Thermal Performance of Fenestration Systems in the Hot Climate of Saudi Arabia

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ABSTRACT

Glass-clad buildings have become a common sight in the Middle East despite the extremely hot summer temperatures. This research work was initiated because of the significant overheating problems and poor provision of thermal comfort experienced within such buildings. The study has specifically concentrated on the problem of overheating caused by the solar gain through the fenestration of buildings in the Kingdom of Saudi Arabia (KSA).

The thermal performance of several different glass types is examined in order to predict the effect they would have on solar control and environmental conditions within the building. Four test cells were constructed in Dammam, Saudi Arabia, that were initially calibrated with clear single-sheet glass and then glazed with different solar control glasses. The thermal behavior of the cells was then monitored over a summer period under actual climatic conditions.

A dynamic thermal model was then used to simulate the performance of the test cells, and experimental data were compared with computer predictions. Once confidence had been gained in the thermal model, it was then used to design retrofit glazing systems for existing buildings so as to improve their provision of thermal comfort.

INTRODUCTION

The effects of excessive solar radiation falling onto glazed buildings in Dammam, Kingdom of Saudi Arabia (KSA), can give rise to severe overheating and cause high levels of discomfort for their occupants. Such constructions, first introduced during the building boom of the 1970s, were originally designed with little or no thought given to the local climatic conditions or to the impact this would have on their occupants. As a result, a number of such buildings have remained unoccupied since they were first built and many of those that are currently in use have exceedingly high operating costs for cooling energy.

Environmental cooling to promote comfort accounts for more than half of the total energy generated in the KSA. This makes energy conservation a matter of great concern (Khasham 1986; Sayigh and Awadhi 1989) and, hence, enhances the necessity to find and apply the best energy conservation opportunities available, including any passive means of thermal control. One way to achieve some control over the internal environmental impact is by taking advantage of recent developments in solar control glass. The appropriate choice of the facade glazing influences the building occupants by

- controlling the heat gain or loss through the glass, which either raises or lowers the internal air temperature, and
- limiting radiation exchange between the glass and the occupant.

For an occupant close to a window, the internal glass surface temperature influences thermal comfort due to heat from longwave radiation exchange between the occupant and the window. In Dammam, when sunlit glass gets hot, room glass surface temperatures of 45°C to 55°C are not uncommon and the radiant exchange between the hot glass and the occupant invariably gives rise to sensations of discomfort. Work reported in the U.S. (Vieria 1987) has shown that low-emission windows provide reasonable comfort conditions for people inside buildings even when they are standing close to a large expanse of glass on a sunny day.

Today, coated glass products have an improved thermal insulation compared with ordinary double and triple clear glass units. Enhanced performance is achieved by reducing

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the direct solar transmittance (Berman 1975; Skolmik 1977). Excessive heat gain in a hot climate can also be reduced by means of a number of sun control devices ranging from external controls (shutters, awnings), internal controls (curtains, blinds), special treated glass, or a combination of methods. Such techniques ultimately aim to promote human comfort for building users.

METHOD USING TEST CELLS AND SIMULATION PROGRAMS

A method was developed so that the desired comfort conditions within glass-clad buildings in Dammam, KSA, could be determined with reasonable accuracy. To obtain realistic data, the experiments were conducted under actual weather conditions, and external and internal glass surface temperatures, indoor air temperature, and solar radiation transmittance were monitored.

The research method was twofold.

a. Experiments were designed using the well-established MoWitt and Passys test-cell approach to measure the on-site solar control performance of glazing systems (Klems and Keller 1985; McCabe and Ducas 1986; Gicquel and Cools 1989).

b. A simulation model (ESP-r) was used to compare the experimental results with predicted results and also to gain confidence in the technique before using it to evaluate the thermal performance of a building incorporating a number of different glazing configurations.

Field Experiments

The field trials were carried out during a summer period. Four identical test cells were constructed behind the facade of a building at a Dammam university. The selection criterion for the location of the cells was based on the southwestern orientation of the building, which gave the chosen site maximum exposure to solar radiation. The dimensions of each cell were 1.45 m wide, 1.50 m deep, and 2.92 m high. The cells were separated from each other by hollow, concrete walls insulated with polystyrene boards. Figure 1 shows a typical section through a cell and Figure 2 shows a plan arrangement. The frames that accommodated all the glass types used in the experiment were made of white coated-aluminium section.

At the start of the field trials, the test cells were calibrated using single-sheet clear glass in each cell. Considerable effort was put into eliminating discrepancies in internal air temperature readings between the test cells. Once the cells had been calibrated, the single-sheet clear glass was replaced by various double-glazing configurations:

- a clear, double-glass system was installed in one cell,
- low-e coated glass on the outside (coating on surface 2) and clear glass on the inside of a second cell,
- reflective silver-coated glass on the outside (coating on

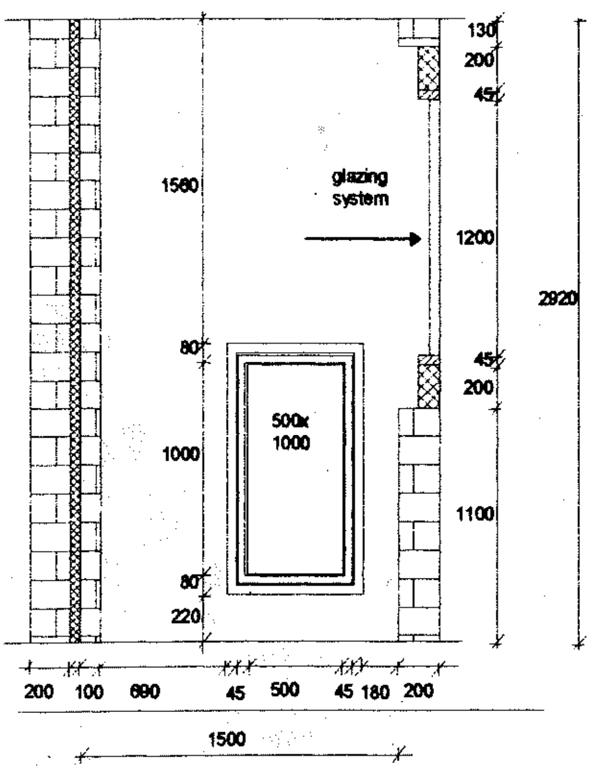

Figure 1 *Section through a test cell.*

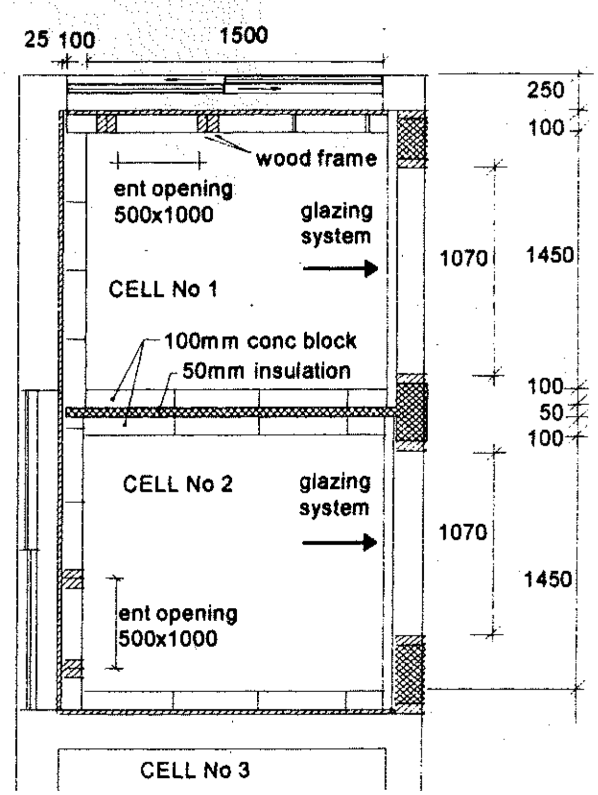

Figure 2 *Plan of two test cells.*

TABLE 1
Specifications of Double-Glass Configurations using 6 mm Clear Sheet on the Inside

Glass Configuration	Light Transmittance	Solar Properties			
		Transmittance	Reflectance	Absorption	U-Factor ($W/m^2·K$)
Clear Double	0.76	0.61	0.11	0.28	2.80
Low-e	0.44	0.29	0.07	0.64	1.90
Reflective Silver	0.42	0.23	0.45	0.32	1.65
Anti-Sun Bronze	0.44	0.36	0.06	0.58	2.80

surface 2) and clear glass on the inside in a third cell, and

- body-tinted anti-sun bronze glass on the outside and clear glass on the inside in the fourth cell.

These glass systems are commonly available worldwide to control solar radiation transfer. The solar properties of the glass appropriate to the study location were supplied by the manufacturer and are listed in Table 1. The U-factor quoted in the table is based on the traditional method of calculating the "nighttime" U-factor and the solar energy transmittances separately.

Once the glazing systems had been installed, the internal air temperature in the test cells, the internal and external glass surface temperatures, and the amount of solar radiation admitted into the test cells through each glass system were recorded every hour. Temperatures were recorded using T-type thermocouples and solar radiation was measured using solarimeters. Weather data were recorded at a local meteorological station.

Simulation Modeling

Once the field trials had been completed the test cells were computer-generated using ESP-r—a dynamic thermal model analysis program. Simulation modeling was performed using the same glass parameters as above under the same climatic conditions that were experienced during the field trials.

Experimental Results Obtained from the Field Trials

Hourly values of the internal air temperature measured inside the test cells are plotted against time in Figure 3. The maximum internal and external glass surface temperatures of the four glazing systems are shown in Figure 4 and Figure 5, respectively. The outstanding feature of these measurements was that some of the external glass surface temperatures reached 60°C with corresponding internal surface temperatures of 52°C. Such exceedingly high internal

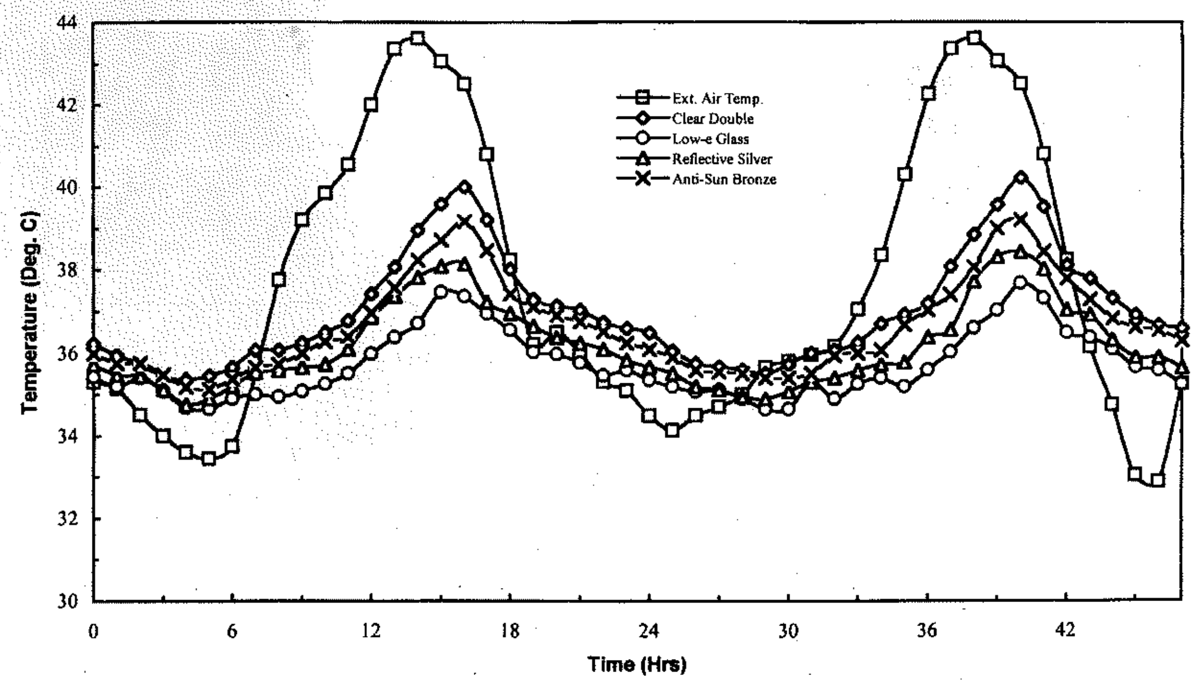

Figure 3 *Internal air temperature of test cells fitted with various glass configurations.*

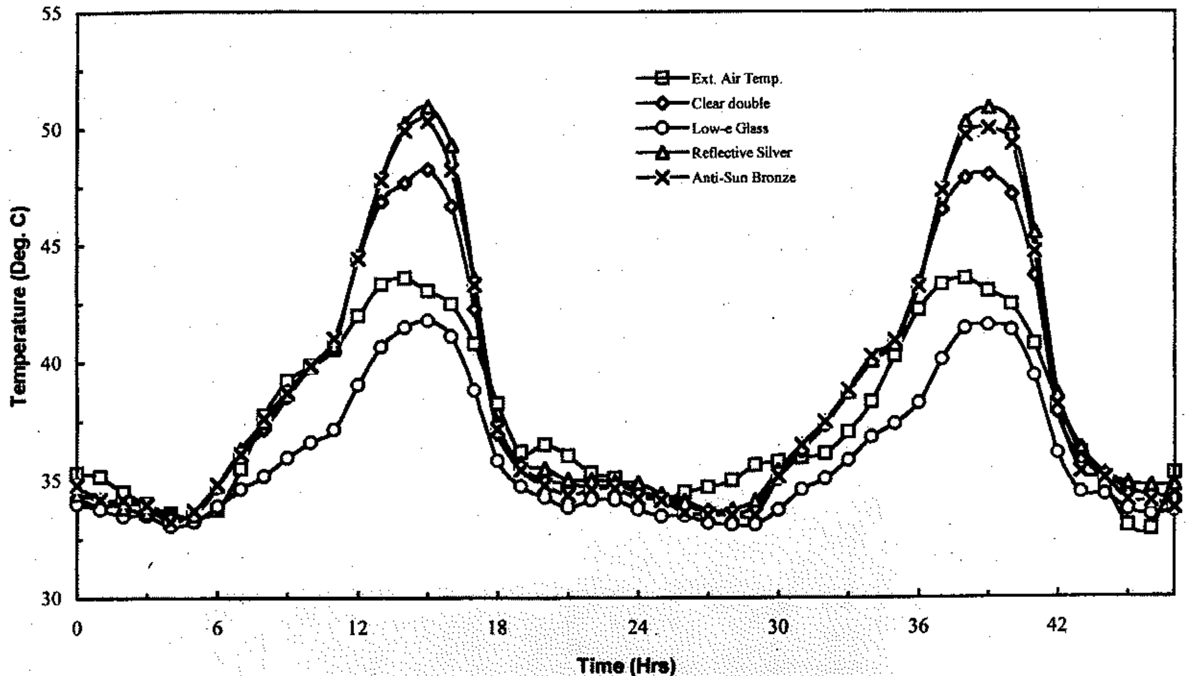

Figure 4 *Internal glass surface temperature of the various glass configurations.*

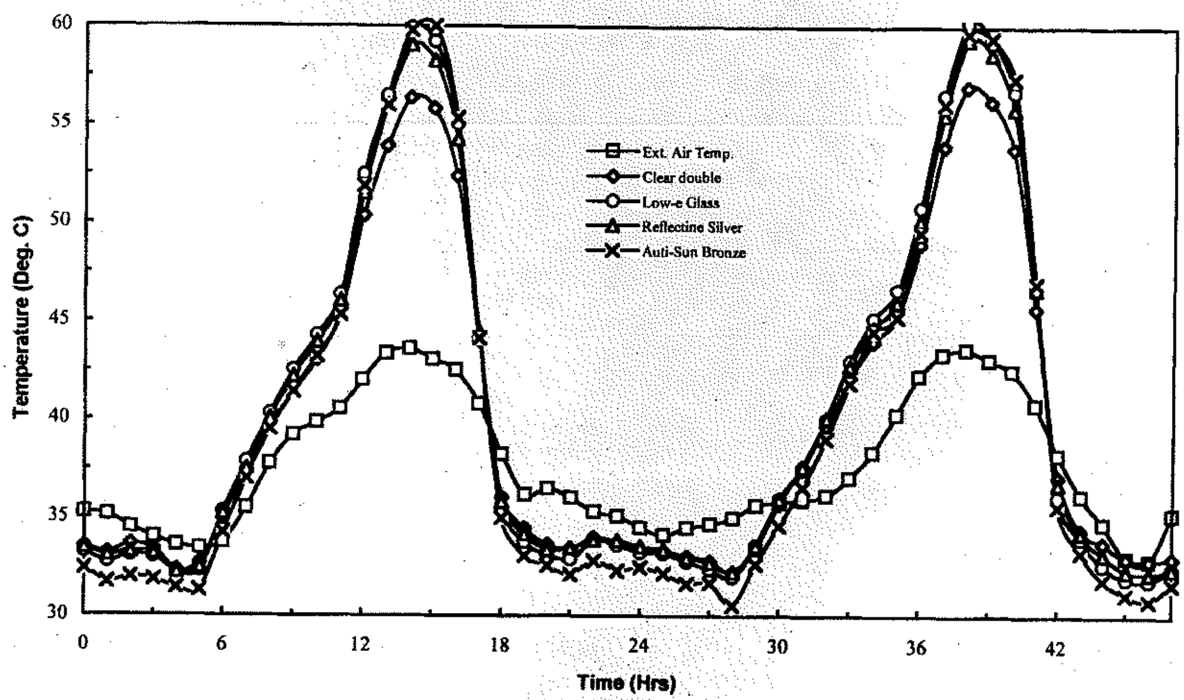

Figure 5 *External glass surface temperature of the various glass configurations.*

surface temperatures are major contributors of energy radiating into rooms and influence the thermal comfort. The transmission of solar radiation into the test cells is shown in Figure 6. External solar radiation in Dammam can rise up to 700 W/m^2 on southwest-facing walls for up to three hours in a typical summer afternoon. When this amount of radiation strikes the surface of the glass, it inevitably has a direct impact on the internal environment. When clear double glass is fitted, the results show that up to 400W/m^2 are admitted into the indoor environment; that is 57% of the total solar radiation falling onto the outside surface.

Simulation of the Test Cells using ESP-r

The ESP-r computer simulations of the thermal performance of the test cells fitted with the various glass systems predicted internal air temperatures and glass surface temperatures that were in close agreement with the field measurements. Table 2 lists the percent differences obtained between

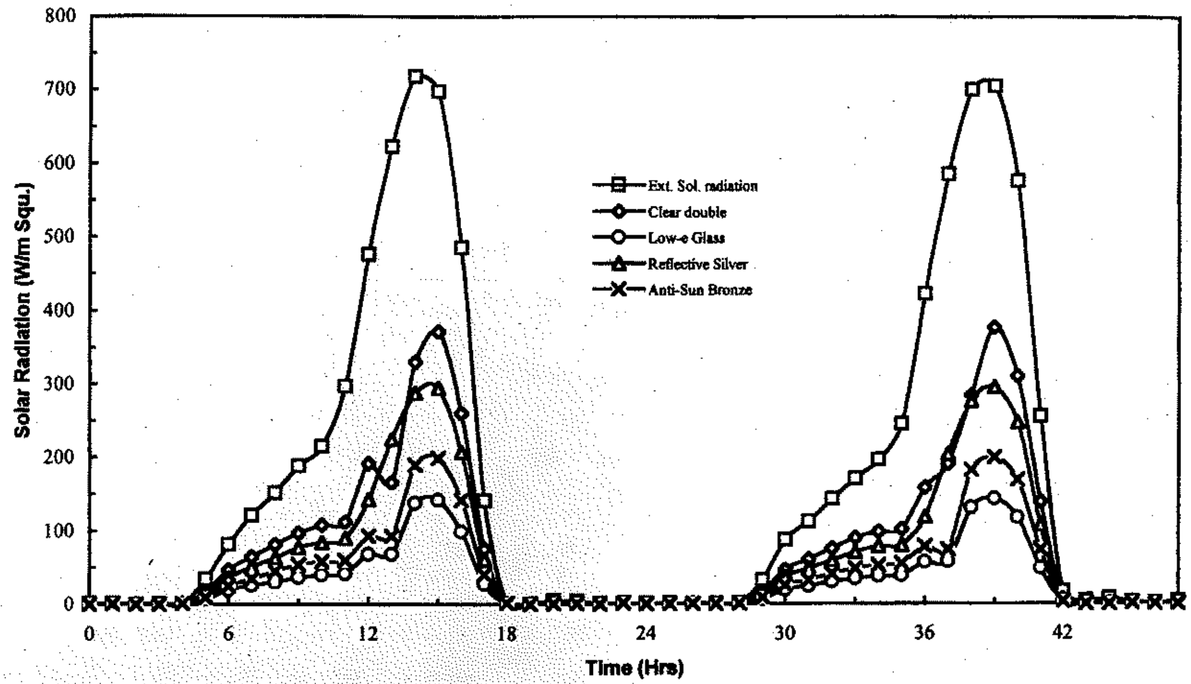

Figure 6 *Solar radiation transmitted through the various glass configurations.*

TABLE 2
Comparison of Simulated and Measured Indoor Air Temperatures Using Different Glass Configurations

Glass Configuration	Peak Indoor Temperatures (°C)		% Difference
	Simulated	Measured	
Clear Single	40.0	39.5	−1.25
Clear Double	40.2	40.0	−0.50
Low-e	38.0	37.5	−1.30
Reflective Silver	38.7	38.0	−1.80
Anti-Sun Bronze	38.8	39.3	+1.29

the simulated and measured peak indoor air temperatures using the various glass configurations in the test cells. Similar percent differences were obtained when comparing internal and external glass surface temperatures and transmitted solar radiation (Al-Buijan 1997).

As can be seen from the table above, the simulated results were in close agreement with the measured values, which led to the use of the glass specifications in Table 1 in further simulation work.

Discussion of the Results Obtained from the Test Cells

The characteristic feature of clear glass is to transmit and subsequently trap a large proportion of the solar radiation that falls onto a building. The function of solar control glass is to reduce the solar transfer as much as possible by either reflection or absorption (see Table 1 for solar properties).

Low-e, reflective silver, and anti-sun bronze coated-glass systems aim to minimize excessive solar radiation from entering into a building, thus lowering internal glass temperature and promoting comfort. Test cell results indicated that the reflective silver and anti-sun bronze glass configurations produced an outdoor-indoor air temperature reduction in the test cells of about 60°C. In comparison, the low-e configuration performed slightly better. Another important difference in the thermal behavior of the various glazing products is clearly illustrated by their varying internal-external surface glass temperatures. These were measured at the center of the pane and are summarized in Table 3.

From Table 3, it is clear that the highest internal-external glass surface temperature difference is achieved by the low-e glass, which has a high absorption coefficient of 0.64. This is due to the characteristic properties of the low-e coating present on the internal surface (surface 2) of the double-glass unit that blocks the infrared part of the solar radiation from entering a

TABLE 3
Maximum Internal-External Glass Surface Temperatures for the Four Configurations

Glass Type	Internal Tempera-ture (°C)	External Tempera-ture (°C)	Difference (°C)
Clear Double	48	56	8
Low-e	41	60	19
Reflective Silver	51	60	9
Anti-Sun Bronze	52	60	8

building by absorption. The absorbed heat is released back out of the glass once its temperature has increased above ambient.

Measured solar transmission values illustrate the efficiency of low-e in this respect. Clear double-glazing admitted 380 W/m^2 of solar radiation at its maximum rate; reflective silver, 295 W/m^2 maximum; anti-sun bronze, 200 W/m^2 maximum; while the low-e glass only admitted 150 W/m^2 at its maximum rate.

BUILDING SIMULATION

Once confidence had been gained in the computer simulation, ESP-r was used to predict the cooling energy load required to maintain the internal air temperature in a building at a comfortable temperature of 23°C. The building was a typical 100% glazed 12-floor office block in Dammam, 34 m long, 32 m wide, and 36 m high. The simulation considered the four glazing systems used in the field experiments. Because most of the glass-clad buildings constructed in the 1970s in the KSA were initially clad with single glass, an analysis using this type of glazing system was included in the simulation and used as a reference.

RESULTS AND DISCUSSION

Solar heat gain through the facade is one of the main heat flow mechanisms responsible for the rise in temperature inside a building and is also a major cause of thermal discomfort for its occupants. The amount of solar radiation penetrating into the simulated building per floor over a 24-hour period for the various glass types is listed in Table 4. The total amount of solar radiation entering over the 12 floors of the building is also given in the same table. The data show that clear single- and clear double-glazing systems allow the most solar radiation to penetrate into the building. The use of reflective silver low-e glass systems are the most effective. The anti-sun bronze glass only transmitted 43% of the radiation transmitted through the clear single-glass system, while the use of low-e glass reduces this to 38%.

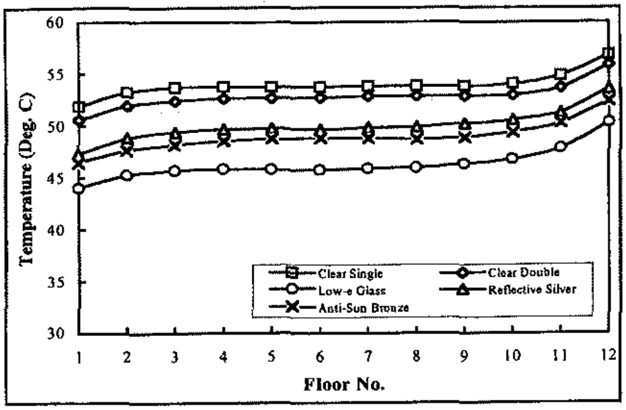

Figure 7 *Maximum internal air temperature within each of 12 floors of the glazed building fitted with the various glass configurations (16:00 hours).*

The corresponding maximum internal air temperatures occurring at 16:00 hours caused by the transmission of the solar radiation are shown in Figure 7.

The indoor air temperatures on floors 1 and 2 were relatively cooler due to, among other things, the conduction of heat into the ground floor slab, whereas temperatures on floors 11 and 12 were considerably warmer due to additional radiant heat transfer through the roof and stack effect inside the building. Temperature profiles over floors 3 to 10 followed a stable pattern. The highest maximum indoor air temperatures predicted over all the floors were recorded by both the clear single and clear double glasses, followed some degrees cooler by reflective silver and anti-sun bronze glasses. By a significant margin, the lowest maximum indoor air temperature was predicted for the low-e glazing and was approximately 7.5°C lower than the predicted values of the single-glazing system for all floors. Little difference was observed in resulting indoor air temperatures when either clear single or clear double glasses were used, mainly due to their similar solar transmission values.

Generally, internal air temperature predictions for untreated glass were noticeably higher than those of the various solar control glasses. Comparison of a selection of glazing products including low-e, reflective silver, and anti-sun bronze glasses demonstrates the potential for achieving reductions in internal air temperature values and the enhancement of

TABLE 4
Twenty-Four Hour Radiation Penetrated into the Simulated Building

	Clear single	Clear double	Low-e Glass	Reflective Silver	Anti-Sun Bronze
Solar Radiation Per Floor (kW·h)	92.3	69.3	35.3	55.8	39.7
Total Radiation Over Twelve Floors (kW·h)	1106.5	831.2	424.8	669.7	477.4

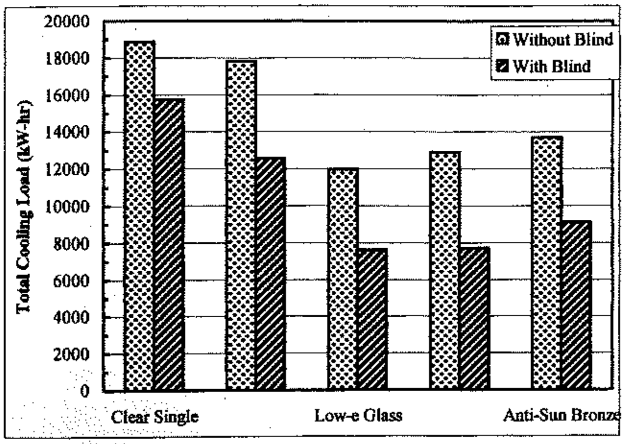

Figure 8 *Twenty-four hours energy requirement for the twelve-floor building with and without blinds.*

comfort conditions in a building. The potential for significant energy savings must also be appreciated because the indoor air temperature has to be cooled down to a comfort temperature of 23°C.

A relatively simple and easy way to reduce the internal air temperature is by the use of blinds. These affect the heat transfer by blocking the transmission of solar radiation, thus achieving a reduction in heat gain and internal air temperature. Simulation results on the same building, but this time incorporating blinds, yielded the temperature differences listed in Table 5.

Mean temperature values show that the blinds are able to reduce the average ambient conditions over all the floors for all the glazing types. The intermediate floors generally showed the most significant temperature reductions with the top floor showing the least reduction due to the influence of the solar gain through the roof and the stack effect. The untreated glasses with blinds obtained the most significant drop intemperature, which can be explained by the fact that the blinds, in this case, constitute the only physical barrier for blocking solar radiation admittance through the glass, hence the apparently high reduction in direct solar gain. With solar control glass, solar radiation passing through the windows has already been reduced by the coated surface before hitting the blinds and resulting in a further reduction in solar transmittance into the building.

The energy-saving benefits that result from the use of blinds in a building are shown in Figure 8, which shows the energy consumption values required to cool the building to a comfort temperature of 23°C over a 24-hour period.

CONCLUSIONS

Research efforts into passive cooling systems for fully glazed buildings is still in its infancy in the KSA. Results obtained in this study have assessed the performance specifications of several glazing systems currently available in the international market. The work has shown that solar control glass goes a long way toward achieving some control over excessive heat gain.

The specification of a high-performance glass in a hot climate like that of Dammam has to balance the additional expense of the system against the reduction in cooling energy load and the provision of improved thermal comfort in the building.

It is important that new material imports such as special glasses be subjected to performance evaluation under local climatic conditions before they are made available for widespread use in that market. The research work has attempted to satisfy this requirement. Because of the continuing popularity of glass-clad buildings, the necessity to establish KSA standards and regulations specifying thermal performance and restricting the extensive use of glazed areas on building envelopes and their consequential energy demands is all the more urgent.

It is hoped that this work will encourage other investigators to conduct similar studies on a somewhat larger scale

TABLE 5
Mean Indoor Temperatures Obtained for the Five Glazing Configurations with and without the Use of Blinds

Floor No. and Type of Glass	Without Blinds (°C)	With Blinds (°C)	Temperature Difference (°C)
Clear Single			
Floor 1	44.5	38.7	5.8
Floors 2-11	46.6	40.2	6.4
Floor 12	47.8	42.3	5.5
Clear Double			
Floor 1	44.1	36.8	8.3
Floors 2-11	46.3	38.2	8.1
Floor 12	49.1	41.7	7.4
Low-e			
Floor 1	36.1	30.9	6.2
Floors 2-11	37.3	31.3	6.0
Floor 12	41.7	37.4	3.3
Reflective Silver			
Floor 1	38.7	32.3	6.4
Floors 2-11	40.6	32.8	7.8
Floor 12	43.7	38.7	5.0
Anti-Sun Bronze			
Floor 1	38.3	33.4	4.9
Floors 2-11	39.8	34.0	5.8
Floor 12	43.4	38.3	5.1

using the test cell and simulation approach to verify the findings in this study and permit accurate, realistic, and cost-effective retro-fit solutions for the many problem buildings in Saudi Arabia.

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