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Empirical Validation of Simple Calculation Method for assessment of energy performance in Double-Skin Façade building

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ABSTRACT

When designing new buildings a Double-Skin Facades (DSF) concept is recurrently discussed as an energy saving solution. There is a strong demand for a tool, which could estimate the energy performance of a DSF building in an early design stage, in order to assess whether it fulfills the Energy Performance Building Directive. Therefore, the Bestfacade Project Group has developed the Simple Calculation Method (SCM).

In this paper the calculations of DSF performance using SCM are compared against experimental data gathered in a full-scale model for three data-sets from different periods of the year.

The SCM is recommended for assessing a seasonal DSF performance, however, it gives more reliable results if SCM is applied for shorter periods. Detailed calculation results tend to differ from the measurements, mainly due to overestimating the cooling demand. The validation described in this paper led to conclusions regarding possible improvements of SCM.

INTRODUCTION

Double Skin Façade (DSF) is an increasingly popular solution among architects aiming to give a building an impression of a modern and light construction. It appears mainly in office buildings, where a transparent building envelope is most welcome. Recently however, this concept has evolved from a merely esthetical one to a solution presenting many practical virtuous in several disciplines. One of the most important reasons for DSF gaining focus, are stricter building energy consumption requirements introduced by several countries, as well as the European Union, after formulating the Kyoto Protocol in 1997 [1].

Finally, one of the most interesting aspects of DSF is applying the air cavity to purposes of ventilation. The construction must then contain several openings at different levels of both the external and internal skin, which are operated accordingly to the ventilation concept and amount of air passing through them. This paper is considered with a ventilation strategy of mechanically driven air supply through DSF, which is characteristic for the heating season.

Such a solution seems to have a lot of potential in decreasing the building energy consumption. However, the detailed performance of air supply through DSF depends on several factors, such as: the orientation of DSF; the properties of the construction, including U-values for both layers, glazing g-value and heat absorbance; the external and internal air temperature; the instantaneous airflow rate; geometry of the DSF and the openings; the building's heat capacity; the solar reflectance of internal and external surfaces, etc. It should be noted that a poorly designed or operated DSF can have the opposite effect of increasing the energy consumption due to a higher heat loss during the heating season and overheating during the cooling season [2]. Therefore, is important to assess the performance of DSF in as much detail as possible, while the project is still in the design phase and drastic changes can be made. To perform this task, engineers need to be equipped with the proper tools to predict the performance of such a solution.

This paper focuses on the Simple Calculation Method (SCM), developed by the BESTFACADE project group. The main aim of SCM is to be easily integrated in the calculation methods of the EPBD (Energy Performance Building Directive) as well as offer sufficient accuracy for the early planning stage of the thermal behavior and the energy performance of the buildings with double skin façade [3]. However, simulating the DSF performance is still something new and thus the quality of results obtained from computer models must be validated by comparison with the measured performance. This paper presents the comparison of calculations results for several periods of the year and corresponding measurements from a real size laboratory 'the Cube', which formed the basis for evaluating the quality of the SCM model. The drawbacks and inaccuracies of SCM were analyzed and conclusions were drawn considering possible improvements as well as application recommendations.

METHODS

Experimental Data

The calculations of the DSF performance using SCM are compared against the experimental data gathered in the full-scale outdoor test facility 'the Cube', see Figure 1. The empirical data-sets are collected for double skin façade operating in air supply mode cooperating with a mechanical ventilation system. The air flow through DSF is constant, independent of the weather conditions and natural driving forces and equals 143 m^3/h. In this mode, fresh air enters the DSF at the bottom openings in the external façade, flows through the façade cavity and then is exhausted through the top openings in the internal façade to the interior. The flow motion of air is driven by a fan.

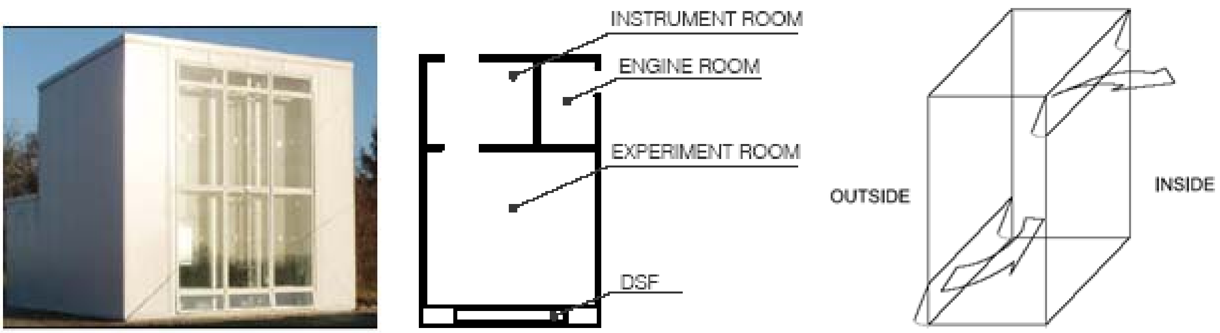

Figure 1.Test facility 'the Cube' (left). Plan of 'the Cube' (centre). Illustration of principle of air supply mode (right).

The measurements are divided into three periods: fall 2006 (data-set 1), early spring 2008 (data-set 2) and late spring 2008 (data-set 3). Detailed information regarding each data-set is presented in Table 1and can be also found in [2]. The energy performance, the air temperature in the DSF cavity, the temperature of the shading device in the cavity and the temperature of the glass surface are the main focus of the empirical measurements. Both, the interior and exterior environment define the boundary conditions for the DSF. In order to minimize the influence of the interior environment the air temperature in the experiment room of 'the Cube' is kept uniform and constant at apx.22^{o}C. Additional information about the test facility can be found in [4].

Table 1. Data-sets specification ('-'stands for no, '+' stands for yes).

Model			Data-set 1	Data-set 2	Data-set 3
Measurement period			09.11 - 30.11.200	26.04 - 12.05.200	14.05 - 27.05.200
Shading device			-	-	+
Measured parameters	Air temperature in DSF cavity	tc_{out}	+	+	+
		tc_{in}	-	+	+
	Glass surfaces temperature		+	+	+
	Shading surface temperature		-	-	+
Average outdoor air temperature [°C]			7,5	13,4	12,2
Average global solar irradiation [W/m^2]			102,6	311,9	343,1

Simple Calculation Method

With the goal to assess a preliminary energy consumption of the DSF building, the Bestfacade Project Group has developed a Simple Calculation Method based on European Standards. The energy demand for heating and cooling for a building with DSF is calculated accordingly to the periodically based balancing method as described in EN/ISO 13790. The calculation of the net heating and cooling demand is described by an energy balance of a conditioned zone takes into considerations the transmission and ventilation losses, solar and internal heat gains. This is described by the following equations.

$$Q_{H,nd} = Q_{H,ls} - \eta_{H,gn} \cdot Q_{H,gn} \qquad (1)$$

where $Q_{H,nd}$ is the energy need for heating, $Q_{H,ls}$ are the total heat losses for the heating mode, $Q_{H,gn}$ are the total heat gains for the heating season and $\eta_{H,gn}$ is the dimensionless gain utilisation factor for heating, where the building heat capacity is included.

$$Q_{C,nd} = Q_{C,gn} - \eta_{C,ls} \cdot Q_{C,ls} \qquad (2)$$

where $Q_{C,nd}$ is the building energy need for cooling, $Q_{C,ls}$ is the total heat losses for the cooling mode, $Q_{C,gn}$ are the total heat gains for the cooling season, $\eta_{C,gn}$ is the dimensionless gain utilisation factor for cooling.

$$Q_{ls} = Q_{tr} + Q_{ve} \qquad (3)$$

where Q_{ls} are the total heat losses, Q_{tr} are the total transmission heat losses Q_{ve} are the total ventilation heat losses

$$Q_{gn} = Q_{\text{int}} + Q_{sol} \qquad (4)$$

where Q_{gn} are the total heat gains, Q_{int} is the sum of the internal heat gains over a given period, Q_{sol} is the sum of the solar heat gains over a given period

The influence of DSF on building energy consumption is calculated accordingly to German standard DIN V 18599, where DSF construction is treated as a subsystem of unheated glazed annex. The glazing of an annex must be taken into consideration when calculating the heating - $Q_{H,gn}$ and cooling - $Q_{C,gn}$ gains due to solar radiation. Direct solar heat gains due to opaque components of the dividing wall are ignored. These are evaluated indirectly by including them in the temperature increase within the glazed annex.

The mean temperature in the DSF's cavity is calculated as described in EN ISO 13789 and is taken into consideration when calculating the heating - $Q_{H,ls}$ and cooling - $Q_{C,ls}$ losses due to transmission and ventilation from the heated building space to the annex (DSF cavity). It takes into consideration the buffer effect between the space and the external environment.

$$\vartheta_u = \frac{\phi_u + \vartheta_i (H_{T,iu} + H_{V,iu}) + \vartheta_e (H_{T,ue} + H_{V,ue})}{H_{T,iu} + H_{V,iu} + H_{T,ue} + H_{V,ue}} \qquad (5)$$

where Φ_u is the heat flow (from heat sources) into the unheated building zone (e. g. due to solar heating or internal heat sources) ν_i is the internal temperature $H_{T,iu}$ is the heat transfer coefficient of transmission of the components between the zone being evaluated and the adjacent unheated building zone $H_{T,ue}$ is the heat transfer coefficient of transmission of the building components between the unheated building zone and the exterior $H_{V,iu}$ is the heat transfer coefficient of ventilation between the building zone being evaluated and the adjacent unheated building zone (normally, $H_{V,iu} = 0$ can be assumed) $H_{V,ue}$ is the heat transfer coefficient of ventilation between the adjacent unheated building zone and the outside atmosphere.

The air temperature in the outlet from the DSF is calculated according to equation 6.

$$\vartheta_{out} = 2 \cdot (\vartheta_u - \vartheta_{in}) \qquad (6)$$

where, ν_u is the mean temperature in the unheated building zone-DSF, ν_{in} is the inlet temperature to the unheated building zone-DSF [K]

The heat, which is retained in the DSF cavity and causes the air temperature to increase, is calculated as a sum of two parameters. The total solar radiation entering through the external glazing decreased by the radiant heat, which is transferred directly via transparent building components into the building zone and internal heat sources in the cavity.

The shading and solar protection devices of the transparent components of internal glazing must be accounted for, when calculating the direct heat gains in the building zones. The solar protection devices must be taken into consideration when calculating the total energy transmittance of the internal glazing. It has to be also taken into consideration as internal heat sources, when calculating the heat gains affecting the unheated annex. However, in this paper the absorbance of the shading material is not taken into consideration due to insignificant mass [3].

RESULTS

Although, the Simple Calculation Method is recommended for assessing a monthly or even seasonally energy performance of DSF, in this paper the calculations have been performed on hourly basis, since a detailed approach could provide more insight in the accuracy of the calculation method. The calculated mean value of total energy consumption for the entire period is underestimated comparing to empirical measurements, especially in data-set 1, where the difference equals 351 kWh, see Figure 2. However, the results of SCM based on 24-hour averages for data-set 2 and data-set 3 were more satisfactory due to overestimating the energy usage, and therefore being on the 'safe side'. It should be noted, that the case of data-set 1 differs from the two others, since not only the calculation results for the entire period but also those based on averages of shorter periods underestimate the measured power load.

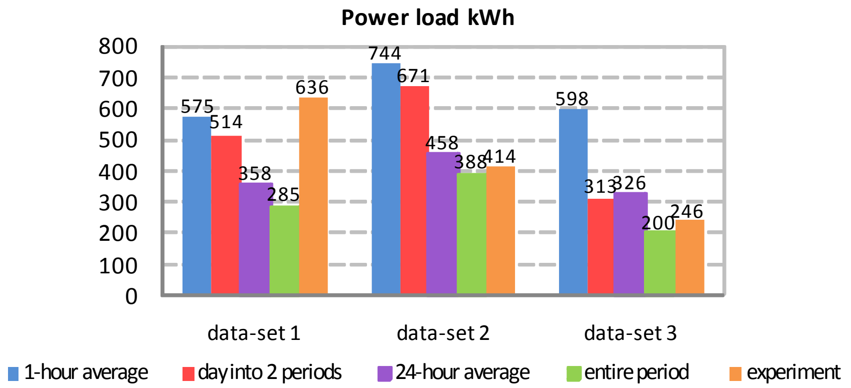

Figure 2. Measured and calculated total energy use[kWh] for different averages for each data-set.

In Figures 3-5 is depicted calculated power load for different averages and measured hour by hour energy usage in test facility for data-set 1, 2 and 3, respectively. It should be noted, that for 1-hour averages for every data-set the SCM follows the tendency of the experimental data. However, the cooling demand is significantly overestimated, even for the case with shading device. The heating demand gives opposite results, which are especially noticeable for data-set 1. There are few reasons why SCM decreases the energy need for heating. Firstly, in the SCM the thermal bridges in the building constructions are not included, and therefore heat losses due to transmission are lower. Secondly, it overrates the influence of solar radiation on the performance of DSF, which can be an explanation for difference in both the heating and cooling demand.

Results obtained from the calculations, in which twenty-four hours were divided into two averages (8-16-working hours and 17-7), are very similar to 1-hour average outcome for data-set 1 and data-set 2. This demonstrates, that significantly increasing the time intervals between input variables still gives equally reliable calculation results, which distinguish between the type of energy consumed.

As mentioned above for 24-hour averages the calculation results for energy consumption, as one value for the entire period, are acceptable for data-set 2 and data-set 3 and sufficient for the preliminary assessment of energy performance. However, when not only the value of energy consumption is significant, but also distinguishing between its quality (cooling and heating) and duration, then a more detailed analysis is desirable.

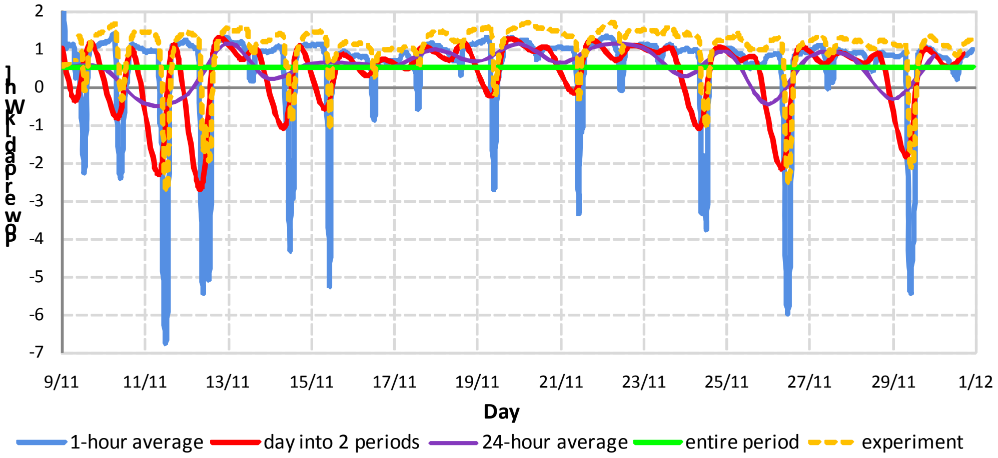

Figure 3. Data-set 1

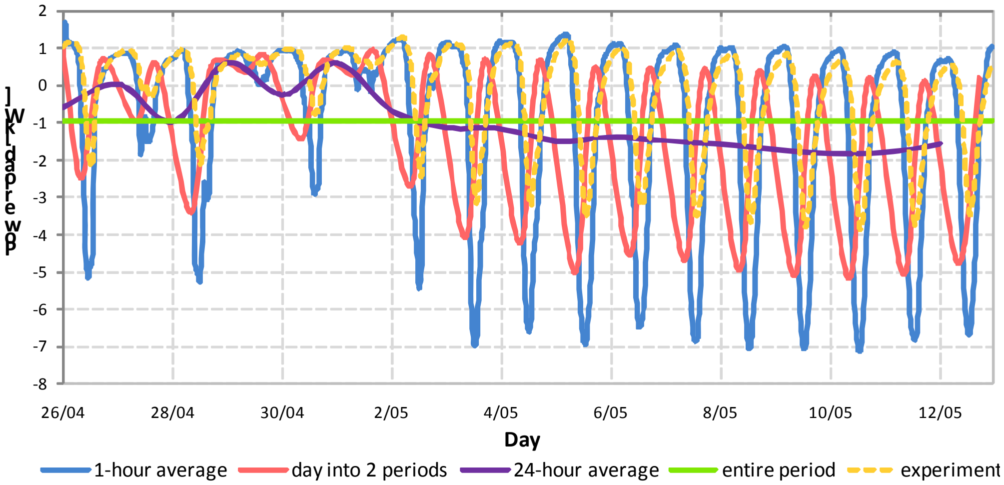

Figure 4. Data-set 2

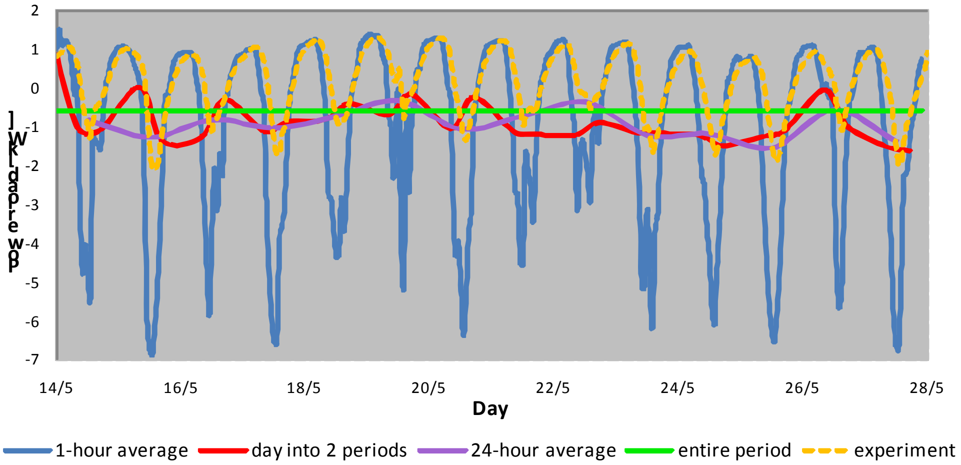

Figure 5. Data-set 3

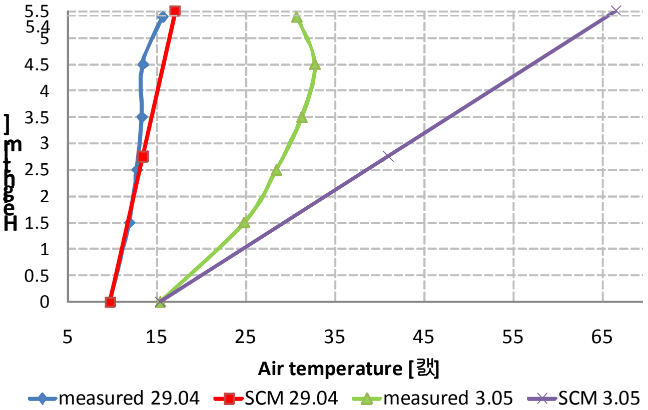

Figure 6. Temperature gradient inside the DSF cavity based on data-set 2 measurements and SCM calculations for 29.04.2008 12:00 and 3.05.2008 12:00.

The reason for the differences between SCM calculation and measurement results is investigated in more detail on the example of hourly values from data-set 2. At that period cloudy and relatively cold days occurred almost as often as sunny ones. Firstly, the measured and calculated temperature gradients inside the DSF cavity at 12:00 on the day with the lowest (29.04.2008) and highest (3.05.2008) solar radiation were compared, see Figure 6. The graph clearly shows that SCM assumes the temperature gradient to be linear, which is close to reality when direct solar radiation does not have a decisive influence on the DSF's performance. For sunny days however, SCM significantly overrates the temperatures, which results in overestimating the cooling load by up to 285%. Therefore, considering the temperature gradient in the cavity to be linear is thought to be a too big simplification. Another drawback of SCM is the lack of inputs indicating the specific DSF geometry, such as cavity depth and height, which are important when analysing the air temperature distribution.

To further evaluate the drawbacks of SCM, it is necessary to asses at what point the biggest error occurs. Therefore, two additional types of SCM calculations for data-set 2 were conducted. In the first one 'SCM + measured temp. 1' the calculated temperature in the middle of the cavity, see equation 5 (height of 2,75 m) was replaced with the measured one at the height of 2,5 m. In the second one 'SCM + measured temp. 2' both the temperature in the middle and at the top of the cavity, see equation 6, representing the outlet to the room, were replaced by the measured ones. The results of energy consumption obtained from those SCM calculations as well as the original one and measurements are compared in Figure 7. The overall difference between the calculations and the measured total energy consumption is smallest but still quite significant for 'SCM + measured temp. 2'. In the case of the original SCM results, the assumed temperatures in the cavity are responsible for 31,4% of the error.

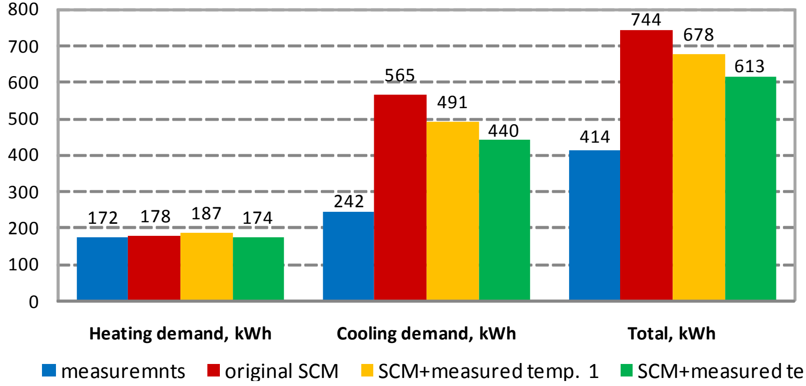

Figure 7. Comparison of energy consumption during the entire period of data-set 2 obtained from measurements and three types of SCM calculations.

When considering the energy consumption due to heating, it is clear that the temperature gradient in the cavity is a key factor. This is especially the case for the outlet temperature, which directly influences the heat transfer due to ventilation between the DSF and the room. Considering this value as a linear continuation of the difference between the outside and measured temperature in the middle of the cavity, as was done in 'SCM + measured temp. 1', does not improve the results. In the case of cooling, air temperatures in both points of the cavity seem to have a similarly positive influence on the results, which indicates that both the heat transfer due to transmission and ventilation play an equally important role.

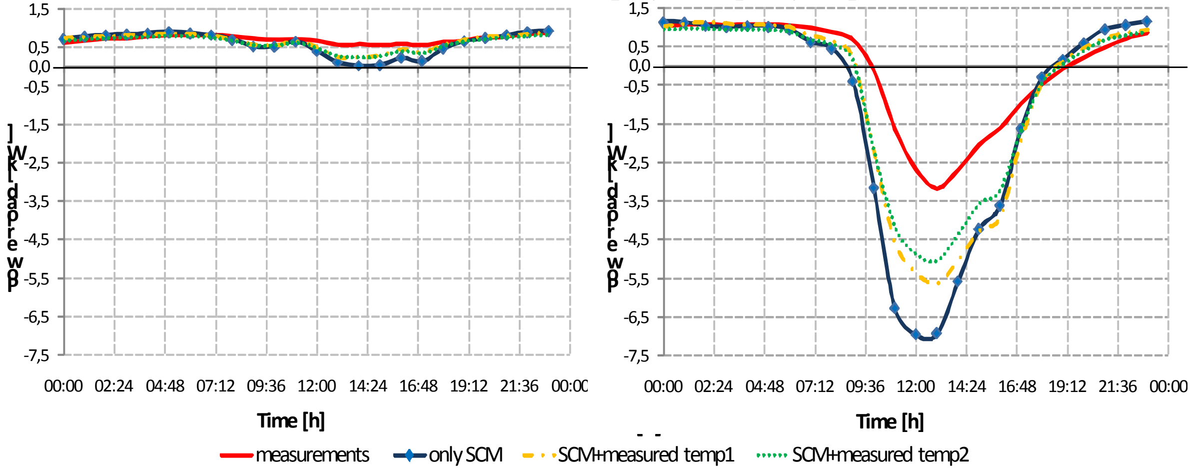

Figure 8. Hourly results of energy consumption during 29.04.2008 (left) and 3.05.2008 (right) obtained from data -set 2 measurements and three types of SCM calculations.

The power load based on measurements and three types of SCM calculations for a cloudy and sunny day has been shown in Figure 8. The tendency of all SCM results is to indicate higher and earlier fluctuations in the power load than shown by the measurements. Therefore the time lag representing the building time constant, and thus the heat capacity, is underestimated. It should be noted that this parameter is considered in a simplified form in SCM as part of the gain utilisation factor. The graphs also clearly indicate that the error of SCM is drastically higher in the case of high solar radiation, whereas at night time all results are nearly identical. This confirms again that direct solar gains affecting the DSF building are overestimated in SCM.

CONCLUSIONS

The above evaluation of SCM based on empirical measurements leads to an overall positive assessment of the calculation method. When applying the SCM to predicting the DSF performance for an entire period, as recommended by the Bestfacade project group, the value of total energy consumption is underestimated. In the case of data-sets 2 and 3, the value is close to the measured one, but for data-set 1 the difference is unacceptably high. This is thought to be mainly a result of neglecting the influence of thermal bridges in 'the cube's' construction. Such drawbacks can easily be eliminated by using supplementary U-values including thermal bridges. Data-set 1 is especially vulnerable to this problem, because, as shown in Table 1, the difference between the average outdoor temperature and the desired indoor one is highest.

The SCM assumes the temperature gradient in the DSF cavity to be linear, which is only close to reality, when direct solar radiation does not have a decisive influence on the DSF's performance. For sunny days, SCM significantly overestimates the cavity temperatures, which results in overestimating the cooling load by up to 285%. Therefore, a new relation for the temperature gradient in the cavity depending on solar radiation and cavity geometry should be developed.

Another disadvantage of SCM is overestimating the influence of solar radiation. Therefore, the energy need for cooling is overrated. This has been especially well illustrated on the examples of data-sets 2 and 3. The constructions of the full-scale model absorbed the less solar radiation than assumed by SCM, as the calculations do not take into consideration the solar reflectance from the indoor surfaces to the outside. It should be noted that all the surfaces in 'the cube' were light coloured and therefore, had a high reflectance factor.

The SCM could be further improved by specifying a more accurate g-value for the DSF windows. When defining the g-value of a glass pane, it is usually assumed that air movement occurs mainly on one side of it, corresponding to the outdoors. However, in the case of DSF there are strong air currents inside the cavity, which increases the heat transfer due to convection. This dynamic parameter is also influenced by the air temperature and angle of solar radiation. However, the calculation method is too simple to include such variations, which could be an additional source of error.

The above analysis shows that the DSF is a complex construction to describe as a numerical model and further research is needed. Despite all the drawbacks of the Simple Calculation Method, it is still thought to have much potential in the preliminary assessment of the DSF building energy consumption. The popularity of Double-Skin Façade constructions creates an increasing need for such a tool on the building market.

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