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INFLUENCE OF THE COATINGS ON THE THERMAL PERFORMANCE OF INSULATING GLASS UNITS

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ВЛИЯНИЕ НА ПОКРИТИЯТА ВЪРХУ ТОПЛИННИТЕ ХАРАКТЕРИСТИКИ НА СТЪКЛОПАКЕТИ

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Abstract: A mathematical model of 3D conjugated heat transfer at insulating glass units (IGU) is composed and applied for numerical calculations by computational fluid dynamic technique with ANSYS. Temperature field in glass panes and temperature, pressure and velocity fields in gas space are calculated for several variants of flat double glazed IGU: uncoated glass panes; low emissivity coating on inner pane and uncoated outer glass pane, and solar control coating on outer pane and uncoated inner glass pane. The numerical calculations are made for winter and spring conditions in order to validate the models and to analyze the coatings influence on thermal behaviour of IGU.

Keywords: IGU, coatings, CFD calculations, heat transfer, free convection

1. INTRODUCTION

The thermal performances of insulating glass units (IGU) with different construction and different coatings on the glass panes are important for the building energy efficiency and for the mechanical behavior of the glass. The thermal loads on IGU cause thermal stresses in glass elements and contribute to glass deflection due to pressure differences [1] between the pressure in the gas cavity and the environmental one:

$$\Delta p_{is} = C_1 . \Delta T + C_2 . \Delta H + \Delta p_{met}, \tag{1}$$

where C_1=0,34 kPa/K and C_2=0,012 kPa/m.

ΔT in (1) is a temperature change of the gas cavity according the temperature during the containment of IGU.

The methods for one and two directional calculation of the heat transfer at IGU, based on energy balance, are well known and standardized [2, 3]. Numerical investigations of 1D and 2D temperature fields in IGU with or without coatings have been published [4, 5]. But they don't reflect fully influence of the geometrical shapes, elements and edge system on the radiation heat transfer and free convection in the gas cavity.

The aim of the presented investigation is to calculate three dimensional temperature fields in IGU units with different coatings and geometries, and to analyze the influence of the temperature distribution on thermal performance and mechanical behavior of the units. The aim can be achieved by mathematical modeling and numerical simulations of the conjugate heat transfer in IGU.

In the present paper mathematical models and results of computer simulations are presented for a flat rectangular IGU.

2. SIMULATION MODELLING USING FINITE ELEMENT TECHNIQUE IN ANSYS/ FLOTRAN.

2.1 System of equations

The mathematical model of 3D conjugated heat transfer at flat IGU is defined by the below equations in Cartesian coordinate system [6].

Fluid domain (gas cavity):

- Continuity equation.
- Momentum equations (on x, y, z direction) for a turbulent case.
- Uncompressible energy equation.
- Two-equations standard turbulent k-ε model with constants: C_μ= 0.09; C_1 = 1.44; C_2 = 1.92; σ_k = 1; σ_ε=1.3; σ_t=1, C_3=1; C_4=0 and β=0.

The boundary layer parameters can be determined in term of Van Driest conductivity model [6] with constants A=26, E=9, χ=0,4.

Solid domain (glass panes, edge system and frame):

- Uncompressible energy equation at Vx=Vy=Vz=0:

$$\rho . c . \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \dot{q}_v . \tag{2}$$

The volumetric heat generation rate can be used to model the total flux of solar radiation S_i, absorbed at the i^{th} glazing layer:

(3) $S_i = A_i.I_s$

(4) $\dot{q}_{vi} = \dfrac{S_i}{l_i}$

For double-glazed IGU:

(5) $\dot{q}_{v1} = \dfrac{S_1}{l_1} = \dfrac{\hat{A}_1.I_s}{l_1}$

(6) $\dot{q}_{v2} = \dfrac{S_2}{l_2} = \dfrac{\hat{A}_2.I_s}{l_2}$

The solar irradiation I_s, including direct and diffuse solar incidence, can be taken from the meteorological data according the glass pane orientation [7] or can be calculate by:

(7) $I_s = I_D + \left(\dfrac{1+\cos S}{2}\right)I_d + a\left(\dfrac{1-\cos S}{2}\right).(I\,\mathrm{sinh} + I_d)$

Direct and diffuse solar radiations are given by the expressions [8]:

(8) $I_D = I\cos q = I_{sc}.C.A.\exp(-B/\mathrm{sinh}).\cos q$

and

(9) $I_d = I_{sc}.C.\sin(h.T_d)$

where

(10) $T_d = 0{,}271 - 0{,}2939.A.\exp(-B/\mathrm{sinh})$,

I_{sc} is the solar constant: I_{sc}=1380 W/m^2. A and B are coefficients according the atmospheric air pollution.

The total absorptance of i^th glass pane $\hat{A}_i$ is calculated by the steps, given bellow or can be taken according producers of structural glass and IGU [9].

The solar irradiance, absorbed by the glass panes is emitted predominantly in infrared spectrum, outside the solar one. The infrared radiation exchange between the gas cavity walls (internal glass pane walls and spacer walls) can be modelled by ***Radiosity solver method*** [6]. It involves computing of the view factor for the radiating surfaces (finite elements surfaces) in enclosures using the hemi cube method and solving the radiosity matrix coupled with the conduction problem. For grey diffuse radiation between N surfaces:

(11) $\sum_{i=1}^{N}\left(\dfrac{d_{ji}}{e_i} - F_{ji}\dfrac{1-e_i}{e_i}\right)\dfrac{1}{A_i}\dot{Q}_i = \sum_{i=1}^{N}\left(d_{ji} - F_{ji}\right)s\,T_i^4$

2.2. Conditions and loads.

A) Geometrical model

The geometrical model is consisted of glass panes, gas space and edge system. If the IGU is line fixed the geometrical model must include the frame of the window to reflect the frame influence on the heat transfer. All parts of the model share common faces.

In that paper the geometrical model covers the transparent part of the IGU, accepting that they are point fixing and the influence of the edge system on the heat transfer is not significant. That influence increases with decreasing of sizes of IGU.

The main vertical surfaces of the IGU are numbered (Fig. 1) according the standards [2].

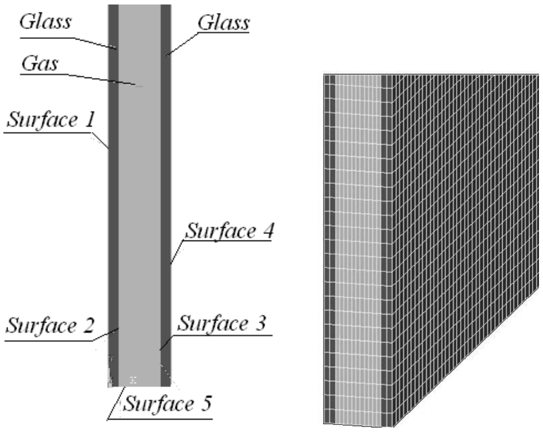


Fig. 1 Geometrical model and finite element mesh

B) Physical conditions

- Optical properties of glass panes in solar spectrum.

The steps for the calculation of total absorbtance and transmittance of IGU are standardized.

If the some of the glass panes are coated, the absorptance and reflectance are different for the front and back side (Fig. 2):

(12) $A_1^f(l) + R_1^f(l) + T_1 = 1$; $A_1^b(l) + R_1^b(l) + T_1 = 1$

The average optical glass properties for standardized wavelengths Δλ of the solar spectrum, based on spectral characteristics, given by the producers:

(13) $A_i(l_{j,j+1}) = \frac{1}{2}\left(A_i(l_j) + A_i(l_{j+1})\right)$

(14) $T_i(l_{j,j+1}) = \frac{1}{2}\left(t_i(l_j) + t_i(l_{j+1})\right)$

are used to calculate the average transmittance, reflectance and absorptance in the glazing system. For double glazed IGU (fig. 4):

(15) $$T_{12} = \frac{T_1.T_2}{1-R_1^b.R_2^f}$$

(16) $$R_{12}^f = R_1^f + \frac{T_1^{\,2}.R_2^f}{1-R_1^b.R_2^f} \quad R_{12}^b = R_2^b + \frac{T_1^{\,2}.R_1^b}{1-R_1^b.R_2^f}$$

(17) $$\hat{A}_1^f = R_1^f + \frac{T_1.R_2^f.A_1^b}{1-R_1^b.R_2^f}\,;\ \hat{A}_2^f = \frac{T_1.A_2^f}{1-R_1^b.R_2^f}$$

Then the average integral absorptance and transmittance for all solar spectrum are determinate and used in eq. (5) and (6):

(18) $$\hat{A}_1 = \frac{\sum_{j=1}^{N-1}\left[A_1^f\left(l_{j,j+1}\right)+\frac{A_1^b\left(l_{j,j+1}\right)T_1\left(l_{j,j+1}\right)R_2^f\left(l_{j,j+1}\right)}{1-R_1^b\left(l_{j,j+1}\right).R_2^f\left(l_{j,j+1}\right)}\right].E_s\left(l_{j,j+1}\right)\Delta l_j}{\sum_{i=1}^{N-1}E_s\left(l_{j,j+1}\right)\Delta l_j}$$

(19) $$\hat{A}_2 = \frac{\sum_{j=1}^{N-1}\left[\frac{A_2^f\left(l_{j,j+1}\right)T_1\left(l_{j,j+1}\right)R_2^f\left(l_{j,j+1}\right)}{1-R_1^b\left(l_{j,j+1}\right).R_2^f\left(l_{j,j+1}\right)}\right].E_s\left(l_{j,j+1}\right)\Delta l_j}{\sum_{i=1}^{N}E_s\left(l_{j,j+1}\right)\Delta l_j}$$

(20) $$T_{12} = \frac{\sum_{l=300nm}^{2500nm}\left[\frac{T_1\left(l_{j,j+1}\right)T_2\left(l_{j,j+1}\right)}{1-R_1^b\left(l_{j,j+1}\right).R_2^f\left(l_{j,j+1}\right)}\right].E_s\left(l_{j,j+1}\right)\Delta l_j}{\sum_{i=1}^{N}E_s\left(l_{j,j+1}\right)\Delta l_j}$$

where

(21) $$E_s\left(l_{j,j+1}\right) = \frac{1}{2}\left(E_s\left(l_j\right)+E_s\left(l_{j+1}\right)\right)$$

The values of spectral distribution of the incident solar radiation E(λ) are reported at N values of λ [2, 3]

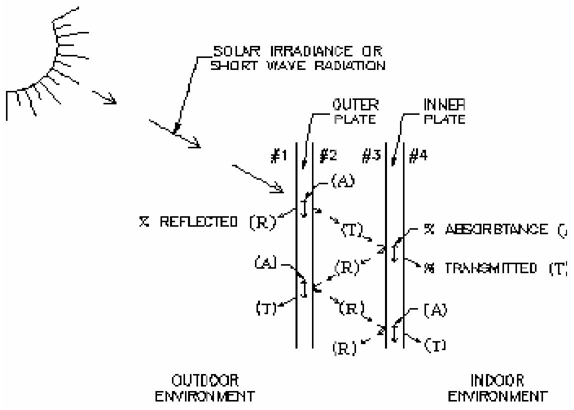


Fig. 4. Ray tracing

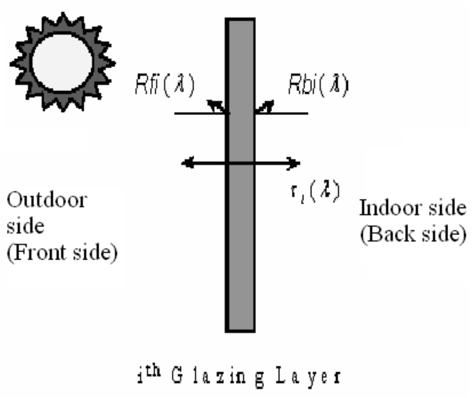


Fig. 3

The physical properties of gas cavity and the glass can be accepted according:

Air:

c_p=1000 J/(kg.K)

(22) $$K = 0,02454.\left(\frac{T}{T_o}\right)^{1.5}\left(\frac{T_o+147,7}{T+147,7}\right)$$

(23) $$r = 1,293.\frac{p}{T}.\frac{273,15}{101325}$$

(24) $$m = 17,1.10^{-6}.\left(\frac{T}{T_o}\right)^{1.5}\left(\frac{T_o+89,77}{T+89,77}\right)$$

Glass:

c_p=1000 J/(kg.K);

ρ=2500 kg/m3

K_{xx}=K_{yy}=K_{zz}=1 W/(m.K)

Glass transmittance, reflectance and absorptance in infrared spectrum (outside the solar spectrum) depend on glass thickness. They are given by glass producers. Typically A=0,86; T=0,03 and R=0,11.

Glass emissivity is also known by producer's data. For example:

Clear glass: ε=0,86

Low emissivity coated glass: ε=0,03

C) Boundary conditions

The boundary conditions for the external surfaces of IGU are used as function of the temperature.

Surface 1:

(25) $$\dot{q} = h_{out}.\left(T_{out}-T\right)+s\,.e_e.\left(T_{r,m}^4-T^4\right)$$

The mean radiating environment temperature is:

(26) $$T_{r,m=} = \left(F1.T_{out}^4+F2.T_{sky}^4\right)^{1/4}$$

The sky temperature is calculated by Swinbank equation:

(27) $$T_{sky} = 0,0552.T_{out}^{1,5}$$

The view factors, depending on the glass pane orientation and the environment are:

(28) $$F1 = 1 - F2$$

(29) $$F2 = \cos(q/2)^2$$

Surface 4:

(30) $$\dot{q} = h_{in}.(T_{in} - T) + s.e_{in}.(T_{in}^4 - T^4)$$

Surfaces of the gas cavity are applied as radiating walls of closed enclosure. Surface 2 and 3 belong on glass panes, surfaces 5, 6, 7 and 8 are spacers walls.

$$Enclouser\ 1\ (closed)\begin{cases}\text{Surface } 2 : e_2\\ \text{Surface } 3 : e_2\\ \text{Surface } 5 : e_2\\ \text{Surface } 6 : e_6\\ \text{Surface } 7 : e_7\\ \text{Surface } 8 : e_8\end{cases}$$

For all enclosure surfaces $V_x = V_y = V_z = 0$.

3. NUMERICAL CFD CALCULATION FOR DOUBLE GLAZED IGU

The models above are used to calculate the heat transfer and temperature fields in several variants of vertical IGU with sizes 0.35 x 0.50 m and thicknesses: 4 mm glass / 16 mm gas space / 4 mm glass. The absorptances of glass panes $\hat{A}_1$ and $\hat{A}_2$ are calculated by front and back side properties of the glasses below, given by the producers [10], directly by (15), (16) and (17). The calculations are validated by comparisons of the received total transmittances T_{12} and producer's data.

Variant 1: panes 1 and 2 – clear uncoated glass

g=0,67; U=2,7 W/(m^2.K)
$\varepsilon_1=\varepsilon_2=\varepsilon_3=\varepsilon_4=0{,}84$
$\varepsilon_5=\varepsilon_6=\varepsilon_7=\varepsilon_8=0{,}06$ (aluminum spacer)
$A_1^f=A_2^f=0{,}08$; $T_1=T_2=0{,}76$;
$R_1^f=R_1^b=R_2^f=R_2^b=0{,}16$
$\hat{A}_1=0{,}09$; $\hat{A}_2=0{,}06$; $T_{12}=0{,}6$

Variant 2: pane 1 - clear uncoated glass, pane 2 – glass with low emissivity coating on position 3

g=0,69; U=1,9 W/(m2.K)
$\varepsilon_1=\varepsilon_2=\varepsilon_4=0{,}84$; $\varepsilon_3=0{,}03$
$\varepsilon_5=\varepsilon_6=\varepsilon_7=\varepsilon_8=0{,}06$
$A_1^f=0{,}08$; $T_1=0{,}82$; $R_1^f=R_1^b=0{,}11$
$A_2^f=0{,}25$; $T_2=0{,}68$; $R_2^f=0{,}07$
$\hat{A}_1=0{,}07$; $\hat{A}_2=0{,}21$; $T_{12}=0{,}56$

Variant 3: Pane 1 - glass with sun control coating on position 2; pane 2 – clear uncoated glass

g=0,47; U=2,04 W/(m^2.K)
$\varepsilon_1=\varepsilon_3=\varepsilon_4=0{,}84$; $\varepsilon_2=0{,}03$
$\varepsilon_5=\varepsilon_6=\varepsilon_7=\varepsilon_8=0{,}06$
A_1f=0,45; $T_1=0{,}47$; R_1^f=R1b=0,08
A_2f=0,08; $T_2=0{,}82$; R_2f=0,11
$\hat{A}_1=0{,}47$; Â2=0,04; $T_{12}=0{,}39$

The IGU are south oriented. The calculations are done by clear sky, normal air pollution (A=0,88; B=0,36) at two seasons:

Spring conditions

I_s=657 W/m^2
t_{in}=20 °C, t_{out}=25 °C, t_{sky}=10 °C

Winter conditions

I_s= 350 W/m^2
t_{in}=20 °C, t_{out}= -5 °C; t_{sky}= -10 °C

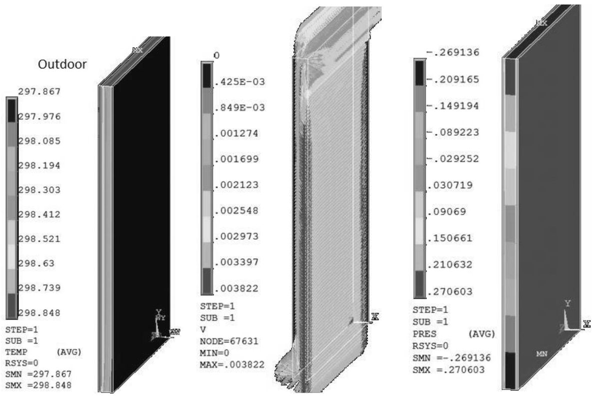
The convection heat transfer coefficients and the view factors are accepted:

h_{out}= 20 W/(m^2.K)
h_{in}= 3,6 W/(m^2.K)
$F_1=0{,}5$; $F_2=0{,}5$

4. RESULTS

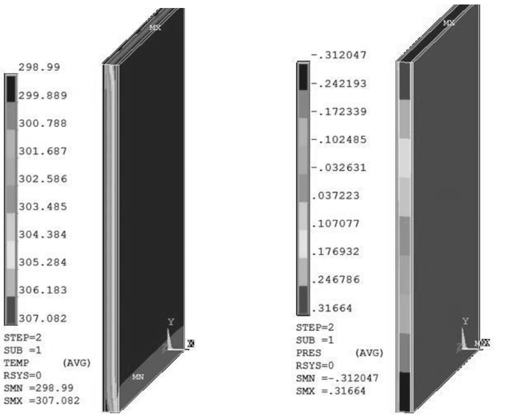
Numerical results about temperature, pressure and velocity fields in the investigated variants are visualized on Figs 5 – 8.

The validation of the models are done by comparisons between the surface temperatures – measured by thermocouple and calculated for the case of variant 1 and 3 for the winter conditions. The differences between measured and calculated temperatures are in term of 2 K.



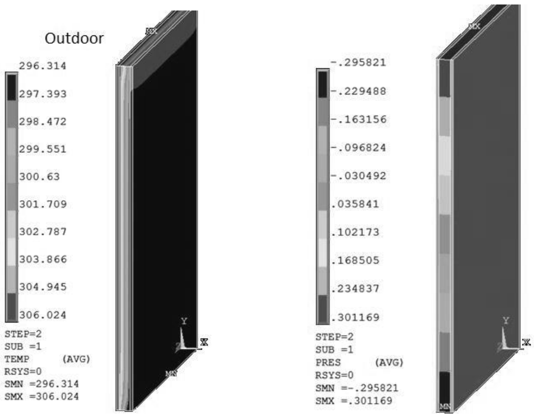
a) Temperature, K b) Velocity, m/s
c) Pressure, Pa

Fig. 5. Variant 1. Uncoated glass panes. Spring conditions.



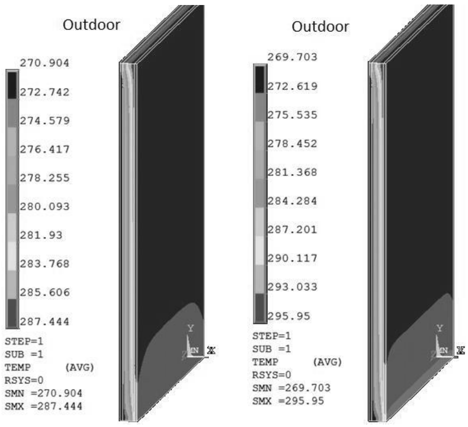
a) Temperature, K b) Pressure, Pa

Fig. 6. Variant 2. Low emissivity coating on position 3. Spring conditions.



a) Temperature, K b) pressure, Pa

Fig. 7. Variant 3. Sun control coating on position 2. Spring conditions.



a) Uncoated glasses b) Low emis. coating on position 3

Fig. 8. Winter conditions. Temperature fields

Average glass temperatures of 296 K for the inner glass pane and 306 K for the outer pane are established at variant 3 (sun control coating on position 2) at spring conditions. At the same time the temperature of the inner pane at variant 2 (with low-e coating) is 307 K.

The temperatures for the uncoated glasses are near to the environmental one.

For the winter conditions the inner glass temperature at variant 2 is 296 K (higher than the room temperature), while the temperature of the inner uncoated glass is 287 K – near the dew point temperature.

The average gas temperatures are calculated for the investigated variants:

Spring conditions:

Variant 1: Uncoated glass panes – 298 K

Variant 2: Low emis. coating on position 3 - 303 K

Variant 3: Sun control coating on position 2 – 304 K

Winter conditions:

Variant 1: Uncoated glass panes – 279 K.

Variant 2: Low emis. coating on position 3 - 282 K

Higher temperature difference according the initial temperature of gas space in the hot seasons is established in the case of sun control coating on position 2. That difference is higher at IGU with uncoated glass in the cold seasons.

5. CONCLUSIONS

The coating on the inner glass surface increases the absorptance of the glass and decrease the long wave radiation heat transfer between the glass panes.

That cause increasing of the temperature of the coated glass and the thermal transmittance U of IGU due to the rise of the free convection heat transfer coefficient. The solar factor g of the IGU is decreased at sun control coating on outer glass pane and increased at low emissivity coating on the inner pane. That thermal behavior of the IGU with coatings has to be taken into account at the glazing of the buildings according the façade orientation and the climate conditions.

From mechanical point of view the higher deflection of the gas pane is expected in the case of IGU with sun control coating on position 2 in the summer and at IGU with uncoated glass at the winter.

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Nomenclature

A- absorptance, dimensionless or area, m^2
T- transmittance, dimensionless
R – reflectance, dimensionless
E_s - solar spectral irradiance function (ISO 9845)
I_s - total flux of incident solar radiation
l – glass thickness, m
c_p – isobaric specific heat, $kJ.kg^{-1}.K^{-1}$
T – temperature, K
V_x, V_y, V_z – velocity on x, y, z direction, $m.s^{-1}$
p – pressure, Pa
K – conductivity, $W.m^{-1}.K^{-1}$
k – turbulent kinetic energy, $J.kg^{-1}$
h – convection heat transfer coefficient, $W.m^{-2}.K^{-1}$ or sun elevation angle
H - altitude, m
N = number of radiating surfaces
S_i - flux of absorbed solar radiation at i^{th} glazing layer, $W.m^2$
F1, F2 = radiation view factors respectively glass-ground (buildings) and glass- sky, dimensionless
Fji = radiation view factors between finite element surfaces, dimensionless
$\dot{q}$ - heat flux, W
$\dot{Q}$ - heat flow, W
$\dot{q}_v$ - volumetric heat generation rate, $W.m^{-3}$

Greek symbols

C_μ – turbulence constant
σ_k, σ_ε – Schmidt numbers for turbulent kinetic energy and turbulent kinetic energy dissipation rate
σ_t - Turbulent Prandtl (Schmidt) Number.
ρ– density, кg.m-3
ε - turbulent kinetic energy dissipation rate, $W.kg^{-1}$, emissivity, dimensionless
τ – time, s
μ - dynamic viscosity, Pa.s
λ – wavelength, μm
δji = Kronecker delta
θ – incident angle

Subscripts

i – glass pane number
in – inner
out – outer
d – diffuse solar radiation
D – direct solar radiation

Superscripts

f – front side
b – back side

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