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PHYSICAL EXPERIMENT IN AIR DISTRIBUTION RESEARCH

Summary. Air distribution is a complex flow process that is difficult to predict owing to many aerodynamical effects occurring in various geometrical conditions in ventilated rooms. The paper presents, on the background of flow phenomena analysis, a part of physical experiment in the realization of the research on air distribution predicting, including the necessary scope of tests in situ and the possibilities of physical modelling. The required manner is determined, in which mathematical modelling and physical experiment ought to co-operate together. The paper is illustrated with examples of tests.

1. Introduction

Ventilation systems in various objects are to fulfill different tasks within air distribution process. They may operate with various air amounts, from several hundred to several million m^3/h and consume or transport heat energy varying from several dozen kW to several MW in one object. Thus, various problems and difficulties may arise when air motion is predicted. The idea of that can be given when some different ventilation cases are considered in this aspect e.g. ventilation of office rooms, a department store, paper-making machine halls, a steal plant, a rolling mill or greenhouses.

In the above mentioned objects, generally, air distribution in large spaces is considered and those problems are the subject of the paper. Variety of the objects and their destination contributes to significant differentiation of geometrical ratios, thermal loads and mutual effects of aerodynamical factors in ventilation processes. Therefore, air distribution in ventilated spaces is a process that consists of often unsteady and sometimes also unstable flows, deforming one another. Thus, air distribution forming, according to the aims assumed in advance, is difficult to predict and in particular, to simulate mathematically.

Ventilation engineering requires desing-friendly methods of air distribution predicting, just those with a complex approach to the element of such the processes in complicated ventilation cases that entail large investment and energy consumption expenses.

The purpose of scientific research within this field ought to be finding a possibly short way to work out such methods. This problem is worth discussing, all the more so as larger and larger groups of specialists have been getting engaged in it

Problems of measurement methods and equipment as well as of automation and computerization of tests are not analyzed in the paper, in consideration of its volume.

2. Analysis of flow phenomena of air distribution

Air distribution in ventilated rooms is a flow process which consists of several aerodynamical factors, such as supply jets, exhaust flows, convective plumes, secondary flows, flows in boundary regions, infiltration and flows aruound bodies.

From the point of view of aerodynamics turbulent flows are mainly dealt with. Extensive problems of turbulence are the reason that the following kinds of flows may be separated from the above mentioned aerodynamical elements:

- Flows which can be adapted to similarity principles and mathematically described.
- Flows which are difficult to describe as the result of action of a complex system of aerodynamical forces and geometrical conditione or their mathematical identification still does not pay.

It is related, among others, to difficulties in describing the flow phenomena summing up and in predicting what is the share and the activity level of viscosity in general image of turbulent flow. As a rule those flows are transient and sometimes they may be unstable as well.

However, just those difficult to describe flow phenomena, in secondary and confined flow regions, usually determine the quality and the efficiency of a ventilation process. Complexity of flows in air distribution process is illustrated in fig. 1.

From the point of view of ventilation the task of air distribution consists in maintaining required air parameters in the room. Therefore, among the aerodynamical factors mentioned above one may separate:

- Forming flows that should be used to form air parameter fields, e.g. supply jets and powerful convective plumes
- Disturbing flows that must be overcome durign a ventilation process, e.g. weak convective plumes, infiltration.

- Strong dependence of ventilation flow properties on geometrical conditions of the room and its equipment that individualizes and complicates air distribution.

Fig. 1. Pictorial presentation of air flows in a ventilated space

Rys. 1. Obrazowe przedstawienie rozpływu powietrza w przestrzeni wentylowanej

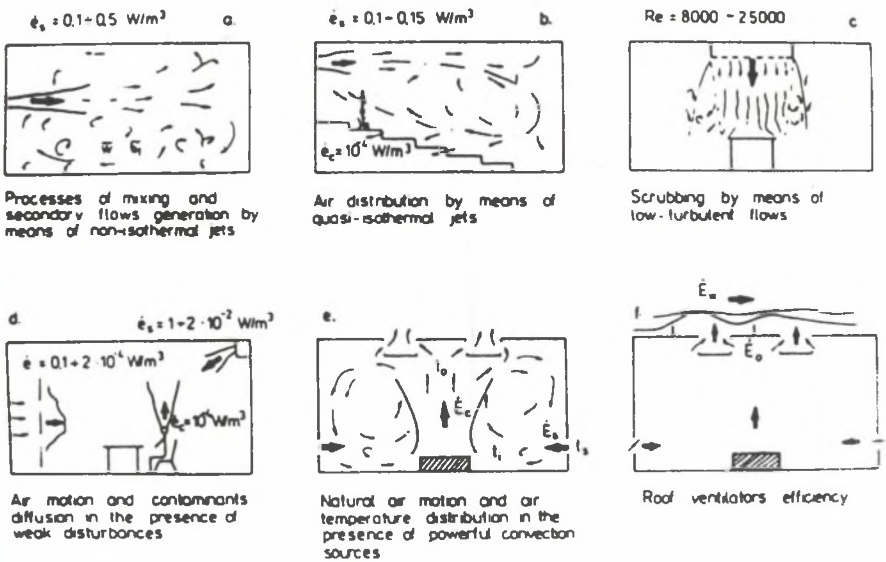

Fig. 2. Some characteristic air distribution processes

Rys. 2. Pewne charakterystyczne procesy rozdziału powietrza

a) procesy mieszania i generowania przepływów wtórnych za pomocą strug nieizometrycznych, b) rozdział powietrza za pomocą strug quasi-izometrycznych, d) odpylanie za pomocą przepływów o małej turbulencji, d) ruch powietrza i dyfuzja zanieczyszczeń w obecności słabych zakłóceń, e) naturalny ruch powietrza i rozkład temperatur powietrza w obecności silnych źródeł konwekcji, f) skuteczność wywietrzników dachowych

When considering ventilation, one may also separate some simple cases of air distribution in which it is still relatively easy to determine the part and the needed properties of aerodynamical factors e.g. the following (see fig. 2):

a) aerodynamical mixing and secondary flows generation by means of non-isothermal jets,
b) air distribution in a room by means of quasi-isothermal jets in the presence of weak convection sources,
c) zone scrubbing by means of low-turbulent flows,
d) air motion in the presence of weak disturbances,
e) natural air motion and air temperature distribution in the presence of powerful convection sources,
f) roof ventilators efficiency.

3. Setting the course for air distribution research

Ability to predict air motion in ventilated rooms may be acquired in two ways, namely be means of:

- mathematical modelling and simulation,
- physical experiment.

When the progress of science and technology in this field is observed one must conclude that neither of those ways should be treated as individual and self-sufficient. Fig. 3 illustrates the parts and mutual relations between experiment and mathematical analyses in acquiring, in a possibly short way, practical abilities to form air distribution for real geometrical conditions in ventilated rooms and for real aerodynamical disturbances.

Mathematical analyses of flow phenomena are based on the simulation procedure of a virtual system. Mathematical description of the system ought to be based on its physical identification.

In experimental aerodynamics, experiments in real objects, in situ, are sometimes tiresome and physical model tests often refer to half-empirical methods. Mathematical models are then helpful as skeleton that can be corrected and filled in with the substance in order to create a proper image of the phenomenon.

Thanks to the development of computers there is a strong and justified tendence to simulate phenomena on the numerical way in applied aerodynamics and optimization analyses and therefore to reduce the part of experiment. However, mathematical models of air distribution known so far, refer only to the elements and simple cases of the process. Thus, when testing processes of air distribution in rooms one may choose the methods of experiment, modelling and simulation in different ways according to one's knowledge, experience and the equipment in possession. The parts of analysis and experiment in the assumed course of the research ought to be balanced in particular situations in order to avoid both result errors or excessive costs. One should also take into account whether it is possible to obtain results practically useful in ventilation objects.

4. The part of experiments

Experiments are presently unavoidable for (see fig. 3):

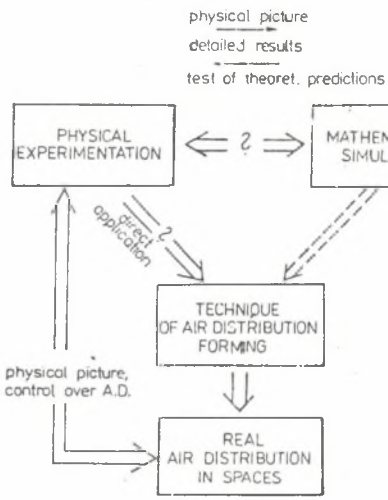

Fig. 3. Methods of air distribution research
Rys. 3. Metody badań rozdziału powietrza

- Identification of physical image of air distribution process including its individual disturbances and other conditions.
- Verifying and completing mathematical modesl within half-empirical equations and parameter distribution in boundary conditions.

The necessary range of physical experiment in the research on air distribution is illustrated in detail in fig. 4.

On the basis of flow problems analysis (presented in the chapter 2) one can separate:

- Tests of natural objects, in situ
- Laboratory tests, in particular physical modelling
- The choice of methods and measurement apparatus

It is worth pointing out that the research experience and measurement equipment play essential part both in the approach and in the experiment results. In consideration of the paper volume the problems of methods and measurement equipment will not be discussed here.

5. Tests in real objects, in situ

The tests include (see fig. 4):

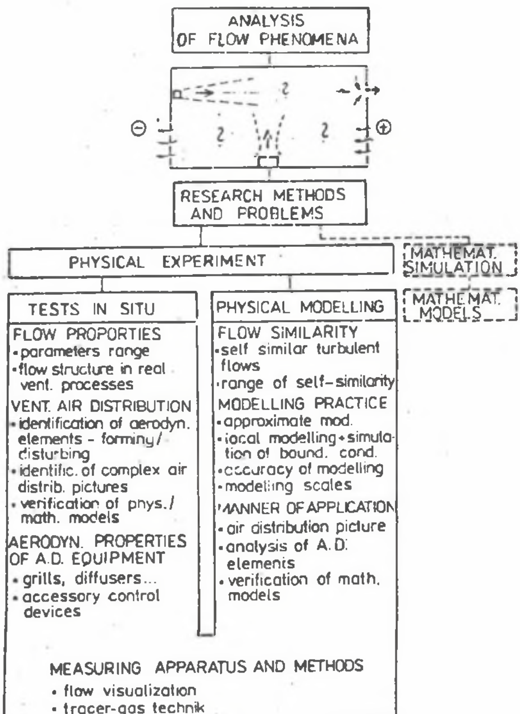

Fig. 4. Physical experiment on air distribution in spaces

Rys. 4. Eksperyment fizykalny w badaniach rozdziału powietrza w przestrzeniach

- Tests of real flow properties, contributing to air distribution process in a room
- Observations of general image of air motion and identification of individual characteristic elements of air distribution process
- Tests of aerodynamical characteristics of air distribution equipment

Discernement and minuteness of detail of flow phenomena identification in natural conditions ought to be confined to the necessary range since such the tests require a real object very similar to the one being analysed. It is not easy to generalize such the cases. Therefore, one should make use of various measurement methods combining experiment in situ with laboratory tests.

5.1. Flow properies

Flows related to ventilating air distribution show characteristic range of velocities and turbulence intensity.

We are interested in flows, velocities of which are lower than 10 m/s while particular attention is given to velocities lower than 1 m/s in regard to measurement difficulties within this field and to interpretation of results at high turbulence intensity as well as to the importance of those two parameters for the sensation of thermal conditions by a man. This range of parameters requires specific methods and measurement equipment, sometimes individual in relation to the equipment used in other fields of applied aerodynamics. Results of velocity measurements in highly turbulent flows also require their proper interpretation. These problems [16] are not included in the paper.

Idenfification of real mean values of parameters and their distributions as well as dominating factors in turbulent flow structure in various ventilation processes is necessary to gather data for mathematical and physical models of air motion in ventilated rooms.

Some examples:

Measurements of parameter distribution in air jets close to supply openings and to partition surfaces, performed in order to formulate boundary conditions for numerical calculation, significantly improve calculation results of the flow image in the whole room.

In parameter transport equations, resulting from semi-empirical theory of turbulence $k - \varepsilon$, so called coefficients C_1 and Prandtl numbers Pr_t, Pr_k, Pr , are introduced, including in their description averaged products of air parameter pulsations. Those quantities ought to be determined/experimentally verified since they are the features of air motion structure, individual for each case. It requires, however, a difficult experiment. Therefore, those quantities have been assumed for calculation and they are different for different authors.

Experimental identification of parameter distribution and turbulence structure of a convective plume over an extensive heat source in one of the initial cross-sections of its self-similarity of the mean flow zone, makes it possible to calculate further development of the plume by means of the integral method [8, 9].

5.2. Air motion picture

In tests IN SITU, the picture of air motion in a ventilated room is used to:

- Show the real air distribution and the efficiency of air exchange related to it,
- Identify the factors of air distribution process that are characteristic of the case considered, particularly the properties of aerodynamical disturbances.

The image of air motion in a ventilated room may be presented:

- Pictorially, as the presentation of various visualization techniques
- In detail, as air parameter field (isothermal lines, lines of equal velocity etc. measured in a certain measurment point system)
- Intermediate, as a visual image of air flows in which parameter values are placed in characteristic positions of the space observed.

The way and the accuracy of such the tests ought to depend on their purpose and on the further use of the results, e.g.:

- Pictorial presentation is sufficient to recognize air distribution qualitatively in complicated cases as well as to spot out the importance of the effect of the process characteristic elements.
- Detailed presentation, particularly presentation treated fragmentarily, difficult to realize, may be applied to mathematical verification of models and to preliminary identification of disturbing factors.
- Intermediate way is commonly applied to determine ventilation balances, efficiency of air exchange, efficiency of general ventilation, local exhausts and conditions at work stands as well as to define the range and the way of physical modelling.

Intermediate picture of air distribution in a finishing hall is illustrated in fig. 5. It shows simplified velocity and temperature distributions, zones of heating equipment effect and of the effect of air flowing through open gates. The range of the gate effect is given at different periods of time after its opening.

5.3. Properties of air diffusion equipment

The shape and the accesory devices of ventilation supply-air openings condition the initial aerodynamical properties of air jets within the range of:

- flow direction,
- velocity profile,
- flow structure.

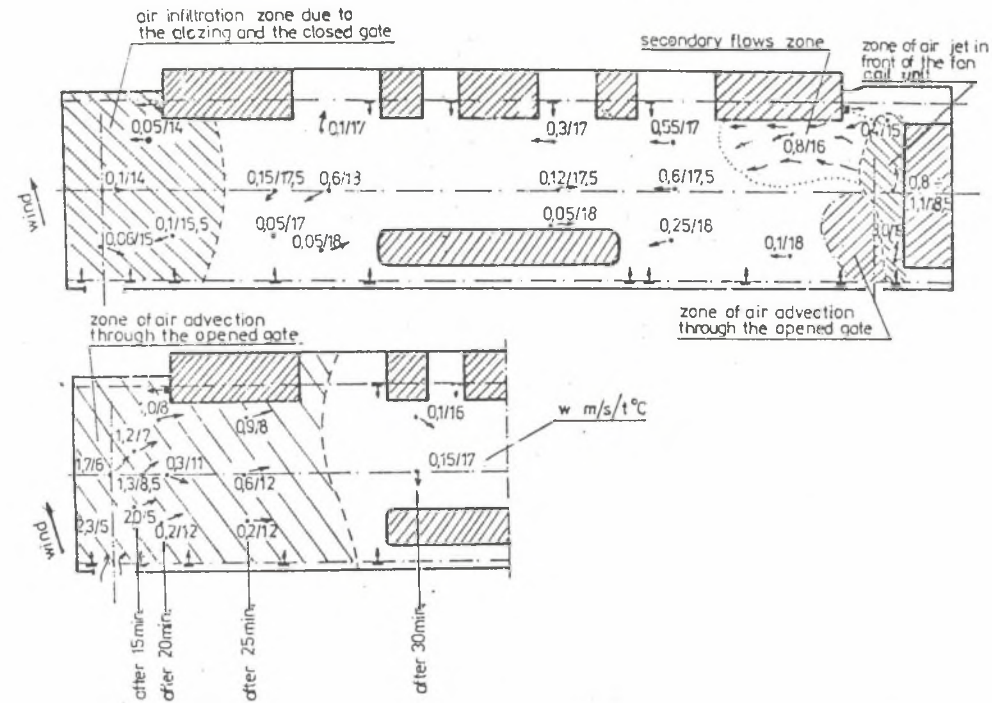

Fig. 5. Air velocity and temperature distribution at the level of 1,5 m in a finishing hall, when $t_{out} = 4^oC$

Rys. 5. Rozkład prędkości i temperatury powietrza na wysokości 1,5 m w hali wykończalniczej przy temperaturze zew. = $+4^oC$

The part of supply openings in air distribution forming is evident. There are several publications and firms' catalogues that present design conceptions and characteristics of such openings.

Some results of tests illustrating the ways in which the initial structure of supply jet motion is generated are presented in the dissertation [10] as crosswise profiles of standard deviation of velocity longitudinal fluctuations at the distance x/d = 1 from the supply opening equipped in six different ways. It is worth pointing out that the laminar core of the jet has been effectively removed by means of a trubulizer placed inside the supply duct.

The work [11] presents possibilities to obtain a quasi-laminar air flow of negligible mixing inside and at the external boundaries when Re = = 5000-20000 in relation to the parameters of the whole supply opening. The jet has been produced by means of equipping the opening with a microporous layer.

6. Physical modelling

Thanks to physical modelling it is possible to imitate experimentally and to analyse air distribution processes. The method of the extensively applied experiment is based on similarity rules which, however, in complex cases of thermal-flow processes cannot be fully fulfilled. Therefore, various simplifications and replacing simulations are introduced but they influence the results accuracy.

Without going into details of physical model tests and the theory of similarity it is worth mentioning the following aspects of the tests applied:

- Similarity of flows in air distribution processes
- Physical modelling realised in practice
- Possibilities of application.

6.1. Similarity of flows

In the case of room ventilation the modelled process comprises forced and convective flows of air as well as heat transport on the way of convection and radiation. Therefore, the conditions of mechanical and thermal similarity ought to be fulfilled. When modelling ventilation processes in the steady state, the following defining similarity criteria may be assumed for the conditions of mechanical and thermal similarity. Comparison of the expressions for Re, Ar and Gr - numbers shows apparently that those three criteria cannot be satisfied at the same time in the orginal, full-size system and in its small-scale model.

As it is proved experimentally, in turbulent flow when $Re > 10^5$, the mean motion and the interacting larger element of the turbulence settle into a developing equilibrium in which they can expand without changing their essential character. Such patterns of mean flow and turbulence are said to be self-preserving [5] and Reynolds-number-idependent. Hence, velocity profiles and flow patterns are self-similar [5]. But when viscosity influences the mean flow, the larger scales are not independent of Re. Air flows in ventilated rooms generally are said to be fully turbulent. However, in models, as their geometrical dimensions are decreased the part of large size vortices in turbulent flows gradually decreases as well. Thus the effect of viscosity gradually increases.

In order to reduce the cost of tests we are trying to make small-scale models as small as possible. Then, however, at the simplified modelling technique that is applied, Reynolds number would decrease much below 10^5. We tried to answer the question: at what the least boundary Re - number the above-mentioned self-preservation as well as Re - number independence of the turbulent flow may occur.

The results of jet tests in models A, B, C, D in relation of sizes: A : B : C : D = 1 : 0,5 : 0,25 : 0,2, are shown in fig. 6 [10]. The results have been put into the following formulations as functions of Re - number:

- mean velocity profile $(\bar{w}_x/\bar{w}_{xo})_{0,5} = f(Re)$
- turbulence intensity $\varepsilon_x = f(Re)$
- turbulent and laminar shear stresses ratio $\tau_b/\tau_l = f(Re)$.

Apparently, quasi-stabilization of the mean velocity profiles in jets occurs already when Re = 2000-4000 depending on the size of the model whereas quasi-stabilization of turbulence intensities and of shear stresses occur only above Re = 4000 and Re = 6000-8000, respectively.

The case of self-similarity of secondary flows and flows in aerodynamical mixing areas is not evident. One should expect that the smallest elements of turbulence would have greater part in those regions and at the same time, as the length scale of the model is reduced, the part of the smallest frequencies gradually vanishes therefore the part of the intermediate elements increases. Measurements of mean velocity profiles in a cross-section of the model show [10] that the accuracy of velocity distribution modelling in secondary flows will be less than in jets.

When natural convection phenomenon is modelled under ventilation conditions, the turbulent convection flow occurs when $GrPr > 10^6$ to $3{,}3 \cdot 10$ depending on the heat source shape. Under such the conditions the convective heat-transfer coefficient does not depend on the heat source dimension and thus it does not depend on the model length scale.

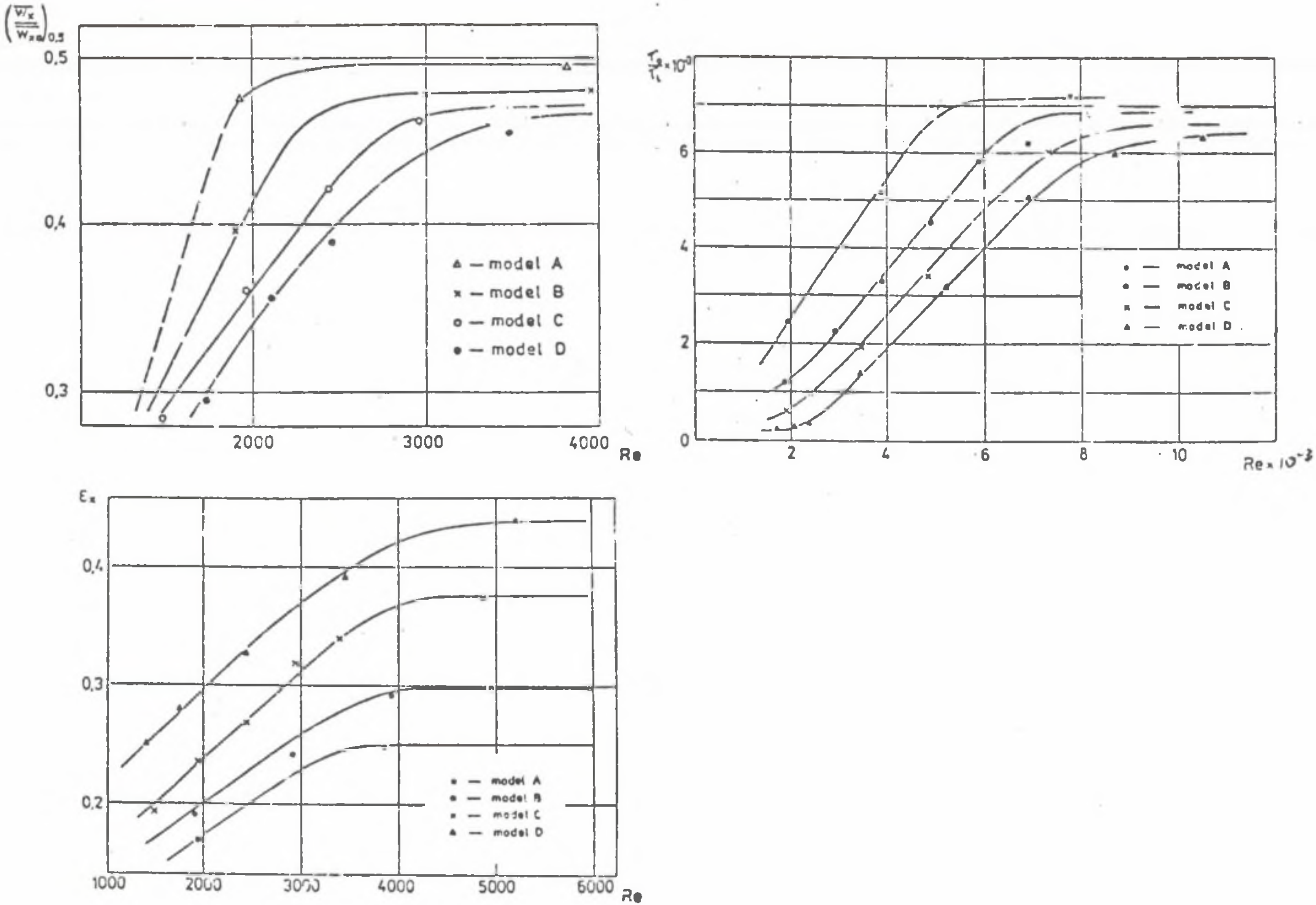

Fig. 6. Re number independence of flow parameters in jets in models of different sizes [10]
Rys. 6. Niezależność liczby Re od parametrów przepływu w strugach i w modelach o różnej wielkości

6.2. Physical modelling in practice

A series of interesting ways has been worked out [4, to avoid difficulty in satisfying the set of similarity criteria.

So-called approximate physical modelling [1, 2, 6] is based on the Re and Gr numbers independence of turbulence and on the quasi-self-similarity of mean velocity profiles. Therefore, for approximate modelling of the process in which forced flow and natural convection occur it is sufficient to maintain:

$$Ar = idem \qquad Re > Re_b \qquad Gr\ Pr > (Gr\ Pr)_b$$

In some instances of the modelling it may be dificult to maintian the similarity of velocity fields at the boundary of the tested region e.g. when model represents only a part of the real object. There is also a problem of the modelling scale of temperature difference wall-fluid. Then, it is necessary to confine the model observation region to those places in which the tested process is subject to similarity contions. The boundary conditions of the tested region, deformed in the model, may be also put right by means of physical simulation of aerodynamical actions and heat fluxes.

Therefore, the more the model geometry and flow parameters are similar to those of natural object the more reliable the results of tests in small-scale models are. Sufficiently good results, the accuracy of which is from several to about a dozen per cent, are achieved at the model linear scale up to about 1:15 when testing ventilating flows in rooms or ventilating equipment [2, 13].

The problem of model test accuracy should be treated with a sense of reality in the light of the aim and the application of such tests.

In the case of tests of fundamentary character one oguht to maintain high requirements in reference to quantitative results and to the similarity of flow phenomena.

In the case of applied research it is usually more important to avoid significant errors in the choice of general conception of air distribution than to get a good accuracy in details that are subject to stochastic changes, characteristic in ventilation objects.

Physical modelling may be very useful in the research of both kinds, but only at the proper approach to experiment. Attention should be given to:

- The dependence of the similarity of mean parameter distribution and the flow structure on the scale of the model
- Conscientiousness in the choice of properties of aerodynamical factors which influence air distribution process in a tested space
- Conscientiousness of physical simulation of boundary conditions at local physical modelling.

It is also worth taking into account that for many ventilation cases we have no alternative method that would enable us to get better results.

6.3. Possibilities of application

Some examples chosen from various possibilities of physical modelling application in air distribution tests are presented below:

a. Fig. 7 [12] presents qualitative observations of air distribution in a steel plant, taking into account spatial location and power of

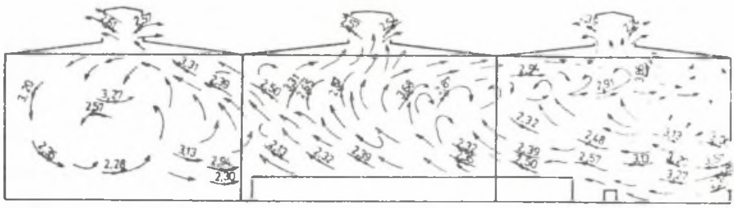

Fig. 7. Air distribution picture in a steel plant
Rys. 7. Obraz rozdziału powietrza w stalowni

sources of aerodynamical influences connected with parameter measurements in characteristic points (intermediate method, chapter 5.2). Such the tests make it possible to analyse some ventilation conceptions and the choice of the proper one, to determine the values of parameter simplexes and gradients, the range of jets and drifting motion of air etc. - for ventilation design needs.

b. Papers [14, 17] and fig. 2 present the results of detailed, quantitative analysis of air distribution process carried out in a fragmentary model of large geometrical scale, taking into account physical features of the process, rules of physical experiment carrying out and the results estimation. The purpose of such the teste is to work out design methods of air distribution and estimation of the obtained results quality. Paper [14] presents test results of the history of air distribution efficiency. Paper [17] presents the results of statistic analysis of air velocity and temperature distributions in the working zone, used to work out design instructions for warm air heating. Fig. 2a,b,d presents data on kinetic energy of supply jets, $\dot{e}_s$, needed to obtain the required air distribution in ventilation systems shown systematically.

c. Fig. 8 [16] shows some data referring to the numerical model verification by means of measurement of air parameter fields carried out in physical model of a swimming - pool in scale 1:1 when boundary conditions are taken into account in detail.

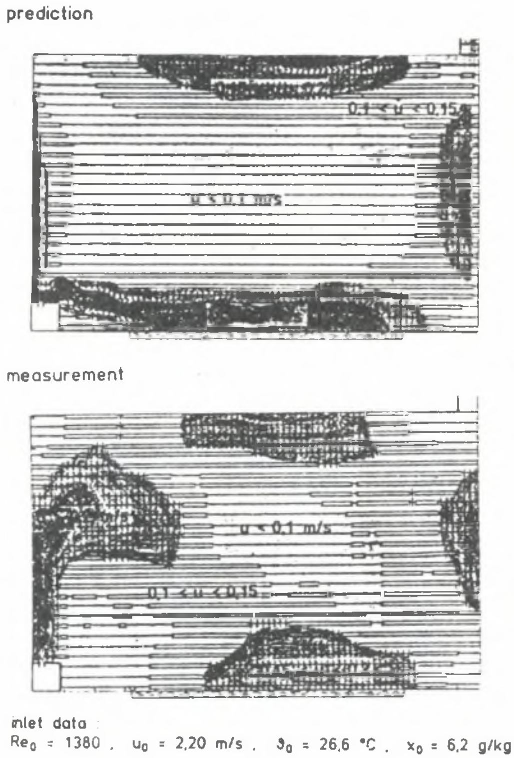

Fig. 8. Velocity distribution - comparison between prediction and measurement [15]

Rys. 8. Rozkład prędkości - porównanie rozkładu przewidzianego z zamierzonym

7. Conclusions

1. It is necessary to increase the possibilities to predict ventilation air distribution, in aerodynamically and geometrically complicated cases, particularly when substantial costs of building and energy consuption are related to the ventilation efficiency.

2. Such the cases may be solved on the way of physical experiment but sometimes it is worth paying attention to the fact that such the experimental research is time-and costs-consuming.

3. Labour consumption and costs of experiment in studies on air distribution depend on the range, approach and methods of laboratory and in situ tests. Specialization, the choice of equipment, automatation and

computerization of test may advance the experiment, facilitate it and realize it with the required accuracy, according to the needs.

4. Numerical prediction of air distribution has included simple cases, that has not so far been close to the range of real demands of ventilation engineering.

5. As numerical research on air distribution progresses, the range of physical experiment must be changed, making use of its necessary part in identification of flow phenomena of air distribution as well as in verification of mathematical models within the model conceptions and their empirical completing.

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EKSPERYMENT FIZYKALNY W BADANIACH ROZDZIAŁU POWIETRZA

S t r e s z c z e n i e

Rozdział powietrza jest złożonym procesem przepływowym, trudnym do przewidzenia ze względu na wiele oddziaływań aerodynamicznych występujących w różnych warunkach geometrycznych pomieszczeń wentylowanych. Na tle analizy zjawisk przepływowych przedstawiono w referacie rolę eksperymentu w realizacji prac badawczych dotyczących przewidywania rozdziału powietrza, łącznie z koniecznym zakresem badań w obiektach naturalnych, "in situ" oraz z możliwościami modelowania fizykalnego. Określono wymagany sposób w jaki modelowanie matematyczne i eksperyment fizykalny powinny ze sobą współpracować. Referat zilustrowano przykładami badań eksperymentalnych.

ФИЗИЧЕСКИЙ ЭКСПЕРИМЕНТ В ИССЛЕДОВАНИЯХ РАСПРЕДЕЛЕНИЯ ВОЗДУХА

Р е з ю м е

Распределение воздуха - это сложный проточный процесс, который трудно предусмотреть из-за многих аэродинамических влияний в разных геометрических условиях вентилированных помещений. В настоящей работе на фоне анализа проточных явлений указана роль эксперимента в осуществлении исследовательских работ, касающихся предусмотрения распределения воздуха вместе с необходимым объёмом

исследований в натуральных объектах и возможностями физического моделирования. Определено способ, по которому математическое моделирование и физический эксперимент должны содействовать.

В настоящей работе помещены примеры экспериментальных исследований.