Research on the Reduction Effect of Transparent Glass on Cooling Power Energy Consumption

Research on the Reduction of Cooling and Heating Loads by Transparent Solar Heat Absorbing Glass Panels

(Part 2)

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Abstract

Based on an experimental study, this paper discusses the savings obtained by various kinds of single-layer and double-layer glass panels on the cooling power consumption in the air-conditioning of buildings. Heat transfer coefficients are measured in order to evaluate the savings obtained. Results show that double-layer glass panels offer significantly larger savings compared to single-layer glass panels, and the flow of the air layer within the double-layer glass panels is not significantly helpful to improve the energy-saving effects. It is also found that the Low-E glass material has the greatest reduction effects.

Keywords: cooling power consumption; double-layer glass; heat transfer coefficient; solar heat absorption coating; solar heat absorption film

1. Introduction

To enhance the visibility from outdoors to indoors, transparent glass is adopted in most stores and automobile exhibition halls. However, such an arrangement involves a challenge of reducing the cooling power consumption. In order to inhibit the solar heat from transmitting to indoors, double-layer hollow transparent glass is usually used. The hollow layer close to the indoors can absorb solar heat, and then the heat in the hollow layer can be transmitted outdoors by means of ventilation, thus inhibiting the transmission of solar heat to the indoors. This experimental study aims to determine the saving in cooling power consumption occurring due to various kinds of heat-absorbing transparent glass panels.

Some studies have focused on the effect of glass panels on the energy consumption in air-conditioning. Kurayama1) performed a high-precision indoor experiment for determining the solar heat collection rate, which is based on the solar heat simulation program. Ichinose2) developed a 'high-precision determination method', which can be used to measure the optical properties and heat transfer performance of glass. The shielding effects of double-layer glass with shading material have also been studied3, 4). The shading material was taken as the measurement object in those studies, but does not aim to guarantee the transparency of the measurement object. Moreover, the research cases of Takeda et al.5) have shown that the internal temperature of the hollow layer is reduced by generating mist and vaporizing water while guaranteeing the transparency of double-layer glass.

In this study, based on the previous report6), the heat transfer coefficient of the objects (float glass, coating glass, film glass, Low-E glass) and the caloric value of heat conducted to the indoors (including solar heat penetration) are quantitatively studied by employing outdoor testing devices. The devices and the test objects are made at an actual scale to the typical buildings. The real COP (coefficient of performance) of an air-conditioner is calculated as the ratio of the actual heat loss to the power consumption of the air-conditioner. Moreover, a real heat transfer coefficient by dividing the heat quantity calculated in a real COP at a temperature difference between the indoor and outdoor was calculated and compared.

2. Large Experimental Device

2.1 Experimental Set-up

The large test device used in the previous report6) was used in this study. Picture 1 shows the overall appearance, and Fig.1. shows the structural plan. The test device was an iron container (outline dimensions: 6m x 2.4m x 2.6m) and was divided into four separate chambers along the
length, defined as Chamber A, B, C and D in sequence from north to south. Aluminum window frames were set for the installation of various objects in the openings of chambers in the west side. The locations of aluminum window frames were divided into two types: front surface (referred to as the outer frame) and 550mm inward from the front surface (referred to as the inner frame). Except for the opening, the other five surfaces were equipped with extruded polystyrene (50mm thick) for insulation. Moreover, the inner surface of the chamber was painted with a black heat insulating material. Air-conditioners (manufactured by Daikin Industries, model No. S22JTNS-W) were used as coolers for each Chamber (A-D), and the wind direction was monitored. Temperatures of all chambers were remotely controlled. Power consumption was measured by an ammeter (input: 100V; measurement interval: 1h). The power consumption of the data recorder in all chambers was automatically measured by the current clamp. The temperature measurement points were the central points of five surfaces except for the opening, in which temperature was measured at the center of the indoor panel and at two surfaces of the objects. The T-type thermocouple (diameter: 0.2 mm) and thermometer were used for temperature measurement and a data recorder (Thermodac-F model 5030A) was used for automatic recording. The outdoor temperature was measured by setting an SAT meter on the west side, inserting the thermocouple into the aluminum tube in the location shown in Picture 1 and discharging the air in the aluminum tube with a DC electric draft fan. The solar radiation intensity was measured by a pyrheliometer (Picture 1) at the roof of the test device on the west side. The test was conducted in the Toyota Biology Green Research Institute, and the test device was set on its lawn.

2.2 Experiment Method

The experiment method is based on JIS A 1420 standard. Before calculating the heat flux with objects installed at the opening of different chambers, thermal properties of the device outside the opening must be determined. The heat correction formula was adopted by taking the outer frame as the reference. The specific algorithm was as follows: (1) install the float glass on the outer frames of Chambers A to D; (2) Set the temperature of all chambers at 30°C with a low-temperature electric heating furnace; (3) measure the values for five days with solar heat influence and five nights with no solar heat influence; (4) measure the difference in indoor and outdoor temperatures of all chambers and the heat generated by the electric furnace; (5) calculate the heat transfer coefficient of the objects based on the heat transfer coefficient (6.0W/m²K) of the electric furnace as adopted in the previous report; (6) determine the heat correction formula by the amount difference between the heat generated and flow-through. The calculated result is the same as that in the previous report, the devices in Chambers A and D had the same thermal properties, while those in Chambers B and D had the same thermal properties. Fig.2. shows the heat correction formulas based on the

Table 1. Experiment Cases

| Measurement Case | Window Frame Structure | Glass Location | Chamber A | Chamber B | Chamber C | Chamber D | Measurement Time |
|------------------|------------------------|----------------|-----------|-----------|-----------|-----------|-----------------|
| Case ①           | Single-layer           | Outer frame    | —         | —         | Insulation, 50mm | Insulation, 50mm | 2008/8/15,17   |
| Case ②           | Single-layer           | Inner frame    | Float glass | Coating  | Film     | —         | 2009/8/12~17    |
| Case ③           | Double-layer (sealed)  | Outer frame    | Float glass | Coating  | Film     | Float glass | 2009/8/17~21    |

Fig.1. Plan of Chamber A

Fig.2. Heat Correction Formula
inner and outer frame. Based on the previous report\(^6\), the coated float glass (hereinafter referred to as the coating) and float glass film (hereinafter referred to as the film) with good heat absorption effects and high transparency\(^6\) were used as the experiment objects, and the 3 mm thick transparent float glass (hereinafter referred to as the float glass) and Low-Emissivity glass (hereinafter referred to as Low-E glass) were used as the reference objects. Experimental cases considered in this study are shown in Table 1. and are broadly divided into two types as: single-layer glass with objects installed on the outer frame and double-layer glass with float glass installed on the outer frame and objects installed on the inner frame. The double-layer glass was further divided into sealed hollow type and open hollow type. The open hollow type, as shown in Picture 1, is different from the sealed hollow type such that the upper and lower glass panels of the sealed hollow type are removed. The experiment was performed from August 15~21, 2008 and August 1 to September 9, 2009.

3. Results and Discussion of Single-layer Glass

3.1 Experiment Results

Figs.3. and 4. show the relationship between the difference in the indoor and outdoor temperatures and 1h cooling power consumption when float glass was the objects of each chamber (Experimental Case ③). The temperature difference in Fig.3. refers to the difference between the outdoor temperature and indoor temperature, and the temperature difference in Fig.4. refers to the difference between the temperature of the SAT meter on the west and the indoor temperature. When solar heat was not directly transmitted to the indoors, the indoor and outdoor temperature difference, as shown in Fig.3., was direct proportional to the power consumption, however they are almost independent from each other between 13:00 and 18:00. Fig.4. shows the strong dependency (correlation coefficient \(r=0.99\)) in the case of using an SAT meter, and the temperature of the SAT meter was adopted for the outdoor temperature in this paper. The temperature of the SAT meter on the west was used as the outdoor temperature in calculating the heat transfer coefficient of the objects. Experimental Case ④ was used as one of the measurement cases, Figs.5.–12. show the measurement results taken on August 15. Fig.5. shows the daily variation in the outdoor temperature, the temperature of the SAT meter on the west and the wind speed. The highest outdoor temperature was observed at around 14:00, and the highest temperature of the SAT meter appeared, at around 15:00 (1h later). Except for the period from night to morning, the wind speed was approximately 1.5m/s to 3m/s. Fig.6. shows the variations in cooling power consumption with time for all chambers. When the value of the SAT meter reached the maximum value at 15:00, the corresponding power consumptions of all chambers were the largest. Fig.7. shows the temperature changes of all walls of Chamber B. When the indoor temperature was 18.5 ± 0.5°C, the ground temperature increased rapidly at around 14:00 due to solar heat effects and reached the maximum value of 30°C at 16:00. The temperature of the top and the east sides began increasing from around 7:00 a.m., reached the maximum value at 15:00 and dropped thereafter, indicating the solar heat effects on the roof and the outdoor portion on the east side. Fig.8. shows the variation in the difference between the outer surface temperature of glass and the indoor temperature between 13:00 and 17:00. The temperature difference of the float glass is the smallest, followed by the coating, the film and the Low-E, respectively. It can be concluded that objects exhibited significantly large differences in their solar heat absorption...
capacities. Figs.9.~12. show the relationship between the difference in the indoor and outdoor temperature of each object and the 1h cooling power consumption. Black round dots show the values from 21:00 to 4:00 the next day, gray round dots show the values from 5:00 to 12:00, and white round dots show the values from 13:00 to 20:00. The temperature differences of all objects showed a linear relationship with the power consumption. For quantitative research on the heat consumption of all chambers during cooling, the total heat transmitted to the indoors, i.e. the corrected heat of the device (Fig.2.) should be calculated by using Formula (1); the heat transfer coefficient of the objects should be calculated by using Equation (2); and the amount of solar heat transmitted by the objects should be calculated by using Equation (3).

\[
Q_e = Q_b + Q_s \quad \quad \quad (1)
\]

\[
Q_s = K \cdot (\theta_{SAT} - \theta) \cdot A \quad \quad \quad (2)
\]

\[
Q_b = a \cdot A \quad \quad \quad \quad \quad (3)
\]

Where

- \( Q_e \): heat consumption for cooling (W)
- \( Q_b \): corrected heat (W)
- \( Q_s \): heat transmitted to each test object (W)
- \( Q_t \): amount of solar heat transmitted by each object (W)
- \( a \): solar heat transmissivity (%)
- \( K \): heat transfer coefficient (W/m²K)
- \( A \): heat transfer area of each test object (m²)
- \( \theta_{SAT} \): temperature of SAT meter on the west (°C)
- \( \theta \): indoor temperature (°C)

The product of these three values is the heat projected by the sun onto the objects. Table 2 shows the heat transfer coefficients and the solar heat transmission amounts of each object, based on the previous report\(^6\). To verify the solar heat transmissivity of each object, the SAT meters (solar heat absorption rate: 0.9) were set to measure the temperature in each chamber. The solar heat transmission amount of the objects was calculated based on the SAT standards according to the surface temperature of the SAT meter, the indoor temperature and the heat transfer coefficient\(^6\). Fig.13. shows the relationship between the solar heat transmissivity and the solar heat transmission amount obtained through the SAT meter data. The two variables are related to each other for each object indicating that the solar heat transmissivity can be considered as a constant. Based on the above method, Fig.14. shows the daily variation in the indoor heat transmitted to different objects. The quantity of transmitted heat was decreased successively for the float glass, the coating, the film and the Low-E glass.

### 3.2 Cooling Capacity

The power consumption of the air-conditioner and the removed heat quantity (\(Q_t\)) of all chambers at different moments in the experiment case \(^4\) were obtained. Fig.15. shows one case, in which the relationship between the power consumption and the removed heat quantity was calculated for the float glass as the test object. Based on the calculation results, a relationship between the difference in the indoor and SAT temperatures and the COP (cooling) was obtained by dividing the removed heat quantity by the power consumption, as shown in Figs.16.-19. Compared to the float glass in Chamber A and the Low-E glass in Chamber D, the correlation coefficients (r) were smaller for the coating in Chamber B and the film in Chamber C. However, the differences in the indoor and outdoor temperatures of all chambers were in positive correlation with the COP. The ratio of power consumption was calculated by dividing the power...
consumptions during different periods by the maximum consumption rating of 440W, and then a relationship between the ratio of power consumption and COP was calculated as shown in Fig.20. The ratio of power consumption varied from 0.2 to 0.7. There are minor differences of test objects, but the power consumption rate and COP had a linear relationship \( r=0.94 \). To verify the stability of COP, two experiments were carried out. In the first experiment, extruded polystyrene insulation material (50mm thick) (Cases ① and ②) were used, and the heat transfer coefficient and heat conduction coefficient of the insulation material was calculated as per the following steps: ① calculate the cooling power consumption and power consumption rate of different periods, and calculate the COP value based on the power consumption rate; ② calculate the heat transmitted \( Q_L \) for indoor cooling; ③ calculate the heat transfer coefficient of the test object by deducting corrected heat \( Q_C \) from \( Q_L \); ④ calculate the heat conduction coefficient according to the temperature difference of two surfaces of the test object. Figs.21. and 22., respectively, show the heat transfer coefficient and the heat conduction coefficient of the test object. The results are almost identical with the results in winter in the previous report\(^6\) (corresponding to the heat transfer coefficient of 1.2W/m\(^2\)K and the heat conduction efficiency of 0.07 W/m\(^2\)K). Therefore, it can be said that the COP value is stable when the power consumption rate is approximately 0.2.

The second experiment aimed to determine the results of the test objects in the presence of the inner frame (Case ⑤). Fig.23. shows the power consumption of each chamber for different periods. In the case of the float glass, the removed heat quantity was calculated based on the COP related to the power consumption rate, as shown in Fig.24. This figure also shows the values of \( Q_C \), as well as \( Q_N \) and \( Q_L \), calculated according to Formula (1). In this case, the inner frame standards (Fig.2.) were applied for the heat correction. The value of \( Q_L \) calculated according to Formula (1) was greatly different from that calculated according to the COP, especially between 12:00 and 17:00. When the float glass was installed on the outer frame, the maximum amount of heat transmitted from the test object into the chamber \( Q_N+Q_I \) was about 1,200W (Fig.14.), which was nearly identical with that in the case of having the inner frame installed, i.e., \( Q_N+Q_I = Q_L-Q_C \). Considering the outdoor temperature, solar heat intensity, and wind speed, the difference must have been caused by the change in the sun location from north to west in the afternoon. In other words, the thin wall between the outer and inner frames in Fig.1. was projected to the test object on the inner
frame, thereby reducing the solar heat transmission area and cooling power consumption of the test object and further reducing the $Q_L$ value calculated based on the COP. Thus, the size of the shadow onto the test object on the inner frame should be measured. It was found that the shadow on the northern wall was about 25~30 cm long. Based on the width of 130 cm of the test object, the solar heat transmission area was reduced by approximately 20% to 25%. Therefore, this value should be taken into account in Formula (3) to calculate the solar heat transmission. Thus, the ratio of solar heat transmission area $(b)$ was taken as 0.8, and the $Q_L$ calculated accordingly is shown in Fig.24.

$$Q_L = a \cdot I \cdot h \cdot b \quad \cdots \cdots (3)$$

The value of $Q_L$ for $b=0.8$ was approximately one half of that for $b=1.0$. Fig.25 compares the $Q_L$ values calculated with the solar heat transmission areas of 100% and 80% and the $Q_L$ value calculated based on the COP. As shown in the figure, the $Q_L$ value corresponding to the solar heat transmission area of 80% was strongly correlated to the $Q_L$ value based on the COP.

4. Power Consumption with Double-layer Glass

According to the experimental method shown in Fig.26, the float glass was installed on the outer frame of each chamber, and various test objects were installed on the inner frame. The power consumption of the air-conditioner of each chamber was recorded once every hour when the hollow layer was sealed (Experimental Case ⑥), for which the results are shown in Fig.27. Fig.28 shows the difference between the surface temperature of the hollow layer of each test object and the indoor temperature of the chamber from 13:00 to 18:00. The temperature differences of the coating and the film were almost identical. The temperature difference of the float glass was relatively smaller while that of the Low-E glass was relatively larger. Fig.29 shows the comparative relationship between the $Q_L$ value calculated according to the COP and the $Q_L$ value calculated according to Formula (1), when the float glass was installed on the inner frame. To use Formula (1), the heat transfer coefficient and the sunlight transmissivity was calculated according to the following method. First, a low-temperature electric furnace was used to control the indoor temperature of each chamber; then, the heat generated by the furnace was calculated; the difference in the indoor and outdoor temperatures was calculated; and the corresponding heat of the inner frame was estimated. Experimental measurements were taken on several nights during winter time (December 15~18, 2009). All test objects were set horizontally. The float glass parts were installed in parallel with a spacing of 50 cm. The pyrheliometers were installed under and outside the test objects, and the sunlight transmissivity was calculated according to the values of both pyrheliometers. The results are shown in Table 3.

Compared to the results in Table 2 for the single-layer panels, the heat transfer coefficient of the double-layer panels dropped markedly, especially for the float
glass and the coating. The solar heat transmissivity of the double-layer panel with the float glass decreased by about 20%, and with the coating decreased by about 15%. The single-layer and double-layer film and the Low-E glass had nearly identical solar heat transmissivity. Fig.29. compares the $Q_L$ values calculated according to Formula (1) and according to the COP based on the thermal and physical properties of the objects. The cases of the sunlight transmission area ratios of 100% and 80% in calculating the $Q_L$ values (removed heat quantity) according to Formula (1) are also shown in Fig.29. When the ratio was 80%, the $Q_L$ value of the float glass was larger than that calculated according to the COP. Except for the float glass, the two $Q_L$ values were almost identical for other test materials. Therefore, when the ratio is 80% in the experiment of the inner frame, the relationship between the power consumption rate of the air-conditioner and the COP may be regarded as constant and the directory value of the COP of the air-conditioner was 5.0. Fig.30. shows the measurements of the power consumption of the air-conditioner over time when the open hollow layer (Experimental Case ⑦) was used. Fig.31. shows the difference between the surface temperature of the hollow layer of the objects and the indoor temperature from 13:00 to 17:00. The comparison between the open type and the sealed type (Fig.28.) is shown in Fig.32. For both the single-layer and double-layer glass (sealed and open) panels, Fig.33. shows the relationship between the difference in the indoor and outdoor temperature and the heat flux of the objects, when the float glass was installed on the inner frame. It is found that the heat in the hollow layer with the open frame flowed in the vertical direction. Therefore, the heat transfer coefficient of the objects could not be calculated according to the heat transfer coefficient (Table 3.). In the figure, the difference between the two $Q_T$ values is the heat flux $Q_T$. The heat flux of the objects on the outer frame was larger than that on the inner frame. Both in the sealed and the open cases, the heat flux of the outer frame was slightly smaller than or basically identical with that of the inner frame. Fig.34. shows that the greatest sunlight intensity occurred at 15:00 among all test results. The comprehensive coefficient of heat transfer was calculated as the ratio of the $Q_T$ value of each object calculated based on the COP to the product of the difference in the indoor and outdoor temperatures and the area of the objects. Table 4. shows the ratio of the comprehensive coefficient.
of heat transfer of each object and float glass. The film was approximately 0.15 less than that of the float glass and the coating when the objects were installed on the inner frame. The comprehensive coefficient of heat transfer of the Low-E glass was 0.55, the least among the objects. In the case of the double-layer sealed experiment, the comprehensive coefficient of heat transfer of the objects were smaller than that of the inner frame, and the sunlight transmissivity was also lower. Compared to the double-layer sealed type, the coefficient of the outer surface of the float glass and the coating decreased by approximately 0.20 and of the film by 0.14. The heat transfer coefficient of the Low-E glass decreased insignificantly. The sunlight transmissivity did not decrease much, but the surface heat transfer coefficient increased substantially. For the difference between the sealed hollow layer and the open hollow layer in the comprehensive coefficient of heat transfer, the value of the Low-E glass was the largest (0.18), followed by the film (0.08). The float glass and the coating showed no difference. Therefore, the double-layer inner frame absorbed solar heat, and the temperature of the air in the hollow layer was increased. Consequently, the hot air was discharged outdoors through ventilation. The coating had almost no effect on the inhibition of the solar heat transfer through the objects into the chamber. Comparatively among the different objects, the film may achieve the desired effects. According to Table 3, when the film with good heat absorbing effects was installed on the double-layer inner frame and the open type was applied to improve the ventilation effects, the comprehensive coefficient of heat transfer was larger than that of the Low-E glass on the inner frame, that is, the Low-E glass had the greatest effects in reducing power consumption during the cooling of buildings.

5. Conclusions
This paper investigated the effects of transparent single-layer and double-layer glass on saving the cooling power consumption of buildings. Experiments were performed on real scale window objects, and the tests were carried out such that solar heat was transmitted to the indoors through the objects. In the analysis, the heat capacity of the test apparatus was neglected, and the heat transfer was considered as steady. The quantitative research on the heat conduction capacity and the solar heat transmissivity was divided into two approaches as, (i) calculation based on the heat transfer coefficient and solar heat transmissivity of each object, and (ii) based on the COP corresponding to the reduced power consumption of the air-conditioner. Results from the two approaches were compared. It should be noted that the shadow of the objects was taken into account while determining the solar heat transmission area, that is, the solar heat transmission area was taken as 80% of the original area. The relationship between the power consumption rate and the COP was stable in this case. In addition, to understand the effects of different objects on reduction of power consumption, the heat transfer coefficient and the solar heat transmission amount of objects was calculated. The heat transfer coefficient of the surface was calculated according to the difference in the indoor and outdoor temperatures; and then the heat transfer coefficient of the surface was applied for controlling the reduction in cooling power consumption. The following conclusions were obtained based on the shapes and dimensions of the objects used in the experiment.

(1) Single-layer glass
The coating with heat absorbing effects had the same shading effects as those of float glass. However, no reduction in energy consumption during cooling was observed for the coating.

For the film with heat absorbing effects and with the sunlight transmissivity lower than that of the float glass, the reduction in energy consumption was 15% larger than that for the float glass.

Furthermore, the reduction effect of the Low-E glass was approximately 50% larger than that of the float glass.

(2) The reduction effect of the double-layer glass was about 15% to 20% higher than that of the single-layer glass. This effect was, however, not observed for the Low-E glass.

(3) In the case of the double-layer open type, film and Low-E is effective to reduce the cooling load. However, this effect was not observed in the case of the float glass and the coating.

(4) For the cooling load reduction effect, at the double-layer open type, the film is the most effective. However, the Low-E at the single (Inner sash) is better.

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