Double skin façades: definition of an ideal depth for cavities

F. Lembo[1], F.P.R. Marino[2] and G. Lacava

University of Basilicata – 10, Viale dell'Ateneo Lucano – Potenza

Email: [1] filiberto.lembo@unibas.it
[2] francesco.marino@unibas.it

Abstract:
This study defines a computational algorithm to calculate and evaluate termical performances of a double skin façade (DSF). The definition of the algorithm, expressed in the unit Simulink of Matlab, has been obtained through: the physical-mathematical treatment of the air stream model and the thermal model; the solution of differential equations through the routine writing in Simulink; the simulations to evaluate the constructive parameters of DSF.
Simulations have been made in order to evaluate the ideal depth of a single cell of DSF, establishing its dimensions, deflectors height, the position of Venetian curtains in the interstice and appraising the efficiency of pre-heating "η" in winter and the "g" solar factor in summer.
Simulations made possible to calculate an ideal depth of 20-30 cm for no-access cavities and to demonstrate that an ideal depth of 60 cm for accessible cavities.

Keywords:
DSF, simulations, Simulink, thermal and airflow model, movable blinds.

1. Introduction

Nowadays consciousness as for ambient pollution and demand for transparent façades carries out research towards the minimization of energy consumption and location of new solutions to increase thermal performances of buildings. These researches have introduced new concepts, among these double skin façades (DSF) assume a very important role.

1.1. Definition of double envelope system

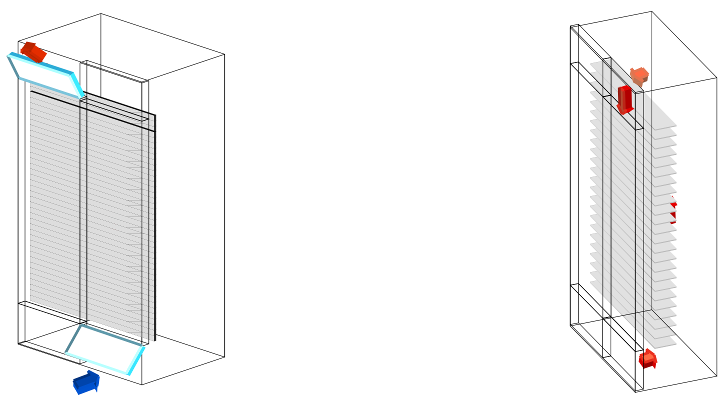
Two glass skins parted with an air corridor which acts as insulation against outer temperature, wind and noise form double skin façades. The DSF exploit passively solar energy realizing a splitting of vertical closing and creating an air gap between external and internal frontier; hot air tends to go up in this cavity, replacing cold air in its place trough a stack effect guaranteed for baffles positioned at the bottom and at the top of double skin façade (DSF).

Intervening with restrain on air displacements caused by a difference of temperature and/or pressure, it is possible to manage climatic conditions and façade's performances at any period of the year, reducing in this way the hardships due to solar irradiation in summer and thermal losses in winter.

DSF's working is different according to season:

- During summer period baffles are open so that the difference of temperature between air inside cavity and external one allows hot air to go up, as a result of its lower density, permitting cold air entry from basic baffle; Venetian blinds are closed to obstruct direct entry of sun radiation, heat accumulated between glass sheet and Venetian blinds is removed through natural night ventilation;

- During winter period baffles are closed and Venetian blinds are inclined at sixty degrees (60°) to permit the entry of sun radiation and consequently store of heat inside cavity. Moderate air speed and positive thermal gradients inside cavity allow air to exchange heat with internal surfaces realizing a raise in temperature near internal windows.



(a) (b)

Fig. 1.1. Double skin façade's working

1.2. Typologies of double skin façades

Double skin façade's typologies are different according to cavity's physical characteristics and they can be classified into four systems:

Full-surface systems where outside skin is completely parted from building not being either horizontal or vertical partitions between two skins.

The cavity develops along all envelope surface and cavity's ventilation is guaranteed by baffles placed at the bottom and at the top of building (fig.1.3.a);

Horizontal-channel systems where is generated a longitudinal channel cavity corresponding to building's width and gap's height; every ditch module has got a baffle for air input /output (fig.1.3.b);

Cell systems with vertical well where is generated an alternation of modules up to gap and a vertical duct which extends in height along more floors. Every module is provided with baffles for air input and with lateral openings for air ejection into channel, which will provide for air escape.(fig.1.3.c);

Single cells systems are constituted of aggregation of glazed cells with vertical partitions in correspondence with every stanchion and horizontal baffles in correspondence with ceilings. Every cell is endowed with own baffles for air input/output with independent cavities (figure 1.3.d);

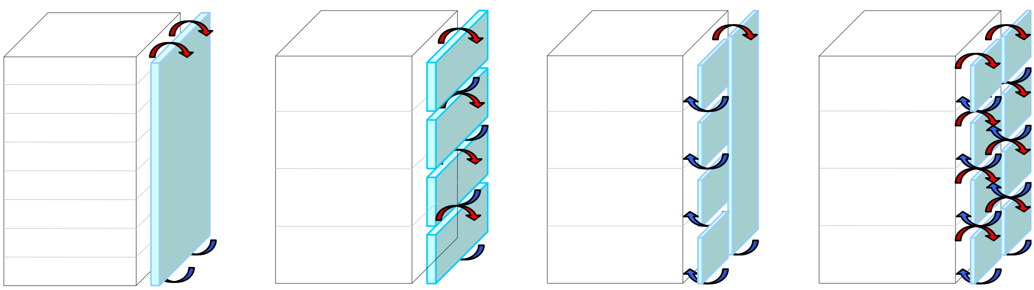


Fig. 1.2. Typologies of double skin façades.

2. Physical-mathematical modelling

Thermal performances of a double skin façade (DSF) have been translated by means of physical-mathematical modelling constituted of interaction between two subsystems:

- Airflow model;
- Thermal model;

2.1. Airflow model

Ventilation is very important in everyday life because a bad air quality indoor can reduce people comfort and their working productivity; for this reason some studies about airflow generated inside double skin cavity (DSF) have been carried out, to understand the action's mechanism and to improve its effects.

Airflow overcomes resistances of input baffle inside cavity and inside grids set in correspondence with every floor (in DSF case extended for more floors) as a result of following guide forces:

1. *Stack effect or buoyancy* (flotation) is generated by a difference of temperature between external air and internal cavity's one; the latter temperature increases because of sun radiation's absorption from Venetian blinds positioned between two skins. Lapse rate determines a difference of pressure such as to trigger an airflow in vertical direction bottom-up if Tout < Tin or down from above if Tout > Tin;
2. Wind effect generates some differences of pressure on building façade.

To value flow inside a double skin façade (DSF) some simplifications are necessary because of dynamic complexities; in figure 2.1. an exemplifying scheme is shown about airflow which passes trough a double skin façade (DSF):

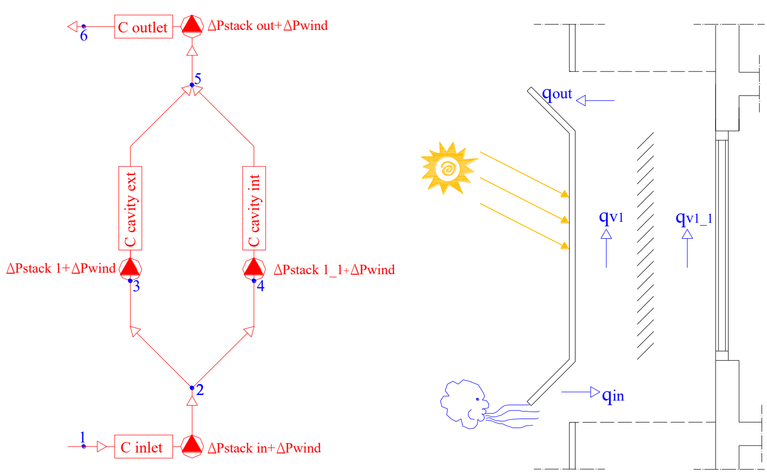


Fig. 2.1. Airflow model with close window

Airflow model is composed of following generators:

- Pressure generator;
- Airflow generator;
- *Stack* generator;

- *Wind* generator;

2.2. Pressure generator

Inputs of this generator are the flows calculated by airflow generator, outputs are input and outlet pressures, these pressures have been valued making use of theory of control volumes based on F. Di Maio's studies to Delft University. Making use of appropriate mathematical developments and considering that these pressures are time functions we arrive at final formulas for variation of pressure, input and outlet according to professor Van Paassen's studies (TU Delft).

$$\frac{d\Delta P_2}{dt} = \frac{P_2}{V} \cdot \left(q_{vi} - q_{vu}\right) = K_1 \cdot \left(q_{in} - q_{v1} - q_{v1\_1}\right) \tag{2.1}$$

$$\frac{d\Delta P_5}{dt} = \frac{P_5}{V} \cdot \left(q_{vi} - q_{vu}\right) = K_2 \cdot \left(q_{v1} + q_{v1\_1} - q_{out}\right) \tag{2.2}$$

2.3. Airflow generator

Inputs of this generator are absolute pressure, differences of pressure due to *stack* and *wind* effect and admittance coefficients C. Outputs are entry flows, inside two cavities and outlet flows. Making use of Bernoulli's Theorem and considering load losses, the formula used to calculate loads is the following:

$$q_{i-j} = C_{i-j} \cdot \sqrt{\Delta P_{i-j}} \tag{2.3}$$

$$C_{i-j} = \sqrt{\frac{2 \cdot A_{i\_j}^2}{\xi_{i\_j} \cdot \rho_{air}}} \tag{2.4}$$

Total difference of pressure to calculate loads is constituted of the following terms:

$$\Delta P_{i\_j} = P_i - P_j + \Delta P_{stacki\_j} + \Delta P_{wind\,i\_j} \tag{2.5}$$

Where:

$P_i - P_j$ Difference of pressure among the network nodes;

ΔP_{stacki_j} Difference of pressure due to *stack* generator;

$\Delta P_{wind\,i\_j}$ Difference of pressure due to *wind* generator.

2.4. Stack generator

When air movement is due to the difference of temperature between the indoor and outdoor, the flow of air is in the vertical direction and is along the path of least resistance. The difference of temperature causes density differentials, and therefore pressure differences, that drive the air to move.

Difference of pressure due to *stack* effect has been valued, according to Liddament's studies integrating Chauchy's indefinite balance equations and arriving to following formula:

$$\Delta P_{stack} = P_{out} - P_{in} = \rho_{out} \cdot g \cdot (h_{lpn} - h) \cdot \left(\frac{T_{in} - T_{out}}{T_{in}} \right) \qquad (2.6)$$

2.5. Wind generator

When air flow is due to wind, air enters through openings in the windward walls, and leaves through openings in the leeward walls. Wind pressures are generally high/positive on the windward side of a building and low/negative on the leeward side.

Distribution of static pressure generated by wind on DSF's surface has been determined using Swami's formula:

$$\Delta P_{wind} = P_{w1} - P_{w2} = \left(C_{p1} - C_{p2} \right) \cdot \frac{1}{2} \cdot \rho \cdot v_w^2 \qquad (2.7)$$

In case of single cell DSF previous formula becomes:

$$\Delta P_{wind} = C_{p(in-out)} \cdot \frac{1}{2} \cdot \rho_{out} \cdot v^2{}_{w,h} \qquad (2.8)$$

$$v_{w,h} = v_{w,met} \cdot \alpha \cdot \left(\frac{H}{H_{met}} \right)^{\gamma} \qquad (2.9)$$

2.6. Thermal Model

This model input are:

- External temperature θ_0;
- Comfort internal temperature θ_{room};
- Input temperatures inside two cavities θ_{0v1} e θ_{0v2};
- Heat exchange coefficients for convection, convection and conduction, and for radiation;
- Airflows deduced from airflow model;
- Values for sun radiation and wind speed.

Outputs are the temperatures on external glass θ_1, inside two cavities θ_{c1} e θ_{c2}, on Venetian blinds θ_2, on internal double glazing θ_3, θ_4.

Thermal network, shown in figure 2.2, highlights thermal balances in every Double Skin Façade (DSF) node, which, in a dynamic system as double skin façade, can be described in non-stationary conditions resorting to differential equation's solution.

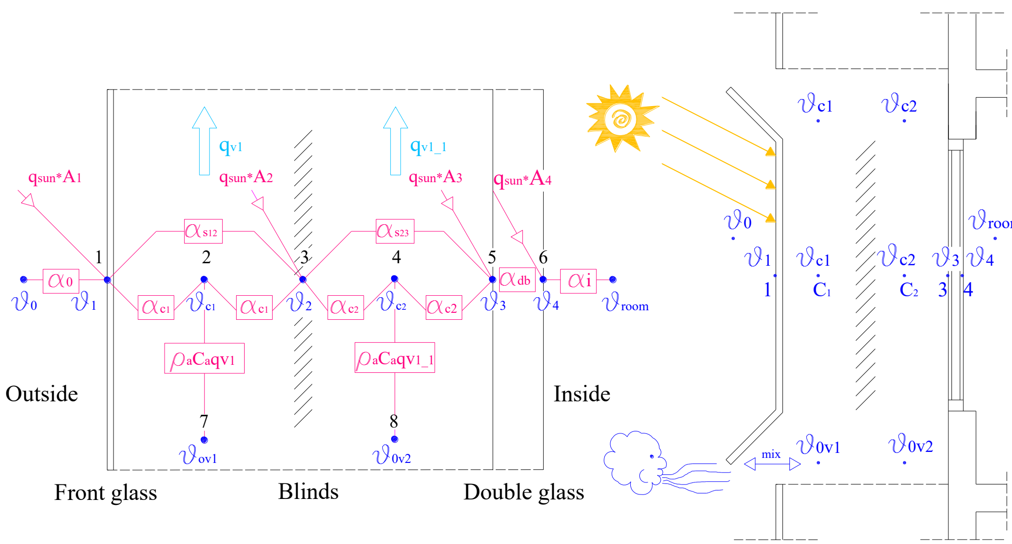


Fig. 2.2. Thermal model network

For energetic balance formulas concerning thermal exchanges are used and trough the first law of Thermodynamics and appropriate mathematical developments, we arrive to the formula to calculate thermal equations in non-stationary conditions:

$$q^{*} \cdot A = q = c \cdot \rho \cdot \frac{d\theta}{dt} \cdot V \qquad (2.10)$$

Making explicit the equation 2.10 we can write six differential equations for every node of thermal network. Their solution will allow to calculate six unknown temperatures: on external glass, inside two cavities, on Venetian blinds and on internal double glazing.

$$\frac{d\vartheta_1}{dt} = \left[\frac{\alpha_0 \cdot (\theta_0 - \vartheta_1) + \alpha_{c1} \cdot (\theta_{c1} - \theta_1) + \alpha_{s12} \cdot (\vartheta_2 - \vartheta_1) + A_1 \cdot q_{sun}}{C_g \cdot \rho_g \cdot A_g \cdot d_g} \right] \cdot A \qquad (2.11)$$

$$\frac{d\vartheta_{c1}}{dt} = \frac{\alpha_{c1} \cdot (\theta_1 - \vartheta_{c1}) \cdot A + \alpha_{c1} \cdot (\theta_2 - \theta_{c1}) \cdot A + \rho_a \cdot C_a \cdot q_{v1} \cdot (\vartheta_{0v1} - \vartheta_{c1})}{C_a \cdot \rho_a \cdot A_{c1} \cdot d_{c1}} \qquad (2.12)$$

$$\frac{d\vartheta_2}{dt} = \left[\frac{\alpha_{c1} \cdot (\theta_{c1} - \vartheta_2) + \alpha_{c2} \cdot (\theta_{c2} - \theta_2) + \alpha_{s12} \cdot (\vartheta_1 - \vartheta_2) + \alpha_{s23} \cdot (\vartheta_3 - \vartheta_2) + A_2 \cdot q_{sun}}{C_b \cdot \rho_b \cdot A_b \cdot d_b} \right] \cdot A \qquad (2.13)$$

$$\frac{d\vartheta_{c2}}{dt} = \left[\frac{\alpha_{c2} \cdot (\theta_2 - \vartheta_{c2}) \cdot A + \alpha_{c2} \cdot (\theta_3 - \theta_{c2}) \cdot A + \rho_a \cdot C_a \cdot q_{v1\_1} \cdot (\theta_{ov2} - \vartheta_{c2})}{C_a \cdot \rho_a \cdot A_{c2} \cdot d_{c2}} \right] \qquad (2.14)$$

$$\frac{d\vartheta_3}{dt} = \left[\frac{\alpha_{c2} \cdot (\theta_{c2} - \vartheta_3) + \alpha_{s23} \cdot (\theta_2 - \theta_3) + \alpha_{db} \cdot (\vartheta_4 - \vartheta_3) + A_3 \cdot q_{sun}}{C_g \cdot \rho_g \cdot A_{g1} \cdot d_{g1}} \right] \cdot A \qquad (2.15)$$

$$\frac{d\vartheta_4}{dt} = \left[\frac{\alpha_i \cdot (\theta_{room} - \vartheta_4) + \alpha_{db} \cdot (\vartheta_3 - \vartheta_4) + A_4 \cdot q_{sun}}{C_g \cdot \rho_g \cdot A_{g2} \cdot d_{g2}} \right] \cdot A \qquad (2.16)$$

3. Simulations and Results

Practical application of calculation algorithm, obtained through characterization of airflow and thermal model with relating differential equations which characterize them, has been effected for the typology of single cell DSF.

The simulations carried out have permitted to define ideal DSF's depth fixing cell dimensions, baffles height and determining efficiency factors of a DSF, distinguishable for season:

- for winter season we calculate efficiency of preheating η, which represents capacity of DSF to preheat air inside cavity:

$$\eta = \frac{\theta_{c2} - \theta_0}{\theta_{room} - \theta_0} \tag{3.1}$$

- for summer season we value solar factor g, which represents heat quantity which arrives inside building unit [1]:

$$g = \frac{DT \cdot q_{sun} + \alpha_i \cdot (\theta_{surface} - \theta_{inside})}{q_{sun}} \tag{3.2}$$

Cavity's depth has been chosen comparing all simulations for season and choosing the DSF which shows the lowest value of solar factor g and the highest efficiency value of preheating η.

The simulations carried out, getting to vary DSF's depth from 10 to 100 cm have allowed define the following ranges:

- temperatures range on external glass, inside external cavity, on Venetian blinds, inside internal cavity, on external and internal double glazing;
- range of input/ output airflows, inside external cavity, inside internal cavity, and trough internal window;
- air speeds range inside external and internal cavity;
- range of input and outlet pressures;
- range of solar factor g during summer period;
- efficiency range of preheating η during winter period;

Summary results of these simulations can be described during summer period by range of solar factor g in function of depth as shown in graphic 3.1.a, while during winter period the results of simulations are described by efficiency range in function of depth as shown in figure 3.1.b. As it is pointed out by previous graphics, the lowest values of factor g take place in correspondence of the following cavities:

- not accessible cavities: 20 and 30 cm;
- accessible cavities: 60 cm;

During winter period the highest efficiency values η take place in correspondence of the same depths:

- not accessible cavities: 20 and 30 cm;
- accessible cavities: 60 cm;

Previous observations are deduced taking into account the results obtained for summer period too; therefore a depth equal to 10 cm has been rejected because even if it shows the highest efficiency value, it doesn't appear suitable for summer period. Figure 3.1 a) and b) show an improvement of 2.3% and 1.5%, respectively. Even if this improvement is small it is really and isn't due to the different approximations used in the model presented.

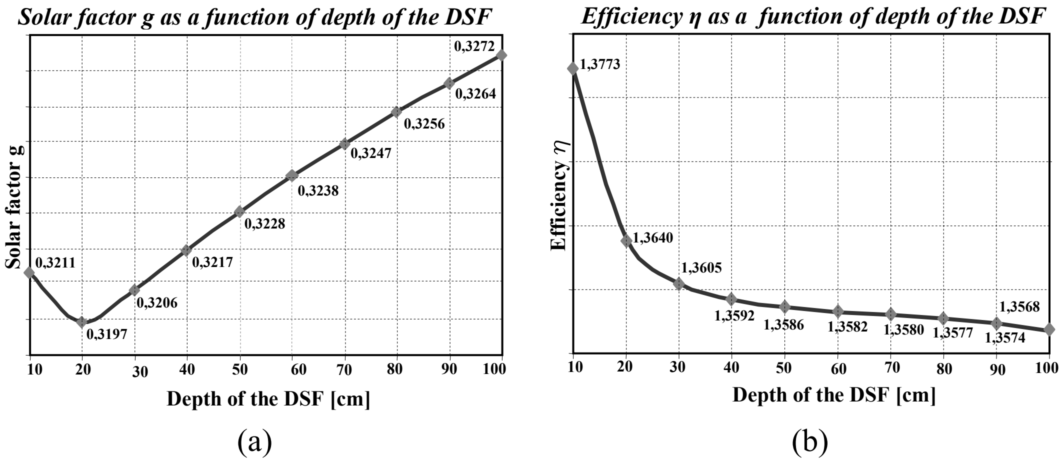


Fig. 3.1. Results of simulations

3.1. Simulations varying Venetian blinds position

To improve farther performances of a single cell DSF we have carried out simulations varying Venetian blinds position inside cavity according to considered season; Venetian blinds optimal position, during summer period is near to the outside skin so that the narrowest external cavity results more overheated, while internal one is larger, fresher and more ventilated. In fact, moving the Venetian blinds from inside to outside skin, with a step of 5 cm, we can observe a reduction of solar factor "***g***", as shown in the following graphic.

Furthermore, the fact that the Venetian blinds are near the outside skin makes it possible a better ventilation of internal cavity, a decrease of temperature and a minor risk of internal over-temperature. In fact, comparing these last simulations with the ones where Venetian blinds are in the middle of the cavity, we note the following advantages:

- a decrease of temperature in the internal cavity;
- an increase of air stream in the internal cavity;
- a quicker circulation of air in the internal cavity.

During winter period Venetian blinds position is near to inside skin so that external cavity, larger, is more overheated from sun radiation with a larger heat storage to transfer inside building unit; in fact carrying out the simulations varying Venetian blinds position from outside to inside skin with a step of 5 cm an increase in heating efficiency takes place, as shown straight. In winter placing Venetian blinds near the inside skin produce also an increase of temperature in internal and external cavity.

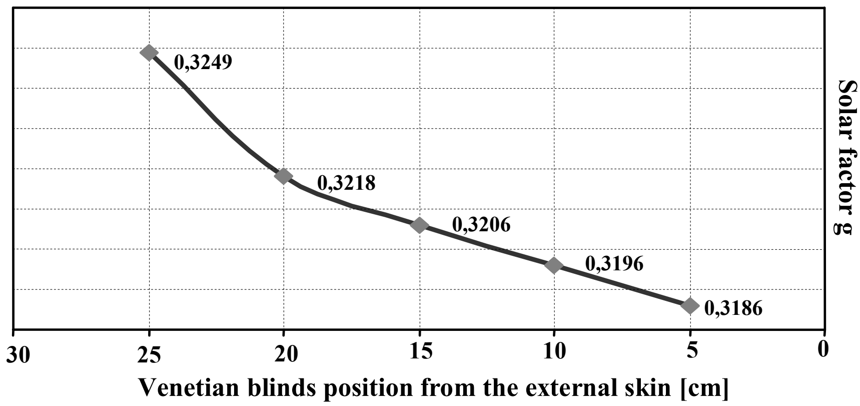


Fig. 3.2. Solar factor *g* as a function of the Venetian

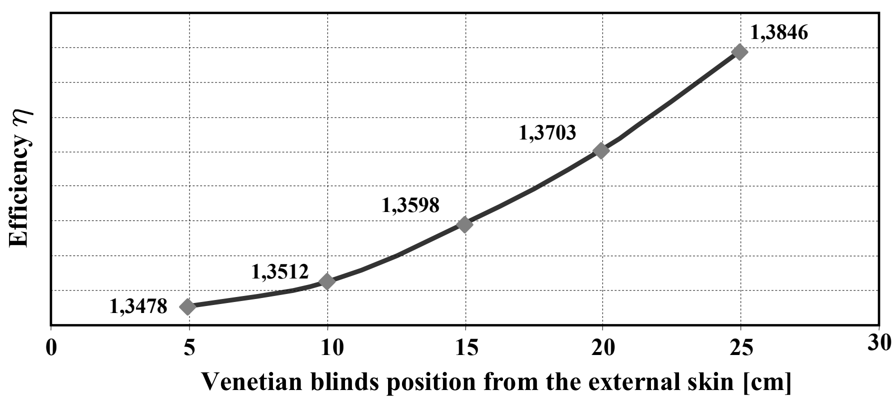


Fig. 3.3. Efficiency η as a function of the Venetian blinds position

3.2. Simulations to value baffle height

Fixing dimensions of a DSF, its depth, Venetian blinds position and getting to vary baffles height simulations to establish its ideal height have been carried out.

Baffles heights considered for simulations are 15, 30 and 45 cm and their results in terms of medium temperature inside cavity, maximum loading capacity, air speed and solar factor g, are reported straight.

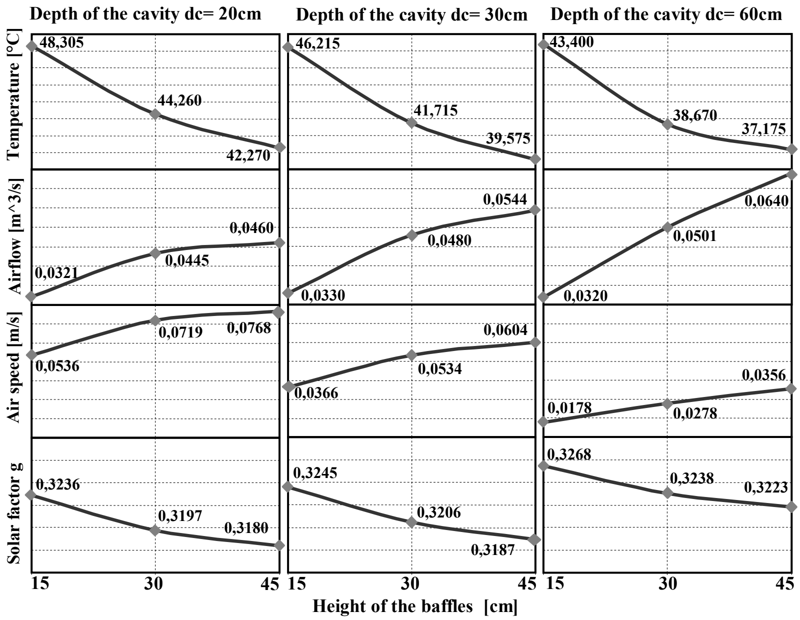


Fig. 3.4. Results to value baffle height

The last simulations carried out allow to affirm that depths chosen for cavities and the established baffles height satisfy requirements of minimum capacity equal to 0,011 m^3/s per head provided for UNI 10339 Law (National Association for Industrial Uniformity) and for ASRAHE Standard 62 (American Society of heating, Refrigerating and Air conditioning Engineers).

In fact, if we consider a typical office of our case study (Print Media Academy), each DSF module has to provide a circulation of air of 0,044 m^3/s for four persons (4x0,011 m^3/s).

From previous graphic we observe that the most suitable values take place in correspondence of a baffle high 30 cm, rejecting the baffle high 15 cm because of an insufficient air delivery according to requested values and rejecting the baffle high 45 cm because it shows higher values of air speed which can reduce acoustic insulation.

All these considerations show that double skin façades (DSF), if are projected correctly, safeguard energetic performances reducing thermal summer increase and improving winter insulation.

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NOMENCLATURE

q_{vi}	- Airflow entering the control volume [m^3/s];
q_{vu}	- Airflow leaving the control volume [m^3/s];
ΔP_2, ΔP_5	- Pressure difference between the atmosphere and façade (2 and 5) [Pa];
P_2	- Pressure in point 2 flow model [Pa];
P_5	- Pressure in point 5 flow model [Pa];
$K_{1,2}$	- Constant [$Kg*m^{-4}*s^{-2}$];
q_{i-j}	- Airflow through the part of the double skin façade [m^3/s];
ΔP_{i-j}	- Pressure difference for the specified part of the model [Pa];
C_{i-j}	- Admittance of a specified part of the model [-];
A_{i-j}	- Area of the cross section of the inlet, cavity, outlet [m^2];
ξ_{i-j}	- Air resistance of the specified material [-];
ρ_i	- Density (i=**a**ir, **g**lass, **b**linds, **o**ut) [Kg/m^3];
q_{in}	- Flow through the inlet [m^3/s];
q_v	- Flow through the external cavity [m^3/s];
q_{v1-1}	- Flow through the internal cavity [m^3/s];
q_{out}	- Flow through the outlet [m^3/s];
P_{in}	- Inside pressure [Pa];
P_{out}	- Outside pressure [Pa];
g	- Acceleration due to gravity [m/s^2];
h	- Height of observation [m];
h_{lpn}	- Height of neutral pressure level [m];

T_{out} - Outside temperature [°K];
T_{in} - Inside temperature [°K];
P_{w1} - Static pressure of the wind to the base of the building [Pa];
P_{w2} - Static pressure of the wind to the top of the building [Pa];
v_w - Average wind speed [m/s];
C_{p1}, C_{p2} - Local wind pressure coefficient for building surface [-];
$C_{p(in-out)}$ - Difference between outdoor and indoor pressure coefficients [-];
$v_{w,h}$ - Wind speed to a height specifies [m/s];
$v_{w,met}$ - Wind speed from the metereological station tower [m/s];
H - Height of observation [m];
H_{met} - Meteorological station tower height [m];
α - Terrain dependent parameter [-];
α_0 - Convective heat transfer coefficient from the outside glass panel to the air [W/m^2*K];
α_{c1} - Convective heat transfer coefficient in the cavity nr.1 [W/m^2*K];
α_{c2} - Convective heat transfer coefficient in the cavity nr.2 [W/m^2*K];
α_{s12}, α_{s23} - Radiant heat transfer coefficient in the cavity [W/m^2*K];
α_{db} - Heat transfer coefficient(conduction, radiation and convection) [W/m^2*K];
α_i - Heat transfer coefficient from the inside window to the room air [W/m^2*K];
q_{sun} - Solar radiation [W/m^2];
A - Surface perpendicular to energetic flow [m^2];
C_k - Specific heat of the given layer of the façade (k=**g**lass, **a**ir, **b**linds) [J/Kg*K];
A_j - Part of solar radiation absorbed (j=1, 2, 3, 4);
d_k - Thickness of each layer (k=external **g**lass, **c**avity nr.**1**, **b**linds, **c**avity nr.**2**, **g**lass nr.**1** and nr.**2** of double pane) [m];
A_k - Surface of each layer (k=external **g**lass, cavity nr.**1**, **b**linds, **c**avity nr.**2**, **g**lass nr.**1** and nr.**2** of double pane) [m^2];
DT - Ratio of solar radiation directly transferred to the room [-];
$\theta_{surface}$ - Temperature of the inner surface of the façade [°K];
θ_{inside} - Temperature of the inside air [°K];
θ_{c1} - Temperature in the cavity nr.1 [°K];
θ_{c2} - Temperature in the cavity nr.2 [°K];
θ_{room} - Temperature in the room [°K];
θ_0 - Temperature outside [°K];
θ_1 - Temperature of the external glass [°K];
θ_2 - Temperature of the blinds [°K];
θ_3 - Temperature of the double pane glass (cavity side) [°K];
θ_4 - Temperature of the double pane glass (room side) [°K];
θ_{0v1} - Temperature of the air in cavity nr.1 after mixing [°K];
θ_{0v2} - Temperature of the air in cavity nr.2 after mixing [°K];