International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2011
E. Oñate, B. Kröplin and K.-U.Bletzinger (Eds)

NUMERICAL INVESTIGATIONS FOR AN ALTERNATIVE TEXTILE INVERTER BUILDING IN THE AREA OF SOLAR POWER GENERATION

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Key words: Textile composites, environmental technologies, photovoltaics, cooling, converter, latent heat, radiation, convection, phase change material, CFD, inverter building, numerical methods, power generation

Abstract. *Within electrical power generation by solar applications such as photovoltaics, the direct electric current is transformed into alternating current by converters. By the conversion of the current, heat is released from the electrical equipment into the building where the converters are placed. The building itself is made from concrete. Hot air (mediterranean area like Spain) sucked from the ambient by the converters into the building is the only heat sink. Water is not available. By the heat release from the inverters the indoor temperature increases up to 50°C which decreases the convective cooling effect for the inverters. Furthermore during a day cycle the concrete is heated too and the heat can not sufficiently be released from the concrete during the night.*

To avoid this critical thermal situation an alternative inverter building based on textile structures (membrane) has been designed. The indoor climate and energy balance of textile buildings depend highly on the optical properties of the roof's membrane material. The heat capacity and heat resistance can be neglected (no storage effects). So the radiation becomes dominant for the thermal situation in the building during day and night. By covering the textile material, to ensure specific optical properties, the thermal impact from outside can be minimized and heat release during night to the sky becomes possible.

To validate the concept, a complex three-dimensional numerical model has been set-up including heat sources inside the building. To prohibit temperature increase during the day a passive cooling system based on phase change materials [2] has been integrated into the model. Based on the numerical model a time dependent computation of the thermal behaviour of the textile building has been performed including irradiation of the sun (solar, diffuse). The influence of the wind on the building has been modeled, too. The results of the simulation show that the complex thermal transport mechanism for textile buildings can be well predicted by the used computing technology (CFD). Furthermore it can be demonstrated that the concept of the textile building can be a good alternative to a building made of concrete.

1 Introduction

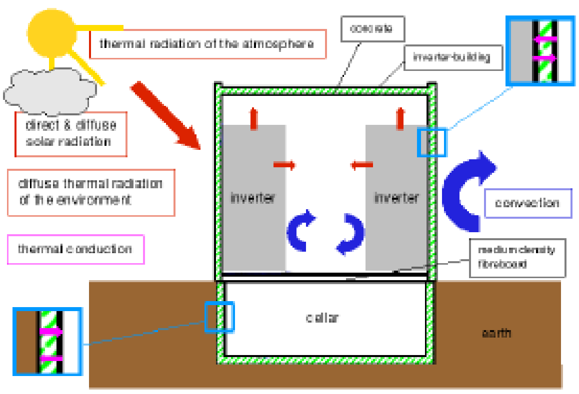
Photovoltaic systems need beneath the solar panels an additional equipment like converters which transform the direct current into alternating current. Thereby heat is released by the electrical components of the converter. Therefore they must be cooled. This is mostly realized by air which is conducted through the converters. The converters are sucking air from the interior of the building. The buildings have openings to ambient. Therefore air from ambient is indirectly conducted into the building. The ambient temperature in hot areas like Spain may be above 40°C, so the temperature gradient is not sufficient to cool the inverters effectively. The concrete is heated by the inverters inside and by thermal solar load from outside. During the night the heat stored in the concrete is partially released into the building. The building itself stores most of the heat until the morning. Therefore the interior air temperature in the building is not decreasing much. The new current production cycle starts in the morning with a room temperature of nearly 30°C, whereas the ambient temperature is below 20°C.
To improve the thermal situation inside the building a new innovative concept was developed and thermally analysed by numerical computations. The alternative concept for the building is based on textile materials instead of concrete. The approach of textile materials for walls and roofs leads to an improved heat transfer to the environment during the night. The reason for this is that textile materials do not store much energy and have a good heat transmission by radiation. The benefit of this effect helps to reduce the temperature of structures and air inside the building during night. Furthermore textile materials can be made with appropriate surface properties to achieve good radiation reflectivity during day, so that the heat impact on inner structure components is reduced. The numerical results show that the thermal problems in inverter-buildings can be solved using a design of a coated fibre cloth shell and an integrated latent heat cooling system.

2 Thermal behaviour of an inverter-building made of concrete

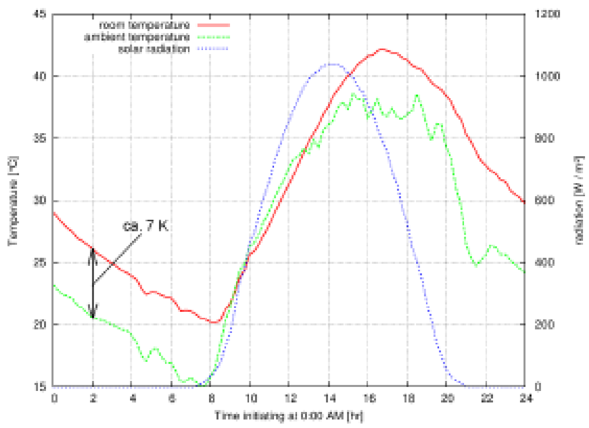
Mostly two inverters are placed in a special building. The walls of the building consist of concrete. Also, there is a cellar embedded in earth for better installation of wire leads. Interior room and cellar are seperated by a medium density fibreboard. In figure 1 (a) the building is schematically pictured in a sectional drawing. The walls of the building (concrete) are green shaded. Additionally in the figure the heat transfer processes are represented. Following heat transport processes occur:

- thermal conduction
- convection
- thermal radiation

In figure 1 (b) the measured time-depended temperature development of room and ambient temperature is shown. All measurement data in this paper is provided by Phoenix Solar AG. Furthermore the according solar irradiation is plotted (San Clemente, Spain). It can be seen that the room temperatur is about 7 K higher than the ambient temperature (within a time shift). The air in the building is heated up by the power loss of the inverters, the released heat of the walls and the sucked air from ambient.



(a) Thermal load and heat transfer processes



(b) Measured temperatures in a inverter-building placed in Spain, San Clemente (August 2009, 16^{th})

Figure 1: Thermal behaviour of an inverter-building made of concrete

The inverter-building made of concrete has pros and cons. A big con is the material concrete. Concrete has a bad thermal conductivity. The properties are tabulated in table 1. In comparison to concrete copper has a thermal conductivity of 400 $W/m/K$. As a consequence the thermal conduction through a wall made of concrete is very bad. Figure 2 exemplarily shows the steady thermal conduction through a flat wall. Because of the temperature gradient between the inner and outer face a heat flow through the wall arises

Table 1: Properties of concrete [3]

density	ρ	2400	kg/m^3
thermal conductivity	λ	2	$W/m/K$
specific heat	c_p	1000	$J/kg/K$

(Eq. 1). The heat flow depends on the thermal resistance R, the temperature gradient $\Delta T = T_1 - T_2$ and the surface A. The thermal resistance is a function of wall thickness s and thermal conductivity λ of the material (see Eq. 2). For example an inverter building has a wall thickness of $s = 0.1\ m$ with a thermal conductivity of $\lambda = 2\ W/m/K$. The outcome of this is a thermal resistance of $R_{concrete} = 0.05\ m^2\ K/W$ (Eq. 3). Due to the bad thermal resistance the walls made of concrete store a part of the conducted heat by day. At night the walls partially conduct the stored heat to ambient and interior. To clarify the bad thermal conduction through the concrete a numerical example is used at this point.

A wall may have a surface area of $A = 1\ m^2$. The temperature of the outer wall is $T_1 = 25°C$ and the inner wall is $T_2 = 30°C$. From this a temperature gradient of $\Delta T = 5\ K$ results.

- If the wall is made of concrete ($\lambda = 2\ W/m/K$) with a thickness of $s = 0.1\ m$, the heat flow amounts to $\dot{Q} = 100\ W$.
- If the wall is made of copper ($\lambda = 400\ W/m/K$) with a thickness of $s = 0.1\ m$, the heat flow amounts to $\dot{Q} = 20000\ W$.
- If the wall is made of PVC (membrane, $\lambda = 0.17\ W/m/K$) with a thickness of $s = 0.001\ m$, the heat flow amounts to $\dot{Q} = 850\ W$.

The comparison shows that the heat flow through a wall made of concrete is very bad. This demonstrates that concrete stores heat during day because of the bad thermal conduction. Also the heat is conducted very slow to ambient at night. For this reason the air inside the inverter-building is not cooled effectivly during the night. In figure 1 (b) it can be seen that the temperature inside the building is 7 K higher than the ambient temperature at night. A solution is to replace the walls made of concrete with a textile reinforcement (membrane). Membranes are very thin whereby marginal heat can be stored. Because of their coating membrane has special optical properties (transmittance, emissivity, reflectivitiy) which influence the thermal radiation. Based on radiation exchange membrane conduct more energy from inside to ambient day and night. The aim of the concept study is to use this special membrane properties to cool the interior (inverters) indirectly at night.

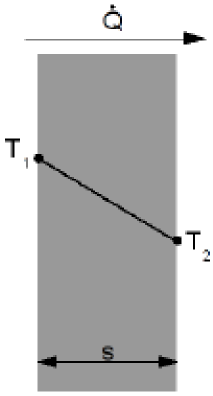


Figure 2: Thermal conduction through a flat wall (steady)

heat flow through a plate

$$\dot{Q} \equiv \frac{dQ}{dt} = \frac{1}{R} \cdot A \cdot (T_1 - T_2) \quad (1)$$

with the thermal resistance

$$R = \frac{s}{\lambda} \quad (2)$$

thermal resistance of a wall made of concrete (thickness 0.1 m):

$$R_{concrete} = \frac{0.1\ m}{2\ \frac{W}{m\ K}} = 0.05\ \frac{m^2\ K}{W} \quad (3)$$

3 Concept of a textile building

3.1 Membrane

Today there are many configurations of fibre cloth on the market like fibre cloth consisting of PET[1]-fibre coated with PVC[2] or glass-fibre reinforcement coated with PTFE[3]. The main difference are the optical properties. In table 2 the properties of different membrane configurations are displayed. Thermal conductivity, specific heat or density of the textile structures are insignificant in this case because the membranes are very thin. The surface coating is affected by the optical properties (transmittance, emissivity and reflectivity) in the solar and infrared radiation band. For example ETFE-foil has a high transmission factor and Glass/PTFE has a low transmittance in the solar radiation band (see table 2). Because of the optical distinctions a study has been made to find the optimal properties of the membran coating for the alternative, textile inverter-building.

A variation of transmittance, reflectivity and emissivity of the membranes were accomplished in the solar and infrared radiation band separately. For the computation a simulation model for two-or-more-layered membrane roofs [6] based on the thermal net radiation method [4] was used. The variation of transmittance, reflectivity and emissivity has shown that the heat exchange between interior and exterior is influenced by the membrane coating. The membran of the alternative, textile building should reflect all of the solar irradiation. Therefore the reflectivity of the coating must be high and the transmittance and emissivity must be low in the solar radiation band. The transmittance in the infrared radiation band has to be large so that the thermal radiation is submitted

[1]PET = Polyethylentherephtalat
[2]PVC = Polyvenylchlorid
[3]PTFE = Polytetrafluorethylen

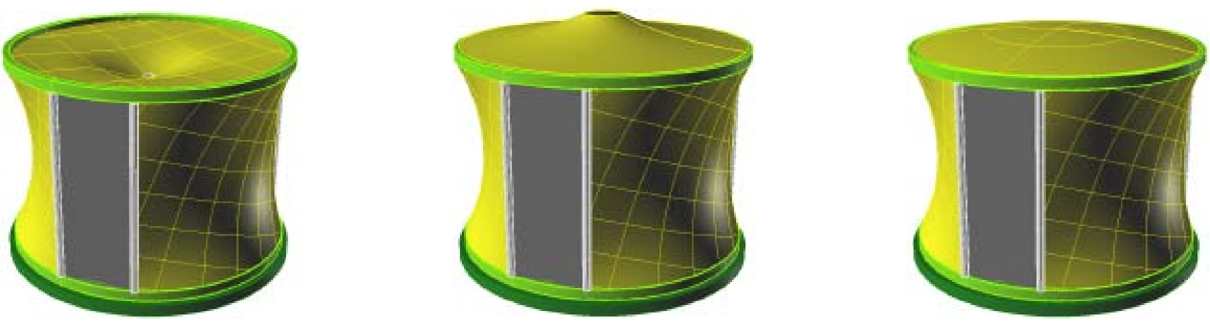
to ambient. In addition to a large transmittance a low reflectivity in the infrared range occurs. Because of these criteria a glass-fibre reinforcement coated with PTFE is selected for the concept study.

Table 2: Properties of different membrane configurations [9]

spectral range		glass/PTFE	PET/PVC	PET/silicone	ETFE-foil
solar	ε_{sol}	0.22	0.36	0.28	0.05
	τ_{sol}	0.13	0.04	0.20	0.90
	ρ_{sol}	0.65	0.60	0.52	0.05
infrared	ε_{ir}	0.82	0.91	0.90	0.60
	τ_{ir}	0.02	0.01	0.02	0.35
	ρ_{ir}	0.16	0.08	0.08	0.05

3.2 Membrane-building

The idea is to design a round membrane-building to minimize the surface area. Also, a round floor is innovative and forms a contrast to the straight solar panels of a solar power plant. Figure 3 shows different designs of a round membrane-building. The three different designs vary in the roof construction. The design in figure 3 (c) is chosen because water drains off and does not retain on the roof. Due to the design the inverters are placed at the center of the building.



(a) Design 1 (b) Design 2 (c) Final Design

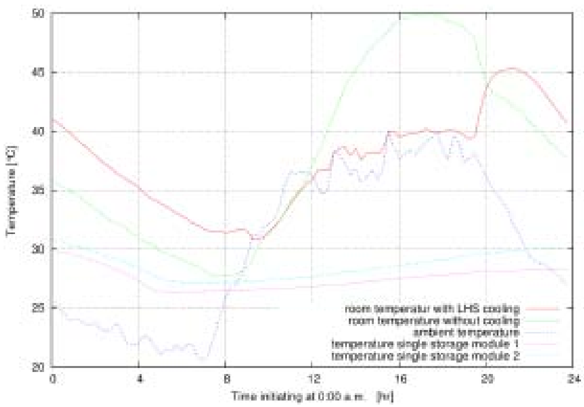
Figure 3: Designs of the alternative, textile buildings

3.3 Latent Heat Storage (LHS)

Phase Change Materials (PCM) like paraffin have the advantage that the melting temperature can be fixed to a specific temperature by additives. If PCM's are melting

the latent heat stores energy applied by any heat source without significant temperature change. The stored heat may be released at a later time by any heat sink. This time shift can be used for inverters if heat is applied to the PCM during the day and the stored heat is removed during the night. As long as material is availble for melting, the temperature is nearly fixed to the melting temperature. To develop a cooling system based on PCM, the main problem of low thermal conductivity of PCM's was solved by using metal foam. Metal foam exists as foam with open porosities and foam with closed porosities. The foam with open porosites can be flown through. This effect is helpful to fill PCM into the open porosities.
A prototype of a latent cooling system has been built in La Solana (Spain) in cooperation with Phoenix Solar AG. The cooling system was installed in the cellar of the inverter-building and consists of fifteen single storage modules. Each of these storage modules contains the same mixture of paraffin and metal foam and then have a optimized ordering scheme. Therefore a channel was designed to conduct the flow from ambient to the latent cooling system. The melting temperature of around $29°C$ has been chosen. Figure 4 (a) shows the cooling system during the installation process. From the figure the single storage modules on the left side can be seen how they are embedded into the channel for air circulation. The temperature development in the building with and without cooling system is shown in figure 4 (b). The two buildings are placed at the same solar power plant.
Due to the good results of the LHS in Spain the same configuration of single storage modules is chosen for the concept of the alternative, textile building. Only the flow channel has to be adapted to the design of the membrane-building.

(a) LHS during installation in Spain



(b) Comparison of measured temperatures in buildings with and without cooling system

Figure 4: LHS in La Solana, Spain

4 Numerical analysis

4.1 Model

After having found a practicable design, a three-dimensional model for CFD (Computational Fluid Dynamics) calculations has been set up. The numerical model consists of two inverters (heat source), a latent cooling system, a membrane-shell and other elements. In figure 5 the whole numerical model with all components is represented. In the simulation a closed air circuit is concepted, because only the influence of the membrane properties are demonstrated. The surface area of the inverters is the heat source in the model. The surface temperature is fixed at 50°C for the first 12 hours (inverters are running). That is a worst case scenario. After 8 p.m. the inverters are shut down and have no fixed surface temperature any more.

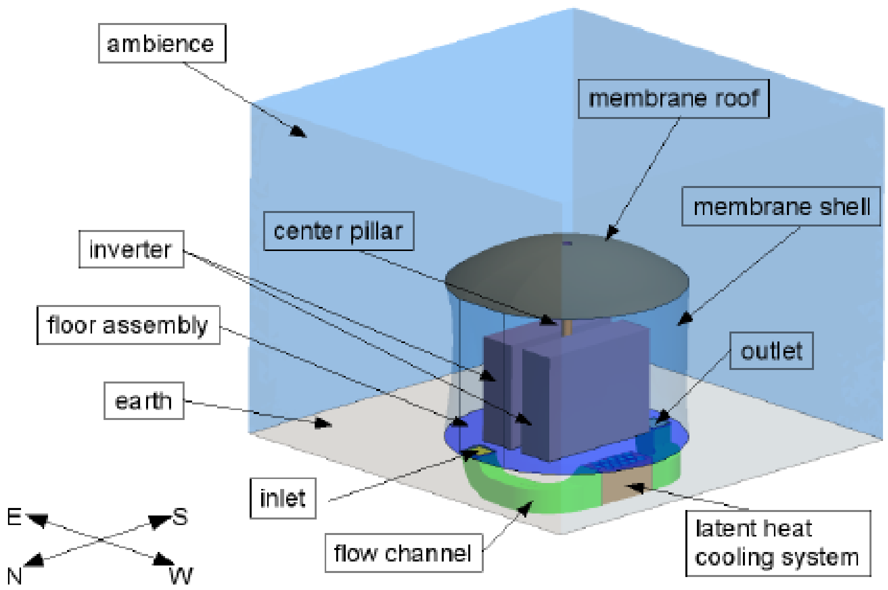
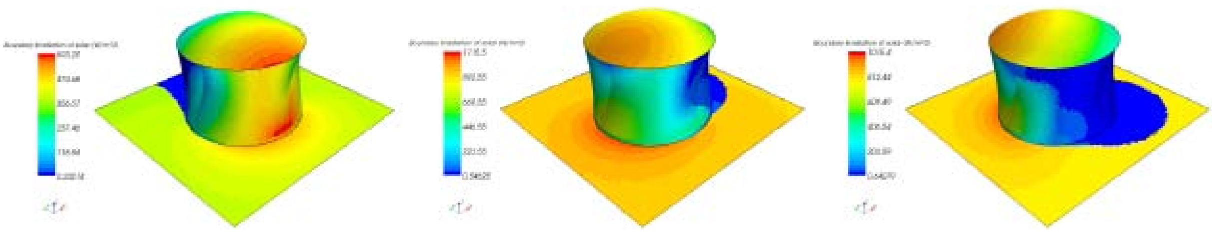


Figure 5: Numerical Model of the textile building

In figure 5 the latent heat cooling system and the constructed flow channel is pictured, too. The configuration is the same as the prototype. The location of the LHS is under the floor assembly of the building. There is no extra cellar needed. The melting temperature is 29°C. The flow channel has an inlet and an outlet at the floor. Both are closed until the average temperature of 41°C is reached inside the building. It becomes clear that no connection to ambient exists. So the effects of the membrane properties can be analyzed. After all the paraffin in the cylinders is melted the LHS is shut down. That means that there is no heat exchange between the LHS and the air inside the inverter-building, because the openings are closed. The re-cooling of the LHS and the solidification of the paraffin is not considered in our simulation, because this must be realized by ambient air. The simulation model consists of two regions, a flow region (ambient atmosphere, air inside the building, air in the channel) and a solid region (paraffin-metal foam composit cylinders). By defined interfaces between the fluid of the interior and the fluid of the ambience (membran-interface) and between the fluid and the solid the heat exchange can be calculated. The used method to simulate the phase change is called method of Volume of Fluid. This additional equation (to the conservation equations) solves for the volume fraction of the liquid phase per finite volume. The flow around the single storage modules and in the other fluid regions have been solve for mass and momentum. As turbulence model a $k - \varepsilon$ model has been selected.

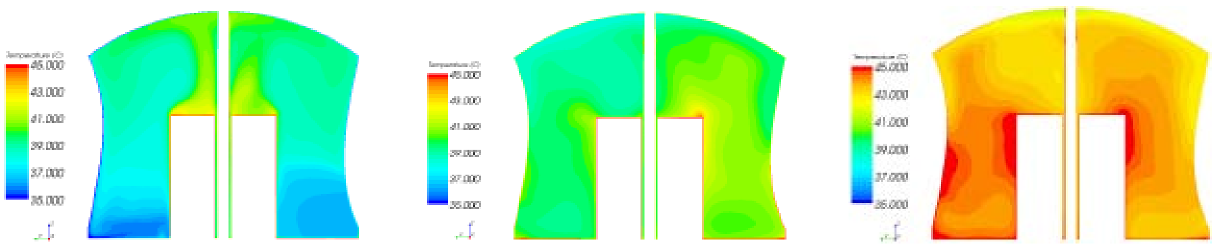
4.2 Results

The computation has been performed with the CFD-Solver StarCCM+ [8]. To evaluate the developed configuration a full day-night-cycle using the measured ambient temperature and the solar irradiation (San Clemente, Spain) as boundary conditions has been computed. Also, the different solar altitudes and the sun movement in San Clemente, Spain, has been computed for a full day cycle in August. In figure 6 the solar irradiation at the building surface is pictured for three different time stamps. According to the sun movement the solar irradiation is moving, too. In the afternoon the sun is standing low. Therefore the shadow of the building is quite long.



(a) 11:00 a.m. (b) 02:00 p.m. (c) 05:00 p.m.

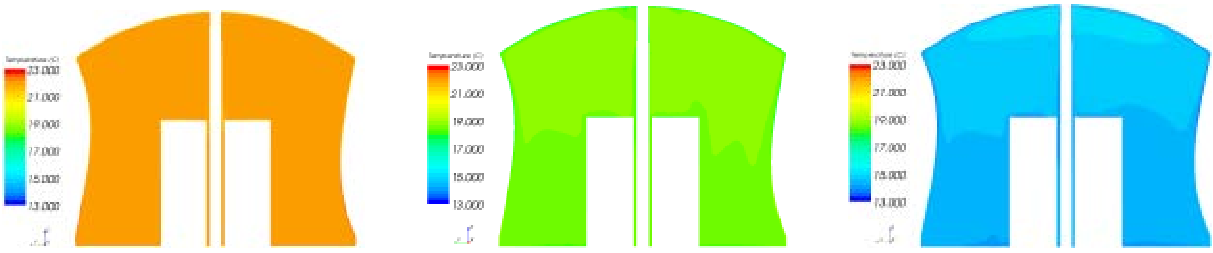
Figure 6: Solar irradiation



(a) 11:00 a.m. (b) 02:00 p.m. (c) 05:00 p.m.

Figure 7: Temperature inside the building during the day

The temperature inside the building increases (see figure 7) until the afternoon up to about 45°C. The reason for this is the hot surface area of the inverters and the solar impact. During the night the heated structures are releasing heat by radiation through the membrane to the sky. Figure 8 shows the temperature drop inside the building during the night with the help of three time stamps. The room temperature decreases below 13°C until the next morning because there is no heat source left inside (inverters shut down) and due to the radiation heat exchange with the environment.



(a) 11:00 p.m. (b) 02:00 a.m. (c) 05:00 a.m.

Figure 8: Temperature inside the building at night

Figure 9 shows the temperature profile of the membrane roof and shell. Further the ambient temperature is plotted, too. The averaged temperature of the roof and the shell increases very fast. After three hours and 48 minutes (at 11:48 a.m.) the LHS is activated. The fan blows the cool air from the LHS channel into the room. So the surface temperature of the membrane decreases a short time. Because the radiation intensity and the elevation angle of the sun increases until the afternoon the temperature of the membrane surface increases, too. Also the hot inverter surface area influences the temperature of the membrane. The developing of the membrane roof and shell temperature depends on the ambient temperature (see figure 9). The maximum temperature of membrane roof and shell were achieved in the afternoon at 3:00 p.m.. After 12 hours (8:00 p.m.) the temperature of the membrane surface area decreases very fast because the inverters were shut down and the temperature of the environment drops down. Due to the membrane coating (optical properties) the temperature of the membrane surface is falling below ambient temperature at night. That can be traced back to the radiation exchange with the sky because the temperature of the sky falls below 0°C during a clear night.
Figure 10 summarizes the achieved results. The graphic shows the temperature gradient of

- the room temperature of the membrane building with LHS cooling (case 1)
- the room temperature of the membrane building without LHS cooling (case 2)
- the room temperature of an inverter building made of concrete (case 3)
- the ambient temperature.

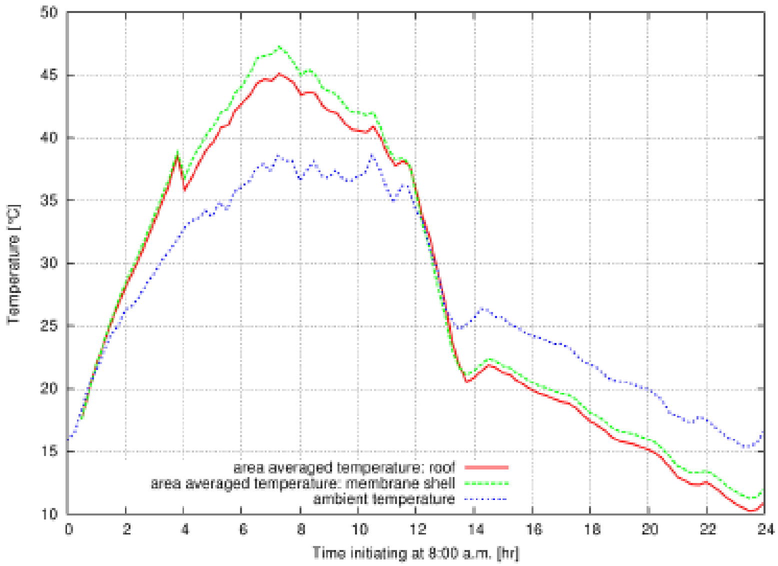


Figure 9: Area averaged temperature of membrane roof and shell

The temperature development inside the building is the same at the first two hours for all three cases. This can be traced back to the heated inverter surface area. After that time interval the room temperature of the membrane buildings continue increasing. In contrast the developing of the room temperature of case 3 is gently declined in comparison with case 1 and 2 because the concrete stores a part of the released heat. The LHS cooling system (case 1) is activated if the temperature inside the building exceeds $41°C$. This mark is achieved after three hours and 48 minutes. In the graphic it becomes apparent on the sudden drop of temperature because cold air stored in the channel of the LHS gets into the building. Thereby the room temperature temporary falls below $35°C$. The room temperature of case 2 and 3 increases above $45°C$ until the afternoon. Due to LHS the air temperature of the cooled inverter-building does not exceed the temperature of $45°C$ during the day. The temperature inside the textile inverter-building can be further decreased by a modification of the LHS. The cooling effect of the LHS can be optimised by a larger LHS or a different melting temperature.
After 12 hours (8:00 p.m.) the inverters were shut down and the ambient and sky temperature decreases. The paraffin of the LHS is completely melted at this time and the LHS is deactivated. These factors become apparent in figure 10. The temperature inside the building of case 1 and 2 quickly decrease within two hours. The developing of the room temperature of case 1 and 2 is similar again after 15 hours (11:00 p.m.). The decrease of the air temperature inside the building (case 3) is very slow in comparison with case 1 and 2. This can be traced back to the walls (thickness of 0.1 m) made of concrete because of the bad thermal conduction. At night the room temperature of the membrane building is 4 K less than ambient temperature. As conclusion it can be shown that the

fibre coated reinforcement conduct more energy to the environment at night than applied to them. Equally textile structures do not store much heat because of their thinness. After a day-cycle of 24 hours in the morning the temperature inside a membrane building is 12.5°C and inside a building made of concrete 25°C. Due to the special properties of textile structures the interior temperature of an inverter-building can be reduced about 12.5 K.

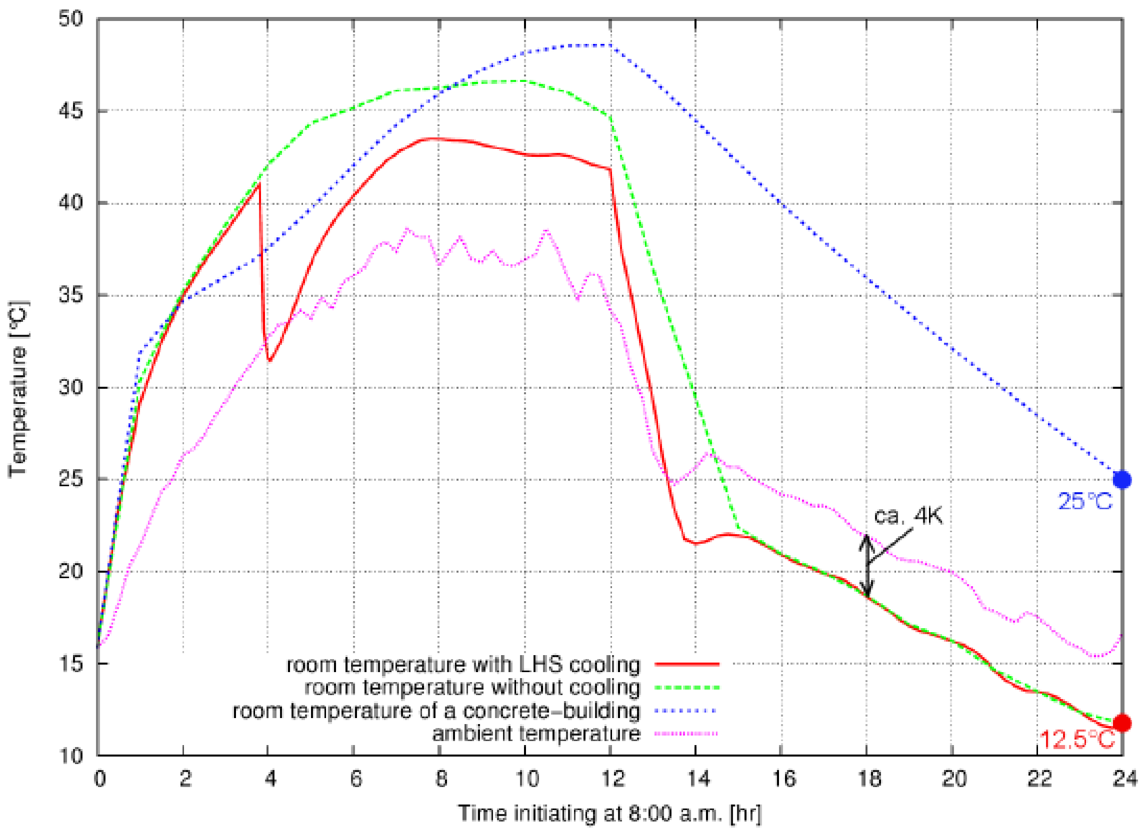


Figure 10: Volume averaged temperature inside different inverter-buildings

5 Conclusion

The concept study shows that a textile inverter-building of coated fibre cloth with integrated LHS solve the thermal problems of the current inverter-building. The numerical computation has shown that membrane-buildings have considerable advantages compared to buildings of concrete at night. Due to their optical and material properties and their low density they conduct energy to ambient at night. Thereby the temperature inside the building decreases after an operating day under ambient temperature at night.

From the numerical computation it follows that

- the room temperature is under ambient temperature at night
- the room temperature (membrane building) is lower than the room temperature of a concrete-building during the day and at night
- the coated fibre cloth conduct more energy to the environment during the day and at night than applied to them
- the integration of a LHS shows, that the temperature inside the building can further be decreased
- the membran structures do not store much heat

Because of these scientific findings a realisation may be possible. A prototype has to be build to test the functionality of the building for one year in a field test, because the simulation needs much time and there is no possibility to compute the whole circle of a year.

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