Development of Simplified and Dynamic Model for Double Glazing Unit Validated With Full-Scale Façade Element

MINGZHE LIU¹, KIM B. WITTCHEN¹, PER KVOLS HEISELBERG² AND FREDERIK VILDBRAD WINTHER²

¹Danish Building Research Institute (SBi), Aalborg University, Hørsholm, Denmark
²Department of Civil Engineering, Aalborg University, Aalborg, Denmark

ABSTRACT: The project aims at developing simplified calculation methods for the different features that influence energy demand and indoor environment behind “intelligent” glazed façades. This paper describes how to set up simplified model to calculate the thermal and solar properties (U and g value) together with comfort performance (internal surface temperature of the glazing) of a double glazing unit. Double glazing unit is defined as 1D model with nodes representing different layers of material. Several models with different number of nodes and position of these are compared and verified in order to find a simplified method which can calculate the performance as accurately as possible. The calculated performance in terms of internal surface temperature is verified with experimental data collected in a full-scale façade element test facility at Aalborg University (DK). The advantage of the simplified method is that the models are based on the standards EN 410 and EN 673 taking the thermal mass of the glazing into account. In addition, angle and spectral dependency of solar characteristic will also be considered during the calculation. Using the method, it is possible to calculate the whole year performance with different time steps, e.g. in simple energy and comfort compliance checking tools.

Keywords: simplified method, double glazing unit, dynamic, surface temperature, energy

INTRODUCTION

Glazed façades are more and more popular for office buildings because of the requirement of higher light transmittance and better view by users; however there are drawbacks of these façades as more glazing gives a higher cooling and heating demand. Furthermore results from static solutions of glazed façade shows that the energy demand cannot be reduced significantly simply by optimizing technologies [1].

In order to minimize the energy demand of glazed office buildings, “intelligent” glazed façades has already been developed, which can react dynamically according to the environment and take advantage of the microclimate to provide optimum indoor environment and minimum building energy demand. Research has been done to evaluate the performance of the “intelligent” glazed façade [1]. Since this concept is still relatively new and some existing simulation tools are either too detailed or not accurate enough to be used for energy analysis in design stage of building design. An on-going PhD project is currently developing simplified calculation model for the “intelligent” glazed façades to accurately calculate its performance in terms of energy use and indoor environment in the building.

The expected output of the simplified calculation model is the energy needed to maintain an optimal comfort level of the room. Thermal comfort will also be evaluated, which means the internal surface temperature of façades should be one of the outputs. Together with other parameters of indoor environment, it contributes to comfort level described in the criteria [2].

Some simulation tools, standards and calculation methods has already been developed to simulate double glazing unit [3, 4, 5, 6, 7], but they either require much time and professional knowledge from the users to build the model and get the result or are not detailed and accurate enough to calculate the performance. In the method developed in the BESTFACADE project [3] a continuous procedure for calculating the impact of Double Skin Façade (DSF) constructions on the overall energy demand of buildings is applied. However, the calculation method is only suitable for double skin façade with ventilated cavity but not for single skin façade like double glazing unit. It cannot calculate the surface temperature of glazing. WIS software [4] can calculate the U-value and g value together with the internal surface temperature of different kind of glazing unit, but the method in WIS Software considers only steady state condition and it can only calculate performance in one time step, which results in much time
Methods defined in ISO 15099 can calculate the surface temperature of glazing. But the methods do not take the thermal mass of glass and temperature of cavity into account in its heat balance. Danish simulation tool BSim [6] and compliance checking tool Be10 [7] are simplified calculation tools to calculate the energy demand of building and internal surface temperature of glazing, but their glass models are not detailed and accurate enough to calculate the surface temperature taking into dynamic features of facade.

So a simplified though dynamic calculation method that can predict the energy and comfort performance of double glazing unit with acceptable accuracy needs to be developed for used in the early design stage of building and facade. This paper describes part of the simplified calculation method, focusing on the development of the simplified calculation method of the basic element of the “intelligent” glazed facade, i.e. the double glazing unit.

**METHOD**

Simplified calculation method is developed to calculate the internal surface temperature of double glazing unit together with the energy exchange through it. The performance of the simplified calculation method is compared with WIS software and evaluated by measurements performed at the test facility “The Cube” at Aalborg University. The purpose of this is to see how the simplified calculation method performs in terms of determination of internal surface temperatures. Internal surface temperatures of the double glazing unit are measured every 6 minutes from 15:00 24th January 2011 to 14:00 31st January 2011. The calculation by the simplified calculation method is conducted through all the time when temperatures are measured. But because of its time consuming, the calculation of WIS software is only conducted in 28th and 30th, representing a cloudy day and a clear day.

By calculating the internal surface temperature, the heat exchange through the double glazing unit can be calculated by the simplified calculation method. Together with the solar transmittance through the glazing, the total heating or cooling energy demand caused by the facade can be predicted.

**GRID SENSITIVITY OF THE METHOD**

In order to test the grid sensitivity of the simplified method, models with the same principle and heat balance equations but different number of variable nodes are constructed in matrices calculating the internal surface temperature. Figure 1 shows the layout of the double glazing unit and an example of node positions and numbers in model 3_1_3 (3 variable nodes in the external pane, 1 node in the cavity and 3 variable nodes in the internal pane). Calculations are conducted from model 3_1_3 to model 129_1_129, where number of nodes increases step by step in external pane and internal pane of the double glazing unit.

Figure 2 shows the calculated results and deviation of different models compared with model 129_1_129 in terms of internal surface temperature in one time step. The last four models (2_0_2 surfaces, 1_0_1 surfaces, 1_1_1 middle and 1_0_1 middle) are potential simple models from which the simplified method is chosen.

The result shows that all the four simple models have good accuracy with deviation of under 0.2 % compared with model 129_1_129. But model 2_0_2 surfaces and model 1_0_1 surfaces are better than the other two simple models. Considering the complexity and time consumption of solving equations with four variables, model 1_0_1 surfaces is chosen.

According to Figure 2, the deviation of the 1_0_1 surface model is around 0.02 %, which is adequately accurate for the simplified calculation method. The 1_0_1 surface model can be used to calculate the internal surface temperature with only two nodes, which are located on the internal surface and external surface of the double glazing unit. In time step 1, calculation is taken as steady state. After time step 1 calculation is conducted dynamically taking thermal mass of glass into account.
Figure 2: Deviation of different models compared with model 129_1_129 in terms of internal surface temperature (2_0_2 surfaces means two nodes on surfaces of internal and external pane but there is no node in the cavity).

SIMPLIFIED CALCULATION METHOD

According to the comparison of grid sensitivity, the 1_0_1 surface model is finally chosen as the simplified model. The simplified calculation method is implemented making use of finite volume energy balance equations by Clarke [8] to calculate the temperature of internal and external surfaces, taking into account of the thermal mass of the glass, spectral and angle dependence of the solar radiation [10, 11]. There are two variable nodes in the equations representing the internal and external surface temperature with the volume of ¼ of the thickness of glass. It is assumed that the temperature of glass in the volume is homogeneous. The equations take both implicit and explicit conditions into account considering the boundary conditions of both the present and previous time steps to increase the accuracy of the result.

The following equations are the results of the method calculating the temperatures of internal and external surface of the glazing.

Internal and external surface temperatures for time step 1 can be calculated by equations (1) and (2):

\[ T_{ls}(t+\delta t) = \left[ (T_{o1}(t+\delta t)h_{ce}(t+\delta t) + T_{re}(t+\delta t)h_{re}(t+\delta t) + \Phi_{soloi}(t+\delta t) + a)h_{t}(t+\delta t) + (T_{i1}(t+\delta t)h_{ci}(t+\delta t) + T_{ri}(t+\delta t)h_{ri}(t+\delta t) + \Phi_{solit}(t+\delta t) + b) \right] \]

\[ \left[ (h_{t}(t+\delta t) + h_{ce}(t+\delta t) + h_{re}(t+\delta t) + \frac{2C_p\rho V}{\delta t} \right] / \left[ (h_{t}(t+\delta t) + h_{ci}(t+\delta t) + h_{ri}(t+\delta t) + \frac{2C_p\rho V}{\delta t} \right] \] (3)

\[ T_{os}(t+\delta t) = \left[ (T_{o1}(t+\delta t)h_{ce}(t+\delta t) + T_{re}(t+\delta t)h_{re}(t+\delta t) + \Phi_{soloi}(t+\delta t) + a) \right] \]

\[ \left[ (h_{t}(t+\delta t) + h_{ce}(t+\delta t) + h_{re}(t+\delta t) + \frac{2C_p\rho V}{\delta t} \right] / \left[ (h_{t}(t+\delta t) + h_{ci}(t+\delta t) + h_{ri}(t+\delta t) + \frac{2C_p\rho V}{\delta t} \right] \] (4)

\[ a = (T_{ls}(t) - T_{os}(t))h_{t}(t) + (T_{o1}(t) - T_{os}(t))h_{ce}(t) + (T_{re}(t) - T_{os}(t))h_{re}(t) + \Phi_{soloi}(t) + \frac{2C_p\rho V}{\delta t} T_{os}(t) \] (5)

\[ b = (T_{os}(t) - T_{ls}(t))h_{t}(t) + (T_{i1}(t) - T_{ls}(t))h_{ci}(t) + (T_{ri}(t) - T_{ls}(t))h_{ri}(t) + \Phi_{solit}(t) + \frac{2C_p\rho V}{\delta t} T_{ls}(t) \] (6)

After calculating the internal surface temperature, the total energy exchange between inside and outside can be calculated by equation (7):

\[ Q_{total} = Q_{tr} - Q_{sol} \] (8)

\[ Q_{sol} = \tau_{gw}Q_{dir} + \tau_{g,str}Q_{diff} \] (9)

\[ Q_{tr} = (T_{i} - T_{ls})h_{ci} + (T_{ri} - T_{ls})h_{ri} \] (10)

\[ Q_{tr} = (T_{l} - T_{os})h_{ce} + (T_{re} - T_{os})h_{re} \] (11)

By inputting the results of the variables and parameters of subsystems in excel, the simplified calculation method can be realised. This method can be used in the early design stage of building and façade to predict the energy and comfort performance of double glazing unit. Compared with software like ESP-r and WIS, it requires less time and professional knowledge to input the parameters and build the model. The method can also be implemented in calculations using any number of time steps, saving much time compared with WIS software which can only calculate the performance of one time step.

Dynamic heat transfer coefficient in subsystems

This method not only takes into account the thermal mass of the glass, but also dynamic properties of the convective and radiative heat transfer coefficients. The present heat transfer coefficients decided by temperature difference are calculated using the results of surface temperature of previous time step.
Convective heat transfer

Interior surface convective heat transfer coefficient [8]:

\[ h_{e,i} = \left[ 1.5 \left( \frac{\Delta T}{H} \right)^{0.25} \right]^{6} + \left[ 1.23(\Delta T)^{0.33} \right]^{6} \left( \frac{W}{m^2 \cdot K} \right) \]  

(12)

Dynamic solution can be realized in (11) [8], calculating \( h_{e,i} \) with the parameters of previous time step:

\[ h_{e,i(t+\delta t)} = \left[ 1.5 \left( \frac{T_{(t+\delta t)} - T_{(t)}}{H} \right)^{0.25} \right]^{6} + \left[ 1.23(T_{(t+\delta t)} - T_{(t)})^{0.33} \right]^{6} \left( \frac{W}{m^2 \cdot K} \right) \]  

(13)

Exterior surface convective heat transfer coefficient can be calculated by (12) [8]:

\[ h_{e,e} = 5.678[a + b \left( \frac{V}{0.3048} \right)^n] \left( \frac{W}{m^2 \cdot K} \right) \]  

(14)

If \( V < 4.88 \) m/s then \( a=0.99, b=0.21 \), and \( n=1 \).
If \( 4.88 \) m/s < \( V < 30.48 \) m/s then \( a=0, b=0.5 \), and \( n=0.78 \).

For climate of Aalborg, the average wind speed in January 2011 according to Windfinder [15] is taken as 5.5 m/s.

Long-wave radiative heat transfer

Longwave radiative heat transfer coefficient between internal surface and internal walls is calculated as described in the following.

The internal radiative heat transfer coefficient of time step 1 is 4.4 W/(m²·K) according to EN 673 [9].

After time step 1, dynamic solution can be realized in (13), calculating \( h_{r,i} \) with the parameters of previous time step.

\[ h_{r,i(t+\delta t)} = \varepsilon_{i} \varepsilon_{r,i} \sigma \left( A \right)_{(t)} \frac{T_{i(t)}}{1 - \epsilon_{i}} \left( 1 - \epsilon_{r,i} \right) \left( 1 - \epsilon_{r,i} \right) \]  

(15)

Long-wave radiative heat transfer between external surface and surroundings can be calculated by (14) and (15) [8]:

In time step 1, \( h_{r,e} \) can be calculated by (14) assuming the mean temperature of \( T_{r,e} \) and \( T_{os} \) is outdoor air temperature \( T_{o} \).

\[ h_{r,e(t+\delta t)} = \frac{\varepsilon_{o} \left( T_{r,e}^{4} - T_{os}^{4} \right)}{T_{r,e} - T_{os}} \]  

(17)

VERIFICATION OF SIMPLIFIED METHOD

The model is verified by empirical data of internal surface temperature from experiments. The measurement is implemented in the full-scale test facility of façade and room (The Cube at Aalborg University) (figure 3). The test facility has two identical rooms facing south, with the internal dimension of \( 5.66 \times 2.46 \times 1.65 \) m³ (H×W×D). The entire window systems face south and each has a size of \( 1.5 \times 4 \) m². There are two operable windows, one large window in the middle and a filling at top of the window system. The operable windows has a size of \( 1.5 \times 0.5 \) m² including frame area, and the middle window has a size of \( 1.5 \times 2.2 \) m². The filling at the top of the window system has a size of \( 1.5 \times 0.8 \) m². The measurements for the double glazing unit were conducted in one of the rooms in the end of January 2011 with low outdoor temperature.

The glazing type used in the experiments is a double glazing unit with a 22 mm argon-filled cavity and low-e coating on the internal pane. The layout of the double glazing unit is showed in table 1.

The thermocouples, used for measuring the internal surface temperatures of the glazing were shielded from the outside to prevent solar irradiance from influencing the measurements [16]. The vertical gradient of the room temperature was measured at 0.91 m, 1.82 m and 2.73 m above the floor in the room.

<table>
<thead>
<tr>
<th>Position</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>Planilux 4 mm SGG</td>
</tr>
<tr>
<td>Cavity</td>
<td>Argon 22 mm</td>
</tr>
<tr>
<td>Inside</td>
<td>PItutran 4 mm SGG</td>
</tr>
</tbody>
</table>

Table 1: Layout and glass type of double glazing unit used in the simplified method and WIS.
Figure 3: Full-scale façade element test facility.

Figure 4 shows the overall results of simplified method compared with the measured performance during all the days when the measurements are conducted. It shows that during night or daytime with less solar radiation the simplified method overestimates the internal surface temperature with the deviation less than 1°C. While during sunny days it underestimates the internal surface temperature probably because it underestimates the solar absorption of the internal pane.

The calculation results of the simplified method are compared with the performance calculated by WIS software. Because it takes much time to do calculation of different time steps, calculations from WIS software are only conducted on 28th and 30th of January. The 28th of January is a typical overcast day with less solar radiation while the 30th of January is a typical sunny day with high solar radiation. The calculations conducted in WIS use the same input of external and internal air and surrounding temperatures as the simplified method. The heat transfer coefficients used in WIS calculation are taken from EN673 [9]. Figure 5 and 6 show the internal surface temperature calculated by the simplified method and WIS compared with the measured in the test facility. The results show that during the time with no or less solar radiation, both simplified and WIS overestimate the internal surface temperature. But the simplified method is closer to the measured performance compared with WIS, with a deviation less than 0.5°C. During the time with high solar radiation, the simplified method underestimates the internal surface temperature, possibly because of the underestimation of the solar absorption of internal pane, while WIS overestimates the performance during most of the time. The reason for the difference between the results of the simplified method and experiments could also be the tolerance of the convective and radiative heat transfer coefficient. Internal convective and radiative heat transfer coefficient significantly influence the calculated temperature. The reason for the overestimation of WIS software during the overcast day could probably be the overestimation of the internal convective heat transfer coefficient (3.6W/m²K) according to EN673 [9]. It could also be the overestimation of the default emissivity of internal surface εi,i used in WIS resulting in more heat exchange between the internal glazing surface and the internal surroundings.

Figure 5: Temperature Comparison between simplified method, WIS and measurement on 28th January 2011.
CONCLUSION
A new simplified calculation method is developed to calculate the heat exchange and internal surface temperature of double glazing unit. Together with the state of art method of calculating solar transmittance [12, 13], the total energy exchange through the façade between inside and outside can be calculated. Furthermore the internal surface temperature can be calculated with reasonable accuracy according to the measurements conducted in the test facility. The method is a dynamic calculation method which can be used for whole year energy performance calculations considering angle of incidence and spectral dependence of solar radiation. From the calculation and verification, it shows that the simplified calculation method has better performance of calculating the internal surface temperature than WIS during the two select days.

FUTURE WORK
This method can stand alone for calculating the performance of the double glazing unit. But it is taken as a basic model to calculate the performance of “intelligent” glazed façade. Properties of other features like external shutter, blind and natural ventilation will be added to the method and validated by the measurements from the experiments in full-scale test facility.

NOMENCLATURE
Simplified calculation method:
\( T_{is} \) internal surface temperature of glazing;
\( T_{os} \) external surface temperature of glazing;
\( T_i \) indoor air temperature;
\( T_o \) outdoor air temperature;
\( T_{r,i} \) internal surface equivalent temperature;
\( T_{r,e} \) external surrounding equivalent temperature;
\( h_i \) total thermal conductance of glazing;
\( h_{c,e} \) external convective heat transfer coefficient;
\( h_{c,i} \) internal convective heat transfer coefficient;
\( h_{r,i} \) indoor radiative heat transfer coefficient between glazing and other surfaces;
\( h_{r,e} \) outdoor radiative heat transfer coefficient between glazing and surroundings;
\( \Phi_{solo} \) absorption of solar radiation in external layer of glazing;
\( \Phi_{solf} \) absorption of solar radiation in internal layer of glazing;
\( C_p \) heat capacity of glass;
\( \rho \) density of glass;
\( V \) volume of glass per square meter;
\( \delta t \) time step;
\( Q_{total} \) is the total heat exchange from inside to outside (W/m²);
\( Q_{sol} \) is the solar radiation to the inside (W/m²);
\( Q_{tr} \) is the heat transfer from inside to outside (W/m²);
\( Q_{dir} \) is the direct solar radiation (W/m²);
\( Q_{dif} \) is the diffuse solar radiation (W/m²);
\( \tau_{e,gaz} \) is the angle dependent direct solar transmittance;
\( \tau_{e,dif} \) is the diffuse solar transmittance;
\( \Delta T \) is the temperature difference between the wall and the ambient air (K) (for time step 1, \( \Delta T \) is assumed as 293 K);
\( H \) is the wall height (m);
\( e_i \) is the emissivity of in internal glazing surface;
\( e_{r,i} \) is the emissivity of in internal surround surface;
\( T_n \) is the mean absolute temperature of internal glazing surface and internal wall surface;
\( A_i \) is the area of internal glazing;
\( A_{r,i} \) is the area of total internal wall;
\( f_{is-r,i} \) and \( f_{r,i-is} \) are the view factor between internal glazing surface and internal wall surface, which are assumed as 1 in the simplified method for whole room.

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