Determining Optimum Configurations of Solar Collecting Window Systems for Double Skin Envelope

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Abstract

This study investigates the influence of cavity depth and the conditions of louvers on indoor thermal environments to propose optimum configurations of solar collecting window systems that can be effectively applied to double skin envelopes. Field measurements were performed for a reduced-scale mock-up model to represent the analysis results for a full-scale model. Computer simulations were performed using computational fluid dynamics (CFD) under a variety of cavity and horizontal louver conditions to validate the results from the field measurements. Two theoretical computation models, namely the k-e RNG and k-e standard models, were applied to the simulations.

The results of field measurements imply that a cavity depth of 0.2 m was most effective in supplying air from a cavity to an indoor space with the required velocity and temperature. The validated computer simulation results imply that the k-e RNG model was more effective than the k-e standard model in predicting the properties of airflow in cavities where turbulent patterns occur due to the buoyancy effect.

According to the analysis based on the k-e RNG model, a cavity depth of 0.2 m appeared to be optimum to achieve the required ventilation rates with energy savings. The temperature and velocity of air supplied from the cavity to the indoor space was most effective when the tilt angle of the horizontal louver was 45°. While airflow passed through the cavity exchanging heat with the louvers, it was not significantly blocked by the tilted louvers. This improved natural convection and ventilation rates in the cavity. This study suggests that the solar collecting window system could be effectively applied to building envelopes in winter.

Keywords: solar collecting window system; double skin; airflow; natural convection; optimum cavity configuration

1. Introduction

For the past several decades, tightly-sealed and well-insulated building envelopes have been used for commercial buildings due to the rapid escalation of energy costs. The envelopes contributed to the reduction of energy consumption, but resulted in less infiltration from the outdoor to indoor space due to the reduced infiltration through them. In addition, the ventilation rate was recommended to be reduced based on the standards\(^1\). The reduced ventilation rates failed to completely remove potentially hazardous contaminants, and caused significant health problems in residents, such as sick building syndrome. Due to this, ventilation rates increased again based on the standards\(^2\).

However, the increased ventilation rates require additional energy consumption and generate environmental loads. Under this circumstance, double skin envelopes and solar collecting window systems with cavities are viable design options for sustainable building strategies, since they effectively provide additional ventilation using natural ventilation and diminish the loads of mechanical ventilation systems.

A variety of designs with various cavity configurations have been proposed and practically applied to buildings\(^3\)\(^,\)\(^4\). However, the optimum dimensions of a cavity have not been clearly proposed. The dimensions of a cavity are very critical, since the air induced into the cavity from outdoors is heated by solar radiation and supplied to the indoor space according to the amount of natural convection. The temperature and velocity of air in a cavity, which are the eventual properties of the air supplied to an indoor space, vary according to the dimensions of the cavity and the conditions of shading devices in the cavity.

Since the temperature and velocity of air in the cavity critically influence the indoor thermal environment, specific attention should be paid to them when a double skin envelope system is designed. Optimum cavity dimensions and shading conditions significantly diminish energy cost for the entire life cycle of buildings.
Therefore, this study examines the influence of cavity dimensions and louver conditions in cavities on indoor thermal environments to propose an optimum configuration of double skin envelopes for solar collecting systems that can be effectively applied to building façades. Field measurements were performed on a reduced-scale mock-up model. Using the measurement data, computer simulations based on two theoretical backgrounds were carried out to validate the measurement results. The theory that achieved better validation results was applied to further simulation to determine the optimum configuration.

2. Research Method
2.1 Field Measurement

Field measurements were performed on a reduced-scale mock-up model, which represented the full dimensions of the space. A scale of one to three (1/3) was applied to the original dimensions of space to create the reduced model. The reduction of scale used in this study was based on the principle that was effectively applied to other studies\(^7\). This principle of scale reduction is that the outdoor factors generate similar reactions in both a reduced and full-scale model. It is known that a reduced model can be used to represent the variation of air velocity in a full-scale model when the airflow in the two models is turbulent.

The original dimensions of the space considered in this study were 3 m wide by 3 m deep by 3 m high. A cavity was installed in front of the room for a solar collecting shading device. The dimensions of the cavity were 1 m wide by 0.1 m deep by 2 m high. Fig.1 shows the details of the original space. A reduced scale of 1/3 was applied to the original space to build a reduced model for field measurements. The model faced south so that the influence of solar heat gain on the cavity space was effective.

To examine the influence of cavity depth, three other depths such as 0.2 m, 0.3 m, and 0.4 m were applied to the model while the width and height was kept constant. Openings were installed at the bottom and top of the cavity to allow air flow into and out of cavity. The opening at the top was connected to the indoor space. The dimensions of the openings were 10 cm by 5 cm for the reduced-scale model. The opening area was kept constant when the depth of the cavity increased from 0.2 m to 0.4 m. The position of the opening is shown in Fig.1.

Louvers that function as solar collecting surfaces were installed in the cavity. Each louver surface consists of material that collects solar radiation. The distance between transparent material and louver surface was 1 cm. Between them was a vacuum. Each louver was tilted by 45° and the distance between each louver slat was 0.25 m. A detailed description of the cavity and louver conditions is shown in Fig.2.

The reduced model was located on the rooftop of a university building in Seoul, South Korea (Latitude: 37°35’N, Longitude: 127°03’E). No shadow was cast from neighboring buildings on to the reduced model. Data monitoring was performed from January 7 to 12, 2006. The physical properties for the thermal analysis and airflow analysis were monitored using an automatic data-logging system. The monitored data were outdoor and indoor temperature, surface temperature of the solar collecting louver in the center of the cavity, the air velocity at air inlet and outlet, outdoor air velocity, outdoor horizontal irradiance and vertical irradiance. The measurement data were the fundamental input for computer simulations to determine the optimum configurations of the solar collecting window system proposed in this study.

2.2 Computer Simulation

A series of computer simulations were performed for the reduced-scale mock-up model used for field measurements. Fluent version 6.0, which is based on computational fluid dynamics (CFD) theory was primarily used for the simulation in this study. This software is considered to be effective in predicting airflow patterns, air velocities, and variation in thermal properties for a given space. Since Fluent uses a specific coordinate system to represent prediction results, and is capable of predicting turbulent and laminar flows. It was predominantly used to predict the variation of airflow in the space\(^6\).
In this study, the airflow in the cavity is considered to be potentially turbulent, since the accumulated solar radiation in the cavity causes buoyancy effects in the air and natural convection occurs. Therefore, the k-e standard model and renormalization group (RNG) k-e model were used to validate field measurement results.

The k-e standard model is typically applied to most CFD programs that analyze air flow in space by certain power sources, such as mechanical ventilation systems or fire. Based on this model, further modifications were made and several k-e models were proposed. The k-e RNG model, which adapts renormalization group theory, utilizes low Reynolds numbers for viscosity and is effectively applied to airflow that recirculates in space.

In this study, simulation results from the two models were compared with field measurement results. A theoretical model that generates results closer to those from field measurements was used in further computer simulations to propose optimum cavity configurations and louver conditions for a full-scale space.

The room and cavity dimensions used for computer simulations were considered to be equal to those applied to field measurements. The cavity depth was assumed to be 0.1 m, 0.2 m, 0.3 m, and 0.4 m, so that simulation results could be compared with those from field measurements. Solar collecting louvers were assumed to be installed in the cavities. The physical properties and conditions of louvers were equal to those used in measurements. Tilt angle and variation of louver area was assumed to increase or remain constant as the cavity depth increases. In addition, to the building code in Korea.

For each of the four cavity depths, the surface area of the louver was assumed to increase or remain constant as the cavity depth increases. In addition, to examine the effect of tilt angle of louver under each change of cavity depth, the louver was considered to be tilted by 30°, 45°, 60°, and 75° without a change in louver area when the cavity depth increases.

The surface temperature of the louver was assumed to be equal to that monitored in the field measurement. The detailed dimensions of the cavity conditions are shown in Fig.2. The opening in the cavity where air is induced was assumed to be exposed to atmospheric conditions. It was assumed that the temperature of the air induced into the cavity from outdoors was 0°C, and the indoor temperature was 20°C for winter. This assumption was applied to all simulations in this study.

3. Results
3.1 Thermal Properties in Field Measurements

The surface temperature of a solar collecting louver in a cavity increased as solar radiation increased. Fig.3 shows the temperature variation of the louver surface according to four different cavity depths. Overall, the temperature was the lowest when the cavity depth was 0.4 m, but temperature did not vary significantly with changes in the cavity depth. The temperature variation did not appear to be significantly influenced by changes of cavity depth. The surface temperature of louver reached a maximum of 52°C around noon when the solar radiation was greatest. The temperature appears to be more strongly influenced by direct solar radiation than diffused solar radiation. Due to the accumulation of solar radiation on the surface, the temperature became high enough to cause buoyancy effects in the cavity, and it could circulate the air naturally and supply it to the indoor space.
In general, the temperature of the air that was supplied indoors from the cavity did not show significant variation when the cavity depth changed from 0.1 m to 0.4 m. Fig.4. shows the variation of temperature based on cavity depth. The temperature difference between the different cavity depths had a range of 2°C. As solar radiation increased, the temperature of the supplied air increased.

The air temperature reached its maximum value at a cavity depth of 0.1 m and the air temperature was lowest when the cavity depth was 0.4 m. Generally, this result implies that the narrower the depth of the cavity, the more significant solar radiation will be in the air cavity. Accordingly, the buoyancy effect in the narrow cavity will occur more effectively compared with the wide cavity. For the most of the daytime, when direct solar radiation had an influence on the cavity, the temperature of the air that was supplied into the indoor space from the cavity was higher than 15°C. This air which was naturally ventilated to the indoor space effectively provided a higher ventilation rate thereby reducing the heating load, since the difference between the preheated air in the cavity and the outdoor air can be as great as 15°C.

The velocity of airflow into the indoor space from the cavity varied for the four cavity depths, as shown in Fig.5. The differences in air velocity occurred because the amount of heat transfer by convection that happened after the louver was heated by solar radiation. The air in the wider cavity was apt to be heated weakly, and the air in the narrower cavity was not effectively circulated and supplied into the indoor space. Among all cases, the air velocity was the greatest when the cavity depth was 0.2 m. The air velocity ranged from 0.13 to 0.47 m/s for the reduced-scale model. Based on the theory that governs the reduction of a full-scale model to a reduced-scale model, these values correspond to values of 0.23 to 0.84 m/s for full-scale models.

### 3.2 Validation of Variation in Thermal Properties by Computer Simulations

Computer simulations for the reduced-scale model generated the specific thermal properties of air in the cavity as the cavity depth varied. The simulation results by the k-e standard model and k-e RNG model were compared with the results from measurements to examine which model should be used for further simulations to determine the optimum configurations for cavity depth and the solar collecting louver.

The comparison in mean temperature of supplied air to indoor space is shown in Fig.6. The data showed the values in the center of the diffuser that is connected to the indoor space at the top of the cavity. Overall, the simulation results by the two theoretical models showed greater values than those obtained from field measurements, although the input data for the simulations were equal to the data measurements.

The deviation between the measured and simulated data decreased when the k-e RNG model was used, since this model uses low Reynolds numbers. In addition, the airflow analyzed in this study has a buoyancy effect in the cavity due to the accumulation of solar radiation on the solar collecting louver. The buoyancy effect in the cavity is believed to generate turbulent airflow. Therefore, the simulation using the k-e RNG model showed less deviation from the field measurement results for all conditions of cavity depth.

The relationship between measured and simulation results by the two models was analyzed using linear regression to determine which model would work effectively in predicting the physical properties of air.
in a cavity. The linear correlations between the velocity obtained from field measurements and simulations are shown in Fig.7. ANOVA tests were performed to examine if the correlation was acceptable under a lower significance level. A summary of the test is shown in Tables 1. and 2.

Overall, the velocity predicted by the two models showed a reasonable relationship with the measurement results. The relationship between measurements and the k-e RNG model was stronger than that between measurements and the k-e standard model. Coefficients of determination for the former and latter were 0.8312 and 0.8091, respectively. This means that the variations in air velocity through prediction using the k-e RNG and k-e standard model were reduced by 83.12% and 80.91%, respectively, when the measured air velocity was considered for the linear regression. The ANOVA test results implied that an acceptable linear relationship existed between the measured and simulated velocity for the k-e standard model and k-e RNG model respectively.

The k-e RNG model had a stronger relationship with the measured data since the airflow pattern in the cavity was natural convection powered by the heat that accumulated on the louver surfaces from solar radiation. In summary, the k-e RNG model appears to be more useful than the k-e standard model for further simulations to determine the optimum cavity depth and the conditions of the solar collecting louvers since solar radiation accumulates on the louver and functions as the source of heat in the cavity.

3.3 The Influence of Cavity Depth for Louver Surface Area

The air velocity in the cavity changed as the cavity depth varied. Fig.8. shows the variation of air velocity for each of the four cavity conditions. When the cavity depth was 0.1 m, the mean velocity was so much slower than 0.2 m/s that it did not appear to provide adequate ventilation rates to the indoor space. The airflow under this condition generally appears to be laminar flow, and the circulation of air was not dynamic. As the depth increased to 0.2 m, the mean air velocity in the cavity became less than 0.4 m/s, and started to circulate actively.

The circulation of air occurred dynamically since the solar radiation accumulated on the louvers was enough to create a buoyancy effect in the cavity. For the case of a cavity depth of 0.3 m, airflow was not effective near the lower parts of the louvers, but occurred primarily near the upper parts of the louvers. This implies that the lower parts of the louvers did not contribute effectively to the air circulation in cavity.

When the cavity depth increased to 0.4 m, the airflow pattern was similar to that for the 0.3 m cavity depth. For these two cases, airflow in the cavity occurred near the upper part of each louver slat and reduced the buoyancy effect. As the cavity depth increased, the system became less efficient since the efficiency of the solar collecting surface decreased. As for the measured results, a cavity depth of 0.2 m was most effective.

The air temperature in the indoor space was also influenced by the change in cavity depth, since the air in the cavity was assumed to be supplied indoors after it was warmed up by the heat gain from the solar radiation and louver surface. Fig.9. shows the temperature variations in the indoor space. For a cavity depth of 0.1 m, the air in the cavity was not warmed up enough due to insufficient heat from the louver surface. The heat from the louvers was very little due to the small surface area of each louver. The small surface area was incapable of generating enough heat that was released in to the cavity to warm the air. Effective air circulation was not detected due to the insufficient amount of heat.

At cavity depths of 0.3 m and 0.4 m, the air supplied to the indoor space was not warm enough for indoor use. The heat transferred from the louver surface to the cavity was not enough to warm the air in the cavity since the volume of the cavity increased. It does not appear that the heat exchange between the air and louver surface occurred effectively since the air induced into the cavity passed through the louver with high velocities without enough time to exchange heat with the louver surface.
However, when the cavity depth was 0.2 m, the louver surface functioned most effectively. The indoor temperature varied within the comfortable range suggested by the guidelines due to air supplied from the cavity. This variation occurred because the airflow in the cavity had less velocity, facilitating heat exchange with the louver. In summary, a cavity depth of 0.2 m functioned best to generate the airflow necessary to provide air to the indoor space from the cavity due to the effective contribution of the louver. In this case, the indoor temperature was kept within the comfortable range proposed by the guidelines.

This result implies that heating load in winter could be reduced when the appropriate controls of a solar collecting window system are applied to buildings, since the air in the cavity was preheated by the accumulated irradiance and supplied to the indoor space.

The solar collecting window systems are expected to effectively contribute to forming a comfortable indoor air environment when they are applied to provide natural ventilation. In this case, the system could effectively save heating energy and supply pretreated air from cavities on a continuous basis. This result is expected to mitigate heating loads for the mechanical systems of buildings with improved ventilation rates.

### 3.4 The Influence of Cavity Depth and Louver Angle for Constant Louver Surface Area

When the surface area of the solar collecting louver increases proportionally to the cavity depth, the upper parts of the louver slats could be covered by the shadow cast by other louver slats located above them. Under clear sky conditions, the shadow effect appeared to be negligible when the cavity depth was 0.1 m or 0.2 m, although the surface area of the louver increased. However, the shadow effect could be significant when the louver slats are installed in a 0.3 m or 0.4 m deep cavity.

To avoid this potential problem, this study also examines the case in which the shadow effect was excluded when solar collecting louveres were installed in the cavity. The air velocity in the cavity varied as cavity depth increased. Fig. 10 shows the variation of air velocity in each of the four cavity conditions.

For a cavity depth of 0.1 m, the velocity remains very slow. This implies that natural convection caused by the louver did not occur effectively for a narrower cavity even if the number of louver slats increased. A cavity depth of 0.2 m was most effective for natural ventilation, since the air in the cavity appeared to flow very dynamically and exchanged heat with the slats.

For cavity depths of 0.3 and 0.4 m, the air velocity near the upper and lower parts of each louver slat was slow. In particular, it appears that the airflow from the lower regions in the cavity passed through a limited part of the louvers and exchanged heat with them. This implies that the edge of the slat did not contribute significantly to the movement of air in the cavity.

When the depth was 0.1 m, the overall airflow in the cavity looked similar to laminar flow, since natural convection due to the heat from the louver surface was not effectively transferred to the cavity space. For cavity depths of 0.3 m and 0.4 m, airflow constantly occurred near the surface area of the louver. However,
it does not appear that the overall airflow was stronger in these cases than in the case of a cavity depth of 0.2 m.

The tilt angle of the louver is a critical factor that should be considered when analyzing the influence of cavity configuration on an indoor thermal environment, since heat from solar radiation accumulates on the louver slats and airflow in the cavity has to pass through them. The influence of the louver angle on the thermal properties of air was examined when the surface area of the louver slat remains constant as the cavity depth increases.

Figs.11.-13. show the influence of the louver angle on the air temperature and airflow in the cavity. Overall, the temperature and velocity of the airflow at the opening connected to the indoor space were influenced by the tilt angle of the louver. These properties reached maximum values when the louver angle was 45°. The mean velocity was 0.51 m/s, and the mean temperature was 27.7°C. These values decreased as the louver angle increased beyond 45°.

Airflow was not effectively conveyed into the indoor space when the tilt angle was 30°, since the louver slats functioned as resistance that blocked airflow in the cavity, and the heat transfer between the air and louver surface was ineffective. Due to the reduction of air velocity caused by the louver, the natural convection in the cavity was weak. This result implies that a louver angle of 30° might not achieve adequate ventilation rates through the cavity. The up-streaming airflow did not pass effectively through the louver surface where solar radiation accumulated. This could possibly result in the cold air induced into the cavity from outdoors being supplied into the indoor space without being adequately preheated.
When the tilted angle of the louver was 45°, the air temperature in the cavity was warm enough to be supplied to the indoor space. Heat was effectively exchanged between the airflow and louver slats due to the louver configuration and airflow velocity in the cavity. The louver surface that contains solar radiation was contacted effectively by the air streaming up toward the opening at the top of the cavity. Under this condition, the airflow velocity and temperature were balanced so effectively that the air supply from the cavity was efficient enough to achieve additional ventilation rates with energy savings.

In the case of louver angles of 60° and 75°, the ventilation rates supplied from the cavity decreased and the air temperature in the cavity was not high enough. It does not appear that the heat released from the louver surface was transferred effectively to the air that passed through the cavity, since excessive airflow with high velocities occurred in the cavity. In addition, the majority of the airflow did not appear to pass through the main body of the louver, but moved along the cavity surface. This pattern of airflow caused insufficient heat exchange between the louver and airflow in the cavity. Accordingly, the supplied air was not warm enough to be utilized effectively in an indoor space in winter.

In summary, a louver angle of 45° appears to be optimal since air convection in the cavity was significantly influenced by the heat released from the louver surface and the pathway of airflow in the cavity.

4. Conclusions

Computer simulations and field measurements were performed under various combinations of cavity depths and louver tilt angles to determine the optimum configuration for solar collecting window systems. A summary of the general findings of this study are as follows:

1) Field measurement results from a reduced-scale model imply that solar collecting window systems can be effectively applied to building envelopes in winter, since the temperature of solar collecting surfaces increased up to 52°C even when the outdoor air temperature was lower than -7°C. Under various outdoor temperature conditions, a cavity depth of 0.2 m was most effective in supplying air from the cavity to the indoor space with the requisite velocity and temperature.

2) Computer simulation results were validated by field measurement results in a reduced-scale model. The results from the k-ε RNG model were closer to the field measurement results than the results from the k-ε standard model, since the cavity contained turbulent airflow caused by the buoyancy effect, which was influenced by solar radiation and the heat emission from the louver surface to the air in the cavity.

3) Using the k-ε RNG model, this study specifically determined the optimal cavity configuration for solar collecting window systems. A cavity depth of 0.2 m was optimal to achieve ventilation rates and energy savings. This condition provided a better thermal environment using pretreated air in the cavity.

4) The temperature and velocity of air supplied from the cavity to the indoor space was most effective when the louver slats were tilted by 45°. Under this condition, the airflow was not blocked significantly by the louver slats, and there was effective heat exchange between the air and the louver as the air passed through the cavity. This caused better natural convection in the cavity with improved ventilation rates.

5. Limitation and Future Work

This study used field measurements for a reduced-scale model and computer simulations based on the measurements. Due to this, the monitored data were not identical to those that would be obtained in a full-scale model, even though this approach is theoretically justified. Further research based on field measurements on a full-scale model or actual building would be useful to validate the results from computer simulations. The algorithms used for computer simulations have limitations. Additional simulations using various theoretical models would be useful.

Since the contribution of louver and cavity configuration was the primary concern of this study, the influence of a solar collecting window system on the reduction of heating and cooling load was not discussed specifically. It was obvious that the solar collecting window system could effectively reduce heating load compared with a typical window system. However, the comparison on the load by these two window systems was not discussed specifically in this study. Detailed analysis on them would be beneficial in future studies and is being carried out at the authors' institution in order to expand on this study.

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