Identification of dynamic U-values for supply-air double windows based on experiments

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Abstract. The double windows with supply-air are recommended for both new and retrofitted buildings where preheating fresh air is needed especially when dealing with historical and protected buildings. To evaluate their energy saving potentials in buildings and optimize their performance, building energy simulations are necessary. In building energy simulation tools, the thermal transmittance (i.e., *U*-value) is one of the most important input parameters. The conventional *U*-value is a static indicator and a number of numerical studies have been proposed to identify *U*-value with varying window parameters. However, there is still a lack of laboratory experimental studies to get accurate *U*-value and evaluate numerical modelling results. Moreover, the performances of supply-air windows are related with environmental parameters and thus the use of conventional *U*-value might lead to a significant deviation between the simulated building energy and the real one. The purpose of this study is to provide dynamic *U*-values which could be varied according to environmental conditions. Firstly, an adapted guarded hot box is set up and it is calibrated by controlling air velocities and air temperatures in both cold and hot sides. Secondly, the *U*-values of supply-air windows are measured with varying environmental parameters and window parameters. Thirdly, the regression analysis is applied to describe the correlation between *U*-values and the influential factors, and thus one can easily evaluate *U*-value under different environment conditions. A future work is to integrate the regression correlation with energy simulation tools to have a comprehensive exploration of supply-air windows in different climate regions.

Keywords. Supply-air double windows; *U*-values; Guarded hot box method; Experiment
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1. Introduction

Utilizing supply-air double windows is an effective way to reduce heating demand in winters for both new built and existing buildings [1–4]. Supply-air windows have several advantages. First, they can provide fresh air to improve indoor air quality. Second, they can preheat fresh air before air enters into the room and thus reduce the ventilation heating load. Third, they can be retrofitted by putting an additional window inside or outside of the existing window, without damaging the building structure. Fourth, using them do not affect the view to the outside.

U-value is an important indicator in characterizing window thermal performance and analysing building energy consumption. The *U*-value defined in ISO 15099 [5] represents the heat transferred through the window per square meter under one degree of the air temperature difference between indoor and outdoor environment. Different from conventional windows, the heat loss through the interior glazing of supply-air double windows could be partly recovered by the flowing air. This is not considered in the conventional *U*-value, and thus additional *U*-values, including U_{loss}-value, U_{use}-value and U_e-value, were proposed for supply-air double windows [6,7]. The detailed description of U_{loss}-value, U_{use}-value and U_e-value could refer to [7].

Most of the existing studies on *U*-values of supply-air windows are based on simulations or in-situ experiments.

Wright [6] performed simulations to get U_e-value based on 2D analytical solutions. In their study, eleven supply-air windows with different inner and outer glazing were simulated with and without ventilation. The air flow channel was 15 mm. They found that attributed to the ventilation, the U_e-value could be reduced by 30%-50%.

Baker and Mcevoy [8] measured air temperature within the gap between two panes to calculate the U_e -value. They concluded that the U_e -value are dependent on the ventilation rate.

Mcevoy et al. [9] conducted in-situ experiments in the PASSYS test cell and they directly placed a heat transfer mat in the middle of the outer window to deduce the U_e-value, using shading screen. Test were performed with 10, 20, 30 mm air flow channels and 6, 10, 13 l/s flow rates. They concluded that, regardless of the width of air flow channel, increasing the ventilation rate results in a decrease in the U_e-value. In particular, as the ventilation rate increased from 5.6 l/s to 14 l/s, the U_e-value of the window with 30 mm gap was decreased from 1.12 to 0.67 W/m^2 K. Moreover, they found that placing the Low-E coating in the surface facing the air flow channel could reduce the U_e-value by approximately 50%. They also established an ESP-r model and simulated U_e-value. Based on the simulation result, it was found that the higher U_e-value is coinciding with higher exterior air temperature.

Southall and Mcevoy [10] investigated the effect of window size on the U_e-value based on experiments and CFD model. They found that the aspect ratio had very little effect on the U_e-value when the window aera was the same. In addition, the U_e-value could be larger for the larger window size. They also established a correlation between U_e -value and window size.

Carlos et al. [7] investigated U-values based on experiments and numerical analysis. They found that compared to the supply-air double window with an inner single-glazed unit, the window with an inner double-glazed unit had a lower U_{loss}-value, a lower U_{use}-value and a lower U_e-value. When the air flow rate increased, the U_{loss} -value and U_{use} -value increased, while the U_e-value decreased. They also found that when the air temperature difference between cold and hot sides increased, the U_{loss}-value and U_{use} -value increased, while the U_e -value decreased.

Mcevoy and Southall [11] performed CFD to simulate the U_e-value and also compared the simulated value with measured value. The comparison results showed that the simulated value agreed with the measured one when the temperature difference between cold and hot sides was 44 °C, while a large deviation between the simulated value and measured one could be observed when the temperature difference was 33 °C.

There is still a lack of laboratory experiments to identify U-values of supply-air windows. In this study, we conducted experiments in an adapted guarded hot box to measure the U-values with varying the air flow rate and air temperature difference between cold and hot sides. Moreover, dynamic U-values, which could be varied according to environmental conditions, were proposed based on the regression analysis.

2. Definition of *U*-values

The U-value defined in ISO 15099 [5] can be expressed by the following equation,

$$U = \frac{q}{\Delta T} \tag{1}$$

Where q is the heat flux through the tested sample per square meter (W/m^2), without incident solar radiation; ΔT is the air temperature difference between the indoor and outdoor environment (K).

The U_{loss}-value represents the heat loss through the interior window per square meter under one degree of air temperature difference between the indoor and outdoor environment [7]:

$$U_{loss} = \frac{q_1}{\Delta T} \tag{2}$$

Where q_1 is the heat flux through the interior window per square meter (W/m^2), without incident solar radiation.

The proposed U_{use} -value could represent the capability of supply-air double windows in recovering the heat loss through the interior glazing. It can be calculated as Eq. (3) [7]:

$$U_{use} = \frac{c\dot{m}(T_{ol} - T_{il})}{A \cdot \Delta T} \tag{3}$$

Where A is the window area, m^2; c is the heat capacity of air, J/kg °C; $\dot{m}$ is the air mass flow rate, kg/s; T_{ol} is the outlet air temperature and T_{il} is the inlet air temperature, °C.

The U_e-value is the heat loss through the exterior window per square meter under one degree of air temperature difference between the indoor and outdoor environment. It can be calcualted based on U_{loss}-value and U_{use}-value [7]:

$$U_e = U_{loss} - U_{use} \tag{4}$$

3. Methods

3.1 Apparatus and sensors

(1) Guarded hot box

The guarded hot box (GHB) in LTDS/ENTPE laboratory (as shown in Fig.1) is used to measure the U-values of supply-air double windows. It comprises a metering box, a guard box, a cold box and a sample frame between metering box and cold box to hold samples.

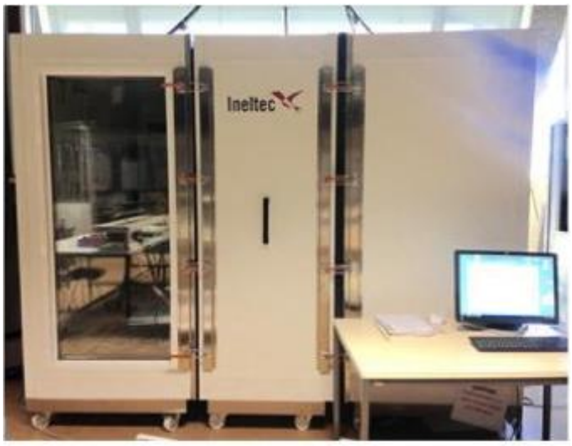


Fig.1 - GHB in LTDS/ENTPE laboratory

Inside the metering box, there are four resistance heaters to maintain the air temperatures at desired values. In addition, a wooden Baffle painted black was placed in the metering box, and three DC powered axial flow fans were installed on the top of baffle to achieve uniform air circulation between the baffle and surface of the tested sample. The input voltage to the heaters and fans was controlled using LABVIEW. It should be mentioned that, under steady state conditions, the input power of the fans was considered to be fully converted into heat.

The function of the guard box is to minimize the heat loss through the walls of metering box. There are four heaters in the guard box to maintain the air temperature of the guarded box the same as that of metering box.

In the cold box, there is a glycol cooling system. Similar to the measuring box, a baffle and three DC powered axial flow fans were installed in the cold box.

(2) Adapted GHB

As mentioned in [12], to prevent insufficient air mixing and to achieve an even temperature distribution in metering box, the flowing air was returned to the cold box through a tube instead of entering the metering box. The tube was installed as shown in Fig.2.

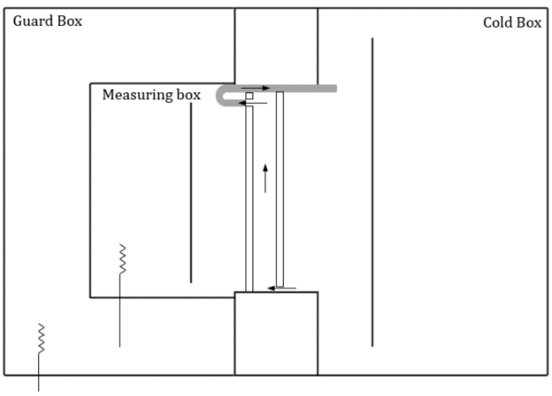


Fig.2 - Schematic of the adapted GHB

(3) Sensors

According to the standard ISO 8990 [13], fourteen air temperature sensors were installed in metering box, guard box and cold box to measure air temperatures. In addition, eighteen surface temperature sensors were placed on the baffle surfaces. Three hot wire anemometers were applied to measure the inlet air velocity, the air velocity in cold side and that in hot sides. Two air temperature sensors were utilized to measure the inlet and outlet air temperature. The energy input to the heaters and fans were measured by energy meters. Also, heat flux meters were put at the middle of each side of the tested sample to measure the heat flow rate. The sensor positions are shown in Fig.3 and the sensor accuracy is shown in Table 1

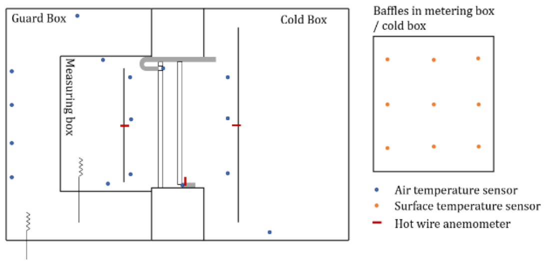


Fig.3 – Positions of sensors

Table. 1 Sensors for experiments

Sensors	*Accuracy of sensor*
PT100 temperature sensor	±0.1 °C
Energy meter	±1%
Heat flux meter	±3%
Hot wire anemometer	±3%

3.2 Calibration of guarded hot box

The metering box wall loss and flanking loss need to be calibrated before testing the supply-air double window. The sum of metering box wall loss and flanking loss can be calculated as

$$Q_{loss} = Q_{in} - Q_{XPS} \quad (5)$$

Where Q_{loss} is the sum of metering box wall loss and flanking loss, W; Q_{in} is the heat input into metering box; Q_{XPS} is the measured heat flow through the XPS plate placed in the sample frame.

The calibration tests were performed under four conditions, as shown in Table. 2. The velocity in hot side was kept at 0.1m/s and that in cold side was kept at 1.5 m/s. The air temperatures of metering box and guard box were set at 30 °C and that of cold box was varied from 1 to 15 °C.

Table. 2 Test conditions in calibration tests

No.	*Ta*-CB (°C)	*Ta*-MB (°C)	*Ta*-GB (°C)	*v*-MB (m/s)	*v*-CB (m/s)
1	1	30	30	0.1	1.5
2	5	30	30	0.1	1.5
3	10	30	30	0.1	1.5
4	15	30	30	0.1	1.5

(*Ta*-MB: air temperature in measuring box, °C; *Ta*-GB: air temperature in guard box, °C; *Ta*-CB: air temperature in cold box, °C; *v*-MB: air velocity in hot side, m/s; *v*-CB: air velocity in cold side, m/s)

The controllers shall keep air temperature fluctuations within 1% of the air temperature difference between cold and hot sides. Calculations of heat loss were done after all of the air temperatures were stabilized. Fig. 4 shows the correlation between the measured heat loss and air temperatrue difference.

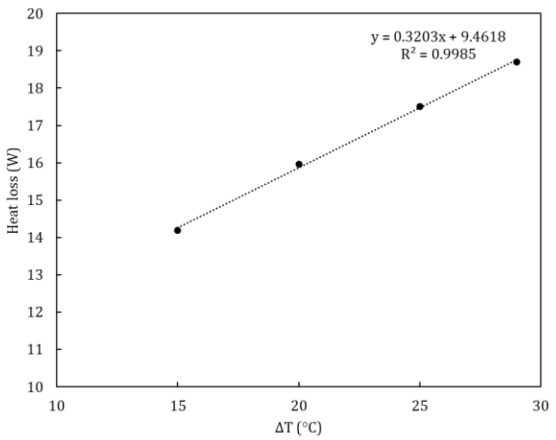


Fig.4 – Heat loss against temperature difference betwen cold and hot sides

As shown in Fig.4, the heat loss of guarded hot box has a positive linear correlation with the air temperature difference between cold and hot sides. This can be explained by the fact that the heat flow from metering box to cold box increases with increasing air temperature difference, leading to an increased heat loss.

3.3 Test configurations and test conditions

The tested window configuration is shown in Fig.5. It is composed of an inner single-glazed window (located in hot side) and an outer single-glazed window (located in cold side). The window frame is made of wood and the glazing is 4 mm clear glass. The air flow channel is 95 mm. The ventilation inlet is on the bottom of the outer window and the outlet is on the top of the inner window.

Fig.5 - Picture of the test configuration

Tests were carried out for the supply-air double window with different air flow rates and air temperature differences. As shown in Table 3, tests were performed under eleven test conditions. Calculations of U-values were done after all the air temperatures were stabilized.

Table. 3 Test conditions for the supply-air double window

No.	*Ta*-CB (°C)	*Ta*-MB (°C)	*Ta*-GB (°C)	$\dot{V}$ (l/s)	*v*-MB (m/s)	*v*-CB (m/s)
1	1	30	30	3	0.1	1.5
2	1	30	30	6	0.1	1.5
3	5	30	30	3	0.1	1.5
4	5	30	30	6	0.1	1.5
5	5	30	30	9	0.1	1.5
6	10	30	30	3	0.1	1.5
7	10	30	30	6	0.1	1.5
8	10	30	30	9	0.1	1.5
9	15	30	30	3	0.1	1.5
10	15	30	30	6	0.1	1.5
11	15	30	30	9	0.1	1.5

($\dot{V}$: air flow rate, l/s)

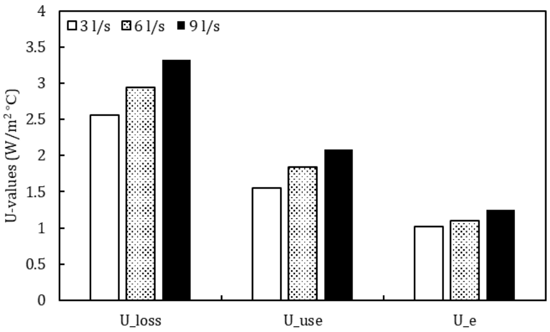
4. Results

In this section, the effects of air flow rate and air temperature difference on U-values of the tested supply-air double window are analysed. Also, the multi-linear linear regression model is used to learn the correlations between the U-values and influential factors (i.e., air flow rate and air temperature difference), and the expressions of dynamic U-values are given in this section.

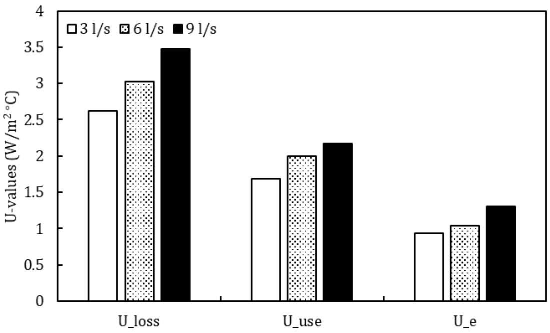
(1) Effect of air flow rates on U-values

As shown in Fig.6, the trends of U-values against the air flow rate are the same under different air temperature differences (i.e., 15, 20 and 25 °C). In particular, the U_{loss} -value and U_{use} -value always increase with increasing the air flow rate from 3 l/s to 9 l/s. This is consistent with the fact that the heat transfer between the window surfaces and the flowing air is enhanced when the air flow rate increases.

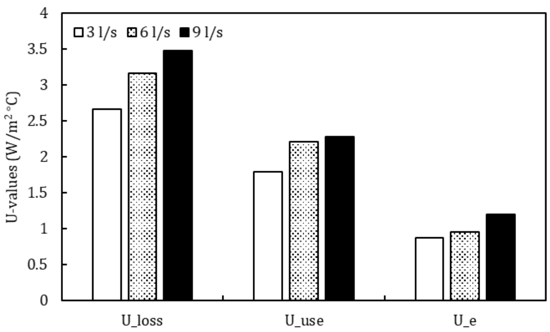
For the U_e-value, it also increases when the air flow rate increases from 3 l/s to 9 l/s, which indicates the increase rate of U_{loss}-value is higher that that of U_{use}-value.



(a) ΔT= 15 °C



(b) ΔT= 20 °C

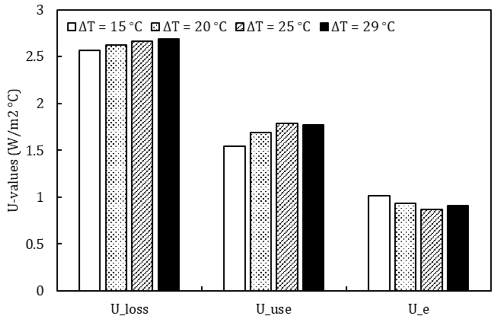


(c) ΔT= 25 °C

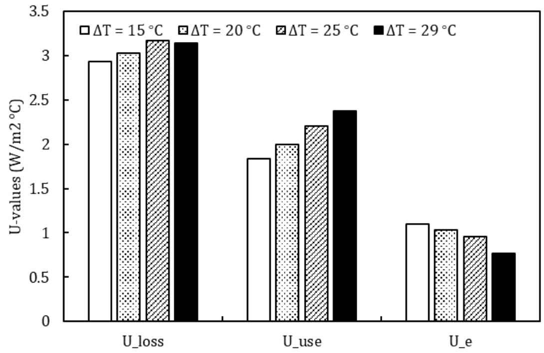
Fig.6 - *U*-values against air flow rates

(2) Effect of temperature difference on *U*-values

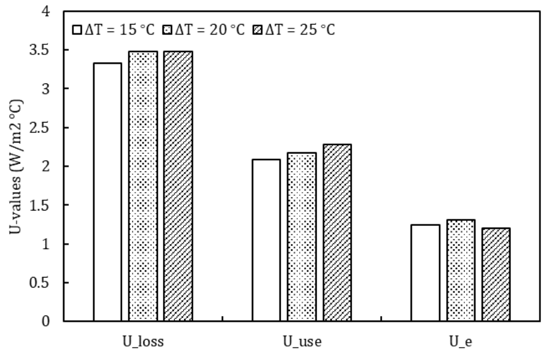
The U-values measured under different air temperature difference between cold and hot sides are shown in Fig.7. It can be observed that the effect of temperature difference on U-values is less significant than the effect of air flow rates on U-values. For the U_{use}-value, it increases by increasing the tempeatrue from 15 to 25 °C. A further increase in the U_{use}-value could be observed in the case with 6 l/s air flow rate when the air temperature difference further increases from 25 to 29 °C.



(a) $\dot{V}$ = 3 l/s



(b) $\dot{V}$ = 6 l/s



(c) $\dot{V}$ = 9 l/s

Fig.7 - *U*-values against air temperature difference between cold and hot sides

(3) Dynamic *U*-values

The multi-linear regression model [14] was adopted to get dynamic *U*-values. The expression of multi-linear regression equation is shown in Eq. (6), and the goal is to determine values of β coefficients.

$$U_i = \beta_{i,0} + \beta_{i,1}\dot{V} + \beta_{i,2}\Delta T \quad (6)$$

The equations of U_{loss}-value, U_{use}-value and U_e-value are shown in Eq. (7)-(9).

$$U_{loss} = 1.93116 + 0.13793\dot{V} + 0.01329\Delta T \quad (7)$$

$$U_{use} = 0.84398 + 0.09244\dot{V} + 0.02786\Delta T \quad (8)$$

$$U_e = 1.08719 + 0.0455\dot{V} - 0.01458\Delta T \quad (9)$$

5. Conclusions

In this study, experiments were performed in an adapted guarded hot box to measure U-values of supply-air windows.

From experimental results, it could be concluded that U-values are dependent on the air flow rate and air temperature difference between cold and hot sides. In particular, the U_{loss}-value, U_{use}-value and U_e-value are all increased when the air flow rate increases from 3 l/s to 9 l/s. The trends of U-values against the temperature difference are related with air flow rate. Furthermore, dynamic U-values are given in this study by using multi-linear regression model to learn the correlation betwen U-values and influential factors. Based on the given dynamic U-values, one can easily calculate window heat loss and recovered ventilation heat in real applications according to corresponding environment.

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Data Statement

The datasets generated during and/or analysed during the current study are not available because they are proprietary and confidential in nature but the authors will make every reasonable effort to publish them in near future.