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# ON THE INFLUENCE OF THE INLET TEMPERATURE IN MULTIPLE-SKIN FACADE MODELLING

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## ABSTRACT

This paper draws the attention to the importance of a correct modelling of the inlet temperature of naturally and mechanically ventilated multiple-skin facades. A sensitivity study illustrates the significance of the inlet temperature as a boundary condition for numerical multiple-skin facade models. Measurements demonstrate that the assumption of an inlet temperature equal to the interior or exterior air temperature is usually not valid. Finally, whole building energy simulations indicate the influence of the inlet temperature modelling on the energy performance of naturally and mechanically ventilated MSFs.

*Keywords:* multiple-skin facade, building envelope, advanced envelope, energy simulation, fenestration.

## INTRODUCTION

The sensibility for environmental friendly and energy conscious building design urges the need to develop new facade technologies. In this search towards energy efficient, comfortable and visually attractive facades, multiple-skin facades (MSFs) are regularly presented as being valuable solutions to put up with the desires of modern architecture. MSFs consist of two panes with in between a cavity through which air flows by means of natural or mechanical ventilation. In the cavity, usually a shading device is provided. Generally, distinction is made between naturally and mechanically ventilated MSFs. Extensive literature on MSF-typologies can, amongst others, be found in Compagno [1995] and Lang [1998].

In order to evaluate the energy performance of MSFs, models with different levels of complexity should be implemented in building energy simulation programs. A typical approach of such an implementation is represented in Figure 1. The simulation domain is split up into a MSF-model and a building model.

Several researchers provide models to simulate specific MSF-typologies without linking the envelope level results to the building energy performance [e.g. Tanimoto and Kimura, 1997]. Only few combinations of MSF-modelling and building energy simulation are available. Most of these analysis are restricted to one MSF-typology. Müller and Balowski [1983] analyse airflow windows, Oesterle et al. [2001] give a comprehensive survey of double skin facades, Hensen et al. [2002] study the behaviour of multi-storey naturally ventilated MSFs and Haddad and Elmahdy [1998] discuss the behaviour of supply air windows.

Typically, the MSF-model and the building model are linked through a surface temperature ($T_{si}$) or a heatflux ($Q_i$) (Fig. 1). Depending on the typology the interior (Fig. 1a) or the exterior (Fig. 1b) air temperature is used as an input parameter for the MSF-model.

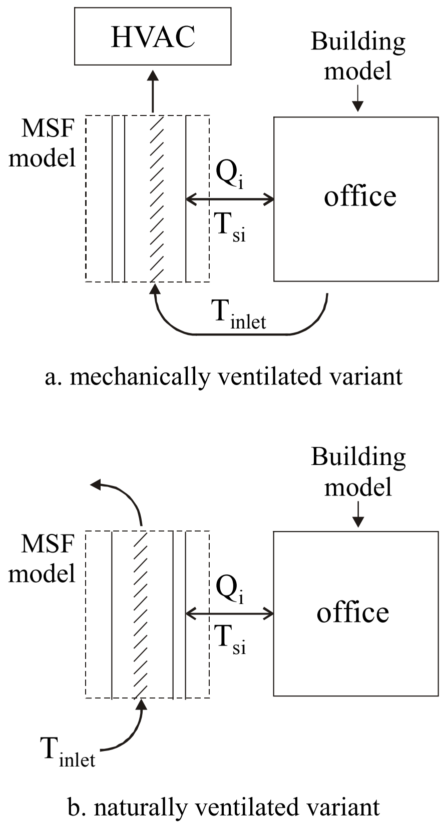



**Figure 1:** Typical implementations to calculate the energy performance of multiple-skin facades.

The results of such an energy performance assessment are sensitive to a variety of parameters such as:

- The correct application and accurateness of the climatic boundary conditions and the material characteristics.
- The accurateness and complexity of the MSF-models. Saelens et al. [2001] discuss the influence of the complexity of mechanically ventilated MSFs while Hensen et al. [2002] discuss the possibilities to model naturally ventilated facades. Both studies illustrate large deviations for the different models that were applied.
- The accurateness of the energy simulation program and erroneous input by the program user. Lomas et al. [1997] compared different building energy simulation programs and demonstrated considerable deviations between different programs.
- The implementation of the MSF-model into the building energy simulation program. Hensen et al. [2002] and Saelens [2002] illustrate that a whole building analysis is necessary to obtain reliable results.

To illustrate the importance of a correct boundary condition modelling for MSF-models, this paper studies the importance of the inlet temperature as an input parameter for MSF-models.

First, a sensitivity study applied on a numerical model for MSFs shows the importance of the inlet temperature as an input parameter. Then, measurements illustrate that the assumption of an inlet temperature equal to the interior or exterior air temperature is usually not valid. Finally, the influence of the inlet temperature modelling on the energy performance of naturally and mechanically ventilated single-storey MSFs is illustrated with building energy simulations.

## SENSITIVITY

The results of numerical models for MSFs are very sensitive to the inlet temperature. To illustrate this, a sensitivity study on a mechanically and naturally ventilated facade is performed with a numerical model, details of which can be found in Saelens [2002].

Dimensionless temperatures $DT_{ai}$ and $DT_v$ (Fig. 2 and Eqs. 1-3) are used to assess the sensitivity. They describe the main energy features of a multiple-skin facade: $DT_{ai}$ (Eq. 1) is a measure for the heat flux through the interior pane and $DT_v$ is a measure for the enthalpy change of the air flowing through the cavity. The enthalpy change is compared to the interior temperature for the mechanically ventilated variant (Eq. 2) and to the exterior temperature for the naturally ventilated variant (Eq. 3).

$$DT_{ai} = \frac{\theta_i - \theta_{ai}}{\theta_i - \theta_e} \ (-) \qquad (1)$$

$$DT_{v,AFW} = \frac{\theta_i - \theta_{outlet}}{\theta_i - \theta_e} \ (-) \qquad (2)$$

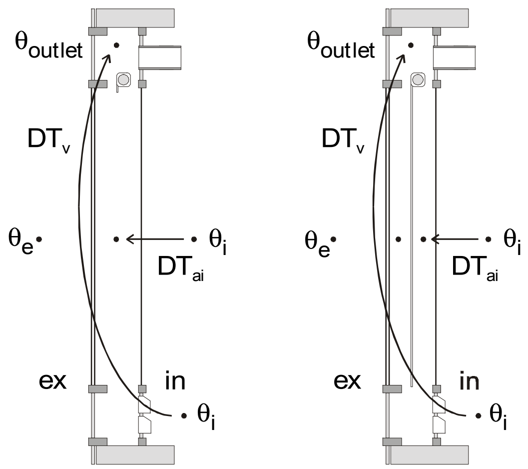
$$DT_{v,DSF} = \frac{\theta_e - \theta_{outlet}}{\theta_i - \theta_e} \ (-) \qquad (3)$$

In Equations 1-3, $\theta_i$ and $\theta_e$ represent the interior and exterior air temperature, $\theta_{ai}$ the average interior cavity air temperature and $\theta_{outlet}$ the cavity outlet temperature.

Table 1 gives a comparison between the measured and simulated dimensionless temperatures for a naturally and mechanically ventilated facade during a sunny winter day (16 February, 2000). The calculated dimensionless numbers show a good agreement with the measured values. The best agreement is found for the mechanically ventilated variant. In general the enthalpy change of the air ($DT_v$) is more difficult to predict.

Figure 3 illustrates that the sensitivity of the heat flux through the interior pane as well as the enthalpy change is considerable: $DT_{ai}$ changes up to 35 % and $DT_v$ changes up to 18 % for a change of the inlet temperature with 1 K. In the investigated inlet temperature range of  1 K, the relation between the change in dimensionless temperature and the change in inlet temperature can be assumed linear.

The results depend on the typology and the meteorological situation. In this example $DT_{ai}$ and consequently the heat flux through the inner pane is most sensitive to a correct inlet temperature modelling in the case of the naturally ventilated facade with lowered roller blind. The enthalpy change, represented by $DT_v$, is most sensitive in the case of the naturally ventilated facade with raised roller blind.

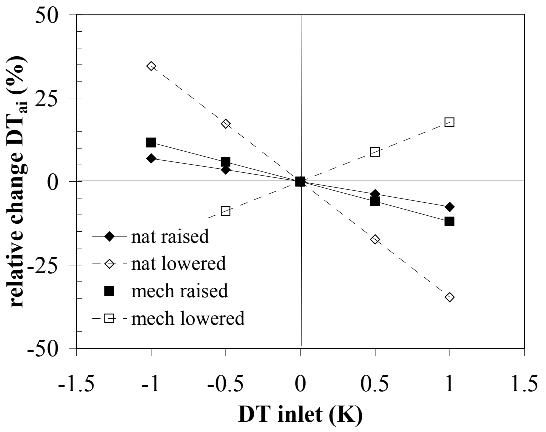



a. raised shading device b. lowered shading device

**Figure 2:** Definition of the dimensionless temperatures. The diagrams show the definition for a mechanically ventilated airflow window with a raised (left) and lowered (right) shading device.

**Table 1:** Comparisson between the measured and simulated dimensionless temperatures.

| shading device | raised | | lowered | |
|---|---|---|---|---|
| | $DT_{ai}$ (-) | $DT_v$ (-) | $DT_{ai}$ (-) | $DT_v$ (-) |
| Mechanically ventilated facade (AFW) | | | | |
| measured | 0.18 | 0.19 | -0.27 | -0.44 |
| simulation | 0.18 | 0.18 | -0.28 | -0.44 |
| difference (%) | -0.3 | -4.3 | 2.0 | 1.1 |
| Naturally ventilated facade (DSF) | | | | |
| measured | 0.80 | -0.25 | 0.40 | -0.80 |
| simulation | 0.81 | -0.24 | 0.37 | -0.83 |
| difference (%) | 1.2 | -6.8 | 1.2 | -6.8 |



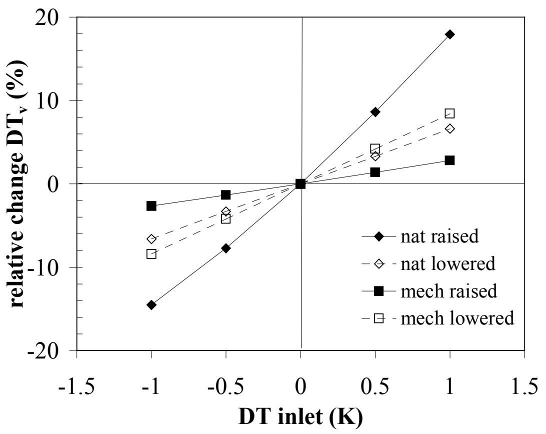




**Figure 3:** Sensitivity of the dimensionless temperatures $DT_{ai}$ and $DT_v$ to the inlet temperature.

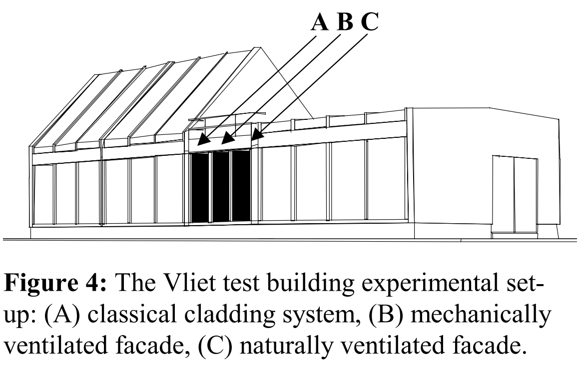



**Figure 4:** The Vliet test building experimental set-up: (A) classical cladding system, (B) mechanically ventilated facade, (C) naturally ventilated facade.

## MEASUREMENTS

At the Laboratory for Building Physics of the K.U.Leuven, an experimental facility for multiple-skin facades has been built in the Vliet test building (Fig. 4). The facility consists of three facade systems: a classical cladding system with external shading device (Fig 4a), a mechanical flow multiple-skin facade (Fig 4b) and a naturally ventilated multiple-skin facade (Fig 4c). The envelopes face south-west. A speed controllable circular duct ventilates the mechanically ventilated variant with interior air. The fan is able to produce an airflow rate between 30 and 150 $m^3/h$. The air flows up from the bottom. The double glazing is positioned at the outside. In the natural flow variant, the double glazing is situated at the inside because exterior air vents the cavity. The direction of the airflow depends on the windspeed and wind direction but is mostly directed upward [Saelens and Hens, 2001]. In both cases the double glazing is an argon-filled double-glazed unit (4-15-4 mm ) with low-E coating (coating emissivity = 0.09). According to the manufacturers data, the U-factor of this glazing is 1.23 $W/(m^2{\cdot}K)$ and the g-value is 0.64 (-). The other pane consists of a single clear glass (8 mm). Both systems are equipped with an automated roller blind in the middle of the cavity.

Figure 5 shows the construction details of the inlet zone of the naturally (Fig. 5a) and mechanically (Fig. 5b) ventilated variant. The airflow rate, cavity air and surface temperatures were measured every 3 minutes and averaged on a 15 minute basis. Meteorological data were gathered by an automatic weather station, from which 15 minute averages are used.

Figure 6 shows the measured inlet temperature of the mechanically and naturally ventilated facade as a function of the interior and exterior temperature respectively during summer conditions. In both cases the cavity air inlet temperature hardly ever equals the interior air temperature for the mechanically ventilated variant or the exterior temperature for the naturally ventilated variant. Both plots show two distinct regions:

1. In the first region, the inlet temperatures are positioned parallel to the line where the exterior or interior temperature is equal to the inlet temperature. This region represents the period without solar radiation. The inlet temperature is determined by the transmission losses and gains through the bounding surfaces. For the mechanically ventilated airflow window (Fig. 6a), the cooling of the inlet temperature is caused by transmission losses through the exterior surface. The inlet temperature depends on the airflow rate: the inlet temperature cools down more when the airflow rate is lower. For the naturally ventilated facade (Fig. 6b), most inlet temperatures are slightly higher than the exterior air indicating that

the air heats up while passing through the inlet zone. The temperatures above the line are caused by flow reversal.

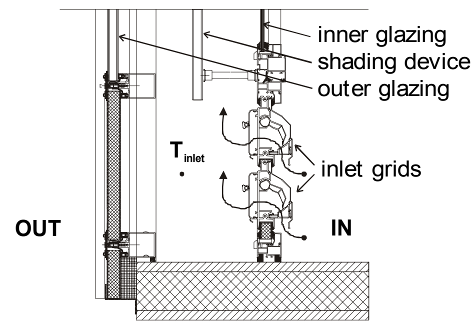
2. In the second region, the inlet temperatures are notably higher than the exterior or interior temperature. This region represents the day situation, during which absorption of solar radiation causes heating. This is more pronounced for the naturally ventilated facade. Heating in the airflow window again depends on the airflow rate. Comparison of the + and o signs in Figure 6a shows that when the airflow rate is higher, the inlet temperature is lower.

The experimental data show that the inlet temperature is governed by the heating and cooling due to contact with the bounding surfaces and heating due to solar radiation. Furthermore the inlet temperature depends on the airflow rate.

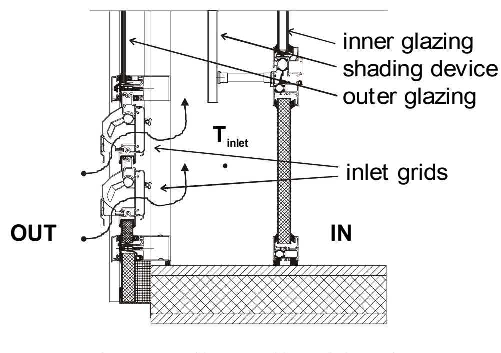
## INLET TEMPERATURE SIMULATION

The above sensitivity study and experimental results show that assuming the interior or exterior temperature equal to the inlet temperature is an unacceptable simplification. The question now raises how to model the inlet temperature to be used as a boundary condition for MSF-models.

Two models are presented and discussed in case of a mechanically ventilated airflow window (Fig. 5a).




a. mechanically ventilated facade



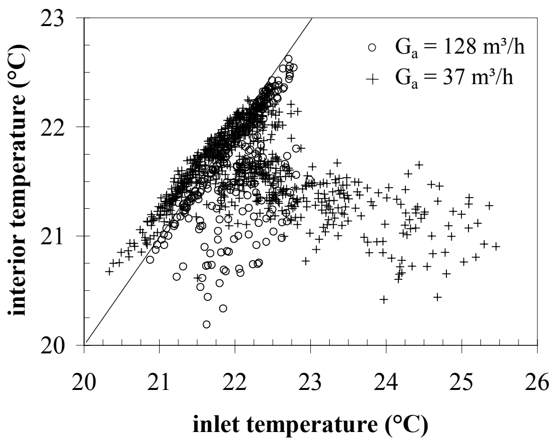

b. naturally ventilated facade

**Figure 5:** Construction details of the inlet zone of the mechanically and naturally ventilated MSF.

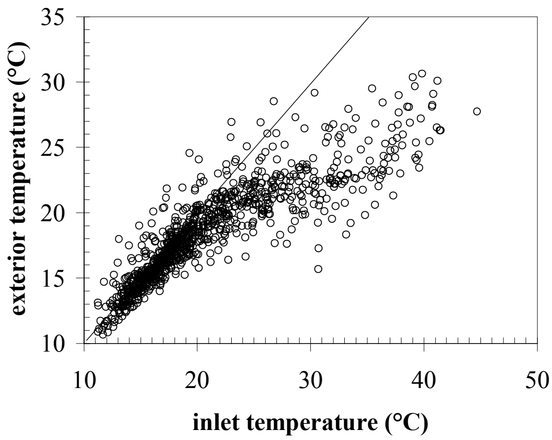
The first model calculates the inlet temperature from a simple steady-state heat balance:

$$\theta_{inlet} = \frac{\begin{aligned}&\rho_a \cdot c_a \cdot g_a \cdot \theta_i \\ &+ U_i \cdot A_i \cdot \theta_i + U_e \cdot A_e \cdot \theta_e \\ &+ A_s \cdot \alpha_s \cdot \left(\tau_d \cdot I_{d,t} + \tau_b \cdot I_{b,t}\right)\end{aligned}}{\rho_a \cdot c_a \cdot g_a + U_i \cdot A_i + U_e \cdot A_e} \tag{4}$$

where $\rho_a$ is the air density (kg/m³), $c_a$ is the specific heat capacity (J/(kg·K)), $g_a$ is the air flow rate (m³/s), $\theta_i$ is the interior temperature (°C), $U_i$ and $U_e$ are the 3D calculated thermal conductances of the interior and exterior surface (W/(m²·K)) and $A_i$ and $A_e$ are their respective surface areas (m²). The last term in the numerator represents the incoming solar radiation. The area through which solar radiation comes ($A_S$ (m²)) is estimated as the area between the exterior and interior




a. mechanically ventilated facade




b. naturally ventilated facade

**Figure 6:** Scatter plot of the inlet temperature of the mechanically (a) and naturally (b) ventilated MSF versus the interior (a) and exterior (b) temperature during summer conditions.

window frames, $\alpha_s$ is the average solar absorption coefficient in the inlet zone (-). The transmitted diffuse ($\tau_d \cdot I_{d,t}$) and direct ($\tau_b \cdot I_{b,t}$) solar radiation (W/m²) are separated and are calculated as a function of the angle of solar incidence angle.

The second model is a transient model and is implemented in the below described energy simulations. It relies on the star-temperature method [Seem, 1987] and uses z-transfer functions to describe the bounding surfaces [Mitalas, 1978]. The inlet zone is a separate zone in the building simulation component (Fig. 7). The bounding surfaces have the same conductances as in the first model. Only now, also thermal capacity effects are considered. The incident solar radiation ($q_s = \tau_d \cdot I_{d,t} + \tau_b \cdot I_{b,t}$) is not inserted in the air node but is distributed over the surfaces. In this airflow window example, the air node ($T_{a,1}$) is coupled to the air temperature of the interior zone ($T_{a,3}$).

Figure 8 shows a comparison of the measured and calculated inlet temperature for an AFW-variant in summer. As a reference also the interior air temperature is mapped. Especially during daytime the inlet temperature differs from the interior temperature. The interior temperature in fact underestimates the inlet temperature by several degrees.

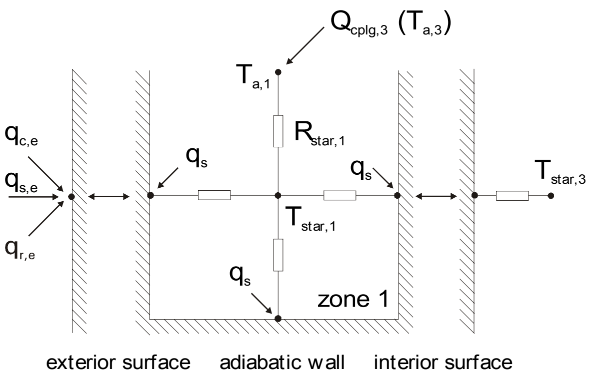



**Figure 7:** Representation of the inlet zone as a separate zone in a building energy simulation program.

During the night, both the steady state and the transient model represent the measurements quite well. The average difference is less than 0.2 K, which is within the measurement uncertainty (0.5 K). During the day, Figure 8 shows that the phase shift and amplitude difference between the measured data and the transient model is much smaller than for the steady state model. The above results stress the need to take into account the transient effects that occur in the inlet and outlet zone when performing transient energy simulations.

## ENERGY PERFORMANCE ANALYSIS

From the above it is clear that a correct modelling of the inlet temperature is important to assess the energy performance of MSFs correctly. As an illustration, an energy simulation of three types of MSFs and a traditional facade are presented:

1. DSF (Fig. 9a): A naturally ventilated window where the air comes from the outside, flows through the cavity and returns to the outside.
2. AFW (Fig. 9b): A mechanically ventilated airflow window where the air comes from the inside, flows through the cavity and then flows to the HVAC-system.
3. SUP (Fig. 9c): A mechanically ventilated supply window where the air comes from the outside, flows through the cavity, enters the office and serves as ventilation air.
4. IGU (Fig. 9d): As a reference the results of an office building equipped with conventional insulated glazing units (IGUs) and an exterior shading roller blind are given.

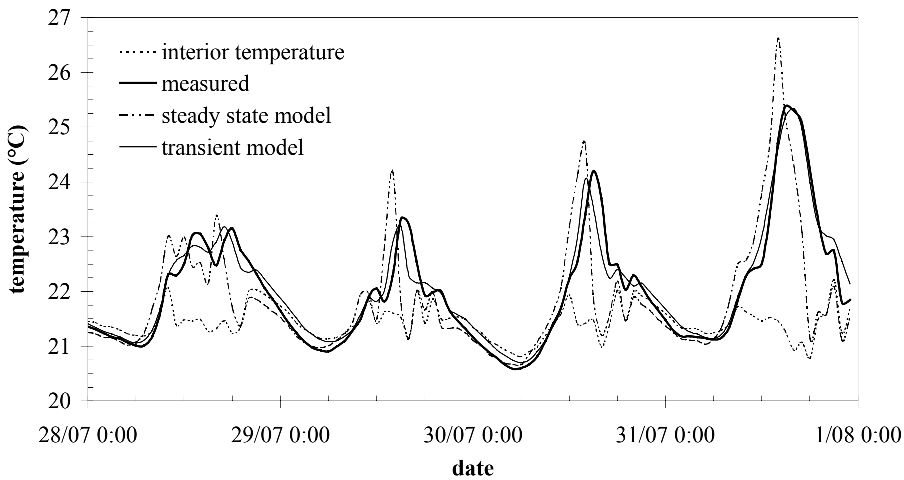
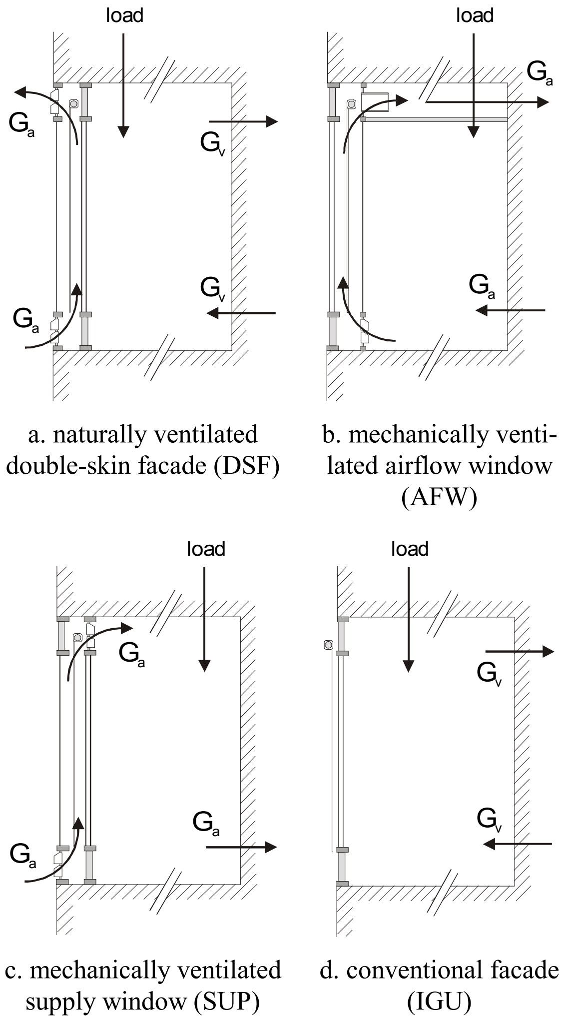



**Figure 8:** Comparison of the measured inlet temperature with the inlet temperature as calculated by the steady state and transient model. for an airflow window ($G_a$ = 37 m³/h).




a. naturally ventilated double-skin facade (DSF)

b. mechanically ventilated airflow window (AFW)

c. mechanically ventilated supply window (SUP)

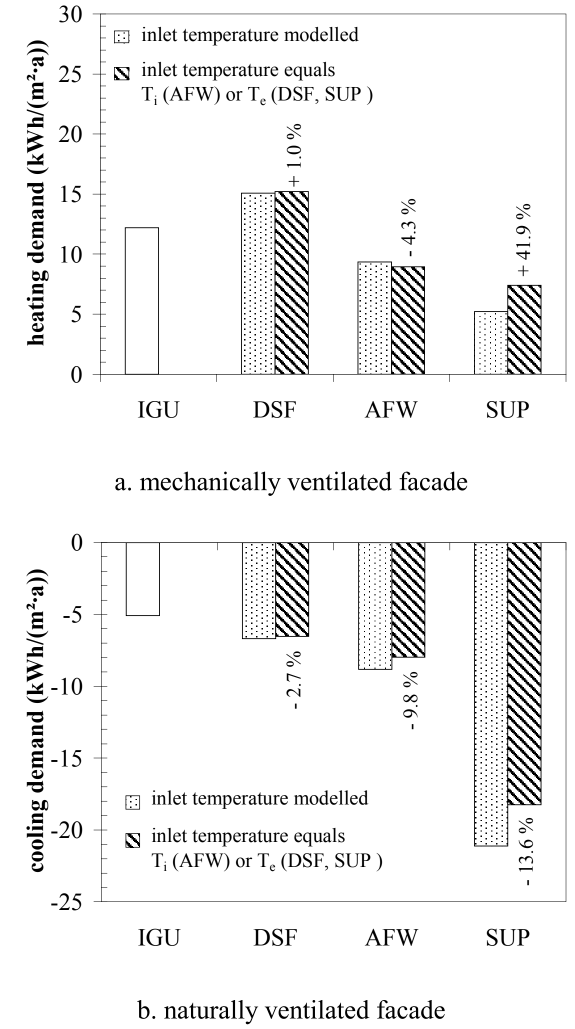
d. conventional facade (IGU)

**Figure 9:** Diagram of the simulated multiple-skin facades; $G_a$ represents the airflow rate through the multiple-skin facade cavity, $G_v$ is the minimum hygienic ventilation rate.

Since it is assumed that the DSF is not used to naturally ventilate the building, the office has to be ventilated mechanically with a hygienic ventilation rate ($G_v$ = 36 m³/h). The airflow rate ($G_a$) through the cavity of the DSF depends on the weather conditions and varies with time. For the mechanically ventilated MSFs (AFW and SUP) the cavity airflow rate equals the hygienic ventilation rate ($G_a$ = $G_v$ = 36 m³/h). The office equipped with the IGU is mechanically ventilated with the hygienic ventilation rate ($G_v$).

The net energy results (Fig. 10) are presented for two situations: (1) the inlet temperature is not modelled and equals the exterior (for the naturally ventilated and supply window) or the interior temperature (for the airflow window) and (2) the inlet temperature is modelled with the transient model schematically presented in Figure 7.

In winter, when heating prevails, the exterior air temperature underestimates the inlet temperature of the DSF and the SUP. The main reason is the heating of




a. mechanically ventilated facade

b. naturally ventilated facade

**Figure 10:** Influence of the inlet temperature model on the energy demand of multiple-skin facades.

the inlet air by transmission losses from the inside. Consequently, the cavity temperature is estimated too low when the inlet temperature is not modelled. This causes an overestimation of the heating demand (Fig. 10a). The overestimation of the heating demand in case of the DSF is marginal because the inner pane is insulated. The overestimation in case of the SUP-window is significant because the cavity air is used as ventilation air. The inlet temperature of the AFW is lower than the interior temperature because of transmission losses in the inlet zone. Hence, assuming that the inlet temperature equals the interior air temperature causes a moderate underestimation of the AFW heating demand (Fig. 10a).

In summer, when cooling prevails, solar radiation is more important. It causes the inlet temperature to be significantly warmer than the exterior or interior air temperature. As a consequence, the cooling demand is underestimated if the inlet temperature equals the exterior or interior air temperature (Fig. 10b). The underestimation is more pronounced for the AFW than for the DSF because the inner pane thermal resistance of the latter is higher. As for the heating demand the effect is most pronounced for the SUP-window. Again the reason is the direct use in the office of the air flowing through the cavity.

To improve the energy performance of the AFW, it is important to have the inlet temperature as close as possible to the interior temperature. This can best be achieved by an airtight and well insulated exterior surface. In case of the DSF and the SUP-window the interior surface should be well insulated to minimise the condensation risk at the interior side of the inlet zone. To avoid overheating for all MSF-typologies, excessive absorption of solar radiation should be avoided by choosing light finishing colours. Furthermore, thermal mass will help to dampen peaks.

The influence of a correct modelling of the inlet temperature is most pronounced when the cavity air is reused in some way. In the above examples this was illustrated by the results of the SUP-window. For energy performance assessments of MSFs in general, a reliable inlet temperature model is necessary for facade typologies in which the reuse of the cavity air is a primary aim. Typical examples are DSFs used to naturally ventilate the office and AFWs that are coupled to the HVAC-system.

## CONCLUSIONS

The energy performance of multiple-skin facades attracts a lot of attention. To support the claimed benefits whole building simulation programs should be used to predict the energy performance. By analysing the influence of the inlet temperature, this paper demonstrates that a reliable energy assessment needs a correct implementation of the boundary conditions and modelling parameters.

The inlet temperature influences both the transmission losses and the enthalpy change of the air flowing through the cavity. The influence on the energy demand proved to be considerable. Especially when the air flowing through the cavity is to be reused, a correct inlet temperature modelling is of major importance to come to reliable energy assessments.

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