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Flow of Microorganisms in a Hospital Stair Shaft – Full-scale Measurements and Mathematical Model

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SUMMARY

Measurements of air flow and microorganism concentration have been made in the stair shafts of a hospital, using a diving bell-type of pressure-recording instrument, and a sampler for the microorganisms, respectively. Results of experiments were used to calculate the flow rate of microorganisms between the floors of the hospital. A mathematical model based on simplified transport equations is proposed, which would allow the prediction of the flow field and the distribution of microorganisms in the stair shaft. Comparisons between measurements and numerical calculations indicate that the mathematical model is able to predict the global flow field, qualitatively. The application of the numerical method can help to reduce the experimental work, as well as to investigate the complex exchange mechanisms of microorganisms.

Key words: air distribution, contamination in hospitals, leakage, air mass transfer, microbiology.

INTRODUCTION

Most rooms of a building are connected by common corridors, hallways, stairwells, etc., therefore, air flow from one room to another room is possible, even if the rooms are located far apart from each other. The principal reasons for air movement are the chimney effect, wind action and the operation of mechanical ventilation systems.

According to the air stream pathogens, microorganisms as well as gaseous or solid toxic agents can be spread. A positive correlation between the infection rate and the height of hospitals and apartment houses has been reported by Fanning [1], Haase and Walker [2], Hurst *et al.* [3], Schafir *et al.* [4] and Wehrle [5].

Up to now, the complex flow of microorganisms and toxic agents in large buildings has not been understood in full detail. For this reason, the air movement in stair shafts has been investigated by physical and microbiological methods in this report. Parallel to the experimental investigation a mathematical model for the prediction of the flow in stair shafts has been developed. This model is employed to verify the experimental data and to calculate the flow field for different boundary conditions.

FULL-SCALE MEASUREMENTS

The measurements were carried out in two stair shafts of the Klinikum Steglitz, Berlin, a hospital with 1400 beds. Figure 1 shows a typical section of such a stair shaft with:

— a corridor leading to different areas of the hospital;

— the staircase itself.

The stair shaft has no vertical subdivision. It is situated between the treatment wing and the dormitory wards of the hospital.

The air flows in the shaft are composed of different single streams which are created by the porousness of the building materials

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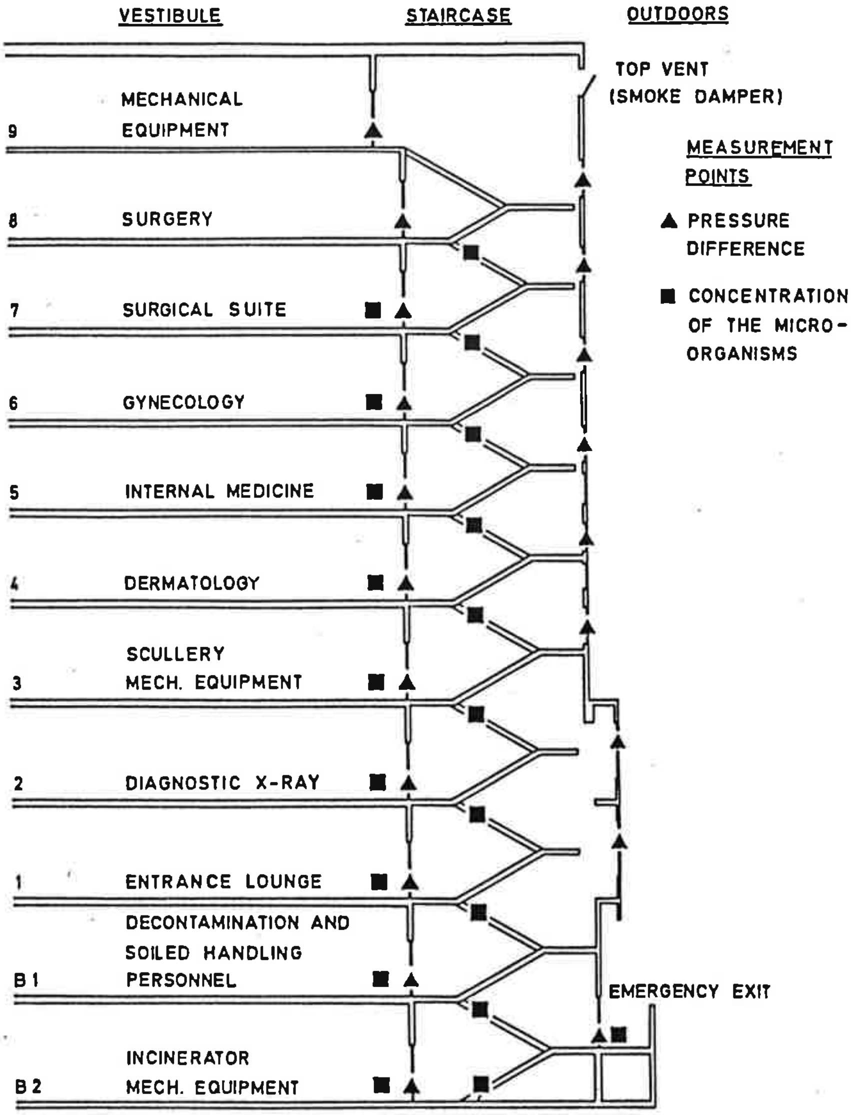

Fig. 1. Sectional view of the staircase including the measurement points.

as well as the cracks and openings of the shaft enclosure. In this study we concentrated only on the flows through the cracks caused by windows and doors being closed.

In order to obtain evidence of the amount of direction of the air through these cracks, the difference in pressure across each of the doorways and windows was measured every twelve seconds using a diving bell-type of pressure-recording instrument. During a three-week period 400 000 readings were made.

The pressure distribution of the stair shaft is presented in Fig. 2(a). It shows a typical pattern of pressure differences, which were recorded on the 14th day of the measurement period with a temperature difference between inside and outside of 19 K. The stairwell doors and the windows were closed, whereas the top vent for the smoke release was open.

The results were obtained before and during the first cycle of germ concentration measurements of the day. In reference to the pressure inside the building, there was a change from negative to positive pressure above the 7th floor. The distribution across the exterior wall is nearly linear as expected from theoretical considerations of Tamura *et al.* [6] and Brinkmann [7]. The distribution across the wall to the vestibules was determined by the activity in the hospital, and different leakages in the vestibules.

To trap the viable airborne contamination, Sartorius samplers with gelatine foam filters

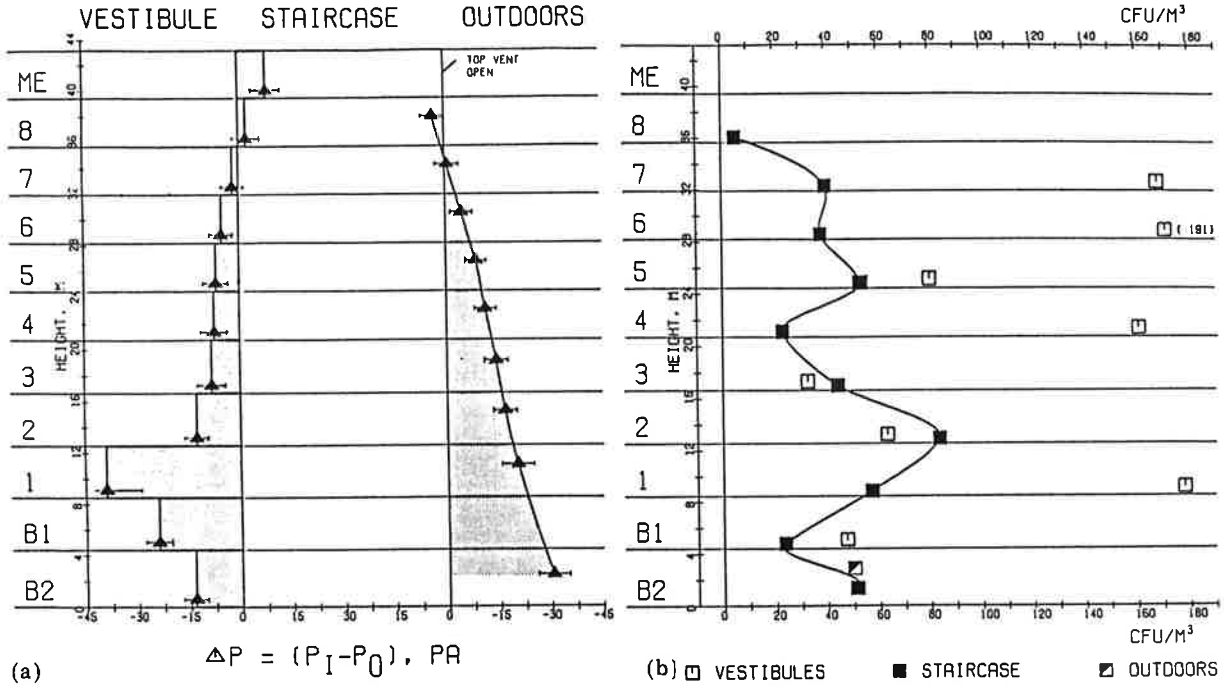

Fig. 2. (a) Pressure differences enclosing the staircase, (b) concentration of the microorganisms.

were used. As shown in Fig. 1, samplers were positioned at 20 locations as follows:
— at every door leading into the staircase in order to measure the concentration in the staircase as the air flow was entering;
— outside at the emergency exit for the same reason;
— and inside the staircase at the upper end of each story, in order to determine the concentration of the bacteria mixture.

The germs were measured in cycles, each cycle lasting ten minutes, with an interval of about one hour between each cycle. After incubation of the foam filters on blood agar plates, the number of bacteria in the air was estimated by counting the colony-forming units (CFU). All together 185 measuring cycles were carried out, this involved 185 changes of the filters at each of the 20 positions with a total of 370 samples.

Figure 2(b) shows the corresponding sampling of the microorganisms at the pressure measurement line. As often occurred, quite different concentrations were collected in the vestibules. Inside the staircase, the figures indicated an increase in the count of microorganisms per cubic metre on the ground floor and a decrease above.

The flow rates through the simple unbent cracks of the thresholds were calculated with the method given by Esdorn and Rheinländer [8]. Using the concept of pipe flow, they established relationships between pressure difference and the resulting airflow rate, taking into account the geometrical description of the flow path.

$$\dot{V} = lh\sqrt{\frac{2\Delta p}{\rho\left[\lambda\left(\frac{t}{2h}\right)^{m} + \Sigma\xi\right]}} \tag{1}$$

where

l = breath of crack (m)
h = width of crack (m)
t = length of the crack in flow direction (m)
Δp = pressure difference (Pa)
ρ = density (kg/m^3)
λ = pipe friction factor
m = exponent
ξ = pressure drop.

Due to several bends and a weatherstrip, the design of the window cracks were extremely complicated, so that an exact measurement of the geometry of the path was not possible.

Since the contribution to the total flow rate of the flow rate through the window cracks was small, the latter was calculated by a frequently used empirical power function with a medium leakage coefficient.

$$\dot{V} = al\Delta p^{2/3} \tag{2}$$

where a = leakage coefficient ($m^3/mhPa^{2/3}$). With respect to *DIN 4701* [9] and the investigation of Schüle [10] the value $a = 0.44$ $m^3/mhPa^{2/3}$ is suggested. Naturally this procedure does not deliver exact results, but with regard to generally less exact measurements of the germ concentration, this method is applicable.

The flow of microorganisms $\dot{D}$ is obtained by multiplying the different air flows by the corresponding germ concentration M.

$$\dot{D} = M\dot{V} \tag{3}$$

According to the shown pressure differences and measured cracks, the calculated flow rates from eqns. 1 and 2 are shown in Fig. 3(a). From the ground floor up to the 7th floor, air entered the staircase from the adjacent vestibule floor spaces as well as from outdoors. Above the 7th floor, the flow was in the opposite direction. Because of the threshold gaps, the flow rates on the corridor side were about ten times larger than those on the outside. The resulting flow rate inside the staircase is shown in Fig. 3(b).

The flow of microorganisms received from eqn. 3 is given in Fig. 4(a). Regarding the transport of the microorganisms, there was no connection between the single storeys up to the 7th floor. In contrast to this fact, the 8th floor received a mixture of bacteria from the lower floors. The measured value in the staircase was used as the concentration value of the mixture. The microorganism rate in the staircase is shown in Fig. 4(b).

MATHEMATICAL MODEL AND THE SOLUTION PROCEDURE

The flow of microorganisms in a staircase is a very complex problem. It is not possible to solve the balance equations which describe the transport mechanism in full detail. Even for simplified equations, additional difficulties arise in the solution of equations, which, in general, can only be solved numerically. For this reason, we have to apply certain assumptions concerning the staircase geometry and the flow of the fluid which consists of air and microorganisms.

It is assumed that the steady flow is laminar and isothermal. The Newtonian fluid behaves like an ideal gas mixture of constant density, where the fluid properties are constant throughout the whole flow field. In addition, the three-dimensional flow problem

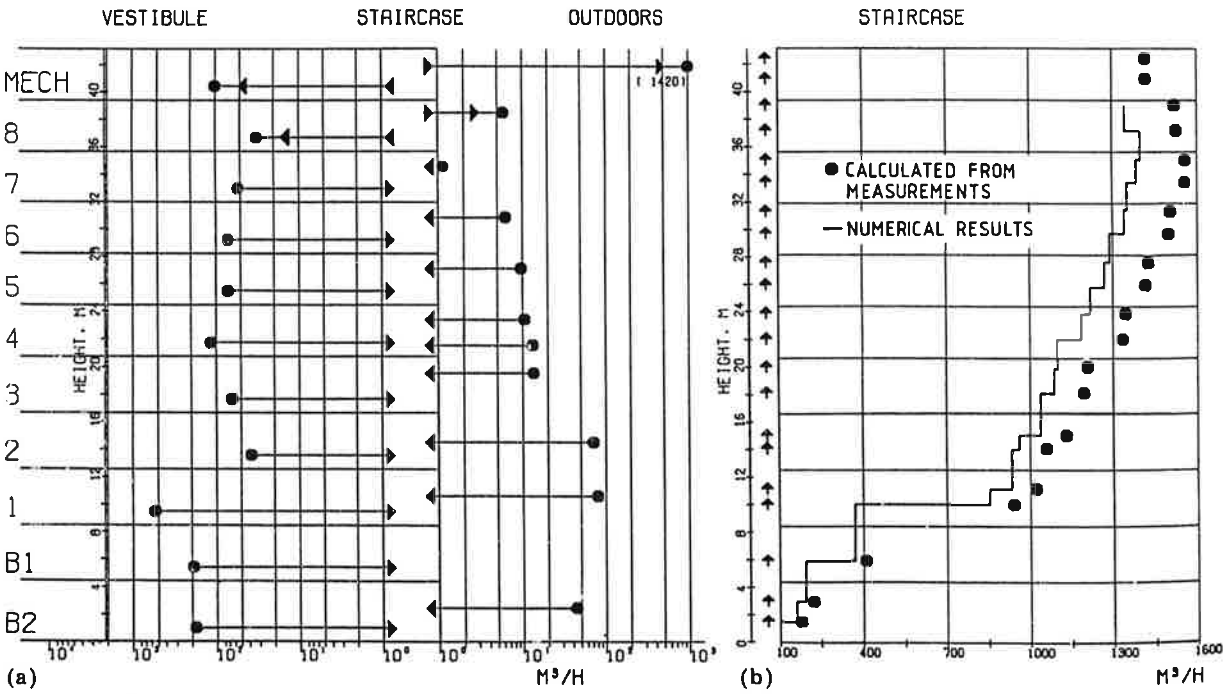

Fig. 3. (a) Air flows through door and window cracks, (b) resulting air flow in the staircase.

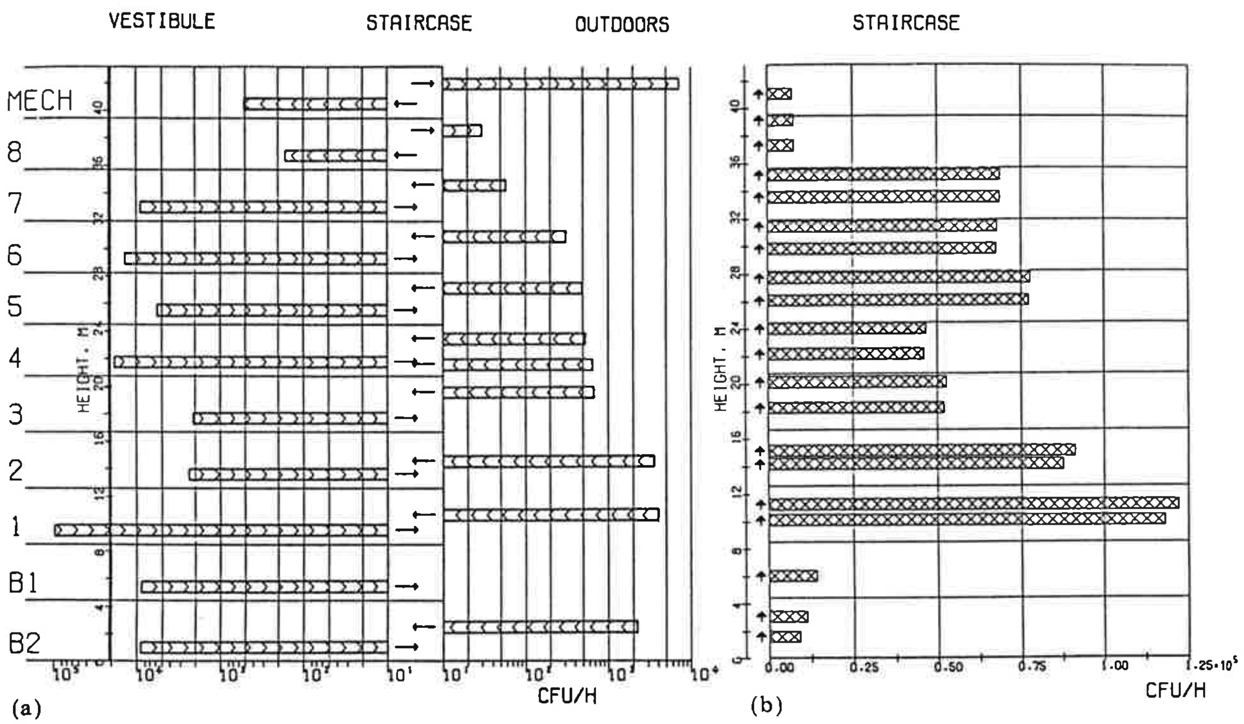

Fig. 4. (a) Flow of microorganisms through door and windows cracks, (b) resulting flow of microorganisms in the staircase.

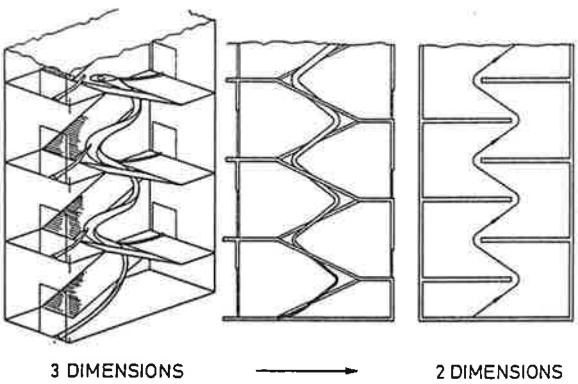

Fig. 5. Three-dimensional flow problem replaced by a two-dimensional one.

will be replaced by a two-dimensional one (see Fig. 5) which takes the main motion of the fluid into account.

Under these assumptions the air flow in the staircase can be mathematically described by the governing equations as follows.

Continuity equation:

$$\frac{\delta U}{\delta X} + \frac{\delta W}{\delta Z} = 0 \tag{4}$$

Navier–Stokes equations:

$$\frac{\delta U}{\delta T} + U\frac{\delta U}{\delta X} + W\frac{\delta U}{\delta Z} = -\frac{1}{\rho}\frac{\delta P}{\delta X}$$

$$+ \nu\left(\frac{\delta^2 U}{\delta X^2} + \frac{\delta^2 U}{\delta Z^2}\right) \tag{5}$$

$$\frac{\delta W}{\delta T} + U\frac{\delta W}{\delta X} + W\frac{\delta W}{\delta Z} = -\frac{1}{\rho}\frac{\delta P}{\delta Z}$$

$$+ \nu\left(\frac{\delta^2 U}{\delta X^2} + \frac{\delta^2 U}{\delta Z^2}\right) \tag{6}$$

Species concentration equation:

$$\frac{\delta C}{\delta T} + U\frac{\delta C}{\delta X} + W\frac{\delta C}{\delta Z} = \rho D\left(\frac{\delta^2 C}{\delta X^2} + \frac{\delta^2 C}{\delta Z^2}\right) \tag{7}$$

where

C = mass concentration of microorganisms
D = binary diffusion coefficient
P = pressure
T = time
U = mean velocity component in X-direction
W = mean velocity component in Z-direction
X = axial coordinate
Z = normal coordinate
ρ = density
ν = kinematic viscosity.

It should be pointed out, that only the steady-state solution of the governing equations is required. The unsteady terms have been added for numerical reasons as proposed by Mallinson and de Vahl Davis [11].

The boundary conditions are specified for solid surfaces by the no-slip condition.

$$U = W = 0 \tag{8}$$

For the inlet flow, as well as for the outlet flow, the boundary conditions are derived from the experimental data. It was assumed, that the width of all cracks was the same and equal to 20% of the door height. Using the pressure difference of the crack, the velocity profile was chosen to be a free jet.

The specification of the microorganism concentration is such that no mass flux can occur at solid walls

$$\frac{\delta C}{\delta X} = \frac{\delta C}{\delta Z} = 0 \tag{9}$$

The microorganism concentrations at the cracks were taken from measurements.

For the numerical solution of the partial differential eqns. (4) - (7) we introduce the dimensionless quantities

$$t = \frac{T}{L} U_r \quad x = \frac{X}{L} \quad z = \frac{Z}{L} \quad p = \frac{P}{\rho U_r^2}$$

$$u = \frac{U}{U_r} \quad w = \frac{W}{U_r} \quad c = \frac{C}{C_r} \tag{10}$$

$$Re = \frac{U_r L}{\nu} \quad Sc = \frac{\nu}{D_{KL}\rho}$$

where

U_r = reference velocity
C_r = reference concentration
Re = Reynolds number
Sc = Schmidt number.

The numerical calculations are performed under the assumption that momentum and mass transport are analogous, that means $Sc = 1$.

For the numerical solution of the differential equations the stream function ψ and the vorticity ω are introduced by:

$$\frac{\delta \psi}{\delta x} = -v \qquad \frac{\delta \psi}{\delta z} = u \tag{11}$$

$$\omega = \frac{\delta w}{\delta x} - \frac{\delta u}{\delta z} \tag{12}$$

Hence, we can write the balance equations (eqns. (4) - (7)) in terms of these variables.

Vorticity equation:

$$\frac{\delta^2 \omega}{\delta x^2} + \frac{\delta^2 \omega}{\delta z^2} = Re\left[\frac{\delta \omega}{\delta t} + \frac{\delta}{\delta x}\left(\frac{\delta \psi}{\delta z}\,\omega\right) - \frac{\delta}{\delta z}\left(\frac{\delta \psi}{\delta x}\,\omega\right)\right] \tag{13}$$

Stream function equation:

$$\frac{\delta^2 \psi}{\delta x^2} + \frac{\delta^2 \psi}{\delta z^2} = -\omega \tag{14}$$

Species concentration equation:

$$\frac{\delta^2 c}{\delta x^2} + \frac{\delta^2 c}{\delta z^2} = Re\,Sc\left[\frac{\delta c}{\delta t} + \frac{\delta \psi}{\delta x}\frac{\delta c}{\delta z} - \frac{\delta \psi}{\delta z}\frac{\delta c}{\delta x}\right] \tag{15}$$

The boundary conditions for the stream function equation can easily be specified by using the definition (eqn. (11)) together with the natural boundary conditions for the velocity components. As the boundary conditions for the vorticity equation are not directly known, the boundary values have to be determined by using an approximation of the stream function equation (eqn. (14)) at the boundaries.

For the numerical solution, the derivatives with respect to the time are approximated by backward finite-differences. Then, eqns. (13) - (15) can be written in the general form for each time step μ as

$$\frac{\delta^2 f}{\delta x^2} + \frac{\delta^2 f}{\delta z^2} + \frac{\sigma}{\Delta t} f = \frac{\sigma}{\Delta t} f^{\mu-1} + r^{\mu-1}(x, z) \tag{16}$$

The stream function equation is obtained for $\sigma = 0$ with the known right side of the equation $r^{\mu-1}(x, z) = -\omega$. For $\sigma = -Re$ we get the vorticity equation, where $r(x, z)$ contains the convection terms from the previous iteration $\mu - 1$, $\sigma = -Re \cdot Sc$ yields a similar equation for the concentration of microorganisms.

The numerical solution of eqn. (16) is performed with regard to a rectangular domain. In this way we can make use of an efficient Poisson solver based on the Fast Fourier Transform (FFT) procedure introduced by Hockney [12]. For the constant mesh spacing h_1, h_2 the partial derivatives of eqn. (16) are replaced by central differences. At the grid point x_i, z_i the finite-difference approximation results in the general equation:

$$f_{i-1,j} + f_{i+1,j} + a(f_{i,j+1} + f_{i,j-1}) + bf_{i,j} = \Gamma_{i,j} \qquad (17)$$

where the abbreviations are

$$\Gamma_{i,j} = h_1^2\left(r_{i,j} + \frac{\sigma}{\Delta t} f_{i,j}^{\mu-1}\right)$$

$$a = (h_1/h_2)^2, \qquad b = -\left(2 + 2a + h_1^2 \frac{\sigma}{\Delta t}\right)$$

By applying the approximation to all grid points within the rectangular region we obtain a system of linear algebraic equations. This system is directly solved by using the FFT with cyclic reduction. The FFT method consists of:

— Fourier analysis of the right-hand side of eqn. (17);

— Gaussian elimination of the tridiagonal system;

— final Fourier synthesis.

In order to make use of this direct solution method, the flow geometry considered is divided into a set of rectangular regions as shown in Fig. 6. It is important that two consecutive rectangular regions A and B as well as B and C overlap each other. This

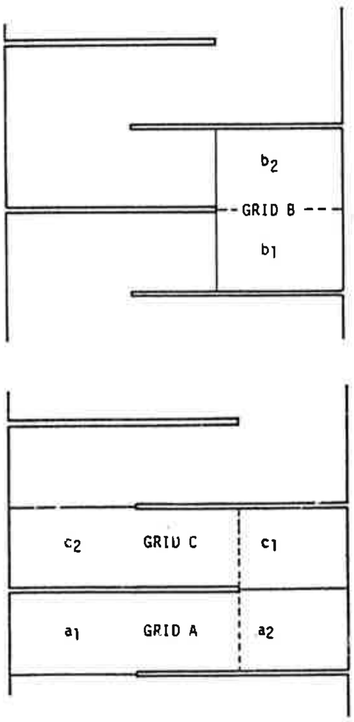

Fig. 6. Flow geometry, divided into a set of overlapping rectangular regions.

method, proposed by Schkalle and Thiele [13], has already been applied with success to the calculation of a flow over a backward facing step. Here, we used a 33×17 grid for the rectangular subregion. This yields a 33×347 grid for the whole stair shaft.

As the differential equations (eqns. (13) - (15)) are coupled with each other, an iteration procedure would be required for each time step μ. Since we are only interested in the steady-state solution, eqns. (13) - (15) are solved once per time step. The unsteady time iteration will approach the steady-state flow field.

Results of the numerical calculations

The flow field in the stair shaft depends on the value of the Reynolds number. A realistic value would be around $Re = 20\,000$. One difficulty in solving the Navier–Stokes equations is the problem of high Reynolds numbers. In order to avoid this problem, the investigations were carried out using lower values of the Reynolds number. Here calculations have been executed up to $Re = 400$. Due to limited space, only some of the results will be presented. For more detailed information, the reader is referred to ref. 14.

As an example, Fig. 7 shows the velocity distribution in the section between basement 1 and the second floor. The flow field is determined by the velocity at the cracks. As indicated, regions of reverse flow appear at higher Re numbers in the corners formed by the side walls and the floor. The extent of the reverse flow region depends on the Reynolds number. A comparison between the two Reynolds numbers indicates a larger reverse flow region and higher velocities.

Figure 8 shows the distribution and concentration of microorganisms for two different Schmidt numbers and $Re = 400$. The concentration decreases from the door in the main flow direction. For higher values of the Schmidt number ($Sc = 1$) we recognize a stronger decline in the concentration close to the door.

Based on the numerical results presented, the airflow rate in the staircase can be evaluated by simply integrating the velocity profile at each cross-section. Figure 3(b) shows a comparison of the measurements and the prediction (solid line) for the flow

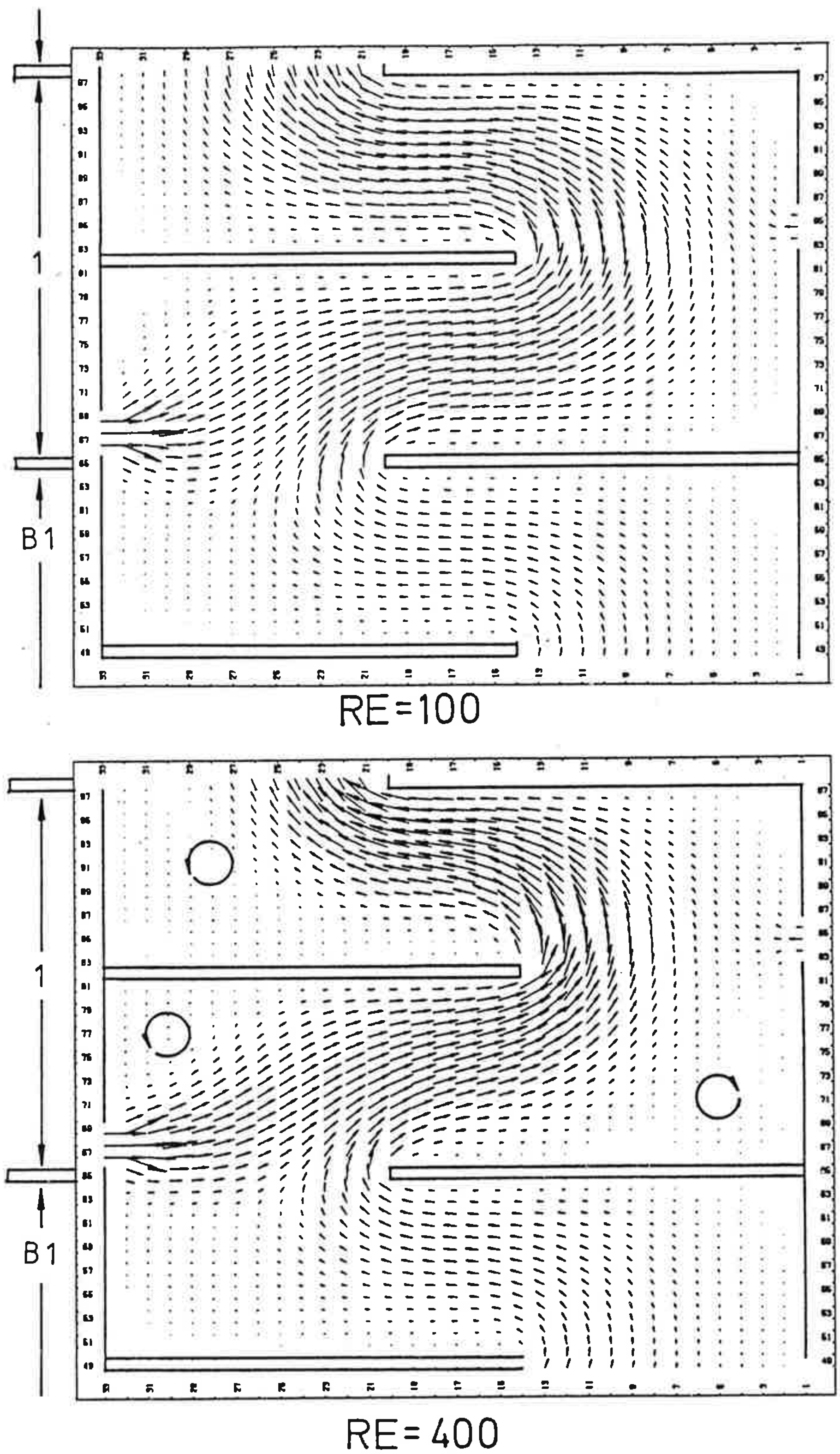

Fig. 7. Calculated flow between basement 1 and the second floor in the stairwell: Re = 100, and Re = 400.

rate inside the stairwell. The difference between the measurements and the theoretical model is in the range of 10%. These results indicate that it is reasonable to use this method for the simulation of the complex flow in stairwells.

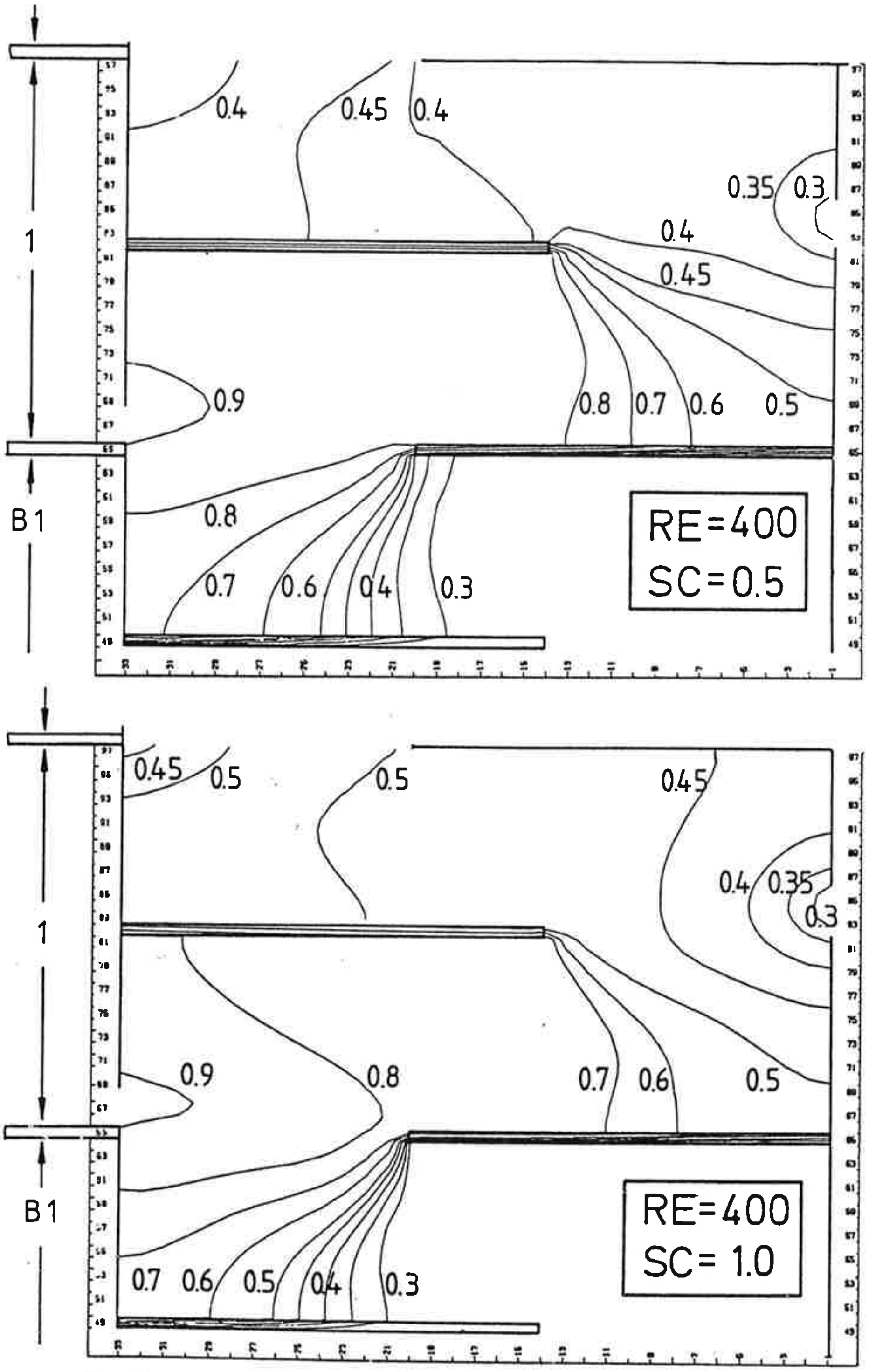

Fig. 8. Distribution of the germ concentration between basement 1 and the second floor in the stairwell: Re = 400, Sc = 0.5 and 1.0.

CONCLUSION

With respect to building design, especially regarding hospitals, the measurements recorded indicate that the transport of microorganisms depends strongly upon the difference in air temperature of the stairwell and its surroundings. In the case of a higher air temperature inside the stairwell, microorganisms are transported by air from the lower level to the top, due to the so-called chimney effect. This statement is in agreement with the fact that the infection rate increases with the height of hospitals or apartment houses. Direction and concentration of microorganism flow depends mainly upon the cracks caused by windows and doors in connection with the thermodynamic conditions. Only a knowledge of the air movements and the sources of microorganisms allows a prediction of the distribution of infections. From the measurements as well as the theoretical investigations it can be concluded that those parts of the hospital with a high risk of infection, e.g., surgery, should not be situated on the top floors. Otherwise special construction arrangements such as additional doors are necessary.

The results of the numerical calculations confirm that the physical model developed is generally able to predict the flow field and the distribution of microorganisms in a staircase. In comparison with the time-consuming measurements, the prediction procedure proposed is much more efficient in estimating the influence of various boundary conditions. However, a more precise prediction method requires improvement in the modelling of the physical transport processes as well as in the numerical method, especially at a higher Reynolds number.

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