7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Experimental Validation of a Model for Naturally Ventilated Double-Skin Facades

Alessandro Dama[1,*], Matteo Dopudi[1] and Olena Kalyanova Larsen[2]

[1]Politecnico di Milano, Italy
[2]Aalborg University, Denmark

[*]*Corresponding email: alessandro.dama@polimi.it*

ABSTRACT
The steady state thermal model discussed in this paper is devoted to predict the temperatures and heat fluxes through a naturally ventilated DSF, having solar radiation and environmental temperatures as inputs. It is coupled with a fluid-dynamic model, based on a pressure loop, which takes into account both buoyancy and wind pressure at the openings.
The model has been validated against experimental data, basing on the prediction of the internal surface temperature of the DSF. Results show acceptable accuracy in the prediction of the heat flux towards the inside, even though they reveal a slight heat flux overestimation associated with dynamic effects. These observations lead to further investigate the role of DSF component capacities in order to increase the model accuracy and its applicability.

KEYWORDS
Building simulation, Airflow measurement, Natural ventilation, Temperature measurements.

INTRODUCTION

The Double Skin Facade (DSF) is a well-known technology, which might offer interesting adaptive features and improvements in terms of comfort and energy efficiency in buildings with large transparent facades. The evaluation of these benefits is still an open issue, due to reappearing difficulties in prediction of DSF thermal and energy performance as an integrated part of building envelope by means of well-established building simulation tools or recently developed models (Kalyanova et al. 2009; Manz & Frank, 2005).
Highly dynamic performance, initiated by fluctuating boundary conditions explain great complexity of experimental work for double-skin façade performance evaluation and thereby limited number of experimental studies to support validation of new and existing models for double-skin facades. Furthermore, existing experimental investigations (Kalyanova et al. 2007; Marques da Silva et al. 2015) underline multiple challenges related to investigation of DSF performance. Airflow measurement in a naturally ventilated cavity, measurement of the temperature under the strong solar exposure, as well as lack of standard, well-studied experimental methods for the measurement of the surface temperatures (with and without solar exposure) are found among the challenges. Experimental work carried in the of IEA ECBCS ANNEX 43/SHC Task 34 (IEA, 2007) had addressed some of these challenges in order to assemble a data set for empirical validation of building simulation software tools when double-skin façade performance evaluation is in question. This data set is applied for the validation of the model in this publication.
The thermal model discussed in this paper is an extension of a model already presented (Angeli at al. 2015, Dama et al. 2016 and 2017) in which the thermal and fluid dynamic 'core' of the ventilated cavity was validated having the channel surface temperatures as boundary conditions. In this work a suitable thermal network has been implemented to simulate the DSF having wind, solar radiation and environmental temperatures as inputs.

EXPERIMENTAL SETUP

The Cube is an outdoor full-scale test facility located near the main campus of Aalborg University, Denmark. T. A photo of Southern and Northern façade of the facility is shown in Figure 1.

Figure 1. The Cube. Photo of Southern façade (left) and photo of Northern façade (right).

The double-skin façade is facing South and consists of an internal double-glazed layer (4-Ar16-4) and a single-glazed exterior layer. Specifics of the material properties of all constructions in the Cube can be found in (Larsen et al. 2014). The experiments are performed in the external air curtain functioning mode, i.e. with naturally ventilated air cavity.

Particularly relevant to the task of this paper is to mention the procedures for the measurement of air and surface temperatures when the sensors are exposed to direct solar radiation, as well as the measurement of incident solar radiation. In (Kalyanova et al. 2007) it is explained that the presence of direct solar radiation is an essential element for the façade operation, but it can heavily affect measurements of air temperature and may lead to errors of high magnitude using bare thermocouples and even adopting shielding devices. Taking this into consideration, the thermocouples in DSF cavity were protected from the influence of direct solar radiation. The air temperature was measured using the silver coated and ventilated tube to reduce the impact of incident solar radiation. Meanwhile, surface temperature was measured by attachment of the thermocouples (type K) to a surface, using highly conductive paste and then fixed to the surface using the transparent tape. Surface temperature sensors were also protected from the impact of incident solar radiation, using two following strategies, depending on position of the sensor (Figure 2):

- Highly reflective film of apx. size 20x20 mm shields the thermocouple 1.
- Highly reflective shield made out of thin aluminum foil has the dimensions to ensure shielding both thermocouples 2 and 3.

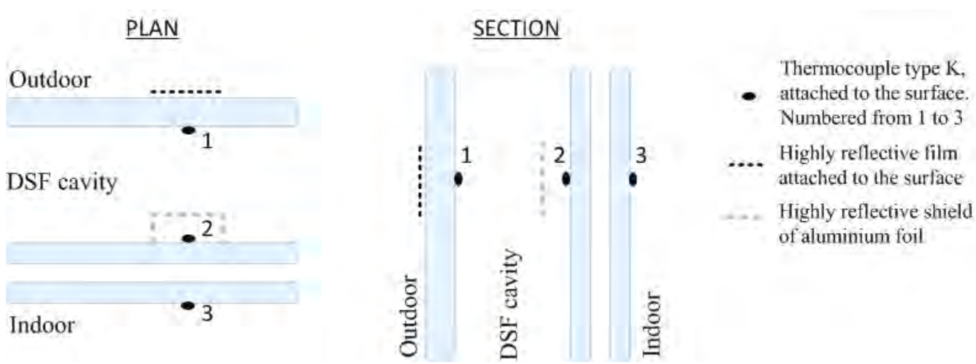

Figure 2. Shielding strategy from incident direct solar radiation. Left: Plan of DSF cavity. Right: Section of DSF cavity.

Thermocouples for the air temperature measurement were placed in the DSF at six different heights. Surface temperature is measured in the center of each glass pane.
Uncertainty of equipment for the temperature measurement is estimated to maximum +/- 0.14 ºC, this uncertainty, however does not address the issues of the solar exposure, as well as the limitations of the surface temperature measurements related to attachment of the sensor to the surface.

MODEL DESCRIPTION

The thermal model developed is based on steady state energy balance equations. It considers both convection and long wave radiation. The convection inside the channel is modelled by a simplified integral approach employing average bulk temperatures and superficial heat transfer coefficient correlations. The thermal model is coupled with a fluid-dynamic model, based on a pressure loop which takes into account both buoyancy and wind differential pressure at the openings as described by Dama (2017). Figure 3 describe the implemented DSF thermal network.

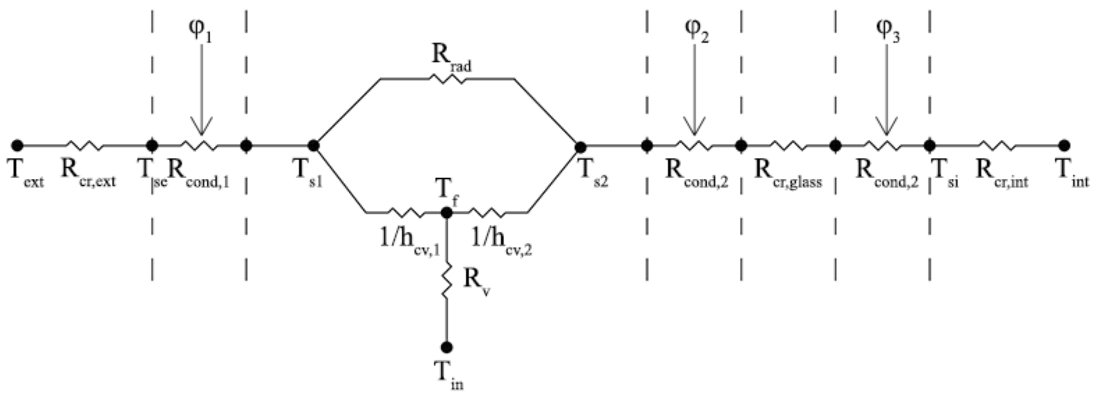

Figure 3. Thermal network of the ventilated channel. φ_1, φ_2 and φ_3 correspond to the solar radiation absorbed respectively by the glass of the outer skin, the external glass and the internal glass of the inner skin (double glazed unit).

Table 1 shows a summary of the correlations used for the surface heat transfer coefficients.
A fictitious thermal resistance, R_v, is introduced to couple the air in the channel with the outdoor air, and is defined as in the follow:

$$R_v \equiv \frac{T_f - T_{in}}{\varphi_v} \quad \varphi_v \equiv \frac{\Phi_v}{H \cdot L} = \frac{L \cdot s \cdot \rho \cdot v \cdot c_p \cdot (T_{out} - T_{in})}{H \cdot L} \tag{1}$$

where T_f is the air bulk temperature inside the channel, φ_v is the heat per unit area removed by ventilation, T_{in} is the inlet air temperature and T_{out} the outle
Using the definition in Equation 1 is possible to derive the following expression for R_v, which depends only on the air velocity and on the surface heat transfer coefficients:

$$R_v = \frac{e^{-kH} + kH - 1}{(h_{cv1} + h_{cv2})(1 - e^{-kH})} \quad k \equiv \frac{(h_{cv,1} + h_{cv,2})}{s \cdot \rho \cdot v \cdot c_p} \tag{2}$$

The complete angular characterization of the DSF glazing systems was obtained from LBNL Window. Table 2 reports the normal incidence properties of the glazing adopted in the experiments and in Window calculation. The Window optical characterization provides the inputs for Equation 3, which describes the heat absorbed by each glass.

$$\varphi_i = \alpha_i(\theta)G_{beam}(\theta) + \alpha_i^{diff}G_{diff} \quad i = 1,2,3 \tag{3}$$

Table 1. Surface heat transfer

	External side	Channel	Internal side
Convective part	Sharples (1984)	McAdams (1954)	Churchill and Chu (1975)
Radiative part	T_{sky} based on Swinbank (1963)	Grey surfaces Linearized exchange	Grey surfaces Linearized exchange

RESULTS AND DISCUSSION

An experimental validation of the thermal and fluid dynamic model of the ventilated channel using as boundary condition the glass surface temperatures was already presented (Dama at al. 2017). This work focuses on the thermal network implementation, which employs as input the environmental temperatures and the solar irradiance and allows to calculate the convective and radiative (long wave) heat transfer through the DSF towards the interior. This flux strictly depends on the surface temperature of the internal glass of the inner skin (double glazed unit). Figure 3 shows the measured and modelled internal surface temperature (position 3 in the drawing of Figure 2) during the 15 days of the experimentation. Table 3 reports the daily integrated values of the surface heat fluxes form the DSF toward the inside of the Cube, separating the positive contributes to negative ones.

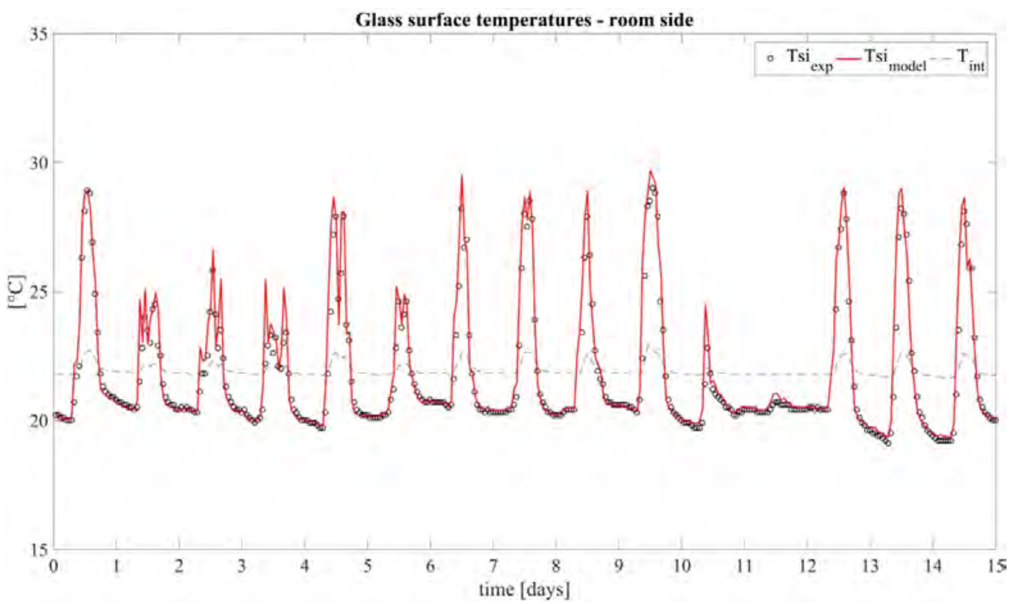

Figure 4. Internal surface temperature of the inner skin, model versus measurements (Tsi_{model}/Tsi_{exp}). T_{int} – internal air temperature.

The results show that the internal surface temperature is predicted with acceptable accuracy, even though a general overestimation is observed when solar irradiance heats up the DSF. For outward heat fluxes, the daily relative errors are below 6% during night time and around 12% in cloudy days. For inward fluxes the average overestimation is about 25%, and reduces to 15% in the last three days of the experimentation, with more stable solar and wind conditions.
In order to have better picture of model predictions versus measurements, Figure 5 shows also inlet and outlet air temperatures and surface temperature of the glasses facing the channel.
It can be noticed that, while the internal surface temperature is slightly overestimated, the outer surface temperatures, facing the ventilated channel, are underestimated.

It can also be observed that, while the modelled temperatures have the same dynamic profile, which instantaneously responds to the solar irradiance, the measured values show a bit more complex dynamics. The internal surface temperature increases slower than modelled and the surfaces temperature 1 and 2 (respectively of outer glass and external surface of the inner skin) decrease slower than modelled. Component capacities are often omitted when modelling DSF performances, in this case it might have led to an overestimation of the heat transmitted to the inside. Further investigation is therefore advisable first of all to identify the exact origin of heat gain overestimation and then to evaluate significance of the heat capacity of the glazing for better prediction of complex dynamic processes in the DSF and thereby increasing the accuracy and the applicability of the model.

Table 2. Heat exchange towards interior. Model versus experimental results. Daily integrated values calculated separately for hours with flux inwards (+) and hours with flux outwards (-)

Day	Q_{int} (+) Model [Wh/m]	Q_{int} (+) Exp. [Wh/m]	Rel error (+)	Q_{int} (-) Model [Wh/m]	Q_{int} (-) Exp. [Wh/m]	Rel. error (-)
1	1380	1238	11%	670	684	-2%
2	620	392	58%	723	684	6%
3	590	386	53%	708	703	1%
4	526	227	132%	850	827	3%
5	1415	1035	37%	891	900	-1%
6	481	367	31%	727	765	-5%
7	1016	790	29%	715	761	-6%
8	1309	1130	16%	784	819	-4%
9	808	697	16%	644	658	-2%
10	1857	1515	23%	753	717	5%
11	142	27	429%	1038	1176	-12%
12	0	0	-	1004	1144	-12%
13	1216	1073	13%	835	832	0%
14	1228	1040	18%	1157	1208	-4%
15	1133	988	15%	1079	1142	-6%

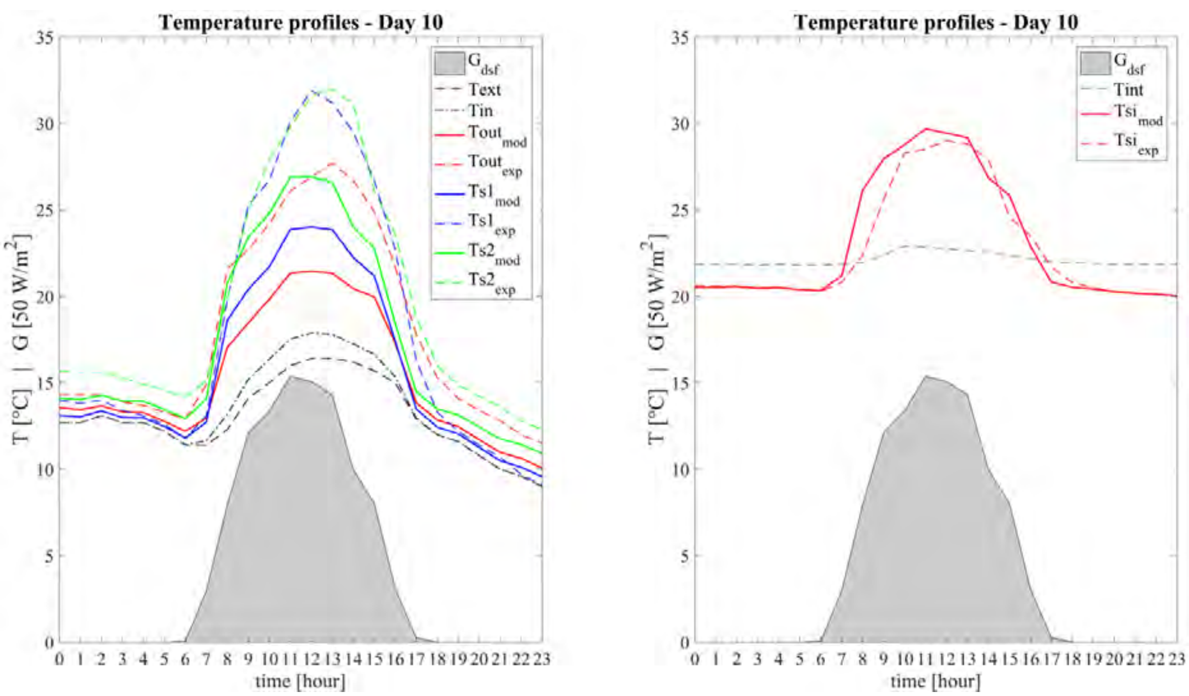

Figure 5. Glazing surface temperature and air temperature. Model versus measurements for a single day (October the 10th). On the left the air and the surface temperature of the glazing facing the ventilated cavity, on the right the internal surface temperature of the inner skin.

CONCLUSIONS

A thermal model for simulating naturally ventilated Double Skin Facades under variable boundary conditions – wind, solar radiation and environmental temperatures - has been implemented and results have been compared with measured data from a full scale test facility.

The validation, based on the prediction of internal surface temperature of the DSF, has showed acceptable accuracy even though an overestimation is observed when solar irradiance heats up the DSF. This leads to an overestimation of the heat transmitted inwards of about 15%, limiting to the three days with more stable wind and irradiance, and around 25% averaging over the 15 days of the experimental campaign.

The presence of dynamic effects, which might be associated to the DSF component capacities, has been observed and will be furtherly investigated in the future model implementation in order to increase its accuracy and applicability in the frame of building performance simulation.

REFERENCES

Angeli D., Dama A., 2015. Modelling natural ventilation in double skin facade. Energy Procedia, Vol. 78, pp. 1537-1542.

Churchill S.W., Chu H.H.S., 1975. Correlating equations for laminar and turbulent free convection from a vertical plate. International Journal of Heat and Mass Transfer, Vol. 18 No. 11, pp. 1323-1329.

Dama A., Angeli D., Larsen O.K. 2017. Naturally ventilated double-skin facade in modelling and experiments. Energy and Buildings, Vol. 144, pp. 17-29.

Dama A., Angeli D. 2016. Wind and buoyancy driven natural ventilation in double skin façades. International Journal of Ventilation, Vol.15(3-4), pp.288-301.

IEA – SHC Task 34/ECBCS Annex 43: Testing and Validation of Building Energy Simulation Tools, 2007.

Kalyanova, O. et al. 2009. An Empirical Validation of Building Simulation Software for Modelling of Double-Skin Facade (DSF). Building Simulation : Proceedings of the 11th International Building Performance Simulation Association Conference. Glasgow: University of Strathclyde.

Kalyanova, O. et al., 2007. Measuring Air Temperature in Glazed Ventilated Facades in the Presence of Direct Solar Radiation. The International Conference on Air Distribution in Rooms, Roomvent.

Larsen, O.K., Jensen, R.L. & Heiselberg, P.K., 2014. Experimental Data and Boundary Conditions for a Double-Skin Facade Building in External Air Curtain Mode, Aalborg, Aalborg University.

LBNL, LBNL Window & Daylighting Software, https://windows.lbl.gov/software/window. Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Manz, H. & Frank, T., 2005. Thermal simulation of buildings with double-skin façades. Energy and Buildings, Vol.37, pp.1114–1121.

Marques da Silva, F., Gomes, M.G. & Rodrigues, A.M., 2015. Measuring and estimating airflow in naturally ventilated double skin facades. Building and Environment, 87, pp.292–301.

McAdams W.H. 1954. Heat Transmission. McGraw-Hill, New York, NY.

Sharples S. 1984. Full-scale Measurements of Convective Energy Losses from Exterior Building Surfaces. Building and Environment, Vol. 19, No. I, pp. 31-39.

Swinbank W.C., 1963. Long-wave radiation from clear skies. Quart. J. R. Meteorol. Soc., Vol. 89, pp. 339-348.