Energy performance of a hybrid DSF-inspired solar heating façade for office buildings

Suyeon Bang1, Nari Yoon2, and Yeonsook Heo*

1School of Civil, Environmental, and Architectural Engineering, College of Engineering, Korea University, Seoul, Republic of Korea
2College of Architecture and Design, University of Ulsan, Ulsan, Republic of Korea

Abstract. Double-skin façade (DSF) is a passive design strategy that enhances building energy performance and improves indoor thermal comfort. In addition, DSF has been proposed as a hybrid façade that uses a cavity to preheat fresh air supplied to an air-handling unit (AHU) to reduce energy consumption for heating. However, to the authors' knowledge, there is no study about the design of DSF tailored for the hybrid system application yet. Therefore, this study focuses on the usability of DSF as a hybrid system and evaluates the performance. First, parametric analysis of the hybrid solar heating façade geometry and thermal properties of glazing and absorber materials was performed to identify the most influencing design parameters. Second, the multivariate linear regression (MLR) model was developed to predict the performance of all parameters comprehensively affecting the hybrid solar heating façade. Finally, the performance of various design alternatives for hybrid solar heating façade that provide the minimum fresh air supply was evaluated through case studies. The analysis results confirmed that the hybrid solar heating façade can reduce the heating energy due to the preheating effect by up to 38%.

1 Introduction

According to the World Energy Outlook 2021 [1] report, energy consumption in the building sector accounts for about one-third of the world's final energy consumption. As energy consumption in buildings continues to increase, many studies are being conducted around the world to reduce energy consumption in buildings. One of the passive strategies for improving the energy performance and indoor thermal comfort of a building is a double-skin façade (DSF) system. The DSF system consists of two or more layered structures which create a cavity between the outdoors and indoors [2]. The cavity of the DSF system acts as a buffer space between the outdoors and indoors to reduce the influence of the outdoor environment. With a strategic operation varying by season to regulate the airflow in the cavity, it can reduce the cooling and heating load and help ventilation [3].

In general, DSF systems can be classified into four types according to the partitioning as described in Fig. 1. There are a box type and a corridor type (Fig. 1(a-b)) as the single-floor DSF system, which is separated by each floor. In this case, it has the advantage of being able to operate a DSF system according to the characteristics of each room or floor. However, since the height of the cavity is set to be the same as the height of the floor, which limits the amount of airflow driven by the buoyancy effect. On the other hand, a multi-floor DSF system (Fig. 1(c-d)) can get an enhanced ventilation rate due to the increased cavity height. However, it is difficult to control for each floor, and cooling energy may be rather increased due to the high temperature of the upper part of the cavity [4].

Fig. 1. Various types of DSF system: (a) box window (top-left), (b) corridor (top-right), (c) shaft (bottom-left), (d) multi-story (bottom-right) double skin façades.

In general, DSF systems have been designed and evaluated as passive strategies that utilize natural ventilation as an additional façade for buildings. The effect of DSF design parameters on energy performance has been studied in several papers. Perez-Grande [5] highlighted the effect of the thermal properties of glazing on the cavity temperature by comparing 10 designs consisting of different internal and external glazing combinations. Safer [6] confirmed that the distance between the blind and the outer glazing located...
in the cavity affects the speed of airflow in the cavity. In addition, the DSF system can be applied as a hybrid system by utilizing ventilation or integrating it with the building's HVAC system. Choi [7] proposed a hybrid system that integrates multi-story DSF systems and air-handling units (AHU). This study showed that heating energy can be reduced by preheating outdoor air through the cavity. The effect of the multi-story DSF system installed in the front of the building on the heating energy reduction when operated in the form of a hybrid system was analyzed.

Therefore, this study evaluates the performance of the hybrid system and the usability of the DSF system as a hybrid system. The hybrid solar heating façade is designed to extend the height of the cavity to the whole height of the building to maximize the preheating effect and supply the preheated outdoor air to the building's existing AHU system. Cavity height (in association with building height) and width (in terms of fan flow rates per hybrid solar heating façade width) and thermal properties of external glazing and internal absorber were considered as design parameters. The impact of each parameter on the energy performance of the hybrid solar heating façade was analyzed. The multivariate linear regression (MLR) model was developed as a design analysis tool to predict the performance of various hybrid solar heating façade designs. Finally, the amount of heating energy savings during the heating period was quantitatively analyzed for different design alternatives of the hybrid solar heating façade.

2 Proposal of a hybrid DSF-inspired solar heating façade

2.1 Design concept

The DSF-inspired, hybrid solar heating façade (hereinafter the hybrid solar heating façade) proposed in this study has the same structure as the DSF system but is designed to reduce heating energy in the heating period by utilizing the preheating effect in the cavity. Fig. 2(a) shows the basic principles of the hybrid solar heating façade and the system operation strategy during the heating period. An inlet is located at the bottom of the cavity, and an outlet is located at the top of the cavity. Negative pressure is formed in the cavity by a fan installed at the top of the cavity so that the amount of fresh outdoor air required for the building can be provided through the inlet. The cavity allows for preheating the outdoor air so the preheated outdoor air within the cavity is moved through the plenum to the building's AHU system at the top of the building and provided as the supply air to meet the minimum ventilation rates. Instead of directly using outdoor air, the proposed design can reduce heating energy in the heating period by supplying preheated outdoor air to the AHU system.

The hybrid solar heating façade proposed in this paper consists of a cavity between the additional and existing building façades, and a solar absorber is coated on the existing building façade. The design flow rates of the fan installed at the top of the cavity are set to be the same as the minimum ventilation rates of the building to consider both the fresh outdoor air and the reduction of heating energy in the heating period. An illustrative example of this system installed on an existing building is provided in Fig. 2(b). Unlike a typical DSF system as a passive strategy, it is designed to be implemented as separate units between building windows rather than the whole southern façade of the building. As a passive strategy, the DSF systems need to be connected to each space and hence, usually applied to the whole southern façade. In contrast, the hybrid solar heating façade is implementable as separate modules connected to the AHU system and can be applied to some areas of the southern façade according to the target energy performance.

2.2 Modeling approach

Methods used to evaluate the energy performance of DSF systems include experiments [8], computational fluid dynamics [9], and building energy simulations [10, 11]. Among them, a building energy simulation model with coupling building energy simulation (BES) and airflow network (AFN) was used to properly model both the airflow and heat transfer behavior of the proposed system. Kim and Park [12] studied the suitability and limitations of the BES-AFN coupled model in EnergyPlus through a comparison of measured data and simulation results in the context of evaluating the performance of the DSF system. Blanco [13] developed the BES-AFN coupled model of a DSF system made of perforated sheets and verified the model developed in EnergyPlus against experimental data and other simulation results.
In this study, the performance of the hybrid solar heating façade was analyzed using EnergyPlus, a building energy simulation tool developed by the Department of Energy (DOE). EnergyPlus is based on building a thermal model but provides an environment for creating an AFN model, calculating flow rates based on pressure differences, and integrating these two models. The AFN model in EnergyPlus includes a network of AFN nodes, and airflows between them expressed as AFN linkages [14].

The hybrid solar heating façade is modeled by integrating the BES and AFN. As the AFN and BES models share air nodes within the cavity, it is possible to derive simulation results that reflect both heat transfer and airflow in the cavity. The cavity is divided into 24 zones as described in Fig. 3. Two external nodes were created, each of which was connected to one of the cavity nodes located at the inlet and outlet. The external node connected to the inlet represents the outdoor air whose pressure was determined by the external wind speed and wind direction. The external node connected to the outlet is an air node representing the AHU system. Therefore, this node was set to maintain a constant pressure by applying a zone exhaust fan object in EnergyPlus. To reflect the heat transfer between nodes within the cavity, the horizontal area between zones was modeled as a horizontal opening in the BES model, and the predicted airflow in the AFN model was used as an input. Weather data from Seoul, Korea, provided by the Korea Passive Architecture Association was used for the simulation [15].

We designed the test unit to be 1 meter wide and a half meter deep. The east and west sides of the test unit were set as adiabatic conditions because the same unit could be extended and applied. For the north wall, we set a constant surface temperature of 22°C during the occupied hour (8 a.m.-7 p.m.). The simulation period was set from November to February to determine the effect of heating energy saving in the eating period. To evaluate the energy performance of the hybrid solar heating façade, we chose the temperature difference between the outlet node of the hybrid solar heating façade ($T_{cav, out}$) and outdoor air node ($T_{out}$) as a performance indicator (PI). The PI represents how much the incoming fresh outdoor air is warmed by solar radiation while passing through the cavity, which we call the preheating effect. The PI is expressed as equation (1).

\[
PI = T_{cav, out} - T_{out}
\]

2.3 Design parameter

We selected a total of six parameters, including architectural and material parameters, through an investigation of the literature on DSF systems and solar air heaters. First, the architectural parameters include (1) cavity height and (2) cavity width, expressed in terms of fan flow rates per cavity width. For the cavity height, one-story was set to 3.9m, and a total of twelve-story were considered. Also, instead of changes in the cavity width that requires manual modeling of a cavity with different widths, we reflected the change in the cavity width with the use of fan flow rates: this indicates the design volume flow rate per unit (1 meter-wide). A minimal ventilation rate should be provided through the cavity to the AHU system. When considering the fixed ventilation requirement for a given building, the higher the fan flow rates, the fewer number of the hybrid solar heating façade unit. Hence, the fan flow rates were used to investigate the effect of the installation area under the minimum ventilation rates of the building. As illustrated in Fig. 2(b), multiple hybrid solar heating façade units can be installed onto a building. Because the heating energy savings are directly related to the number of hybrid solar heating façade units, multiple simulations with varying numbers of cavities should be conducted to fully understand the influence of the number of cavities. However, to enhance the modeling and simulation efficiency, we fixed the test unit as a single, 1 meter-wide cavity and applied different design flow rates of the fan to represent the varying number of cavities.

Second, material parameters include the thermal properties of external glazing and internal absorber, which are components of the hybrid solar heating façade. Among the thermal properties of external glazing, we considered (3) solar heat gain coefficient (SHGC), (4) thermal transmittance (U-value) of the external glazing, (5) solar absorptance, and (6) thermal emittance of the internal absorber. We referred to the literature [16, 17] regarding the range and the most frequently used values of the thermal properties used in our study. Table 1 summarizes the minimum and maximum values tested for each parameter.

![Fig. 3. BES-AFN coupled model of a test unit.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min/Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity height</td>
<td>3.9/46.8</td>
</tr>
<tr>
<td>Fan flow rates (as a surrogate to cavity width)</td>
<td>0.010/24.00</td>
</tr>
<tr>
<td>External glazing</td>
<td>0.972/0.995</td>
</tr>
<tr>
<td>U value</td>
<td>1.573/5.894</td>
</tr>
<tr>
<td>Internal absorber</td>
<td>0.001/0.999</td>
</tr>
<tr>
<td>Solar absorptance</td>
<td>0.001/0.999</td>
</tr>
<tr>
<td>Thermal emittance</td>
<td>0.001/0.999</td>
</tr>
<tr>
<td>Outdoor dry-bulb air temperature</td>
<td>-</td>
</tr>
<tr>
<td>Wind speed</td>
<td>-</td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>-</td>
</tr>
</tbody>
</table>
2.4 Exploring the design space

This study uses the sampling method, Latin hypercube sampling (LHS), to explore the design space specified in Table 1. The LHS is a type of stratified Monte Carlo sampling designed to uniformly cover the design space with reduced samples in comparison to the Monte Carlo sampling. It provides a sampling of the parameters from distributions of $P_1$, $P_2$, …, $P_k$. The workflow of generating simulation results of the design space exploration is shown in Fig. 4.

First, DesignBuilder was used to create an IDF file to be used in JEPlus and EnergyPlus. DesignBuilder is a software program that allows EnergyPlus to create geometry for use. In this step, the cavity height was considered, and a model was created for the height corresponding to the one to twelve-story. Second, JEPlus generated 600 LHS considering the remaining five parameters (cavity width, SHGC, U value, solar absorptance, thermal emittance). JEPlus is a tool used to perform parametric analysis with EnergyPlus. EnergyPlus and Seoul's typical meteorological year (TMY) data were used to simulate the sample. To understand the uncertainty due to climate conditions, three additional weather parameters, (7) outdoor dry-bulb air temperature, (8) wind speed, and (9) global solar radiation were included in the simulation process. Therefore, there were a total of nine parameters considered, six design parameters, and three weather parameters.

Fig. 4. Schematic workflow for sampling.

3 Statistical analysis

3.1 Correlation analysis

As the first step, the correlation between the PI and each parameter was analyzed at the hourly resolution. Through the scatterplot of each parameter, it was confirmed that a noticeable consistent trend with a moderate correlation coefficient value was exhibited only in the case of the fan flow rates. Furthermore, the scatterplot between the fan flow rates and PI was shown to be nonlinear and as shown in the top scatterplot of Table 2.

Table 2 summarizes the scatterplots and correlation coefficient of various forms associated with the fan flow rates parameter. Instead of the existing fan flow rates, $1/fan$ and $\sqrt{1/fan}$ were considered as a potential predictor to the MLR model. Both $1/fan$ and $\sqrt{1/fan}$ yielded not only higher correlation coefficient values than the original parameter but also a more linear relationship to the PI. Since the correlation coefficient of $1/fan$ was the highest, further analysis steps were conducted using $1/fan$, as a substitute for the fan flow rates.

Table 3 summarizes the Pearson correlation coefficients of the total nine parameters to the PI at different time resolutions. Pearson correlation coefficient is an extensively used mathematical method to measure the level of relation between linearly related variables. If the Pearson correlation coefficient has a positive value between 0 and 1, it means when one variable changes, the other variable changes in the same direction. In the results, the architectural parameters showed a much stronger correlation to the PI than the material parameters. Among the weather parameters, global solar radiation had the greatest influence on the PI. Of all parameters tested, $1/fan$ showed the strongest correlation to the PI. Regarding the temporal resolution of PI, both hourly and daily resolutions showed a similar ranking of correlation coefficients, although the daily resolution yielded higher correlation coefficient values than the hourly resolution. This may be due to higher variability in the hourly data in comparison to average daily data.
Table 3. The correlation coefficients of parameters to the PI.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hourly</th>
<th>Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity height</td>
<td>0.121</td>
<td>0.168</td>
</tr>
<tr>
<td>1/Fan</td>
<td>0.569</td>
<td>0.706</td>
</tr>
<tr>
<td>SHGC</td>
<td>0.068</td>
<td>0.084</td>
</tr>
<tr>
<td>U value</td>
<td>−0.042</td>
<td>−0.052</td>
</tr>
<tr>
<td>Solar absorptance</td>
<td>0.041</td>
<td>0.051</td>
</tr>
<tr>
<td>Thermal emittance</td>
<td>−0.027</td>
<td>−0.033</td>
</tr>
<tr>
<td>Outdoor dry-bulb air temp</td>
<td>−0.067</td>
<td>−0.068</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.062</td>
<td>0.105</td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>0.265</td>
<td>0.279</td>
</tr>
</tbody>
</table>

3.2 Sensitivity analysis

The Pearson correlation coefficient used in Section 3.1 is an indicator of a linear relationship and does not properly capture the nonlinear relationship and parameter interactions. Therefore, to fully reflect these factors in the identification of important parameters, the variance-based sensitivity analysis was performed using JMP. JMP is a software for statistical analysis developed by JMP, a subsidiary of SAS Institute. We compared the first-order effect of individual parameters and the second-order effect by the interaction of two parameters. A logworth of a parameter was used as the measure of the statistical significance of the parameter. Logworth is a p-value transformation based on Pearson Chi-Squared test. The greater this value is, the more significant the parameter is.

The first-order effect of individual parameters and second-order effect by the interaction of two parameters are expressed as logworth and are shown in Fig. 5. Only five top parameters, including the first-order effect and second-order effect are presented. Both hourly and daily data showed similar trends. 1/Fan particularly the interaction of 1/Fan with global solar radiation and cavity height is crucial to be considered in addition to the first-order effect of individual parameters.

3.3 Multivariate linear regression

Multivariate linear regression (MLR) model was developed to predict the performance of the hybrid solar heating façade. Key factors identified as important in Sections 3.1 and 3.2 were used as predictors in the model development. We used both hourly data and average daily data to develop corresponding statistical models. We compared the MLR model with only individual parameters with that with both individual parameters and two major interaction terms.

R-squared ($R^2$, or coefficient of determination) and root-mean-square error (RMSE) was used to evaluate the model prediction accuracy. The prediction accuracy of MLR models at the hourly and daily resolution is summarized in Tables 4 and 5. It was confirmed that the model accuracy was higher in the case of average daily prediction than in the case of hourly prediction. This trend is expected as the hourly data showed not only a wide range of variations in the outdoor and indoor conditions but also time correlations within time series data. In addition, the prediction accuracy increased significantly when both interaction terms were added. The equation of the daily MLR model with two interaction terms with the highest $R^2$ is expressed in (2).

\[
P_I = -0.03x_{CH} - 1.14x_{Fan} + 0.36x_{SHGC} - 0.01x_{U value} + 0.004x_{Sx} - 0.002x_{TE} \\
- 0.005x_{TP} + 0.25x_{WS} - 0.0007x_{GSR} + 0.005x_{Fan} \cdot x_{GSR} + 0.06x_{CH} \cdot x_{Fan} - 0.62
\]

In Section 3, we analyzed the relationship between the PI and each parameter through correlation and sensitivity analysis. We developed the MLR models based on different time resolution data by introducing interaction terms. As a result, the highest $R^2$ was found in the daily MLR model with two interaction terms. Therefore, we conduct a case study in the next section to show how this MLR model can be used to support designing the hybrid solar heating façade.

4 Case study

4.1 DOE reference building

Among DOE reference office buildings provided by the U.S. Department of Energy, we selected the case building as a twelve-story office building with a width of 73.10 meters, a depth of 48.73 meters, and a height of 46.80 meters. We calculated the minimum ventilation rates according to the minimum ventilation rates criteria.
specified by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [18] which is shown in equation (3). $V_{bz}$ is a minimum ventilation rates of the occupiable space. $R_p$ and $R_a$ are the coefficient per person and per floor area for different building types, respectively. $P_z$ indicates the number of occupants, and $A_z$ the floor area. Considering the number of occupants and floor area of the case building, the minimum ventilation rate is 23.973 m$^3$/s.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \quad (3)$$

### 4.2 Design analysis based on the MLR model

In Section 3, the fan flow rates (as a surrogate parameter of the cavity width) showed by far the greatest influence on the PI than the other five design parameters. Therefore, this section focuses on investigating the effect of increasing cavity width while fixing the five design parameters. First, the cavity height of the hybrid solar heating façade was designed to be the same as the building height to obtain the maximum preheating effect. The parameters representing the thermal properties of external glazing and internal absorbers used the values of materials used as materials for the hybrid solar heating façade [16, 17]. SHGC was fixed at 0.762, U value at 3.159, solar absorptance at 0.88, and thermal emittance at 0.084.

Two performance indicators were used for design analysis: the preheating effect and heating energy savings. The preheating effect was calculated through equation (1). The heating energy savings were calculated through equation (4). $Q$ is the heating energy saving, $c$ is a value of 1.012 kJ/(kg·K) as the specific heat of air, $\dot{m}$ is the mass flow rate of airflow through the hybrid solar heating façade, and $\Delta T$ is increased in the outdoor air provided to the AHU system as the result of the preheating effect. The annual heating energy saving value calculated through equation (4) was divided by the total building area of the reference building and expressed as the amount of heating energy savings per floor area.

$$Q = c \cdot \dot{m} \cdot \Delta T \quad (4)$$

Fig. 6 shows the average daily temperature difference predictions by the developed MLR model in relation to the proportion of cavity width to the total southern façade area. The temperature difference predictions by the MLR model are compared against those by the simulation model. The range of temperature differences shown in the boxplots indicates its variation due to the weather parameters (outdoor dry-bulb air temperature, wind speed, global solar radiation). Although the trends of the two boxplots were similar, it was confirmed that the predictions by the MLR model (equation (2)) exhibited a preheating effect about 1°C lower than those by the simulation model. Although the MLR model results tend to predict relatively lower results than the simulation results, in both cases, both models provide the same trends to support design decisions. Fig. 7 shows the heating energy saving according to the cavity width (the proportion of cavity width). As expected, an increase in the width of the hybrid solar heating façade led to an increase in both the preheating effect and heating energy savings. Moreover, the heating energy saving was increased by a minimum from 0.26 kWh/(m$^2$·year) to a maximum of 10.00 kWh/(m$^2$·year). These correspond to the 1.02% and 38.39% of heating energy savings. Even when the installed area of the hybrid solar heating façade was small, a certain degree of heating energy saving was obtained.

![Fig. 6. Comparison of daily average temperature different predictions by the MLR model and the simulation model according to the fan flow rates.](image)

![Fig. 7. Heating energy savings according to the fan flow rates.](image)

### 5 Conclusion

In this study, the hybrid DSF-inspired solar heating façade was proposed and energy simulations were conducted. A statistical MLR model was developed and a case study conducted on the potential of an active system integrated with the building's AHU system was evaluated by utilizing the airflow of the cavity, and the preheating effect according to the parameters was analyzed. The main results derived from the case study are as follows.

1. The analysis of the energy performance of the hybrid solar heating façade confirmed that the fan flow
rates of the hybrid solar heating façade had the greatest effect on the parameter and that the solar radiation energy compared to the inflow of outdoor air is the most important on preheating effect.

(2) In the design parameters, the greater preheating effect was correlated to a higher cavity, greater fan flow rates, a higher SHGC, a higher solar absorptance, a lower U value, and a lower thermal emittance.

(3) When the preheated outdoor air is conveyed into an existing AHU system in the heating period, the heating energy of at least 0.26kWh/(m²·year) to up to 10.00kWh/(m²·year) could be reduced through the hybrid solar heating façade.

(4) It was verified that the preheating effect predicted by the MLR model (equation (2)) was around 1°C less than that predicted by the simulation model although both showed similar trends.

This study analyzed the effect of heating energy savings achieved by the hybrid solar heating façade through the preheating effect as an active system during the heating period. It has been confirmed that the hybrid solar heating façade can be implemented as a separate module connected to the AHU system and various designs can be selected depending on the target energy performance. In addition to the role of the active system, the hybrid solar heating façade can serve as a passive system when an active system is disabled. Therefore, to comprehensively evaluate the performance of the hybrid solar heating façade, it is necessary to evaluate not only the heating energy savings through the preheating effect but also the energy load reduction of the building through passive performance.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A5A1018153) and the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant KAIA22HSCT-C157909-03).

References