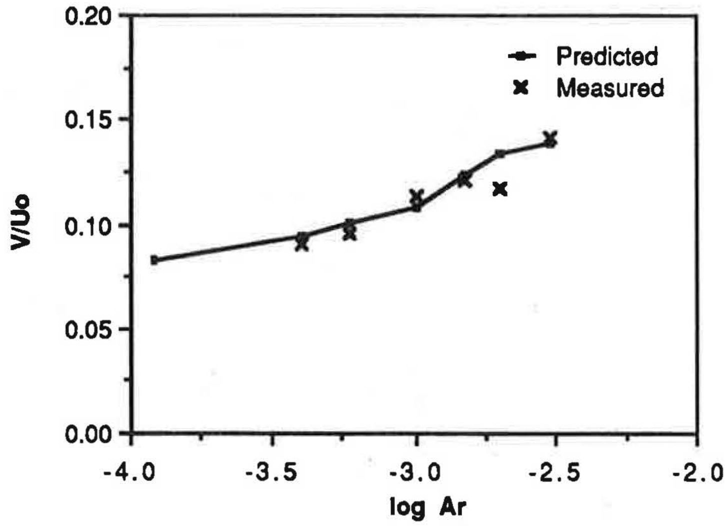

Fig.2 Effect of Archimedes number on the average velocity

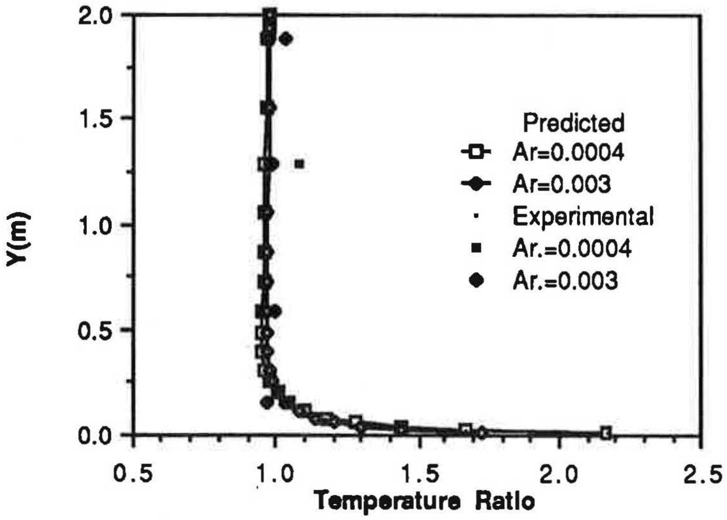

Fig.3 Temperature distribution in occupied zone for different Ar

CONCLUSIONS

The results from this study show that when modelling isothermal flows in a room, it is important to perform the model test at the same Re as in the prototype, since Re was found to influence the velocity in the occupied zone. In case of a reduced-scale model this means a supply velocity equal to that in the prototype divided by the sale factor S, ie a higher velocity.

In the case of non-isothermal flows the velocity distribution in the occupied zone is affected by both Re and Ar, but it has been found that it is more important to perform the model test at the same value of Ar as in the prototype when
$Ar > 1 \times 10^{-3}$ and to perform the model test at the same Re as in the prototype when $AR < 1 \times 10^{-3}$.

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