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Development and sensitivity study of a simplified and dynamic method for double glazing facade and verified by a full-scale façade element

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ABSTRACT

The research aims to develop a simplified calculation method for double glazing facade to calculate its thermal and solar properties (*U* and *g* value) together with comfort performance (internal surface temperature of the glazing). Double glazing is defined as 1D model with nodes representing different layers of material. Several models with different numbers of nodes or in different positions are compared and verified in order to find a simplified method which can calculate the performance as accurately as possible. The performance calculated in terms of internal surface temperature is verified with experimental data collected in a full-scale façade element test facility at Aalborg University (DK). Comparison was conducted between the simplified method and WIS software on the accuracy of calculating internal surface temperature of double glazing facade.

The method is based on standards EN410 and EN673, taking the thermal mass of the glazing into account. In addition, angle and spectral dependency of solar characteristic is also considered during the calculation. By using the method, it is possible to calculate whole year performance at different time steps, which makes it a time economical and accurate tool in design stage of double glazing façade.

1. Introduction

Double glazing facades are widely used in modern buildings. Its solar and thermal properties have a significant effect on both the energy consumption and indoor thermal comfort. Both the energy (*U*-value) and the comfort (internal surface temperature) performances of the double glazing façade are dynamic and vary according to the change of both indoor environment and outdoor weather conditions. In addition, it is preferred by architects to evaluate the whole year performance of the facade with hourly dynamic simulation at the beginning stage of the building design.

Therefore, it is important to develop a method which must have following qualities:

- Simulation is performed hourly for the whole year (thus 8760 h);
- Capable of simulating energy and comfort performance with dynamic properties;
- Set of requirement of indoor environment for both winter and summer;
- To be fast and user-friendly with simple input.

Some simulation tools, standards and calculation methods have already been developed to simulate the double glazing facade [1–6], 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 methods developed in the BESTFACADE project [1] and by Saelens [2] continuous procedure for calculating the impact of Double Skin Facade (DSF) constructions on the overall energy demand of buildings was applied. However, the calculation methods were 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 [3] can calculate the *U*-value, *g* value and the internal surface temperature of different kind of double glazing unit, but the method in WIS software considers only steady state condition.

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Nomenclature

Simplified calculation method

T_{is} internal surface temperature of glazing [°C]
T_{os} external surface temperature of glazing [°C]
T_i indoor air temperature [°C]
T_o outdoor air temperature [°C]
$T_{r,i}$ internal surface equivalent temperature [°C]
$T_{r,e}$ external surrounding equivalent temperature [°C]
h_t equivalent heat transfer coefficient between the internal pane and the external pane [9] [W/(m^2 K)]
$h_{c,e}$ external convective heat transfer coefficient [W/(m^2 K)]
$h_{c,i}$ internal convective heat transfer coefficient [W/(m^2 K)]
$h_{r,i}$ indoor radiative heat transfer coefficient between glazing and other surfaces [W/(m^2 K)]
$h_{r,e}$ outdoor radiative heat transfer coefficient between glazing and surroundings [W/(m^2 K)]
ϕ_{solo} absorption of solar radiation in external layer of glazing [W/m^2]
ϕ_{soli} absorption of solar radiation in internal layer of glazing [W/m^2]
C_p heat capacity of glass [J/(kg K)]
ρ density of glass [kg/m^3]
V volume of glass per square meter [m^3]
δt time step [s]
Q_{total} total heat exchange from inside to outside [W/m^2]
Q_{sol} solar radiation to the inside [W/m^2]
Q_{tr} heat transfer from inside to outside [W/m^2]
Q_{dir} direct solar radiation [W/m^2]
Q_{dif} diffuse solar radiation [W/m^2]
λ thermal conductivity of glass [W/(m·K)]
d thickness of the glass [m]
h_r radiative heat transfer coefficient between two panes [W/m^2]
h_g convective heat transfer coefficient in the cavity [W/m^2]
σ Stefan–Boltzmann's constant [W/(m^2 K^4)]
T_m mean absolute temperature of the gas space [K]
ε_1 and ε_2 corrected emissivities of the internal surface of the outer pane and the external surface of the inter pane at T_m [dimensionless]
s width of the space [m]
λ_{gas} thermal conductivity of the gas in the cavity [W/(m K)]
Nu Nusselt number of the gas in the cavity [dimensionless]
G_r Grashof number of the gas in the cavity [dimensionless]
P_r Prandtl number of the gas in the cavity [dimensionless]
ΔT temperature difference between glass surfaces bounding the gas space (fixed to 15 K in the calculations) [K]
ρ density of the gas in the cavity [kg/m^3]
μ dynamic viscosity of the gas in the cavity [kg/m s]
c specific heat capacity of the gas in the cavity [J/(kg K)]

For vertical glazing

A 0.035 [dimensionless]
n 0.38 [dimensionless]
$\tau_{e,gzg}$ angle dependent direct solar transmittance [dimensionless]
$\tau_{e,dif}$ diffuse solar transmittance [dimensionless]
ΔT temperature difference between the wall and the ambient air (K) (for time step 1, ΔT is assumed as 293 K)
H wall height [m]
ε_i emissivity of in internal glazing surface [dimensionless]
$\varepsilon_{r,i}$ emissivity of in internal surround surface [dimensionless]
T_n mean absolute temperature of internal glazing surface and internal wall surface [K]
A_i area of internal glazing [m^2]
$A_{r,i}$ area of total internal wall [m^2]
$f_{is\rightarrow r,i}$ and $f_{r,i\rightarrow is}$ view factor between internal glazing surface and internal wall surface, which are assumed as 1 in the simplified method for whole room [dimensionless]
α_{e1} direct angle dependent solar absorption coefficient of external pane [W/m^2]
$\alpha_{e1,dif}$ diffuse solar absorption coefficient of external pane [dimensionless]
$\alpha_{e1,dir}$ direct solar absorption coefficient of external pane [dimensionless]
α_{e2} direct angle dependent solar absorption coefficient of internal pane [W/m^2]
$\alpha_{e2,dif}$ diffuse solar absorption coefficient of internal pane [dimensionless]
$\alpha_{e2,dir}$ direct solar absorption coefficient of internal pane [dimensionless]

Table 1
Layout and glass type of double glazing unit used in the simplified method and WIS.

Position	Material
Outside	Planilux 4 mm SGG
Cavity	Argon 22 mm
Inside	PlTutran 4 mm SGG

Furthermore, it can only perform the calculation of one time step each time, which makes it quite time consuming to simulate the whole year performance of the facade. Using the method defined in ISO 15099 [4], people can calculate the surface temperature of glazing. However, the methods do not take the thermal mass of glass into account. Danish simulation tool BSim [5] and compliance checking tool Be10 [6] 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.

Therefore, it is necessary to develop a simplified though dynamic calculation method that can predict the energy and comfort performance of the double glazing facade at the early design stage of building and façade. The study aims to develop the simplified calculation method to accurately calculate the performance of the double glazing facade in terms of energy consumption and thermal comfort. The result of the method has already been shown in [7], but the detail development and the sensitivity analysis of the thermal mass of the glazing need to be shown. A method with the same principle used to simulate the façade with night insulation was shown in [8]. This paper describes the simplified calculation method and its validation by the full-scale façade element at Aalborg University. Comparisons on the calculated results between the method and WIS programme are also shown in this paper.

2. Description and research method

The first part of the study was the development of the simplified method. The method was developed to calculate the performance of the double glazing facade. The results of the method were two variables (the internal glazing surface temperature T_{is} and the external glazing surface temperature T_{os}), which were calculated by solving the heat balance equations of them. Fig. 1 illustrates the heat balance of the variables and the thermal connection between different thermal parameters inside and outside the room [9].

After the development of the method, its results were validated by the measurements performed in the test facility “The Cube” at Aalborg University. The purpose of this was to evaluate the accuracy of the method in terms of calculating the internal glazing surface temperatures. In addition, the performance of the method was compared with that of WIS programme. The internal surface temperatures of the glazing were measured every 10 min during a winter period of one week in 2011, and the calculations by the simplified method were conducted through all the time the temperatures were measured. Because it was time consuming to conduct the calculation in WIS, WIS calculations were only implemented on two days of the week, i.e., one cloudy day on 28th of January and one sunny day on 30th of January. The sensitivity on the thermal mass of the glazing was also analysed for the simplified method. The result of the method calculated considering the heat capacity of the internal and the external panes was compared with that calculated without considering the heat capacity of the panes.

After the validation of the method, the heat exchange through the façade can be predicted according to the result of the temperatures T_{is} and T_{os}. Together with the solar transmittance through the glazing [10–12], the total heating or cooling energy demand caused by the façade can be predicted.

2.1. Experiment setup

The method was validated by the empirical data of the internal surface temperatures of the glazing measured in the experiments. The measurements were implemented in the full-scale test facility consisting of façades and rooms (The Cube at Aalborg University [13]) (Fig. 2 [7,8]). The test facility had two identical south-facing rooms with the internal dimension of 5.66 m × 2.46 m × 1.65 m ($H \times W \times D$). Both of the facade systems faced south and had a dimension of 1.5 m × 4 m. The measurements of the double glazing façade were conducted in the west room of the facility.

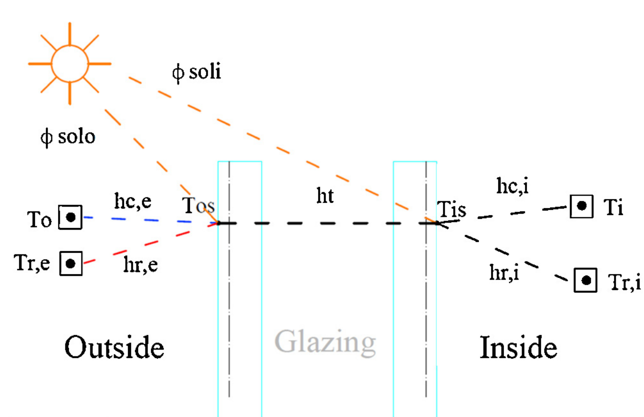

Fig. 1. The heat balance of the variables and the thermal connection between different thermal parameters inside and outside the room.

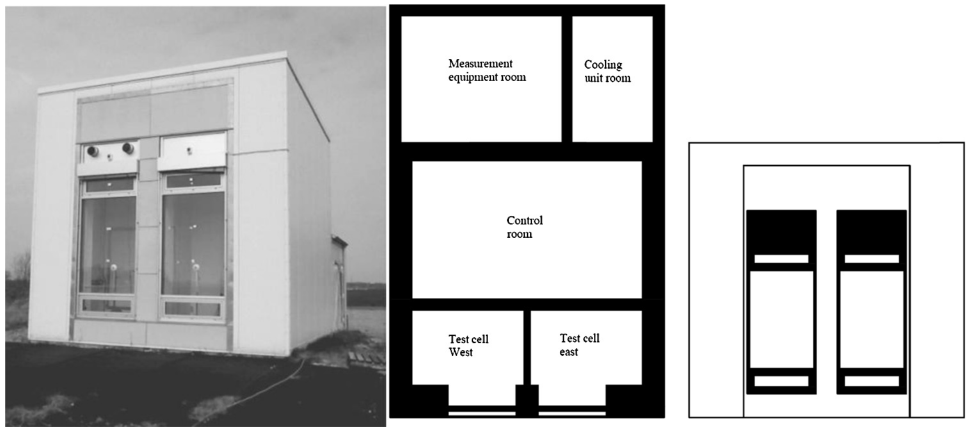

Fig. 2. Full-scale façade element test facility (left: test facility, middle: top view, right: front view).

The glazing type used in the experiments was a double glazing unit with a 22 mm argon-filled cavity and low-E coating on the internal pane. The facade in the west cell where the measurements were conducted was the double glazing facade. The layout of the double glazing unit is shown in Table 1. The measurements of the internal surface temperature on the glazing of the west room were conducted in the end of January 2011 (winter condition). The experiment is time consuming, therefore only the double glazing with low-E coating was tested in this experiment. Glazing with other type of coating (like solar control) needs to be investigated in the future work.

The surrounding internal surfaces of the room were built up of 15 mm plywood and were painted white, apart from the floor, which was made of 150 mm concrete. The heat loss due to infiltration was minimized to a minimum by sealing all joints with silicon.

Temperatures were measured using thermocouples type K, which were calibrated with a reference thermocouple at reference temperatures of 10 °C, 20 °C and 30 °C. The temperature was logged using Helios data logger connected to an ice point reference. The calibration of the thermocouples was done using a reference thermometer with an accuracy of 0.01 °C, insuring an accuracy of 0.6 °C for the thermocouples. All thermocouples were connected to a compensating box in order to increase accuracy in measurements [14]. The thermocouples measured internal surface temperatures of the glazing, shielded from the outside to prevent solar irradiance from influencing the measurements [13]. The temperature gradient was measured at 0.91 m, 1.82 m and 2.73 m heights in the room.

The room was heated by 1 kW electrical convective heating system heating the air to keep the air temperature stable. There was no other internal heat source in the room. The indoor air temperature was controlled using Danfoss Devireg^{TM} 535. The achieved temperature was 22 °C.

Irradiance was measured using CM21-pyranometer, CM11-pyranometer, Wilhelm Lambrecht pyranometer and BF3-pyranometer. BF3 and Wilhelm Lambrecht were placed externally measuring the diffuse and global irradiance on a horizontal surface. CM21 and CM11 pyranometers were placed in each of the test cells, measuring transmitted irradiance through the glazing system. The pyranometers were prior to the installation calibrated in reference to CM21, which was calibrated in sun simulator and corrected by Kipp&Zonen B.V [13].

3. Simplified calculation method

3.1. Choice and grid sensitivity of the method

In order to improve the accuracy of the simplified method, grid sensitivity of models were tested. The matrices of models with the same principle and heat balance equations but different number of variable nodes were constructed to calculate the internal surface temperature. Fig. 3 shows the layout of one double glazing unit example showing the positions and numbers of nodes 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 were conducted from model 3_1_3 to model 129_1_129, where number of nodes increases step by step in the external pane and the internal pane of the double glazing unit.

In addition, four potentially simplified models were also chosen to perform the calculations in order to find a simplified method with fewer variable nodes and acceptable accuracy. The four simplified models were 2_0_2 surfaces, 1_0_1 surfaces, 1_1_1 middle and 1_0_1 middle, shown in Fig. 4. The simplified method was chosen among the four models.

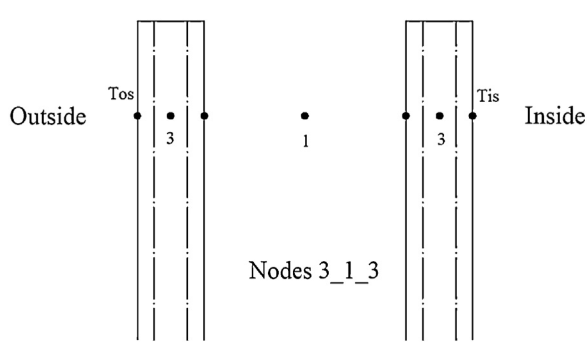

Fig. 3. The Layout of model with nodes 3_1_3 (number of nodes in external pane_number of nodes in cavity_number of nodes in internal pane).

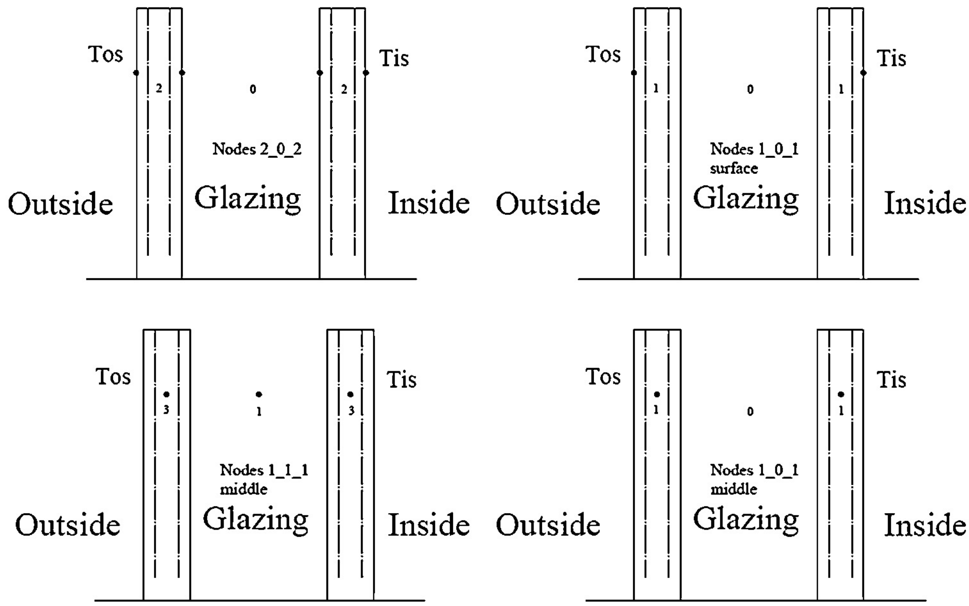

Fig. 4. The four potentially simplified models.

Fig. 5 shows the calculation results and the deviation of all the different models compared with model 129_1_129 in terms of internal surface temperature at one time step. The result shows that all the four simple models have good accuracy with deviation of under 0.2% compared with model 129_1_129. However, 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, the 1_0_1 surfaces model was more suitable than the model 2_0_2. According to the Fig. 5, the deviation of the 1_0_1 surfaces model is around 0.02%, which is adequately accurate for the simplified method. Therefore, the 1_0_1 surfaces model was chosen 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.

3.2. Development of simplified method

According to the comparison of the different models, the 1_0_1 surface model was finally chosen as the simplified model. The simplified calculation method was implemented making use of finite volume energy balance equations by Clarke [9] to calculate the temperature of internal and external surfaces, taking into account of the thermal mass of the glass, the spectral and angle dependence of the solar radiation [10–12]. There were two variable nodes in the equations representing the internal and external surface temperature with the volume of ¼ of the thickness of glass. It was assumed that the temperature of glass in the volume was homogeneous. The equations took both implicit and explicit conditions into account [9] considering the boundary conditions of both the present and previous time steps to increase the accuracy of the result.

Following equations are the procedure of the development and the results of the method calculating the temperatures of internal and external surface of the glazing.

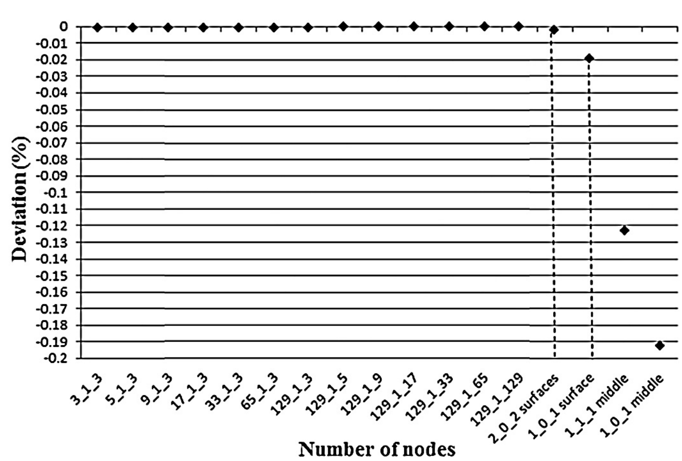

Fig. 5. The deviation of different models compared with model 129_1_129 in terms of internal surface temperature.

At the first time step, equations were developed for steady state conditions. The heat balances of the nodes standing for the internal and the external surfaces of the glazing were built in Eqs. (1) and (2). The internal and external surface temperatures at the first time step can be calculated by solving the equations:

$$(T_{is1} - T_{os1}) \times h_{t1} + (T_{o1} - T_{os1}) \times h_{c,e1} + (T_{r,e1} - T_{os1}) \times h_{r,e1} + \phi_{solo1} = 0 \tag{1}$$

$$(T_{os1} - T_{is1}) \times h_{t1} + (T_{i1} - T_{is1}) \times h_{c,i1} + (T_{r,i1} - T_{is1}) \times h_{r,i1} + \phi_{soli1} = 0 \tag{2}$$

The internal and external surface temperatures at the first time step were calculated in Eqs. (3) and (4):

$$T_{is1} = \frac{(T_{i1}h_{c,i1} + T_{r,i1}h_{r,i1} + \phi_{soli1}) \times (h_{t1} + h_{c,e1} + h_{r,e1}) + (T_{o1}h_{c,e1} + T_{r,e1}h_{r,e1} + \phi_{solo1}) \times h_{t1}}{(h_{t1} + h_{c,i1} + h_{r,i1}) \times (h_{t1} + h_{c,e1} + h_{r,e1}) - h_{t1}^2} \tag{3}$$

$$T_{os1} = \frac{(T_{i1}h_{c,i1} + T_{r,i1}h_{r,i1} + \phi_{soli1}) \times h_{t1} + (T_{o1}h_{c,e1} + T_{r,e1}h_{r,e1} + \phi_{solo1}) \times (h_{t1} + h_{c,i1} + h_{r,i1})}{(h_{t1} + h_{c,i1} + h_{r,i1}) \times (h_{t1} + h_{c,e1} + h_{r,e1}) - h_{t1}^2} \tag{4}$$

After the first time step, equations were built dynamically taking the thermal mass of the glazing into account. During the calculation of the dynamic conditions, explicit and implicit conditions were considered [9]:The explicit condition:

$$(T_{is(t)} - T_{os(t)}) \times h_{t(t)} + (T_{o(t)} - T_{os(t)}) \times h_{c,e(t)} + (T_{r,e(t)} - T_{os(t)}) \times h_{r,e(t)} + \phi_{solo(t)} = \frac{C_p \rho V}{\delta t} \times (T_{os(t+\delta t)} - T_{os(t)}) \tag{5}$$

$$(T_{os(t)} - T_{is(t)}) \times h_{t(t)} + (T_{i(t)} - T_{is(t)}) \times h_{c,i(t)} + (T_{r,i(t)} - T_{is(t)}) \times h_{r,i(t)} + \phi_{soli(t)} = \frac{C_p \rho V}{\delta t} \times (T_{is(t+\delta t)} - T_{is(t)}) \tag{6}$$

The implicit condition:

$$(T_{is(t+\delta t)} - T_{os(t+\delta t)}) \times h_{t(t+\delta t)} + (T_{o(t+\delta t)} - T_{os(t+\delta t)}) \times h_{c,e(t+\delta t)} + (T_{r,e(t+\delta t)} - T_{os(t+\delta t)}) \times h_{r,e(t+\delta t)} + \phi_{solo(t+\delta t)} = \frac{C_p \rho V}{\delta t} \times (T_{os(t+\delta t)} - T_{os(t)}) \tag{7}$$

$$(T_{os(t+\delta t)} - T_{is(t+\delta t)}) \times h_{t(t+\delta t)} + (T_{i(t+\delta t)} - T_{is(t+\delta t)}) \times h_{c,i(t+\delta t)} + (T_{r,i(t+\delta t)} - T_{is(t+\delta t)}) \times h_{r,i(t+\delta t)} + \phi_{soli(t+\delta t)} = \frac{C_p \rho V}{\delta t} \times (T_{is(t+\delta t)} - T_{is(t)}) \tag{8}$$

In order to increase the accuracy of the results, explicit and implicit conditions were added together. Then Eqs. (9) and (10) were resulted to build the heat balance standing for the nodes of the internal and the external surfaces at time step $t+\delta t$:

$$(T_{is(t)} - T_{os(t)}) \times h_{t(t)} + (T_{o(t)} - T_{os(t)}) \times h_{c,e(t)} + (T_{r,e(t)} - T_{os(t)}) \times h_{r,e(t)} + \phi_{solo(t)}(T_{is(t+\delta t)} - T_{os(t+\delta t)}) \times h_{t(t+\delta t)} + (T_{o(t+\delta t)} - T_{os(t+\delta t)}) \times h_{c,e(t+\delta t)} + (T_{r,e(t+\delta t)} - T_{os(t+\delta t)}) \times h_{r,e(t+\delta t)} + \phi_{solo(t+\delta t)} = \frac{2C_p \rho V}{\delta t} \times (T_{os(t+\delta t)} - T_{os(t)}) \tag{9}$$

$$(T_{os(t)} - T_{is(t)}) \times h_{t(t)} + (T_{i(t)} - T_{is(t)}) \times h_{c,i(t)} + (T_{r,i(t)} - T_{is(t)}) \times h_{r,i(t)} + \phi_{soli(t)} + (T_{os(t+\delta t)} - T_{is(t+\delta t)}) \times h_{t(t+\delta t)} + (T_{i(t+\delta t)} - T_{is(t+\delta t)}) \times h_{c,i(t+\delta t)} + (T_{r,i(t+\delta t)} - T_{is(t+\delta t)}) \times h_{r,i(t+\delta t)} + \phi_{soli(t+\delta t)} = \frac{2C_p \rho V}{\delta t} \times (T_{is(t+\delta t)} - T_{is(t)}) \tag{10}$$

The time step was 600 s, which was the same as the measurements.

By solving the Eqs. (9) and (10), the internal and external glazing surface temperatures at time step $t+\delta t$ can be calculated by Eqs. (11) and (12):

$$T_{is(t+\delta t)} = \frac{\left[(T_{i(t+\delta t)}h_{c,i(t+\delta t)} + T_{r,i(t+\delta t)}h_{r,i(t+\delta t)} + \phi_{soli(t+\delta t)} + b) \times \left(h_{t(t+\delta t)} + h_{c,e(t+\delta t)} + h_{r,e(t+\delta t)} + \frac{2C_p \rho V}{\delta t}\right) + (T_{o(t+\delta t)}h_{c,e(t+\delta t)} + T_{r,e(t+\delta t)}h_{r,e(t+\delta t)} + \phi_{solo(t+\delta t)} + a) \times h_{t(t+\delta t)}\right]}{\left[\left(h_{t(t+\delta t)} + h_{c,i(t+\delta t)} + h_{r,i(t+\delta t)} + \frac{2C_p \rho V}{\delta t}\right) \times \left(h_{t(t+\delta t)} + h_{c,e(t+\delta t)} + h_{r,e(t+\delta t)} + \frac{2C_p \rho V}{\delta t}\right) - h_{t(t+\delta t)}^2\right]} \tag{11}$$

$$T_{os(t+\delta t)} = \frac{\left[\left(T_{i(t+\delta t)}h_{c,i(t+\delta t)} + T_{r,i(t+\delta t)}h_{r,i(t+\delta t)} + \phi_{soli(t+\delta t)} + b\right) \times h_{t(t+\delta t)} + (T_{o(t+\delta t)}h_{c,e(t+\delta t)} + T_{r,e(t+\delta t)}h_{r,e(t+\delta t)} + \phi_{solo(t+\delta t)} + a) \times (h_{t(t+\delta t)} + h_{c,i(t+\delta t)} + h_{r,i(t+\delta t)} + \frac{2C_p \rho V}{\delta t})\right]}{\left[\left(h_{t(t+\delta t)} + h_{c,i(t+\delta t)} + h_{r,i(t+\delta t)} + \frac{2C_p \rho V}{\delta t}\right) \times \left(h_{t(t+\delta t)} + h_{c,e(t+\delta t)} + h_{r,e(t+\delta t)} + \frac{2C_p \rho V}{\delta t}\right) - h_{t(t+\delta t)}^2\right]} \tag{12}$$

where

$$a = (T_{is(t)} - T_{os(t)}) \times h_{t(t)} + (T_{o(t)} - T_{os(t)}) \times h_{c,e(t)} + (T_{r,e(t)} - T_{os(t)}) \times h_{r,e(t)} + \phi_{solo(t)} + \frac{2C_p \rho V}{\delta t} T_{os(t)} \tag{13}$$

$$b = (T_{os(t)} - T_{is(t)}) \times h_{t(t)} + (T_{i(t)} - T_{is(t)}) \times h_{c,i(t)} + (T_{r,i(t)} - T_{is(t)}) \times h_{r,i(t)} + \phi_{soli(t)} + \frac{2C_p \rho V}{\delta t} T_{is(t)} \tag{14}$$

After calculating the internal surface temperature, the total energy exchange between inside and outside can be calculated by Eq. (15):

$$Q_{total} = Q_{tr} + Q_{sol} \tag{15}$$

where

$$Q_{sol} = \tau_{e,gzg} Q_{dir} + \tau_{e,dif} Q_{dif} \quad (16)$$

$$Q_{tr} = (T_{os} - T_{is}) \times h_t \quad (17)$$

By inputting the results of the variables and the parameters of subsystems in excel, the simplified calculation method can be realised.

3.3. Thermal parameters used in the method

The internal and the external surface temperature of the glazing T_{is} and T_{os} can be calculated by the method. All the other parameters in the equations were already known. Some of the known parameters were measured in the experiment at each time step, e.g., the indoor equivalent surface temperature $T_{r,i}$, the indoor and the outdoor air temperatures T_i and T_o, the direct and the diffuse solar radiation I_{dir} and I_{dif}. The outdoor surrounding equivalent temperature $T_{r,e}$ was calculated according to the outdoor air temperature T_o [9]. Furthermore, the absorption of the solar radiation by the internal and the external pane ϕ_{soli} and ϕ_{solo} were the function of the amount of the solar radiation and the solar incident angle [10–12,15,16]. The convective and the radiative heat transfer coefficients are calculated according to Clarke [9].

3.3.1. Thermal transfer coefficient of the double glazing unit

Equivalent heat transfer coefficient between the internal pane and the external pane h_t can be calculated according to EN673 [17]:

$$\frac{1}{h_t} = \frac{1}{h_s} + \frac{2d}{\lambda} \quad (18)$$

$$h_s = h_r + h_g \quad (19)$$

where the radiative heat transfer coefficient h_r between two panes is given by:

$$h_r = 4\sigma \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right)^{-1} T_m^3 \quad (20)$$

According to EN673 [17], standardized boundary condition for the mean temperature of gas space T_m is used as 283 K at the first time step.

According to EN673 h_r is constant in all the time steps. Dynamic solution can be realized in Eq. (21) [9], calculating h_r making use of the parameters at the previous time step.

$$h_{r(t+\delta t)} = \frac{\varepsilon_2 \varepsilon_1 \sigma \times \left(A_1 T^4_{is(t)} f_{1\to 2} - A_2 T^4_{os(t)} f_{2\to 1} \right)}{A_1 \times (T_{is(t)} - T_{os(t)})[1 - (1-\varepsilon_1)(1-\varepsilon_2) f_{1\to 2} f_{2\to 1}]} \quad (21)$$

According to EN673 [17] the convective heat transfer coefficient in the cavity h_g is given by Eq. (22):

$$h_g = Nu \frac{\lambda_{gas}}{s} \quad (22)$$

where

$$Nu = A(G_r P_r)^n \quad (23)$$

$$G_r = \frac{9.81 s^3 \Delta T \rho^2}{T_m \mu^2} \quad (24)$$

$$P_r = \frac{\mu c}{\lambda} \quad (25)$$

3.3.2. Dynamic heat transfer coefficient

The method not only takes into account of the thermal mass of the glass, but also the 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 the surface temperature of previous time step.

3.3.2.1. Convective heat transfer coefficient.

Interior surface convective heat transfer coefficient [9]:

$$h_{c,i} = \left\{ \left[1.5 \left(\frac{\Delta T}{H} \right)^{0.25} \right]^6 + \left[1.23 (\Delta T)^{0.33} \right]^6 \right\}^{1/6} \quad (26)$$

Dynamic solution can be realized in Eq. (27) [9], calculating $h_{c,i}$ with the parameters of previous time step:

$$h_{c,i(t+\delta)} = \left\{ \left[1.5 \left(\frac{T_{is(t)} - T_{i(t)}}{H} \right)^{0.25} \right]^6 + \left[1.23 (T_{is(t)} - T_{i(t)})^{0.33} \right]^6 \right\}^{1/6} \quad (27)$$

Exterior surface convective heat transfer coefficient can be calculated by Eq. (28) [9]:

$$h_{c,e} = 5.678 \left[a + b \left(\frac{V}{0.3048} \right)^n \right] \quad (28)$$

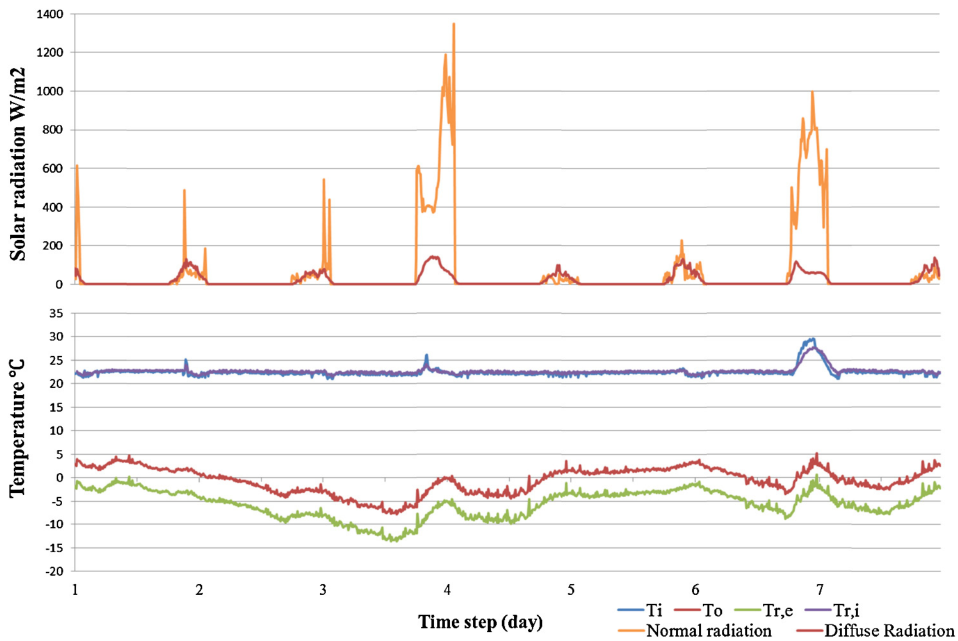

Fig. 6. Indoor and outdoor thermal parameters used to calculate the variables.

where V is the wind speed: 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 during the test period according to Windfinder [18] is taken as 5.5 m/s.

3.3.2.2. *Long-wave radiative heat transfer coefficient.* Long-wave 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/(m^2 K) according to EN673 [17].

After time step 1, dynamic solution can be realized in Eq. (29), calculating $h_{r,i}$ with the parameters of previous time step.

$$h_{r,i(t+\delta t)} = \frac{\varepsilon_i \varepsilon_{r,i} \sigma \times \left(A_i T_{is(t)}^4 f_{r,i\to is} - A_{r,i} T_{r,i(t)}^4 f_{is\to r,i}\right)}{A_i \times (T_{is(t)} - T_{r,i(t)})[1-(1-\varepsilon_i)(1-\varepsilon_{r,i}) f_{is\to r,i} f_{r,i\to is}]} \tag{29}$$

Long-wave radiative heat transfer between external surface and surroundings can be calculated by Eqs. (30) and (31) [9]:

At time step 1, $h_{r,e}$ can be calculated by Eq. (30) assuming the mean temperature of $T_{r,e}$ and T_{os} is outdoor air temperature T_o.

$$h_{r,e1} = 4\varepsilon\sigma T_o^3 \tag{30}$$

After the first time step, dynamic solution can be realized in Eq. (31), calculating $h_{r,e}$ with the parameters of previous time step.

$$h_{r,e(t+\delta t)} = \frac{\varepsilon\sigma(T_{r,e}^4 - T_{os}^4)}{T_{r,e} - T_{os}} \tag{31}$$

3.3.3. *Temperature and solar radiation*

Fig. 6 shows the indoor and the outdoor environment data measured in the experiments. If the method is used in practice project, the outdoor weather data should be the reference weather data of the locations or defined by the users. The indoor environment temperatures could be set by the users according to the requirement of the buildings. In order to simulate the façade in different orientations, the global solar radiation should be converted for different orientations [16].

Sky temperature can be calculated as following:

$$T_{r,e} = 0.05532 T_o^{1.5} \tag{32}$$

The solar absorption ϕ_{solo} and ϕ_{soli} of the external and the internal glazing layers can be calculated by Eqs. (33) and (34).

$$\phi_{solo} = \alpha_{e1} Q_{dir} + \alpha_{e1,dif} Q_{dif} \tag{33}$$

$$\phi_{soli} = \alpha_{e2} Q_{dir} + \alpha_{e2,dif} Q_{dif} \tag{34}$$

According to EN410 [12] α_{e1} and α_{e2} are calculated by Eqs. (35) and (36) in double glazing unit. Spectral properties of glazing can be obtained from ISO9050 [15] and WIS [4].

$$\alpha_{e1} = \frac{\sum_{300\ \text{nm}}^{2500\,\text{nm}} S_\lambda \left\{\alpha_1(\lambda) + \frac{\alpha_1'(\lambda)\tau_1(\lambda)\rho_2(\lambda)}{1-\rho_1'(\lambda)\rho_2(\lambda)}\right\} \Delta(\lambda)}{\sum_{300\ \text{nm}}^{2500\,\text{nm}} S_\lambda \Delta(\lambda)} \tag{35}$$

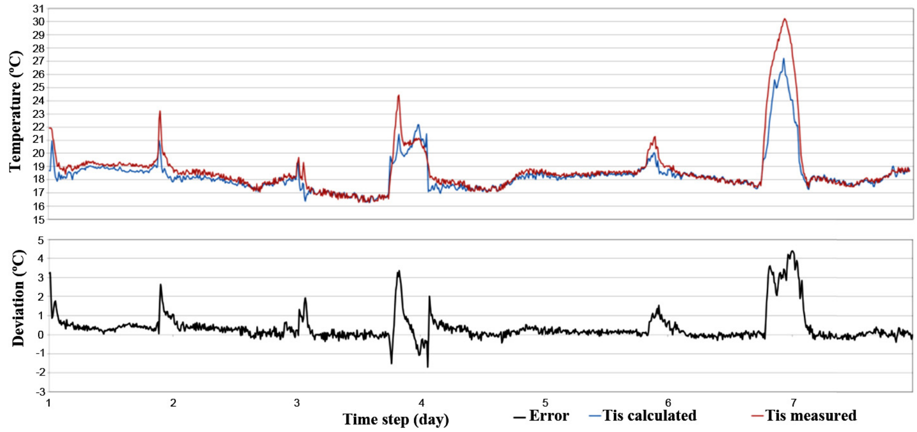

Fig. 7. The calculated and measured internal surface temperature of the glazing in the test cell and the deviation between them.

$$\alpha_{e2} = \frac{\sum_{300\ \mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \left\{ \frac{\alpha_2(\lambda)\tau_1(\lambda)}{1-\rho_1'(\lambda)\rho_2(\lambda)} \right\} \Delta(\lambda)}{\sum_{300\ \mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \Delta(\lambda)} \tag{36}$$

The solar absorption of different panes and solar transmittance of the whole glazing system are calculated taking incident angles of solar radiation into account. The solar absorption coefficients are calculated by Eq. (37) [11].

$$\alpha(\alpha_{in}) = 1 - \rho_{e,gzg}^{x}(\alpha_{in}) - \tau_{e,gzg}(\alpha_{in}) \tag{37}$$

where [10]

$$\tau_{e,gzg}[\alpha_{in}] \approx \tau_{e,gzg}[0^\circ] \left(1 - a_{roos} \left(\frac{\alpha_{in}}{90^\circ} \right)^{\alpha_{roos}} - b_{roos} \left(\frac{\alpha_{in}}{90^\circ} \right)^{\beta_{roos}} - c_{roos} \left(\frac{\alpha_{in}}{90^\circ} \right)^{\gamma_{roos}} \right) \tag{38}$$

$$\rho_{e,gzg}^{x}[\alpha_{in}] \approx 1 - \tau_{e,gzg}[\alpha_{in}] - [1 - \rho_{e,gzg}^{x}(\alpha_{in} = 0^\circ) - \tau_{e,gzg}(\alpha_{in} = 0^\circ)], \quad \alpha_{in} \le 75^\circ \tag{39}$$

$$\rho_{e,gzg}^{x}[\alpha_{in}] \approx 1 - \tau_{e,gzg}[\alpha_{in}] - \alpha^{x}(\alpha_{in} = 0^\circ) \frac{\alpha_{in} - 90^\circ}{15^\circ}, \quad \alpha_{in} > 75^\circ \tag{40}$$

where a_{roos}, b_{roos}, c_{roos}, α_{roos}, β_{roos}, γ_{roos} are calculated in [10].

The solar transmittance and reflectance under normal incident solar radiation can be calculated by Eqs. (41) and (42) [12].

$$\tau_{e,gzg}[0^\circ] = \frac{\sum_{300\,\mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \tau(\lambda) \Delta(\lambda)}{\sum_{300\ \mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \Delta(\lambda)} \tag{41}$$

$$\rho_{e,gzg}^{x}[0^\circ] = \frac{\sum_{300\,\mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \rho(\lambda) \Delta(\lambda)}{\sum_{300\ \mathrm{nm}}^{2500\,\mathrm{nm}} S_\lambda \Delta(\lambda)} \tag{42}$$

The solar incident angle at different time steps can be calculated according to the longitude and latitude angle of the sun and the orientation of the façade [16].

4. Result

Fig. 7 shows the overall results of the simplified method compared with the measured performance during all the days when the measurements were conducted. It shows that when there is little or no solar radiation, the simplified method overestimates the internal surface temperature with a deviation of less than 1 °C. During sunny days it underestimates the internal surface temperature, which is 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 is time consuming to carry out the calculation of different time steps, calculations in WIS software were only conducted on 28th and 30th of January. The 28th of January was a typical overcast day with little solar radiation while the 30th of January was a typical sunny day with high solar radiation. The calculations carried out in WIS used the same inputs of the external and the internal air temperature and the outdoor and the indoor surrounding temperatures as that of the simplified method. The heat transfer coefficients used in WIS calculations were taken from EN673 [17]. Figs. 8 and 9 show the internal surface temperatures calculated by the simplified method and WIS programme [7]. The temperatures were compared with that measured in the test facility.

The comparisons show that during the time of little or no solar radiation, the result of the simplified method was closer to the measured performance compared with that of the WIS software, with a deviation of approximately 0.5 °C. The reason for the overestimation of the internal surface temperature by WIS software during the cloudy day was probably be the overestimation of the internal convective heat transfer coefficient (3.6 W/m^{2}K) according to EN673 [17]. It could also be the overestimation of the default emissivity between the internal pane and the internal surround surfaces $\varepsilon_{r,i}$ used in WIS, which could result in more heat exchange between the internal pane and the internal surroundings.

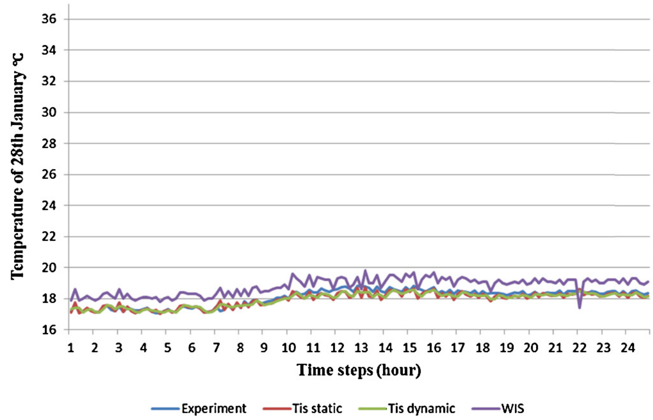

Fig. 8. Temperature comparison among WIS, measurement and the simplified method considering (Tis dynamic) and not considering (Tis static) thermal mass of glazing on 28th January 2011.

When the solar radiation was high, the simplified method underestimated the internal surface temperature, which was possibly because of the underestimation of the solar absorption of the internal pane. The reason for the difference between the results of the simplified method and the experiments could also be the tolerance of the internal convective and radiative heat transfer coefficient, which could significantly influence the calculation result. On the other hand, WIS overestimated the performance most of the time. The reason for the overestimation of WIS software during the sunny day was probably be the overestimation of the angle-dependent solar absorption of the panes. The internal surface temperature calculated by WIS was almost the same under solar radiation at different incident angles.

The sensitivity on the thermal mass of the glazing was also analysed for the simplified method. The result calculated considering the heat capacity of the internal and the external pane (dynamic) was compared with that calculated without considering the heat capacity of the panes (static). Figs. 8 and 9 show the calculation results of “Tis dynamic” and “Tis static” on 28th and 30th January. According to the figures, it indicates that “Tis dynamic” has relatively gentler curve than “Tis static” as the change of indoor and outdoor environment. However, the difference between “Tis dynamic” and “Tis static” is not significant, which because the heat capacity of the glazing is not big enough.

4.1. Validation of the simplified method

The accuracy of the model is validated through the R^2-value [19]. This value indicates how accurate the method and WIS programme fit the measurements, by comparing the values at each time step to the measurements and determining the level of accuracy as an evaluation of the overall differences between them. The R^2 value is not only a measure of how well the pattern of the model follows the pattern of the measurements, but also a measure of accuracy determining the error at each time step.

Eqs. (43)–(45) show the calculation of the R^2 value. Where y_i is the measured value; f_i is the calculated value; $\bar{y}$ is the mean of the measured value.

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \tag{43}$$

$$SS_{err} = \sum_{i}^{n} (y_i - f_i)^2 \tag{44}$$

$$SS_{tot} = \sum_{i}^{n} (y_i - \bar{y})^2 \tag{45}$$

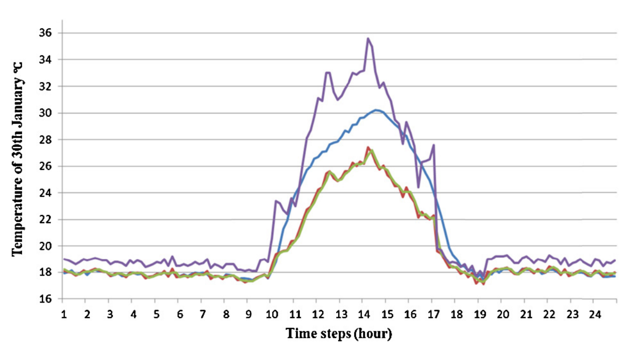

Fig. 9. Temperature Comparison among WIS, measurement and the simplified method considering (Tis dynamic) and not considering (Tis static) thermal mass of glazing on 30th January 2011.

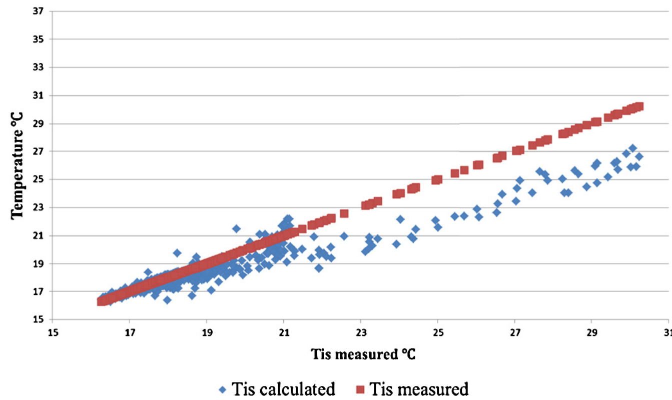

Fig. 10. Comparison on the internal surface temperature of the glazing among the simplified method, WIS programme and the measurements in the whole week.

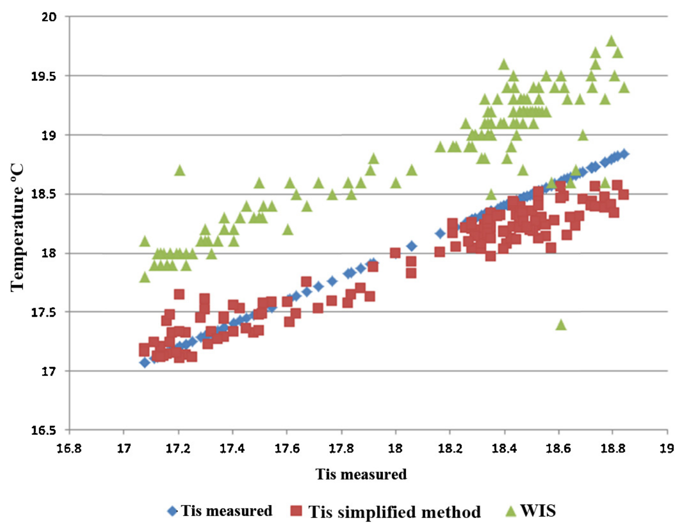

Fig. 11. Comparison on the internal surface temperature of the glazing between the calculation and the measurements on 28th January 2011.

The calculation result of the simplified method for the whole week is $R^2 = 0.83$.

Fig. 10 shows the linear regression of the calculation result by the simplified method in the whole week when the measurements were conducted. The temperature calculated by the simplified method corresponds with the measurements much better when it is below 20 °C (when there was little or no solar radiation).

Figs. 11 and 12 show the linear regression of the calculation result by the simplified method and WIS programme on 28th and 30th January. According to the figures, the simplified method has better performance than WIS programme on cloudy days. Moreover, the

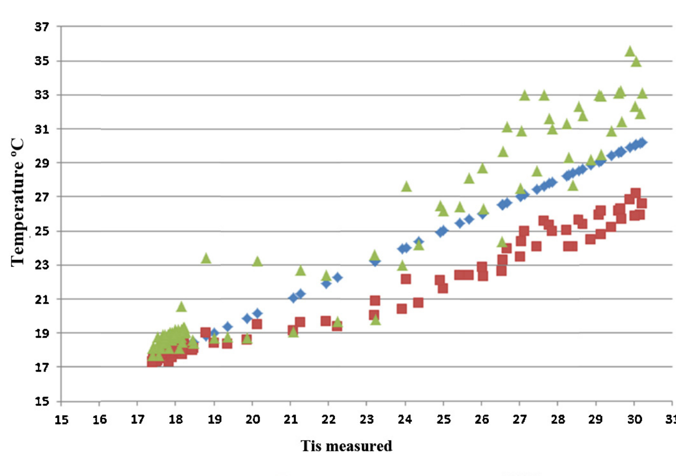

Fig. 12. Comparison on the internal surface temperature of the glazing between the calculation and the measurements on 30th January 2011.

simplified method underestimates the internal surface temperature when the solar radiation is high. WIS overestimates the internal surface temperature when the solar radiation is high.

The calculation result of the simplified method on 28th is $R^2 = 0.85$.
The calculation result of the WIS programme on 28th is $R^2 = -1.14$.
The calculation result of the simplified method on 30th is $R^2 = 0.83$.
The calculation result of the WIS programme on 30th is $R^2 = 0.88$.

5. Conclusion

A new simplified calculation method is developed to calculate the energy and comfort performance of the double glazing facade. The total energy exchange through the double glazing 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 tool which can be used for whole year energy performance calculations considering angle and spectral dependence of solar radiation. According to the calculation and the validation, it shows that the simplified calculation method has better performance in terms of calculating the internal surface temperature than WIS during the two select days.

This method can be used in the early design stage of building and façade to predict the energy and comfort performance of the double glazing facade. Compared with software like WIS, it requires less time and professional knowledge to input the parameters and build the model.

The method can also be implemented at any number of time steps, saving much time compared with WIS software which can only calculate the performance of one time step in each simulation.

Sensitivity analysis on the thermal mass of the glazing shows that the method including heat capacity of the glazing has slightly better accuracy than the static situation and slightly closer result to the reality.

However, the validation was only for the double glazing with the pane of low-E coating. More work need to be done for the glazing with panes of other types like solar control, etc. According to the results, the method works better for cloudy days. And the experiments were conducted in a week in winter time only on the south façade. Therefore, the errors between the calculated results and the measurements can be greater in summer when the solar radiation is higher. Future work needs to be done for the façades on other directions of the building. In addition, more deep investigation about why these errors occurred when the solar radiation was high needs to be implemented.

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