A sensitivity analysis of a double-skin façade for a building located in La Rochelle
Analyse de sensibilité d'une façade double-peau dans un bâtiment situé à La Rochelle

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RESUME. Une façade double-peau est un élément du bâtiment qui est souvent utilisé dans les immeubles à bureaux. Leur utilisation peut permettre d'améliorer le confort visuel, acoustique, thermique et de réduire les déperditions thermiques du bâtiment. Dans ce travail, un modèle numérique basé sur une approche nodale a été développé pour évaluer la performance thermique des façades double-peau. Le modèle thermique intègre les transferts de chaleur par rayonnement (grande et courte longueur d'onde), par convection et par conduction. Le flux d'air dans la cavité est modélisé par une approche de différence de pression, tenant compte du tirage thermique et de l'effet du vent. L'efficacité des façades à double peau est fortement influencée par les conditions météorologiques et la configuration géométrique. Pour évaluer l'impact de certains paramètres, une analyse de sensibilité est réalisée. Des simulations ont été effectuées pour les mois de janvier et juillet pour le climat de La Rochelle afin d'évaluer la performance thermique.

MOTS-CLÉFS. façades double-peau ; simulation thermique dynamique ; analyse de sensibilité.

ABSTRACT. A double-skin façade is a building element that is often used in office buildings. Their use can improve visual, acoustic, and thermal comfort and reduce heat loss from the building. In this work, a numerical model based on a nodal approach was developed to evaluate the thermal performance of double-skinned façades. The thermal model integrates heat transfer by radiation (long and short wavelengths), convection, and conduction. The airflow in the cavity is modeled using a pressure difference approach, considering thermal buoyancy and wind effect. The efficiency of double-skin façades is strongly influenced by weather conditions and geometric configuration. To evaluate the impact of some parameters, a sensitivity analysis is performed. Simulations have been carried out for January and July for the La Rochelle climate, to evaluate the thermal performance of this type of façade.

KEYWORDS. double-skin façades ; dynamic thermal simulation ; sensitivity analysis.

1 Introduction

A double-skin façade (DSF) is an element of the building envelope characterized by two parallel surfaces, which are separated by a central air cavity. The outer skin is normally composed of a shatterproof glass, while the inner skin can be of glass or an actual building façade (glass and other materials). A detailed review of double-skin façades can be found in Lucchino et Goia (2019).

Double-skin façades can improve visual, acoustical and thermal comfort, and at the same time, decrease the energy demand if properly designed. The double-skin façade can adapt its operation according to weather conditions, with the control of the air openings and sometimes with mechanical air circulation, making it suitable for the whole year (Pomponi et al., 2016).

During the winter, the double-skin façade acts as a buffer zone. The air in the cavity is heated up by the sun, works like insulation and reduce the heating demand. In hot weather, the cavity can be ventilated and works as a cooling system to decrease the heat load on the façade. The hot air in the cavity can be extracted by wind-driven forces. However, if the outside air is too hot, the façade temperature may not cool down naturally. As we are dealing with more than one story, the type of double-skin façade considered is the multi-story mode. In this façade geometry, the airflow goes through the entire height of the building (Alberto et al., 2017).

In this work, we will treat double-skin façades in multi-story buildings of medium height (up to 12 meters), with naturally ventilated cavities, considering two types of airflow paths (the external air courting mode and the air buffer mode). The thermal efficiency of a double-skin façade depends on several parameters. Therefore, to perform simulations we developed a numerical model based on a nodal approach, which is capable of predicting the temperature at the surfaces and the airflow rate in the cavity. With this model, we can assess the performance of the double-skin façade.

Simulations are performed for a double-skin façade located in the French coastal city, La Rochelle, to evaluate the thermal performance for oceanic climates. Then, a sensitivity analysis based on the Fourier Amplitude Sensitivity Test (FAST) method is performed to assess the most important parameters for a double-skin façade according to the specific climate.

2 Mathematical model

The assessment of the thermal performances require the application of different physical phenomena. The pressure and temperature fields in the cavity and surfaces are the results of the interaction between thermal, optical, and fluid flow processes as shows Figure 1. These phenomena interact simultaneously with each other and are highly dynamic. The coupled thermal and fluid-dynamic problem is very complex, and modelling and simulating the heat transfer in DSFs is not trivial (Lucchino et Goia, 2019).

The airflow in the cavity varies based on wind and/or thermal stratification. The short-wave radiative heat transfer $\mathbf{q}_{rad}^{sw}$ occurs through the glazed surfaces and leads to absorption, reflection, and transmission of the solar radiation hitting the façade. The long-wave radiative exchange $\mathbf{q}_{rad}^{lw}$ happens between the surfaces of the façades, and at the interfaces with the surroundings. Conduction $\mathbf{q}_{cond}$ occurs in the solid surfaces of the façade. Convection $\mathbf{q}_{conv}$ is the main mechanism in the fluid dynamics, which influences the airflow $\dot{m}_c$ in the cavity and the global heat transfer within the system ($T_1, T_2, \dots, T_8$). The main physical phenomena used in the modelling of the double-skin façade are described in the sequence.

In the solid part, the heat transfer is governed by diffusion and short-wave radiative mechanisms (Howell et al., 2015), which are written as :

$$\rho\, c_p \, \frac{\partial T}{\partial t} \;=\; \nabla \Big(k \, \nabla T \Big) \;+\; \mathcal{S} \tag{1}$$

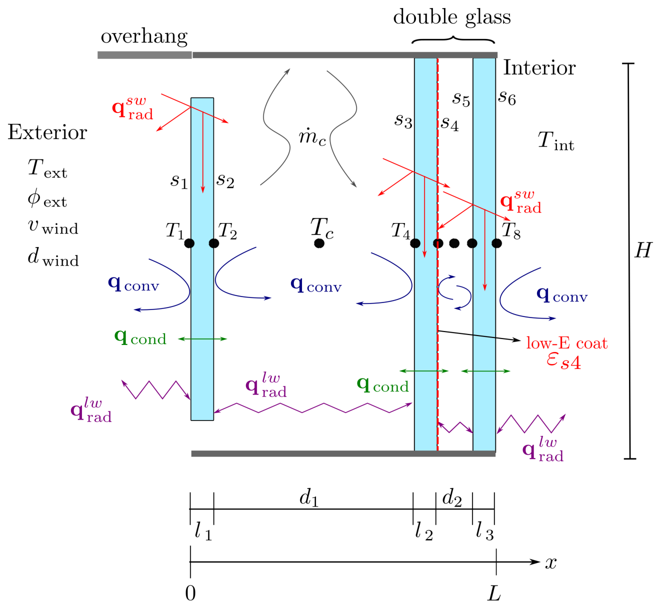


FIGURE 1. Transfer configuration of the double-skin façade.

where c_p is the material specific heat [J/(kg · K)], ρ is the material density [kg/m^3], t is the time [s] and $\mathcal{S} = A \cdot I$ is a volumetric energy source term [W/m^3], in which A is the fraction of absorbed short-wave radiation [1/m] and I is the global incident solar radiation [W/m^2]. The fraction of absorbed short-wave radiation is computed based on the portion of reflected and transmitted solar irradiation for each glass layer.

The calculation of the long-wave radiation flux inside the cavity require the knowledge of the absolute temperature T_i at the surface of the material and also the radiosity J_i :

$$\sum_{j=1}^{m} \left[\delta_{ij} - (1 - \varepsilon_i) F_{i \to j} \right] J_j = \varepsilon_i \sigma T_i^4 \tag{2}$$

where n is the number of surfaces and F is the view factor. Equation 2 leads to a non-linear system of equations to solve, which increase the difficulty in solving the numerical model due to the term T_i^4.

For the cavity zone, it is assumed that the air temperature is the same in the entire cavity. Thus, the evolution of the cavity air temperature T_a can be obtained by a lumped zone model (Alberto et al., 2017; Inan et Basaran, 2019) :

$$\rho_a c_{p,a} V \frac{\mathrm{d}T_c}{\mathrm{d}t} = \sum_{i=1}^{N_s} h_c S_i \cdot \left(T_c - T_{s_i} \right) + \dot{m}_c c_{p,a} \cdot \left(T_{\text{ext}} - T_a \right) \tag{3}$$

where ρ_a is the cavity air density [kg/m^3], $c_{p,a}$ is the air specific heat capacity [J/(kg · K)], V is the volume filled with air [m^3], T_c is the mean value of the air cavity temperature [K], t is the time [s], h_c is the convective heat transfer coefficient [W/(m^2 · K)], S_i is the surface area [m^2], T_{s_i} is the glass surface temperature [K], T_{ext} is the outside air temperature [K], $\dot{m}_c$ is the total mass flow rate [kg/s] due to natural ventilation and, N_s is the number of surfaces. The correlations used for computing the natural convective heat transfer are the same as in Wang et al. (2019), and for forced convection the relation is the same as in Inan et Basaran (2019). For mixed convection, the correlation used is a function of both convections (Ghadimi et al., 2013).

The mass flow rate within the cavity is computed considering the following formulation :

$$\dot{m}_c = C_d \rho_o S_c \cdot \left(\frac{2 \left| \Delta P_t \right|}{\rho_a} \right)^{0.5} \cdot \text{sgn} \left(\Delta P_t \right) \tag{4}$$

where C_d is the flow coefficient, S_c is the section area [m^2], and, ΔP_t is the total pressure difference [Pa], which is calculated according to wind and stack effects :

$$\Delta P_{t,j} \;=\; \rho_o\, g\, \frac{T_c - T_{\text{ext}}}{T_c}\,(H_0 - H_j) \;+\; \frac{1}{2}\, C_{p,j}\, \rho_o\, v_{\text{ref},j}^2 \;-\; Pi_t \tag{5}$$

where j denotes the openings, and the total pressure difference ΔP_t is given by $\sum_{j=1}^{N} \Delta P_{t,j}$.

3 Computational strategy and validation

The mathematical problem described is non-linear since the airflow and heat transfer computations are interdependent. To compute the airflow, the radiosity and the heat transfer coefficient inside of the cavity one needs the values of the temperature at the surfaces of the cavity.

To simplify computations, equations (2, 4) are explicitly calculated, so the non-linearity problem is temporally put away. The procedure of implementation can be seen in Algorithm 1. Note that n and N_t are related to the time discretization, where n is the temporal node and N_t is the total number of temporal nodes. This strategy allows the direct computation of the heat transfer through the DSF with a small error in the final solution.

Algorithm 1 : DSF modelling problem.

while $n \leqslant N_t$ **do**
1. **Solve** the radiosity problem $J\,(T^{\,n-1})$: Eq. 2
2. **Compute** the airflow problem $m_c\,(T^{\,n-1})$: Eq. 4
3. **Compute** the convective heat transfer coefficient $h_c\,(T^{\,n-1})$
4. **Solve** the heat transfer problem $T\,(T^{\,n}, T^{\,n-1})$: Eq. 1 and Eq. 3

return : $T^{\,n}$

end while

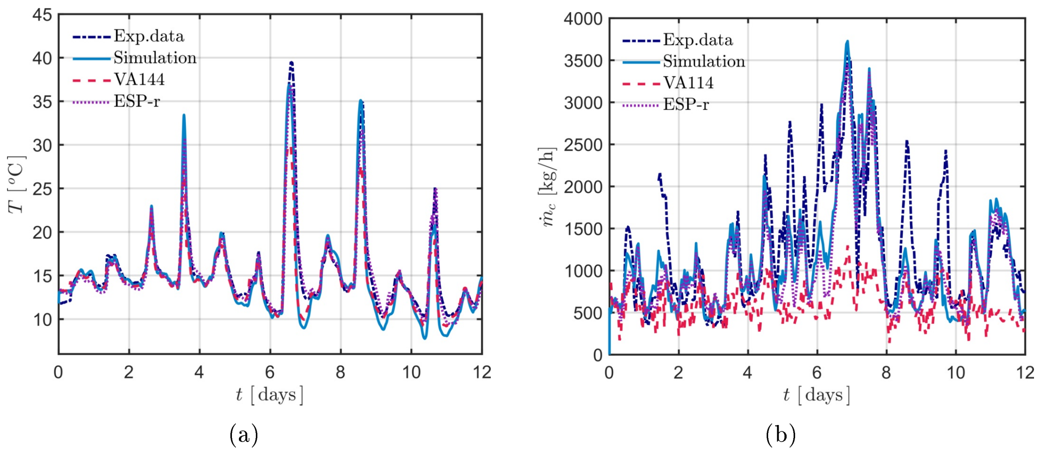


Figure 2. Comparison of the model with experimental data from the Annex 43, for the case with cavity closed (a) and the case with the cavity ventilated (b).

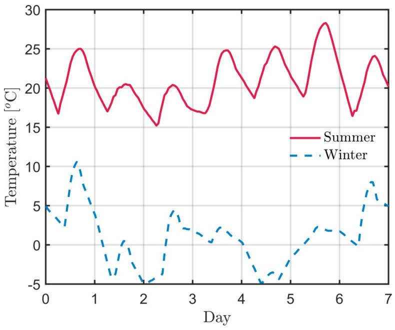
This model has been compared with experimental data from the International Energy Agency in the frame of IEA ECBCS Annex 43 (Kalyanova et Heiselberg, 2009). VA114 and ESP-r are the simulation softwares used in the Annex project. Figure 2(a) gives the values of the cavity air temperature for the closed case. According to the chart, our results are in reasonable agreement with the experimental data and the other simulation software. The mean absolute error for our simulations is 1.2°C, for the VA144 simulation software is 1.13°C and for the ESP-r is 0.7°C. The higher errors occur at the 7th and 11th days. One reason can be short-wave radiation model that needs improvement.

The model has also been compared with experimental data for the ventilated case. Results for the mass flow rate inside of the DSF cavity are presented in Figure 2(b). If we compare our simulation with the experimental data, we can observe a big difference in some parts. According to (Kalyanova et Heiselberg, 2009), the measurement of the mass flow rate presents a lot of uncertainty. However, our simulations provide similar results if compared to the other Annex participants. For the mass flow rate, we have a mean absolute error of 364 kg/h, while the ESP-r has 400 kg/h and the VA144 has 659 kg/h of error. Thus, we can affirm that our results are in better accordance with the experimental data than the other simulations. If we analyze the cavity temperature we have a mean absolute error of 1.2°C, as in the closed case.

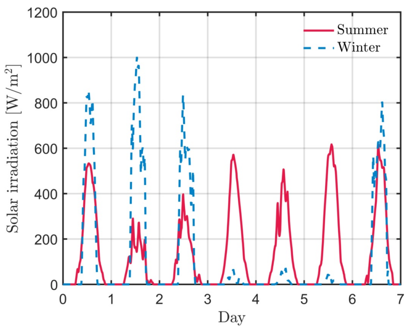
4 Thermal performance of the DSF for La Rochelle

4.1 Case study description

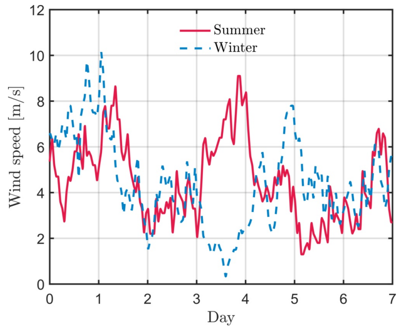
Simulations are performed for a building located in La Rochelle, a French coastal city with oceanic climate. The temperature, the solar irradiation and the wind speed for 7 days of summer and winter are presented in Figure 3. The weather data is taken from the *Meteonorm* database (TMY2 format).



(a)



(b)



(c)

Figure 3. Weather data from La Rochelle for the months of January and July.

The office building as 6 m of height, the equivalent of two-story. The glazed façade is south oriented and the indoor is controlled with a constant temperature of 21°C. The combined heat transfer coefficient is assumed to be $h_{\text{comb}} = 7$ W/(m^2·K) (EN ISO 6946).

Input	*Value*	*Input*	*Value*
Horizon of simulation	7 days	Cavity length	0.6 m
External glass thickness	6 mm	DSF height	6 m
Double glass thickness	4 mm (each)	External conv. heat transfer coeff.	18 W/(m^2 · K)
Internal temperature	21°C	Internal conv. heat transfer coeff.	7 W/(m^2 · K)
Height of opening 1	0.23 m	Discharge coefficient 1	0.65
Height of opening 2	5.77 m	Discharge coefficient 2	0.70
Area opening 1	0.39 m^2	Area opening 2	0.32 m^2

Table 1 – Input data for the simulation of the DSF.

The double-skin façade has two openings, one at the bottom, here called opening 1, and other opening at the top, called opening 2. The values used for the C_p are the same used for the validation (Dama et al., 2017).

The double glazing has a low-E coat at the interior of the double glazing. The U-value of the double-glazing window with the low-E coat is 1.1 W/(m^2·K). The use of sun control and shading devices is an important aspect of many energy-efficient building design strategies, specially for fully glazed façades. The solar protection considered for the study are the overhangs and a the solar-control glazing on the outside, with a reduced coefficient of solar transmission.

For the analysis, the double-skin façade is considered open to ventilation for the summer, and the cavity is closed to ventilation for the winter. The input parameters for this simulation case are presented in Table 1.

4.2 Results

To evaluate the efficiency of the double-skin façade, simulations are also performed for a building without the extra layer of glass, which is called single-skin façade (SSF). The total heat flux (convective and the long-wave radiation fluxes) at the glass surface facing the interior ambient is given in Figure 4, for summer and winter periods, and for the two types of façade.

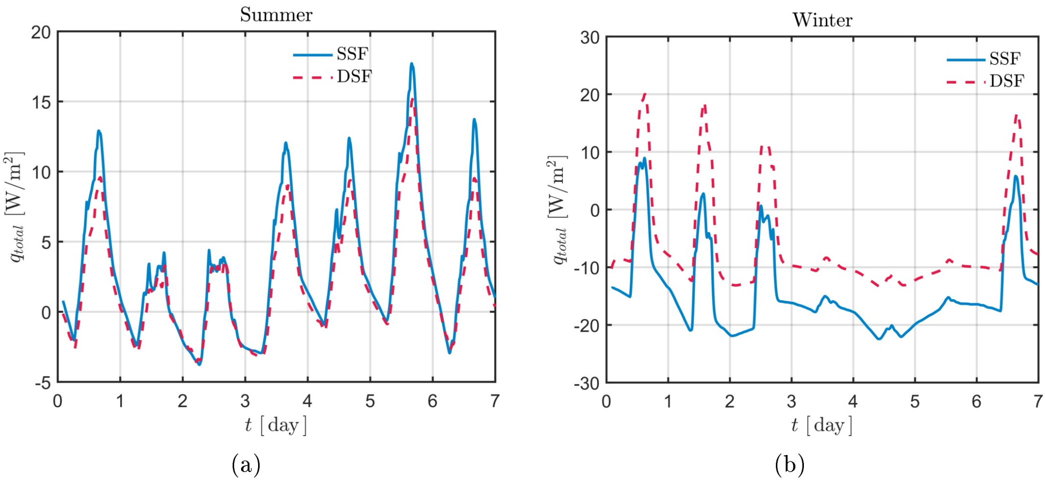


Figure 4. Total heat flux density at the glass surface facing the interior ambient for summer (a) and winter period (b).

For the summer, the double-skin façade is slightly more efficient than the single-skin façade. The extra layer of glass has a lower transmission which allows the reduction of the thermal flux through the façade. However, during winter, the advantage of the double-skin is even more evident. It allows a reduction in the flux through the glazed façade while allowing the heat gain during the day.

Façade	*Summer*	*Winter*
Single-skin	0.56 kWh/m^2	−2.56 kWh/m^2
Double-skin	0.37 kWh/m^2	−1.13 kWh/m^2

Table 2 – Thermal loads of the double- and single-skin façades.

Table 2 presents the thermal loads for summer and winter periods, also comparing with the single-skin façade (SSF). This output is computed as the integration of the heat flux density regarding the time :

$$E = \int_0^t q_{\text{total}} \, dt \,. \qquad (6)$$

The positive value means it had a thermal gain, while the negative value means a thermal loss. During summer it was possible to reduce the heat gain and during winter was possible to reduce the heat loss. Compared to the single skin façade, the double-skin can reduce the thermal loads in both periods if well designed. To better understand which are the important parameters a sensitivity analysis is carried out.

5 Sensitivity analysis

The sensitivity analysis is performed considering the same weather conditions as in the previous case. The method used for the analysis is the Fourier Amplitude Sensitivity Test (FAST). This method allows the computation of the global contribution of each input factor to the output's variance (Saltelli et al., 1999).

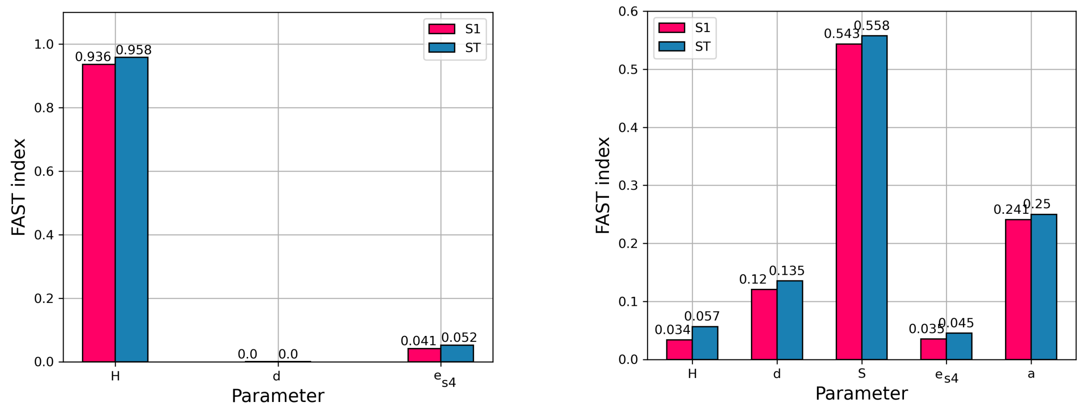
5.1 Case study description

The parameters to be studied in this analysis are the height of the façade (H), the cavity width (d), and the size of the openings ($S = S_1 = S_2$), the emissivity of the interior surface of the double glazing (ε_{s4}) and a parameter related to the density of the surroundings (city center, country, ...) (a). The latter will influence in the difference of pressure. Low values means the building is located at the city center and higher values it indicates that the building is located in an open space. The sensitivity analysis is performed in both configurations, with the cavity open and with the cavity closed. The bound values used for each variable are H = [3, 12]m, d = [0.1, 1] m, S = [0.1, 0.4] m^2, ε_{s4} = [0.1, 0.8] and a = [0.2, 0.7].

The output to be analysed is the thermal load of the façade E which is calculated as equation (6). With this integration we can have a single value as output for the dynamic simulation.

5.2 Results

Figure 5(a) present the FAST indexes for the winter mode. The parameters regarding the ventilation are not included because the cavity is closed. According to the graphic, the most important parameter is the height of the façade. High façades contribute to the stack effect, which makes it suitable for the cold season. The height impacts the flow development, the flow regimes and consequently the convective transfers. The emissivity of the coat is less sensible than the height of the façade, but it is also important to reduce the thermal loss. According to the results, the depth of the cavity is not a relevant parameter for this configuration.



(a) (b)

Figure 5. Sensitivity index for the winter and summer case.

Figure 5(b) present the FAST indexes for the summer mode. For this period, the parameters related with the ventilation are more important. The size of the openings is the most sensitive parameter, followed by the density of the surroundings and the cavity thickness. The mass flow rate is very sensible to these three parameters, which are of paramount importance for the double-skin façade. Following these parameters come the height of the façade and the emissivity of the coat. This means the wind effect plays more importance for the opened configuration than the stack effect.

6 Conclusions

A nodal model, representing the thermal behavior of a double-kin façade, was proposed in this work. The energy balances in each node include conduction, convection, and radiation heat transfer. With this model, several investigations were carried out. First, a validation comparing with experimental data from the literature is carried out. Then, simulations for a case in La Rochelle were performed, showing its advantage regarding classical glazed façades. Thus, a sensitivity analysis is performed to enhance the most important parameters on the outputs. The results of the sensitivity investigation showed that summer and winter periods have different influent parameters, and an optimization analysis would be desired for a careful façade design.

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