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Checking of simulation models in a ventilation test room

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Synopsis

Checking models of thermal behaviour or ventilation of a room can be performed in special test cells. At EMPA a ventilation test chamber with several experimental facilities has been designed and built. The inside wall surface temperatures of the chamber can be controlled using a software model which simulates the thermal behaviour of a real wall. As a test case a heated office room was calculated with TRNSYS and compared with measurements made in the chamber.

As an example of checking ventilation models the validation of a CFD-model of a horizontally pivoted window is presented. A parameter analysis was made with this model and the result were compared with the results of a simplified model which is included in the multizone airflow calculation programm COMIS. This simplified model is based on the Bernoulli equation and therefore it needs a discharge coefficient C_d. As a result of the parameter analysis a linear function for the C_d value was found.

List of symbols

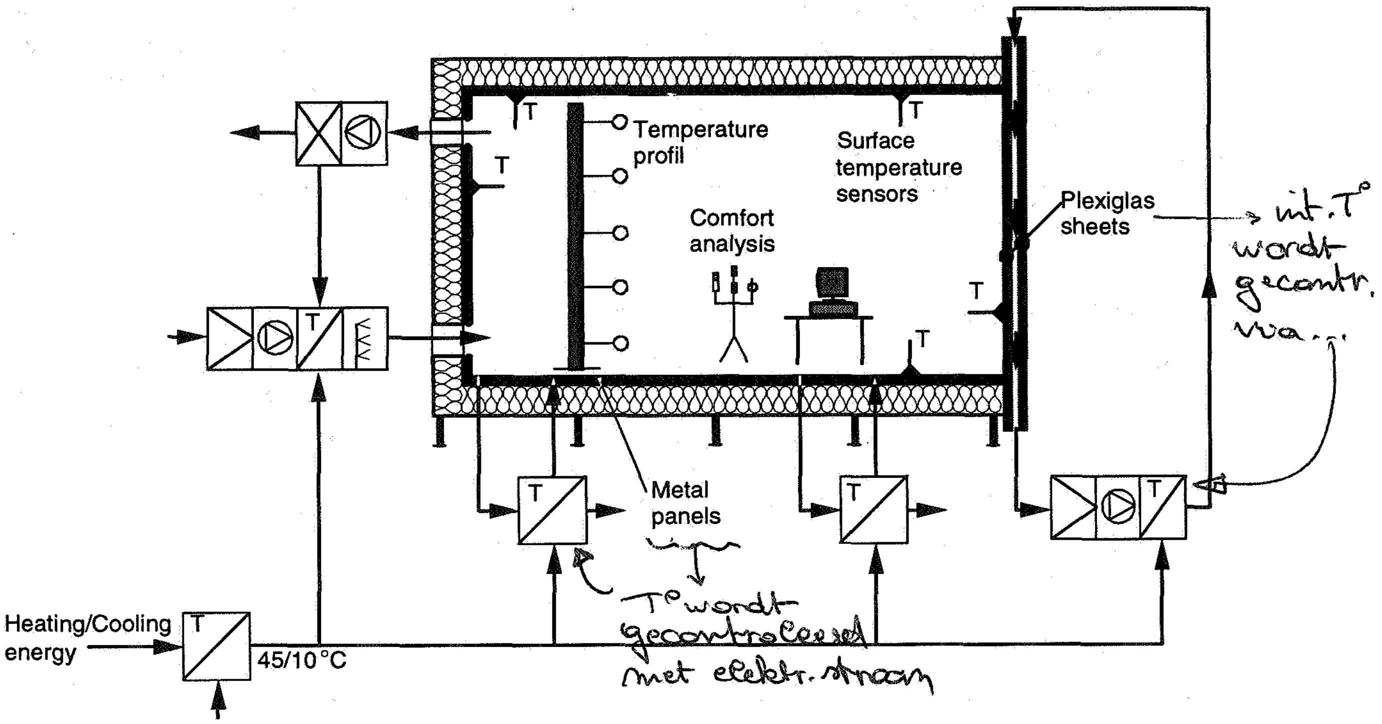
α	tilting angle [°]
C_d	discharge coefficient [-]
c_1	concentration before window was opened in room 1 [ppm]
c_2	concentration before window was opened in room 2 [ppm]
Δc	average of the changes of the concentrations in room 1 and 2 [ppm]
Δc_1	change of the concentration in the room 1 [ppm]
Δc_2	change of the concentration in the room 2 [ppm]
H	height [m]
H_a	height of the pivoting axis [m]
$\dot{m}$	massflow [kg/s]
$\dot{m}_{12}$	massflow from room 1 to room 2 [kg/s]
$\dot{m}_{CFD}$	massflow calculated with the CFD-model [kg/s]
$\dot{m}_{Bernoulli}$	massflow calculated with the Bernoulli-model [kg/s]
Δp	pressure difference [Pa]
ρ	air density [kg/m^3]
t	opening time period [s]
V	volume of one room [m^3]
$w(z)$	width of the opening at the level z [m]
W	width of the window [m]
z	level [m]

1 The ventilation test chamber

For the investigation of room ventilation a test chamber was built at EMPA. This chamber can be used to model the thermal and aerodynamic behaviour in real size.

1.1 Chamber and conditioning equipment

The chamber has a maximum floor area of 6.1m x 4.6m and a maximum height of 3m and can be adjusted to smaller length, width or height. Two walls, the floor and the ceiling are constructed of water carrying metal panels. The other two walls are transparent to allow for air flow visualization viewed from outside the room. These walls are built with two plexiglas sheets forming a channel through which conditioned air is flowing. By controlling the water- or air-temperatures respectively it is possible to adjust the inside surface temperatures. The whole surface is devided in 10 separate temperature zones. An air handling unit delivers conditioned air to the room through air terminals which can be placed anywhere between the metal panels of the room envelope. An overview of the conditioning equipment is given in figure 1.



int. T° wordt gecontr. via ...

T° wordt gecontroleerd met elektr. stroom

Fig. 1: Conditioning equipment and measuring systems

1.2 Control system and data acquisition

All the conditioning parameters appear on a PC monitor and can be controlled manually or by a time step program. The wall surface temperatures are measured directly on the surfaces and are used for the closed-loop control of the water supply temperatures. In addition each surface temperature zone is equipped with heat flow sensors. This allows to control the surface temperature dynamically as if it would be the surface of a thermally heavy wall making up the envelope of the test room. The heat flow values are used in a finite differences model containing the thermal capacity and conductivity parameters of the wall. The temperature of the wall layers is calculated with the software model giving the actual surface temperature which is the setpoint of the water conditioning equipment.

Measuring systems in the room include temperature and velocity sensors and a tracer gas system. The data acquisition stores the measurements in a database from where they can be retrieved in the desired combinations.

1.3 Investigation possibilities - a test case

The thermal and ventilation characteristics of different rooms can be established in the test chamber on 1:1 scale. This allows studies of thermal comfort and ventilation effectiveness of a variety of different rooms. Also very important is the possibility to investigate the convective interaction of the air with the simulated thermal mass of the envelope.

As a test case a heated office room was calculated with the TRNSYS simulation software and also investigated in the laboratory. Several time varying energy transfers like transmission and infiltration loss to the outside, a solar input and a thermostatic heating element as a balance of the total energy were taken into account. In the laboratory the dynamic surface temperature of the exterior wall was controlled by the time varying outside temperature of the wall model and the solar energy was established by light bulbs radiating on the heatflow sensors which control the dynamic temperature of the floor. The comparison between calculation and experiment showed agreement in the wall and room temperatures and partly in the heating power, but during the time phases of low heating power discrepancies were observed. This experiment showed that the dynamic wall surface conditioning with a thermal model is a very efficient feature for the investigation of the thermal behaviour of ventilated rooms.

2 Model validation of a horizontally pivoted window

Measurements in the ventilation test chamber were used to validate a CFD-model of a horizontally pivoted window. Results from this model were compared with the results from a simplified model based on the Bernoulli equation. This was made to find correct values for the discharge coefficient C_d for the Bernoulli-model. The multizone airflow calculation program COMIS includes the Bernoulli-model for different types of large openings [1], [2]. The discharge coefficient C_d is well known for large rectangular openings, but not for horizontally pivoted windows [3], [4].

2.1 Measurements

The chamber was divided into two rooms, one with cold air representing the outside and one with warm air representing the inside. The partition-wall included the investigated horizontally pivoted window. As the test room does not have two separate air conditioning systems, the different air temperatures in both rooms were enforced by controlling the wall panel temperatures. Such, a maximum temperature difference of 17°C could be achieved.

At the beginning of each experiment, the investigated window in the partition was closed. Then the window was opened and the time was measured until the front of the cold airstream passes the point b (figure 2). This was made by filling the cold room with smoke before the window was opened, to visualize the cold airflow entering the warm room.

To determine the airflow quantitatively, SF_6 was injected and mixed by a fan in the warm room until a homogenous concentration of about 6 ppm was reached. Then the window was opened during a short time period. After closing the window the air in both rooms was mixed up by a fan until the concentrations were homogenous again (figure 3).

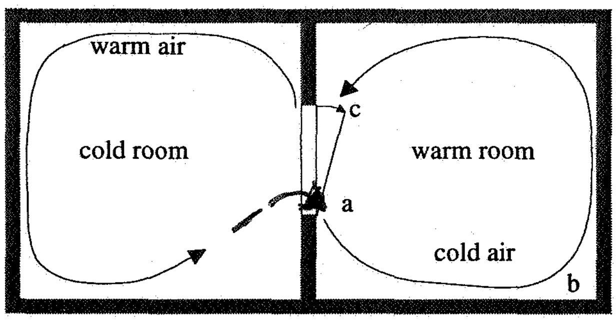


Fig. 2: Trace of the air after the window has been opened

Selected opening times were below the time measured as described above to ensure a constant tracergas concentration and massflow of the airstream during the experiment.
The massflow can be determined using:

$$\dot{m} = \frac{\Delta c \cdot V \cdot \rho}{(c_1 - c_2) \cdot \Delta t} \qquad \text{with:} \qquad \Delta c = \frac{\Delta c_1 + \Delta c_2}{2} \qquad (1)$$

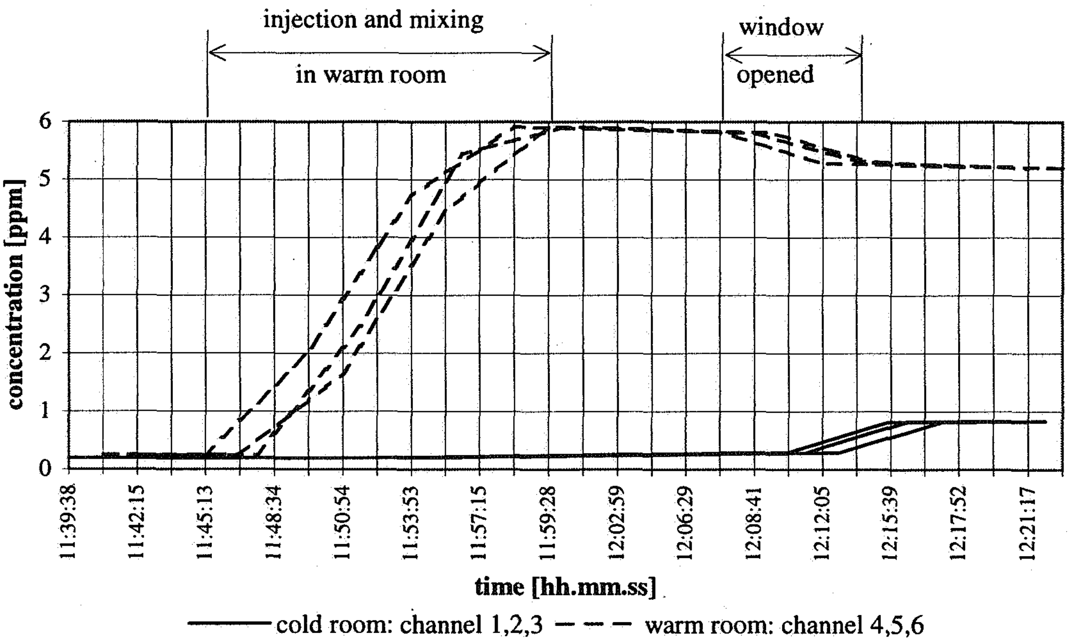


Fig. 3: Example of a tracergas (SF_6) measurement during an experiment

2.2 CFD-model

The CFD-model was made using the program FloVent [5], [6]. The whole test chamber including the partition and the investigated window was modeled. The window was modeled without the frame. The tilted side of the window had to be represented by small rectangular elements (figure 4). Turbulent flow was modeled using the k-ε-model and walls were adiabatic. Start temperatures in the two rooms have been input. In the real test chamber start temperatures were established by heat transfer from inside wall surface. Therefore in the model the airflow pattern of the room is not the same as shown in figure 2, were the incoming flow is warmed up on the floor surface and then rises up. In the model the incoming air stays on the floor and warms up much slower by heat transfer from the warm air above. As the opening time period were selected short enough, this has no effect to the flow in the window. The transient flow after the window has been opened shows also some differences to the reality: In the model, the temperature of that volume of air which is between the tilted side of the window and the plane of the wall is at the start equal to the inside temperature. As a result the flow will be in the first seconds the same like the flow in a totally opened window. In reality, opening the window will cause some turbulence which mixes up cold and warm air in that region right from the beginning. As we took an average massflow over the whole opening time, this effect did not influence the result significantly. Figure 4 shows the temperature distribution calculated with the CFD-model for the situation 4 seconds after the window has been opened.

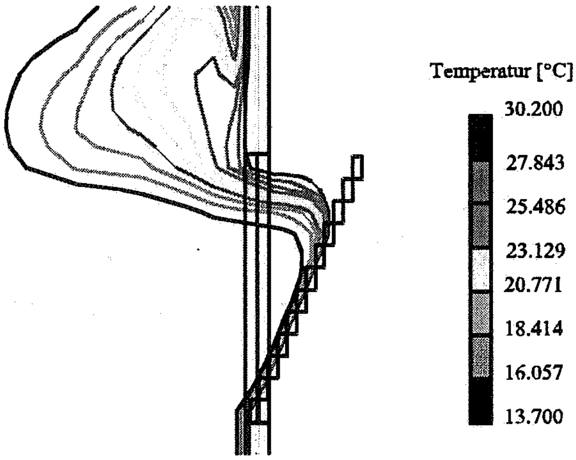


Fig. 4: Temperatures calculated with FloVent

2.3 Validation of the CFD-model with results of the measurement

The dimensions of the investigated window are: Height = 1.14m; Width = 0.78 m
Results from measurement and CFD-calculation are shown in the following table:

α [°]	90	18.67	13.6	8.55	90	18.67	13.6	8.55
ΔT [°C]	10	10	10	10	17	17	17	17
$\dot{m}$ Measurement [kg/s]	0.147	0.050	0.036	0.024	0.175	0.070	0.047	0.014
$\dot{m}$ CFD [kg/s]	0.149	0.047	0.037	0.017	0.196	0.059	0.044	0.023
relative difference [%]	1.3	6.4	5.5	41.2	10.7	18.6	6.4	39.1

Analysis of the measurement data showed that in cases with more than 10% relative difference between measurement and CFD-calculation, the measurement values were not correct due to several reasons. That means the CFD-model is well calibrated for the comparison with the Bernoulli-model. For small tilting angles (≤ 10°) convergence was more difficult to achieve using the current code.

2.4 Bernoulli-model

The massflow in large openings based on the Bernoulli equation is:

$$\dot{m}_{12} = C_d \int_0^H \sqrt{2\rho(z) f_{12}(z)} \cdot w(z) \cdot dz \qquad \text{with:} \qquad f_{12}(z) = \begin{cases} \Delta p(z), & if \quad \Delta p(z) > 0 \\ 0 & , if \quad \Delta p(z) < 0 \end{cases} \tag{2}$$

$$\dot{m}_{21} = C_d \int_0^H \sqrt{2\rho(z) f_{21}(z)} \cdot w(z) \cdot dz \qquad \text{with:} \qquad f_{21}(z) = \begin{cases} \Delta p(z), & if \quad \Delta p(z) < 0 \\ 0 & , if \quad \Delta p(z) > 0 \end{cases} \tag{3}$$

The geometry of the large opening is described with w(z). Figure 5 shows the geometry of a horizontally pivoted window. In the used model it is assumed that the flow is strictly horizontal. That means air at height z flows through two rectangular apertures in series as shown in the figure 5. The width of the equivalent aperture is as follows:

$$w(z) = \begin{cases} W & , \quad if\ (z < H_1)\ or\ (z > H_2) \\ \sqrt{\dfrac{(|H_a - z| \cdot \tan\alpha)^2 \cdot W^2}{(|H_a - z| \cdot \tan\alpha)^2 + W^2}} & , \quad if \quad H_1 < z < H_2 \end{cases} \tag{4}$$

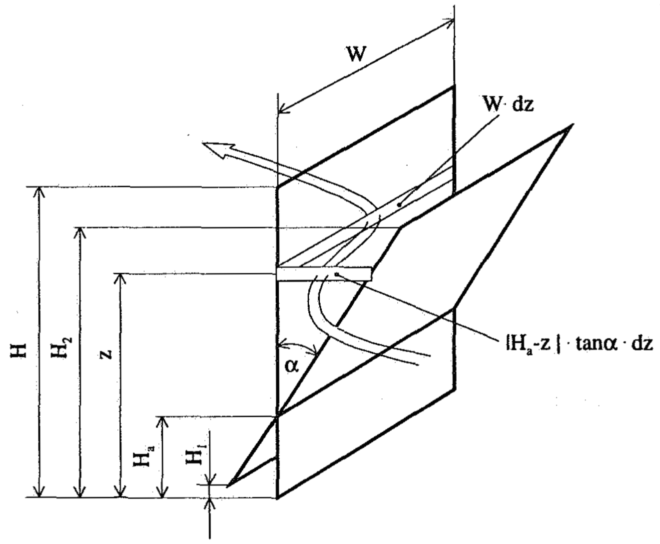


Fig. 5: Geometry of a horizontally pivoted window

2.5 Comparison between CFD- and Bernoulli-model

The tilting angle, the ratio of height and width of the window, and the temperature difference has been varied for the comparison of the two models. Setting $C_d = 1$ in the Bernoulli-model the correct C_d could be identified as:

$$C_d = \frac{\dot{m}_{CDF}}{\dot{m}_{Bernoulli}} \tag{5}$$

With linear regression the following relation was found as:

$$C_d = 0.0147 \cdot \alpha - 0.0928 \cdot \frac{H}{W} + 0.04116 \qquad (6)$$

The C_d-value is not dependent on the temperature difference, which means the Bernoulli-model is describing correctly the effect of the temperature difference.
In the current version 2.1 of COMIS this relation can be input by the user, but in future versions equation (6) will be included in the code.

3 Conclusions

- The ventilation test chamber has shown to be suitable for checking the results of ventilation and thermal simulations.
- The dynamic wall surface conditioning with a thermal model is a very efficient feature for the investigation of the thermal behaviour of ventilated rooms.
- The discharge coefficient C_d for the Bernoulli-model of a horizontally pivoted window is found to be a function of tilting angle and the ratio of height and width of the window with values between 0.36 and 0.58. With this function, the simplified model can be applied with more reliability, since up to now mostly C_d values for rectangular openings were used also for horizontally pivoted windows.

Acknowledgments

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