UNCERTAINTY QUANTIFICATION OF OVERALL HEAT TRANSFER COEFFICIENT(U-VALUE) FOR A GLAZING SYSTEM WITH EXTERNAL VENETIAN BLIND

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ABSTRACT

This study investigates the stochastic characteristics of the U-value of a double-glazing system with an external Venetian blind. The thermal properties of window systems have been treated in a deterministic fashion and physically calculated under static boundary conditions defined by national standards. However, the stochastic variation of the U-value is known to be caused by environmental conditions and blind slat angles. For this purpose, the authors selected two points in time for seasonal comparison, and the U-value was calculated by "pyWinCalc". Latin Hypercube Sampling and Sobol methods were employed for the uncertainty and sensitivity analysis. It is demonstrated that the uncertainty of the U-value according to environmental conditions and the slat angle is significant, and distribution also varies seasonally. Hence, it is suggested that careful attention should be paid to an objective assessment of the thermal performance of such systems and the implementation of dynamic control for external Venetian blinds.

Keywords: external Venetian blind, overall heat transfer coefficient, uncertainty analysis, sensitivity analysis, performance gap.

1 INTRODUCTION

The transparent building envelope has been widely used because it can provide daylight and outside view and also introduce transmitted solar radiation for passive heating. However, it could transmit unwanted solar energy into the indoor space and cause severe visual discomfort under over-daylit environment. Hence, to control the amount of absorbed/transmitted solar energy through the transparent envelope as well as the amount of daylight, indoor/outdoor shading devices are generally introduced. For thermal performance measures of the transparent building envelope, two factors are mainly used such as the overall heat transfer coefficient (U-value) and solar heat gain coefficient (SHGC) (ASHRAE 2021).

The U-value of the window system is calculated through physical experiments. For this purpose, national and international standards have been developed to define boundary conditions prescribed in a deterministic fashion (Table 1) because in order to quantify dynamic variation in U-value, an infinite number of tests should be conducted. In South Korea, U-value experiments of the window system are conducted according to KS F 2278 (2017) set by Korean Industrial Standard (KS). In the United States, National Fenestration

ANNSIM '23, May 23-26, 2023, Mohawk College, ON, CANADA; ©2023 Society for Modeling & Simulation International (SCS)

Rating Council (NFRC) provides ANSI/NFRC 100 (2020) for U-value calculations. Even though there is a difference in boundary conditions between the two methods (Table 1), both employs a deterministic testing method. This *static* U-value obtained from the experiments (KS F 2278, ANSI/NRFC 100) has been used as input parameters in most building simulation tools.

Table 1: deterministic boundary conditions for calculation of fenestration U-values.

KS F 2278	interior temperature: 20℃, exterior temperature: 0℃
NFRC 100	interior temperature: 21.1℃, exterior temperature: -18℃, wind velocity: 5.5m/s

It has been acknowledged that many types of uncertainties exist in building energy modeling (de Wit and Augenbroe 2002; Hopfe 2009), which can result in the performance gap between dynamic simulation predictions and reality (de Wilde 2014). The indoor/outdoor environment of an actual building has a stochastic characteristic that differs from the deterministic conditions mentioned above (Table 1). Therefore, the deterministic U-value calculation approach may not represent the actual thermal behavior of the window system under constantly varying environment. Kim and Park (2022) quantified the uncertainty in the SHGC value caused by weather, window type, and orientation and suggested the concept of stochastic SHGC and U-value. Yet the study was limited to double-glazing windows without any internal or external shading devices. However, many window systems are installed with manual or automatic shading devices. To the best of the authors' knowledge, there have been limited studies conducted on detailed uncertainty quantification of the U-value of the window system with adjustable external blinds. Hence, this study aims to quantify the uncertainty in the U-value of the window system with an external Venetian blind under dynamic environmental conditions such as outdoor air temperature, wind velocity, solar radiation, etc. In addition, a ranking of dominant environmental parameters will be provided.

2 TARGET WINDOW SYSTEM

For this study, a general window system was selected. It is assumed that the system is located in Seoul, South Korea and south-facing. It consists of two layers of interior and exterior 6mm clear glazing with a 12mm air gap, and external Venetian blinds. The width and height of glazing are 1,000mm (Figure 1, Table 2), and the effect of the frame is not considered for an intuitive interpretation of simulation results. The blind slats are opaque white with a solar reflectance of 0.64, solar transmittance of 0.0, and infrared emittance of 0.80. The slat's width and vertical spacing are 50mm. It is assumed that the blind slats can rotate from -90˚ to +90˚. Two points in typical seasons (June 21st at 1 pm and December 21st at 1 pm) were selected to quantify the uncertainty of the system's U-value under sufficient direct and diffuse solar radiation.

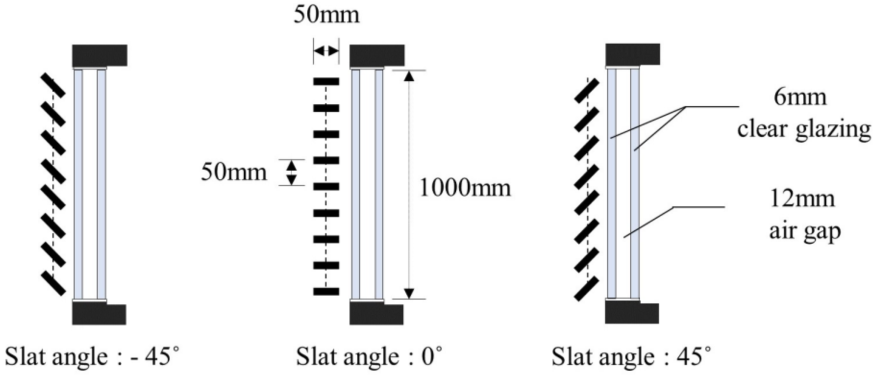


Figure 1: Target window system with external blind slats.

Table 2: Experimental conditions and properties of target window system.

Location	Seoul, South Korea (longitude=126°E, latitude=37.5°N)	
Date and time	1:00 pm, June 21st (solar altitude: 75.08˚, solar azimuth 21.59˚) 1:00 pm, December 21st (solar altitude: 28.73˚, solar azimuth 7.12˚)	
Glazing properties	Width	1,000 mm
	Height	1,000 mm
	Composition	6 mm clear glazing + 12 mm air + 6 mm clear glazing
Slat properties	Width	50 mm
	Spacing	50 mm
	Thickness	0.2 mm
	Tilt angle of slat	-90˚, -80˚, -70˚...70˚, 80˚, 90˚ (10˚ intervals)
	Solar reflectance	0.64
	Infrared emittance	0.80

For simulating the target window system, ‘pyWinCalc’, a python package of WINDOW Calc Engine developed by Lawrence Berkeley National Laboratory (LBNL), was used. ‘pyWinCalc’ can calculate various thermal and optical properties of glazing systems and shades (Kohler et al. 2019). In the pyWinCalc module, glazing, blinds and materials of the window system can be imported from International Glazing and Shading Database (IGSDB) (LBNL; https://igsdb.lbl.gov/). Parametric simulation runs were performed in a python virtual environment by changing indoor/outdoor boundary conditions.

3 UNCERTAINTY AND SENSITIVITY ANALYSIS

For uncertainty analysis, Latin Hypercube Sampling (LHS) was used. It divides the parameter space into bins of equal probability with the goal of attaining a more even distribution of sample points in the parameter space that would be possible with pure random sampling (McKay 2000). As shown in Table 3, the min and max values of four environmental variables, namely global solar radiation, ratio of direct solar radiation to global solar radiation, outdoor wind velocity, and outdoor air temperature were selected in the months of June and December according to the standard weather data in Seoul, South Korea (TMY3 format) (Energyplus; https://energyplus.net/weather). Then, 2,000 samples were generated by the LHS method. Please note that the ratio of direct solar radiation (W/m^2, I_{dir}) to global solar radiation (I_{glo}) was added as an environmental input to account for the cloud factor (Table 3).

Table 3: Min and max values of four environmental variables for LHS.

Month		Slat angle [˚]	Global solar radiation [I_{glo}, W/m^2]	Ratio (I_{dir} / I_{glo})	Outdoor wind velocity [m/s]	Outdoor air temperature [˚C]
June	min	-90	247.5	0.09	0.27	18.50
	max	90	417.3	0.53	1.81	30.50
December	min	-90	89.6	0.00	0.26	-8.60
	max	90	872.8	0.82	1.94	11.30

For sensitivity analysis, the Sobol method, one of the global sensitivity methods, was used because it can effectively quantify fluctuations in the output for the entire input parameters that were sampled simultaneously (Sobol 1993). The Sobol method derives the sensitivity of input parameters by dividing the conditional variance ($V_{X_i}(E_{X_{\sim i}}(Y|X_i))$) for an input variable (X_i) with respect to the output variable (Y) by the total variance ($V(Y)$) of the output variable as shown in Equation 1. The sensitivity ranking of input variables was obtained using the first-order sensitivity index (S_i). It is the stand-alone sensitivity of the i^{th} input variable, representing the independent sensitivity of each input variable in the state of the interaction with other variables being removed. The second-order sensitivity index (S_{ij}) refers to the effect of the interaction effect between the target input variable and other input variables, and the n^{th} sensitivity index refers to the effect of interaction between the input variable and *(n-1)* other variables. The sum of the sensitivity indices of all input variables except the overlapped effect by the interaction corresponds to 1.0 (Equation 2). The Sobol method can quantify the importance of all input variables, and the first-order sensitivity index (S_i) of each variable is expressed as a number between 0.0-1.0, and the closer it becomes to 1.0, the greater the influence on the output variables. 64 (=2^6) samples were generated according to the Saltelli sampling scheme (Saltelli et al. 2008).

$$S_i = \frac{V_{X_i}(E_{X_{\sim i}}(Y|X_i))}{V(Y)} \tag{1}$$

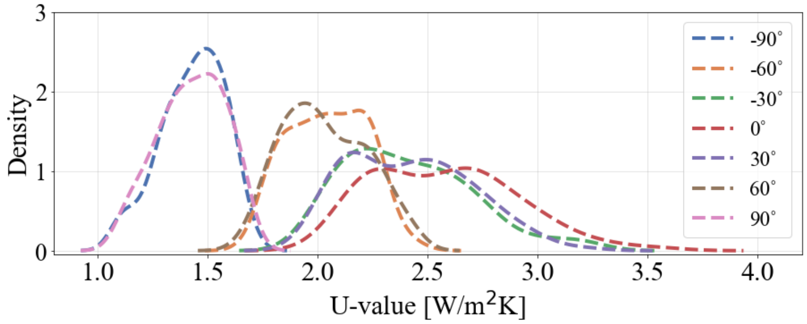
$$\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \sum_i \sum_{j>i} \sum_{k>j} S_{ijk} + \cdots + \mathrm{S}_{123\ldots\mathrm{z}} = 1 \tag{2}$$

4 RESULTS

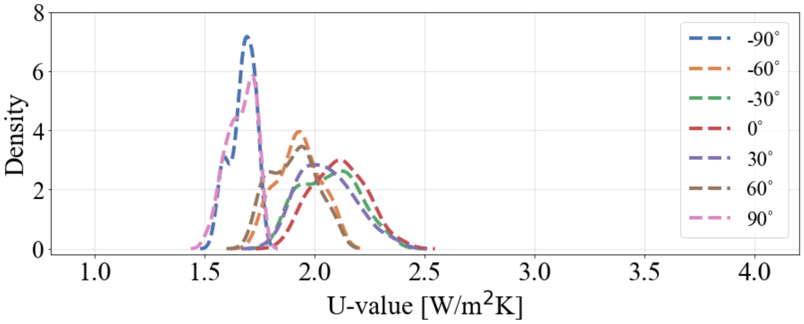
4.1 Uncertainty Analysis

Figure 2 shows the distribution of the U-values according to different slat angles under varying environmental conditions. As shown in Figure 2, the degree of uncertainties in the U-values is significantly dependent on both of the slat angles and the environmental conditions. It is interesting that similar distributions (uncertainties) are observed when the absolute values of the slat angles are equal, e.g. -90˚ and 90˚, -60˚ and 60˚, etc. It can be inferred that the slat angle would influence the convective heat transfer between the exterior glazing and outdoor air as well as radiative heat exchange between the exterior glazing and surroundings.

In addition, the smaller the absolute value of the slat angle, the higher the mean value and standard deviation of the U-value were observed. In other words, when the slat angle becomes close to 0˚ (Figure 1), it would increase the aforementioned convective and radiative heat transfer, leading to higher U-value as well as higher uncertainties in the U-value. Conclusively, it should be noted that in assessing the thermal performance of the window system with external Venetian blinds, the impact of environmental variables and slat angles on the U-values must be carefully reflected.



(a) June

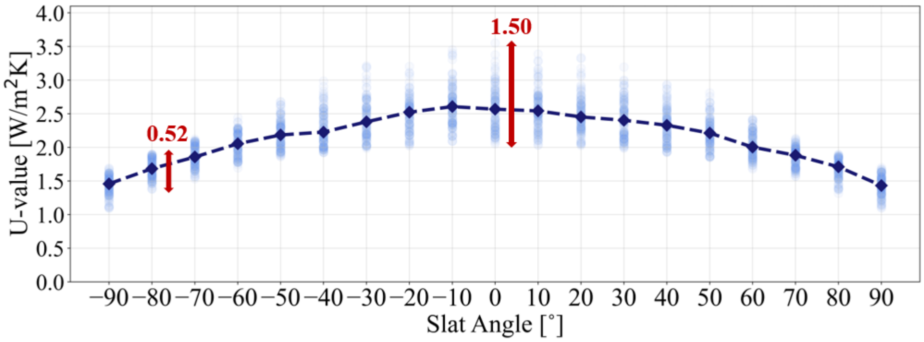


(b) December

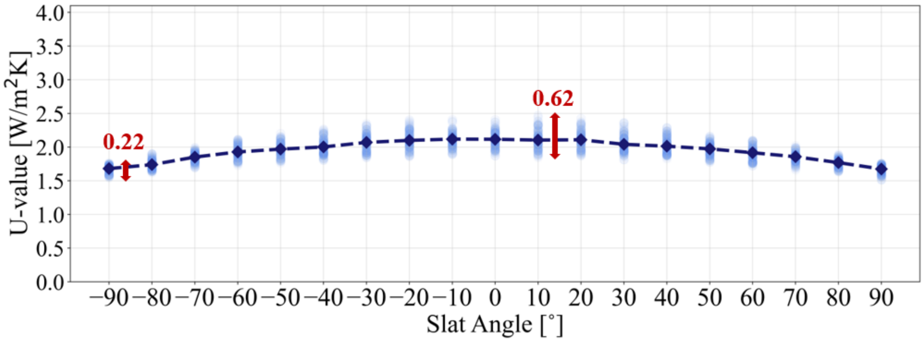
Figure 2: U-value uncertainties.

Blue dots in Figure 3 represent 2,000 samples out of the LHS method. In June, the maximum mean value and the maximum standard deviation of the U-value are 2.61 W/m^{2}K at the slat angle of -10˚ and 0.32 W/m^{2}K at the slat angle of 0˚, respectively (Figure 3(a), Table 4). Similarly, in December, the maximum mean value and the maximum standard deviation of the U-value are 2.12 W/m^{2}K at the slat angle of 0˚ and 0.14 W/m^{2}K at the slat angle of 10˚, respectively (Figure 3(b), Table 4). It is noteworthy that the U-value in June ranges from 1.09 to 3.55 [W/m^{2}K], while in December, it ranges from 1.51 to 2.47 [W/m^{2}K] (Figures 2-3).

The mean value curves denoted by the dotted blue line in Figure 3 are almost symmetrical with respect to the slat angle of 0˚. It indicates that as mentioned earlier, the slat angle significantly influences the convective and radiative heat transfer between the exterior glazing and the outdoor environment.



(a) June



(b) December

Figure 3: Uncertainties in U-values depending on slat angles and environmental variables.

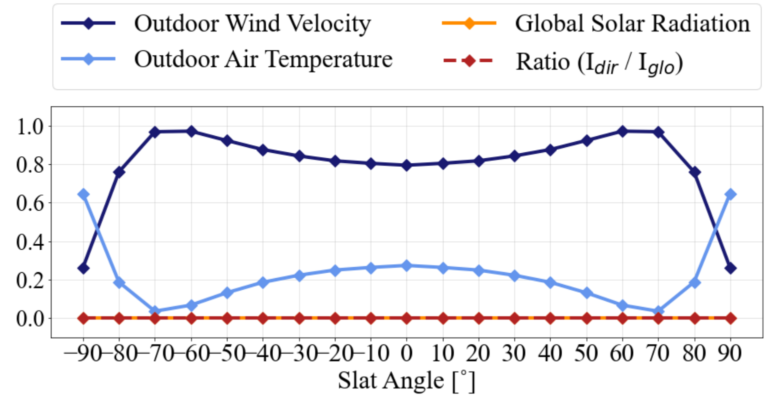
Table 4: Mean values and standard deviation of the U-values.

	June		December	
Slat angle	Mean value [W/m^{2}K]	Standard deviation [W/m^{2}K]	Mean value [W/m^{2}K]	Standard deviation [W/m^{2}K]
-90˚	1.43	0.14	1.67	0.06
-80˚	1.68	0.14	1.74	0.07
-70˚	1.86	0.15	1.85	0.07
-60˚	2.05	0.17	1.93	0.10
-50˚	2.20	0.21	1.97	0.10
-40˚	2.28	0.26	2.01	0.12
-30˚	2.41	0.29	2.07	0.13
-20˚	2.49	0.26	2.11	0.13
-10˚	2.61	0.30	2.11	0.11
0˚	2.58	0.32	2.12	0.12
10˚	2.56	0.30	2.11	0.14
20˚	2.49	0.27	2.11	0.13
30˚	2.42	0.28	2.05	0.13
40˚	2.33	0.25	2.03	0.12
50˚	2.21	0.22	1.97	0.10
60˚	2.03	0.19	1.91	0.10
70˚	1.86	0.14	1.85	0.08
80˚	1.68	0.14	1.76	0.07
90˚	1.43	0.15	1.66	0.07
Min	1.43	0.14	1.66	0.05
Mean	2.14	0.22	1.95	0.10
Max	2.61	0.32	2.12	0.14

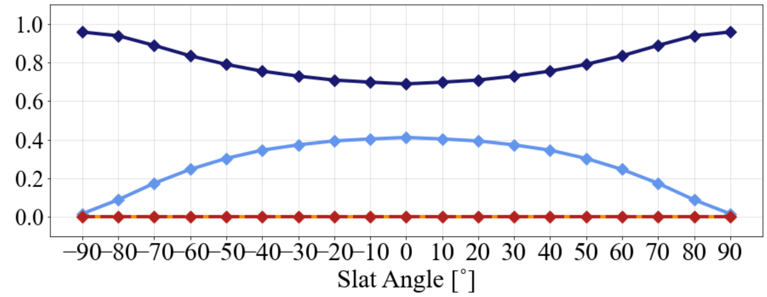
4.2 Sensitivity Analysis

Figure 4 shows the first-order sensitivity indices of the four environmental variables (outdoor wind velocity, outdoor air temperature, global solar radiation, and solar radiation ratio) in June and December. The first-order sensitivity indices of the four variables are symmetrical with respect to the slat angle of 0˚, or horizontal. In addition, outdoor wind velocity and outdoor air temperature account for more than 95% of the total uncertainty. The sensitivity index of the outdoor wind velocity is dominant at most slat angles (average: 0.86).

In June, when the slat angles become greater than 70˚, the sensitivity index of the outdoor wind velocity decreases, while that of the outdoor air temperature increases. As the slat angle becomes horizontal, the influence of the outside temperature increases (Figure 4). It can be inferred that as the slats become horizontal, it increases convective heat transfer between the exterior glazing surface and outdoor air. It is interesting that global solar radiation and the ratio (I_{dir} / I_{glo}) exhibit negligible influence on the uncertainty of the U-value, and accordingly their sensitivity indices are close to 0 at every slat angle.



(a) June



(b) December

Figure 4: First-order sensitivity indices of four environmental variables that influence the U-value uncertainty.

5 CONCLUSION

In this study, the stochastic characteristics of the U-value of a window system with an external Venetian blind were quantified. Four environmental variables that influence the U-value were selected, and the pyWinCalc module was used to simulate the thermal behavior of the window system. The LHS and the Sobol methods were used for uncertainty and sensitivity analysis, respectively. In addition, two points in time, June and December, were selected to investigate the seasonal difference in the uncertainty of the U-value of the given system. The results can be summarized as follows:

- Significant uncertainty in the window's U-value was observed according to the environmental variables and slat angles (Figures 2-3, Table 4). The degree of U-value uncertainties in June and December are as follows: 1.09–3.55 [W/m^{2}K] in June, 1.51-2.47 [W/m^{2}K] in December (Figures 2-3). Also, as the slat angle becomes horizontal, the uncertainty in the U-value increases.

- According to the first-order sensitivity indices obtained from the Sobol method, outdoor wind velocity and outdoor air temperature account for more than 95% of the total uncertainty. Not surprisingly, the impact of global solar radiation and the radiation ratio (I_{dir} / I_{glo}) are found to be negligible. Similar to the aforementioned uncertainty results, the sensitivity of the outdoor wind velocity and outdoor air temperature varies according to the slat angle.

- The influence of the slat angle on the thermal performance of the window, or U-value, as well as its corresponding uncertainty and sensitivity, must be carefully reflected for assessing the thermal performance of the window system. Without objective quantification of the slat angle's influence on transparent building envelopes, it would lead to a significant performance gap (Augenbroe 2019). In addition, such slat angle's influence could be beneficially applied to optimal control of dynamic shades (Kim and Park 2012).

Conclusively, it is demonstrated in this study that the U-value of an external blind window system can be quantified using a *stand-alone tool* (pyWinCalc), not resorting to dynamic *whole-building* simulation tools. In addition, contrary to the static U-value testing methods such as ANSI/NFRC 100 and KS F 2278, it was found that the uncertainty in U-value is significant and influenced by environmental variables. It can be expected that this study can contribute to objectively evaluating the thermal performance of adjustable shading devices, and to developing a guideline for optimal slat angles by occupants. In a future study, the simulation results will be compared to the actual U-value of windows under dynamic environmental conditions.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20202020800360).

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