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CFD-SIMULATIONS FOR EVALUATION OF THERMAL COMFORT IN SPARSELY OCCUPIED LARGE ROOMS

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SUMMARY

Faulty design of ventilation and heating of large rooms are some times costly to rectify. There is a demand for methods which can be used to achieve the best possible evaluation of design proposals for indoor environments.

In this work, methods using computational fluid dynamics (cfd) are described, applied and discussed.

It is found to be most essential that approximations and boundary conditions to be used in the numerical model are properly applied.

It is also found that the computational grid chosen is very important in order to achieve a correct solution.

A way of computing and presenting graphical results for thermal comfort, based on cfd-computations, is demonstrated and found easily interpreted.

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INTRODUCTION

In the process of designing an indoor environment, specifications for thermal comfort, to be required in different zones of occupancy, have to be set. A sound reference for setting such specifications would be the International Standard ISO 7730[1].

Common knowledge, experience from earlier work with similar design, and the use of simplified calculations and building energy simulation programs are all available to contribute to a "best possible" proposal for design of an indoor environment.

Prior to starting the construction work for a building, it is essential that the proposed design is evaluated in order to avoid poor thermal comfort conditions to be experienced locally when the building is completed. Thus, in such evaluations of design proposals, the best available tools should be utilized for predictions.

The objective of this paper is to contribute to the development and to the use of cfd-simulations as tools for evaluating design proposals for atria and other large enclosures.

In order to be a proper tool for the evaluation process, some demands have to be met by the cfd-program itself, by the application of boundary conditions and other approximations, and by the interpretation of the results.

In this work, an atrium is considered. Boundary conditions are presented, cfd-simulations are performed and results are presented and discussed along with temperature measurements for the atrium. Cases considered for simulations are a night- and a day-condition in the month of March. One additional case for a day-condition in July is also presented.

THE CFD-SIMULATION PROGRAM

The computational fluid dynamics (cfd) program being applied is KAMELEON. The code has been developed at NTH-SINTEF Division of Thermodynamics, The Norwegian Institute of Technology [2].

This simulation program is capable of solving two- or three-dimensional steady state or transient time-averaged equations for conservation of mass, momentum, energy, turbulent energy and dissipation of turbulent energy by the application of finite-volume considerations.

The $k - \epsilon$ model of turbulence, basically as published by Jones and Launder[3] , is being used. The turbulence model is described by Tjelflaat and Frydenlund[4].

The finite difference equations are solved in a staggered grid. One of several options for differencing is chosen. Upwind differencing is the default one. A numerical integration procedure called SIMPLEC is applied to iterate towards a converged solution. The numerical solution procedure is basically as described by Patankar[5].

The program code is written in FORTRAN and is vectorized to run efficiently on CRAY computers. Pcs and work stations are used for pre- and post-processing of data.

THE ATRIUM

Building description

The atrium used for the present study is one of three similar atria built as parts of an extension to existing buildings on the campus at The Norwegian Institute of Technology.

The atrium has been used for several studies. A complete description of the building construction and its heating and ventilating system can be found in a review of Norwegian atria by Hestnes[6].

The main dimensions for the atrium considered is the length, the width and the height being 46 m, 10 m and 16 m respectively. The total volume of the atrium is 6624 m^3.

The roof and the end-walls are glazed and are facing the outdoor environment. The U-value for those glazed areas is $U = 2.1 W / m^2 K$.

The side walls and the floor are having an average U-value $U = 3.2 W/m^2K$ and are separating the atrium volume from office areas and service areas being heated to a temperature about 20°C in winter time. One of the side-walls and the floor are of heavy construction while the other side-wall is of light construction and with an outer covering of venetian blinds. The latter wall is facing southwards.

During most of the year, supply air to the atrium is admitted only by infiltration along the sealing around the smoke ventilation hatches in the glazed end walls. Air is leaving the atrium partly by mechanical exhaust to the adjacent buildings and partly by exfiltration along the sealing around the smoke ventilation hatches in the roof. The smoke ventilation hatches are normally activated to achieve increased ventilation and thereby free cooling on hot summer days.

The atrium is partly heated by the heat loss from the adjacent buildings. However, the main heating and compensation of drafts is by convectors located at several height levels close to the end-walls. The atrium is characterized as sparsely occupied. Heat gain from occupants, lighting and equipment is small and is not accounted for in the simulations described below. Except for mid-winter, diffuse and direct solar radiation are the main sources for heat gain during day-time.

The atrium is situated at latitude 63.3°N and at elevation 50 m. The atrium is shown in Figures 1 and 2.

Fig. 1. Inside view of the atrium. From [6].

Fig. 2. Overview of the building complex. The atrium considered is the leftmost of the three parallel atria shown. From [6].

The atrium was monitored for several periods in 1987 in order to evaluate the thermal comfort. Temperatures at different height levels in the middle of the atrium and at a distance of 10.5 or 11.5 m from the western end-wall were measured. The measurements are reported by Baglo[7] and Jacobsen[8].

Tracer gas technique was used to evaluate the air change rate for ventilation. Measurements taken with closed hatches showed an air change rate of 0.5. The average temperature in the atrium was 22°C while the outdoor temperature was 12°C during measurements. Air change rates for other temperature conditions than the one measured, were estimated on the basis of the measured values and simple expressions for natural ventilation by chimney effect in the atrium. Possible wind-effects were not accounted for. Wind velocities during air change measurements are reported to 2 m/s.

Boundary conditions for March-simulations

Two simulations were performed; one for a night-condition and one for a day-condition. The measurements were taken on March 14th, 1987. The sky was heavy overcast.

The night-condition was set at 4:00 a.m. The outdoor temperature was measured to 1°C while the average indoor temperature in the atrium was about 18°C. The infiltration rate has been estimated to $\dot{V} = 1.21\,m^3/s$ which corresponds to 0.66 air changes per hour.

The day-condition was set at 2:00 p.m. The outdoor temperature was measured to 3°C while the average indoor temperature in the atrium was about 20°C. The infiltration rate was also here estimated to $\dot{V} = 1.21\,m^3/s$.

A nearly uniform numerical grid was chosen for the simulation. In length-, width- and height-direction, 52, 12 and 29 grid-cells were used respectively. However, a relatively fine grid was used close to the end-walls compared to the grid used in the middle of the room.

The heat fluxes through the different boundaries were calculated on the basis of the U-values for the glazing and the average temperature differences between the air temperature for the atrium and for the surrounding environments. The calculated heat fluxes were then used as boundary conditions for the numerical simulations. The impact of thermal mass was assumed negligible. Thus, a steady state case was considered. The heat supply from the convectors on the end walls had not been measured and was therefore estimated on the basis of a heat balance for the atrium. The convectors were modelled as internal heat sources in the numerical representation.

For the day-condition, the gain from diffuse solar radiation was calculated by using the building energy simulation code FRES[9]. The power from the diffuse solar radiation was modelled by evenly smearing it out as heat sources on the inner side of the side walls of the atrium.

Boundary conditions for July-simulation

One simulation was performed for day-condition. The measurements were taken on July 18th, 1987. The sky was clear.

The conditions for the simulation was set at 11:00 a.m. The outdoor temperature was measured to 23.5°C while the average and maximum indoor temperature in the atrium were 32°C and 40°c respectively. Temperatures in adjacent office buildings were measured to 26°C. The infiltration rate was now estimated to $\dot{V} = 0.47 m^3/s$.

A different approach was here tried out for the boundary conditions. The inner surface temperatures for all surfaces were calculated on the basis of U-values, temperature differences, absorbed solar heat gain and outdoor and indoor heat transfer coefficients. Detailed calculations are reported by Kvikne[10]. The inner temperatures on surfaces were now given as boundary conditions. Good estimates for surface temperatures are, in addition to values for air velocities, turbulence intensity and air temperature, required in order to evaluate thermal comfort conditions.

The direct solar radiation is, at the time chosen, only admitted into the atrium through the glazed roof and is only striking the upper part of one of the side walls. In fact, the direct solar radiation is heating only the venetian blinds located 1 m apart from the wall itself. The solar heating of the venetian blinds is causing a thermal plume convecting heat from the blinds to the upper part of the atrium volume.

The atrium has an extension in the western end. The northern of the two adjacent office buildings has a larger length compared to the main atrium. The extension is glazed and is facing southwards. The solar heat gain from the atrium appendix is modelled as an internal heat source in the northwest corner of the numerical model representation of the atrium.

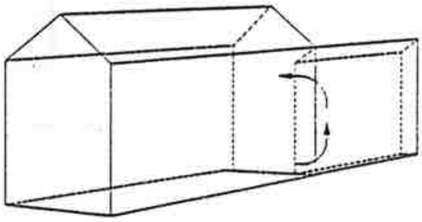

Fig. 3. Atrium extension in western end. Typical pattern of thermal convection flow is indicated.

RESULTS FROM SIMULATIONS

The March-simulations

Temperature measurements were taken 11.5 m from the western end-wall. Results from the simulation of the night-condition are shown in Figure 4 for a crossection at that location in the atrium.

Results for the same crossection from the simulation of the day-condition is shown in Figure 5.

Stratification in the temperature distribution can be seen for both cases. However, the temperature gradient is below 0.2°C/m for both cases and lowest for the night-condition.

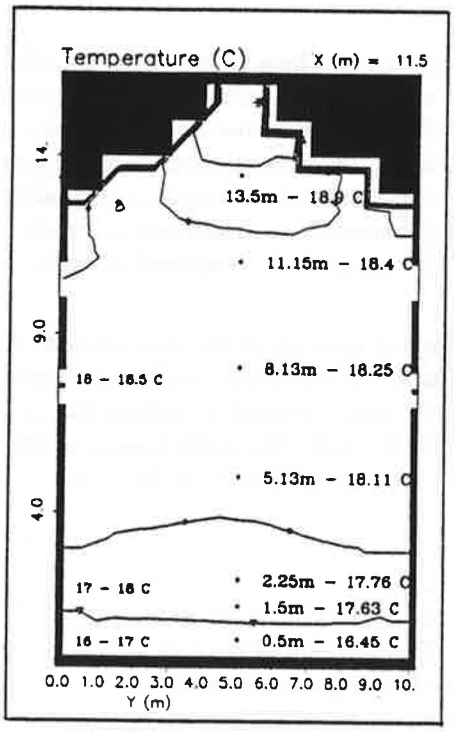

Fig. 4. Results from simulations of March, night-condition. Isolines and values for some points for temperature in the atrium are shown.

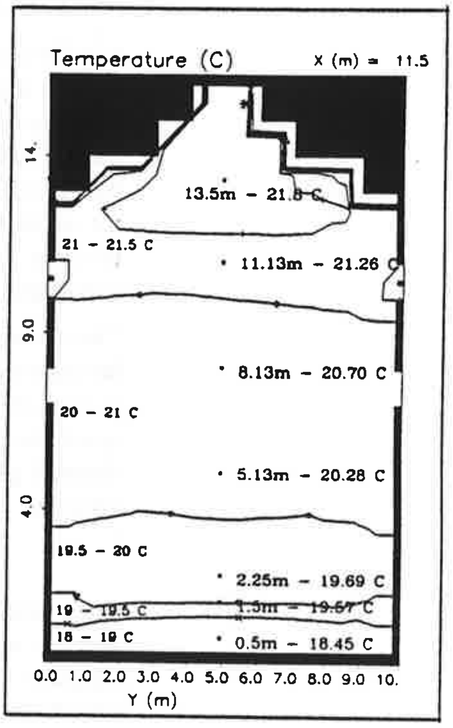

Fig. 5. Results from simulations of March, day-condition. Isolines and values for some points for temperature in the atrium are shown.

The July-simulations

Temperature measurements were taken 10.5 m from the western end-wall. Results from the simulation of the day-condition are shown in Figure 5 for a crossection at that location in the atrium. Despite the strong convection flows caused by direct solar radiation on the south-facing wall, a distinct thermal stratification occurs. The average vertical temperature gradient is here about 0.6°C/m.

Isolines for mean speed and velocity vectors for the same crossection is shown in Figure 6. The solar heating of the venetian blinds is seen to cause a upward flow with velocity 0.25 m/s.

Isolines for mean speed are also shown for a longitudinal section in Figure 7. The influence from the solar heating of the atrium appendix on the western end is clearly seen. The resirculating flows caused by solar heating are seen to be damped in the upper part of the atrium, Velocities in the zone of occupancy are seen to stay below 0.1 m/s.

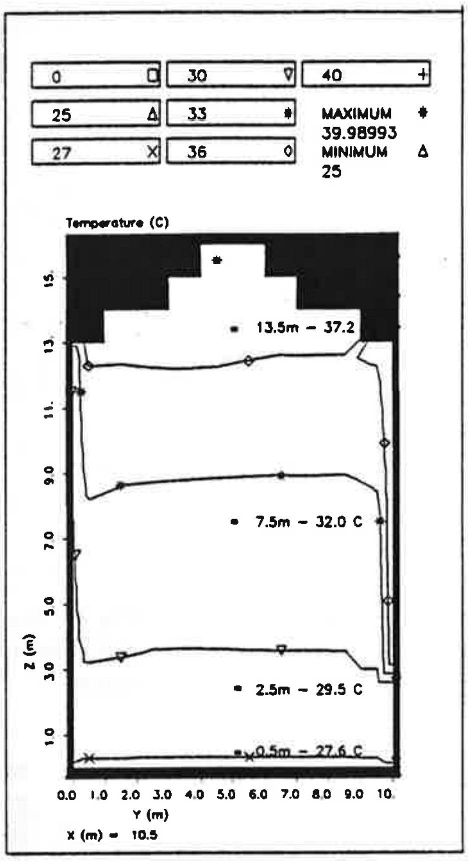

Fig. 6. Results from simulations of July, day-condition. Isolines and values for some points for the temperature in the atrium are shown.

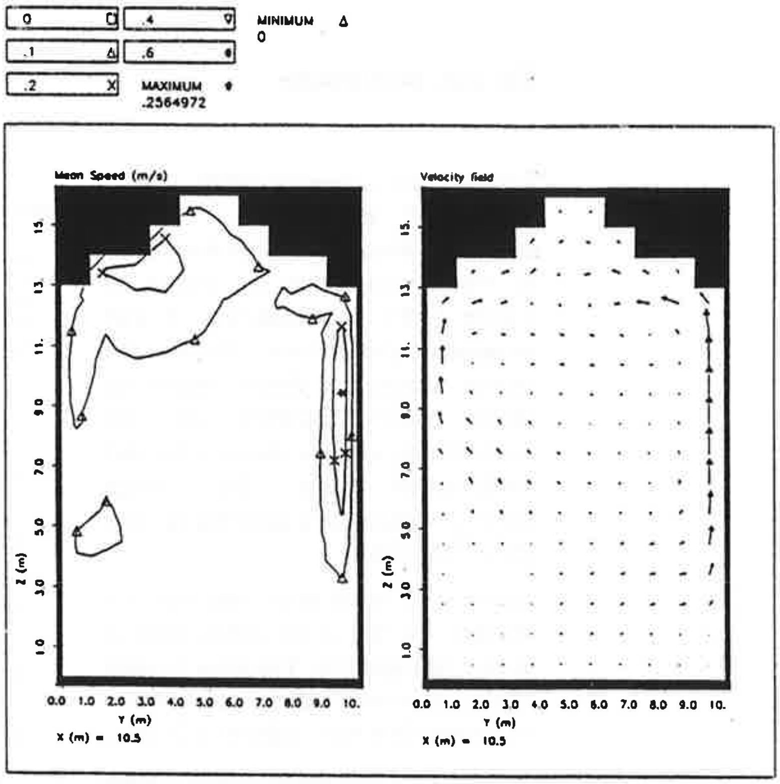

Fig. 7. Results from simulations of July, day-condition. Isolines for mean speed and velocity vectors are shown for the crossection where the measurements were taken.

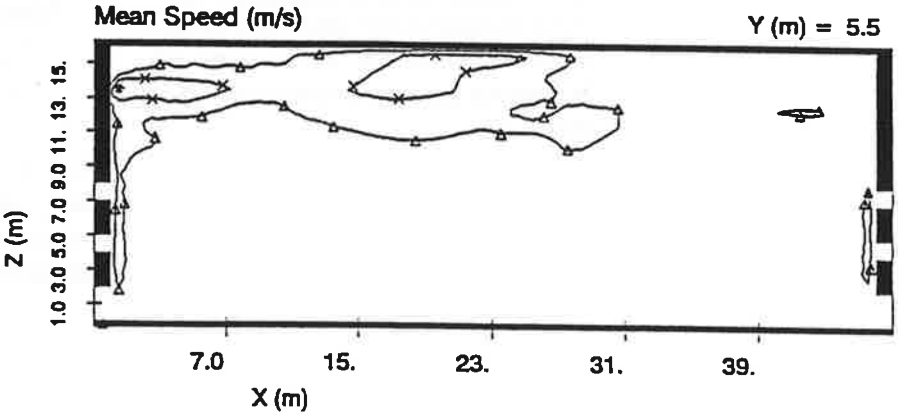

Fig. 8. Results from simulations of July, day-condition. Isolines for mean speed are shown. Maximum speed is 0.33 m/s. Legend is as for Figure 7.

EVALUATION OF THE CFD-PROGRAM, THE USE OF IT AND THE RESULTS FROM COMPUTATIONS

The main demand is that the cfd-program being used should be able to give realistic solutions for the flow and heat transfer problem considered; the finite difference equations being solved should give a proper representation of the physical problem. KAMELEON does, as most cfd-programs do, satisfy that condition to a high degree. The most questionable part of cfd-programs is the turbulence model. With respect to KAMELEON, it is a task to implement an $k - \epsilon$ that takes the thermal stratification into account. The inclusion of procedures for calculation of long-wave radiant exchange is also a wish for future versions of KAMELEON.

A second demand is that numerical grid-design, boundary conditions, and approximations used for the simulation model should give realistic representations of the actual building envelope.

Detailed information of the case being simulated is often not available at the time of the design stage when results from cfd-simulations are demanded. In that case, a somewhat coarse grid and the use of heat fluxes as boundary conditions, as for the March-cases, may be a good choice. The grid should be refined where high gradients are expected and where a detailed solution is required. The numerical grid chosen for the atrium is possibly to little refined close to boundaries and heat sources.

The correct representation of the end-walls and the heating from convectors in the considered cases are certainly a difficult tasks. Walls should generally be represented with their thickness, heat capacity, and thermal conductance. Then boundary conditions could be given for the outside of walls and then time-dependent problems where thermal mass in walls is important could be solved more correctly.

A third requirement is that one should be able to evaluate the normally huge amount of data resulting from numerical simulations. A good evaluation procedure would be one that makes it possible to easily detect zones where the specified comfort not has been achieved.

The usual graphic presentation of velocity vectors and isolines for temperatures are most valuable when thermal comfort not has been satisfied and reasons for the discomfort has to be found in order to seek improvements in design.

The calculated temperatures from the three different simulations and the measured temperatures [9] are compared, see Figure 9. The comparison is made for the location in the middle of the atrium where temperatures are measured in different heights.

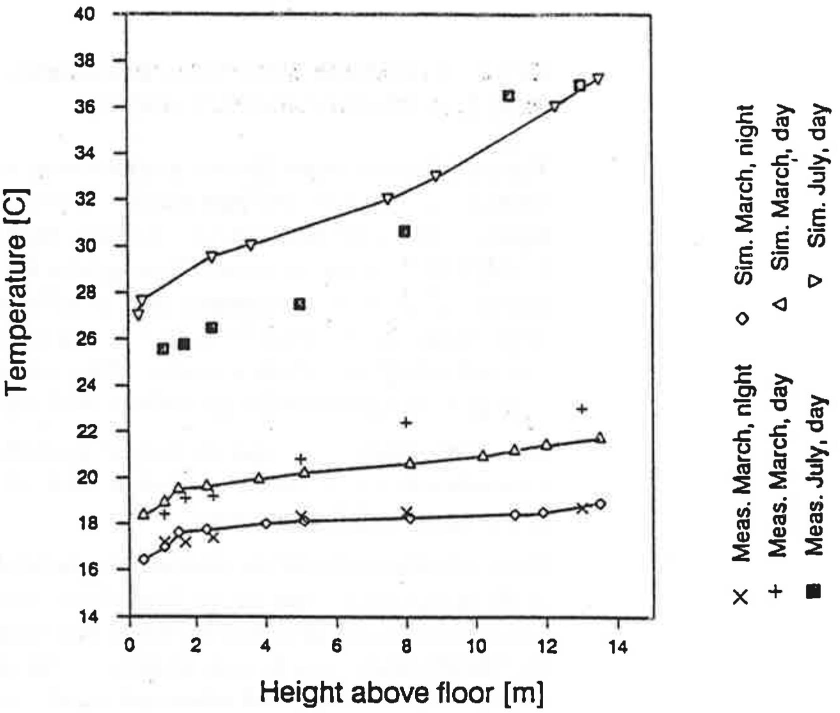

Fig. 9. Computed temperatures from simulations compared to measured temperatures in different heights in a position in the atrium.

Results from simulation of the night- and day-cases for March seem to agree very well with the measurements of temperature. Some disagreement is seen for the upper part of the atrium at the day-condition.

Results from the July, day-condition show that the simulated results overestimate temperatures in the zone of occupancy with about 3°C. Several reasons can be suspected to have caused that difference.

Looking into the measurements, it seems that the three upper measurement points have been exposed to direct solar radiation at the time of the day being considered. Thus, it is likely that the simulated temperatures also overestimate air temperatures for those points. The remaining discrepancy is a general temperature difference of about 3°C between simulations and measurements.

Jacobsen[8] has used the same atrium temperature measurements for a comparison with the building simulation program TARP. That comparison shows about 3°C lower temperature for the simulations at 13 m above the floor at the time considered. Good agreement is seen at times of the day when the measurement points not are exposed to solar radiation. That investigation supports the argumentation given.

The main difference between the modelling of the March-cases and the July-case is, except from the solar radiation, that the boundary conditions are modelled differently. When the March-cases show correct simulated results for level of temperature, it is not surprising. As heat fluxes through the building envelope directly are given as boundary conditions.

The July-case is modelled by giving temperatures at the boundaries. Then, the total heat loss from the indoor air through the building envelope is dependent on the heat transfer computed by the cfd-code. The computed heat transfer is not only dependent on the computer code itself but it is also dependent on the knowledge and the experience of the user when chosing the numerical grid. The conclusion is then that the numerical grid for the July-case should be more refined at boundaries in order to improve the results from simulations.

EVALUATING THERMAL COMFORT

Activity level and clothing to be used in different zones of occupancy and for different time periods have to be set based on the requirements for the use of the different areas. The goals for thermal comfort can be specified according to ISO 7730 in terms of predicted percentage of dissatisfied (PPD) for general thermal discomfort and in terms of draft risk (DR), vertical air temperature gradient and horizontal and vertical radiant temperature asymmetry for local discomfort. The terms for thermal discomfort are described in detail in publications by Fanger[11] and Melikow[12].

The mathematical expression for the PMV-index is developed from the heat balance for a person. The heat transfer correlations and has been related statistically to thermal sensation votes. The PMV-index then predicts only the mean value of the thermal votes of a large group of people. The scattering of votes around the mean value is not expressed by that index.

In order to establish a more relevant expression, the PPD-index was introduced. The PPD predicts the percentage of dissatisfied persons among a large group of people. The value of the PPD-index is directly dependent on the value of the PMV-index. It is recommended that the PPD be lower than 10 % to achieve sufficient thermal comfort in indoor environments. That corresponds to $-0.5 < PMV < +0.5$.

Tables and mathematical expressions for the PMV- and PPD-indices can be found in the ISO 7730. The expressions are given as:

$$PMV = (0.303e^{0.036M} + 0.028)[(M - W) - 3.05\,10^{-3}[5733 - 6.99(M - W) - p_a]$$

$$-0.42[(M - W) - 58.15] - 1.7\,10^{-5}M[5867 - p_a] - 0.0014M(34 - t_a)$$

$$-3.96\,10^{-8} f_{cl}\left[(t_{cl}+273)^4-(\bar{t}_r+273)^4\right]-f_{cl}h_c(t_{cl}-t_a)] \qquad (1)$$

where

$$t_{cl}=35.7-0.028)(M-W)-0.155I_{cl}(39.6\,10^{-9}f_{cl}\left[(t_{cl}+273)^4-(\bar{t}_r+273)^4\right]+f_{cl}\alpha_k(t_{cl}-t_a))$$

where α_k is the largest of the expressions

$\{2.38(t_{cl}-t_a)^{0.25}\}$ and $\{12.1\,v_{ar}^{0.25}\}$

and where $f_{cl}=1.00+1.290I_{cl} \quad for \quad I_{cl}\leq 0.078$

or $f_{cl}=1.05+0.645I_{cl} \quad for \quad I_{cl}\geq 0.078$

$$PPD=100-95e^{-(0.003353PMV^4+0.2179PMV^2)} \qquad (2)$$

The activity level expressed by the metabolism and the thermal insulation of clothing expressed by the clo-value have to be set according to planned use of the atrium. External work can be assumed to zero.

Air temperature and air velocity in every location in the zone of occupancy is be found by performing cfd-simulations for the atrium like for the cases reported above.

The mean radiant temperature that goes into the equation is not easily found. That value has to be found by calculating the net exchange of radiation between a person and the surroundings. Generally, a lot of information on geometry and radiation properties for different surfaces have to be specified. A somewhat simplified approach for mean radiant temperature calculation, which is suitable to be used along with cfd-simulations, is suggested by Tjelflaat[13]. Calculations are based on the ideal assumption that the atrium be empty except from one person placed in any location in the zone of occupancy, i.e. sparsely occupied. The PPD-value can now be calculated as a postprosessing of the computational results from the cfd-simulations.

When the general thermal comfort is satisfied, it is important to evaluate also the local discomfort for people being in a vertical position and having low metabolism and low clo-value. Such characteristics are common to occupants of atria.

Draft is often causing local discomfort and is defined as heat loss by convection from parts of the body to the room air. The average air speed is taken into account in the PMV-index. However, it has been found that velocity fluctuations enhance the heat loss considerably. Draft has been considered and discussed by Fanger[14], and later his co-worker Melikow[12] has given an extensive review of the field and has developed a mathematical expression for draft risk.

The percentage dissatisfied due to draft DR is given by:

$$DR = (34 - t_a)(\bar{v} - 0.05)^{0.62}(0.37\bar{v} \cdot Tu + 3.143) \qquad (3)$$

Tu is related to the turbulent kinetic energy k as:

$$Tu = [100(2k)^{0.5}]/\bar{v} \qquad (4)$$

All data needed for calculation of draft risk DR are found in the results from cfd-simulations.

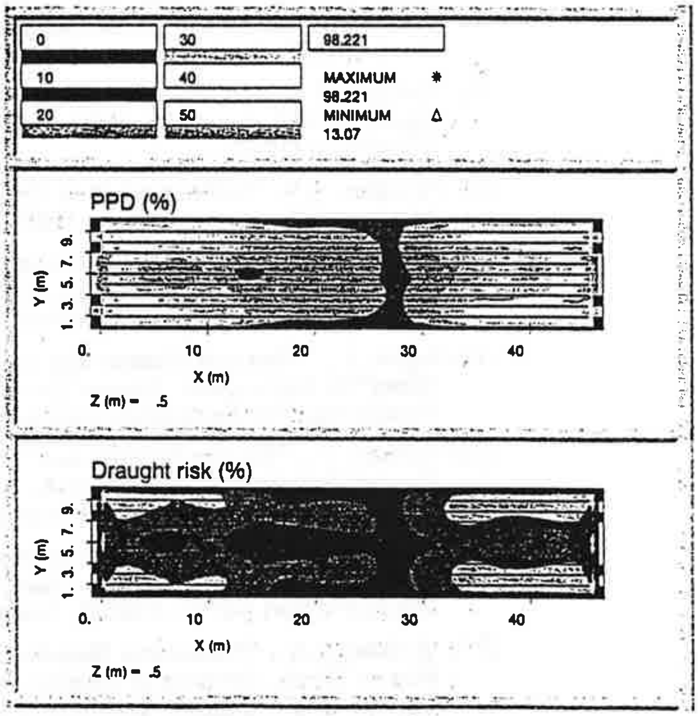

Fig. 10. Computed values for PPD and DR for a horizontal crossection in the zone of occupancy. Thermal discomfort is likely to occur in areas having percentage higher than 10.

Calculations of PPD and DR for the March, day-case are shown in Figure 10. Such a graphic presentation is in fact a concentrated and easily interpreted form of the results from cfd-simulations. It can be seen that areas close to end-walls not are very comfortable. By looking more closely into the problem, it was found that draft was allowed to develop in the vertical corners of the atrium. The reason was that the horizontal convectors at the end-walls just were covering the central part of the wall.

LITERATURE

[1] ISO 7730-1984(E)**Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort**, Modified version-October 5th, 1990, International Organization for Standardization

[2] Holen, J. And Magnussen, B.F. **"KAMELEON-A general purpose program system for simulation of fluid flow, heat and mass transfer"**. Dep. of Applied Thermodynamics, NTH, Trondheim, (1989).

[3] Jones, W.P. And Launder, B.E. **"The Calculation of Low-Reynoldsnumber Phenomena with a Two-Equation Model of Turbulence"**. Int.J. Heat and Mass Transfer, Vol. 16, (1973).

[4] Tjelflaat, P.O. and Frydenlund, F. **"Simulation of testcase E"**. Internal report for IEA Annex 20, NTH-SINTEF Division of Thermodynamics, Trondheim (1990).

[5] Patankar, S.V. **"Numerical Heat Transfer and Fluid Flow"**. McGraw-Hill Book Company, (1980).

[6] Hestnes, A.G. **"Passive Solar Commercial Buildings. Four Norwegian Case Studies."**. IEA Solar Task XI, SINTEF Division for Architecture and Building Technology, Trondheim, (1989).

[7] Baglo, T., **"Thermal climate and air movement in glass covered street"**(in Norwegian). Master Thesis, Division of Heating and Ventilating, The Norwegian Institute of Technology, Trondheim, (1987).

[8] Jacobsen, T., **"Energy Savings and Thermal Climate in Passive Solar Heated Buildings"**. Dr.ing Thesis, Division of Heating and Ventilating, The Norwegian Institute of Technology, (1989).

[9] Kolsaker, K., Frydenlund, F. And Bratsberg, F., **"FRES-Flexibel Room climate and Energy Simulator-User Manual"**(in Norwegian). SINTEF-report STF15 A90025, Trondheim, (1990).

[10] Kvikne, S.A., **"Numerical Simulation of Thermal Comfort in Atria"**. Master Thesis, Division of Heating and Ventilating, The Norwegian Institute of Technology, Trondheim, (1991).

[11] Fanger, P. O., **Thermal Comfort. Analysis and Applications in Environmental Engineering**, Mc Graw-Hill, New York, (1970).

[12] Melikow, A.K, **"Quantifying draught risk"**, Brüel & Kjær Technical Review No.2, Nærum, Denmark, (1988).

[13] Tjelflaat, P.O. **"Calculating Thermal Comfort as a Part of CFD-simulations"**. Internal report for IEA Solar Task XII, Atrium Model Development. (To be completed October 1992.)

[14] Fanger, P. O. and N.K. Christensen, **"Perception of draught in ventilated spaces."**, Ergonomics, Vol.29,II,1986.