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Estimating Heat Gain Using Window Filming in Different Geographies

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ABSTRACT: Many disasters are occurring around the world in connection with global warming. Many studies are being carried out to find ways to reduce emission levels of greenhouse gases. Reducing fossil fuel consumption is the most common method used to reduce emissions. In this study, the heat gain of a model building with specific window film properties is estimated. The results are presented comparatively for three film types coated on clear and tinted glass. The heat gain estimation is performed adaptively for summer days considering geographical location, glazing, building and humidity characteristics. Estimations are made for seven types of window films. A cost analysis is carried out considering the location, temperature and façade of the sample building.

KEYWORDS: Window film, Energy efficiency, Carbon emission, Solar heat gain, Cost analysis

I. INTRODUCTION

The economic growth that began in the nineteenth century as a result of the industrial revolution continued into the twentieth century and was accompanied by significant population growth. Rapid population growth, intensive urbanization and improvement in the quality of life have significantly increased energy consumption. This increase in energy use has led to environmental problems and associated costs. The negative impacts of high energy consumption on the environment were largely ignored until they began to visibly affect the global economy and quality of life. However, waste gases contributing to the greenhouse effect have been exacerbated by the increased use of fossil fuels, leading to air, water and soil pollution in cities and global climate changes.

Windows are designed to provide adequate interior lighting and a visual connection between indoors and outdoors. Windows made of transparent materials are the components most vulnerable to heat loss. Buildings play a crucial role in saving energy and reducing greenhouse gas emissions and windows account for about 60% of heat losses. As a result, windows are a critical focus of research aimed at reducing energy consumption in buildings [1]. Energy costs can be reduced by improving the thermal insulation performance of windows, leading to high energy savings. All components of a building function as part of an integrated system, including windows. Energy-efficient windows are designed with specific optical and thermophysical properties for optimum performance in winter or summer, ultimately contributing to the reduction of energy consumption. The thermal efficiency of a building depends on the size and characteristics of the windows [2]. Window films are a cost-effective and efficient solution to minimize heat gain through windows. These thin films consist of metallic-polyester layers with thermal properties designed to reflect solar heat. In addition, they can block UV rays from entering the building and protect the décor inside the building from the harmful effects of solar radiation [3]. The metallic component of the film reflects solar heat, while the polyester component allows sunlight to pass through the metallic layer. Films applied to the outer surface of windows are more expensive due to the need for materials that can withstand outdoor conditions. Studies in the literature have shown that smart window technologies are effective but often costly [4]. Five different climatic conditions were analyzed in China and opaque flexible window blinds were found to be the most effective solution for energy saving. The effect of window size, aspect ratio and position on heat loss was also studied and the effects of window slope and size in cold climates were investigated [5]. While one study reported that double-glazed windows with window films increase energy use [6], another study using simulations showed a 17% to 47% reduction in cooling load in hot and other climates [7]. Human habits significantly affect the heat loss of buildings, suggesting that automatic air conditioning systems can reduce the negative impact of human behavior on energy savings. This study involves the estimation of the heat gain through windows of a building given room and window dimensions. By comparing the results in terms of heat gain efficiency, it is aimed to determine the most efficient window film after cost analysis.

II. METHOD

The method is based on the Kirchoff radiation law. The given radiation law was applied iteratively. The iterative steps are implemented by following the proposed Boles procedure [8]. The formulation includes solar heat gain coefficient, shadowing coefficient and surface area of the window. The final temperature is estimated by implementing a function with inputs of total heat gain, room volume, air mass in the room and air density. Here, the final temperature of the room is estimated by iteratively updating the air density in the room with the developed function and taking into account the humidity effect. In the method proposed in this study, heat gain and final temperature estimation are adaptively integrated iteratively. The types of window films used in this study include clear glass and tinted glass, as well as both types of glass coated with films of types A, B and C [9]. In this study, an iterative method structure for heat gain and final temperature estimation is developed. The glass film properties depend on the shading coefficient (SC), solar heat gain coefficient (SHGC) and surface solar absorption coefficient (SSA) parameters, which are presented in Table 1.

Table 1. Glass and Film SC, SHGC and SSA Coefficients

	Clear	Tinted	Clear with film			Tinted with film		
Film	-	-	A	B	C	A	B	C
SC	0.94	0.69	0.47	0.47	0.24	0.43	0.43	0.31
SHGC	0.82	0.60	0.41	0.41	0.21	0.37	0.38	0.27
SSA	0.88	0.50	0.39	0.36	0.09	0.23	0.21	0.05

The total solar energy incident on the surface in one hour was estimated by estimating the hourly global solar radiation on inclined surfaces according to the method given in a study [10]. For this purpose, diffuse radiation, direct beam radiation and reflected radiation are integrated into calculations. Also, the constants derived from the ASHRAE algorithm are used in the implementation for June, July and August [11]. Iterative estimation of the final room temperature is implemented using the characteristics of mass, heat capacity and initial temperature where heat gain is introduced into calculations iteratively by taking into account dry air pressure and vapor pressure.

A. Implementation and Results

With the specified parameters, it is aimed to estimate the heat gain of a room in a certain volume. Heat gain estimation is performed to estimate the solar heat gain of a window with certain transmittance and reflectivity properties and dimensions in a building volume with certain properties. The method is applied for Abu Dhabi, Moscow and Tokyo. In addition, separate simulations were carried out on certain days of the summer months for the cases where the building volumes face four main directions. The surface inclination of the windows is assumed to be equal to 90°. The calculations were performed for three days in the middle of the three summer months: morning, noon and evening, according to standard local time. In this way, the characteristics of the cities required for the calculation of hourly solar radiation, the longitude and latitude, the number of days , the local standard time and the azimuth angle at the given date and time are given in Table 2.

Table 2. Geographical Characteristics.

	Local time	Latitude	Longitude	Azimuth angle		
				Day 165	Day 195	Day 225
Abu Dhabi	9 AM	54.38°	24.45°	80.56	82.21	91.59
	12 PM			102.03	111.49	146.12
	15 PM			276.36	273.31	261.58
Moscow	9 AM	37.62°	55.76°	108.30	108.08	113.27
	12 PM			167.38	165.46	167.49
	15 PM			235.86	233.08	228.77
Singapore	9 AM	103.82°	1.35°	64.46	66.41	74.43
	12 PM			34.36	38.78	51.66

	15 PM			310.39	309.42	297.08
Tokyo	9 AM	139.65°	35.68°	98.45	99.58	109.07
	12 PM			199.80	192.82	189.66
	15 PM			267.96	265.13	256.79

These four cities are densely populated and have different geographical locations and climatic characteristics. In this respect, consistent results of the simulation can be easily observed. For each city, the total solar energy incident on the surface and the final temperature of the room for all glazing types were calculated. The total heat gain (W/m^2) required for the final temperature calculation was calculated. Total solar energy calculations are given in Table 3.

Table 3. Total Solar Energy Calculations.

		9 AM	12 PM	15 PM
Abu Dhabi	June	804.27 W/m^2	999.31 W/m^2	661.81 W/m^2
	July	753.05 W/m^2	1000.40 W/m^2	708.15 W/m^2
	August	821.28 W/m^2	986.52 W/m^2	587.86 W/m^2
Moscow	June	792.78 W/m^2	788.42 W/m^2	478.80 W/m^2
	July	757.42 W/m^2	786.09 W/m^2	498.14 W/m^2
	August	714.27 W/m^2	682.14 W/m^2	333.40 W/m^2
Singapore	June	807.79 W/m^2	883.12 W/m^2	394.46 W/m^2
	July	775.10 W/m^2	909.22 W/m^2	463.80 W/m^2
	August	886.74 W/m^2	918.45 W/m^2	360.66 W/m^2
Tokyo	June	840.33 W/m^2	964.32 W/m^2	618.94 W/m^2
	July	793.38 W/m^2	964.72 W/m^2	657.48 W/m^2
	August	822.87 W/m^2	916.20 W/m^2	515.06 W/m^2

The calculated total solar energy values are highest in June, when the sunlight comes at the steepest angle to the northern hemisphere, and in parallel with this, the value gradually decreases in the following months. Calculations were made for three periods of the day. The morning period covers the interval between 9-12 AM, the midday period covers the interval between 12-15 PM and the evening period covers the interval between 15-18 PM.

Table 4, 5, 6 and 7 show the difference between the final indoor temperature and the reference temperature at the geographical locations on 15 June, 15 July and 15 August for 8 types of window film usage. The temperature rise is lower in tinted glass than in clear glass. However, the temperature rise decreases significantly with the use of film. It is observed that the temperature difference is at the lowest level when using type C film.

Table 4. Temperature Decrease for the Sample Room in Abu Dhabi.

Clear Window			
	9 AM	12 PM	15 PM
June, 15	1.3513	1.7622	1.2860
July, 15	1.2427	1.7385	1.3407
August, 15	1.2869	1.6560	1.0813
Tinted Window			
	9 AM	12 PM	15 PM
June, 15	0.3797	0.5051	0.3597
July, 15	0.3465	0.4978	0.3764
August, 15	0.3600	0.4727	0.2973
Clear Window - Film A			
	9 AM	12 PM	15 PM

June, 15	0.1301	0.1756	0.1228
July, 15	0.1181	0.1730	0.1289
August, 15	0.1229	0.1638	0.1002
Clear Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.1174	0.1594	0.1107
July, 15	0.1063	0.1570	0.1163
August, 15	0.1108	0.1485	0.0897
Clear Window - Film C			
	9 AM	12 PM	15 PM
June, 15	0.0008	0.0035	0.0003
July, 15	0.0000	0.0033	0.0007
August, 15	0.0003	0.0028	-0.0010
Tinted Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.0514	0.0736	0.0479
July, 15	0.0455	0.0723	0.0508
August, 15	0.0479	0.0678	0.0368
Tinted Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.0456	0.0664	0.0423
July, 15	0.0401	0.0652	0.0451
August, 15	0.0423	0.0610	0.0319
Tinted Window - Film C			
	9 AM	12 PM	15 PM
June, 15	-0.0061	-0.0036	-0.0065
July, 15	-0.0068	-0.0037	-0.0062
August, 15	-0.0065	-0.0042	-0.0078

Table 5. Temperature Decrease for the Sample Room in Moscow.

Clear Window			
	9 AM	12 PM	15 PM
June, 15	1.2825	1.7741	1.3644
July, 15	1.1674	1.7433	1.4160
August, 15	1.2244	1.6804	1.1734
Tinted Window			
	9 AM	12 PM	15 PM
June, 15	0.3587	0.5087	0.3837
July, 15	0.3235	0.4993	0.3994
August, 15	0.3409	0.4801	0.3254
Clear Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.1225	0.1769	0.1315
July, 15	0.1097	0.1735	0.1372
August, 15	0.1160	0.1665	0.1104
Clear Window - Film B			

	9 AM	12 PM	15 PM
June, 15	0.1103	0.1606	0.1187
July, 15	0.0986	0.1575	0.1240
August, 15	0.1044	0.1510	0.0992
Clear Window - Film C			
	9 AM	12 PM	15 PM
June, 15	0.0003	0.0036	0.0008
July, 15	-0.0005	0.0034	0.0012
August, 15	-0.0001	0.0030	-0.0004
Tinted Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.0477	0.0742	0.0521
July, 15	0.0415	0.0725	0.0549
August, 15	0.0445	0.0691	0.0418
Tinted Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.0421	0.0670	0.0463
July, 15	0.0363	0.0654	0.0489
August, 15	0.0392	0.0622	0.0366
Tinted Window - Film C			
	9 AM	12 PM	15 PM
June, 15	-0.0065	-0.0035	-0.0060
July, 15	-0.0072	-0.0037	-0.0057
August, 15	-0.0069	-0.0041	-0.0072

Table 6. Temperature Decrease for the Sample Room in Singapore.

Clear Window			
	9 AM	12 PM	15 PM
June, 15	1.3972	1.7880	1.2590
July, 15	1.2905	1.7702	1.3214
August, 15	1.3481	1.6924	1.0599
Tinted Window			
	9 AM	12 PM	15 PM
June, 15	0.3937	0.5129	0.3515
July, 15	0.3611	0.5075	0.3705
August, 15	0.3787	0.4838	0.2907
Clear Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.1352	0.1785	0.1199
July, 15	0.1233	0.1765	0.1268
August, 15	0.1297	0.1679	0.0978
Clear Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.1221	0.1620	0.1079
July, 15	0.1111	0.1602	0.1143
August, 15	0.1170	0.1522	0.0876

Clear Window - Film C			
	9 AM	12 PM	15 PM
June, 15	0.0011	0.0037	0.0001
July, 15	0.0003	0.0036	0.0006
August, 15	0.0007	0.0030	-0.0012
Tinted Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.0539	0.0749	0.0464
July, 15	0.0481	0.0740	0.0498
August, 15	0.0512	0.0698	0.0357
Tinted Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.0479	0.0677	0.0409
July, 15	0.0425	0.0668	0.0441
August, 15	0.0454	0.0628	0.0308
Tinted Window - Film C			
	9 AM	12 PM	15 PM
June, 15	-0.0058	-0.0034	-0.0067
July, 15	-0.0065	-0.0035	-0.0063
August, 15	-0.0061	-0.0040	-0.0079

Table 7. Temperature Decrease for the Sample Room in Tokyo.

Clear Window			
	9 AM	12 PM	15 PM
June, 15	1.2397	1.7992	1.4226
July, 15	1.1195	1.7653	1.4760
August, 15	1.1985	1.7255	1.2499
Tinted Window			
	9 AM	12 PM	15 PM
June, 15	0.3456	0.5163	0.4014
July, 15	0.3089	0.5060	0.4177
August, 15	0.3330	0.4939	0.3487
Clear Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.1177	0.1797	0.1380
July, 15	0.1044	0.1760	0.1439
August, 15	0.1132	0.1715	0.1188
Clear Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.1059	0.1632	0.1247
July, 15	0.0937	0.1597	0.1301
August, 15	0.1017	0.1556	0.1070
Clear Window - Film C			
	9 AM	12 PM	15 PM
June, 15	0.0000	0.0038	0.0012
July, 15	-0.0008	0.0035	0.0016

August, 15	-0.0003	0.0033	0.0001
Tinted Window - Film A			
	9 AM	12 PM	15 PM
June, 15	0.0454	0.0756	0.0552
July, 15	0.0389	0.0737	0.0581
August, 15	0.0432	0.0716	0.0459
Tinted Window - Film B			
	9 AM	12 PM	15 PM
June, 15	0.0399	0.0682	0.0492
July, 15	0.0339	0.0665	0.0519
August, 15	0.0379	0.0645	0.0405
Tinted Window - Film C			
	9 AM	12 PM	15 PM
June, 15	-0.0068	-0.0033	-0.0057
July, 15	-0.0075	-0.0036	-0.0053
August, 15	-0.0071	-0.0038	-0.0067

The findings indicate that the final temperature approaches the reference temperature as the windows are coated with the specified film. The most energy-efficient glazing film is Type C. All types of films permit a notable reduction in temperature rise compared to a clear window without film application, and a further reduction compared to tinted glazing. The findings of this study can be extended to estimate and demonstrate the efficiency of using glazing films for energy saving. This can be achieved by calculating the amount of energy saved by a reference air conditioner with a given datasheet. Furthermore, the amount of carbon emission saving can also be demonstrated. Additionally, a cost analysis may be conducted to determine the feasibility of window filming in terms of cost. This can be achieved by providing a cost-saving of energy against the cost of film application.

V. CONCLUSIONS

When the cities are compared in terms of , the results follow a complicated pattern due to the locations of cities in reference to the standard meridian of the country and the effect of distance from the equator since the incident angle of the solar light is directly related to latitude. The results show that the total solar energy is highest at midday and lowest in the morning. The cities were selected considering different locations and populations. Therefore, they have different climatic conditions and allow to observe the results at different population scales. The results follow a complex pattern due to the location of the cities relative to the country's standard meridian and the influence of distance from the equator, as the angle of incidence of sunlight is directly related to latitude. Considering the cost of film application, film application must be cost effective and feasible in order to be a successful investment.

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