# A parametric analysis of a double-skin façade for a building in oceanic climate

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# Analyse paramétrique d'une façade double-peau d'un bâtiment sous climat océanique

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*RESUME. Une façade double-peau est un élément qui est souvent utilisé dans les bâtiments de 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 simplifiée, tenant compte du tirage thermique et de la vitesse et direction du vent. L'efficacité des façades à double peau est fortement influencée par différents paramètres, comme la configuration géométrique et les conditions météorologiques et pour évaluer l'impact de ces paramètres, une analyse paramétrique 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 paramétrique.*

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*ABSTRACT. A double-skinned 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 air flow in the cavity is modelled using a simplified approach, considering the thermal draft and the wind speed and direction. The efficiency of double-skin façades is strongly influenced by different parameters, such as the geometric configuration and weather conditions, and to evaluate the impact of these parameters, a parametric analysis is performed. Simulations have been carried out for the months of January and July for the climate of La Rochelle in order to evaluate the thermal performance.*

*KEYWORDS. double-skin façades ; dynamic thermal simulation ; parametric analysis.*

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# 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 6 floors), 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.

Then, a parametric analysis of type one-at-a-time (OAT) is performed in order to assess the most important parameters for a double-skin façade. The parameters to be analyzed are related to the geometry and the climate specifications. Then, simulations are performed for a double-skin façade located in the French coastal city, La Rochelle, to evaluate the thermal performance.

# 2 Mathematical model

The assessment of the thermal performances of DSF is not simple. The pressure and temperature fields in the cavity and surfaces are the results of the interaction between different phenomena, such as 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 occurs through the glazed surfaces and leads to absorption, reflection, and transmission of the solar radiation hitting the façade. The long-wave radiative exchange happens between the surfaces of the façades, and at the interfaces with the surroundings. Conduction occurs in the solid surfaces of the façade. Convection is the main mechanism in the fluid dynamics, which influences the airflow in the cavity and the global heat transfer within the system. 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 radiation mechanisms (Howell et al., 2015), which can be written as follows :

$$\rho\, c_p \frac{\partial T}{\partial t} \;=\; \nabla \Big( k \,\nabla T \Big) \;+\; \mathcal{S} \qquad [\mathsf{W/m^3}] \tag{1}$$

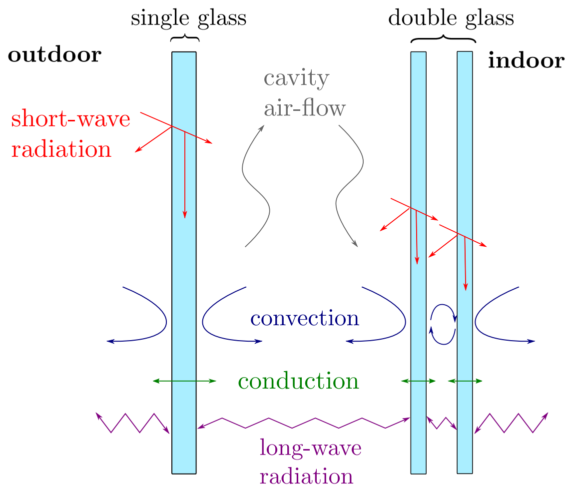



FIGURE 1. Heat transfer configuration of the double-skin façade.

where $c_p$ is the material specific heat [J/(kg · K)], $\rho$ 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 long-wave radiation flux inside the cavity is computed according to (Sacadura, 2009), which require the knowledge of the absolute temperature $T_i$ at the surface of the material and also the radiosity $J_i$ :

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

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

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

where $\rho_a$ 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$^3$], $T_a$ 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], $T_{\mathrm{ext}}$ 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 (Mora, 2003) :

$$\dot{m}_c = C_d\, \rho_o\, S_c \cdot \left( \frac{2\,|\Delta P_t|}{\rho_a} \right)^{0.5} \cdot \operatorname{sgn}\left( \Delta P_t \right) \qquad [\mathrm{kg/s}] \tag{4}$$

where $C_d$ is the flow coefficient, $S_c$ is the section area [$\mathsf{m}^2$], and, $\Delta P_t$ is the total pressure difference [Pa], which is calculated according to wind and stack effects.

# 3 Numerical simulations

## 3.1 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 $J\left(T^{n-1}\right)$ : system of algebraic equations (Eq. 2)
2. **Compute** the airflow problem $m_c\left(T^{n-1}\right)$ : several algebraic equations (Eq. 4)
3. **Compute** the convective heat transfer coefficient $h_c\left(T^{n-1}\right)$ : several algebraic equations
4. **Solve** the heat transfer problem $T\left(T^{n}, T^{n-1}\right)$ : partial differential equation (Eq. 1) and ordinary differential equation (Eq. 3)

**return :** $T^n$

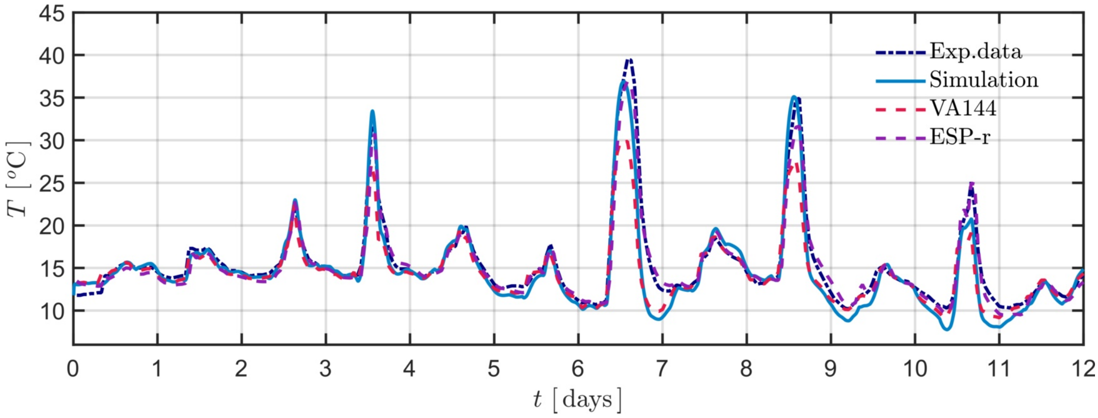
**end while**

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). Figure 2(a) gives the values of the air temperature inside of the cavity for the closed cavity 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.

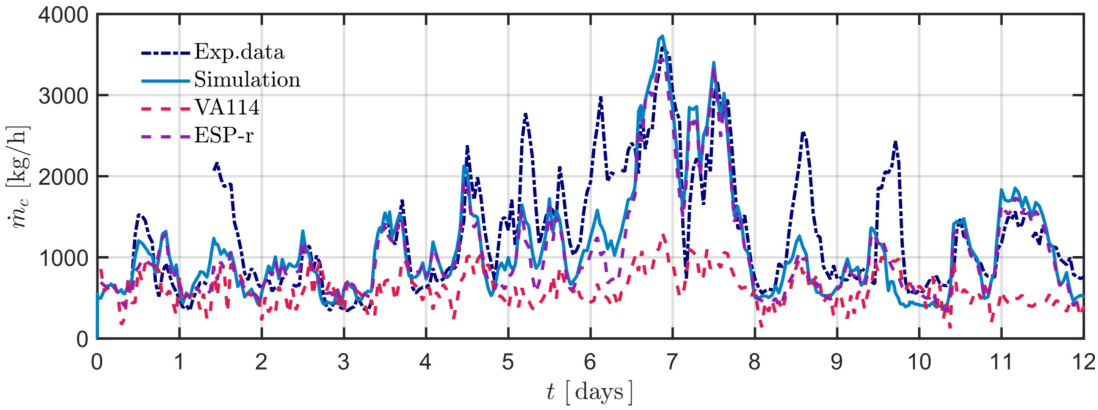
The model have also been compared with experimental data for the open case. The results for the mass flow rate inside the DSF cavity can be seen in Figure 2(b). The measurement of the mass flow rate is very difficult, with a lot of incertitude. If we compare our simulation with the experimental data, we can observe a big difference in some parts. However, our simulations provide similar results if compared with the results of the ESP-r software. For the mass flow rate, we have a mean absolute error 364 kg/h, while the ESP-r has 400 kg/h and the VA144 has 659 kg/h. Thus, we can affirm that our results are in better accordance with the experimental data than the other simulations.

## 3.2 Parametric analysis

With the model validated, a parametric analysis of the type one-at-a-time (OAT) is then performed for some geometric and weather parameters. The geometric parameters to be studied in this analysis are the height of the façade ($H$), the cavity width ($d$), and the size of the openings ($S$). Besides, the weather parameters to be parametrized are the total solar irradiation ($q_{sw}$), the external ambient temperature ($T_{ext}$), the wind velocity ($v_w$), the wind direction ($C_p$) and the environment ($w_f$), which describes if the building is in the country, city center or suburban. The parameter $w_f$ will influence in the air velocity at the top and bottom openings, which changes according to the height of the building and according to its surroundings.




(a)




(b)

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

The parametric analysis is performed in both cases, with the cavity open and with the cavity closed. The values used for each variable are given in Table 1. The intermediate value is used as a reference case and the other parameters are given in Table 2.

| *Input* | *Value* | *Input* | *Value* |
|---|---|---|---|
| $H$ | $3, 6, 9$ m | $d$ | $0.2, 0.6, 1$ m |
| $S$ | $0.2, 0.4, 0.6$ m$^2$ | $q_{sw}$ | $0, 100, 450$ W/m$^2$ |
| $T_{ext}$ | $0, 15, 30$ °C | $v_w$ | $0, 6, 12$ m/s |
| $C_{p,bot}$ and $C_{p,top}$ | windward : 0.61 and 0.58<br>side : -0.71 and -0.55<br>leeward : -0.36 and -0.35 | $w_f$ | center city $w_f = 0.18\,h^{0.68}$<br>country $w_f = 0.52\,h^{0.20}$<br>suburban $w_f = 0.39\,h^{0.36}$ |

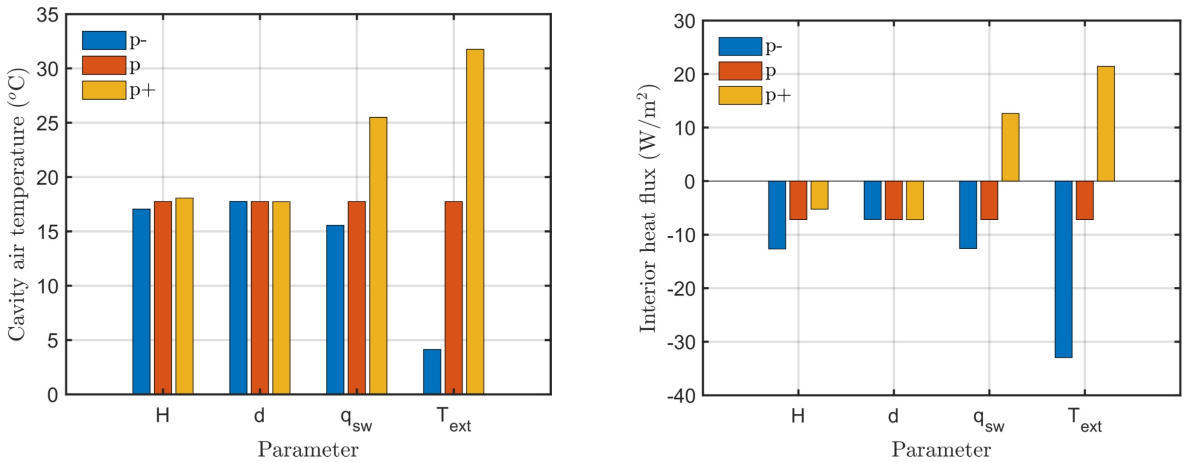
TABLE 1 – Input data for the simulation the parametric analysis.

Figure 3 and Figure 4 present the temperature inside the cavity and the flux at the internal surface of the double-skin for both configurations. The sign of the flux indicates the direction of the flux, if it is positive it means the flux goes from outside to inside and if it is negative it goes from inside to outside. It can be observed an important influence of the weather conditions in the DSF performance, while the geometric factors have a lower impact.

For example, the 9 m height façade is more performance than the 6 m and 3 m façades, it increases the stack effect. For low temperatures such as 0 °C, the open mode is not recommended. Besides, with high solar irradiation incidence, such as in summer, the closed mode increases

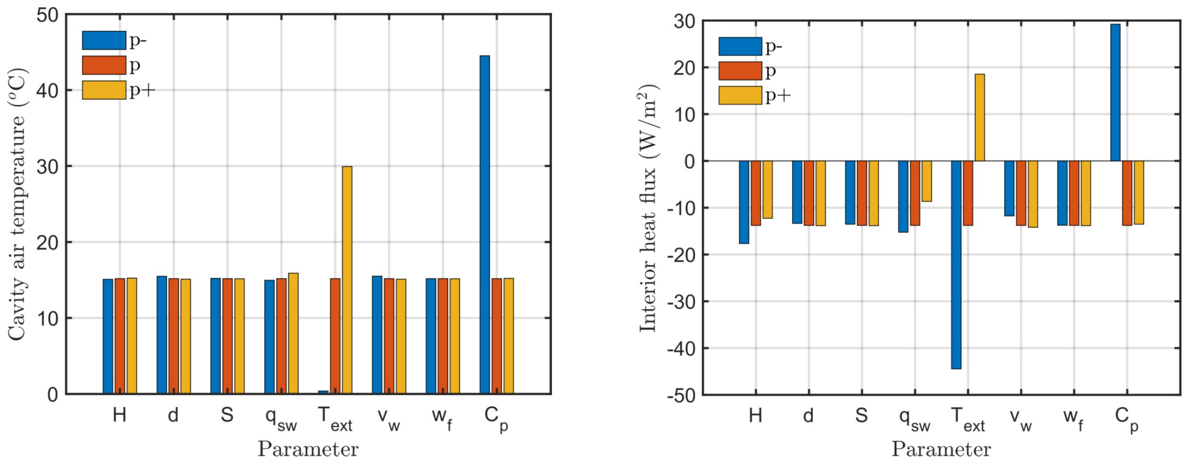
| *Input* | *Value* | *Input* | *Value* |
|---|---|---|---|
| Horizon of simulation | 7 days | Cavity length | 0.6 m |
| Single glass thickness | 8 mm | DSF height | 6 m |
| Double glass thickness | 4 mm (each) | External conv. heat transfer coeff. | $18\,\mathrm{W/(m^2 \cdot K)}$ |
| Internal temperature | 22°C | Internal conv. heat transfer coeff. | $7\,\mathrm{W/(m^2 \cdot K)}$ |
| 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 | $0.39\,\mathrm{m^2}$ | Pressure coefficient 1 | −0.06 |
| Area opening 2 | $0.32\,\mathrm{m^2}$ | Pressure coefficient 2 | −0.2 |

TABLE 2 – Input data for the simulation of the DSF.




(a) (b)

FIGURE 3. Parametric analysis of the DSF for the closed configuration.




(a) (b)

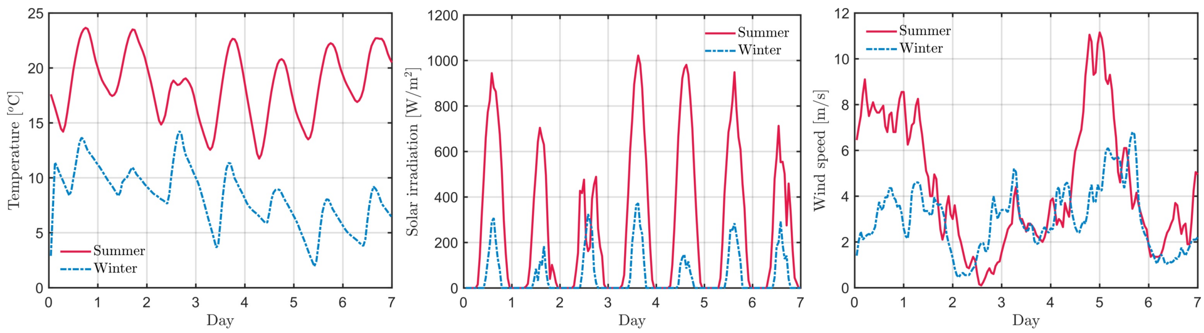
FIGURE 4. Parametric analysis of the DSF for the open configuration.

significantly the heat flux in the direction of the interior, demanding more energy for cooling systems.

# 4 Thermal performance of the DSF for La Rochelle

In previous section, it was found that the meteorological condition is the main influence for the thermal performance of the double-skin. For this reason, the geometry of the reference case is now used for simulating a double-skin façade for La Rochelle, a French coastal city with a tempered climate. The temperature, the solar irradiation and the wind speed for the first 7 days of July and January are presented in Figure 5. Wind intensity and orientation are very important for the good performance of the double-skin façade. The weather data come from is taken from the software TRNSYS© , which is representative of the mean values over the last 30 years.

During summer, solar irradiation and the temperatures are higher than during the winter which can cause the overheating of the façade. Fortunately, the wind speed is still high for this time of the year, which helps the cooling of the façade, allowing it to reduce the thermal gains in this period.




(a) (b) (c)

Figure 5. Weather data from La Rochelle for the months of January and July.

## 4.1 Description of the case-study

For a first analysis, the double-skin façade is considered in external air curtain mode for the summer period. In this configuration, the two air openings of the cavity are opened and it is naturally ventilated, considering wind and stack effects. The input parameters for this simulation case are presented in Table 2. The interior air ambient is kept as constant temperature, while exterior conditions vary according to the weather.

Figure 6(a) presents, in summer, the evolution of temperature over the time for the glass surface facing the exterior, for the air temperature inside the cavity and for the glass surface facing the interior of the building. The temperatures variations follow the solicitations from the boundaries and especially with the solar irradiation. The interior air ambient is kept as 22°C, which makes the temperature on the glass surface facing the interior to no increase as in the first layers of glass.

The mass flow rate in the cavity is shown in Figure 6(b). The computation of the airflow depends on wind and thermal effects. In this case, we have a high airflow rate, which contributes to the decrease of the temperature inside the cavity and in the glass surfaces. This is a good feature for the summer modes, which helps to avoid the overheating of the double-skin façade.

To evaluate the efficiency of the double-skin façade, we performed simulations with the same conditions for a building without the extra layer of glass, which here is called as single-skin façade. The total heat flux at the glass surface facing the interior ambient is given in Figure 7. For the summer mode, the double-skin façade is less efficient than the single-skin façade. To improve the thermal efficiency, the ideal would be the implementation of blinds or curtains to reduce the short-wave radiative effect winter vs summer.

Simulations are also performed for the winter and summer periods to assess the heating/cooling

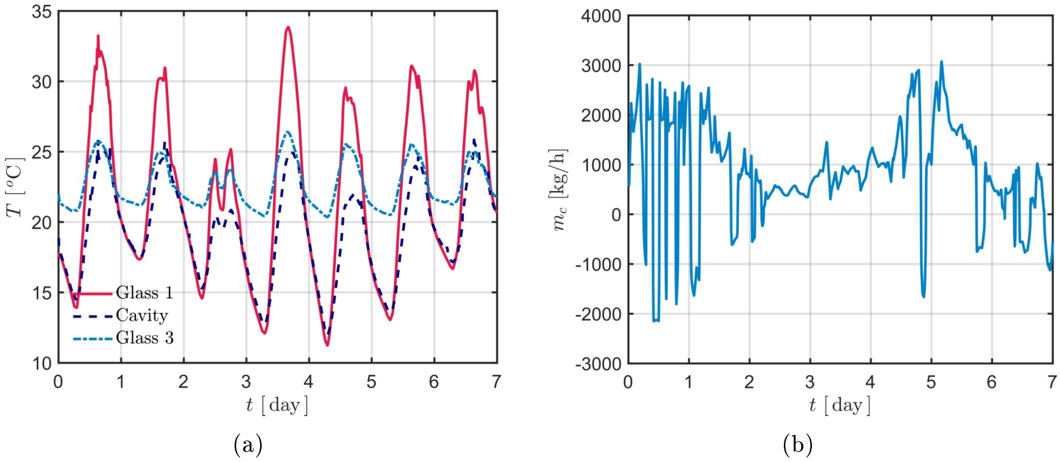



FIGURE 6. (a) Temperature evolution and (b) mass flow rate inside the cavity (Summer).

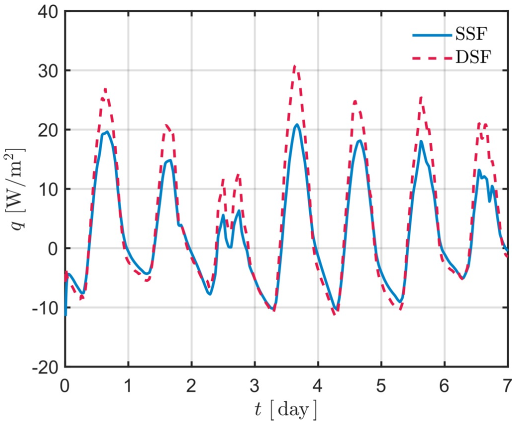



FIGURE 7. Total heat flux at the glass surface facing the interior ambient (Summer).

loads of the façade. Table 3 present the heating/cooling loads for summer and winter comparing also with a single-skin façade (SSF). The energy necessary to keep the interior temperature is much higher in summer than winter. It means the DSF is more efficient for winter. However, in the summer, the single-skin façade presents better performance than the double-skin, which is expected since we do not include venetian blinds in our simulations.

| *Façade* | *Summer* | *Winter* |
|---|---|---|
| Single-skin | 0.49 kWh/m$^2$ | −2.67 kWh/m$^2$ |
| Double-skin | 0.86 kWh/m$^2$ | −1.33 kWh/m$^2$ |

TABLE 3 – Thermal loads of the double- and single-skin façades.

## 5 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 compared with experimental data from the literature was done. Then, a parametric analysis is performed to enhance the most important parameter on the outputs. The results of the parametric investigation showed that the weather conditions have a higher impact on the DSF, which then impacts on the other parameters. Last, simulations for a case in La Rochelle was performed. The next step of the present work is the inclusion of the venetian blinds in the simulations which will improve the thermal performance during the summer.

## Acknowledgements

The work here presented have been carried out in the framework of the Research Project "CITEE – Innovative components for building envelopes", financed by the European Union and the French region Nouvelle-Aquitaine (CPER).

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