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# A SIMULATION MODEL FOR THE YEARLY ENERGY DEMAND OF BUILDINGS WITH TWO-OR-MORE-LAYERED TEXTILE ROOFS

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**Key words:** Optical Properties, Thermodynamics, Radiation Heat Transfer.

**Summary.** This document provides information and instructions for preparing a Full Paper to be included in the Proceedings of *MEMBRANES 2011* Conference.

## 1 INTRODUCTION

The indoor climate and the energy balance of textile buildings depend highly on the optical properties of the roof's membrane material. The main factors for heat transfer from the environment into the building and v. v. are radiation and convection – coming from solar irradiation and outdoor weather conditions - whereas thermal conduction in the membrane itself can be neglected. The simulation of energy balances for a textile building by computational fluid mechanics (CFD) is well understood, but results normally in large models and time expensive calculations. The determination of the yearly energy demand for heating and cooling of a membrane building by CFD is therefore nearly impossible.

Based upon an extended thermal net radiation method [1] and some simplifications we present here a simulation model for two or more layered membrane roofs, that allows to estimate quickly the yearly energy demand of a membrane building under realistic weather conditions. By this method it is furthermore possible to compare and optimize the optical configuration of membrane materials in an early stage of the design of a building.

## 2 OPTICAL PROPERTIES

The optical properties of a membrane material are characterized by its spectral absorptivity, reflectivity and transmissivity that vary over the wavelength. The emissivity of a material equals the absorptivity due to Kirchhoff's law. It is common in engineering to assume that absorptivity and emissivity do not depend on the wavelength (gray body assumption), but examination of the measured spectral values of the optical properties of a typical membrane material (see figure 1) show the differences in two ranges of the spectrum:

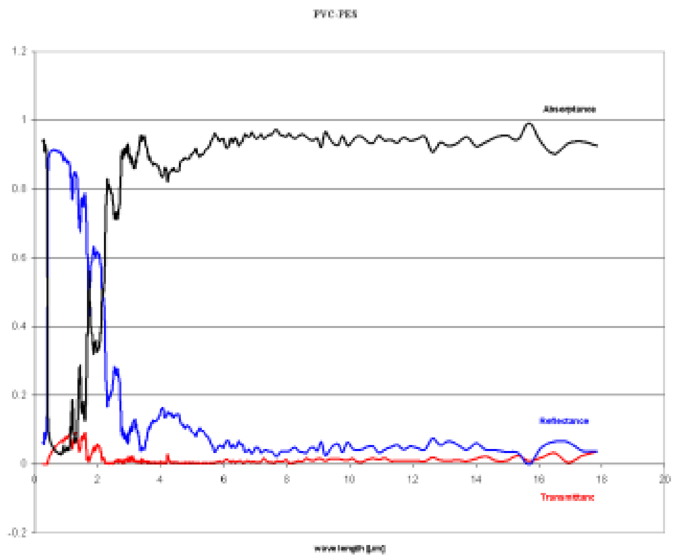


Figure 1: Optical properties of membrane material over the wavelength

In the range from 2500 nm to 18000 nm the optical properties are nearly constant. This range corresponds with the mid-wavelength, long-wavelength and far infrared thermal radiation spectrum. The range below 2500 nm represents the range of the main part of solar radiation including UV radiation, the range of visible light and short-wavelength infrared radiation. For the analysis of the thermal equilibrium of membrane buildings as shown below these two ranges are distinguished and the optical properties are assumed constant in each range. The mean values of the optical properties are found by averaging the measured spectral data over the two ranges.

## 3 NET RADIATION METHOD FOR ENCLOSURES

To analyze the radiation exchange between the surfaces of a membrane building (membrane or cushion, walls and floor) the interior of the building is regarded as enclosure. If the roof is composed by a two-or-more-layered membrane or by membrane cushions, each interior volume forms an additional enclosure. The radiation exchange between the surfaces of these enclosures is quite complex, because radiation that leaves a surface area will be partially reflected and absorbed by other surfaces. The reflected part itself will be many times re-reflected by other surfaces. In the case of translucent materials there are additional effects when radiation is transmitted from one to the neighbor enclosure.

Fortunately it is not necessary to follow all this multiple reflections and transmittances when we use a net radiation method for enclosures [1]. For each surface area $A_k$ we consider first the total incoming radiant energy $q_{i,k}$ per unit area of $A_k$. A part of this will be reflected or transmitted and does not change the energy balance of the surface element. The internal energy flux which is supplied to the regarded surface by the volume the surface belongs to (e.g. by conduction) will be $q_k$. Other external effects like heat transfer by convection will be written as external heat flux $q_{ext,k}$. Finally the surface element at temperature $T_k$ emits temperature radiation $\varepsilon_k\theta_k = \varepsilon_k\sigma T_k^4$. This leads to an equilibrium equation on each surface element $A_k$ :

$$q_{i,k} - \rho_k q_{i,k} - \tau_k q_{i,k} + q_{ext,k} - q_k - \varepsilon_k\theta_k = 0 \tag{1}$$

On the other side the total incoming flux is the sum of all fluxes $q_{o,j}$ leaving the other surfaces $A_j$, weighted by the view factors $F_{j\text{-}k}$:

$$q_{i,k}A_k = \sum_j F_{j-k}A_j q_{o,j} \tag{2}$$

The view factor $F_{j\text{-}k}$ shows which part of the flux leaving surface $A_j$ is received by the surface $A_k$. From view factor algebra we get:

$$F_{j-k}A_j = F_{k-j}A_k \tag{3}$$

and hence:

$$q_{i,k} = \sum_j F_{k-j}q_{o,j} \tag{4}$$

Finally the total outgoing radiation flux $q_{o,k}$ leaving surface $A_k$ results from the reflected part of the incoming flux, the temperature radiation of the surface and the part which is transmitted from the backside of the surface element if the surface is transparent:

$$q_{o,k} = \rho_k q_{i,k} + \varepsilon_k\theta_k + \tau_n q_{i,k^*} \tag{5}$$

The index $k^*$ marks the backside of the surface with index k (if any). Putting all this together we get an equation in $\theta_k$ and $q_k$ for each surface element of the enclosure:

$$\sum_j \left(\delta_{kj} - F_{k-j}(\rho_j + \varepsilon_j)\right)\theta_j - \sum_j F_{k-j}\tau_{j^*}\theta_{j^*} + \sum_j \left(\frac{\delta_{kj}}{\varepsilon_j} - F_{k-j}\frac{\rho_j}{\varepsilon_j}\right)q_j - \sum_j F_{k-j}\frac{\tau_{j^*}}{\varepsilon_{j^*}}q_{j^*} = \sum_j \left(\frac{\delta_{kj}}{\varepsilon_j} - F_{k-j}\frac{\rho_j}{\varepsilon_j}\right)q_{ext,j} - \sum_j F_{k-j}\frac{\tau_{j^*}}{\varepsilon_{j^*}}q_{ext,j^*} \tag{6}$$

Splitting the wavelength spectrum into two ranges, "solar" and "infrared" as shown above, two equations (6) for each surface area are necessary. The internal variable $q_j$ has to be split into a solar and an infrared component ($q_{j,SOL}$ resp. $q_{j,IR}$). In the solar wavelength range the emissivity is neglected, so that the terms in $\theta_j$ will vanish. In the case of outside surface areas oriented to the sky we find the absorbed direct or diffuse solar radiation on the right hand side of (6) in the solar range.

## 4 BOUNDARY CONDITIONS AND EQUATION SYSTEM

Generally, equation (6) is valid for all surface areas of the enclosure, but the different types of surfaces of a membrane building (floor, wall, membrane / cushion) need different boundary conditions as shown below. So we have three unknowns $\theta_k$, $q_{k,SOL}$ and $q_{k,IR}$ for each surface area k of the membrane building to be analyzed on one side and two equations (6) on the other side. Hence there is necessary one boundary condition equation per surface area k to solve the resulting equation system.

*Floor*: Boundary conditions for floor areas could be constant temperature or constant heat flux in the infrared wavelength range. It is also possible to define a constant "earth" temperature and calculate the heat flux by conduction through the thickness and the heat capacity of the floor. Another possibility is to set the interior temperature to a constant value and to calculate the corresponding floor temperature by a additional heat balance of the air in the interior room of the building.

*Wall*: A boundary condition for wall surface areas can be defined by heat conduction through the wall regarding convection effects to the interior of the building and to the environment. Also an adiabatic insulation can be formulated setting $q_{k,SOL} + q_{k,IR} = 0$.

*Membrane*: The boundary conditions for membrane surfaces have to be formulated for a pair of membrane surfaces, because each membrane surface consist of a front and a backside. A simple condition is that the temperature of both sides is the same. This is realistic if the membrane layer is thin. For a heat insulation layer the condition equation is formulated as relation of internal (infrared) heat flux and front and backside temperatures. In both cases the internal heat flux composed of the infrared and solar parts of the front and backside must also be in equilibrium.

The structure of the equation system for each surface element follows:

$$\begin{bmatrix} solar\ equilibrium \\ infrared\ equilibrium \\ boundary\ conditions \end{bmatrix} \begin{bmatrix} \theta_k \\ q_{k,SOL} \\ q_{k,IR} \end{bmatrix} = \begin{bmatrix} solar\ irradiation \\ convection \\ conduction\ or\ 0 \end{bmatrix} \quad (7)$$

The resulting equation system is linear in $\theta_k = \sigma T_k^4$ , but the temperature dependent terms of convection and conduction on the right hand side of (7) have to be iteratively updated to get the final equilibrium. Once inverted the left hand side of (7) the iteration only consists of matrix vector multiplications.

## 4 WEATHER DATA

For the analysis of the yearly energy demand of a membrane building, so-called "Test Reference Years" available from German Weather Service (DWD) are used. Test Reference Years (TRYs) are datasets of selected meteorological elements for each hour of the year. They provide climatological boundary conditions for simulating calculations on an hourly basis and are part of several German engineering standards. For each of 15 German regions a representative station has been determined and a Test Reference Year has been prepared.

A Test Reference Year contains characteristic weather data of a representative year. The weather sequences have been chosen on the basis of an analysis of general weather situations in such a way that the seasonal mean values of the individual meteorological elements (especially of temperature and humidity) of the representative stations mainly correspond with their 30-years mean values. As heating and air conditioning equipment also have to be designed for extreme situations, additional datasets with the same data structure for a very cold winter and an extremely hot summer have been compiled [2]. An example for the irradiation data is shown in figure 2.

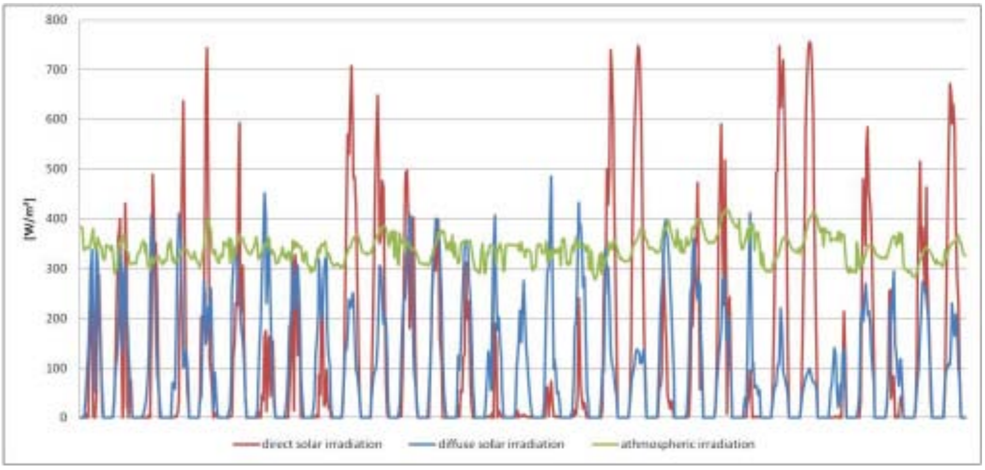


Figure 2: Solar and athmospheric irradiation, July, TRY region 13

## 5 EXPERIMENTAL STUDIES

During a German research project on an alternative design of a textile building, which is capable to generate its energy demand for air conditioning of the interior and water heating from renewable (solar) energy, some test stands ("thermoboxes") were constructed and equipped by measuring devices [3]. Generally the test stands consist of a insulated box with two membrane frames in the upper area and a heatable blackbody area element on the ground. The air flow through the space between the ground and the lower membrane as well as the space between the two membrane layers is controlled by a adjustable fan. If desired a heat absorber element can be positioned between the two membrane layers.

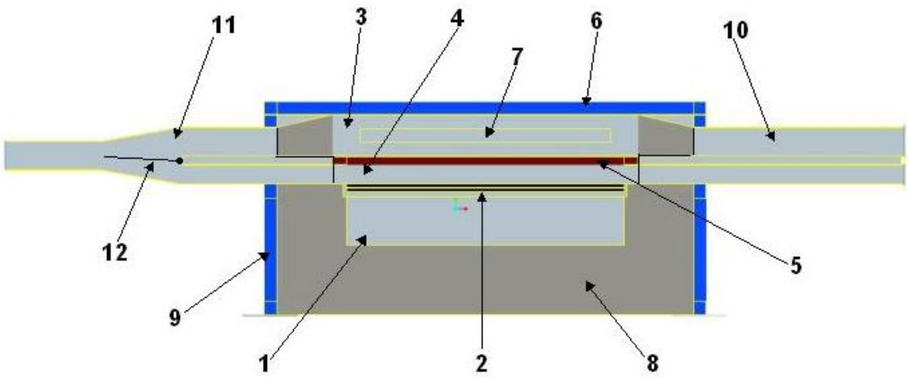


Figure 3: Components of the thermoboxes. 1: heat store, 2: blackbody, 3, 4: flow channels, 5: lower membrane frame, 6: upper membrane frame, 7: absorber, 8: insulation, 9: construction frame, 10: flow outlet, 11: flow inlet, 12: adjustable flat

The thermoboxes are equipped by thermocouples for temperature measurement, hot-wire anemometer and Pitot-tubes for volume flow rate measurement as well as by pyranometers and pyrgeometers for radiation measurement.

The comparison of analysis results of the thermoboxes was started with a simple CFD model. A hot summer day with high solar irradiation as well as a cold and clear winter night were used as boundary conditions. Free convection is assumed. The temperature of the floor is set to constant 20°C. Table 1 and 2 show the good accordance of the temperature and heat flow results of the CFD and the simple two-layer analysis.

| | Hot summer day | | | Cold winter night | | |
|---|---|---|---|---|---|---|
| Temperatures | CFD | Simple Model | ΔT/T | CFD | Simple Model | ΔT/T |
| Component | [K] | [K] | [%] | [K] | [K] | [%] |
| Upper Membrane | 309.85 | 309.59 | -0.08 | 277.27 | 277.55 | 0.10 |
| Cushion | 308.66 | 308.19 | -0.15 | 282.38 | 282.56 | 0.06 |
| Lower Membrane | 307.45 | 306.78 | -0.22 | 287.59 | 287.57 | -0.01 |
| Interior | 300.18 | 299.96 | -0.07 | 290.35 | 290.29 | -0.02 |
| Floor | 273.00 | 273.00 | 0.0 | 293.15 | 293.15 | 0.0 |

Table 1 : Temperatures in the thermobox

| | Hot summer day | | | Cold winter night | | |
|---|---|---|---|---|---|---|
| Heat fluxes | CFD | Simple Model | Δq | CFD | Simple Model | Δq |
| Boundary irradiation (downwards) | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] |
| Upper Membrane (solar) | 768.95 | 788.00 | 19.05 | 307.38 | 315 | 7.62 |
| Upper Membrane (infrared) | 385.47 | 366.42 | -19.05 | 222.34 | 214.72 | -7.62 |
| Upper Membrane (convection) | -62.37 | -50.27 | 12.1 | -31.49 | -23.20 | 8.29 |
| Lower Membrane (solar) | 250.55 | 248.37 | -2.18 | 100.15 | 99.28 | -0.87 |
| Lower Membrane (infrared) | 518.38 | 517.79 | -0.59 | 349.40 | 345.71 | -3.69 |
| Lower Membrane (convection) | 1.54 | -0.42 | 1.12 | -18.44 | -11.78 | 6.66 |
| Floor (solar) | 55.97 | 56.45 | 0.48 | 22.38 | 22.56 | 0.18 |
| Floor (infrared) | 485.42 | 488.30 | 2.88 | 395.26 | 393.58 | -1.68 |
| Floor (convection) | 8.94 | 10.28 | 1.34 | -9.33 | -5.16 | 4.17 |
| Boundary irradiation (upwards) | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] |
| Upper Membrane (solar) | 140.80 | 151.28 | 10.48 | 56.28 | 60.47 | 4.19 |
| Upper Membrane (infrared) | 510.71 | 505.33 | -5.38 | 373.59 | 379.98 | 6.39 |
| Upper Membrane (convection) | -1.54 | -0.44 | 1.1 | 18.21 | 11.78 | -6.43 |
| Lower Membrane (solar) | 13.31 | 11.29 | -2.02 | 5.33 | 4.51 | -0.82 |
| Lower Membrane (infrared) | 439.81 | 432.65 | -7.16 | 411.34 | 413.71 | 2.37 |
| Lower Membrane (convection) | -9.23 | -10.28 | -1.05 | 9.35 | 5.16 | -4.19 |
| Total heat flux | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] |
| Upper Membrane | 18.25 | 16.16 | -2.09 | 60.23 | 58.14 | -2.09 |
| Lower Membrane | -59.98 | -63.67 | -3.69 | 29.19 | 26.19 | -3 |
| Floor (heating / cooling) | 107.07 | 111.09 | 4.02 | -10.22 | -7.23 | 2.99 |

Table 2 : Heat fluxes in the thermobox

Small differences in the heat fluxes occur for two reasons: First, in the simple model the incoming boundary irradiation at the upper membrane is strictly separated into solar and infrared components, whereas the CFD model takes into account that there are small parts of solar radiation in the infrared wavelength range and v. v. Second, convection at the outer side of the upper membrane is slightly underestimated by the simple model, because the heat transfer coefficients for free convection are calculated for a theoretically infinite plate, where the real model has small dimensions. However, the interesting results - membrane and interior temperatures as well as the energy demand for heating and cooling - are well estimated by the simple model.

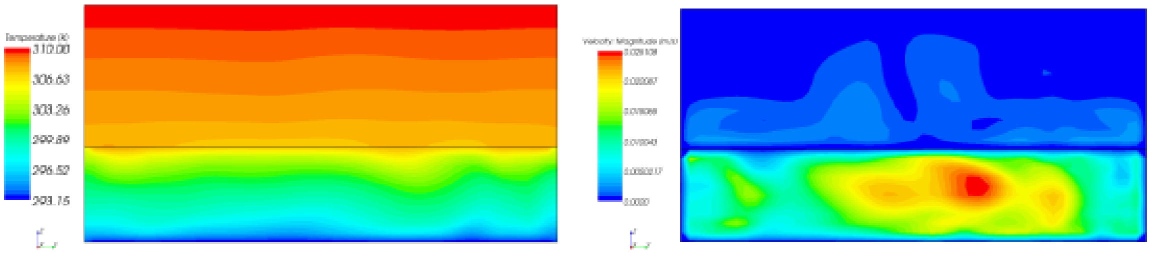


Figure 4: Temperatures and velocities in the simple CFD model (hot summer day)

A second more complex CFD model was examined to analyze the behavior of the thermobox with constant air flow through the volume between the membranes as well as the volume between lower membrane and the blackbody at the ground. Also here a good accordance between this CFD model and the simple model could be reached.

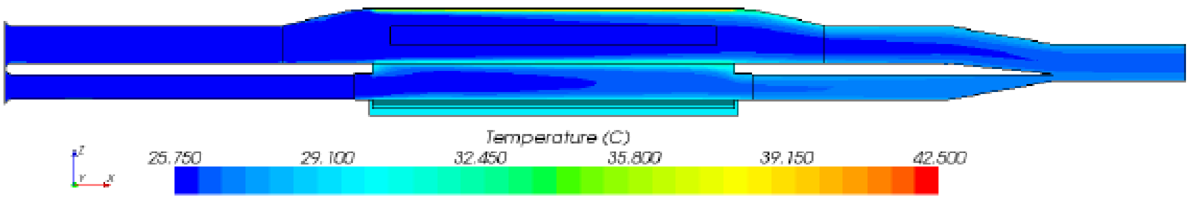


Figure 5: Temperature distribution in CFD model (extreme summer day)

| | Extreme summer day | | |
|---|---|---|---|
| Temperatures | CFD | Simple Model | ΔT |
| Component | [K] | [K] | [K] |
| Upper Membrane | 315.65 | 315.67 | 0.02 |
| Temperature increase | 1.10 | 1.04 | -0.06 |
| Lower Membrane | 305.65 | 305.55 | -0.10 |
| Floor | 302.89 | 302.89 | 0.00 |

Table 3: Temperatures in the thermobox

Finally, the analysis results have been compared to the long-time measurements which are taken on four thermoboxes with different material configurations. First simulations of single states gave also good accordance in temperature results. However, long-time measuring with the boxes goes still on; so integral results will be presented at the conference.

## 6 APPLICATIONS

For a storage building located in Mannheim, Germany, the yearly energy demand had to be determined. The building's roof consists of 6 PVC-PES cushions with optical properties as shown in figure 1. Two extreme weather situations have been chosen to compare CFD results with the simplified analysis presented above: A clear summer day with high environment temperature and an intense solar irradiation and a cold, clear winter night with extreme low environment and sky temperatures.

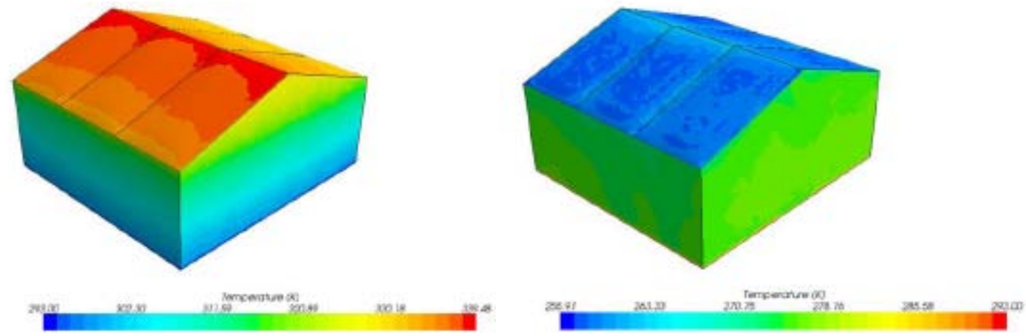

Figure 6: Temperature distribution [K] in the storage building.
(a) hot summer day, (b) cold winter night

| Temperatures | Hot summer day CFD | Hot summer day Simple Model | Hot summer day ΔT/T | Cold winter night CFD | Cold winter night Simple Model | Cold winter night ΔT/T |
|---|---|---|---|---|---|---|
| Component | [K] | [K] | [%] | [K] | [K] | [%] |
| Upper Membrane | 334.36 | 330.59 | -1.13 | 258.88 | 260.21 | 0.51 |
| Cushion | 329.81 | 325.79 | -1.22 | 266.3 | 268.09 | 0.67 |
| Lower Membrane | 321.48 | 316.97 | -1.40 | 274.09 | 276.49 | 0.88 |
| Interior | 308.36 | 305.15 | -1.04 | 283.14 | 285.17 | 0.88 |
| Floor | 273.00 | 273.00 | 0.0 | 293.15 | 293.15 | 0.72 |

Table 4: Temperatures in the building

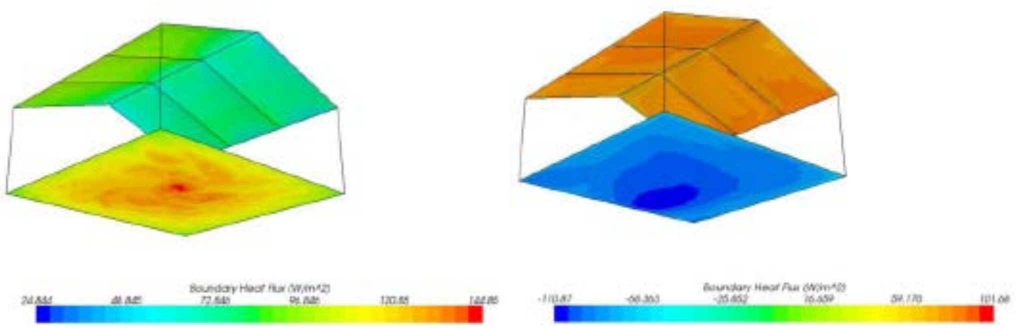

Figure 7: Boundary heat flux [W/m²].
(a) hot summer day, (b) cold winter night

| | Hot summer day | | | Cold winter night | | |
|---|---|---|---|---|---|---|
| Heat fluxes | CFD | Simple Model | Δq | CFD | Simple Model | Δq |
| Component | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] | [W/m²] |
| Upper Membrane | 80.96 | 85.95 | 4.99 | 79.51 | 87.83 | 8.32 |
| Cushion (convection) | 11.38 | 11.99 | 0.61 | 27.80 | 29.53 | 1.73 |
| Lower Membrane | 108.21 | 113.63 | 5.42 | 79.68 | 88.34 | 8.66 |
| Interior (convection) | 9.19 | 8.27 | -0.92 | 29.53 | 28.33 | -1.2 |
| Floor (cooling/heating) | 117.25 | 125.22 | 7.97 | -94.64 | -95.06 | -0.42 |

Table 5 : Heat fluxes in the building

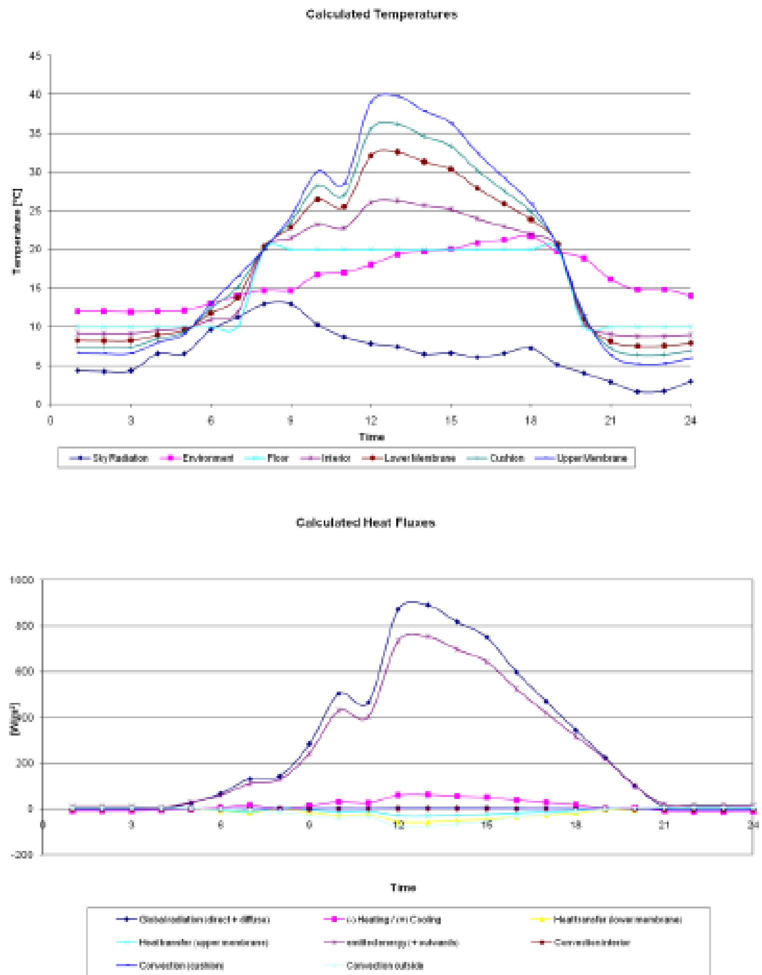


Figure 8 : Calculated temperatures and heat fluxes for a summer day

Finally, the energy demand for heating and cooling of the building under the weather conditions of a test reference year has been calculated by integration of the hourly heat fluxes through the floor of the building. For a ground area of 225 m² the estimation leads to a realistic value of about 45.000 kWh/year.

## 6 CONCLUSIONS

The simple model approach as presented above is able to estimate the energy behavior of membrane buildings within a small error range which can be estimated by few CFD simulations for extreme boundary conditions. So the simulation of the behavior of a building for each hour in a year can be accomplished in a very short time. By this approach it is also possible to study and compare different configurations of the membrane roof of a building under realistic weather conditions.

It should be noted that the output of the simple model simulation is only averaged, that means that peaks in temperatures or heat fluxes could not be determined.

To approve this approach for energy demand calculations and to be able to simulate more complex building geometries, further work will be done on modeling a building by a higher number of surfaces. However, it must be taken into account that the simulation time increases considerably the more radiation surfaces are used in the model.

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