# CALCULATION OF ROTATING AIRFLOWS IN SPACES BY CONFORMAL MAPPING

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SUMMARY

A method has been developed to calculate 2-dimensional rotating air flows in rooms by conformal mapping. The agreement with the velocities measured in a test room and a scale model is in general good except at places where the influence of the air jet is strong. The velocities depend upon the air inlet velocity, the place of the air supply opening and the roughness of the walls.

## 1. Introduction

Air flow in closed spaces is a subject of special interest in research of the indoor environment. But it is believed that knowledge of flows in closed spaces is also of interest in other fields of research.
Air flows can be investigated by:

- experimental research in test rooms,
- experimental research in scale models,
- theoretical models

If reliable theoretical models are available air flows in spaces can be predicted with far less effort than by experiments. Therefore many theoretical models have been developed solving the fundamental equations of transport of momentum and energy by numerical methods.
In closed spaces like rooms the air usually behaves as a rotating mass. Therefore in this research project an attempt has been made to give a mathematical formulation of a rotating flow within a boundary which obviously is not a circle but a rectangular if the flow is approxinated as 2-dimensional. Such a method will give a wider meaning to the concept of rotation and will require far less computer capacity than a numerical model. The reason is that no difference scheme with a large number of points is required and no iteration procedure of a large amount of data is needed. In fact this method proved suitable for a minicomputer having a storage capacity of 8 Kb. In order to investigate the applicability and shortcomings of this method experiments in a test room and in a scale model of this room were carried out.

## 2. General Concept

The air mass in a room can be subject to two kinds of forces:

- supply of air (air jet momentum),
- heating or cooling equipment (buoyancy forces).

The direction of these forces is usually not towards the center of gravitation and therefore the air mass is subject to an angular momentum causing a rotation of the air mass. At the walls skin friction will occur and in the corners of the room secondary vortices will cause extra loss of momentum. This gives an angular momentum opposite the angular momentum of the driving force, i.e. the air jet or the buoyancy force.
By fundamental law these two angular momentums should be equal which makes possible the calculation of an overall resistance coefficient. For a systematic approach some simplifications must be made:

a. The rotation of the air mass is 2-dimensional, i.e. takes place in a vertical cross section of the room determined by the length and the height.

b. The rotation is described by only one vortex covering the whole rectangular cross section.

Ad a. Experiments have been done with air blowing in from a slit over the full width of the room. From literature data [1] it is known that at the ratios between length, width and height of the test room and of the model used in our experiments the approximation of 2-dimensional flow is justified.

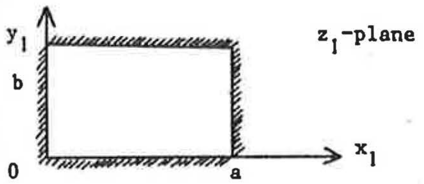
Ad b. At the ratio between the length and the height in our experiments this assumption is justified as has been verified by smoke tests in the scale model. In the corners small secondary vortices are present. If the length is more than about 2.5 times the height the flow breaks up in 2 vortices [2].
For the calculation of a rotating flow first the rectangular boundary has been transformed into a circle. This was possible by a succession of conformal mappings of one complex plane into another. The flow is first considered as being surrounded by a rotating circle. The fluid then rotates as a solid mass and the stream lines are concentric circles within the boundary circle. By reverse transformations the boundary circle is now transformed into a rectangular and the concentric inner circles become closed curves within the rectangular.
We now suppose that these closed curves are still the stream lines of the flow and that the mass flow between two stream lines is invariant for transformations. This means that velocities are relatively high at places where the stream lines are close together and relatively low if the stream lines are far from each other as is the case near the corners. This is analogous to the way potential flow problems are solved but in our case there is no potential flow.
In the experiments there was supply and exhaust of air which is not taken into account in this calculation. But the rotating air mass was much larger than the mass of supply air and therefore this calculation method was used.
It is clear that in this way the velocities can only be calculated from the center of the room until the outer edge of the boundary layers. In the relatively thin boundary layers the velocities decrease to zero at the walls but here we are more interested in the friction forces than in velocities.

## 3. Theory

### 3.a. Stream lines

First the transformation of the rectangular to the circle will be described.

In the complex plane $z_1$ the rectangular has the sides with dimensions a and b, see fig. 1.




$$z_1 = x_1 + i\, y_1$$

Fig.1. Rectangular in the $z_1$-plane

The first transformation is: $z_2 = \frac{\pi}{b} z_1$ (1)

The second transformation is: $z_3 = \cosh z_2$ (2)

Now the rectangular has been transformed into a half ellips, see fig.2.

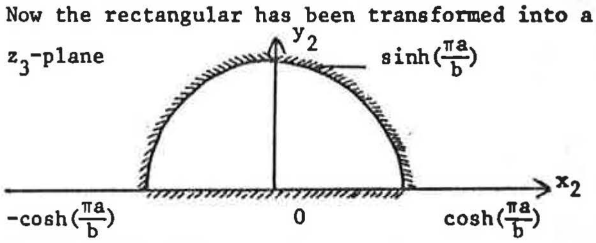



Fig.2. Half ellips in the $z_3$-plane

The length of the horizontal half axis is $\cosh(\frac{\pi a}{b})$ and of the vertical half axis $\sinh(\frac{\pi a}{b})$. If a>b the difference between these values is always below 0.25% and therefore these values are assumed to be equal. Under the condition a>b the rectangular has then nearly been transformed into a half circle, so it is always necessary that the largest side is taken as horizontal.

The third transformation is:

$$z_4 = z_3 + \frac{\cosh^2(\frac{\pi a}{b})}{z_3} \qquad (3)$$

This transforms the half circle into the lower half plane $y_4<0$, see fig.3.

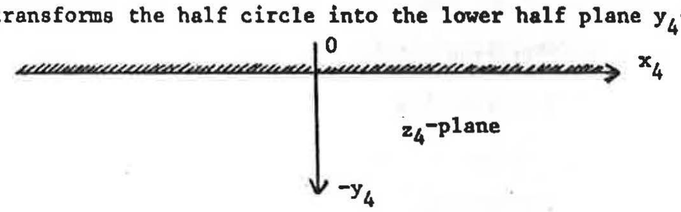



Fig.3. Half plane of $z_4$.

In the rectangular each point can be taken as the center of rotation. This point $z_{1c}$ in the $z_1$-plane is mapped into a point $z_{4c}$ in the $z_4$-plane by equation (1)-(3). The point $z_{4c}$ is replaced to the point -i, so the next transformation is:

$$z_5 = \frac{z_4 - x_{4c}}{-\, y_{4c}} \qquad (4)$$

This includes a horizontal shift over a distance $x_{4c}$ and a contraction with a factor $y_{4c}$.

The $z_5$ half plane is transformed into a circle with radius 1 by the following equation:

$$z_6 = \frac{z_5+i}{z_5-i} \tag{5}$$

In the appendix the equations in x and y for these transformations and the reverse transformations are given.

### 3.b. Velocities

In the $z_6$-plane a rotating flow like of a solid disk with angular velocity $\omega$ is assumed. For the absolute value and the direction of the velocity vector in the $z_6$-plane the following equations hold:

$$|v_6| = \omega\sqrt{x_6^{\,2} + y_6^{\,2}} \tag{6}$$

$$\phi_6 = -\ \mathrm{arctg}\ \left(\frac{x_6}{y_6}\right) \tag{7}$$

In the previous paragraph the assumption was made that the mass flow between two stream lines is invariant for transformation. If the mass flow between two stream lines close together is $d\psi$ then

$$d\psi = |v_i| \cdot |dz_i| = |v_{i+1}| \cdot |dz_{i+1}|$$

$\psi$ is called the stream function which is the general solution of the continuity equation.

In the $z_1$-plane the absolute value and the direction of the velocity then are:

$$|v_1| = |v_6| \cdot \left|\frac{dz_6}{dz_1}\right| = |v_6| \cdot \prod_{i=1}^{5} \left|\frac{dz_{i+1}}{dz_i}\right| \tag{8}$$

$$\phi_1 = \phi_6 - \arg\left(\frac{dz_6}{dz_1}\right) = \phi_6 - \sum_{i=1}^{5} \arg\left(\frac{dz_{i+1}}{dz_i}\right) \tag{9}$$

These equations are a result of the characteristic properties of conformal transformations that in a point an infinitesimal small line element is multiplied with a factor $\left|\frac{dz_{i+1}}{dz_i}\right|$ and turned over an angle $\arg\left(\frac{dz_{i+1}}{dz_i}\right)$ independently of the direction of this element.

### 3.c. Resistance coefficient

One of the input data for a calculation is the angular velocity $\omega$ and it is clear that there must be a relationship between its value and the resistance which the air flow meets at the walls and the corners by skin friction and secondary vortices.
The resistance which the flow meets can be expressed by an overall resistance coefficient.
As an example the case of an isothermal 2-dimensional jet from a vertical wall into the room is considered.

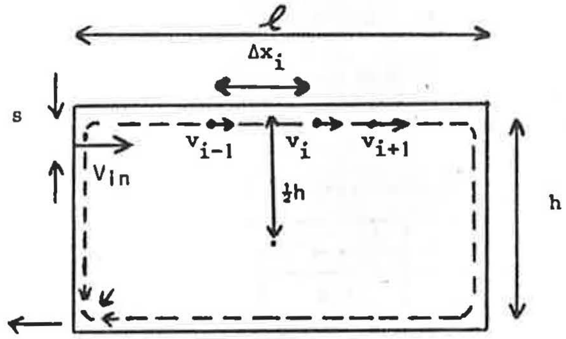



Fig.4. Isothermal jet from the back wall into a room.

The angular momentum caused by the jet per unit of width of the room is:

$$M_1 = \tfrac{1}{2}\rho V_{in}^{\,2} \cdot s \cdot \tfrac{1}{2}h \tag{10}$$

The air outlet causes no angular momentum because the air flows to the outlet opening from all directions and behaves there as a potential flow. Over a length $\Delta x_i$ the resistance force by skin friction is $C_f \cdot \tfrac{1}{2}\rho v_i^{\,2} \cdot \Delta x_i$.

This results in an angular momentum:

$$M_2 = C_f \cdot \tfrac{1}{2}\rho \left\{ \tfrac{1}{2}h \cdot 2\overset{\ell}{\Sigma}\Delta x_i \cdot v_i^{\,2} + \tfrac{1}{2}\ell \cdot 2\overset{h}{\Sigma}\Delta x_i \cdot v_i^{\,2} \right\} \tag{11}$$

The first term includes a summation along the floor and ceilings and the second term includes summation over the two vertical walls. In order to determine $M_2$ it is thus necessary to measure the velocity in a large number of points near the walls and just outside the boundary layers. It must be remarked that in equation (11) the secondary vortices which will be present in the two corners opposite the air inlet and air outlet are not taken into account. The velocities are very low there however and the contribution of the terms $v_i^{\,2}\Delta x_i$ are therefore negligable.

## 4. Experiments

A number of experiments in a climate room and a scale model 1:5 of this room have been carried out to test the validity of the calculation method. The experiments were isothermal, i.e. no heat sources were present. Air was blown in through a slit of 9 cm in the climate room and 1.8 cm in the model over the full width to give a two dimensional flow.
The exhaust opening was a slit with the same dimensions. The place of the inlet and exhaust openings are indicated in fig. 4 but in the climate room also experiments have been done with air blown in from the floor in the corner opposite the exhaust opening. The jet was then directed along the vertical wall. These two ways of air supply are representative for actual air conditioning systems. A smooth and a more rough material for the walls was used to investigate the influence on the velocities. In the climate room in a number of experiments a plate of 70 cm width was placed at an angle of 45° in the corners opposite the inlet and exhaust opening to eliminate the influence of secondary vortices for the most part.
The dimensions of the climate room are:

length 5 m
width 3.85 m
height 3.15 m

The dimensions of the scale model are a factor 5 smaller.
Tabel 1 gives a survey of the experiments.

| Exp.nr. | wall material | $V_{in}$, m/s | position air inlet |
|---|---|---|---|
| **Scale model** | | | |
| 1 | plexiglass | 1.0 | back wall |
| 2 | " | 0.5 | " |
| 3 | board | 1.0 | " |
| 4 | " | 0.5 | " |
| **Climate room** | | | |
| 5 | board | 0.5 | back wall |
| 6 | " | 1.0 | " |
| 7 | hard board | 0.5 | " |
| 8 | " | 1.0 | " |
| 9 | " | 1.0 | floor |
| 10 | " | 0.5 | " |
| 11 x) | " | 0.5 | " |
| 12 x) | " | 1.0 | " |
| 13 x) | " | 1.0 | back wall |
| 14 x) | " | 0.5 | " |

Table 1. Survey of the experiments

x) plates in the corners opposite the inlet and exhaust openings

The air velocities were measured with an anemometer suitable for a velocity range of 0.06- 2 m/s and insensible for the direction of flow. In the climate room measurements were done in 5 vertical planes in the length of the room.by automatically steered equipments. In this way the velocities were measured at 40 levels and 20 distances from the back wall i.e. in 800 points per plane. In the scale model the measurements were carried out in 4 vertical planes in 16x24 points, i.e. 384 points per plane.

## 5. Results

### 5.a. Velocity profiles

In the $z_6$-plane the radius of the circle to be transformed into the rectangular (5x3.15 m) is taken as 1 m. Forthe inner circles values of the radius of 0.1 m, increasing with 0.1 to 0.8 m, then increasing with 0.05 to 0.95 were selected. At each inner circle 36 points determined by $\phi$ values of $0^\circ$, increasing with $10^\circ$ to $350^\circ$, were selected for transformation. The corresponding points in the $z_1$- plane (rectangular) were obtained using equation (5b) to (1b) (see Appendix). The absolute value and direction of the velocity in each point was calculated using equation (8) and (9). For these calculations suitable values of $x_{1c}$, $y_{1c}$ and $\omega$ were required to give the best agreement with measurements.

Experimental values of the velocity (only absolute values) were obtained by linear interpolation between the velocities measured in the 4 points around the considered point of the transformed circle. The following interpolation formula has been used:

$$v = \tfrac{1}{4}\Big[v(i+1,\ j+1)+v(i,j+1)+v(i+1,j)+v(i,j)+$$
$$+\ \frac{2x-x_i-x_{i+1}}{x_{i+1}-x_i}\{v(i+1,j+1)+v(i+1,j)-v(i,j+1)-v(i,j)\}+$$
$$+\ \frac{2y-y_j-y_{j+1}}{y_{j+1}-y_j}\{v(i+1,j+1)+v(i,j+1)-v(i+1,j)-v(i,j)\}\Big] \qquad (12)$$

Fig. 5 shows some transformed circles and velocities calculated above the center of rotation ($\phi = 270^{\circ}$) which has been chosen here at the intersection of the diagonals. But fig. 6 shows that the center of rotation should be chosen higher than the half height to fit the experimental velocity profile. This is due to the influence of the jet along the ceiling caused by the air supply in the back wall at the upper corner. Very low velocities as predicted by the calculations are not observed experimentally. This is due to the anemometer which cannot indicate very low velocities and due to slow fluctuations which can be expected at low velocities.
Fig. 7-9 show some examples of theoretical and experimental velocity profiles along transformed circles near the walls ($R = 0.8$ and $0.85$) in the climate room and the model. For convenience the dimensions of the model are taken as equal to the climate room dimensions ($5\times3.15$ m$^2$). In fact these dimensions and the values of $\omega$ are a factor 5 smaller.
The direction of the flow is from $360^{\circ}$ to $0^{\circ}$ in fig. 7-9.
In fig. 5 the direction of rotation is clockwise in case of air supply from the back wall (left) and counter clockwise in case of air supply from the floor along the front wall (right side).
Especially in fig. 7 the influence of the jet is visible by the sharp rise of the experimental velocity curve between $340^{\circ}$ and $310^{\circ}$. At higher values of R this increase becomes even sharper and this is not explained by the theoretical curve at whatever value of $x_{1c}$ and $y_{1c}$. It means that the calculation method is not suitable for the jet near the inlet opening but for this other theories are available.
Table 2 shows the values of $\omega$, $x_{1c}$ and $y_{1c}$ which give the best agreement between theoretical and experimental velocity profiles along the transformed circles. The values are averaged over the 4 or 5 vertical planes. For the experiments in the climate room the same values could generally be used for all planes but for the model experiments, especially if $V_{in} = 1$ m/s, different values for each plane had to be used. The maximum deviation from the average value was then 15%.

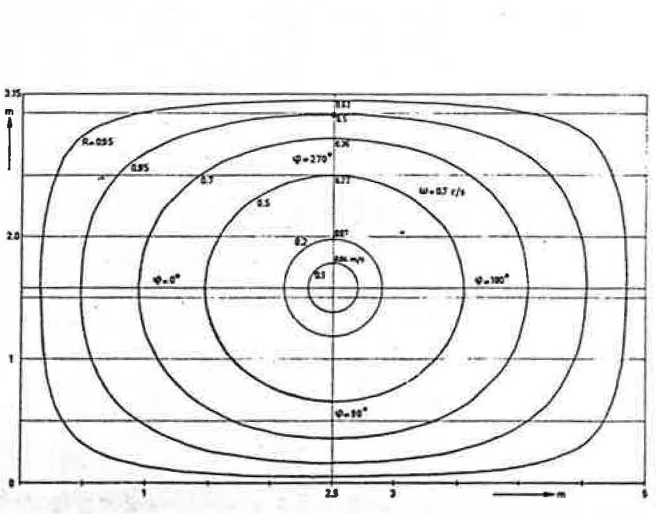


Fig. 5. Transformed circles and calculated velocities along the vertical axis ($\varphi = 270°$)

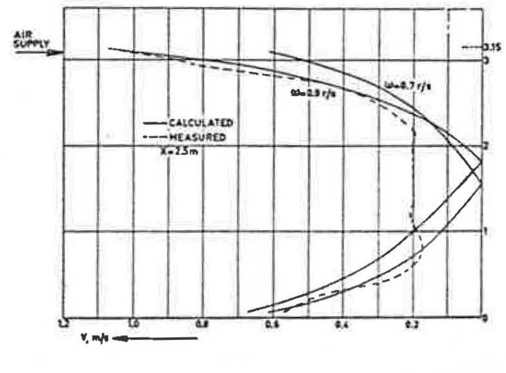



Fig. 6. Theoretical and experimental velocity profiles along the vertical axis ($\varphi = 90°$ and $270°$)

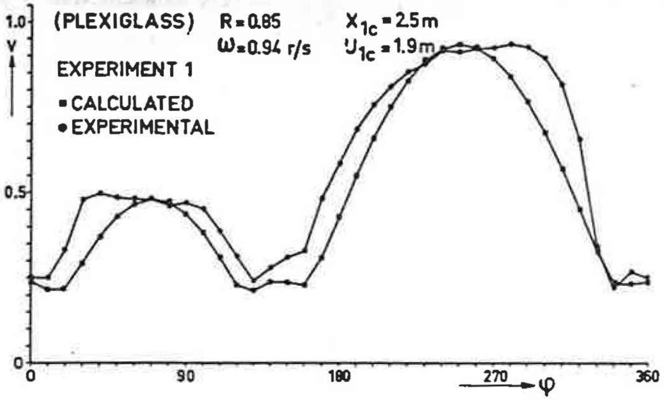



Fig. 7. Velocity profile in a plane in the plexiglass model along a transformed circle ($R = 0.85$)

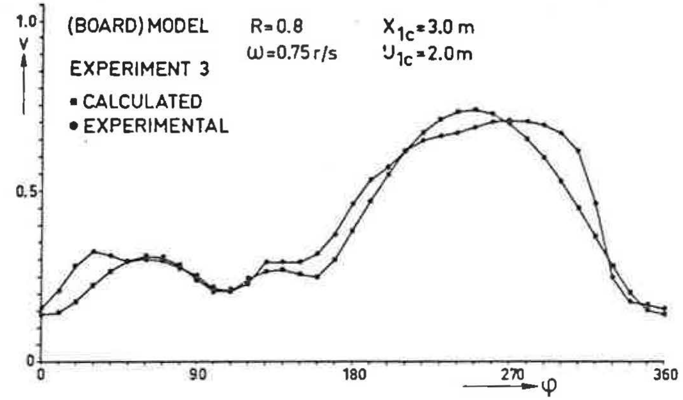



Fig. 8. Velocity profile in the board model along a transformed circle ($R = 0.8$)

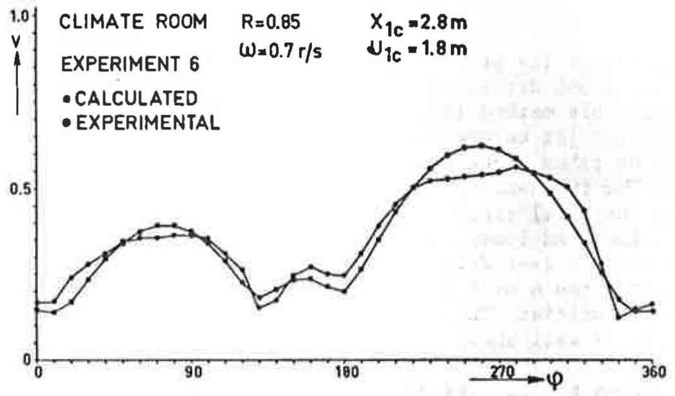



Fig. 9. Velocity profile in the climate room along a transformed circle.

5.b. Resistance coefficient

The angular momentum of the driving force (jet) on the air mass was calculated using equation (10). The terms between the brackets in the right hand side can also be calculated for each vertical plane and then averaged over the 4 or 5 planes for each experiment. Equating of the two formulae gives $c_f$.
Because the flow in the room and the model is turbulent it may be expected that $\omega$ is proportional to $V_{in}$. The value of $c_f$ however is determined by the squared values of $V_{in}$ and the local velocities near the walls just outside the boundary layers. Therefore it is worthwile to calculate also $\frac{\omega\sqrt{c_f}}{V_{in}}$ and see if this value is more or less constant for the experiments. Table 2 shows these values, together with $\omega$, $c_f$, $x_{1a}$ and $y_{1c}$.

| Experiment nr. | $V_{in}$ m/s | $\omega$, rad/s (average) | $c_f$ | $\frac{\omega\sqrt{c_f}}{V_{in}}$, rad/m | $x_{1c}$, m | $y_{1c}$, m |
|---|---|---|---|---|---|---|
| 1 | 1 | 0.957 | 0.0161 | 0.121 | 2.5-3 | 1.7-2 |
| 2 | 0.5 | 0.417 | 0.0223 | 0.124 | 2.3-3 | 1.8-1.9 |
| 3 | 1 | 0.719 | 0.0232 | 0.110 | 2.8-3 | 1.9-2 |
| 4 | 0.5 | 0.325 | 0.0310 | 0.114 | 2.5-2.8 | 1.8-2 |
| 5 | 0.5 | 0.35 | 0.0386 | 0.138 | 2.8 | 1.8 |
| 6 | 1 | 0.704 | 0.0325 | 0.127 | 2.8 | 1.8 |
| 7 | 0.5 | 0.375 | 0.0341 | 0.138 | 2.8 | 1.8 |
| 8 | 1 | 0.750 | 0.0289 | 0.128 | 2.8 | 1.8 |
| 9 | 1 | 0.450 | 0.118 | 0.155 | 3.1 | 1.95 |
| 10 | 0.5 | 0.250 | 0.124 | 0.176 | 3.1 | 1.95 |
| 11 | 0.5 | 0.256 | 0.0709 | 0.136 | 3.1 | 1.95 |
| 12 | 1 | 0.472 | 0.0936 | 0.144 | 3.1 | 1.95 |
| 13 | 1 | 0.720 | 0.0313 | 0.127 | 2.8 | 1.8 |
| 14 | 0.5 | 0.325 | 0.0423 | 0.134 | 2.8 | 1.8 |

Table 2. Values of $\omega$, $c_f$, $x_{1c}$ and $y_{1c}$ in the climate room and the model

5.c. Discussion

Fig. 7-9 indicate that the velocities can be calculated rather accurately by the above described method. Only for the jet near the inlet opening this method is not suitable.
The influence of the jet becomes clear from table 2 because $x_{1c}$ and $y_{1c}$ have to be taken higher than the half values of the rectangular sides. The influence of the roughness of the walls is demonstrated by the model experiments (1-4). Experiment 1 and 2 show higher $\omega$ values and lower resistance coefficients than experiment 3 and 4. In a less degree this is also noticed when comparing experiment 5 and 6 with 7 and 8. In most cases $c_f$ decreases with increasing velocities. This agrees with boundary layer theory which predicts lower wall shear stress coefficients with increasing Reynolds numbers. Experiment 9-12 show considerably lower $\omega$ values and higher $c_f$ values because the air is blown in from the floor and follows a wall of 3.15 m instead of 5 m. Plates in the corners give a small increase of $\omega$ but a strong decrease of $c_f$ in this case (exp. 11, 12). When blowing in air from the back wall the effect of plates in the corners is opposite but much smaller.
Experiments 9 and 10 show much higher values of $\frac{\omega\sqrt{c_f}}{V_{in}}$ than the other experiments. But for the experiments in the climate room with air inlet in the back wall and the model experiments this value can be considered as constant. One finds:

- model experiments (1-4): $\frac{\omega\sqrt{c_f}}{V_{in}} = 0.117$, max. deviation 6%.
- climate room experiments, air inlet in back wall (exp. 5-8, 13, 14): $\frac{\omega\sqrt{c_f}}{V_{in}} = 0.132$, max. deviation 4.5%

For air inlet from the floor such empirical relationships cannot yet be established. Much more experimental work is needed for that. But also the above given relationships need more experimental support and should still be considered as preliminary.

6. Conclusions

6.1. The calculation method described in this paper looks promising for predicting velocities in a room, except near the air inlet opening if the air behaves as a 2-dimensional rotating mass.

6.2. For the calculations reliable data for the coordinates of the center of rotation and the resistance coefficient are required. Much experimental work has still to be done for this.

6.3. The angular velocity can be calculated from the inlet velocity and the resistance coefficient by empirical relationships as given above.
These relationships are determined mainly by the dimensions, the position of the air inlet opening and the wall roughness.

## 7. Nomenclature

| | | |
|---|---|---|
| a | longest side of the rectangular | m |
| b | shortest side of the rectangular | m |
| $c_f$ | resistance coefficient (equation 11) | |
| h | height of the room | m |
| l | length of the room | m |
| M | angular momentum per m width | N |
| R | radius of a circle | m |
| s | seize of a slit | m |
| $V_{in}$ | inlet velocity | m/s |
| v | velocity | m/s |
| x,y | coordinates | m |
| $x_{1c}$, $y_{1c}$ | coordinates of the center of rotation in the rectangular | m |
| z | complex number ($z = x + i\,y$) | |
| $\rho$ | density of air | $kg/m^3$ |
| $\omega$ | angular velocity | rad/s |

indices

| | |
|---|---|
| 1, 2, ............., 6 | sequence of transformation |
| i, j | sequence of points in x and y direction |

## 8. References

[1] Nielsen, P.V. Flow in air conditioned rooms. Ph.D. Thesis, Techn. Univ. of Denmark, August 1976.

[2] Regenscheit, B. Modellversuche zur Erforschung der Raumströmungen in belüfteten Räumen. Staub 24, Januar 1964.

## Appendix. Equations of transformation

$$z_2 = \frac{\pi}{b} z_1 \text{ gives: } x_2 = \frac{\pi}{b} x_1 \text{ and } y_2 = \frac{\pi}{b} y_1 \tag{1a}$$

$$z_3 = \cosh z_2 \text{ gives: } x_3 = \cosh x_2 \cdot \cos y_2 \text{ and } y_3 = \sinh x_2 \sin y_2 \tag{2a}$$

$$z_4 = z_3 + \frac{\cosh^2(\frac{\pi a}{b})}{z_3} \text{ gives: } x_4 = x_3\left(1 + \frac{\cosh^2(\frac{\pi a}{b})}{x_3^2+y_3^2}\right) \text{ and}$$

$$y_4 = y_3\left(1 - \frac{\cosh^2(\frac{\pi a}{b})}{x_3^2+y_3^2}\right) \text{ and} \tag{3a}$$

$$z_5 = -\frac{z_4 - x_{4c}}{y_{4c}} \text{ gives: } x_5 = -\frac{x_4 - x_{4c}}{y_{4c}} \text{ and } y_5 = -\frac{y_4}{y_{4c}} \tag{4a}$$

$$z_6 = \frac{z_5+i}{z_5-i} \text{ gives: } x_6 = \frac{x_5^2+(y_5^2-1)}{x_5^2+(y_5-1)^2} \text{ and } y_6 = \frac{2x_5}{x_5^2+(y_5-1)^2} \tag{5a}$$

The reverse transformations are:

$$x_5 = \frac{2y_6}{(x_6-1)^2+y_6^2} \text{ and } y_5 = \frac{(x_6^2-1)+y_6^2}{(x_6-1)^2+y_6^2} \tag{5b}$$

$$x_4 = -x_5 \cdot x_{4c} + x_{4c} \text{ and } y_4 = -y_5 \cdot y_{4c} \tag{4b}$$

If $x_{41} = \left\{0.5\left(x_4^2-y_4^2-4\cosh^2(\frac{\pi a}{b})\right)+\left(0.25\left(x_4^2-y_4^2-4\cosh^2(\frac{\pi a}{b})\right)^2 + x_4^2\, y_4^2\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}}$, then

$$\left.\begin{aligned} x_3 &= 0.5\,(x_4-x_{41}) \text{ if } x_4 > 0 \\ x_3 &= 0.5(x_4+x_{41}) \text{ if } x_4 < 0 \\ y_3 &= \frac{x_3 y_4}{2x_3-x_4} \end{aligned}\right\} \tag{3b}$$

If $x_{31} = \left\{-0.5(x_3^2-y_3^2-1)+\left(0.25(x_3^2-y_3^2-1)^2+x_3^2y_3^2\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}}$ and

$x_{32} = \frac{x_3 y_3}{x_{31}}$, then :

$$\left.\begin{aligned} x_2 &= 0.5\,\ln\left((x_3+x_{32})^2+(y_3+x_{31})^2\right) \\ y_2 &= \operatorname{arctg}\left(\frac{y_3+x_{31}}{x_3+x_{32}}\right) \text{ if } x_3 > 0 \\ y_2 &= \operatorname{arctg}\left(\frac{y_3+x_{31}}{x_3+x_{32}}\right) + \pi \text{ if } x_3 < 0 \end{aligned}\right\} \tag{2b}$$

$$x_1 = \frac{b}{\pi} x_2 \text{ and } y_1 = \frac{b}{\pi} y_2 \tag{1b}$$

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