Modeling a Naturally Ventilated Double Skin Façade with a Building Thermal Simulation Program

Rasmus Lund Jensen, Research Assistant,,
Aalborg University;
rlj@civil.aau.dk

Olena Kalyanova, Ph.D-student,
Aalborg University;
ok@civil.aau.dk

Per Heiselberg, Professor,
Aalborg University;
ph@civil.aau.dk

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SUMMARY:
The use of Double Skin Façade (DSF) has increased during the last decade. There are many reasons for this including e.g. aesthetics, sound insulation, improved indoor environment and energy savings. However, the influence on the indoor environment and energy consumption are very difficult to predict. This is manly due to the very transient and complex air flow in the naturally ventilated double skin façade cavity.

In this paper the modeling of the DSF using a thermal simulation program, BSim, is discussed. The simulations are based on measured weather boundary conditions, and the simulation results are compared to e.g. the measured energy use for cooling, air temperature, temperature gradient and mass flow rate in the DSF cavity, etc.

The thermal simulation program does not at the moment include a special model to simulate the DSF. However, the results show that it was possible to predict the energy flow, temperature distribution and airflow in the DSF. Some agreement between the measured and simulated results was unfortunately very sensitive to the model. This implies that without the possibility to calibrate the simulation model with measured data the risk of generating poor results is imminent. Therefore further work including both measurements and more detailed and robust simulation programs are necessary.

1. Introduction

Double Skin Façade (DSF) is a relatively young concept, which is distinct from the conventional buildings by its ability to react to and to take advantages from various weather conditions. The use of double-skin façade has increased during the last decade. There are many reasons for this including e.g. aesthetics, sound insulation, improved indoor environment and energy savings. Due to the numerous functioning modes, every double-skin façade building is unique in its physics and performance. Compared to a conventional glazed building and depending on the functioning mode, DSF can function as a barrier for solar radiation or it can preheat the ventilation air; DSF can reduce the penetration of noise (i.e. traffic) from the outside; it can improve perception of comfort (increased surface temperature of the glazing); it allows for application of night cooling and at the same time it is burglary safe; in some cases, it gives better possibility for fire escape and fire protection; it provides better protection of shading devices and allows to open windows on the top floors in a multistory building.

Energy efficiency of the DSF, however, is difficult to achieve due to the lack of a suitable simulation tool, able to deal with the very transient and complex air flow in a ventilated double skin façade cavity. As pointed out by H. Manz and Th.Frank:*"…the thermal design of buildings with the DSF type of envelope remains a challenging task. As, yet, no single software tool can accommodate all of the following three modeling levels: optics of layer sequence, thermodynamics and fluid dynamics of DSF and building energy system"* (Manz and Frank, 2005).

The DSF-buildings are extremely dynamic, especially, if the cavity is naturally ventilated. DSF continuously adjusts its performance not only to the solar irradiation, but also to the highly fluctuating natural driving forces. Due to the extreme dynamics of the system, the changes happen very rapidly and they can rarely be smoothed in time. Consequently, any shortcomings in the design will result in increased energy use and increased temperature fluctuations in the occupied zone.

In the DSF-building the great part of the energy flow happens through the DSF construction and, for that reason, it is extremely important to be able to predict its performance. The main difference between the DSF and a conventional window is that in case of DSF it is difficult to estimate what part of the solar heat gains that will penetrate through the DSF into the adjacent zone and what part of solar gains will be captured by the DSF and then removed with the cavity air. At the same time: "*global heat transfer coefficients, such as overall heat transfer coefficient (U-value) and the solar heat gain coefficient (g-value) cannot be directly applied to ventilated facades"*(Faggembauu, et al., 2003) as these are standard coefficients, which *assume steady state and one directional heat flow.* These coefficients are only wise to apply as characteristics of DSF constructions, yet not as an overall attribute of DSF.

However, U-value and g-value are inevitable inputs in the majority of thermal building simulation tools, so it is important to be aware that: g-value expresses the amount of solar radiation, which is transmitted to the room through the fenestration plus amount of solar radiation absorbed by glass and then re-transmitted towards the interior mainly by means of convection and radiation.

In this case the convective and radiative surface heat transfer coefficients are considered to be characteristic for a building. However, these differ a lot for DSF, since the surface temperature of the glazing and shading in DSF increase significantly with the height of the cavity. Thus the local g-value of the glazing may differ a lot, as well as the actual area averaged g-value of the glazing, compared to its characteristic g-value, normally provided by a producer.

The convective heat transfer contribution to the g-value is also important, since the air velocities in the DSF cavity are normally higher than the ones in a conventional room and the surface temperatures of the glazing/shading can also become relatively high. Finally, the convective and radiative heat transfer contribution in the actual g-value are not straight forward and the g-value is actually varying in time, and depends not only on angle of incidence, but also on surface temperatures and mass flow rates.

Surface heat transfer is also included into the U-value characteristic and therefore the same limitations are valid if it is necessary to estimate an actual U-value of the DSF constructions.

On the whole, the complexity of the DSF concept has already been realized and, in the literature (Gertis, 1999, Saelens, 2002, Zöllner, 2002 and the others) one can frequently meet a request for validation of the building simulation tools for DSF modeling in order to evaluate the limitations of the software.

This paper describes an empirical validation process of the Danish building simulation tool, BSim, where a model of a DSF-building is built up to simulate the outdoor DSF test facility, 'the Cube'. An attempt is also made to demonstrate that the modeling of the DSF requires not only a reliable tool and experience in its application, but also special attention to the input of the DSF constructions properties.

2. Empirical data

In the fall of 2006, a set of experiments was conducted in the outdoor DSF test facility 'the Cube', see Figure 1. An empirical dataset is now available for two double-skin façade functioning modes: thermal buffer mode and external air curtain mode, however only the results for the external air curtain mode are reported in this paper. In this mode, the external operable windows at the top and bottom of the cavity are open to the outside, the air enters the DSF at the bottom of the cavity, heats up when passing through the DSF cavity and then released through the top openings to the external environment, carrying away some amount of the solar heat gains. The flow motion in the cavity is naturally driven.

The empirical data set is available for a 2 weeks period, starting from 1st of October until 15th of October and includes all necessary weather data, such as wind speed, wind direction, outdoor air temperature and humidity, total and diffuse solar irradiation on a horizontal surface, ground temperature under the foundation and atmospheric pressure.

The air temperature in the DSF cavity, vertical temperature gradient in the cavity, surface temperatures of the glazing, mass flow rate in the DSF are available in the empirical data set. During the experiments, the air temperature in the room adjacent to the DSF cavity was kept constant at 22^{o}C. The cooling/heating power load to the room was measured and included into the empirical data set as a parameter that reflects the performance of the DSF.

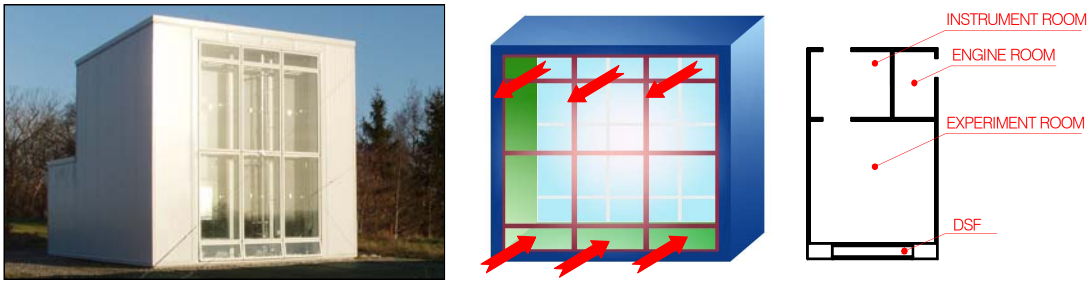


Figure 1. 'The Cube' (left). Illustration of principle of the external air curtain mode (centre). Plan of 'the Cube' (right).

Thermal properties of all constructions in the test facility, its detailed geometry and dimensions were documented during the construction and were updated later during the preliminary measurement phase (see more in Kalyanova, et al. 2008). The spectral properties of the window glazing were tested at the EMPA Materials Science & Technology Laboratory. The information about the optical properties of the surfaces is available as a function of the wave length, in the wave length interval 250-2500nm for the following surfaces: Glazing, Ceiling and wall surface finishing in the DSF; Ceiling and wall surface finishing in the experiment room; Carpet in front of 'the Cube'.

No shading devices were used during the experiments.

3. BSim

BSim is an ISO STEP based, integrated building design tool, BSim (Wittchen et al. 2005). The core of the design tool is a common building data model shared by the different design tools, and a common database with typical building materials, constructions, windows and doors. Figure 2 illustrates the user interface of BSim.

In BSim the direct solar radiation is calculated every ½ hour based on the actual position of the sun. The surfaces where the ray of sunshine hits is also the surfaces that receive the energy and it is possible to have light passing through a room without affecting the heat balance. The diffuse radiation from the sky entering a zone is distributed according to a chosen weight factor.

Calculation of heat flow from a surface is based on dynamic calculations of both the convective heat transfer coefficient and long wave heat exchange. The convective heat transfer coefficients are calculated based on empirical correlations, mainly using dimensionless numbers. This means that the limitations discussed previously are not applicably to the calculation of U-value for BSim, but are for the calculation of the g-value.

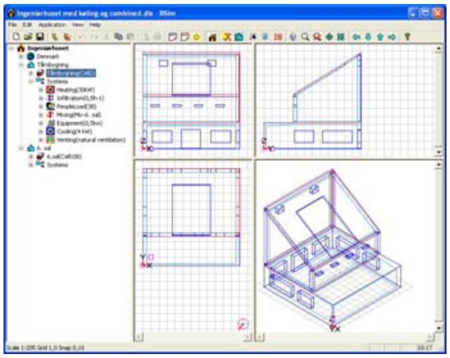


Figure 2. SimView, the user interface of BSim for editing and viewing the layout of the building.

4. BSim model

The model where constructed according to the documented geometry and thermal properties of the constructions in 'the Cube'. It consists of four thermal zones (Figure 1):

- double-skin façade (DSF)
- experiment room
- instrument room
- engine room

Since the thermal simulation program does not, at the moment, include a special model to simulate a DSF unit, the double-skin façade was modelled identically to any other thermal zone. .The external dimension of the experiment room together with the DSF is 6x6x6m. Internal dimensions of the DSF cavity is 0.56m depth, 5.5m height and 3.2m width. The main thermal characteristics of the building and model are available in Table 1.

Table 1. Thermal characteristics of 'the Cube'.

Terrain type	Scattered windbreaks
Longitude	9°59'44.44"E
Latitude	57°0'41.30"N
Total area of windows (visible glazing)	6·3.229(2.693) m^2
Total area of top openings open	0.32 m^2
Total area of bottom openings open	0.39 m^2
External windows of DSF	Clear glass
Internal windows of DSF	4-Ar16-4
U-value of external windows	5.33 W/m^2K
U-value of internal window	1.39 W/m^2K
U-value of external walls	0.08 W/m^2K
U-value of the floor construction	0.15 W/m^2K
g-value of external window	0.8
g-value of internal window	0.63
Net volume of DSF	11.24 m^2
Net volume of exp.room	143.11 m^2

Table 2. Weather conditions during the experiments.

Mean outdoor air temperature °C	Mean wind speed m/s	Mean diffuse solar irradiation W/m^2	Mean total solar irradiation on horizontal W/m^2
12.5	3.6	91*	175*

** Mean for solar irradiation is given only for the periods with sun.*

Simulation period was set according to the length of the weather file for the external air curtain mode (01.10.2006 – 15.10.2006), using the weather data file to define the outdoor thermal conditions.

Available weather data includes a wide spectrum of various thermal conditions: periods with high direct solar radiation, with high diffuse solar radiation, cool and warm outdoor air temperature, various wind directions and wind speeds. This allows to scrutinize the model for different circumstances. In the model, the air temperature in the experiment room was set to 22°C.

No shading devices were included in the model. Natural ventilation mass flow rate in the DSF cavity is defined via the area of the openings, height of the openings, discharge coefficients and pressure coefficients. The discharge coefficient of the top and bottom opening was measured prior to the experiments in a wind tunnel. In BSim, surface average pressure coefficients are used. Therefore the calculated airflow in the DSF is mainly dependent on the calculated thermal driving force.

5. Comparative and Empirical Validation

Prior to the empirical model a set of the comparative test cases were completed with BSim software in the framework of IEA Annex 34/43, subtask E. The subtask was focused on validation of building simulation software for modeling of DSF. Comparative exercises were completed by five different organizations, using different building simulation tools to simulate 'the Cube'.

Completed set of the comparative exercises has demonstrated the magnitude of differences between different building simulation tools and have confirmed the complexity of the task to simulate building with a double skin façade. The most important achievement in the comparative exercise was the experience gained by the modelers regarding DSF modeling, the justification of their models against each other and, finally, the demonstration of how important it is to conduct further empirical validation for modeling of buildings with the DSF, and thus to provide the reference against which modeling predictions could be compared. The empirical model which simulations are presented in this paper was prepared based on the comparative validation results, hence it has been justified against the other models, and the errors have been eliminated.

The empirical validation was completed in the 'blind'-form, which means that the modeler received the experimental results only after submitting the results of simulations.

The building simulation tools can also be validated on their performance *together with their limitations,* yet the best possible software performance must be achieved. Considering limitations of various software tools the quantitative measure for the empirical validation should be chosen between the global parameters, as the accuracy in predictions of minor parameters can be limited.

Only simulation results for the global parameters are reported here. These are the power loads to the experiment room, the air temperature and the mass flow rate in the DSF cavity. Although the experimental data is available for many other parameters such as surface temperatures of the glazing, walls, etc. these are not included into the list of global parameters. The reason for this, is that the resulting surface temperatures, for example, depend on computations and assumptions in a model, such as distribution of solar radiation and shadow to the surfaces, level of detail in longwave radiation exchange calculation, flow regime at the surface and assumptions made towards the calculation of the convective heat exchange at the surface etc. These computations and assumptions vary from one tool to another, but in a larger perspective, the ability of a building simulation tool to model DSF is expressed by its ability to accurately predict the power loads in the building.

The air flow rate in a double skin facade cavity is rather high compared to the temperature difference between the air in the cavity and outdoor therefore it is essential to perform the empirical validation of the air temperature predictions in the models via *'the temperature raise in the DSF '* to track the amount of energy transported by the air flow. Due to the magnitude of mass flow rate, an error in prediction of the air temperature in the range of 1°C can mean hundreds of watts of error in energy balance.

Figure 3 illustrates the temperature raise in the DSF cavity above the outdoor air temperature and power loads to the experiment room for two days with the principally different boundary conditions:

- 10th of October – a day with high direct solar radiation
- 11th of October – a day with mainly diffuse solar radiation

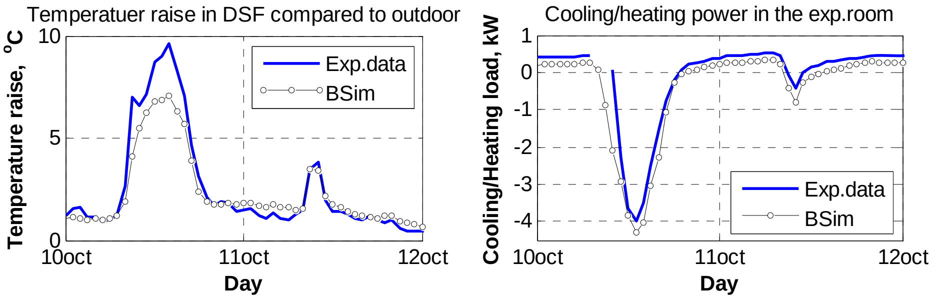


Figure 3.Measured and simulated temperature raise in the DSF cavity compared to outdoor air temperature (left). Measured and simulated power loads to in the experiment room (right).

The power loads in the experiment room vary between day and night time period. Normally the experiment room was cooled during day- and heated during night-time.

The BSim model underestimates the heating loads during night time since the thermal bridges were not included into the model, while days with strong direct solar radiation, cooling loads are overestimated. This, however, depends not only on predicted air temperature in the DSF cavity and mass flow rate, but also on the amount of solar radiation that has been transferred into the experiment room in the first order of solar transmission, as this part does not influence the calculation of the air temperature and mass flow rate in the DSF cavity.

Cooling load in the experiment room is, still, the result of interplay of many parameters, such as mass flow rate in the cavity, convection and radiation heat transfer, transmission of solar radiation etc. At the same time, it is not possible to validate all of these parameters separately, as many of those are the challenge for the whole field of building simulations. Calculation of natural ventilation is particular interesting: as the natural mass flow rate is exceptionally difficult to simulate, yet, it is one of the key actors in DSF performance. So, the mass flow rate was chosen as one of the main targets in evaluation and validation of BSim model.

In Figure 4 it is shown that prediction of the mass flow rate in the DSF cavity is not good enough and, as a consequence, predictions of the air temperature in the cavity and power loads in the experiment room can not be regarded as reliable. The reason for flawed performance of the BSim model towards the mass flow rate calculations is the simplified model for calculation of the naturally driven flow. BSim uses an empirical expression for single sided natural ventilation at different levels. Accordingly, the impact of wind pressure in the model is almost negligible, as in BSim, the average surface pressure coefficients are used. This is in large contrast to the experimental data, as the mass flow rate in the DSF cavity was driven by both buoyancy *and wind*, see Figure 7. In the figure, it is seen that the major part of experimental data is available for the wind dominated or assisted driving forces, although it is common to assume that the mass flow rate in a double-skin façade cavity is buoyancy driven. In the Figure 7 (left) it is also illustrated what was the expected mass flow rate in the cavity if the wind force is neglected.

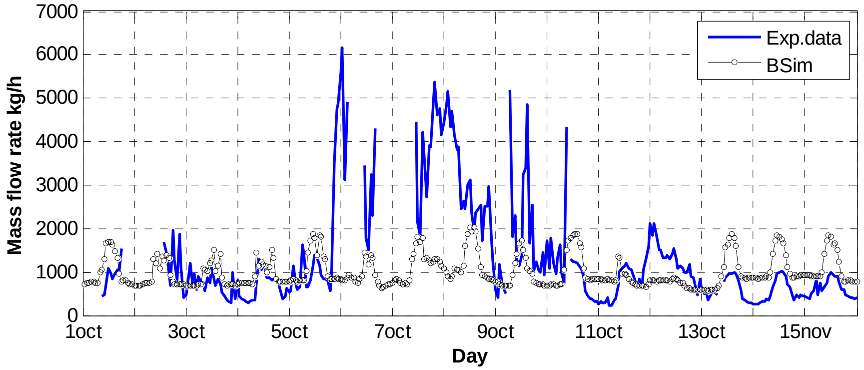


Figure 4. Mass flow rate in the DSF cavity measured with the tracer gas method and simulated in BSim.

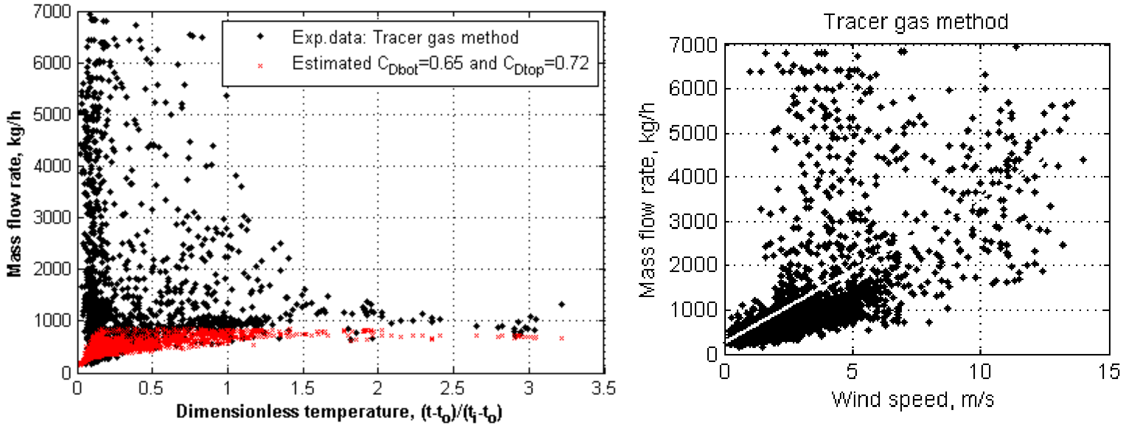


Figure 5. Illustration of the estimated mass flow rate in the DSF cavity for pure buoyancy natural ventilation (left). Mass flow rate as a function of the wind speed- experimental data (right).

When the results from the simulations where compared against the experimental data, then the information about the measurement procedure and experimental set-up can be critical for evaluation of measurement accuracy and the possibility of error. Overall, the main details of measurement procedure were explained in Kalyanova et al.

(2007) and possible errors in the measurements of the mass flow rate measurements were also discussed in the paper.

6. Example

It is important to remember that the performance of the DSF and comfort conditions in the occupied zone in the experiment room, on the preliminary design stage, are defined via the internal window and external window thermal and optical properties. Optical properties mainly determine what fraction of solar radiation is to be kept in DSF and what fraction is to be transferred further. In a detailed model this is done via the transmission, reflection and absorption properties of the glazing, in a simplified model this is done via the g-value. The thermal properties of windows, besides the magnitude of heat transfer, determine also the relationship between the outdoor-DSF and DSF-adjacent room and how fast one thermal zone reacts to the changes in another one.

BSim, as many others building simulation tools uses the g-value for calculation of solar gains into a thermal zone and therefore the software's ability in accurate estimation of secondary solar gains is limited, also, there are no studies available able to asses the impact of this limitation. Whereas the model of a DSF building can be very sensitive to the g-value input in the model.

Table 3. Test cases with modified g-value

Model	g-value	
	External window	Internal window
Low (**L**)	0.75 (-6%)	0.53 (-16%)
Normal (**N**)	0.8 (100%)	0.63 (100%)
High (**H**)	0.85 (+6%)	0.73 (+16%)

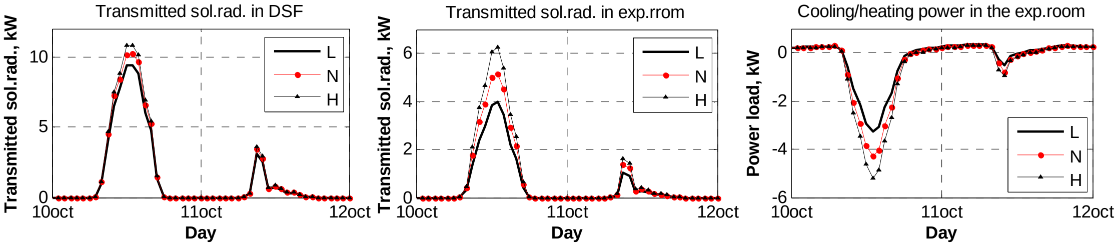
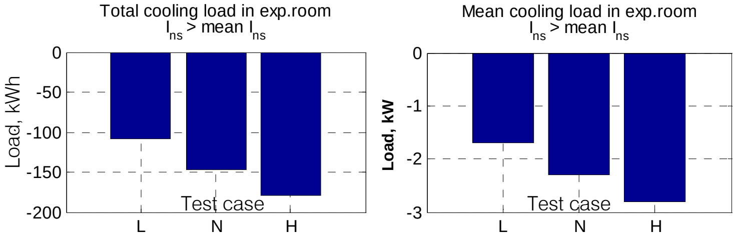


Figure 6. Simulation results for the test cases with different g-value of the glazing.

In this section, a simple sensitivity study was made to investigate how the small variation of g-value in a model will affect the output. Additional simulations have been made, all of them were based on the BSim model described earlier in the paper and only the changes of the g-value took place in the model. Considered cases are explained in Table 3.

In the Figure 6 the results of the simulations from three cases are illustrated. The figure includes results for two days: a day with clear sky and a day with the heavy cloud cover. It must be mentioned, that the changes, given in Table 3, were applied simultaneously to the external and internal window, i.e. the test case Low (L) represents a model, when the g-value of both the internal and external window was reduced as in the Table 3. From the figure, it can be seen that 6% reduction of the g-value of external window, results in 1.5 kW deviation in solar gains to DSF, if compare between test case Normal and test case Low. Comparing the impact of the g-value modification on the solar gains to the experiment room, one can see that the cooling load has changed ±1 kW, depending on the test case. This example, of course is very plain, but the point was to demonstrate the sensitivity of the model to the input parameters associated with heat transfer through the windows in a DSF envelope. Also, this example is limited to the g-value only, which combines together the optical and the thermal properties of the glazing, while repeating of the same study, varying the reflectance/absorbance/transmittance properties of the glazing and convective/radiative surface film coefficients in the model would lead to better technical insight to DSF envelope.

In the Figure 7 it is shown the difference between the test cases when considering the whole set of experimental data. Total cooling load for the whole period, when the normal solar radiation (I_{ns}) is higher than its mean value, represents the differences between the test cases of apx. 40 kWh during two weeks. These are the differences in cost to have a cooling unit running in order to maintain comfort conditions in the experiment room. However, this requires an ideal AC-system that can react immediately to the conditions in the zone. Mean cooling loads in the experiment room are also given in the Figure 7, which demonstrates the difference in the dimensioning of the cooling system if the results of one or another test case is used.



I_{ns} > mean I_{ns} - for the periods when normal solar radiation is higher than mean normal solar radiation

Figure 7. Mean and total cooling load to experiment room for the whole set of experimental data.

The U-value of a window construction, generally, is higher than the U-value of wall construction, also the area of windows in the DSF buildings is high, for example for 'the Cube' (when the outer skin of the DSF is neglected):

$$\sum A_w \cdot U_w = 26.06\ \frac{W}{K} \qquad \sum A_c \cdot U_c = 14.329\ \frac{W}{K}$$

A_w, U_w -area and U-value of a window in 'the Cube'
A_c, U_c -area and U-value of a constructions in 'the Cube'

Accordingly, the heat transfer through the DSF envelope is a significant part of the overall heat transfer in the experiment room and therefore minor inaccuracy of the input parameters can lead to wrong estimation of the energy use.

In this example, the authors have demonstrated the consequence of small errors present in a model when a building with the DSF is simulated. It was shown that even small uncertainties in the thermal properties of windows can be particularly significant for the simulation of energy performance in a DSF building. Hence, a modeler must be certain to use the exact properties of the window construction in his model. In conclusion, it is necessary to say that such a sensitivity of a small and simple model to the input data is exceptionally difficult to work with in practice, as there is a high risk of generating poor results if the simulation model has not been calibrated against experimental data. Also, one must bear in mind, that erroneous results in simulations of DSF buildings are not caused by the wrong input data only, but also the assumptions made towards the convective/radiative heat transfer, mass transfer etc. are very significant. Since these assumptions are very difficult to decide on and there are no guidelines exist, then the assumptions must be empirically validated, as a part of complete model. Empirical validation of each and every DSF model is time consuming and unrealistic in practice. Therefore further work including both measurements and more detailed and robust simulation programs are necessary.

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