Thermal Transfer through Membrane Cushions Analyzed by Computational Fluid Dynamics

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KEYWORDS: *membrane cushions, natural convection, CFD, heat transfer.*

SUMMARY:
The use of membrane cushions in architecture is highly growing. These systems are used as exterior facades or roofs. They need to fulfil all the requirements that are applied to conventional building technologies. In terms of heat transfer a general method or standard to identify the heat loss through the membrane cushions is not available. Furthermore complex processes inside the membrane cushion are not well enough understood to improve the cushions and avoid building physical problems. A test set-up was built to assess the processes inside the cushions. To enlarge the results from these tests computational fluid dynamics (CFD) simulations were performed, where varying boundary conditions in terms of inclination and temperature difference were applied. The simulations showed compareable results for the experimentally measured temperature and heat fluxes. Three different flow conditions were determined by the parameter variation simulations. Surface to surface radiation was determined to be mainly independent from the flow conditions inside the panel. It can therefore be calculated separately. With knowledge of the installation situation and the temperature boundary conditions the flow pattern inside the panel can be predicted. This allows an approximate calculation of the heat transfer through the cushion. Possible improvements of the cushions in terms of thermal performance are shown.

1. Introduction

Building envelopes built of membrane cushions are sometimes called the new face of architecture. This new and innovative building technology stands out due to an increasing growth worldwide. Sometimes it is referred to as “the new building material”.

Because of its newness some standards as for example for U-value or g-value, which are long time established for other types of constructions like massive walls or windows, are not available for membrane cushions. This new construction type differs significantly in terms of used material, shape dimension, or curvature compared to conventional building components. That is why existing standards can not be applied on membrane cushion systems in terms of characteristic building physical values. Standards for these values are nonetheless necessary to avoid expensive special testing of the components and to give ingenieurs and architects tools at hand to easily proof that their construction complies with the requirements.

All three heat transfer mechanisms, radiation, convection and conduction, play an important role for the assessment of the thermal performance of membrane cushions. Even so those mechanisms are well understood in general, a basic understanding of what is happening inside the closed spaces of membrane cushions and the interaction of these transport mechanisms is often missing. There is no deeper knowledge of the dependencies and of the magnitudes of the transport mechanisms under different boundary conditions. In practice this leads to a number of different building physical problems, which can neither be understood nor solved because of missing understanding of the system performance.

2. Approach

Because of the shown problems with the use of membrane cushion systems in practice, a deeper understanding of what happens around and inside the panels is necessary with respect to the development or adaption of codes and standards. A characterization of membrane cushions and their application in practice needs to be done. Furthermore the main transport mechanisms need to be detected and the most influencing boundary conditions need to be assessed.

Depending on the characterization of the membrane cushions and the found important boundary conditions, a test setup was buildt. This setup couldn't represent the whole operating range of membrane cushions. To enlarge possible findings, CFD (computational fluid dynamics) simulations were undertaken. This enabled a comparison of experimental findings with simulations. In a next step simulations with different boundary conditions helped to transfer the findings to changed conditions. This should contribute to a successful processing of the above mentioned problem definitions. The field of application of numerical fluid dynamic simulation for the calculation of the heat transfer through membrane cushions will be shown.

For this purpose only the closed, air-filled inner space of the ETFE (Ethylene Tetrafluoroethylene) membrane cushion is examined. The influence of thermal bridges around the edges of the cushion and of the clamping is not part of the simulations. Boundary conditions are directly applied on the cushion, i.e. possible interactions of the panel with its surroundings are not regarded.

For the simulation of fluid dynamics the definition of the geometry, in which the flow should be examined, is the first step. A grid on which the transport equations are solved needs to be produced to fill this geometry. For a proper CFD simulation more steps than just the comparison with experimental data were necessary. That's why the simulations were run with different physical models for e.g. turbulence and the results were compared to the experimental data. After finding the "best" modelling settings the parameter variations were performed.

This results in a general characterization of the flow conditions inside the panels. Results generalization leads to basic approaches for the simplified calculation of the heat transfer through membrane cushions. All the simulation results are confronted with the real measurements to show how good numerical simulation can reproduce reality.

3. ETFE cushion construction

Membrane cushions consist of two or more layers of ETFE membrane, which are in general welded and clamped around the edges. In the production process the membrane is cut in a way, that the completed cushion offers a camber. A detailed description of the complete system can be found in (Kaufmann, 2004).

In general a cushion can be defined to have a likewise diameter on every location with similar side length. Only in extreme cases like very narrow and stretched cushions a bigger difference is found. But basically also here the distance between the membrane layers is zero on the edges and proportionate to the camber in the middle. The easiest way for the characterization is a round cushion.

This characterizes only the cushion itself. Attached to the cushion is in general a pressure hose with a diameter of four to ten centimeter. The pressure hose provides the compressed air to keep the cushion under an over-pressure between 200 and 1000 Pa. This means that there are defined limitations for lowest and highest pressure and if the pressure in the panels falls below the defined minimum, air is supplied until the maximal pressure is reached. The time for these loading cycles is, compared to the time in which the pressure inside the cushion falls from maximum pressure to minimum pressure, very marginal. The pressure inside the panel drops only because of leaks. Therefore it is useful for the quasi-statical consideration to assume a constant inner pressure.

Furthermore the clamping plays only a minor role for the convection inside the panel. Temperature differences between membrane and frame can only be transmitted by conduction in the membrane. As the membrane is not a good conductor and does not store a lot of heat, this effect can also be neglected.

4. Experimental set-up

On the outdoor testing facility at the Fraunhofer Institut für Bauphysik in Holzkirchen, Germany, a test set-up for the experimental data gathering at a membrane-cushion-system was built. This test set-up allows the acquisition of hygrothermal and interior climate data on ETFE-cushions and its surrounding under realistic conditions.

The test set-up consists of a pentagonal tower with 7.45 m height and an inner diameter of 4.75 m. A horizontal cushion with a maximum distance between its two layers in the middle of the diameter from 1 m serves as roof, as shown in FIG. 1. These dimensions are real cushion dimensions and geometries. The building can be heated to keep the interior temperature at a constant level in winter.

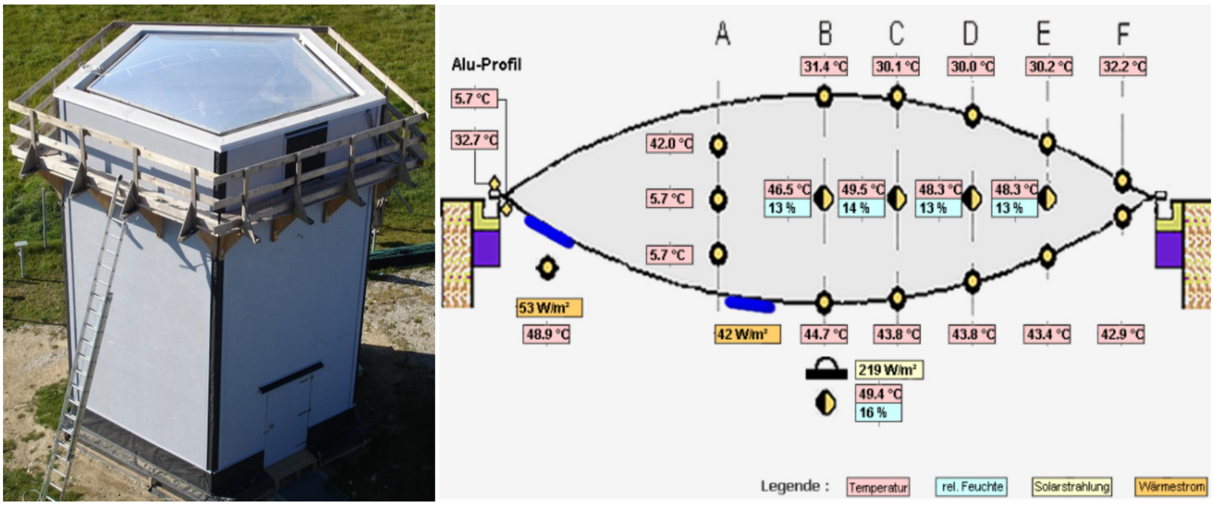

FIG. 1: Picture of the test set-up for membrane cushion tests and distribution of all sensors inside the cushions with visualization of the measured data

In five axes the temperature is measured on the interior and exterior surface as well as in half height of the cross section. The axis in the middle of the cushion is equipped with five temperature sensors across the cross section height. FIG. 1 shows a screenshot of the data visualization of all measured values within the cushion and gives a good overview about the arrangement of the sensors within the pillow. These sensors are ment to provide information about the temperature distributions within the cushion. Temperature sensors are PT100 sensors with an accuracy of +/- 0.1 °C.

In addition to the temperature sensors two heat flux transducers are mounted to the membrane, one in the middle of the inside membrane, one 30 cm from the edge of the cushion. The measurements of all sensors are logged every 30 seconds and saved in an internet based data base for later analysis.

Besides the sensors in and on the cushion also the temperature and relative humidity inside the room below the cushion are measured. These combined with the measurement values from the weather station at the Fraunhofer Institut für Bauphysik provide the boundary conditions for internal and external climate.

5. Model set-up

For the simulation cushions with similar diameter and maximum height as the pentagonal cushion in the test set-up were used. The cushion itself was not modelled as pentagonal but as round. That means that the cushions are defined by the diameter d of the footprint and the maximum height h in the middle of the cushion. For the standard model the height h was 1 meter and the diameter d was 4.75 m.

The boundary conditions were directly applied on the exterior surfaces of the cushions, which enclose the whole volume. This volume was meshed with unstructured tetrahedrons for the whole volume and a structured mesh on every surface. The distance between the two surfaces was set to 0.04 m to avoid meshing problems in the edges

The tetrahedrons maximum size within the volume was set to 0.1 m for the whole volume. Close to the edges the maximum element size was set to 0.02 m. The ratio for growth between two neighboring mesh volumes was set to 1.1. All around the surface a structured grid with 10 element layers was buildt to obtain a higher resolution for the simulation and to apply some of the physical models, which require a very fine mesh on the (Ansys, 2006). Finer and coarser meshes were also used to find the best mesh for the simulations. The selection process is described in (Antretter, 2007). A grid sensitivity analysis as recommended in e.g. (Ferziger, 2002) was not carried out, as an exact duplication or bisection is not possible for the mixed meshes.

Steady state and transient simulations were performed. In the transient case a total time of 25 seconds with timesteps of 0.1 seconds was simulated. This period seems adequate to simulate the transient behaviour of the flow under steady state boundary conditions if the simulation domain is initialized with the results of the steady state simulations.

Fluid models need to be choosen for heat transfer, turbulence and radiation. A study on natural convection inside closed spaces (Haupt, 2001) was used for model selection. A detailed description of the models and other parameters and reasons for their selection for this study can be found in (Antretter, 2006). Parameter simulations with different models in (Antretter, 2007) show the differences among the models. All boundary conditions for exterior and interior surface are set to no slip walls. This represents the real condition on the wall, where the particles closest to the surface do not move because of friction with the wall. It results in the development of a boundary layer. For standard simulations the temperatures on the inner surface were set to 20 °C and on the exterior surface to -10 °C. This does, because of missing heat transfer on the layers, not represent reality, but the simulations are more exact specified with this assumption and easier to compare. With all these settings the fluid domain is specified.

The parameter variations were performed with different temperature differences between the inside and the outside of the cushion. Realistic temperature ranges, where membrane cushions may be used, are between -30 °C and 60 °C. For this study it was assumed that the membrane cushions delimit a room where people stay. The interior temperature is therefore set to 20 °C. The exterior temperature was varied from -10 °C and +30 °C. To limit the effort for the simulations only exterior temperatures of 0 °C, 10 °C, 15 °C and 30 °C were performed additionally to the ones with -10 °C.

Membrane cushions are used as facades as well as for roofs. The main application is therefore 0 degree or 90 degree inclination. However all inclinations between can be found. Therefore simulations with 45 degree inclination were also performed. The different inclinations of the cushion showed the resulting variations of the flow patterns.

6. Results

Temperature differences are the driving force for natural convection. The gravity counteracts the buoyant force, resulting from the temperature differences. Therefore the main focus of this research is to understand the flow patterns inside the cushions on varying temperature differences and different directions of the gravity.

6.1 Temperature

Velocities averaged over the whole domain weighed by volume ratio decreased with a decreasing temperature difference. As the air velocities on the boundaries are mainly responsible for the heat flux through the corresponding boundaries, it is obvious that the convectional heat fluxes also decrease with decreasing temperature difference. TABLE 1 shows the results for simulations with different temperature differences in transient and steady state simulations. Because of transient nature of the flow that can be found inside the panel the steady state simulations are not converged. But a comparison between the results for transient and steady state conditions shows no differences for the values averaged over the whole domain or the surfaces respectively.

TABLE 1: Results for average values of selected variables with different temperature differences for transient and steady state simulations

Transient	-10°C/20°C	0°C/20°C	10°C/20°C	15°C/20°C	30°C/20°C
	Trans / Steady	Trans / Steady	Trans / Steady	Trans / Steady	Trans / Steady
Temperature [K]	278.4 / 278.4	283.1 / 283.1	288.2 / 288.2	290.7 / 290.7	298.1 / 298.1
Velocity [m/s]	0.10 / 0.10	0.08 / 0.08	0.06 / 0.06	0.04 / 0.04	0.01 /0.01
Heat Flux Density Total [W/m²K]	146.3 / 146.6	99.8 / 99.1	49.0 / 48.8	24.3 / 24.2	-44.4 / -44.5
HFD Conv. [W/m²K]	41.9 / 42.2	26.5 / 25.8	10.5 / 10.3	4.5 / 4.4	-1.8 / -1.9
HFD Radiation [W/m²K]	104.4 / 104.4	73.3 / 73.3	38.6 / 38.6	19.8 / 19.8	-42.6 / -42.6

TABLE 2: Convective and radiative ratio of heat flux density on inner surface

Temperatures	-10°C / 20°C	0°C / 20°C	10°C / 20 °C	15°C / 20°C	30°C / 20°C
Convection Ratio	0.29	0.27	0.21	0.19	0.04
Radiation Ratio	0.71	0.73	0.79	0.81	0.96

The total heat flux on the surface sums up from convective and radiative heat flux components. TABLE 2 shows the comparison between the fraction of convective and radiative heat flux on the different temperature differences on the inner surface. At a temperature difference of 30 K approximately 30 percent of the total heat flux is caused by convection and 70 percent is caused by radiation with the membrane properties and emissivity as described above.With higher temperature differences the convective heat flux increases. With negative temperature differences between the inside and the outside, which means a higher temperature on top of the horizontal cushion than on the bottom, a stable temperature layering results in almost no convective fraction and almost all the energy transferred by surface to surface radiation.

6.2 Inclination

FIG. 2 shows streamlines of the flow inside the cushion colored by temperature. In the horizontal case several different eddies are found. Already at 45 degree inclination one big roll on the surfaces with secondary flow to the upper and lower edges fills the whole volume. The same behaviour is found for the vertical cushion. A look at the temperatures shows, that the temperature inside the horizontal cushion is very uniform throughout the whole volume because of very effective mixing inside the panel.. Only in the edges and very close to the surfaces higher temperature gradients are found, which cause most of the energy transport by convection. The temperature distribution in the inclined and vertical cushions is different. Some kind of a temperature layering with highest temperatures on top and lowest temperatures on bottom of the volume is found. Only on the surfaces, which are whether at constant 20 °C or constant -10 °C, the temperatures differ from the general temperature at the given height above zero, which is very constant from a distinct distance of the wall. The average velocity for the horizontal case is 9,6 cm/s but the maximum velocity is only 29,3 cm/s.

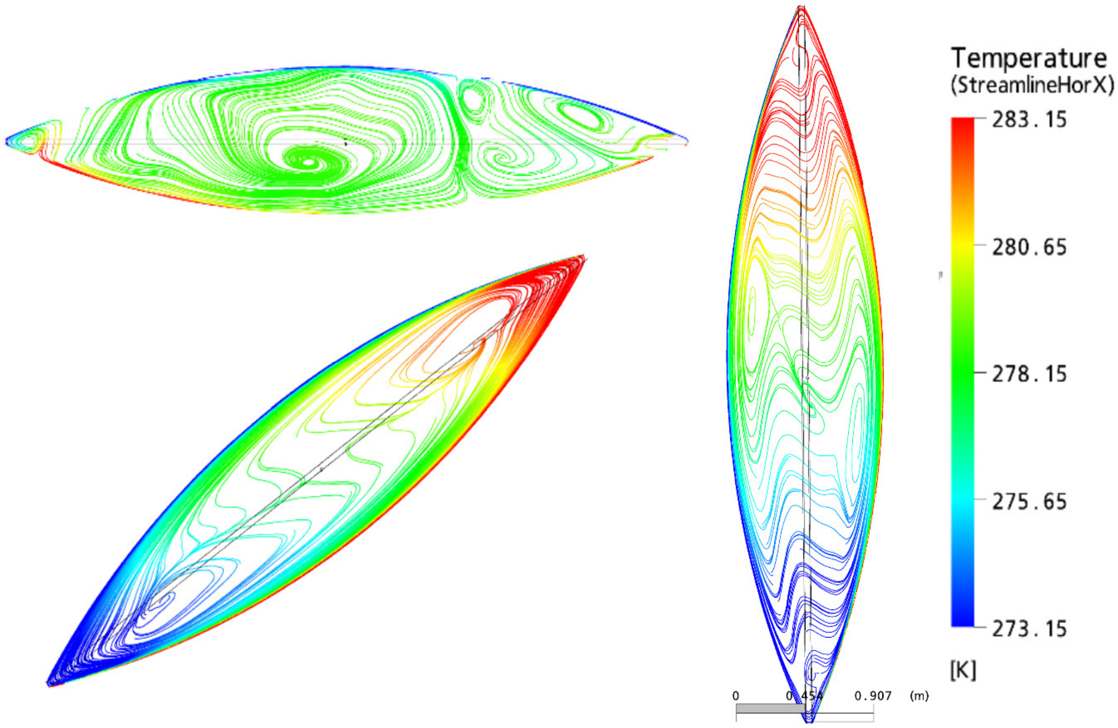

FIG. 2: Streamlines colored by temperature for different inclinations of the cushion

A comparison of the mean values shows as expected, that the surface to surface radiation causes a similar radiative heat flux and is therefore independent of the inclination. It depends only on the temperature difference.

The convective portion of the total heat flux rises with the inclination of the cushion. The increase of the convective heat flux from 0° to 45 ° inclination is double the increase from 45° to 90°. Also these simulations showed that for the mean values no significant difference was found between steady state and transient simulations.

A closer look at the velocities in the enclosed space shows that indeed the mean velocities decrease from horizontal to inclined to vertical cushions. The maximum values for each case show however that higher velocities are achieved in the inclined cushions. The found average and maximum velocities are summed up in TABLE 3.

TABLE 3: Comparison of average and maximum velocities on cushions with different inclinations

Velocities [m/s]	Average	Maximum
Horizontal	0.096	0.293
45 Degree	0.079	0.484
Vertical	0.064	0.420

7. Discussion

The found flow pattern can be divided into three different conditions. The following description of the temperature, velocity and turbulence fields refers to the characterization of these three conditions.

Flow in the first condition feature many small eddies. These flows develop if the membrane layers are horizontal and the temperature rises in direction of the gravity. On the in gravity direction warmer membrane layer energy is supplied to the fluid, which causes a reduction of the fluid density. The buoyant force of the less dense and therefore lighter fluid on the surface prevails the friction forces within the fluid and ascends against the gravity direction. A critical temperature difference between the surfaces must be exceeded, which is small because of the little viscosity of air. Friction acts against further rise. Additionally heat conduction between the fluid particles balances the driving temperature and density differences. Effective mixing and energy exchange occurs within the cushion. This thermal cellular convection or Rayleigh-Bénard convection produces in the ideal case between two infinite parallel plates equal rolls. On the lightly bent surfaces of the membrane cushions a similar behaviour of the flow can be found, but the rolls influence each other because of curvation and the edgewise boundarys. An unstructured, time dependend flow pattern with rising and falling plumes is the result.

This means an effective mixing for the temperature. The heat transfer occurs in a very thin boundary layer, evenly distributed over the surface. The temperature in the middle of the cushion is relatively uniform. Only in the edge zones with smaller distances between the surfaces warmer plumes rise completely from the inner to the outer surface. The velocity distribution in this condition can not be predicted without simulation. The mean velocity is not very high because of the interdependent impact of rising and falling plumes.

The second condition results from gravity not normal to the temperature difference causing walls. This is in the most extreme case a vertical cushion. With rising inclination the fluid particles move a longer way along the walls. They collect more energy on the warm wall and they can more efficiently deliver energy to the cold wall. The result is one big roll within the cushion with high energy exchange and high velocities close to the walls. The mixing over the whole cushion volume reduces compared to the first condition with a horizontal cushion. The temperature field in this case is a layering over the height of the cushion, which is not exactly horizontal because of the movement of the fluid inside the cushion in one big roll. Because of the current, warm air close to the warm surface is pushed upward; cold air is pushed downward on the cold surface. This results in high velocities close to the walls but low velocities in the inside of the volume.

The third condition that can be defined is a stable layering inside the cushion. This is again only possible in a horizontal cushion. The temperature decreases in direction of the gravity. In this case there is no driving potential because of density differences. The most dense – and therefore heaviest – particles are on the bottom, the lighter ones are on the top. This means a stable temperature layering inside the cushion with the biggest temperature gradient in the horizontal middle of the cushion. Air movement happens only on the areas where the surfaces are bent close to the edges. The three described conditions can be found in FIG. 3. It shows the streamlines for all three conditions colored by the temperature of the fluid at every location.

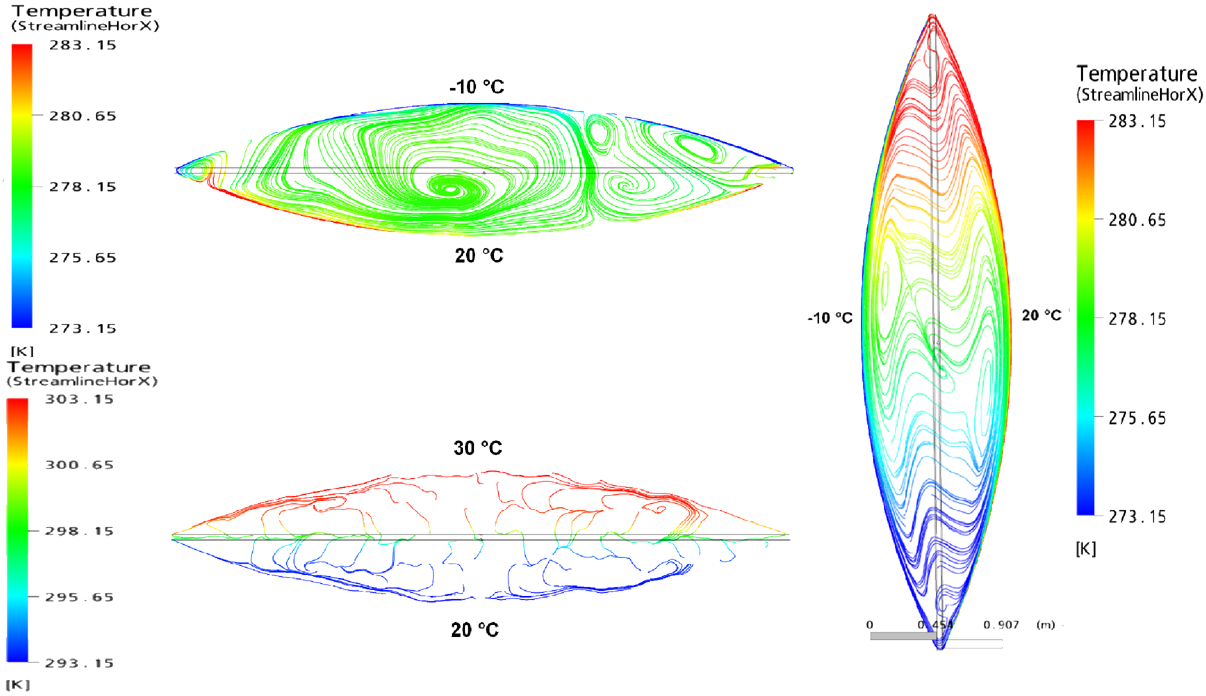

FIG. 3: Comparison of the temperatures on the streamlines for three different conditions

8. Comparison with measurements

The simulations were performed transient, but with steady state boundary conditions. Furthermore the development of the flow patterns is clearer with higher temperature differences. Therefore a short period of time was choosen from the whole measurement period of one and a half year, where the surface temperatures are as constant as possible at high temperature differences. As radiation on the cushion was not modelled, a period without radiation, which means at night, was to be found. Nightly irradiation was not a problem, because the real measured surface temperatures were used as boundary conditions for the simulation. In the choosen night of January 25th, 2007 average surface temperatures of 14.4 °C at the inside and -4.2°C on the outside were calculated. The distribution of the surface temperatures on the four sensors per surface showed only small differences between the measurements, which justifies the assumption of a constant temperature at the whole surface. These temperatures were used as boundary conditions for comparison simulations.

The distribution of the temperatures inside the cushion shows fluctuations of maximal 2 °C around the mean value for the measurements as well as for the simulations. The good mixing and the therefore even temperature distribution can be reproduced by simulation. The rising and falling plumes in the edges with obvious effects on the air temperature found with simulation can be shown with different measured surface temperatures in these areas. The additionally measured heat flux densities with 66.5 W/m² in the middle of the cushion and 85.2 W/m² close to one edge can be compared with an average simulated heat flux density of 84.9 W/m². A better comparison between measurements and simulation is currently not possible, as the experimental set-up was not designed as simulation validation case. However, the general temperature distribution and the order of the heat flux through the panel can be compared.

9. Conclusions

As a result of the parameter variations three different conditions of airflow inside the panel can be defined. The development of these three conditions can be physically explained. For every installation situation with every possible temperature difference between the exterior surfaces of the membrane cushion the resulting flow pattern can be estimated, also without simulation.

A comparison between simulation and measurement was difficult, as the measurement was not intended to provide a basis for simulation validation. However, the found conditions inside the panels are compareable to the conditions as result of the simulation. The measured order of the temperatures and heat flux can be imaged by numerical simulation. The results of the parameter variation can be considered as realistic.

With the shown results an estimation of the U-Value is, simplified, possible. The surface to surface radiation can be calculated with different approaches. The convection inside the panel depends on the temperature differences and the inclination of the cushion. But the heat transfer coefficients can be estimated with knowledge of the installation details of the cushion.

The simulations were carried out as closed systems with temperature boundary conditions. Further simulations should include the influence of the pressure hose as well as possible leakage. The temperature boundary conditions do not represent the real world. Further research is necessary to obtain reasonable heat transfer coefficients. Furthermore heat transport through frames and clamping was not regarded. Radiation from the outside like solar radiation or surface to surface radiation between membrane and internal walls and floor plays an important role in reality but was not part of this study.

Despite these limitations room for improvement for the membrane cushion systems can be detected. The whole heat transfer through the membranes can be reduced with surface coatings with a low emissivity. Especially in the edges the heat loss is high. This may result in condensate at the inner surfaces and lead to further building physical problems. Improvements can be made with thermal isolation of the edge areas and a forced distance between the two membrane surfaces at the edges.

In total it is to say that small changes in the boundary conditions or in the used models produce big changes in the results. Following points may help for good further simulations:

- 3-dimensional: All the flows are three dimensional, therefore two dimensional simulations are disadvised
- Steady state / transient: The mean values of the simulations do not show significant differences between the results, even with no convergence of the simulations because of the transient behaviour of the flow in reality
- Initialization: A good initialization is necessary to obtain quick converging results
- Convergence: The residuals alone are not enough to judge convergence. Imbalances and the observation of variables and global variables during the simulation allow an estimation of the correctness.
- Radiation: With given temperatures on the boundarys the simulation of the convection inside the cushion is possible without the simulation of surface to surface radiation.
- Boundary layer: A fine resolution and the use of complex boundary models are necessary to represent the real situation on the walls.

10. References

Ansys Inc. (2006). CFX solver release 10. Software Manual.

Antretter F. (2006). Analyse relevanter Randbedingungen zur Simulation von Strömungen in Membran-Kissen-Systemen. Project Work, University of Applied Sciences Rosenheim.

Antretter F. (2007). Anwendung eines Computational-Fluid-Dynamic-Systems zur numerischen Simulation der natürlichen Konvektion in leichten transparenten Bauteilen. Master Thesis, University of Applied Sciences Rosenheim.

Ferziger J.H. and Peric M. (2002). Computational methods for fluid dynamics. Springer Verlag.

Haupt W. (2001). Zur Simulation von auftriebsinduzierten Innenraumströmungen. Dissertation, University Kassel.

Kaufmann A. and Mitterer C. (2004). Membrane im Bau – bauphysikalische Optimierung und neue Einsatzbereiche. Fraunhofer Institut für Bauphysik, IBP report RKB-15/2004.