Impact of Window Shading Devices on Energy Performance of Prototypical Buildings

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ABSTRACT External window shading, in its variety of forms, is an important measure for reducing air conditioning energy consumption. How to quickly evaluate and select effective external shading shapes to suit different climate zones and building types is of great significance towards promoting building energy conservation in China. In this paper, firstly, benchmarking models of four prototypical buildings in five climate zones in China are established and calibrated with EnergyPlus. Secondly, four common types of external shading are applied to the established benchmarking models which provide energy-saving rates and economies of the external shading modes in different building types and climate zones. Finally, after a comprehensive analysis of the energy-saving rates and economies, we can determine appropriate external shading devices for different building types in different climate zones, providing a design basis and theoretical support for actual projects.

KEY WORDS: Prototypical buildings, Energy simulation, External window shading, Energy-saving evaluation

INTRODUCTION

According to a research report published by The European Solar Shading Organization in December, 2005, EU housing area is 24.26 billion m^2, half of which applies sun-shading. And building shading is widely used in the United States and Japan to improve building thermal comfort and reduce energy consumption [1]. Currently, Chinese construction area is up to 42 billion m^2, of which at least 90% is for high-energy buildings. Heating and air-conditioning account for 60% of building energy consumption [2]. Heat gained from external windows is one of the main components of the indoor air-conditioning cooling load. According to the literature [3], in northern China, the cooling load from external windows in summer accounts for 20%-30% of the total cooling load, and the situation in southern China is more severe. In cold areas, building energy consumption generated from heat transfer through external windows accounts for 23%-25% of the total building energy consumption, and building energy consumption generated from air infiltration through windows and doors accounts for 22%-37% of the total building energy consumption [4]. In recent years, a number of large commercial buildings with large ratios of window to wall area (for artistic and visual effects) have been built. At the same time, methods like natural ventilation and a combination of artificial light and natural light are being applied to save energy. However, in hot climates, the cooling load from windows and doors is so large that not only does it offset the energy saving effect of natural lighting, but it also results in more energy consumption [4].

According to the literature [5], in hot summer and cold winter zone, in improving the building envelope performance to reduce energy consumption, changing the external window sun-shading has the most significant effect. When the average north-south external window sun-shading coefficient is reduced by 0.1, the building heating and air-conditioning power consumption per unit area is reduced by an average of 2%-3% with fixed sun-shading and

3%-5% with movable sun-shading. Therefore, reasonable sun-shading is a very effective energy-saving measure for summer heat insulation, and of the effective methods for saving energy. At the moment, previous research on design methods for sun-shading systems in China has focused on the hot summer and cold winter zone [6-10]. However, China is a vast country with different climates. Therefore, this paper conducts an analysis of sun-shading energy-saving results from prototypical buildings in different climate zones.

This paper, firstly, use energy simulation software (EnergyPlus) to establish four prototypical building models (high-rise residential building, high-rise office building, comprehensive shopping mall, and hotel) in five typical cities (Beijing, Harbin, Shanghai, Guangzhou, and Kunming) representing five typical climate zones in China. Secondly, different external sun-shading methods are simulated in prototypical buildings. Finally, simulation results are used to decide which sun-shading method when applied in different buildings in the corresponding climate zone achieves the best energy-saving effect.

ESTABLISHMENT AND VERIFICATION OF PROTOTYPICAL BUILDING MODELS

Selection of modeling methods and thermal parameters

There is no way to obtain either the energy consumption data for buildings before and after system retrofits or itemized energy consumption data. Moreover, there is no way to ensure that there are no interrelated effects between the part of the building being tested and other parts of the building. At the same time, factors that influence energy consumption such as the climatic parameter, operation schedule and occupancy rate need to be eliminated. Thus, the reverse modeling method (data driven method) will be adopted in this paper.

Our country has a vast surface area and significant differences among the various climate regions. According to the Civil Building Thermal Design Regulation (GB50176-93), our country is divided into five climate regions: severe cold region, cold region, hot summer cold winter region, hot summer warm winter region, and mild region. There are certain differences between the demands of building design regulations and building energy consumption rates among the different regions. Harbin, Beijing, Shanghai, Guangzhou and Kunming are chosen as the representative cities for the five climate regions, respectively. Their climate data are obtained from the DOE official data base.

In the process of creating the model, every effort was made to represent the characteristic features of prototypical buildings in modern China, such as the building form, thermal properties of building materials, and form of HVAC and building equipment systems. The thermal properties of the building envelope materials used in creating the models are shown in table 1.

Table 1. *Material thermal performance parameters of envelopes*

Material	*Density (kg/m ³)*	*Thermal Coefficient （W/㎡K）*	*Specific Heat Capacity （kJ/kg K)*
Reinforced Concrete	2500	1.740	0.92
Aerated Concrete	700	0.220	1.05
Crushed Stone Concrete	2300	1.510	0.92
Cement Plaster	1800	0.930	1.05
Lime and Cement Mortar	1700	0.870	1.05
Clay Brick Masonry	1800	0.810	1.05
Cement Expanded Perlite	800	0.260	1.17
EPS	30	0.042	1.38
XPS	35	0.034	1.40

Four types of buildings are discussed in this article: office building, shopping mall, high-rise residence building, and hotel.

Establishment of prototypical building models

The parameter settings of the prototypical building models for the four building types are listed in table 2. The building envelope, lighting, equipment, and occupancy settings for a prototypical building are all based on the Public Building Energy Efficiency Design Standards (50189-2005).

The air conditioning systems are assumed to be a constant volume air secondary return air system for a shopping mall; a four pipe fan coil with dedicated outdoor air system for an office building and hotel; and a split-type air conditioning system for a residence building. The central heating system is applied in Harbin and Beijing. This paper uses an electrical chiller and a natural gas boiler as the cold and heat sources, respectively. Their capacity, model, and other parameters are automatically selected by EnergyPlus. Finally, the water system is designed as a constant flow pump system and its model selection is also automatically selected by EnergyPlus.

Verification of prototypical building models

In this article, verification of the model is done through an error analysis of actual energy consumption data and simulated energy consumption data. This main focus of this research targets five different climate regions; however with a lack of measured monthly energy consumption data for all of the regions, measured annual energy consumption data is used for verification. According to the FEMP standard, the model is considered reliable when the error between simulation data and real data is within 10%. After calculation, all models were found to be compliant with this standard. Thus the models are validated.

SIMULATION AND ANALYSIS OF THE IMPACT OF DIFFERENT SHADINGS ON PROTOTYPICAL BUILDING ENERGY CONSUMPTION

How to calculate the energy efficiency of different shading methods

As for the shading effect, external shading is better than glass intermediate shading which is better than inside shading. Thus four typical styles of external shading were selected to simulate the energy consumption and then the analysis and comparison was done in this paper: 1. Fixed shading (horizontal and vertical). 2. External shading with removable shutter. 3. External shading with removable rolling blind (translucent). 4. External shading with removable rolling blind (opaque).

First, we define the annual ratio of energy efficiency, R(%), as shown in Eq. (3-1),

$$R = \frac{C_b - C_a}{C_b} \times 100\% \qquad (3\text{-}1)$$

Where C_b is the total annual energy consumption before improving the energy conservation (GJ), and C_a is the one after improving energy conservation (GJ).

The energy efficiency of different shadings was analyzed by the use of the annual ratio of energy efficiency, and the steps were showed in Figure 1:

Fig. 1. *Outline of energy-saving calculation*

Table 2. *Parameter setting of prototypical building models*

Building type	*Floor*	*Area (㎡)*	*Floor Height (m)*	*Orientation*	*WWR*	*Summer/ Winter Design Temperature(℃)*	*Operation Schedule*	*Zoning*
Shopping Mall	4	96826	5.6(1st and 2nd floor) 5.4(3rd and 4th floor)	south	0.3	24/22	Whole year10:00～22:00；KTV and cinema:9:00~2:00(next day)	1st and 2nd floor: shopping area, restaurant, stair and toilet. 3rd and 4th floor: shopping area, restaurant, stair, toilet KVT, cinema and office
High-rise Office	12	19200	4	south	0.4	24/22	Weekday：8:00～18:00	Office rooms
High-rise Residence	13	3262	2.9	south	0.14	26/18	Whole year 8:00～18:00	Kitchen, toilet, bedroom, sitting room and stair
Hotel	12	23316	5(1st floor) 3.5(others)	south	0.42	24/22	Shopping area and restaurant: 7:00~24:00 whole year; Others:whole year	1st :lobby, cafe, store, laundry, storage; 2nd floor: restaurant, kitchen, corridor and spare room; 3rd -12th floor: guest room, corridor and spare room

Table 3． *Classification standard for evaluating the effect of energy-saving*

Annual ratio of energy efficiency	*Evaluation of the effect*	*Sigh*
R≧10%	Strong	★★★
5%≤R＜10%	Good	★★
1%≤R＜5%	Fair	★
R＜1%	No	☆

Effects of four typical external shading devices

In order to evaluate the effects of exterior shadings and get visual results, these external shadings were divided into four types, according to the value of R with the application of shading. This standard of classification was quoted in following analysis.

These four types of external shadings were applied to four prototypical buildings located in five different cities. The energy-saving effects of adding external shadings to the buildings were showed in Table 4:

After analysis, we can find that the energy-saving effects of different types of buildings may be totally different even in the same area and with the same shading. And the different construction characteristics of public and store buildings lead to this phenomenon. As for the store buildings, due to the big ratio of window to wall (70%), the better energy-saving effect was achieved by using external shadings and energy efficiency glass with better thermal property, compared to public buildings. In contrast, due to the big heating load in winter, exhaust air heat recovery can be an obvious energy-saving technology in office building while its effect is not significant in store buildings.

Table 4. *The evaluation of energy-saving*

City	*Shade Type*	*Fractional Energy Saving（%）*							
		Shopping Mall		*High-rise Residence*		*High-rise Office*		*Hotel*	
Beijing	Fixed Shading	-1.22	☆	1.37	★	1.00	★	2.02	★
	External Window Louver Shading	0.76	☆	2.32	★	6.19	★★	9.03	★★
	External Window Shading Roll (Translucent)	0.03	☆	1.35	★	3.95	★	5.77	★★
	External Window Shading Roll (Opaque)	0.78	☆	2.36	★	6.14	★★	8.96	★★
Ha Er'bin	Fixed Shading	0.66	☆	-1.22	☆	0.65	☆	1.61	★
	External Window Louver Shading	2.22	★	3.71	★	7.06	★★	12.76	★★★
	External Window Shading Roll (Translucent)	1.33	★	2.16	★	4.32	★	9.34	★★
	External Window Shading Roll (Opaque)	2.18	★	3.68	★	8.22	★★	12.64	★★★
Shanghai	Fixed Shading	0.21	☆	2.69	★	0.94	☆	1.12	★
	External Window Louver Shading	0.71	☆	3.87	★	4.92	★	9.31	★★
	External Window Shading Roll (Translucent)	1.22	★	2.53	★	3.18	★	6.08	★★
	External Window Shading Roll (Opaque)	0.92	☆	4.04	★	4.89	★	9.21	★★
Guangzhou	Fixed Shading	0.03	☆	2.71	★	0.18	☆	1.22	★
	External Window Louver Shading	0.25	☆	2.54	★	3.95	★	7.17	★★
	External Window Shading Roll (Translucent)	1.10	★	1.64	★	2.92	★	4.98	★
	External Window Shading Roll (Opaque)	0.45	☆	2.69	★	3.97	★	7.13	★★
Kunming	Fixed Shading	0.07	☆	0.42	☆	0.28	☆	1.16	★
	External Window Louver Shading	2.17	★	0.45	☆	5.11	★★	13.14	★★★
	External Window Shading Roll (Translucent)	1.31	★	0.37	☆	3.25	★	8.65	★★
	External Window Shading Roll (Opaque)	2.12	★	0.47	☆	5.01	★★	12.81	★★★

ECONOMIC ANALYSIS OF DIFFERENT EXTERNAL SHADING DEVICES

The economic analysis of energy-saving building retrofit technologies depends mainly on an analysis of the investment payback period for each energy retrofit method. When analyzing the appropriateness of adopting an energy-saving measure from an engineering perspective, not only does the annual cost savings of a method need to be analyzed, but the payback period also needs to be taken into consideration. The shorter the pay off period, the better the energy-saving results and economy. Using the above simulation results, the payback period for each energy retrofit method is calculated and analyzed according to the following equations:

The yearly benefit equation is: $R=Eb-Ea$ （4-1）

Where R is yearly cost savings after retrofitting, RMB; Eb is the yearly operating cost of the baseline building, RMB: Ea is the yearly operating cost after applying the energy-saving method, RMB.

The payback period (simple investment payback period) is acquired while ignoring the financial interest rate, price variation, bank interest rate, and other variables.

The equation is: PBP=C/R （4-2）

Where PBP is the statistical payback period in years; C is the retrofit cost, RMB; R is yearly cost savings after applying the energy-saving method, RMB.

According to the above economic analysis method, an analysis of the 4 prototypical buildings in 5 typical cities was conducted. The results are shown below:

CONCLUSION

External shading technology is the most effective and has the highest payback period among all retrofit methods. This paper simulated 4 prototypical buildings in 5 cities representative of 5 typical climate zones in EnergyPlus and applied different external sun shading methods: fixed shading (vertical and horizontal shading), flexible louver shading, flexible semitransparent roller shutter sun-shading, and flexible opaque roller shutter sun-shading. The EnergyPlus simulations provided annual energy consumption data. Finally, a comprehensive evaluation was conducted to rate each method with a combination of economic and energy-saving rates.

1． Under normal operation, evaluating the effects of sun-shading results in the following conclusion: flexible shading> fixed shading. When combined with an economy analysis, the results may change. For the high rise residential building, the difference in energy saving rate between fixed and flexible shading is not big (0.05%~1.35%), but the economy of fixed shading is better than flexible shading.

2． Solar shading technology is one example of an effective energy-saving building technology, but its effective is not obvious in every building in every region.

3． For comprehensive public buildings, whose load comes mainly from the occupant and equipment loads, the energy-saving effects of such a technology may not be obvious. It is recommended that external shading be considered by the architect during the design process so the form of the building can be combined with external shading in a way to achieve an ideal energy-saving result.

4． When comprehensively evaluating the energy-saving rate and the economy of different methods of external shading, we can conclude that: for high rise office and hotel buildings, flexible shading (opaque) is recommended; for high rise residential buildings, we recommend fixed shading in Beijing, Shanghai and Guangzhou, and flexible shading (opaque) in Harbin; for comprehensive public buildings, we recommend flexible shading (opaque) in Beijing, Harbin and Kunming, and flexible shading (transparent) in Shanghai and Guangzhou.

Table 5. *Economic analysis of different external shading devices （Unit：Cost/Thousand Yuan，Period/Year）*

City	Shade Type	Shopping Mall			High-rise Residence			High-rise Office			Hotel		
		Cost Saving	Retrofit Cost	Pay off Period	Cost Saving	Retrofit Cost	Pay off Period	Cost Saving	Retrofit Cost	Pay off Period	Cost Saving	Retrofit Cost	Pay off Period
Beijing	Fixed Shading	68.4	141.3	2	1.1	21.8	20	6.9	67.3	10	20.7	95.3	5
	External Window Louver Shading	75.9	1015.5	13	1.8	133.4	73	30.8	1148.8	37	84.1	1522.6	18
	External Window Shading Roll (Translucent)	2.7	812.4	302	1.1	106.7	101	47.8	919.1	19	53.8	1218.0	23
	External Window Shading Roll (Opaque)	77.6	609.3	8	1.8	80.0	43	48.2	689.3	14	83.5	913.5	11
Ha Er'bin	Fixed Shading	90.4	141.3	2	0.2	21.8	105	1.4	67.3	47	14.9	95.3	6
	External Window Louver Shading	223.0	1015.5	5	2.9	133.4	45	55.1	1148.8	21	118.4	1522.6	13
	External Window Shading Roll (Translucent)	133.6	812.4	6	1.7	106.7	62	33.7	919.1	27	86.7	1218.0	14
	External Window Shading Roll (Opaque)	218.4	609.3	3	2.9	80.0	27	64.1	689.3	11	117.3	913.5	8
Shanghai	Fixed Shading	33.1	141.3	4	1.6	21.8	14	8.1	67.3	8	17.3	95.3	6
	External Window Louver Shading	100.9	1015.5	10	2.3	133.4	59	52.3	1148.8	22	123.5	1522.6	12
	External Window Shading Roll (Translucent)	172.6	812.4	5	1.5	106.7	72	33.8	919.1	27	80.6	1218.0	15
	External Window Shading Roll (Opaque)	131.1	609.3	5	2.4	80.0	34	52.0	689.3	13	122.2	913.5	8
Guangzhou	Fixed Shading	2.2	141.3	65	1.8	21.8	12	14.1	67.3	5	22.1	95.3	4
	External Window Louver Shading	37.6	1015.5	27	1.7	133.4	78	48.9	1148.8	24	117.5	1522.6	13
	External Window Shading Roll (Translucent)	168.5	812.4	5	1.1	106.7	97	36.1	919.1	26	81.6	1218.0	15
	External Window Shading Roll (Opaque)	69.2	609.3	9	1.8	80.0	44	49.2	689.3	14	116.9	913.5	8
Kunming	Fixed Shading	8.4	141.3	17	0.16	21.8	138	12.8	67.3	5	8.3	95.3	12
	External Window Louver Shading	220.0	1015.5	5	0.17	133.4	783	39.0	1148.8	30	124.1	1522.6	12
	External Window Shading Roll (Translucent)	132.8	812.4	6	0.14	106.7	769	24.8	919.1	37	81.7	1218.0	15
	External Window Shading Roll (Opaque)	215.9	609.3	3	0.18	80.0	455	38.2	689.3	18	120.9	913.5	8

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