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Determining Overall Heat Transfer Coefficient and Shading Coefficient of Double-skin Facade

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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 U_{period} and SC_{period} 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

1. Introduction

In the last decade, the application of 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.

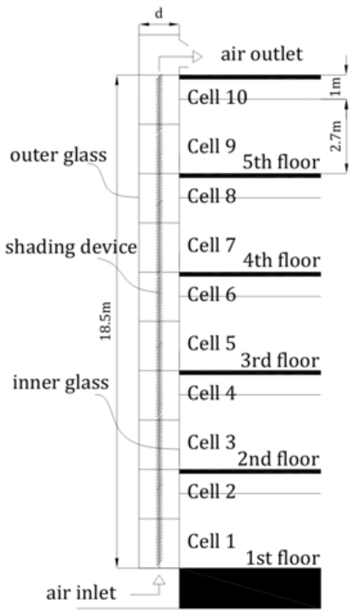
As a part of the building envelope, a double-skin façade is a construction system that comprises of two transparent glass skins (outer and inner), which surround an air cavity. The double-skin façade is equipped with a shading device as well as top and bottom ventilation. The air cavity functions as a channel for air exchange, providing natural ventilation to the double-skin façade, and also functions as a thermal buffer for the building interior (Jiru and Haghighat, 2008, Zhou and Chen, 2010). 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 double-skin façades have been announced by many researchers and building scientists (Poirazis, 2004). Chan et al. (2009) have investigated the performance in Hong Kong of a double-skin façade in comparison with a conventional single-skin façade with absorptive glazing. Furthermore, through a comparison of double-skin and single-skin façades in a hot arid climate, Hamza (2008) found that a double-skin façade with reflective glass can obtain better energy savings than a single-skin façade with reflective glazing. Xu and Yang (2008), have analysed the thermal performance of a double-skin façade that employs natural ventilation and venetian blinds, and Hien et al. (2005), found that a double-skin façade by means of natural ventilation can decrease energy use as well as enhance indoor thermal comfort. 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 (Al-Rabghi et al., 1999). Double-skin façades represent one means of lowering electric power consumption.

Furthermore, the determination of U-value and SC-value of 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.

2. 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.



Source: Mulyadi et al, 2010a-b

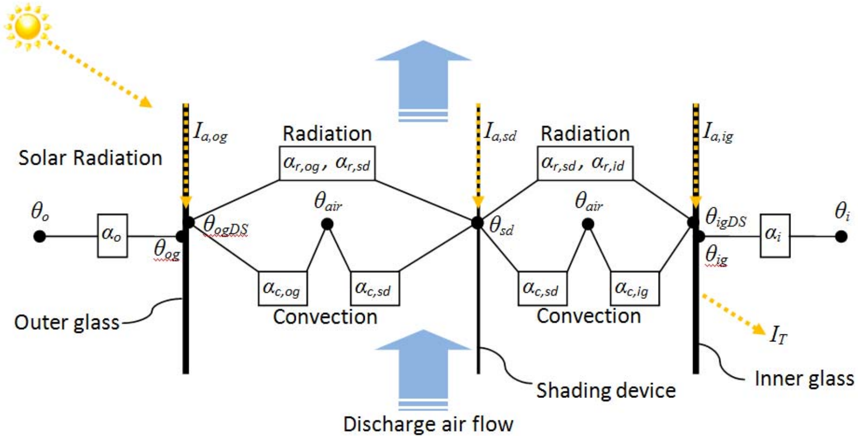
Figure 1: Double-skin façade model

Table 1: 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

Source: Mulyadi et al, 2010a-b

To simplify the calculations, the double-skin façade elements, namely, the outer glass, the inner glass, the shading device, and the air cavity, are segmented into a finite number of cells in the height direction; each story consists of two cells (Figure 1). Table 1 lists the values used in the calculation for the thickness of inner and outer glass skins and for the distance between them. The heat balance calculation for each cell, convective heat transfer, radiation, advective flow, mutual radiation, and multiple reflections of solar radiation are taken into account (Figure 2).



Source: Mulyadi et al, 2010a-b
Figure 2: Outline of numerical analysis model

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

a. Heat balance equation for the outer glass skin:

$$\alpha_o\left(\theta_{og}-\theta_o\right)+\int_{S_{ogsd}}\alpha_r G_{SS'}\left(\theta_{ogDSs}-\theta_{ss'}\right)ds'+\alpha_c\left(\theta_{ogDS}-\theta_{igDS}\right)=I_{aog} \quad ...(1)$$

b. Heat balance equation for the air cavity:

$$\rho cV\frac{\partial\theta_{air}}{\partial z}=\alpha_c\left(\theta_{ogDS}-\theta_{air}\right)+\alpha_c\left(\theta_{igDS}-\theta_{air}\right)+2\alpha_c\left(\theta_{sd}-\theta_{air}\right) \quad ...(2)$$

c. Hat balance equation for the shading device:

$$\int_{S_{ogsd}}\alpha_r G_{ss'}\left(\theta_{sds}-\theta_{ss'}\right)ds'+\int_{S_{sdig}}\alpha_r G_{ss'}\left(\theta_{sds}-\theta_{ss'}\right)ds'+2\alpha_c\left(\theta_{sd}-\theta_{air}\right)=I_{asd} \quad ...(3)$$

d. Heat balance equation for the inner glass skin:

$$\int_{S_{sdig}}\alpha_r G_{ss'}\left(\theta_{igDSs}-\theta_{ss'}\right)ds'+\alpha_c\left(\theta_{igDS}-\theta_{air}\right)+\alpha_i\left(\theta_{ig}-\theta_i\right)=I_{aig} \quad ...(4)$$

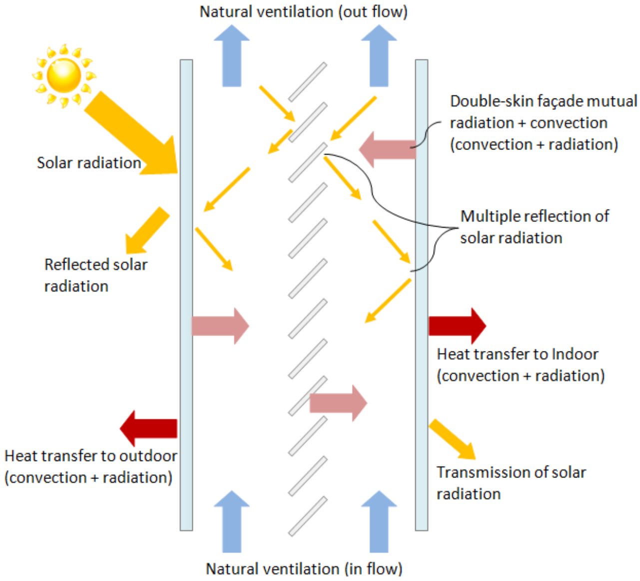
In addition, to define the heat gain for single-skin and double-skin façades, the equations below are used. The solar heat gain is expressed as the amount of direct solar radiation that enters the room through the façade. The thermal transmittance is a function of the overall heat transfer coefficient of the inner glass and shading device and the temperature difference between indoors and outdoors.

- Heat gain by thermal transmittance: $U_{ig}\times\left(\theta_{air}-\theta_i\right)$ ...(5)

- Heat gain by solar radiation: I_T ...(6)

The thermal resistance of the shading device, air cavity, and inner glass, and the heat transfer coefficient of the shading device and interior surface of the inner glass are used to calculate the overall heat transfer coefficient of the glass and shading device of the double-skin façade (U_{ig}). Jurges' formula for rough surfaces is used to calculate the heat transfer coefficient of the shading device surface, and the variation of air velocity in the double-skin façade is taken into account.

Primary transmittance is taken into account as the fraction of solar radiation that straightly enters the room through a façade with respect to the total solar insolation received by the window. The secondary transmittance is the fraction of inwardly flowing solar radiation, absorbed at the outer glass, that is radiated as long-wavelength radiation onto the shading device ($\alpha_{r,og}$, $\alpha_{r,sd}$), and then from the shading device to the inner glass ($\alpha_{r,sd}$, $\alpha_{r,ig}$), with respect to the total solar insolation.



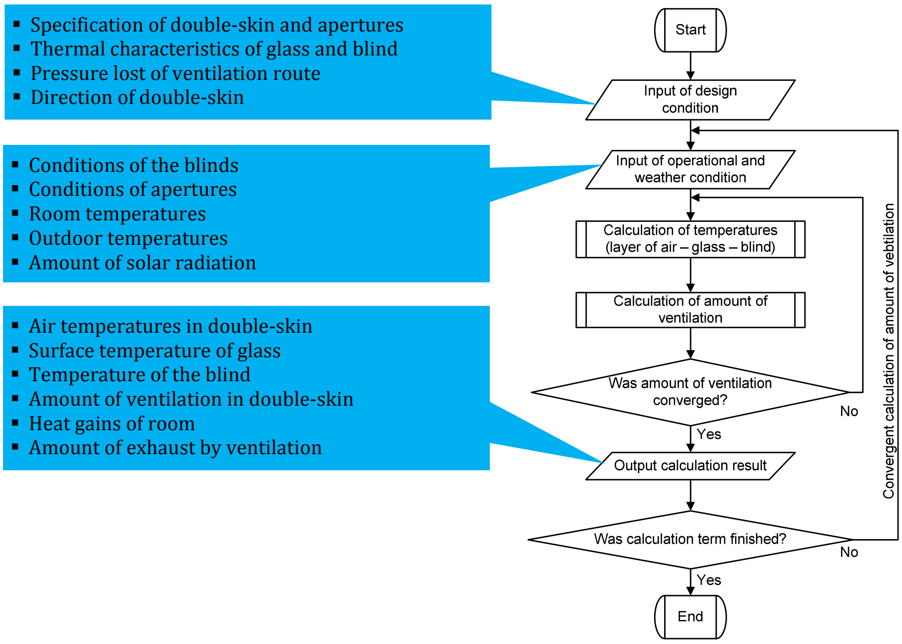
Source: Mulyadi et al, 2010a-b
Figure 3: Multiple reflection of direct solar radiation

The variation in transmittance due to the incidence angle of direct solar radiation is taken into account for the transmittance, reflectance, and absorption of light; the variation of transmittance due to the multiple reflection of long-wavelength radiation inside the air cavity is also considered. Furthermore, the wall and grating in the double-skin façade, which absorbs solar radiation and re-radiate it as heat, are ignored. Figure 3 shows the multiple reflection of direct solar radiation in a double-skin façade.

Table 2: Design and operational parameters

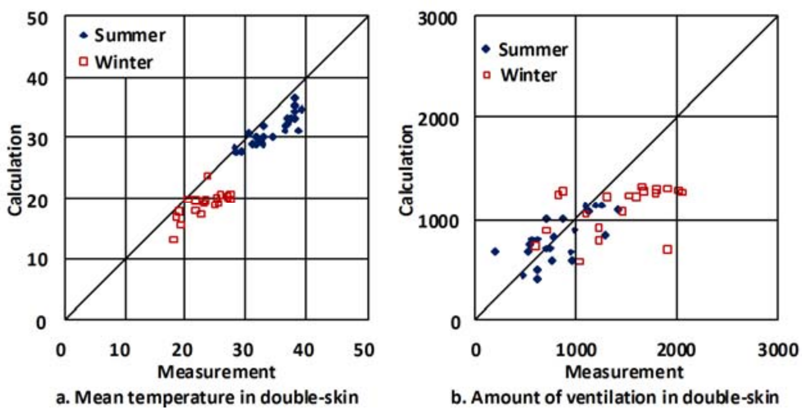
Physical properties	Value
Azimuth angle of North oriented double-skin [°]	0
Azimuth angle of East oriented double-skin [°]	-90
Azimuth angle of West oriented double-skin [°]	90
Azimuth angle of South oriented double-skin [°]	180
Inclined angle of double-skin [°]	90
Thickness of outer glass (refers to Table 1)	
Thickness of inner glass (refers to Table 1)	
Outer layer thick divided by blinds for 200 cm distance [m]	1.9
Outer layer thick divided by blinds for 150 cm distance [m]	1.4
Outer layer thick divided by blinds for 100 cm distance [m]	0.9
Outer layer thick divided by blinds for 80 cm distance [m]	0.7
Inner layer thick divided by blinds [m]	0.1
Slat angle of blinds [°]	45
Solar transmittance of blinds	0.1
Solar absorptance of blinds	0.5
Emissivity of blinds	0.95
Emissivity of glass	0.837
Flow coefficient of lower and upper aperture	0.65
Area of lower and upper aperture [m^2/m]	0.30
Ground reflectance	0.14

Source: Mulyadi et al, 2010a-b



Source: Mulyadi et al, 2010a-b; Mulyadi, 2010
Figure 4: Simulation flow chart

The simulation is based on the design and operational parameters (Table 2) and the input weather condition for working hours from 8:00 am until 17:00 pm. The indoor temperature is set to 25 °C. Natural ventilation through the stack effect is used, and the temperature inside the double-skin façade is calculated according to the heat balance equations. Both the temperature distribution and ventilation volume are calculated until convergence, and a stationary solution condition is obtained at each calculation time (Figure 4).



Source: Mulyadi, 2010
Figure 5: Validation result

In addition, the numerical simulation model is validated with data measured at the Izumi Campus Media Building of Meiji University located in Tokyo, Japan. Figure 5 shows the validation result. On average, the calculated temperatures in summer and winter, respectively, where 3.0 °C and 4.4 °C lower than the actual measured values. Even though the room air temperature used in the simulation is 26°C in summer and 22°C in winter, not all of rooms are air conditioned, which means that the simulation temperature is dissimilar from the actual temperature in the room. However, it is conceivable that the temperature in rooms without air conditioning in winter is higher than 22°C because of the heat loss by way of thermal transmission was reduced and solar radiation penetrating into the room. Furthermore, the calculated amount of ventilation in the double-skin façade is1% smaller in summer and 32% smaller in winter as the comparison with the measured value. The large difference for the winter measurement is due to the difference between the room temperature used in the simulation and the actual room temperature as described above. However, the numerical simulation in this research can generate the thermal behavior of double-skin façade.

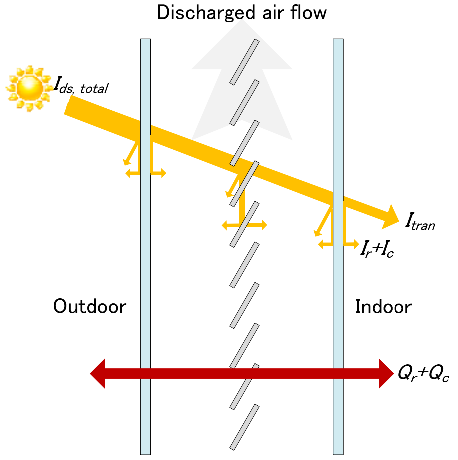
3. Prediction of U_{period} and SC_{period} of double-skin facade

The numerical simulation runs to determine the amount of solar radiation penetrated directly pass through double-skin façade (I_{tran}) and the quantity of solar radiation are absorbed in the outer surface of inner-glass which then transmitted into indoor as reradiated heat (I_r) and convective heat (I_c), the quantity of convective heat transfer (Q_c) and radiative heat transfer (Q_r) due to the temperature differences between indoor and outdoor (Figure 6). Also, air temperature and air flow volume in double-skin façade can be determined through this simulation. Since the I_r and I_c need to be separated from the air temperature in double-skin façade, additional simulation has to be runs by specifying the air temperature and air flow volume at the inside of double-skin façade to determine I_r'and I_c'. The air temperature and air flow volume at the inside of double-skin façade was taken as the result from previous simulation. Thus, then the U-value can be determined as below equation:

$$U = \frac{Q_r + Q_c}{\theta_o - \theta_i} \quad ...(7)$$

The SC-value can be determined through below equation:

$$SC = \frac{I_{tran} + (I_r - I_r') + (I_c - I_c')}{I_G} \quad ...(8)$$



Source: Mulyadi, 2010
Figure 6: Heat transfer in double-skin façade

The least-square method was utilized to determine the approximation formula of U-value and SC-value of double-skin. Below equations are illustrations of prediction of U-value and U_{period} as same as SC-value and SC_{period} of a case of double-skin façade with 10mm outer and inner glass combination with the distance of 80cm. From the calculation, we found that the U-value and U_{period} of double-skin façade respectively is:

$$U = 1.315 I_G^{0.121} + 0.940$$ ...(9)

$$U_{period} = \frac{\sum_{k=1}^{m}\left(1.315 I_{G,k}^{0.121} + 0.940\right)\left(\theta_{o,k} - \theta_{i,k}\right)}{\sum_{k=1}^{m}\left(\theta_{o,k} - \theta_{i,k}\right)} = 3.45$$ ...(10)

The SC-value and SC-period respectively is:

$$SC = 0.732 I_G^{-0.389} + 0,098$$ ...(11)

$$SC_{period} = \frac{\sum_{k=1}^{m}\left(0.732 I_{G,k}^{-0.389} + 0.098\right) I_{G,k}}{\sum_{k=1}^{m} I_{G,k}} = 0.20$$ ...(12)

Table below indicates the U equation, U_{period}, SC equation, and SC_{period} of simulated double-skin façade cases.

Table 3: U equation, U_{period}, SC equation, and SC_{period} 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

Source: Mulyadi, 2010

Note: the example cases code DS80(10+6) mean, DS=double-skin, 80=distance between outer and inner glass, (10+6)= combination of 10mm thick outer glass and 6mm thick inner glass.

4. 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 U_{period} and SC_{period} 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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Nomenclature

θ	Temperature [°C]
α	Heat transfer coefficient [W/(m².K)]
V	Amount of ventilation [m³/(s.m)]
c	Specific heat of air [kJ/(kg.K)]
ρ	Density of air [kg/m³]
G	Coefficient of emission for absorption [-]
I_G	Standard solar gain [W/m²]
I_a	Amount of absorbed solar radiation [W/m²]
U_{SS}	Overall heat transfer coefficient of single-skin façade [W/(m².K)]
U_{ig}	Overall heat transfer coefficient of inner glass and shading device of double-skin façade [W/(m².K)]
I_T	Heat gain by solar radiation [W/m²]
h	Amount of heat transfer [W/m²]
I	Solar radiation [W/m²]
Q	Heat transfer [W/m²]
Subscripts:	
o	Ambient
i	Room
og	Outer glass
ig	Inner glass
sd	Shading device
air	Air layer in double-skin
igDS	Double-skin outer surface of inner glass
ogDS	Double-skin inner surface of outer glass
c	Convection
r	Radiation
DS	Double-skin