The Shading Coefficient and the U-value of a Naturally Ventilated Double-skin Façade Wall in Hot and Humid Climate

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Abstract

The overall heat transfer coefficient (U-value) and the shading coefficient (SC-value) are substantial properties of double-skin façade. They are importantly required for energy-use estimation, particularly for heat load calculation of the air-conditioning system. The determination of the U-value and the SC-value of double-skin façade was done by numerical simulation employing FORTRAN for the one-year duration. By utilizing the least square method, the equation of U-value and SC-value can be determined to define the Uperiod and SCperiod of double-skin façade. The SC-value of the cases varied from 0.16 to 0.20 [-], and the U-value varied from 3.37 to 3.66 [W/m^2.k]

Keywords: overall heat transfer coefficient, shading coefficient, double-skin façade

I. Introduction

In the last decade, the application of ventilated double-skin façade has been growing and widely used in building, especially in office building. Its benefits in provide the fascinating and esthetical view of building facade, the capability in buffering noise from outside, as well as its prospective in decreasing energy consumption in building making it as a distinct trend in the architectural field.

As a part of the building envelope, a ventilated double-skin façade is a construction system that comprises of two transparent glass skins (outer and inner), which surround an air cavity. The double-skin façade is equipped with a shading device as well as top and bottom ventilation. The air cavity functions as a channel for air exchange, providing natural ventilation to the double-skin façade, and also functions as a thermal buffer for the building interior [1][2]. Within the air cavity, open gratings, which allow the free flow of air and serve as platforms for cleaning inside the cavity, are occasionally installed at each floor level. Fresh air from the outside is exchanged with the air in the cavity and vented from the top of the building.

In spite of the fact that double-skin façades are more costly than conventional façades, the advantages of ventilated double-skin façades have been announced by many researchers and building scientists [3]. Chan et al. have investigated the performance in Hong Kong of a double-skin façade in comparison with a conventional single-skin façade with absorptive glazing [4]. Furthermore, through a comparison of double-skin and single-skin façades in a hot arid climate, Hamza found that a double-skin façade with reflective glass can obtain better energy savings than a single-skin façade with reflective glazing [5]. Xu and Yang have analyzed the thermal performance of a double-skin façade that employs natural ventilation and venetian blinds [6], and Hien et al. found that a double-skin façade by means of natural ventilation can decrease energy use as well as enhance indoor thermal comfort [7]. Taken together, these studies reveal that double-skin façades play prominent role in connecting the indoor environment of a building to the outdoors. Buildings with a huge glazed façade incur excessively high electricity demand [8]. Double-skin façades represent one means of lowering electric power consumption.

The overall heat transfer coefficient, which is commonly called U-value, and the shading coefficient (SC) are substantial properties of ventilated double-skin façade wall. Due to the usage of a double-skin façade wall in office buildings become increase in the recent decade, which is expected to be a type of energy efficient buildings; the determination of the overall heat transfer coefficient and the shading coefficient become importantly required for energy-use calculation matter, especially for heat load calculation of the air conditioning system. In this research, the determination of the overall heat transfer coefficient and the shading coefficient of double-skin façade is done by numerical simulation.

Furthermore, the determination of U-value and SC-value of ventilated double-skin façade is quietly difficult since the air flow volume in the cavity of double-skin façade is varying during the time. Therefore, this paper aim to determine the U-value and the SC-value of double-skin façade by using a double-skin façade model; simulate the overall heat transfer and shading coefficient utilizing FORTRAN; and define the U-period and SC-period by utilizing the least-square method. These calculations take into account Indonesia's climate as well as the thickness of the glass skins, the distance between them and the orientation of the double-skin facade.

II. Simulation of double-skin facade

This research is based on a numerical simulation on a model of double-skin façade. The five-story double-skin façade model was selected out of consideration of the effectiveness of the natural ventilation process in the air cavity of the double-skin façade. The height of double-skin façade model is 18.5m. Figure 1 represents the model of double-skin façade. Between the outer and inner glass skins, light colored horizontal blinds are attached. These horizontal blinds are functioned as a shading device. The direction of the façade, the thickness of outer and inner glass skins, and the distance between them, are varied.

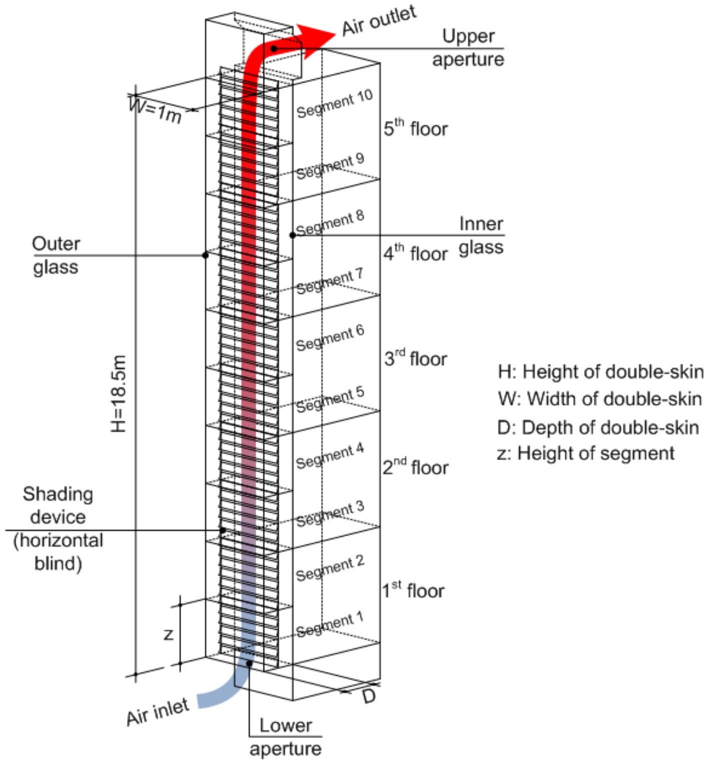

Figure 7. Thickness, orientation and distance between glass skins

Glass skin thickness	Distance between outer & inner glass (d)	Orientation

Outer glass [mm]	Inner glass [mm]	Alt. 1 [cm]	Alt. 2 [cm]	Alt. 3 [cm]	Alt. 4 [cm]	Group 1	Group 2	Group 3	Group 4
10	6	200	150	100	80	North	East	South	West
10	8	200	150	100	80	North	East	South	West
10	10	200	150	100	80	North	East	South	West
10	12	200	150	100	80	North	East	South	West
12	12	200	150	100	80	North	East	South	West

III. Heat balance of double-skin facade

The outer glass, the inner glass, the blinds, and the layer of air (which constitute the double-skin façade) were divided into a finite number of segments height-wise. The heat-transfer in each layer was taken into account for the heat balance of each segment. Radiation, multiple reflections of solar radiation, and mutual radiation were considered. For the glass, the incident angle of direct solar radiation and the transmittance, reflectance, and absorptance ratios were taken into account. For the blinds, the variation in the absorption rate and upward and downward transmissions are changed by the profile angle of the blinds due to direct solar radiation, diffuse radiation, and ground reflection. Figure 2 show the heat balance at each segment.

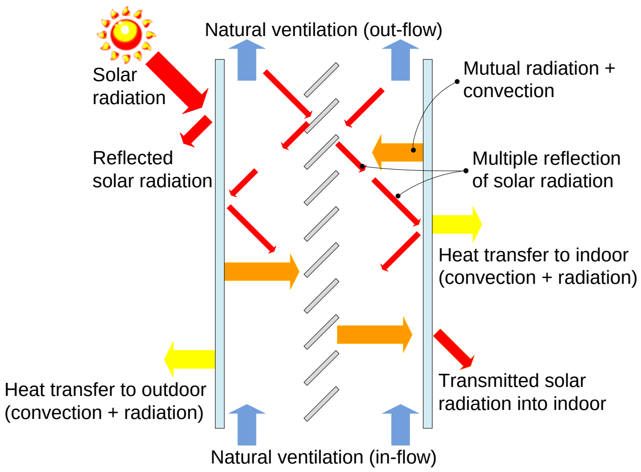

Figure 2. Heat balance at each segments

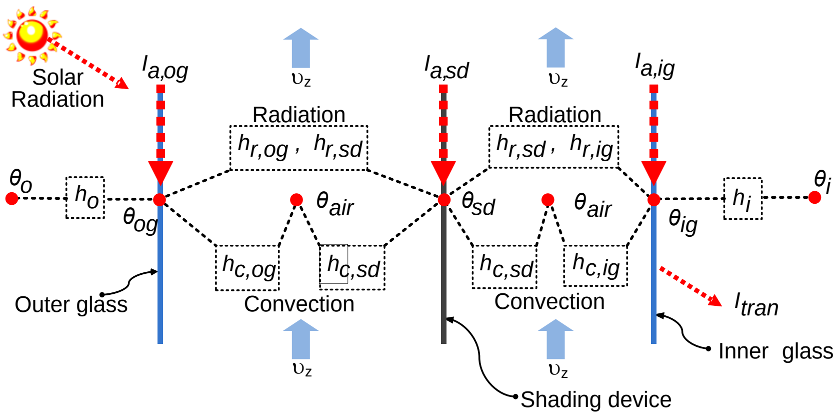

Figure 3. Outline of numerical analysis model

The performance of the double-skin façade model is explained by the following equations.

a. Heat balance at the outer glass

$$h_o\left(\theta_{og}-\theta_o\right)+h_{r,og}\left(\theta_{og}-\sum_{n=1}^{10}G_{og_n,sd_n}\cdot\theta_{sd}\right)+h_{c,og}\left(\theta_{og}-\theta_{air}\right)=I_{a,og} \quad (1)$$

b. Heat balance at the air layer of the cavity of double-skin

$$\rho_{air}c_{air}\upsilon_z\frac{\partial\theta_{air}}{\partial z}=h_{c,og}\left(\theta_{og}-\theta_{air}\right)+h_{c,ig}\left(\theta_{ig}-\theta_{air}\right)+2h_{c,sd}\left(\theta_{sd}-\theta_{air}\right) \quad (2)$$

c. Heat balance at the shading device

$$2h_{c,sd}\left(\theta_{sd}-\theta_{air}\right)+h_{r,sd}\left(\theta_{sd}-\sum_{n=1}^{10}G_{sd_n,og_n}\cdot\theta_{og}\right)+h_{r,sd}\left(\theta_{sd}-\sum_{n=1}^{10}G_{sd_n,ig_n}\cdot\theta_{ig}\right)=I_{a,sd} \quad (3)$$

d. Heat balance at the inner glass

$$h_{r,ig}\left(\theta_{ig}-\sum_{n=1}^{10}G_{sd_n,ig_n}\cdot\theta_{sd}\right)+h_{c,ig}\left(\theta_{ig}-\theta_{air}\right)+h_i\left(\theta_{ig}-\theta_i\right)=I_{a,ig} \quad (4)$$

IV. U-value and Shading Coefficient (SC) of double-skin facade

There are two kinds of heat that could flow into the indoor through the window surface of double-skin. The first is the heat flow by direct transmission of solar radiation (I_{tran}); and radiative (I_r) and convective (I_c) flow of absorbed solar radiation at the windows side double-skin pane. The second is the radiative (Q_r) and convective (Q_c) heat flow due to the temperature difference between the outdoor and the indoor. **Error! Reference source not found.**4 show the heat flow through the window side pane of double-skin.

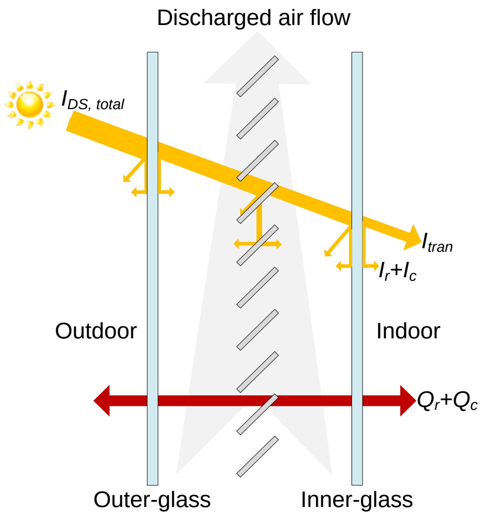

Figure 4. Heat flow to the indoor

The amount of heat flow into the indoor (I_{in}) through double-skin façade due to the transmission of direct solar radiation through the inner glass (I_{tran}), and the radiative (I_r) and convective (I_c) radiation of the absorbed solar radiation can be seen from the equation below.

$$I_{in} = I_{tran} + I_r + I_c \quad (5)$$

The heat transferred into the indoor (Q_{in}) through the double-skin façade, which is the radiative (Q_r) and convective (Q_c) heat-transfer as the temperature difference between the outdoor and the indoor is as follows:

$$Q_{in} = Q_r + Q_c \quad (6)$$

Based on above description, the U-value of double-skin façade can be calculated as a ratio of the amount of heat flow into the indoor (Q_{in}) through the inner pane of double-skin façade to the temperature differences between the outdoor and the indoor (θ_o-θ_i), and can be written as equation below:

$$\mathrm{U} = \frac{Q_{in}}{(\theta_o - \theta_i)} \quad (7)$$

Since the heat flow to the indoor (Q_{in}) is due to temperature difference between the outdoor and the indoor are radiative (Q_r) and convective (Q_c) heat flow, the equation then can be written as follows:

$$U = \frac{Q_r + Q_c}{\left(\theta_o - \theta_i\right)} \quad (8)$$

Furthermore, the SC of double-skin can also be determined as the ratio of the solar radiation reach the indoor (I_{in}) through the inner glass of double-skin to the solar radiation of the standard glass (I_G) (clear glass 3mm thickness) and can be calculated as follows:

$$SC = \frac{I_n}{I_G} \quad (9)$$

Then, the SC equation can be written as follows:

$$SC = \frac{\left(I_{tran} + I_r + I_c\right)}{\left(g_D I_D + g_S I_S\right)} \quad (10)$$

From numerical calculation, we can determine the value of I_r+I_c+Q_r+Q_c as follows:

$$I_r + I_c + Q_r + Q_c = h_i(\theta_{ig} - \theta_i) \quad (11)$$

However, the heat-transfer by radiation (I_r and I_c) and the heat-transfer due to the temperature differences between indoor and outdoor (Q_r and Q_c) shall be separated by performing additional simulation, which based on the. The simulation flow-chart can be seen at Figure 5.

In this simulation, the indoor and ambient temperature was the same and assumed as 0 differences, and the airflow in the cavity of double-skin was determined, which was taken from the previous simulation. By this additional simulation, the temperature of the inner glass (θ_{ig}') can be determined and the radiation heat-transfer can be separated as follows:

$$I_r + I_c = h_i(\theta_{ig}' - \theta_i) \quad (12)$$

and,

$$Q_r + Q_c = h_i(\theta_{ig} - \theta_{ig}') \quad (13)$$

Then, the SC of double-skin can be calculated as follows:

$$SC = \frac{I_{tran} + h_i\left(\theta_{ig}' - \theta_i\right)}{\left(g_D I_D + g_S I_S\right)} \quad \text{.......(14)}$$

and the U-value can be calculated also as follows:

$$U = \frac{h_i(\theta_{ig} - \theta_{ig}')}{\left(\theta_0 - \theta_i\right)} \quad \text{.......(15)}$$

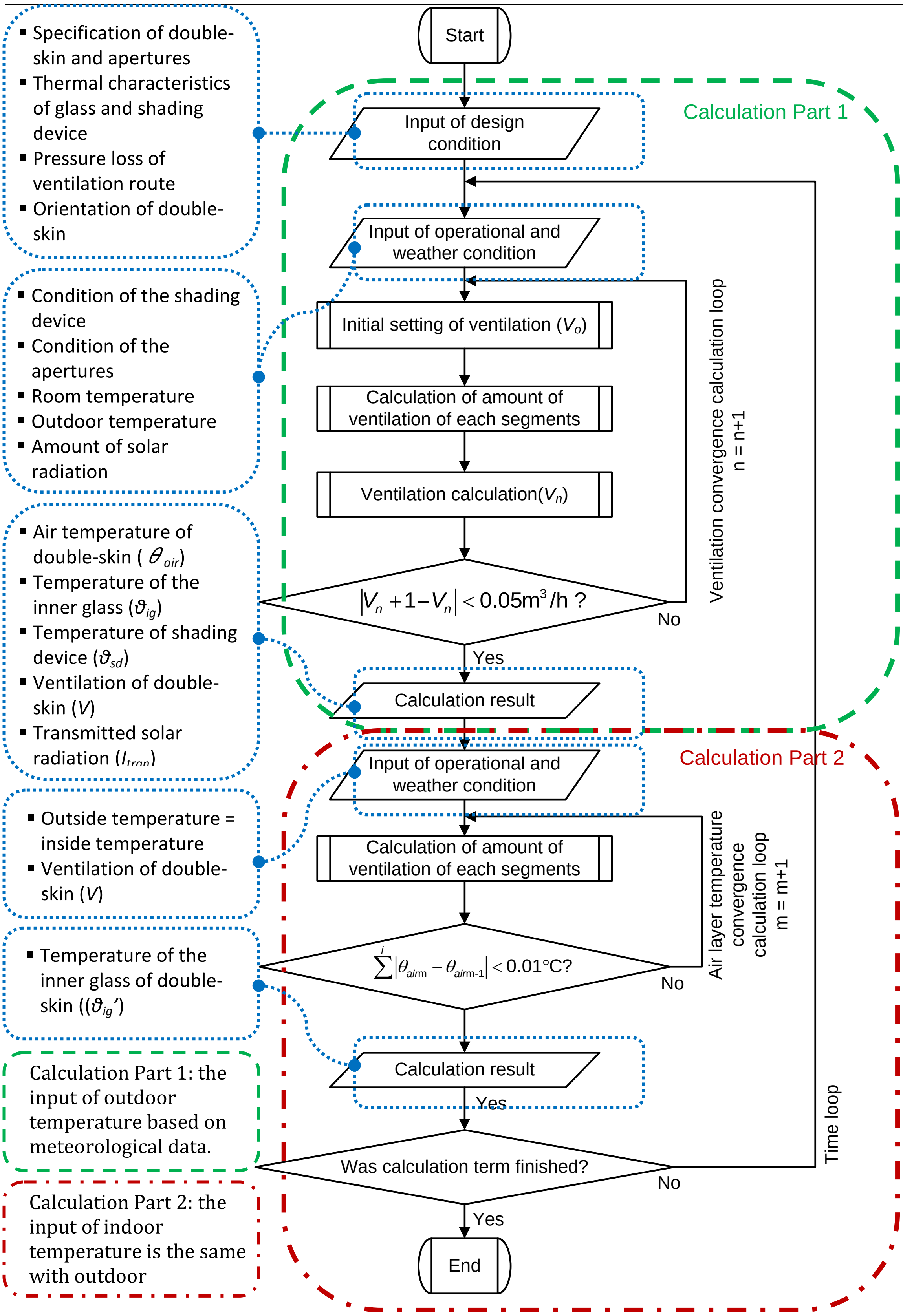

Figure 58. Flow calculation of U-value and SC

The calculation of U-value and SC is based upon the equation 14 and 15. From this part of calculation, a set of hourly data of U-value and SC has been obtained for one-year duration. Therefore, there is a necessity to define the regression equation in order to define the exact value among of those set of U-value and SC data in relation to the standardized solar radiation (I_G).

The least-square method was used to define the approximation formula of the U-value and SC. In this approximation, the calculated U-value and SC in relation to the standardized solar radiation (I_G) were fitted using the polynomial least-square method as can be seen as follows:

$$U = aI_G{}^b + c \quad (16)$$

$$SC = dI_G{}^e + f \quad (17)$$

From those equations we can formulate the equation of the U-value and SC as can be seen in equation below. The curve fitted polynomial least-square can be seen at Figure 6 and Figure 7.

$$U = 1.315 I_G{}^{0.121} + 0.940 \quad (18)$$

$$SC = 0.732 I_G{}^{-0.389} + 0,098 \quad (19)$$

Finally, based on the equation above the U-value of designated double-skin façade can be obtained by below equation.

$$U_{period} = \frac{\sum_{k=1}^{m}\left(1.315 I_{G,k}{}^{0.121} + 0.940\right)\left(\theta_{o,k} - \theta_{i,k}\right)}{\sum_{k=1}^{m}\left(\theta_{o,k} - \theta_{i,k}\right)} = 3.45 \quad (20)$$

and the equation and result for the SC is shown in equation below.

$$SC_{period} = \frac{\sum_{k=1}^{m}\left(0.732 I_{G,k}{}^{-0.389} + 0.098\right) I_{G,k}}{\sum_{k=1}^{m} I_{G,k}} = 0.20 \quad (21)$$

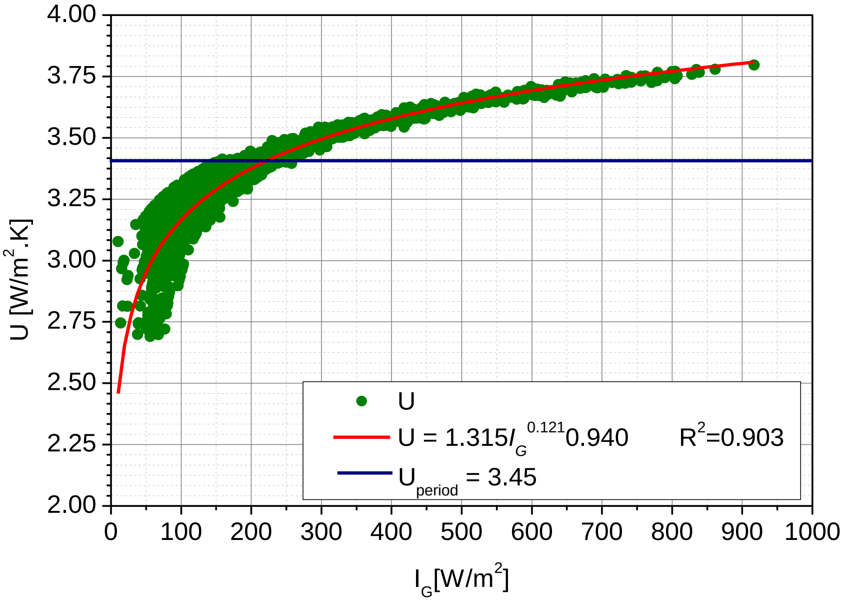

Figure 69. Relationship between U-value and the standardized solar radiation

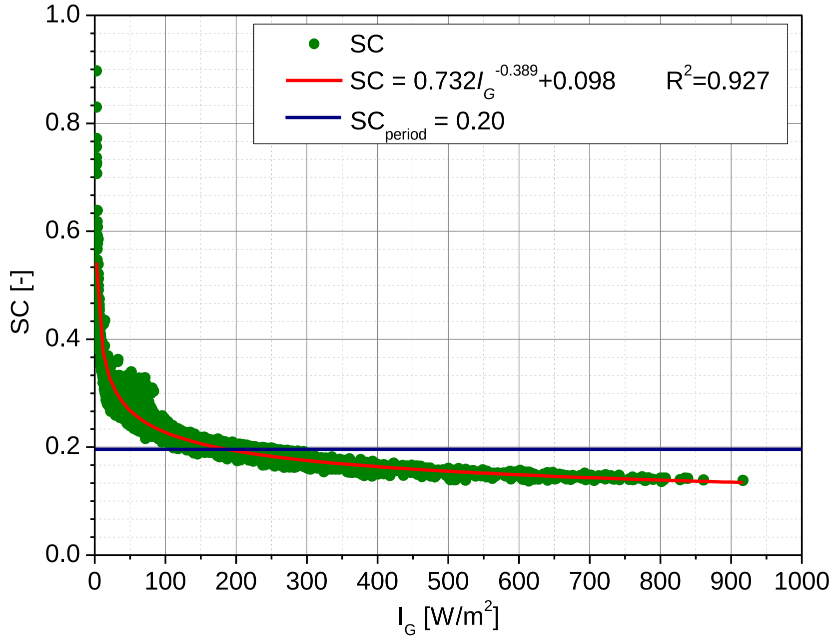

Figure 7. relationship between SC and the standardized solar radiation

Table below indicates the U equation, Uperiod, SC equation, and SCperiod of simulated double-skin façade cases.

Table 1. U equation, Uperiod, SC equation, and SCperiod of simulated cases

Double-skin facade cases	U equation	U_{period} [W/m^2.K]	SC equation	SC_{period} [-]
DS80(10+6)	$1.032 I_G^{0.106}+1.545$	3.37	$1.533 I_G^{-0.918}+0.189$	0.20
DS80(10+8)	$1.264 I_G^{0.124}+0.958$	3.42	$0.716 I_G^{-0.382}+0.101$	0.20
DS80(10+10)	$1.315 I_G^{0.121}+0.940$	3.45	$0.732 I_G^{-0.389}+0.098$	0.20
DS80(10+12)	$1.293 I_G^{0.121}+1.008$	3.49	$0.746 I_G^{-0.392}+0.096$	0.19
DS80(12+12)	$1.345 I_G^{0.119}+0.944$	3.49	$0.754 I_G^{-0.400}+0.092$	0.19
DS80(10+6)	$1.280 I_G^{0.118}+1.017$	3.44	$0.675 I_G^{-0.375}+0.095$	0.19
DS100(10+8)	$1.290 I_G^{0.117}+1.044$	3.47	$0.686 I_G^{-0.377}+0.095$	0.19
DS100(10+10)	$1.314 I_G^{0.116}+1.059$	3.51	$1.511 I_G^{-0.914}+0.179$	0.19
DS100(10+12)	$1.386 I_G^{0.112}+1.015$	3.54	$1.530 I_G^{-0.913}+0.177$	0.19
DS100(12+12)	$1.333 I_G^{0.114}+1.079$	3.54	$1.534 I_G^{-0.913}+0.170$	0.18
DS150(10+6)	$1.356 I_G^{0.105}+1.125$	3.51	$1.286 I_G^{-0.915}+0.171$	0.18
DS150(10+8)	$1.378 I_G^{0.104}+1.136$	3.55	$1.302 I_G^{-0.914}+0.172$	0.18
DS150(10+10)	$1.432 I_G^{0.101}+1.121$	3.58	$1.318 I_G^{-0.913}+0.168$	0.18
DS150(10+12)	$1.424 I_G^{0.100}+1.175$	3.62	$1.335 I_G^{-0.911}+0.166$	0.18
DS150(12+12)	$1.420 I_G^{0.100}+1.182$	3.62	$1.337 I_G^{-0.912}+0.158$	0.17
DS200(10+6)	$1.408 I_G^{0.097}+1.184$	3.56	$1.109 I_G^{-0.913}+0.165$	0.17
DS200(10+8)	$1.428 I_G^{0.095}+1.205$	3.59	$1.122 I_G^{-0.912}+0.166$	0.17
DS200(10+10)	$1.426 I_G^{0.094}+1.253$	3.62	$1.136 I_G^{-0.911}+0.161$	0.17
DS200(10+12)	$1.439 I_G^{0.094}+1.276$	3.66	$1.151 I_G^{-0.909}+0.159$	0.17
DS200(12+12)	$1.454 I_G^{0.093}+1.263$	3.66	$1.150 I_G^{-0.910}+0.152$	0.16

V. CONCLUSION

Double-skin façade model with assorted glass combinations of outer and inner glass, distances, and directions has been simulated employing FORTRAN to predicting the heat gain of double-skin façade. Thus, the U-value and SC-value of double-skin façade has been simulated. The Least-square method was used and found useful to predicting the equation of U and SC value of double-skin façade cases including Uperiod and SCperiod respectively. The SC-value of the cases varied from 0.16 to 0.20, and the U-value of the cases varied from 3.37 to 3.66 [W/m2.k].

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