THE DEVELOPMENT OF SIMPLE CALCULATION MODEL FOR ENERGY PERFORMANCE OF DOUBLE SKIN FAÇADES

by

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Estimating thermal effect of so called double-skin façades on energy performance of buildings with two envelopes, a proprietary mathematical model of heat transfer through double-skin façades has been developed. A very specific approach of the mathematical model presented here is based on prediction of the double-skin façades interspace temperature and assumption that façade could be treated as a single one declaring the interspace temperature and reduced intensity of solar radiation as the "outdoor" conditions.

In this paper results of the heating and cooling loads as well as the interspace temperature prediction compared for three months (January, April, and July) and for the west oriented façade with ordinary and absorption glass are presented. Façade is placed under climatic conditions of Belgrade (45° north latitude). Also, results for weather conditions of sunny and cloudy day are shown. Results includes influence of air velocity in interspace of façades for April and July.

Following a type of the double-skin façade construction assumption it was implied that the space between the two envelopes is closed during the winter mode for air circulation, in order to have temperature higher inside than outside and opposite in the summer mode, air inlet and outlet are opened in order to prevent much higher temperatures than the outside ones, and higher cooling load of an air-conditioned building, as a consequence. Taking only thermal effects into account, presented prediction has proven that double-skin façades decrease both building heat losses and heat gains throughout the year, and give significant contribution to the building energy consumption savings.

Key words: *double-skin façade, interspace temperature, simple calculation method, heating and cooling load, heat transfer*

Introduction

Double-skin façades (DSF) have been favoured by architects for certain time. In the case of DSF, normal façade – in the true sense of the world – separates the inner side of the building from the environment, is developed with a further glass casing. Concept of DSF for offices and commercial buildings was first established in Europe. Through continuous evolu-

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tion and development, it became an important and rising architectural element of buildings all around the world.

The history of DSF is described in several books, reports and articles. Saelens [1] mentions that in 1849, Jean-Baptiste Jobard, at that time director of the industrial Museum in Brussels, described an early version of a mechanically ventilated multiple skin façade. He mentions how in winter hot air should be circulated between two glazings, while in summer it should be cold air. It takes 65 years for the idea to reappear.

The first instance of the double skin curtain wall appears in 1903 in Germany. This building accommodates toy factory and was designed by Richard Steiff.

At the end of 1920‘s double skins were developed in Russia in communal housing by Moisei Ginzburg. Some other projects with double skins by Le Corbusier were also developed in late 1920s.

Little or no progress is made in double skin glass constructions until the late 1970s and early 1980s. In these years, including 1990s a lot of buildings with double skin envelope were built. The most famous among them are: Loyd‘s building in London, UK; Gotz-GmbH office building in Wurzburg, Germany; Commerzbank HQ office building in Frankfurt, Germany; RWE AG office building in Essen, Germany; City Gate in Düsseldorf, Germany; Nationale Nederlanden office building in Prague, Czech Republic; *etc.* In the United States, the interest in DSF is remarkably lower.

Generally a double skin system consists of an external screen, a ventilated cavity and an internal screen. Solar shading can be placed in the ventilated cavity. Oesterle *et al.* [2], gave the most comprehensive definition of DSF. For the author, a double skin façade consists of a multi layered façade envelope, which has an external and internal layer that contains a buffer space used for controlled ventilation and solar protection.

The external and internal screens can be single glass or double glazed unit, the depth of the cavity and the type of ventilation can depend on environmental conditions, the desired envelope performance and the overall design of the building including systems. Andjelković [3] gave parameters that have to be taken into account in the early design stage, weather conditions at the site, orientation of the building, building occupancy and local regulation.

The ventilation in the cavity can be either natural (buoyancy driven), forced (mechanically driven) or mixed (both natural and forced). The direction of the airflow (upwards or downwards) depends on the type of ventilation and the general system design.

A few models for naturally ventilated multiple-skin façades are available. Faist [4] developed a simplified iterative method to model the airflow due to stack effect in multi storey envelopes. Van Paassen *et al.* [5] developed a network model in which the airflow is mainly based on the stack effect. In comprehensive study Saelens [1] developed model that takes into account three elements: heat transfer, optical element and air flow.

From a building physics point of view, DSF are very complex; optical and thermal comfort, heating losses during winter, cooling loads in summertime, ventilation, acoustics, moisture, and fire safety requires careful investigation at the design stage. Thermal behavior of naturally ventilated double skin façades is only possible by using complex simulation tools, which allow interconnections between fluid dynamics, energy balances and optical transport mechanisms. On the other side, performance assessment of mechanically ventilated double skin façades is slightly easier but still requires simulation tools.

Also, influence of passive ventilation is importnat factor on performance of DSF. Manz [6] developed model wih night-time ventilation. Gratia [7] compared heating and cooling loads for DSF and single skin façade building in Belgium with and without day and night ventilation. Hensen [8], note that passive ventilation in DSF system depends on many interacting forces, which can often produce highly erratic flows if not properly design.

Stec [9] simulated the energy use of DSF system in the Netherlands integrated with a model of the building HVAC system. Dragićević [10] developed a simple calculation method based on heat transfer of the modified Trombe solar wall.

After all, this makes it impossible to have reliable predictions on energy efficiency and impacts on comfort in the early planning phase and to reduce uncertainties for designers and investors. Therefore the goal of this paper is to develop simple calculation method, which offers sufficient accuracy of the thermal behavior and the energy performance of the DSF.

Description of the calculation method

In principle, double skin façade (DSF) can be with the interrupted outside envelope, or with the continuous one. Heusler *et al.* [11], classify DSF according geometry and ventilation consept.

The calculation method presented in this text includes the interrupted façade type but it can be also applied at continuous façade models. The interspace air temperatures are determined according to the module thermal balance, which gains or emits heat through the boundary layers (the outer envelope, the base façade window and wall) in dependence of the indoor and outdoor thermal conditions. However, as the outer façade is made of glass, there occurs the influence of solar radiation absorbed by both façade layers. They are heated and a portion of the absorbed heat to the double façade interspace air is emitted. This portion of heat may be calculated following two ways: by former temperature determination regarding all areas of both façades, or knowing the absorbed radiant heat portion transferred into the interspace. Both ways require the determination of the inside/outside module heat transfer coefficients.

Interspace temperature calculation method is based on the iteration with certain time intervals. This method presents modification of a previous method which has been developed by Todorović *et al.* [12-15], with some recommendations followed by Yilmaz's method [16]. This method includes calculation for heating losses in winter time regime and cooling loads in summer time regime. Also, results are presented for spring time regime. Now, new calculation includes impact of diffuse solar radiation, as a part of total solar radiation $I = I_{\mathrm{dir}} + I_{\mathrm{dif}}$ on the exterior surface skin, impact of heat flow from wall's surface to interspace by longwave radiation and influence of air velocity in interspace on heat transfer coefficient for summer time regime. Influence of air velocity between envelopes on heat transfer coefficient by convention is included and according to [17] calculated:

for air velocity $v \leq 5$ m/s: $\alpha = 5.6 + 4v$; for air velocity $5 < v < 30$ m/s: $\alpha = 7.3v^{0.78}$.

For calculation of heating and cooling loads trough DSF, calculated interspace temperatures have been adopted as outdoor air temperature and according to that heat transfer trough inner skin of DSF has been calculated.

Calculation of the outer façade glass temperature

Absorbed portion of solar radiation energy in time τ is:

$$Q_{\mathrm{as}} = a_{\mathrm{s}} F_{\mathrm{s}} I \tag{1}$$

Total solar radiation on exterior surface skin:

$$I = I_{\text{dir}} + I_{\text{dif}} \tag{2}$$

$$Q_{\text{as}} = a_{\text{s}} F_{\text{s}} I = a_{\text{dir}} F_{\text{s}} I_{\text{dir}} + a_{\text{dif}} F_{\text{s}} I_{\text{dif}} \tag{3}$$

Heat transfer through the glass mass:

$$Q_{\text{s}} = F_{\text{s}} D c\, c_p \rho (t_{\text{s}} - t'_{\text{s}}) \tag{4}$$

where t_{s}' is the glass temperature from the previous period $\tau - 1$.

Heat transfer from glass into the surrounding:

$$Q_1 = F_{\text{s}} \alpha_{\text{s1}} (t_{\text{s}} - t_o) \tag{5}$$

Heat transfer into the indoor space:

$$Q_2 = F_{\text{s}} \alpha_{\text{s2}} (t_{\text{s}} - t'_{\text{m}}) \tag{6}$$

Longwave radiation to the surrounding and inside space:

$$Q_3 = \varepsilon_{\text{s1}} F_{\text{s}} C_{\text{s}} \beta_{\text{s1}} (t_{\text{s}} - t_o) \tag{7}$$

$$Q_4 = \varepsilon_{\text{s2}} F_{\text{s}} C_{\text{s}} \beta_{\text{s2}} (t_{\text{s}} - t'_{\text{m}}) \tag{8}$$

In eqs. (5) and (7) t_0 is the surrounding exterior temperature, and in eqs. (6) and (8), t'_{m} is the indoor space temperature that is calculated in the previous calculation step.

Convection heat transfer from the outer façade glass into the inside space air is calculated by the equation where the value from the previous calculation step $\tau - 1$ is used as the inside space temperature.

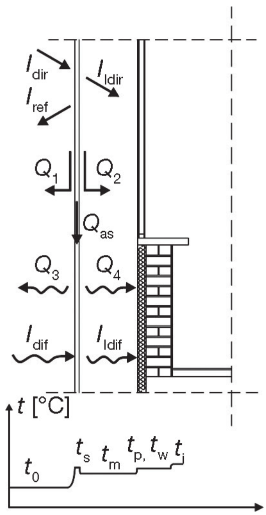

Figure 1. Outer façade-heat balance

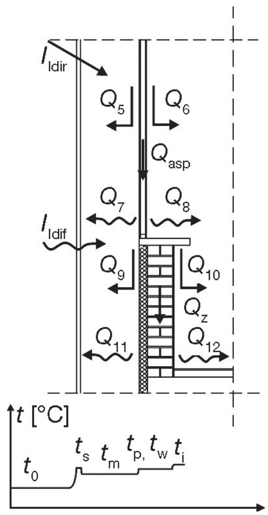

Figure 2. Inner wall and glass heat balance

The calculation of the boundary layers temperatures influenced by solar radiation is performed on the basis of the heat balance (9) for each of the layers. Regarding the façade on fig. 1, the heat fluxes are presented, while the following equation expresses their balance:

$$Q_{\text{as}} = Q_{\text{s}} + Q_1 + Q_2 + Q_3 + Q_4 \tag{9}$$

Result of the equation system (1) to (9) gives the glass temperature:

$$t_s = \frac{a_{\rm dir} I_{\rm dir} + a_{\rm dif} I_{\rm dif} + \rho D c_p t_s' + (\varepsilon_{s1} C_c \beta_{s1} + \alpha_{s1}) t_o + (\varepsilon_{s2} C_c \beta_{s2} + \alpha_{s2}) t_m'}{\rho D c_p + \varepsilon_{s1} C_c \beta_{s1} + \alpha_{s1} + \varepsilon_{s2} C_c \beta_{s2} + \alpha_{s2}} \tag{10}$$

Neglecting the heat exchange through the longwave radiation between the outer façade and its surrounding, on one hand, and the inside façade on the other, expression (10) becomes:

$$t_s = \frac{a_{\rm dir} I_{\rm dir} + a_{\rm dif} I_{\rm dif} + \rho D c_p t_s' + (\alpha_{s1}) t_o + (\alpha_{s2}) t_m'}{\rho D c_p + \alpha_{s1} + \alpha_{s2}} \tag{11}$$

Heat transfer trough the inner façade

Inner façade can be built of glass component (window) and opaque component (wall). Heat storage capacity of these components is a quite different, so heat balance calculation must be obtained separately.

The inner façade window can have the absorbing glass or, more regularly, the ordinary glass with the neglecting solar radiation absorbing capacity. In the former case, the glass temperature should be calculated, as the relevant figure for the heat transfer into the indoor space, as it was calculated for the outer façade (fig. 2):

$$Q_{\rm asp} = Q_{\rm sp} + Q_5 + Q_6 + Q_7 + Q_8 \tag{12}$$

$Q_{\rm asp} = a_p F_p I d = a_{\rm pdir} F_p I_{\rm Idir} d_{\rm dir} + a_{\rm pdif} F_p I_{\rm Idif} d_{\rm dir}$ – absorbed solar radiation on window (13)

$Q_{\rm sp} = F_p D_p c_p \rho (t_s - t_p')$ – heat transfer through the inner window mass (14)

$Q_5 = F_p \alpha_{p1} (t_p - t_m')$ – heat flow (convection) from window to interspace (15)

$Q_6 = F_p \alpha_{p2} (t_p - t_i)$ – heat flow (convection) from window to interior of the building (16)

$Q_7 = \varepsilon_{p1} F_p C_c \beta_{p1} (t_s - t_m')$ – heat flow (longwave radiation) to the interspace (17)

$Q_8 = \varepsilon_{p2} F_p C_c \beta_{p2} (t_s - t_i)$ – heat flow (longwave radiation) to interior of the building (18)

According to calculation for outer façade, in eqs. (12) to (18), temperature of glass of inside window is:

$$t_p = \frac{a_{p\rm dir} I_{\rm Idir} d_{\rm dir} + a_{p\rm dif} I_{\rm Idif} d_{\rm dif} + \rho D_p c_p t_p' + (\varepsilon_{p1} C_c \beta_{p1} + \alpha_{s1}) t_i + (\varepsilon_{ps2} C_c \beta_{ps2} + \alpha_{s2}) t_m}{\rho D_p c_p + \alpha_{p1} + \alpha_{p2} + \varepsilon_{p1} C_c \beta_{p1} + \varepsilon_{p2} C_c \beta_{p2}} \tag{19}$$

Neglecting the heat exchange through the long-wave radiation between the inner window and its surrounding:

$$t_p = \frac{a_{p\rm dir} I_{\rm Idir} d_{\rm dir} + a_{p\rm dif} I_{\rm Idif} d_{\rm dif} + \rho D_p c_p t_p' + \alpha_{p1} t_m' + \alpha_{p2} t_i}{\rho D_p c_p + \alpha_{p1} + \alpha_{p2}} \tag{20}$$

In case when the inner façade window is made of the ordinary glass, the heat transfer into the indoor space is calculated by overall heat transfer through window:

$$Q_p = F_p U_p (t_i - t_m) \tag{21}$$

In the wall part (opaque component) of the inner façade, during the winter, the heat is transferred from the heated indoor space through the wall into interspace air. However, during the sunny days, solar radiation transmitted through the outer façade gets onto the exterior wall side facing interspace where it is absorbed and heats the surface layer (Q_λ – heat flow trough wall by conduction). Because of small temperature difference between the wall's inner surface and the room temperature, heat flow by convection and longwave radiation on that side can be neglected. On the other side of wall temperature difference causes necessity to include heat flow by longwave radiation. According to heat balance for the wall (fig. 2), the absorbed solar radiation heat (gain Q_w) contains heat flux transferred by conduction from the indoor building space into the outer wall layer (Q_λ), total heat transferred by the wall into the interspace air by heat convection (Q_9) and heat flow from wall to interspace by longwave radiation Q_{11}:

$$Q_» = F_w \left(\frac{1}{\frac{\delta}{\lambda} + \frac{1}{\alpha_{w2}}}\right)(t_i - t_w) \tag{22}$$

$$Q_z = a_w F_w I_d = a_{wdir} F_w I_{Idir} d_{dir} + a_{wdif} F_w I_{Idif} d_{dif} \tag{23}$$

$$Q_9 = F_w \alpha_{w1} (t_w - t'_m) \tag{24}$$

$$Q_{11} = \varepsilon_{w1} F_w \, C_c \, \beta_{w1} (t_w - t'_m) \tag{25}$$

From the heat balance:

$$Q_z = Q_9 + Q_{11} - Q_\lambda \tag{26}$$

following the wall surface temperature during the time τ:

$$t_w = \frac{a_{wdir} I_{Idir} d_{dir} + a_{wdif} I_{Idif} d_{dif} + \alpha_{w1} t'_m + \varepsilon_{w1} C_c \beta_{w1} t'_m + \dfrac{1}{\frac{\delta}{\lambda} + \frac{1}{\alpha_{w2}}} t_i}{\alpha_{w1} + \varepsilon_{w1} C_c \beta_{w1} + \dfrac{1}{\frac{\delta}{\lambda} + \frac{1}{\alpha_{w2}}}} \tag{27}$$

In eqs. (17) to (20), as the interspace temperature for the calculation period τ, its value from the previous period, $\tau - 1$, is used.

Interspace temperature in heating regime

Absorbed heat in interspace:

$$Q_v = F_s D c_p \rho (t_w - t'_m) \tag{28}$$

Heat flow from wall to interspace:

$$Q_w = F_w U_w (t_w - t_m) \tag{29}$$

Heat flow from interspace to outdoor:

$$Q_o = F_s U_s (t_w - t_o) \tag{30}$$

Interspace heat balance is based on the exchange of the heat of the "trapped" air mass with both façades (fig. 3), which has interspace volume. The heat balance (absorbed heat in interspace, Q_v), present with interspace heat loss and heat gains, is expressed in the following way:

$$Q_v = Q_\mathrm{p} + Q_\mathrm{w} - Q_o + Q_2 + Q_5 + Q_9 - Q_{11} \tag{31}$$

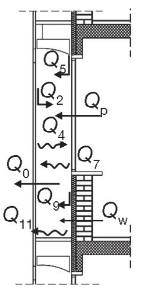

Figure 3. Interspace heat balance for winter period

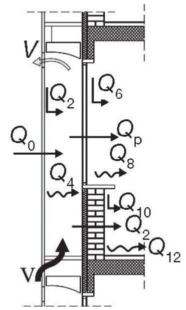

Figure 4. Interspace heat balance for summer period

According to eqs. (6), (15), (21), (24), (25), (28), (29), (30) and (31) the interspace temperature in heating regime is:

$$t_\mathrm{m} = \frac{F_\mathrm{s} D c_p \rho t_\mathrm{m}' + F_\mathrm{p} U_\mathrm{p} t_\mathrm{i} + F_\mathrm{w} U_\mathrm{w} t_\mathrm{i} + F_\mathrm{s} U_\mathrm{s} t_\mathrm{o} + F_\mathrm{s} \alpha_\mathrm{s2} t_\mathrm{s} + F_\mathrm{p} \alpha_\mathrm{p1} t_\mathrm{p} + (\varepsilon_\mathrm{w1} C_\mathrm{c} \beta_\mathrm{w1} + \alpha_\mathrm{w1}) F_\mathrm{w} t_\mathrm{i}}{F_\mathrm{s} D c_p \rho + F_\mathrm{p} U_\mathrm{p} + F_\mathrm{w} U_\mathrm{w} + F_\mathrm{s} U_\mathrm{s} + F_\mathrm{s} \alpha_\mathrm{s2} + F_\mathrm{p} \alpha_\mathrm{p1} + (\varepsilon_\mathrm{w1} C_\mathrm{c} \beta_\mathrm{w1} + \alpha_\mathrm{w1}) F_\mathrm{w}} \tag{32}$$

When absorption in the inner façade glass may be neglected, the interspace temperature in heating regime is:

$$Q_v = Q_\mathrm{p} + Q_\mathrm{w} - Q_o + Q_2 + Q_9 - Q_{11} \tag{33}$$

$$t_\mathrm{m} = \frac{F_\mathrm{s} D c_p \rho t_\mathrm{m}' + F_\mathrm{p} U_\mathrm{p} t_\mathrm{i} + F_\mathrm{w} U_\mathrm{w} t_\mathrm{i} + F_\mathrm{s} U_\mathrm{s} t_\mathrm{o} + F_\mathrm{s} \alpha_\mathrm{s2} t_\mathrm{s} + (\varepsilon_\mathrm{w1} C_\mathrm{c} \beta_\mathrm{w1} + \alpha_\mathrm{w1}) F_\mathrm{w} t_\mathrm{i}}{F_\mathrm{s} D c_p \rho + F_\mathrm{p} U_\mathrm{p} + F_\mathrm{w} U_\mathrm{w} + F_\mathrm{s} U_\mathrm{s} + F_\mathrm{s} \alpha_\mathrm{s2} + (\varepsilon_\mathrm{w1} C_\mathrm{c} \beta_\mathrm{w1} + \alpha_\mathrm{w1}) F_\mathrm{w}} \tag{34}$$

Interspace temperature in cooling regime

During the cooling regime, the air circulation through the interspace must be enabled, so the air slots (fig. 4) are opened. This method does not include venetian blinds built-in between the two façades or inside of building. The circulating air quantity depends on circulation speed, which in turn, in case of natural circulation, depends on air slots size, the difference between the exterior and the interior temperatures, the interspace height, and the its circulation resistance. For a circulation speed v, the heat quantity the air takes is defined by the eq. (21), where the current outside temperature is the entrance air temperature. The temperature the interior air heats to is t_2:

$$Q_v = F_\mathrm{s} D c_\mathrm{p} \rho v (t_2 - t_0) \tag{35}$$

The relevant indoor space temperature is calculated as the entrance and exit temperature mean value:

$$t_\mathrm{m} = \frac{t_2 + t_0}{2} \quad \text{or} \quad t_2 = 2t_\mathrm{m} - t_0 \tag{36}$$

The quantity of heat transferred during cooling regime from the outer façade glass is calculated in the same way as in the winter regime, by glass temperature previous calculation time step (6).

Heat passage through the inner façade window toward the indoor air-conditioned space is defined by the expression (21).

Heat transfer through the wall of one façade building, regarding cooling load, regular is calculated by the equivalent temperature differences, which is including the outside temperature, but also the influence of solar radiation upon the outside wall, and the time lag of temperature oscillations, the consequence of the wall mass. The approximate method can be used for calculation, presenting steady-state conditions of heat transfer (29).

For the more precise calculations, the more relevant is the equivalent temperature difference that should be defined by adaptation and correction of table data in cooling load calculation standards for conditions which are existing in interspace.

$$Q_{\mathrm{w}} = F_{\mathrm{w}} U_{\mathrm{w}} \Delta t_{ekv} \tag{37}$$

Heat flow from outside to interspace:

$$Q_o = F_{\mathrm{s}} U_{\mathrm{s}} (t_o - t_{\mathrm{m}}) \tag{38}$$

From the balance:

$$Q_v = Q_2 + Q_0 + Q_{\mathrm{p}} + Q_{\mathrm{w}} + Q_6 \tag{39}$$

Substituting t_{m} in regard to (36), we get the temperature of the air heated through the indoor space:

$$t_2 = \frac{F_{\mathrm{s}} D c_p \rho v t_0 + F_{\mathrm{s}} \alpha_{\mathrm{s2}} (t_{\mathrm{s}} - \frac{t_0}{2}) + F_{\mathrm{s}} U_{\mathrm{s}} \frac{t_0}{2} + F_{\mathrm{p}} U_{\mathrm{p}} (\frac{t_0}{2} - t_{\mathrm{i}}) + F_{\mathrm{w}} U_{\mathrm{w}}\text{''}\, t_{\mathrm{ekv}} + F_{\mathrm{p}} \alpha_{\mathrm{p2}} (t_{\mathrm{p}} - t_{\mathrm{i}})}{F_{\mathrm{s}} D c_p \rho v + \frac{F_{\mathrm{s}} \alpha_{\mathrm{s2}}}{2} + \frac{F_{\mathrm{s}} U_{\mathrm{s}}}{2} + \frac{F_{\mathrm{p}} k_{\mathrm{p}}}{2}} \tag{40}$$

When absorption in the inner façade glass may be neglected, the temperature of the air heated through the indoor space is:

$$Q_v = Q_2 + Q_0 + Q_{\mathrm{p}} + Q_{\mathrm{w}} \tag{41}$$

$$t_2 = \frac{F_{\mathrm{s}} D c_{\mathrm{p}} \rho v t_0 + F_{\mathrm{s}} \alpha_{\mathrm{s2}} (t_{\mathrm{s}} - \frac{t_0}{2}) + F_{\mathrm{s}} U_{\mathrm{s}} \frac{t_0}{2} + F_{\mathrm{p}} U_{\mathrm{p}} (\frac{t_0}{2} - t_{\mathrm{i}}) + F_{\mathrm{w}} U_{\mathrm{w}}\text{''}\, t_{\mathrm{ekv}}}{F_{\mathrm{s}} D c_{\mathrm{p}} \rho v + \frac{F_{\mathrm{s}} \alpha_{\mathrm{s2}}}{2} + \frac{F_{\mathrm{s}} U_{\mathrm{s}}}{2} + \frac{F_{\mathrm{p}} k_{\mathrm{p}}}{2}} \tag{42}$$

Description of the model room

For the purposes of this calculation model room with following dimensions and characteristics has been used: dimensions are 5 × 4 × 3 m where the external façade length is 5 m (room width), room length is 4 m and the room height from floor to ceiling is 3 m. The area of outer glass surface of DSF is 15 m^2, area of inner wall (opaque part of DSF) is 5 m^2 and area of inner window (transparent part of DSF) is 10 m^2. Single skin façade (SSF) presents inner module of DSF, inner wall (opaque part) and inner window (transparent part). Heat exchange is performed only over the outer façade (SSF or DSF) – all other walls are adiabatic. Width of DSF interspace (distance between two façades) is 0.6 m. This model room is placed under climatic conditions of Belgrade (45° north latitude). On figs. 5 and 6 summer and winter time regime of DSF are presented.

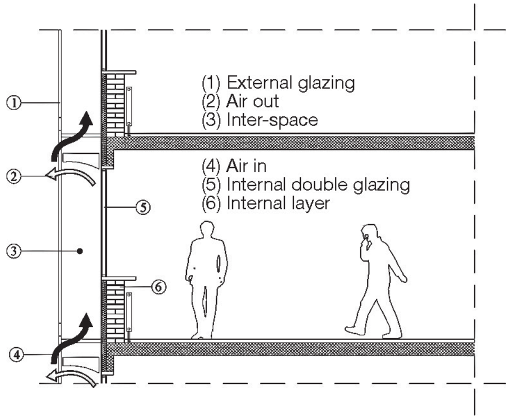

Figure 5. Summer regime of double skin façade

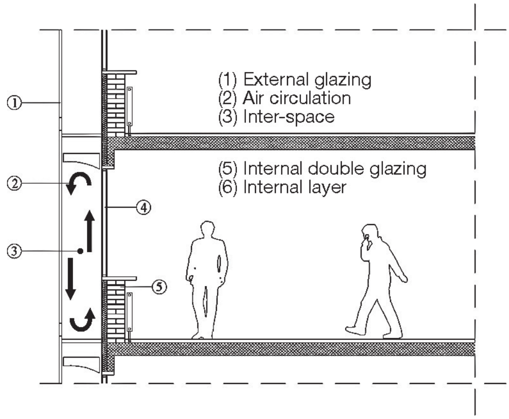

Figure 6. Winter regime of double skin façade

The overall coefficients of heat transfer taken into account are following: $U_w = 0.63$ W/m^{2}K (wall), $U_p = 4.0$ W/m^{2}K (window), $U_s = 5.8$ W/m^{2}K (outer glass). The assumed absorption coefficients are: 0.7 (wall), 0.06 (window), 0.16 (outer glass – ordinary glass) and 0.71 (outer glass – absorption glass). Reflection coefficients of the glass surfaces are: 0.19 (window), 0.09 (outer glass – ordinary glass), 0.04 (outer glass – absorption glass). Transmissivity of the glass surfaces are: 0.75 (window), 0.75 (outer glass – ordinary glass), 0.25 (outer glass – absorption glass).

For such defined room model, temperature calculation in interspace is made for all orientations. After the temperature calculation of interspace, heat gains and losses are compared for the module of room with DSF and SSF. For energy calculation interspace temperature is declared as outside temperature. Calculation is made using the classic method, for all orientations of the module, for one typical sunny and cloudy day in winter period (January), transitional period (April) and summer period (July). Analysis assumed that heating and air-conditioning system provide comfortable conditions for the time interval between 7:00 and 21:00 when the building is occupied. The results for the western orientation of the module room will be presented in this paper.

Calculation results and discussion

In the January interspace is treated as closed and temperatures are presented on figs. 7 and 8. On a sunny day, in the case of DSF whose outer glass is ordinary, the maximum temperature of the interspace is around 13.5 °C, and for DSF whose outer glass is absorption, the maximum temperature of the interspace is slightly above 14 °C. Temperatures in the interspace compared to the outside temperature at the time of its maximum – between 15:00 and 16:00 – is about 10 °C.

For the cloudy January day, and in the case when the outer glass is ordinary and also when it is absorption glass, the temperature in the interspace slightly increases at 15:00 and gets just above 10 °C. After that it starts to decline slightly. It should also be noted that in January, outdoor temperature on a cloudy day is slightly below –2 °C and the temperature in interspace is about 8 °C.

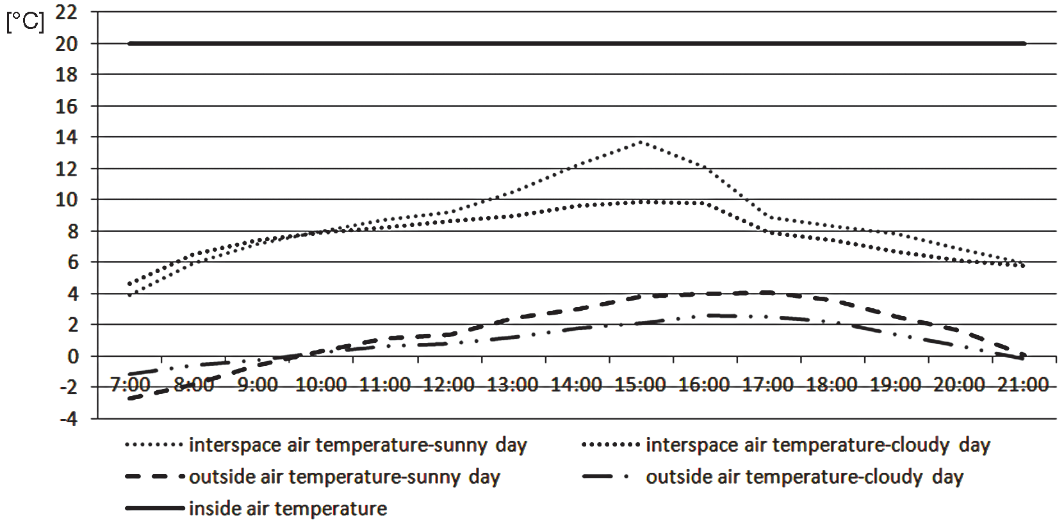

Figure 7. Results of temperatures in January, for west orientation, ordinary glass

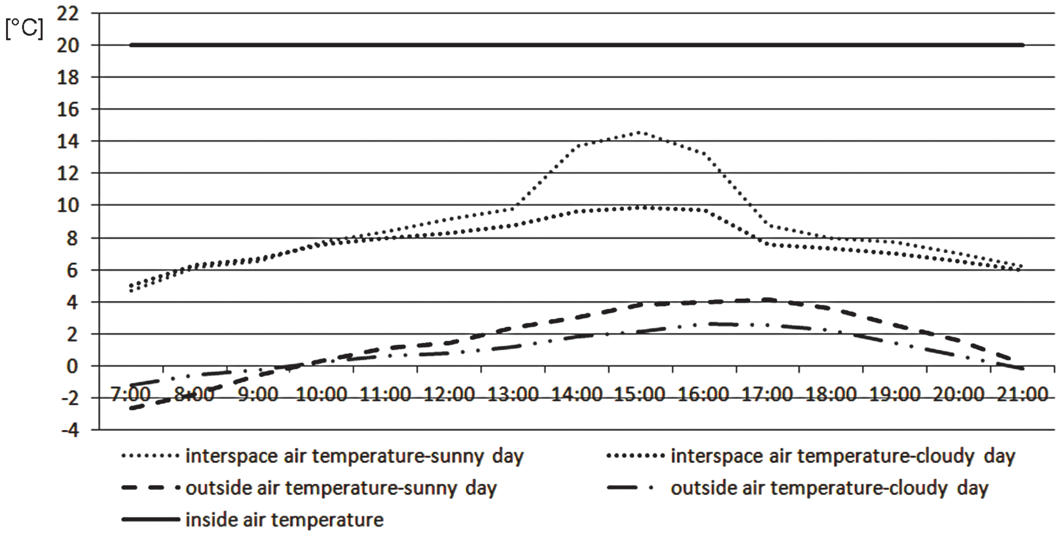

Figure 8. Results of temperatures in January, for west orientention, absorption glass

In the following hours of a sunny day (13:00-16:00) even heat gains in the DSF occur (slightly higher in the case of the DSF with ordinary outer glass in comparison to the DSF with outer absorption glass). Also, on a cloudy day (14:00-15:00) heat gains occur in the DSF with ordinary external glass.

April (as a transitional period of summer and winter) was discussed with and without air flow through the interspace. Temperature values for April, without air flow, are given in fig. 9 and 10. In the case of closed interspace in April, the following conclusions would be.

For a sunny day, we can conclude that the higher temperature in the interspace is achieved with a DSF (absorption glass) compared to the DSF (ordinary glass). For this western orientation, temperatures in the interspace of a DSF with ordinary and absorption glass exceed the internal temperature of 22 °C at 13:00 and remain above the internal temperature up to 18:00 when they fall below the internal temperature again. The maximum temperature of the interspace of DSF with ordinary glass reaches value of 26 °C. Temperature of the interspace of DSF with absorption glass reaches even the value of 28 °C.

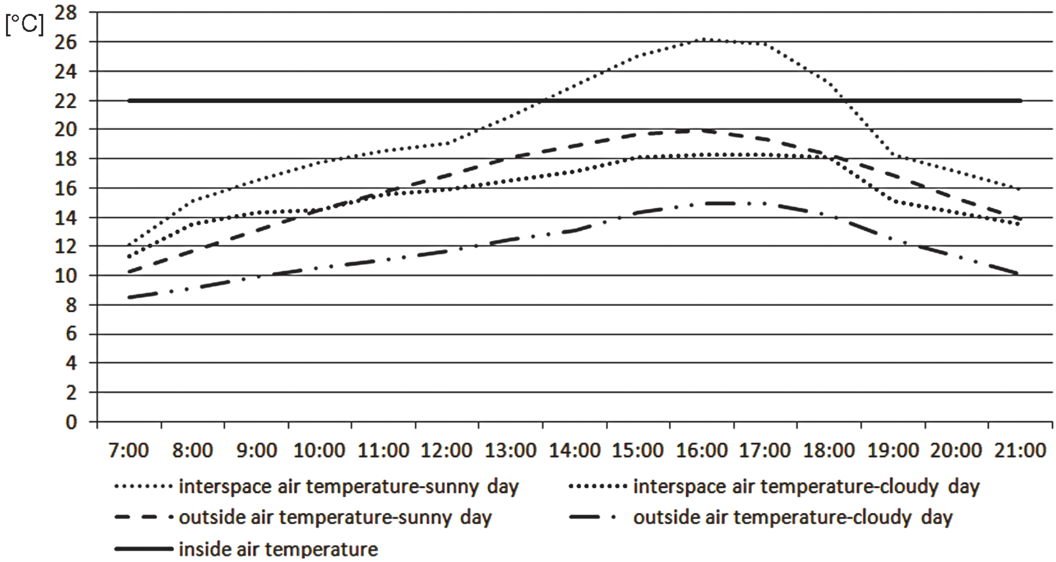

Figure 9. Results of temperatures in April, for west orientation, ordinary glass

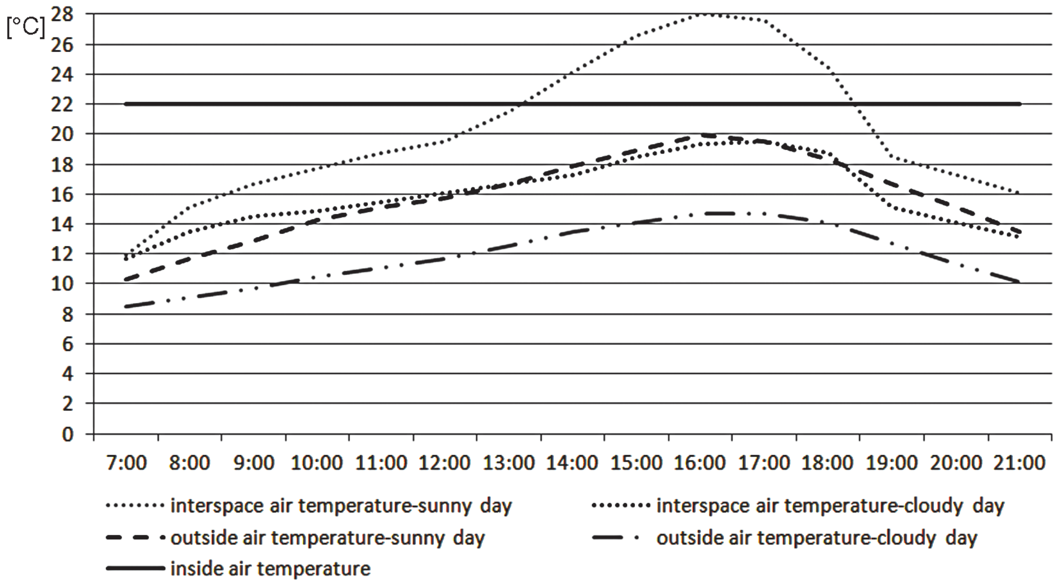

Figure 10. Results of temperatures in April, for west orientation, absorption glass

For the cloudy April day, interspace temperature rises to 19 °C in case of a DSF with ordinary glass and also with the absorption glass. The temperatures of the interspace in the case of a DSF with an absorption glass are slightly higher than in the case of the DSF whose external glass is ordinary. The temperatures do not exceed the internal temperature, but the temperatures in interspace are close to the 22 °C. At one point temperature even exceed the value of 18 °C, while the temperature of the interspace of the DSF with absorption glass reaches a value of nearly 20 °C.

Temperature values for April, with air flow, are given in figs. 11 and 12. In the case of open interspace in April, the following conclusions would be.

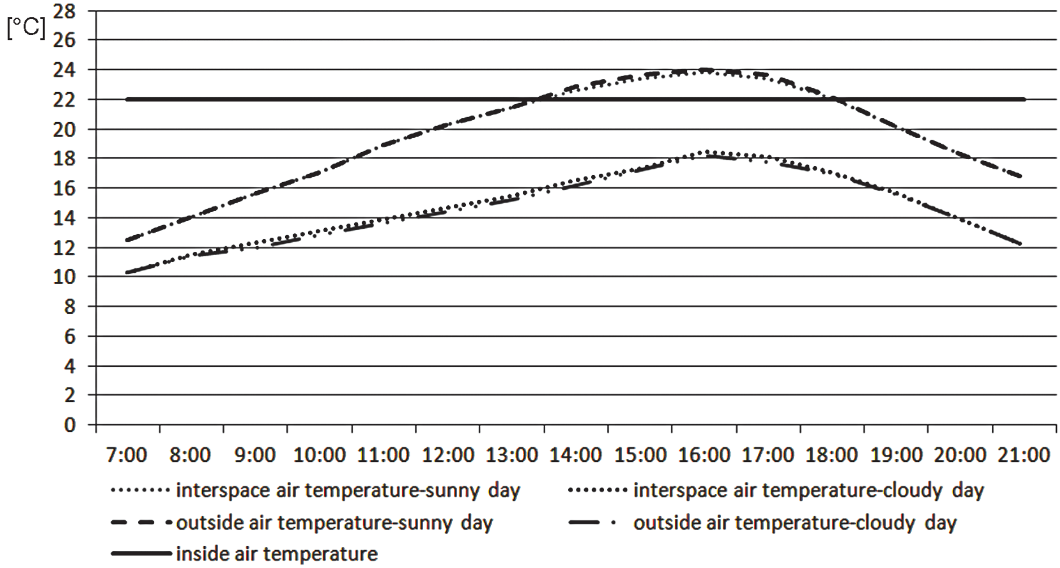

Figure 11. Results of temperatures in April, for west orientation, ordinary glass, v = 1 m/s

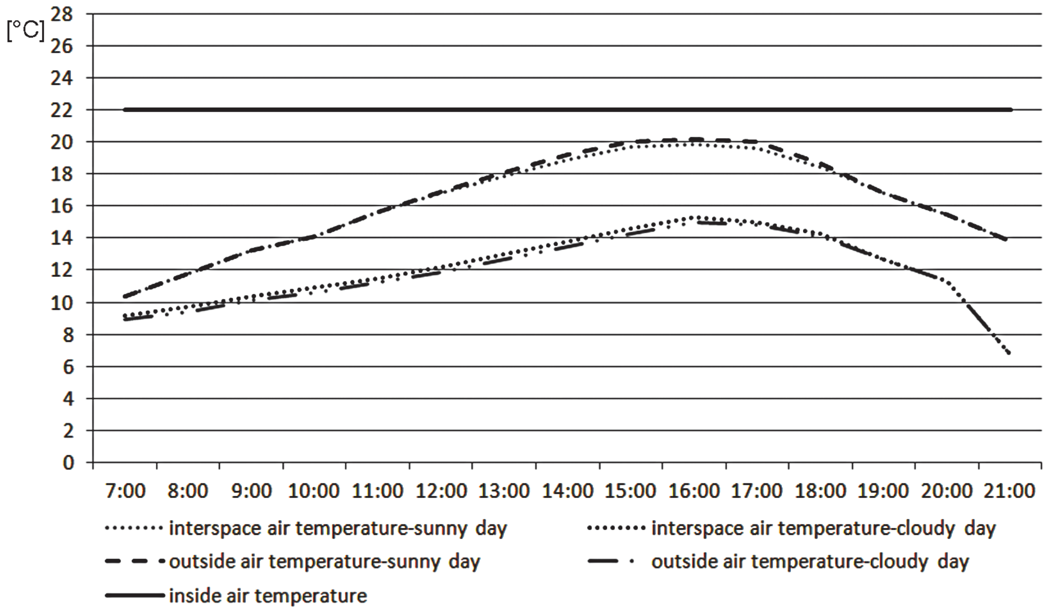

Figure 12. Results of temperatures in April, for west orientation, absorption glass, v = 1 m/s

As soon as the air flow through the interspace is enabled (either in the speed of 1, 2, or 3 m/s) temperature in the interspace, whether it is a DSF with ordinary or absorption glass, become very close to outside temperature. This paper presents the temperatures in interspace in April, when the air velocity through the interspace is 1 m/s.

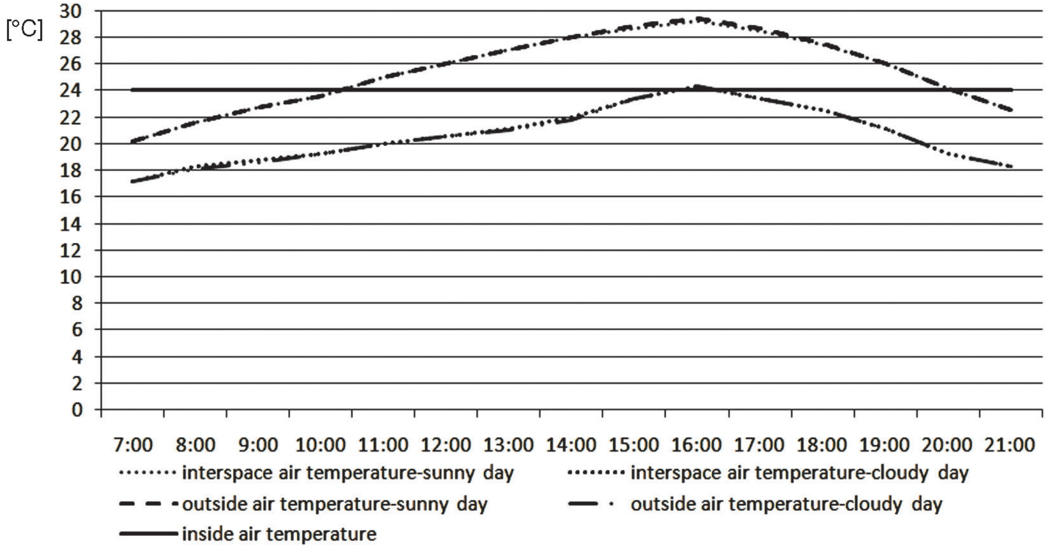

Figure 13. Results of temperatures in July, for west orientation, ordinary glass, *v* = 2 m/s

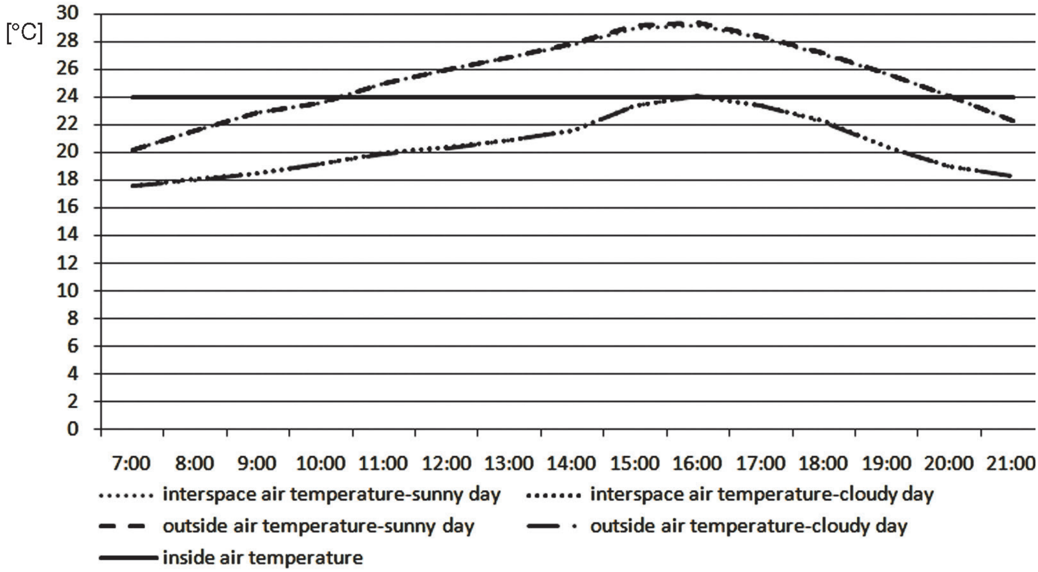

Figure 14. Results of temperatures in July, for west orientation, absorption glass, *v* = 2 m/s

For the module room, when the air flow through the interspace is not enabled, heat losses are relatively small and occur early in the morning and in late evening hours. Significant heat gains occur in the period 12:00-18:00, which is a consequence of higher intensity of solar radiation and temperature increase. Also, minimal heat gains occur even at 10:00 and 11:00. It should be notified that the maximum temperatures difference in April is smaller than in January.

In July the interspace is only treated as open because in the case of closed interspace in this month overheating would occur. In the case of air flow through the interspace in July (regardless of the speed flow 1, 2, or 3 m/s) temperatures in interspace are the same as the outside temperature. The paper presents the temperatures in interspace, in July when the air velocity through the interspace is 2 m/s (figs. 13 and 14).

As for the west oriented module room in July during the sunny and cloudy day at the air flow speed through the interspace of 2 m/s, almost throughout the whole air-conditioning period, we have heat gains.

Conclusions

This paper presents all the expressions necessary to calculate the interspace temperatures. These temperatures are the basis for presented simple calculation method for determination of energy need of DSF. It should be emphasized that this calculation method gives an approximate estimation, but offers sufficient accuracy of the thermal behavior and the energy performance of the DSF.

In January (fig. 15), west oriented DSF with ordinary and absorption glass for sunny and cloudy day has less heat losses by 40% compared to a SSF with the same orientation.

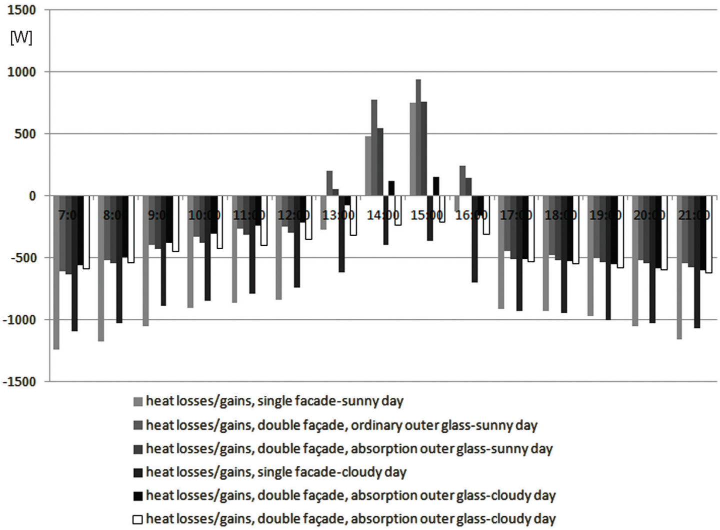

Figure 15. Results of heat losess/gains in January, for west oriented module

Very similar results are obtained for the other module room orientation. So if it's about a decision whether it is convenient to use a single or a double façade in winter, definitely the answer would be a double façade.

In April (figs. 17 and 18), in case of closed and in case of open interspace, DSF heat losses are smaller than the heat losses from SSF. Also, heat gains of DSF are smaller than the heat gain of SSF.

On fig. 16 heat losses and gains for July are illustrated. In July a DSF with absorption glass gives the least gains for sunny and cloudy day. For a sunny and cloudy day heat gains of DSF with ordinary glass are for 50% higher than the heat gains of DSF with absorption glass. For a sunny day, SSF with ordinary glass and DSF with ordinary glass create the highest heat gains.

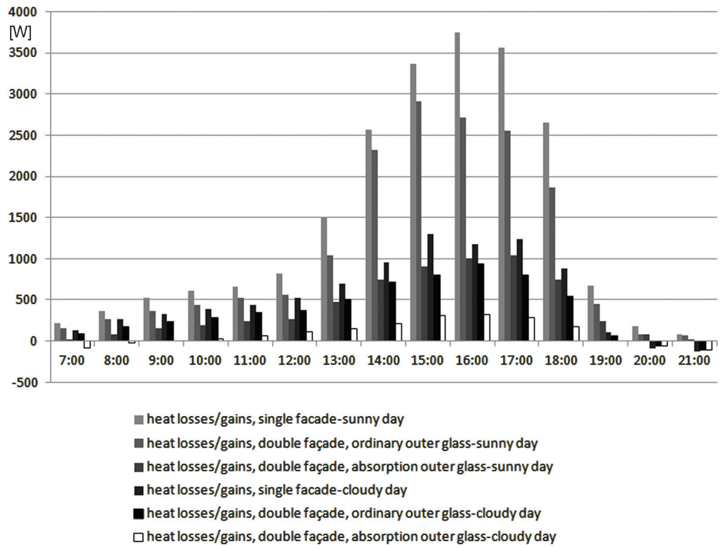

Figure 16. Results of heat losess/gains in July, for west oriented module, *v* = 2 m/s

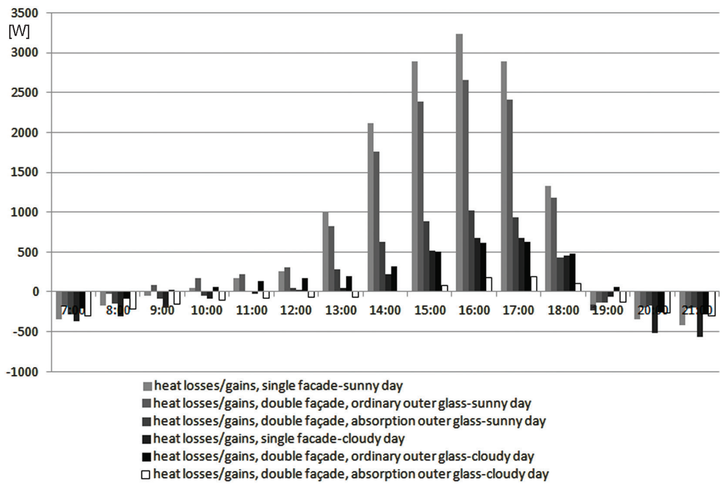

Figure 17. Result of heat losess/gains in April, for west oriented module, *v* = 0 m/s

Referring to the conclusions outlined above it can be observed that the DSF with absorption glass has least heat losses in winter, in April in the case of closed interspace (west and south side) it carries heat gains, while in July, this type of façade has the smallest heat gains.

As the DSF at one time in the past became an architectural trend and since there are still a lot of architectural solutions of buildings with DSF, it can be concluded that this solution, although expensive, can be designed so that the optimal interior comfort is provided. Closing an air interspace in the winter time can provide that heat losses of DSF are less than heat losses of SSF. As for the summer period, it is necessary to ventilate double façades interspace to ensure that the temperature in interspace is reduced to external temperature. Since the outer glass eliminates one portion of the solar radiation, in summer period is possible to have less heat gains with a DSF than with SSF. In the transitional period (spring and fall) it is necessary to measure and control the temperature in interspace, and in accordance with that to open and close interspace of DSF.

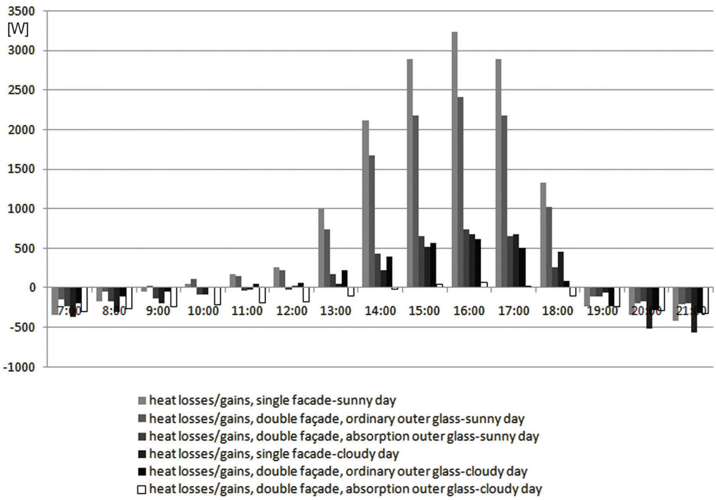

Figure 18. Result of heat losess/gains in April, for west oriented module, *v* = 1 m/s

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Nomenclature

a – absorption coefficient
C_c – black body radiation, (= 5.67 W/(m^{2}K^4)
c_p – specific heat of air (= 1005 J/(kgK)
D – distance between skins [m]
d – transmission factor
F – surface [m^2]
I – solar radiation intensity through outside facade [Wm^{-2}]
Q – heat flux [W]
t_1 – inlet air temperature [^{o}C]
t_2 – outlet air temperature [^{o}C]
t_i – inside design temperature [^{o}C]
t_m – temperature between two façade [^{o}C]
t_o – outside air temperature [^{o}C]
U – heat transfer coefficient [Wm^{-2}K^{-1}]
v – air velocity [ms^{-1}]

Greek symbols

α – coefficient of heat transfer by convection [Wm^{-2}K^{-1}]
β – temperature coefficient [K^3]
δ – wall thickness [m]
ε – surface coefficient of emission
λ – thermal conductivity of material [Wm^{-1}K^{-1}]
ρ – air dencity ρ = 1,25 kg/m^3
τ – time period
$\tau - 1$ – previous time period

Subscripts

dir – direct solar radiation
dif – diffuse solar radiation
ref – reflected solar radiation
p – window
I – interspace
s – glass of outside façade
w – wall
s_1 – glass surface toward outside
s_2 – glass surface toward interspace
p_1 – window surface toward interspace
p_2 – window surface toward inside building
w_1 – wall surface toward interspace
w_2 – wall surface toward inside building

Superscript

' – temperature calculated in previous calculation step

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