slat angle was considered, which can achieve more energy savings than only control blinds fully opened or fully closed.

CALCULATION OF THE ENERGY CONSUMPTIONS OF ARTIFICIAL LIGHTING AND COOLING AT DIFFERENT BLIND SLAT ANGLES

To evaluate the energy saving performance of automated blinds, it is necessary to calculate the cooling and artificial lighting energy consumptions with different blinds control strategies. We used two typical days' measurement data, which are clear sky and partly cloudy sky, as samples for the energy calculation.

We studied an office room located in Beijing, with the size of width 5 m, length 5 m, and height 3 m, with a 2×4m window facing to south, with no obstructions around the room. Luminaires consist of six 36W twin tube fluorescents. In order to compare the effect of automated blinds on the cooling and lighting energy consumptions in different control strategies, six cases were designed for analysis, detailed information is shown in table1.

Table 1 *The energy consumptions*

Case	Blind condition	Weather condition	Cooling energy consumption (kWh)	Lighting energy consumption (kWh)	Overall energy consumption (kWh)
1	Blinds fully closed	Cloudy	0	1.296	1.296
		Sunny	0	1.296	1.296
2	Blinds fully opened	Cloudy	1.213	0.216	1.429
		Sunny	1.774	0	1.774
3	Slat angle is 60°	Cloudy	0.058	0.972	1.030
		Sunny	0.065	0.648	0.713
4	Slat angle is 90°	Cloudy	0.165	0.648	0.813
		Sunny	0.191	0.576	0.767
5	Slat angle is 120°	Cloudy	0.245	0.36	0.605
		Sunny	0.216	0.432	0.648
6	Slat angle is 150°	Cloudy	0.885	0.648	1.533
		Sunny	0.225	0.72	0.945

Four typical blind slat angles were selected in cases 3 to 6 separately, which can check the effect of different slat angles on the cooling and lighting energy consumptions. Additionally, the cases 1 and 2, which are the blinds were fully opened and fully closed respectively, are used to comparing with cases 3 to 6 to check the influence of automated blinds to the cooling and lighting energy consumptions.

The measured data on April 20th (partly cloudy sky) and May 20th (clear sky) are used to calculate the energy consumptions. On April 20th, only when slat angle was 150°

can direct solar radiation entered the room through the window, and there was no direct solar radiation entering the room at the four slat angels on May 20th because of high solar altitude.

Because in the cooling energy consumption only the part of removing radiation solar heat gain relates to blind control, the radiation solar heat gain through window is used to represent the influence of blind control on cooling energy consumption. The total solar heat gain was calculated by multiplying the projection area of the window on the horizontal plane, which can be calculated by solar altitude angle and window area, by measured solar heat gain per unit horizontal area. The cooling energy is calculated by dividing the radiation solar heat gain by the cooling system energy efficient rate (EER), as shown in Equation 1. A typical EER value of 3.0 is used for the calculation. The energy calculation results are shown in table 1 and the hourly solar altitude angle and window area horizontal projection are shown in table 2.

Table 2 *The solar altitude and window area on two measurement days*

Time	Weather condition	The solar altitude angle (°)	The window area in a horizontal plane (m^2)
10:00	Cloudy	48.950	6.967
	Sunny	55.550	5.488
11:00	Cloudy	57.087	5.178
	Sunny	64.849	3.756
12:00	Cloudy	61.181	4.401
	Sunny	69.880	2.931
13:00	Cloudy	59.498	4.713
	Sunny	67.469	3.319
14:00	Cloudy	52.831	6.065
	Sunny	59.352	4.740
15:00	Cloudy	43.339	8.478
	Sunny	48.872	6.986

$$E_1 = \frac{\sum_{i=1}^{n}(Q_i S_i)}{EER} \quad (1)$$

where Q_i and S_i is hourly measured solar heat gain per unit horizontal area and the calculated projection area of the window on the horizontal plane, respectively, and *EER* is the cooling system energy efficient rate .

The lighting energy consumption was calculated by multiplying the luminaire power density by the floor area where the illuminance level does not reach the required illuminance threshold, which is 300lux according to design manual (Lu et al. 2008).

According to the same design manual the luminaire power density is set at 11 W/m^2. The lighting energy consumption calculation is shown in Equation 2.

$$E_2 = \left\{ \sum_{i=1}^{n} \left[0.036 \text{Roundup}\left(\frac{11 A_i}{36}\right) \right] \right. \tag{2}$$

Where E2 is daily lighting energy consumption (kWh), A_i is the hourly floor area where the illuminance level does not reach 300 lux, 11 is the luminaire power density, and 36 is the wattage of twin tube fluorescents.

RESULTS

Case 1: blinds fully closed

In this case, the solar heat gain was considered to be zero, and luminaires need to be used in all areas in any period of working hours. Owing to the solar radiation can enter room only during 10:00 to 15:00 on April 20th and May 20th, we only took this time period into consideration. Consequently, both the cloudy day and the sunny day consumed 1.296 kWh of lighting energy. That is to say the overall energy consumptions of cooling for removing solar heat gain and lighting are 1.296 kWh.

Case 2: blinds fully opened

For the case of blinds fully opened (same as no blind situation), the lighting energy consumption in cloudy day and sunny day were 0 and 0.216 kWh respectively. The cooling energy consumptions in cloudy day and sunny day were 1.213kWh and 1.774kWh respectively. As a result, the overall energy consumptions in cloudy day and sunny day were 1.429kwh and 1.774kwh respectively. Compared with case 1, when blinds were fully closed in cloudy day, although the solar heat gain was zero, which caused zero cooling energy consumption, the luminaires were needed in any period of time to ensure indoor illuminance as being required. Therefore, the lighting energy consumption was the largest. While for case of blind fully opened, despite the lighting energy consumption was the least, the cooling energy consumption was the most. As a result, the overall energy consumption in case 1 was less than that in case 2. This contrast was more apparent in sunny day.

Case 3-6: slat angle were 60°、90°、120°、150° respectively

The blind slat angle definition is as shown in Fig.1.When the blinds are at the horizontal position, the angle is 90 degrees. The energy consumptions under various slat angles were shown in Table1. From Table1 it can be seen that for both weather conditions of cloudy and sunny sky, cases 3-6 consumed less energy than case 1, i.e. blind fully closed case, and case2, i.e. blind fully opened case.

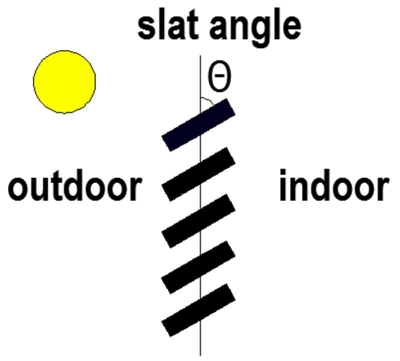

Figure 1. *Definition of the blind slat angle*

For the various blind slat angle cases (cases 3-6), on April 20th when direct sunlight entered the room, i.e. the slat angle was 150°, the solar heat gain became the largest. The cooling energy consumption decreased accompanying to the slat angle decrease. However, the lighting energy consumption was not the least when direct sunlight entered the room through the window. Instead, when the slat angle was 120°, because of plenty diffuse sunlight introduction, the overall energy consumptions achieved the minimum value. On May 20th, when there was almost no direct sunlight entering the room because of high solar altitude, the cooling energy consumption showed a trend that gradually increased and the lighting energy consumption firstly decreased and then increased, accompanying to the slat angle increase, as shown in Fig.2 and Fig.3. Besides, the overall energy consumptions also reach to the minimum value when slat angle was 120°, as shown in Fig. 4. The overall energy consumptions of setting slat angle at 120° were less than the blind fully opened case, which is the largest energy consumption case, by 57.7% and 63.5% on April 20th and May 20th respectively. Comparing with the blind fully closed case, the blind slat angle at 120° can save cooling and lighting energy by 53.3% and 50.0% on April 20th and May 20th respectively.

If the blind slat angle control strategies can be further refined, the overall energy consumptions can be further reduced. As an example, if a slightly more detailed slat angle control strategies are set as follows, the overall energy consumption can be reduced by 1.8% and 14.2% on April 20th and May 20th respectively comparing with the fixed slat angle of 120°.

On April 20th: slat angle is 120°from 10:00 to 13:00 and 90°from 14:00 to 15:00, the overall energy consumptions will be 0.594kWh.

On May 20th: slat angle is 90°at 10:00, 60°from 11:00 to 13:00 and 120°from 14:00 to 15:00, the overall energy consumptions will be 0.556kwh.

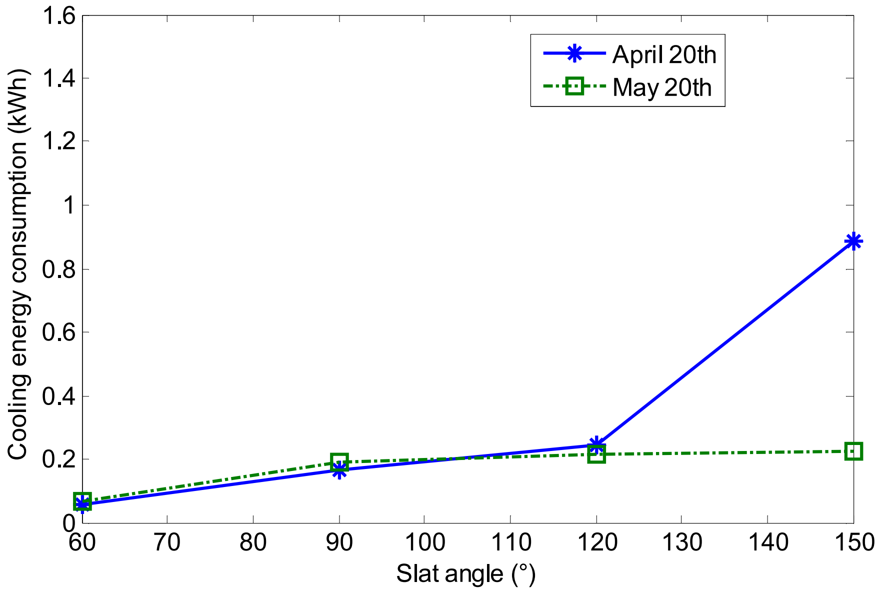

Figure 2. *The cooling energy consumption at different slat angles*

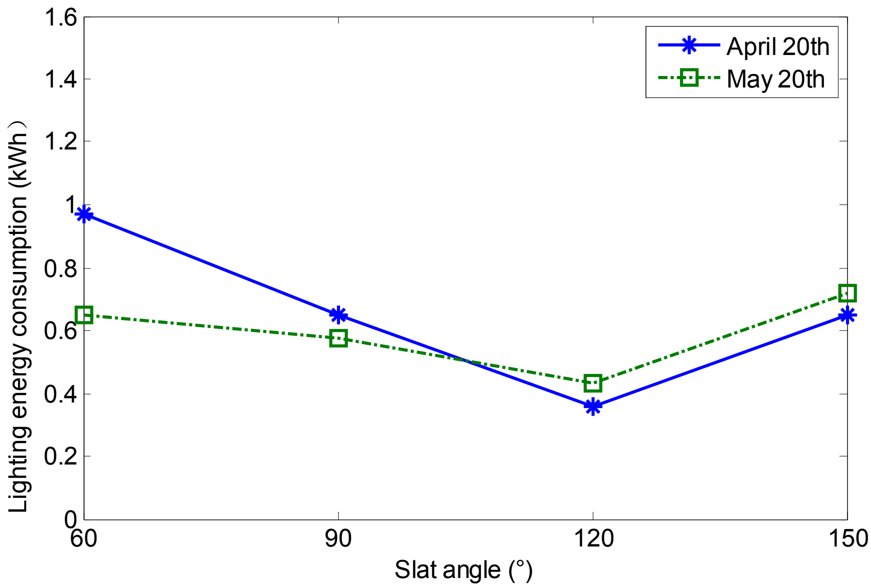

Figure 3. *The lighting energy consumption at different slat angles*

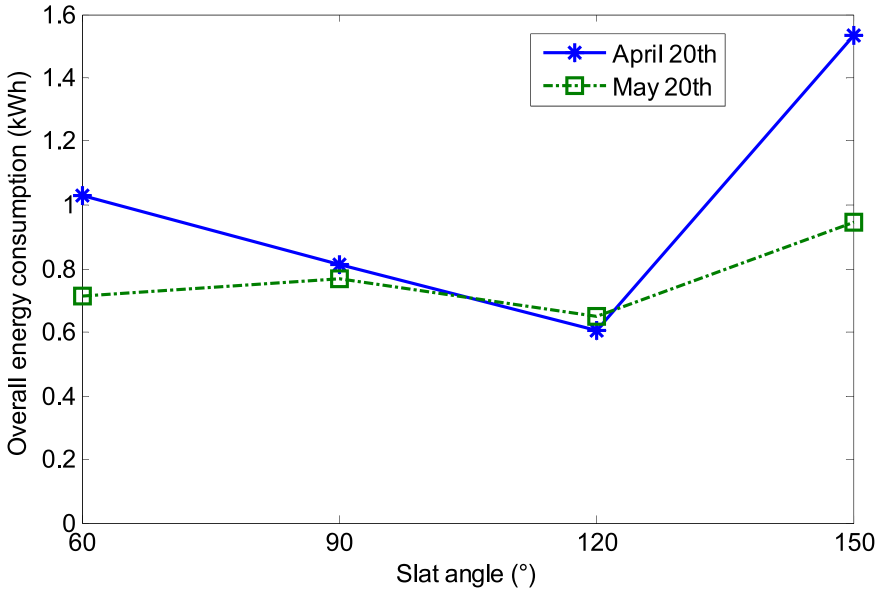

Figure 4. *Overall energy consumption at different slat angles*

CONCLUSIONS

The energy consumptions of lighting and cooling for removing radiant solar heat gain under different slat angle control strategies were calculated. The results show that:

1) For both weather conditions of partly cloudy and sunny sky, the overall energy consumptions with blinds fully closed and blind fully opened were more than that of slat angles can be adjusted.

2) As a rule of thumb, for the two measurement days' weather conditions, if the slat angle is set at 120°, the overall energy consumptions of lighting and cooling can be reduced by about 60% comparing with the blind fully opened case.

3) If a little more detailed blind slat angle control strategies are employed, for example to change the slat angle two to three times in one day, the overall energy consumptions can be further reduced by 1.8% to 14.2% comparing with the fixed slat angle at 120° for the two measurement days' weather conditions.

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