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AIR FLOW CHARACTERISTIC IN SCALE MODELS OF ROOM VENTILATION

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ABSTRACT

Improvement in methods of air flow pattern scale modelling in large enclosure requires above all, precising the conditions necessary in the model in order to maintain Reynolds number independence of the mean flow, as well as defining ways in which the flow turbulent structure could be simulated.

The paper presents the results of experimental analyses of air velocity fields in scale models in the range of Reynolds number 1850 to 98000. The field maps of air velocity mean value were tested. Turbulence energy spectra in the models flows were analysed at the corresponding points of similar systems. The analyses referred to the approximate similarity of air flow fields. Experiment results have been used to identify the threshold Reynolds number, which makes it possible to maintain approximate similarity of mean velocity distribution in the whole area of the flow pattern modelling. The tests show also that it is possible to maintain similarity of turbulence spectrum in scale models when a second threshold Reynolds number is exceeded.

KEYWORDS

Air flow pattern, Model experiments, Self-similarity

INTRODUCTION

The principles and methods of scale modelling in ventilation aerodynamics already have many year tradition. Scale model experiments are considered as wanted and useful tool in a ventilation design process especially of air distribution in large enclosure.

When testing air distribution in scale models, the flow patterns are visualized and temperature and air flow velocity are measured. It is assumed that similarity for the air mean velocity field can be fulfilled when flows in the real object and in its scale model are fully turbulent and Re-number independent. Such the assumption means that in a system of the modelled physical phenomena, the effect of the viscosity is neglected. It results then in approximate similitude and approximate modelling method.

Improvement in scale modelling methods requires, above all, precising the conditions necessary to maintain Reynolds number independence of the flow in the model, as well as characterizing conditions of the flow turbulent structure similarity. It might be required in some modelled ventilation cases, e.g. when predicting air change efficiency or characterizing irregularities of the air flow fields in a ventilated object which are caused by space limit in the room and flow instability of the ventilation system.

However, what does „fully turbulent flow" mean in practice? When turbulence developes at larger Re-number, the flow field becomes asymptotically similar and Re-number independent. Only when turbulence is developed, we find a degeneration of the Re-criterion (Szücs 1980). It becomes no longer valid and flows become self-modelling. Thus, a certain Re value ought to be assumed above which the turbulence of the flow may be considered sufficiently developed in the aspect of Re-number independence. Such the value is defined as threshold Reynolds number, Re_l (Mierzwiński et al. 1998, Kato et al. 1988). Therefore, in the approximate physical scale modelling method it is sufficient to fulfil the following similarity conditions on the full-scale object and (Ob) and its scale model (M):

$$Re_M > Re_l \quad Ar_M = Ar_{Ob} \quad Pr_M = Pr_{Ob} \quad (GrPr)_M > (GrPr)_l$$

Thus, only Ar number is left as the similarity criterion. Taking into account the equality of Archimedes numbers, velocity scale is calculated from the equation: $S_W = (S_L S_{\Delta T})^{0,5}$ where S_W, S_L, $S_{\Delta T}$ are velocity, leugth and temperature difference scales, resprectively.

Apparently, the assumption of the flow independence of Re-number limits the modelling area to the region where Ar criterion is fulfilled and Re_l number kinetically controls the boundary conditions.

In order to properly apply the method of approximate scale modelling in ventilating air distribution tests, the following are of essential importance:

- choice of threshold Re_l number, by which the error of the approximate modelling method, model construction dimensions and velocity measurement accuracy are affected
- good knowledge of ventilating flow structure evolution in models, necessary to decide whether turbulent flow, contributing to pollutant propagation and thermal comfort conditions in the room, can be modelled.

ANALYSIS OF MEAN FLOW SIMILARITY CONDITIONS IN MODELS

The experiments reported after Mierzwiński et al. [1998], included:

- determination of threshold Reynolds number, Re_l, in order to characterize the lower limit of the mean flow self modelling interval,
- tests of similarity of mean velocity distributions in the whole region of air flow pattern modelling in room.

In order to explain these problems, measurements were carried out to make comparatory analysis of the flow mean velocity fields possible:

- in one model, at different Re numbers and different supply velocities
- in models of different sizes at the same (or similar) Re numbers.

The tests were carried out in three similar scale models of a sports hall: small (1:10), medium (1:5) and large (1:1.175). Reynolds numbers varied from 1850 to 98000 and supply velocity varied from 1,5 to 15 m/s. Velocity distributions were measured in the plane including the axis of one of the supply openings. An eightchannel omnidirectional thermoanemometer was used for the air velocity measurements.

For the purpose of anemometric measurements of the air mean velocity in the model, the errors of mean velocity value estimation (5%) and averaging time necessary to get the required repeatability of the results were determined.

A method of graphical presentation of these fields was worked out (occuracy of 1%). The repeatability of the measurement results was verified for this method.

The test results are shown in the form of maps of normalized mean velocities, which can be compared to one another. Figures 1 and 2 show some selected cases illustrating the effect of the model size and the supply kinetic parameters. The comparatory analyses were based mainly on the supply through circular openings in all the models.

The measurements proved high sensitivity of the mean velocity distribution to the way in which boundary conditions were generated, namely:

- non-isothermal jet occurrence (warming in the fan)
- imprecise control of the velocity profile in the openings
- imprecise simultaneous equalizing and maintaing of the momentum stability in the supply jets
- use of slot diffusers or circular nozzles.

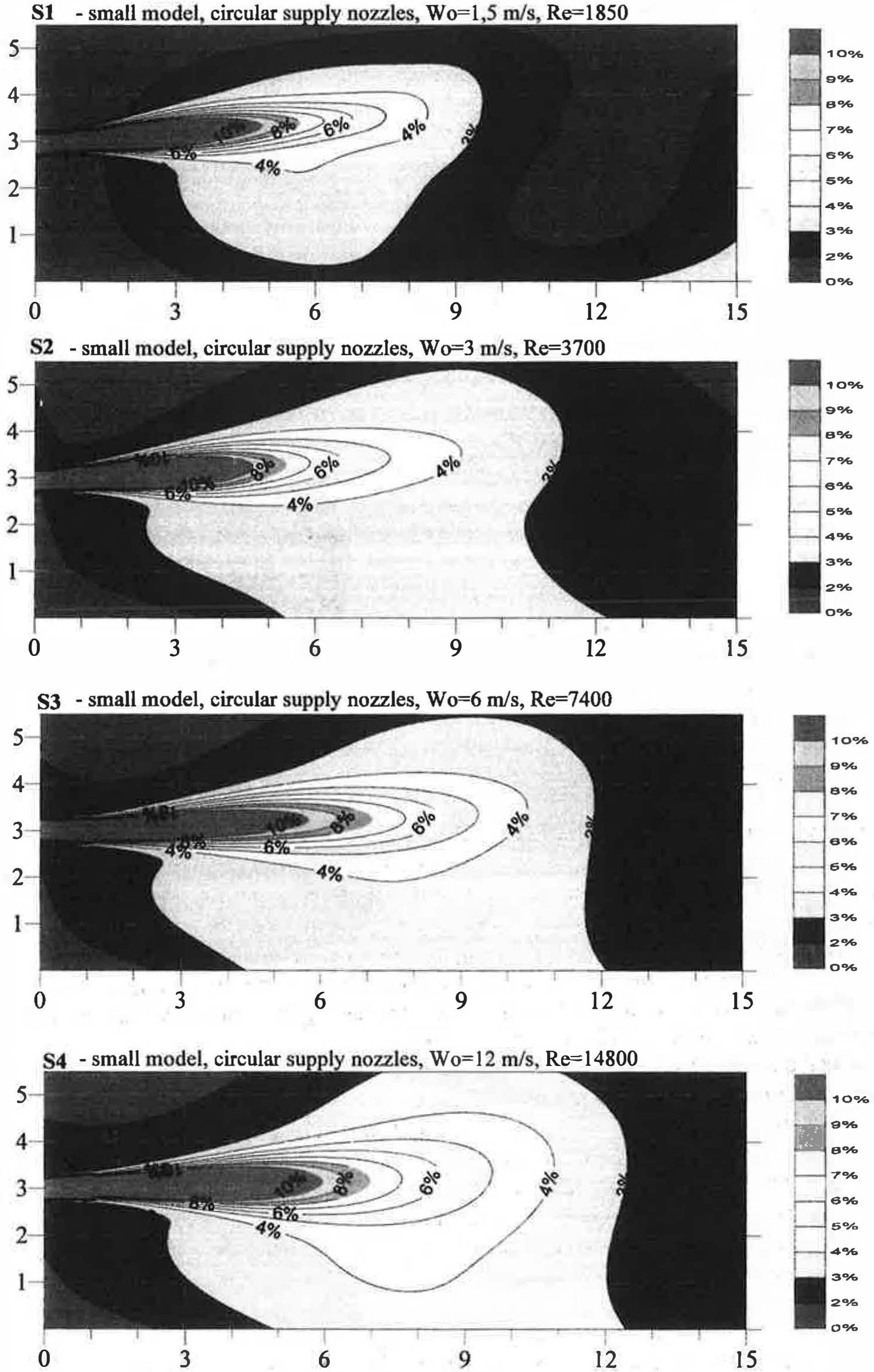

Figure 1. Maps of normalized mean velocities izolines in the small model at Re = 1850 to 14800, Wo = 1,5 to 12 m/s

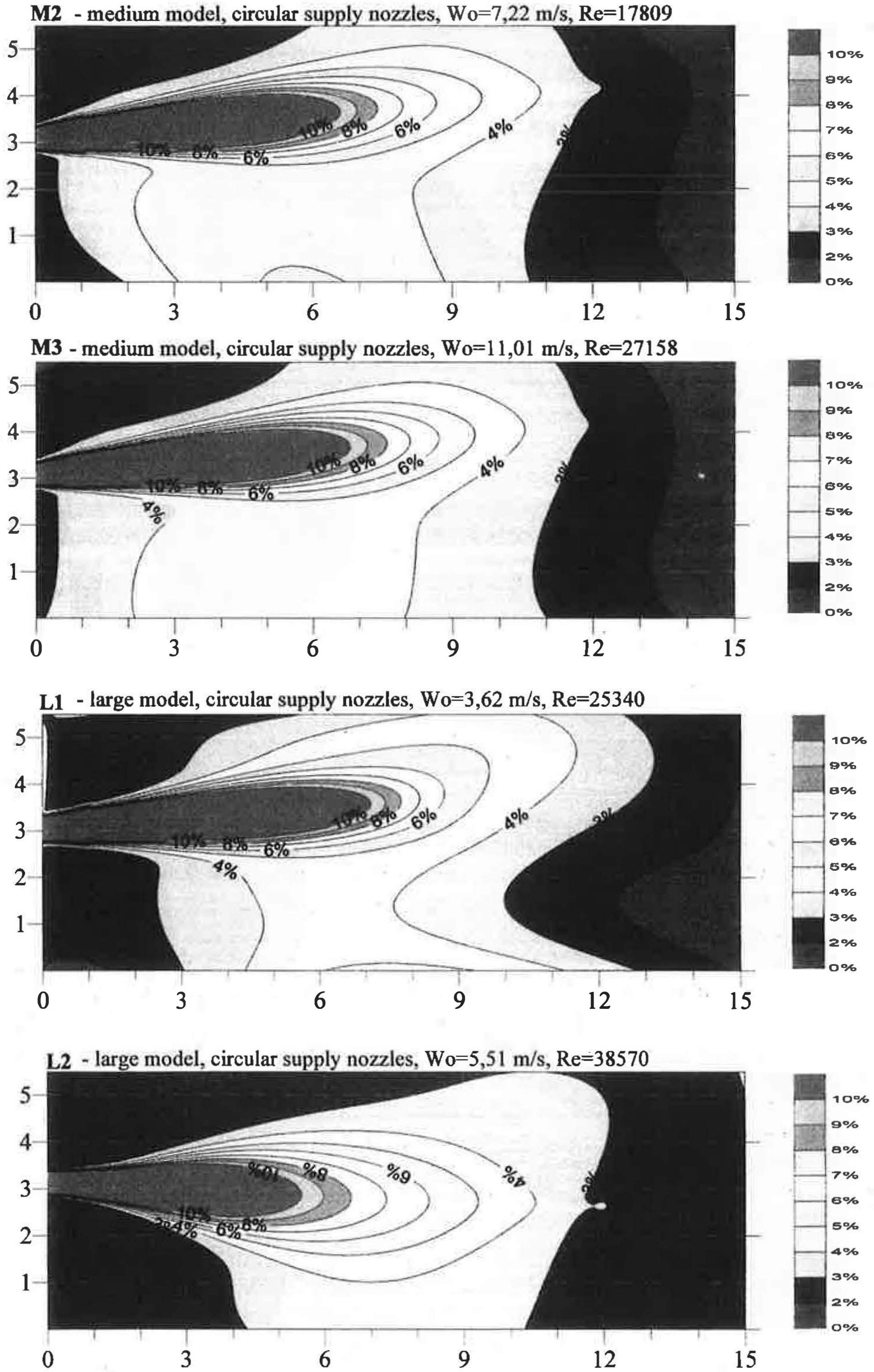

Figure 2. Maps of normalized mean velocities izolines in medium and large models at Re = 17809 to 38570, Wo = 3,62 to 11,01 m/s

When analysing the velocity maps in the separate models (shown in Figures 1 and 2) small (S), medium (M) and large (L), respectively, the following regularities can be observed:

1. At different Re numbers in the same model similarity of mean velocity distributions and the Re-number independence are observed, in respect both to the supply jet region and to secondary flow region. But the degree of the flow similarity varies:
   - at sufficiently high Re numbers, above 8 000-10 000, similarity may be defined as good,
   - at Re numbers decreasing from 8 000-3 500 similarity worsens gradually; discrepancies get apparent at Re numbers lower than 2 000, particularly in the secondary flow region.
2. Taking the above into account the threshold Re number value, Re_l may be assumed for approximate ventilation modelling (Figure 1) as Re_l= 4 000 to 2 000 depending on the required modelling accuracy.
3. When comparing the relevant mean velocity maps in the models of different sizes it may be concluded that:
   - there is good similarity of the mean flow at the same Re numbers (Re=idem) when velocity scale is $S_W=1/S_L$ (M_3 and L_1 compared)
   - similarity of the mean flow worsens at velocities lower than those resulting from the condition Re=idem; it worsens when velocity scales decrease which can be observed when comparing the cases:

     $S_3+M_2+L_2$ where W=idem

     S_1+L_1 and S_3+M_2 where $S_W=S_L^{0,5}$, Ar=idem as in approximate modelling.

Taking the above into account, the approximate physical scale modelling may be therefore considered as a self-modelling process with respect to Reynolds number. In the experiments the kinetic boundary conditions should be particularly careful simulated since the simulation replaces the declining criterion Re=idem.

TURBULENCE SIMILARITY IN PHYSICAL SCALE MODELS OF VENTILATION

The analysis of velocity fluctuation frequency spectrum, gives information about the spatial structure and time run of the turbulence evolution. The turbulent movement is presented as superposition of eddies of various dimensions and time scales.

Relatively little is known about the turbulence structure of ventilating air flows in rooms. The results of measurement of the spectrum and turbulence scales in different points of the ventilated room are presented by Etheridge and Sandberg (1996) and by Finkelstein et al. (1996). It was found that turbulent velocity fluctuations in the occupied zone occur only in the range of frequencies up to 2 Hz. There is lack of publications including more detailed analysis. The problem of the air flow turbulence similarity in ventilated rooms is hardly recognized. Only Soehrich (1979) presented some results of turbulent shear stress measurement in scale models of a ventilated room and ascertained that the stresses get stabilized when Reynolds number higher than 10 000.

In the present measurements a constant temperature hot wire thermoanemometer was used. The signal was sampled for 10 min with the sampling frequency 60 Hz. The measurements were made in 2 models of scales 1:5 and 1:1.75. The air was supplied with different velocities varying from 3 to 15 m/s. The RMS value of velocity fluctuations W_{ef}^*, and spectral function of turbulence, E(f), were determined from the analysis of instantaneous velocity values.

The measure of total turbulence energy is either RMS value or velocity fluctuation variance. Similarity may be analysed by assuming the mean velocity value in the supply opening, W_o, as scale velocity and the supply opening diameter, d_o, as scale linear dimension. Similarity of total turbulence energy was estimated on the basis of the ratio W_{ef}^*/W_o, depending on Reynolds number. The results are shown in Figure 3.

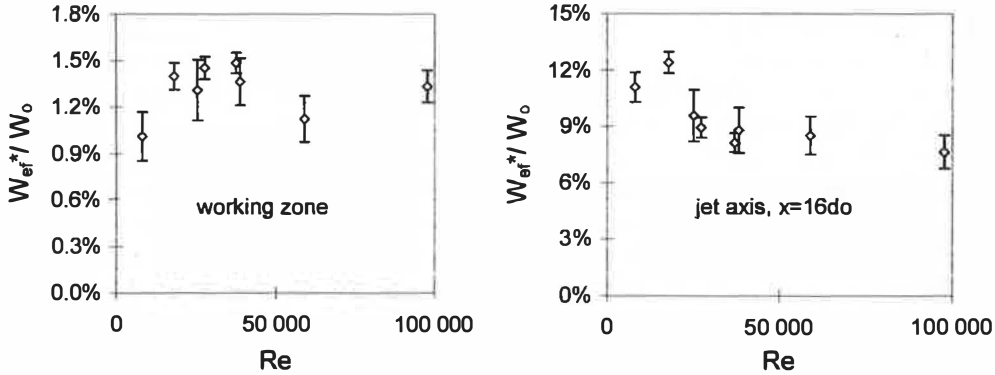

Figure 3. Similarity of total turbulence energy in selected points of the ventilated room

It is observed that for Reynolds numbers from the range tested i.e. 8 000 - 98 000 the ratio W_{ef}^{*}/W_o changes within the range 1÷1.5%, in the working zone whereas in the supply jet, at the distance from the outlet $x=16d_o$ in the range 7.6-12.4%. It means that in the abovementioned Reynolds number range similarity of the total turbulence energy occurs with the accuracy of the order of ±25%. Apparently the ratio W_{ef}^{*}/W_o value increases in the supply jet for Re<20 000 and decreases in the working zone for Re<10 000. The reasons for such changes may be explained when observing the turbulence spectrum in Figure 4.

Similarity of turbulence spectrum was analysed after having normalised the power spectral density function of velocity fluctuation E(f). The spectrum E(f) was divided by $W_o^2\tau_o$ i.e. by $W_o d_o$, dimensionless frequency was introduced by multiplying frequency by the time scale $\tau_o=d_o/W_o$. The results obtained show that for Re>20 000 similarity of turbulence spectrum occurs within the whole frequency range. For Re< 20 000 it may be observed that large scale turbulent eddies appear in the supply jet and the spectrum gets limited in the working zone. The lack of turbulence spectrum similarity for Re< 20 000 may be explained by more intense effect of secondary flows on the supply jet and by limiting the cascade transformation of large-scale eddies to dissipating structure in the working zone.

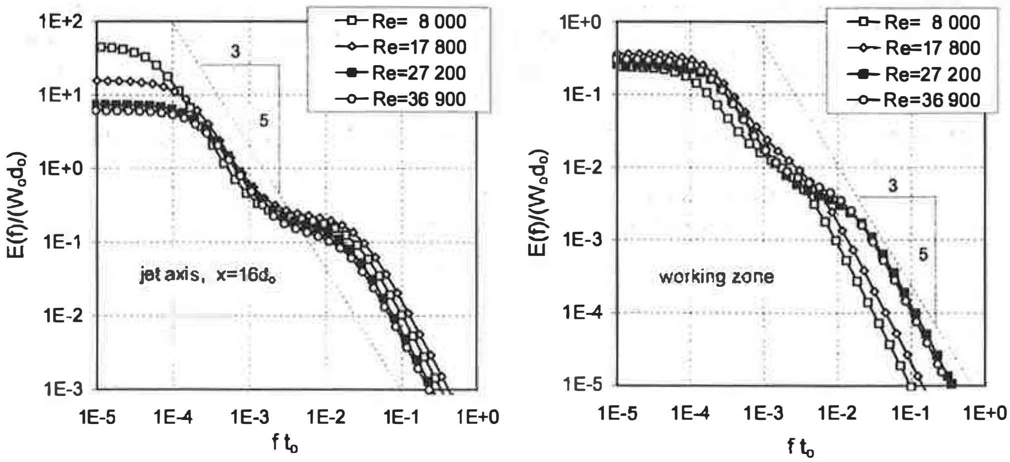

Figure 4. Normalized turbulence spectrum in a supply jet and working zone of the ventilated room scale model

CONCLUSIONS

1. The threshold number Re_l within the limits 4 000 to 2 000 makes it possible to construct a physical scale model of ventilation in which approximate similarity of mean velocity distributions can be maintained in the whole area of the ventilating air flow pattern modelling, i.e. both in supply jets and in secondary flows.

2. The tests of turbulence structure reveal complexity and superposition of the flow phenomena and wide range of turbulence scales of ventilation flows. They show that it is possible to maintain similarity of turbulence spectrum in ventilation models when a second threshold Reynolds number, Re_{l2}, is exceeded, the range of which can be defined as 10 000 to 20 000, depending on the required accuracy of the model analyses.

3. The error of the approximate physical scale modelling method decreases when the scale model dimensions and flow parameters approach the conditions in the real object. Thus, it is advisable to apply the partial modelling method while properly selecting the range and the accuracy of the model analyses.

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