PROGRESS AND TRENDS IN AIR INFILTRATION AND VENTILATION RESEARCH

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Paper 10

AIRFLOW SIMULATION TECHNIQUES - PROGRESS AND TRENDS

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SYNOPSIS

The paper describes the development in airflow simulations in rooms. The research is, as other areas of flow research, influenced by the decreasing cost of computation which seems to indicate an increased use of airflow simulation in the coming years.

It is shown that velocity and temperature distribution can be predicted in small rooms of simple geometry as well as in large areas with a complicated geometry, such as theatres, atriums and covered shopping centres. It is also possible to predict variables which are rather difficult to measure as contaminant and humidity concentration, local age and purging flow rate, heat transfer coefficients, etc.

Airflow simulation has been used for the prediction of air movement in mixing ventilation, and new research shows that it might also be used for predicting air distribution in displacement ventilation.

The paper shows that some development work is necessary to give practical descriptions of air terminal devices. It also shows that it may be necessary to develop a turbulent model which deals with low turbulent flow.

LIST OF SYMBOLS

Ar	Archimedes' number
c_{oc}	Mean concentration in the occupied zone
c_R	Concentration in return opening
h	Slot height of air terminal device
H	Height of room
k	Turbulent kinetic energy
L	Length of room
n	Air change rate
Re	Reynolds number
T	Air temperature
T_o	Supply temperature
T_{oc}	Mean temperature in the occupied zone

T_R	Return temperature
u	Mean velocity
u_o	Supply velocity
u_{tot}	Mean velocity in vertical plane
u_{rm}	Maximum velocity in the occupied zone
u', v' and w'	Velocity fluctuations in the three coordinate directions
y	Vertical coordinate
Δt^*	Dimensionless time step
ε	Ventilation efficiency
ϵ	Dissipation of turbulent kinetic energy

1. INTRODUCTION

The ventilation of rooms may be achieved by different types of air distribution systems. A commonly used system is a mixing system where inlet air is supplied from diffusers in the wall or in the ceiling. The supplied air forms wall jets below the ceiling which are easy to describe in terms of velocity distribution, entrainment, etc. The jets deflect at the wall facing the supply openings, and the resultant flow in the lower part of the room - the occupied zone - has a rather complicated structure. It is possible to predict the air distribution in the whole room including the occupied zone by solving differential equations for the flow using a computer-based numerical method. The method has been explained in a number of publications during the last 15 years, as shown e.g. by Nielsen[1] in an early paper, but it is not generally used by the ventilation industry.

Ventilation with vertical displacement flow is another air distribution method. The air is supplied directly into the occupied zone at low velocity from wall mounted or floor mounted diffusers. The flow is in general driven by buoyancy force, and Davidson[2] has shown that airflow simulation can also be used for predicting the air distribution in this case.

The air distribution in radiator heated rooms may also be analysed by air flow simulation as shown for example by Rheinländer[3].

This paper will review the research on airflow simulations in rooms using computer-based numerical methods and further it will show some trends and new developments.

2. FULL-SCALE EXPERIMENTS AND COMPUTER SIMULATION

Full-scale experiments will produce measurements which can be of very high quality but they are time consuming. The cost of a single experiment is in the range 3,000 US$ to 20,000 US$. More expensive full-scale experiments may involve actual decorating, furnishing and interior fittings so that the owner, architect and consultants can experience the environment at a very early stage as discussed by Lärkfeldt[4]. This is of course an extra advantage of full-scale experiments, and furthermore, it will also ensure an acccurate determination of the flow in the occupied zone and give information of the influence from different shapes in the interior such as lamps, technical installations, etc. Full-scale experiments in the cheaper end of the price scale are made in rooms which can be built in a module system with moveable walls and ceiling.

An alternative possibility are model experiments which are necessary for very large installations. Model experiments are difficult to perform, due to problems with similarity. They are also expensive because they require much elaboration of such details as supply openings, etc.

The practical use of flow simulation for room air distribution is a question of the price level as well as the quality of predictions. The cost of a simulation now correspond to that of a full-scale experiment. Chen[5] has shown that 80 CPU minutes on an IBM 3083 - JX1 are used for predicting different flow situations, and Davidson[2] has to use up to 80 CPU hours on a VAX 2000 to simulate the displacement ventilation created by buoyancy driven flow.

Airflow simulations will increase in importance in the coming years due to the economics. Chapman[6] shows how the relative computation cost is decreasing every year, and this trend will continue in the coming years. The reason is that computer speed and storage have increased much more rapidly than computer costs, and figure 1 shows that the cost of performing a given calculation has been reduced by a factor of 10 every 8 years.

Another trend is the movement from large main frame computers in computer centres to work stations located close to the user. This change in the use of a computer will make more people familiar with standard software packets as programs for airflow simulation.

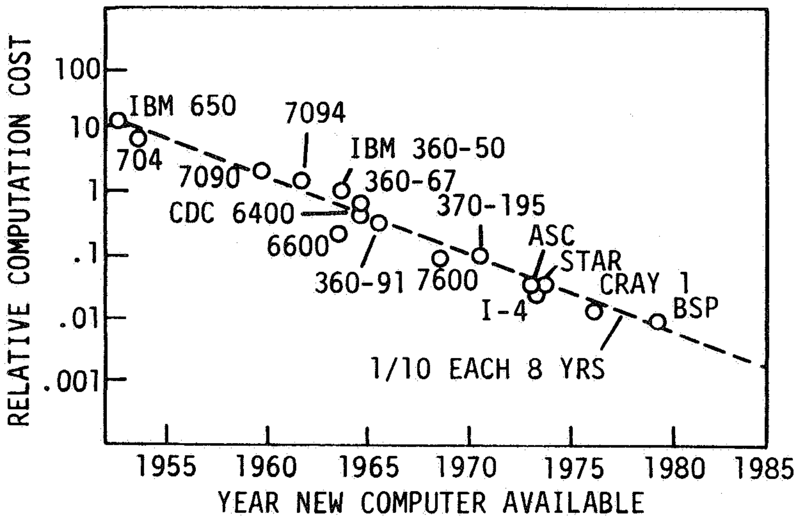


Figure 1. Trend of relative computation cost for a given flow and algorithm.

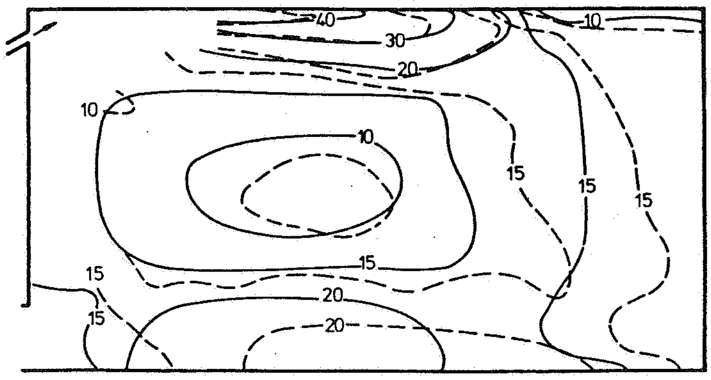
The increasing internal storage capacity is another important trend. Multi-equations turbulence models, LES-models and other new developments necessitates large computers. Large computer capacity will in general make it possible to make predictions of a high quality in complex situations as for example complicated supply arrangements, complicated room geometry or buoyancy driven flow with more plumes.

3. AIRFLOW SIMULATIONS IN ROOMS WITH DIFFERENT VENTILATION SYSTEMS

This chapter will show some results and discuss the potentials of the numerical method. It is divided into mixing ventilation in small rooms, displacement ventilation, and air movement in large areas.

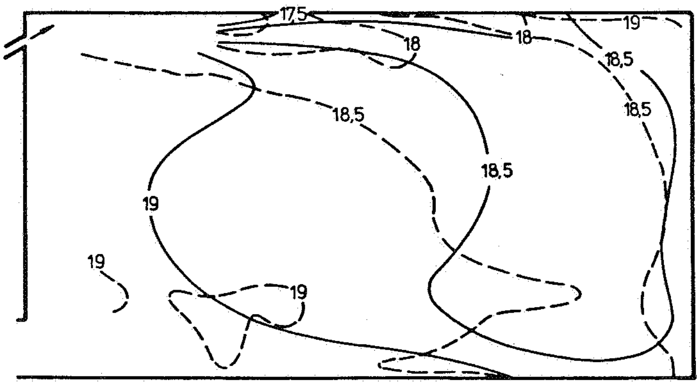
3.1 Mixing ventilation

Figure 2 shows the results for a room with two-dimensional flow and mixing ventilation. The results are typical for the flow in a room with a heat source at the floor simulating e.g. solar radiator. The supply velocity u_o is 2.2 m/s and the velocity in the wall jet decreases to 0.15 m/s in the area where the cold jet leaves the ceiling, and the recirculating flow is accelerated to 0.2 m/s in a larger part of the occupied zone. It is seen that there is a fairly good agreement between measurements and calculations for the general flow and for the maximum air velocity in the occupied zone.



Velocity distribution (cm/s)

——— Predictions — — — — — Measurements



Temperature distribution (°C)

Figure 2. Isovels and isotherms in a room with two-dimensional thermal flow. The tests are made by Hestad[7] and the calculations are made by Nielsen et al.[8]. $h/H = 0.003$, $L/H = 1.9$ and $Ar = 5.5 \cdot 10^{-4}$.

The air distribution in a small room of simple geometry, as the one shown in figure 2 is well understood, and it is fairly easy to make a full-scale test for the study of velocity and temperature distribution. If other parameters as for example the humidity distribution are to be examined much more complicated measurements are necessary. Schmitz and Renz[9] have studied the airflow and humidity transport in a swimming bath, and it is demonstrated that airflow simulation is an effective means to optimize an air distribution system compared to a large number of full-scale or model scale tests with humidity experiments. This situation is also obvious when we want to work with parameters as the age distribution and local purging flow rate, quantities which are difficult to measure, but which are interesting in connection with calculation of air exchange efficiency. Davidson and Olsson[10] have shown some numerical predictions of these quantities in a room with mixing ventilation.

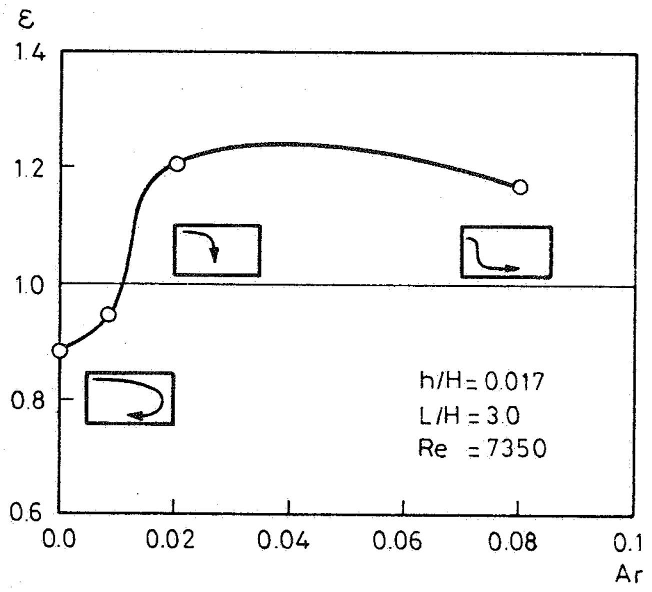
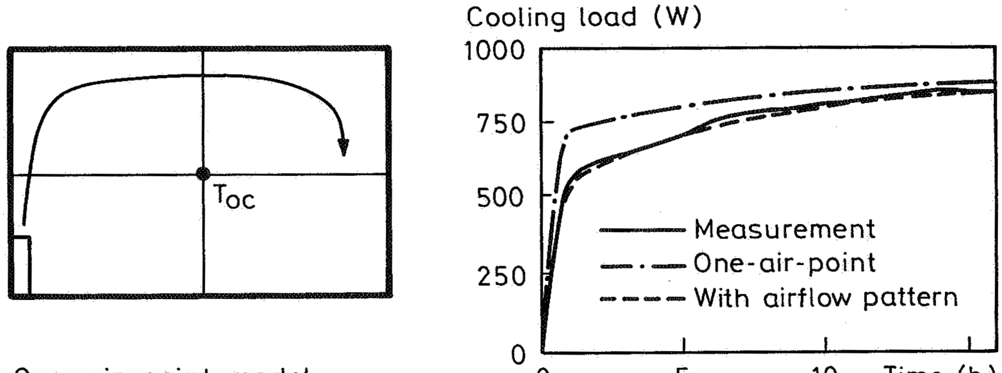


Figure 3. Ventilation efficiency versus Archimedes' number in a room with two-dimensional flow.

Figure 3 shows the ventilation efficiency ε in a room with two-dimensional flow at different Archimedes' numbers Ar. The ventilation efficiency is defined as c_R/c_{oc} where c_R is the concentration in the return opening, and c_{oc} is the mean concentration in the occupied zone. (In this case c_{oc} is the mean value of concentrations at the height 0.35 H above the floor). The contaminant source and heat source are evenly distributed along the floor. The figure shows a high ventilation efficiency in the case when the jet penetrates half of the room length, and this may also be the flow pattern which is optimum for thermal comfort, taking into account that the heat load had to be removed from the room. The results in figure 3 are calculated by airflow simulation, and it is obvious that it would be a time consuming job to perform the necessary concentration measurings although the geometry involved is rather simple.

Chen and Kooi[11] have shown a very interesting combination of airflow simulations in rooms and cooling load calculations for buildings. Cooling load computer programs are normally based on an one-air-point model which means that the values of the whole temperature field in a room are assumed to be uniform, see figure 4. If this model applies to an air-conditioned room with a low ventilation rate or with natural convection or to large industrial halls or theatres it will result in a significant error in the energy comsumption due to the presence of temperature gradients in the room air.



One-air-point model

Figure 4. One-air-point model. Time dependent cooling load of a room. Predictions and measurements by Chen and Kooi[11].

Chen and Kooi use results from airflow simulation in the room to correct the cooling load program. It is too expensive to calculate the time-dependent air flow and temperature distribution of a room from an airflow program at each time step in the cooling load program. A data base with velocity distribution for different Archimedes' numbers is precalculated and used at each time step, and it is only necessary to calculate the energy equation to get the correct temperature distribution. Figure 4 shows the measured and the calculated cooling load in a room where 950 W is applied as a step function. The cooling load is obtained from flow rate and temperature difference between return and supply. An one-air-point model does not take account of the vertical temperature gradient and thus the excessive heat transferred into the ceiling, while a cooling load model with airflow pattern is able to handle this effect and results are in this case in good agreement with measurements.

3.2 Displacement ventilation

Figure 5 shows the principle in displacement flow. The air is supplied directly into the occupied zone at low velocity from a wall mounted diffuser. The plume from the heat source creates a natural convective flow upward in the room and a stratification takes place at a height where the plume entrains an airflow equivalent to the supply flow.

The displacement flow systems have two advantages compared with traditional mixing systems. It is possible to remove exhaust air from the room where the temperature is several degrees above the temperature in the occupied zone, and the vertical temperature gradient implies that fresh air and contaminant air are separated, the fresh air being located in the occupied zone.

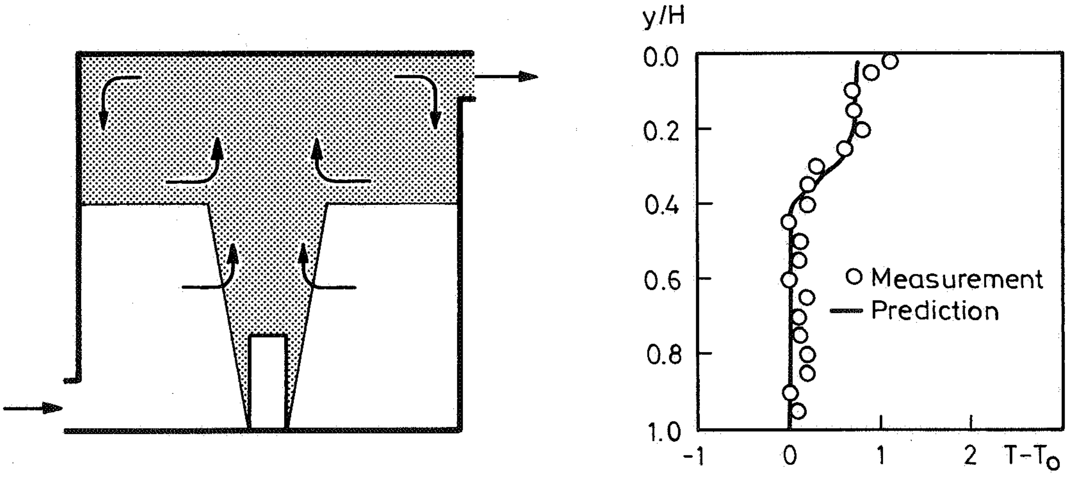


Figure 5. Flow in a room with displacement ventilation and vertical temperature gradient. Predictions are made by Davidson[2] and measurements by Sandberg[12].

The vertical temperature distribution in figure 5 shows the predicted values by Davidson[2]. The comparisons with measured values in a water model show good agreement with respect to temperature distribution and height of the stratification level. As pointed out by Davidson thermal radiation plays an important role in displacement ventilation, and for example Nielsen et al.[13] have shown that the floor temperature is often close to $T - T_o \sim 0.4\ (T_R - T_o)$ instead of $T - T_o \sim 0$ measured and predicted in a water model without radiation (T_o and T_R are supply and return temperature, respectively).

This increase in floor temperature is due to thermal radiation from the ceiling. Some predictions of displacement flow made by Chen[5] take account of radiation by calculating the temperature distribution at surfaces from a cooling load program.

The buoyancy driven flow in displacement ventilation involves elements which could be described by parabolic flow equations. The flow in the plume and cold downdraught are examples, and it might be possible to handle these areas separately using a box method, a prescribed velocity method or direct calculation in the same way as described by Nielsen[14] for the representation of boundary conditions at supply openings.

3.3 Airflow simulation in large areas

Experiments in large areas with complicated geometry can only be made as model experiments. It is also difficult to use the simplified design procedures which can be applied to small rooms as e.g. the room shown in figure 2. Airflow simulation is therefore an alternative possibility and some examples will be discussed in the following.

Figure 6 shows some predictions made by Ehle and Scholz[15]. The experiments were made in a large theatre and the streaklines shown in the upper figure were visualized by smoke. Heat load was simulated by a high number of 60 W light bulbs at the chairs and the volume flow to the main part of the theatre was 67,400 m^3/h.

The experiments show that the flow in the left-hand side of the theatre was rather independent of the main flow pattern and the area was omitted in the numerical predictions. Figure 6 shows good agreement between measurements and predictions, and it is further shown by Ehle and Scholz that there is good agreement between measured and calculated velocities in the occupied zone as well as measured and calculated temperature distribution in the room. The calculations are made as two-dimensional flow.

Waters[16] has worked with airflow simulation for a 13 storey high atrium in Lloyds building in London. The roof and the south elevation of the atrium from seventh to twelfth gallery are completely glazed and in contact with the outside environment. The simulation of cold downdraught on a winter day shows velocities up to 1 m/s at higher levels, but it is destroyed at low level in the atrium by the effect of heat transfer and conditioned air from the offices around the atrium. The downdraught does not disturb the three lower galleries and the ground floor which are directly open to the atrium. The measured air movement pattern corresponds to the predictions showing that airflow simulation can be used also in a case with buoyancy driven flow and larger dimensions.

Different examples of the use of airflow simulation in rooms are reviewed by Whittle[17].

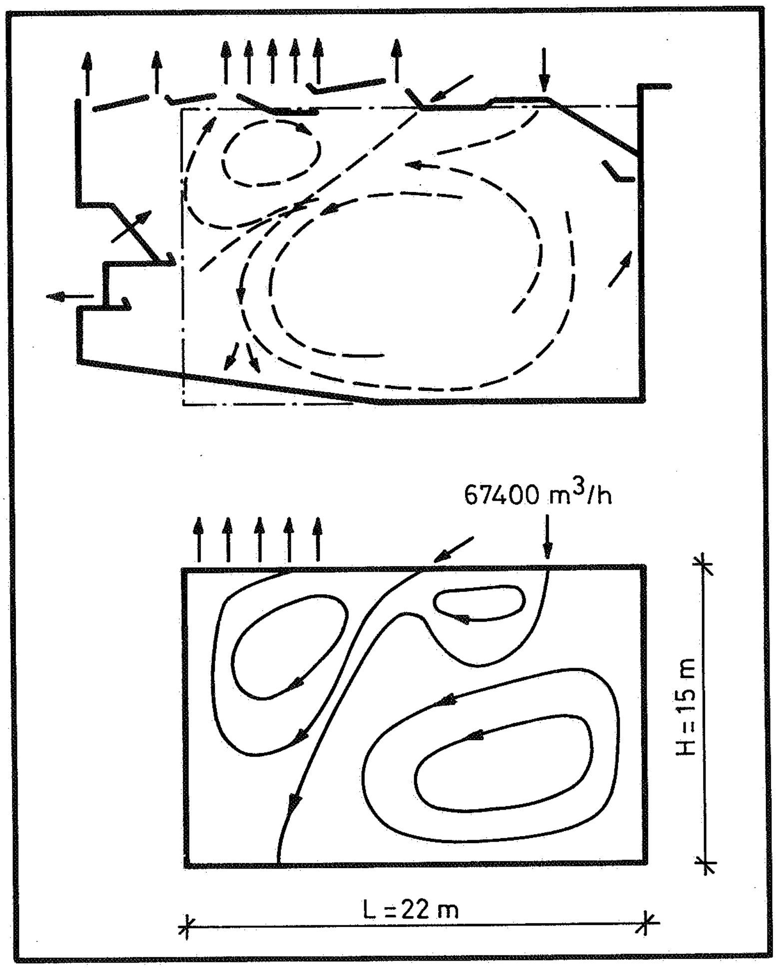


Figure 6. The upper figure shows the flow in a large theatre and the dotted line indicates the area of the flow which is subject to airflow simulation. The lower figure shows the calculated streamline pattern made by Ehle and Scholz[15].

4. DEVELOPMENTS IN THE NUMERICAL METHOD FOR AIRFLOW SIMULATION IN ROOMS

This section will deal with some developments in the numerical method which will make airflow simulation applicable in practice. An improved handling of boundary values such as air terminal devices, handling of low-turbulence effect and large eddy simulations will be mentioned. Other developments and trends in airflow simulation in rooms, as for example influence from furniture and people and representation of the comfort level are discussed by Nielsen[18].

4.1 Representation of boundary conditions at supply openings

An air terminal device is represented by velocity and temperature profiles as well as profiles for turbulent kinetic energy k and dissipation of turbulent kinetic energy ϵ. The velocity distribution close to a diffuser can be very complicated with variations in level as well as direction, and therefore, it will be difficult to measure in detail. Some ceiling mounted diffusers even have areas with return flow for induction inside the diffuser which is a further complication, and it is especially difficult to obtain the distribution of k and ϵ close to the diffuser. The flow from the diffuser will develop into a free jet or a wall jet in the room. It is therefore practical to move the boundary values a short distance from the opening and give them in the form of normalized free jet or normalized wall jet profiles. The procedure will reduce the necessary measurements on the diffuser and it will also save grid points and computation time. Different methods such as the box method and the prescribed velocity method are given by Nielsen[14].

4.2 Turbulence models

Airflow simulation is normally based on the averaged momentum equations, the continuity equation and the energy equation. The averaged momentum equations contain Reynolds stress terms which are modelled by the eddy viscosity concept. The eddy viscosity is further predicted from a $k - \epsilon$ turbulence model consisting of two transport equations for turbulent kinetic energy k and dissipation of turbulent kinetic energy ϵ. The object of the k and ϵ equations is rather to close the equation system, so it is possible to predict for example the mean velocity distribution, than to give a prediction of the turbulence.

Fanger et al.[19] have shown that the thermal comfort is influenced by turbulence. The turbulence is given as a single-directional turbulence intensity by the expression $\sqrt{\overline{u'^2}}/u$, when u is the mean velocity and u' is an instantaneous deviation from the mean velocity. It is difficult to compare results from the k and ϵ calculations with the measured turbulence intensity and it is therefore difficult to predict the influence of turbulence on thermal comfort.

A rough comparison between predicted and measured turbulence can be made in mixing ventilation where the recirculating flow is rather similar to a wall jet. The normal stresses $\overline{v'^2}$ and $\overline{w'^2}$ in a two-dimensional wall jet are more or less equivalent to 0.6 $\overline{u'^2}$ and 0.8 $\overline{u'^2}$ as shown by Nelson[20]. This means that $\sqrt{k} \sim 1.1 \sqrt{\overline{u'^2}}$, and figure 7 show measurements and predictions of $\sqrt{\overline{u'^2}}$ and $\sqrt{k}$, respectively, made by Nielsen[21] which confirms this connection.

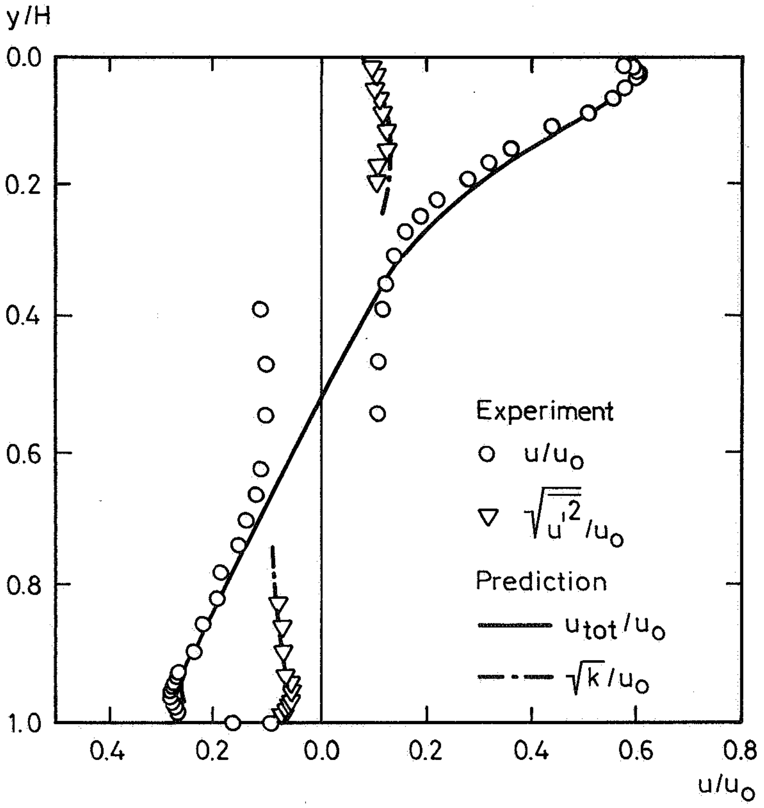


Figure 7. Predicted and measured velocity and turbulence profiles in a room with mixing ventilation. h/H = 0.056, and L/H = 3.0.

It is interesting to note in figure 7 that it is impossible to measure the velocity in a large inner area of the room with hot wire anemometry, and only airflow simulation can show the mean velocity in that area.

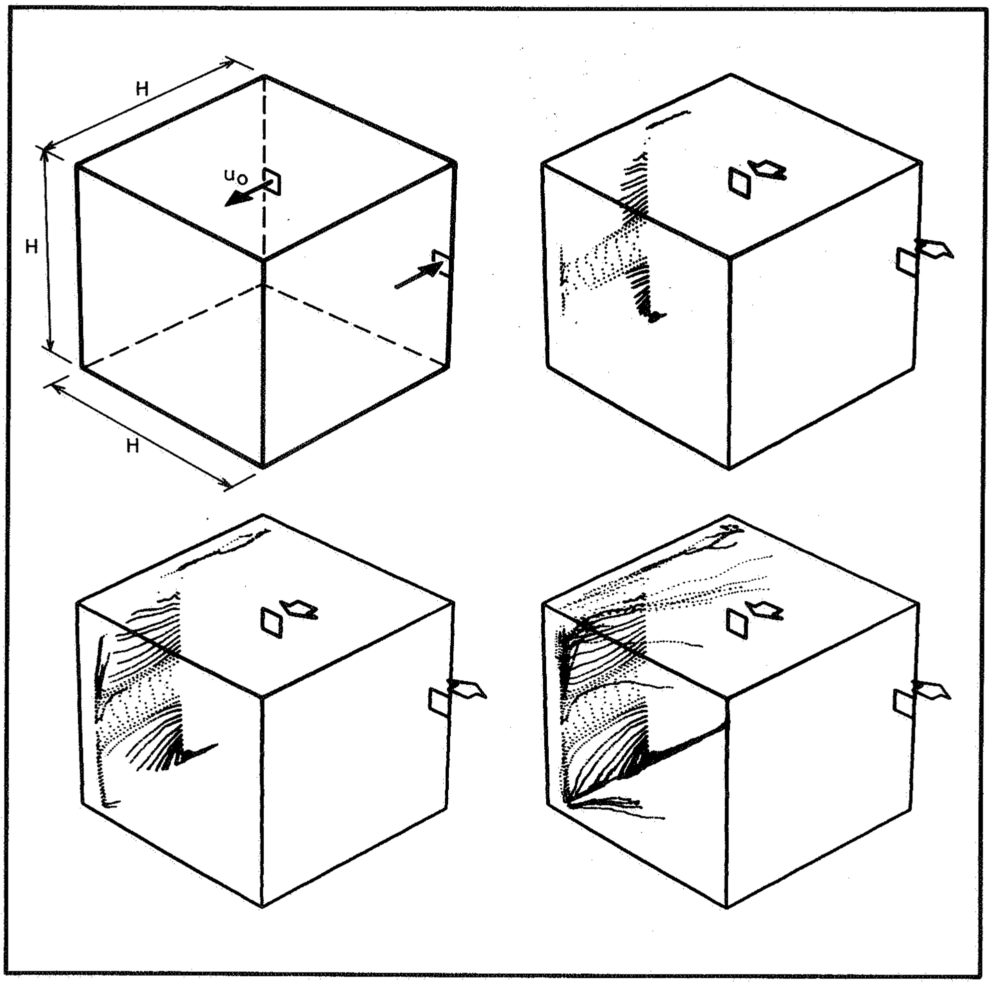


Figure 8. Geometry of a room and three-dimensional streaklines from a vertical line source at three different time steps, $\Delta t^* = 10$, 20 and 50. The calculation and the computer graphic are made by Murakami[22].

Numerical prediction of airflow can also be performed by Large Eddy Simulation (LES). The LES method is based on Navier-Stokes equations, the continuity equation and the energy equation, all filtered with respect to grid space, but not with respect to time. The equation system is closed by an expression for subgrid scale (SGS) Reynolds stresses. The turbulence is represented as the time dependent solution of this equation system, and it is important that the grid spacing is fine enough to allow a description of the energy containing eddies. If mean flow quantities have to be predicted, transient calculation must be conducted over a time which is sufficient to obtain the average values. It is obvious that output from predictions made by the LES method contains much information, and it is possible to predict the parameters in turbulence which can also be measured, as for example $\sqrt{\overline{u'^2}}$.

The high contents of information in the output makes flow analysis possible in a room by means of computer graphics. Murakami[22] has shown this with streaklines, timelines and high-speed animation of turbulent flow field. Figure 8 shows an example of some computer graphics for the flow in a room. Streaklines are produced from a vertical line source in front of the supply opening, and each time step shows the development in the lines. Δt^* is the time from the start, non-dimensionalized by H and u_o.

4.3 Low-turbulent flow

Turbulence models used for the present calculations assume a fully developed turbulence and, consequently, a self-similar flow that is independent of the Reynolds number (a slight influence from the wall functions is disregarded). This indicates that an air velocity at a given point is proportional with the air change rate in the case of isothermal flow.

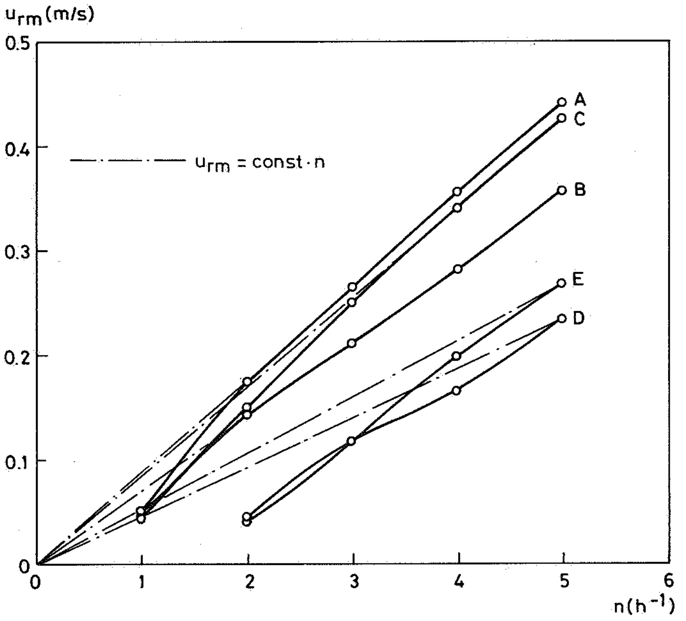


Figure 9. Maximum velocity in the occupied zone as a function of the air change rate n. The tests were performed for five different air terminal devices (A to D).

Figure 9 shows the maximum air velocity in the occupied zone u_{rm} as a function of the air change rate n for five different air terminal devices measured by Heiselberg and Nielsen[23]. The different air terminal devices are of the following types

A. Nozzle

B. Grille

C. Grille with blades adjusted for high diffusion

D. Wall mounted diffuser

E. Ceiling mounted diffuser

It is seen from figure 9 that u_{rm} is proportional with the air change rate n at high airflow rates while there are deviations at low airflow rates. Figure 9 also shows that the low airflow rates have practical relevance ($u_{rm} \sim 0.1 - 0.15$ m/s). It is evident that there are some low-turbulent effect in this situation, which is especially noticeable for air terminal devices D and E. Part of the low-turbulent effect will be found in the air terminal device and therefore, it can be included in the boundary values of an air terminal device if it has been measured in advance. However, there is still a need for a turbulence model capable of treating flow conditions that do not have a fully developed turbulence level, as shown by Nielsen[18].

5. CONCLUSIONS

Airflow simulation i rooms has taken place as research projects for some years. The development of computation cost indicates an increased use of airflow simulation in practice in the coming years.

Air velocity and temperature distribution in a room are important for the evaluation of thermal comfort, and they are main variables in the prediction method as well as in full-scale experiments. The prediction method can be used to get information of variables which are rather difficult to measure, such as contaminant and humidity distribution, local age and purging flow rate, heat transfer coefficients, etc. and this may be an important use of airflow simulation in the future.

Airflow simulation has been successfully used for the prediction of flow in mixing ventilation for some years, and new results indicate that the method will also be useful for the prediction of flow in displacement ventilation and flow in radiator heated rooms.

Airflow simulation in large areas as for example theaatres, atriums and covered shopping centres is an important application, especially because model scale experiments or experience from other projects are the only possibility present.

Development work is necessary to give a practical description of air terminal devices, and it may be necessary to develop a turbulence model which deals with low-turbulent flow in the case of low flow rates in the room.

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Discussion

Paper 10

R. Mokhtarzadeh (Brunel University, UK)

Most calculations presented here or published describe flows in empty rooms. What are the effects of obstructions/obstacles (e.g. furniture) on the calculations, and how can they be accounted for?

P.V. Nielsen (University of Aalborg, Denmark)

Some measurements on flow in rooms with furniture and people are shown in reference (18) in the paper. Furniture may both give a slight increase and a slight decrease of the velocity level in the occupied zone. It might be possible to do some predictions with additional therms in the floor equations, in the occupied zone, as shown in: Scholz, R. and Hanel, B., Compütorgestütze Berechnung der Raumluftströmung, Rühe Luft- und Kältetechnik, VEB Verlag Technik, Berlin, 1988.

B. Fleury (ENTPE LASH, France)

What are the priorities for you?

- developing a computer graphics package to visualize 3D dynamic flow in buildings for an extensive use of existing detailed air flow models.
- developing existing or new models of turbulence leveling to building air flow configuration?

P.V. Nielsen (University of Aalborg, Denmark)

I think both areas are important but the development of computer graphics do take place in the coming years. The development of a model for low-turbulent flow is very important for airflow simulation in rooms.