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A CFD study and measurements of double glazing thermal transmittance under downward heat flow conditions

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ABSTRACT

Fenestration systems are important elements of building facades. Although there are fenestrations placed at different angles in facades, not only vertical and roof glazing, there is little information about calculating procedures of thermal resistance and thermal transmittance for reversed glazing in which heat flows in a downward direction. The aim of this paper is to propose some amendments to EN 673–Glass in building – Determination of thermal transmittance (U value) – Calculation method [1] as well as to ISO 15099 – Thermal performance of Windows – Detailed calculations [2] to improve calculation accuracy for glazing under downward heat flow direction. In the paper CFD modeling of glazing thermal transmittance is presented. CFD calculated data were then validated by measurements performed in a calorimetric chamber in a test stand prepared for thermal transmittance measurements under different glazing angles resulting in a downward heat flow direction. Measurement data are then compared to simulation results. After achieving satisfactory agreement, some additional simulation results are presented and some amendments to glazing thermal resistance calculation procedure given in EN 673 and ISO 15099 standards are proposed.

1. Introduction

During recent decades, there has been a significant development in window constructions. There are vertical windows and roof windows. However, there are also outwardly inclined windows or glazing systems which are becoming more and more popular in modern buildings. Two examples of outwardly inclined glass facades are presented in Fig. 1.

The thermal transmittance of vertical or roof glazing can be calculated according to standard ISO 673 [1]. Glazing thermal transmittance can also be measured according to EN 674 [3] or EN 675 [4] with guarded-hot-plate or heat-flow-meter methods respectively. Neither EN 674 nor EN 675 standards take into account examples of angled glazing. The measurements are supposed to be taken in a vertical position. There is no procedure that provides a method for measuring inclined glazing with heat flowing downward. There are devices with a rotatable heat flow meter, but the measurement method is not standardized.

If the upper pane is maintained at a higher temperature than the lower pane (horizontal glazing with $\alpha = 180^\circ$), the lower-density gas is above the higher-density gas and no convection currents are experienced. The heat transfer through the gas gap is by conduction (conduction regime) and Nusselt number $Nu = 1$ for all Rayleigh number values [5]. In contrast to the horizontal gas gap, the vertical cavity ($\alpha = 90^\circ$) experiences gas flow for any Ra. At small Ra values, $Ra < 10^3$, the velocities are small and parallel to the panes. They contribute little to the heat transfer and again $Nu = 1$ (conduction regime). In fact in glazing cases where the gas gap is thin, the aspect ratio (the proportion of gas-gap length to its width) $L/s > 40$ and for calculation purposes 20 K of temperature difference on both sides of the glazing is assumed. For such cases $Ra > 10^3$, the conduction regime becomes unstable, turbulent transition regime begins leading to a fully developed turbulent boundary layer regime [5–7]. There is little information on natural convection in glazing cavities for angles $90^\circ < \alpha < 180^\circ$ [8,9].

In EN 673 procedure for glazing gas gap thermal resistance calculations, Nusselt number equal 1 is assumed for downward heat flow independently of the actual heat flow direction angle. In ISO 15099 the glazing angle is taken into account in downward heat flow calculations. The calculation procedure of thermal resistance of inclined gas gap is based on Ref. [9].

In the paper, the glazing downward heat flow under different angles was simulated in Ansys Fluent CFD program. To verify calculation results laboratory measurements were undertaken. Two series of experiments were performed:

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Nomenclature

A	Constant
A_{gv}	Glazing cavity aspect ratio
c_p	Specific heat capacity, J/(kgK)
d	Thickness of glass layer, m
Gr	Grashof number
h	Heat transfer coefficient also thermal conductance, W/(m^2 K)
H	Gas gap length, m
n	Exponent
Nu	Nusselt number
Pr	Prandtl number
$\dot{q}$	Heat flux, W/m^2
r	Thermal resistivity of glass, mK/W
R	Thermal resistance, m^2 K/W
Ra	Rayleigh number
s	Width of gas space, m
T	Temperature, K
U	Thermal transmittance, U-value, W/(m^2 K)
α	Angle, $^\circ$
δ	Stefan-Boltzmann's constant, W/(m^2 K^4)
ε	Emissivity
λ	Material thermal conductivity, W/(mK)
μ	Dynamic viscosity, kg/(ms)
ρ	Material density, kg/m^3

Indices

c	Convection
e	External side
g	Gas
i	Internal side
m	Mean
r	Radiation
s	Surface
t	Total

- With a heat flow meter Fox 314. The device measured specimen thermal resistance according to EN 8301 [10] standard in horizontal position and vertical downward heat flow direction and additionally with angles 20° and 25° from horizontal position (glazing angle $\alpha = 160^\circ$ and $\alpha = 155^\circ$).
- With a specially designed and built measurement stand dedicated to measurements of glazing thermal resistance in any angled position.

Table 1
Glass properties applied for the calculations.

Material	ρ [kg/m^3]	λ [W/(mK)]	c_p [J/(kgK)]	ε [–]
Glass	2500	1	840	0.837

Table 2
Air thermal properties applied for the calculations [1].

T [°C]	ρ [kg/m^3]	λ [W/(mK)]	c_p [J/(kgK)]	μ [kg/(ms)]
0	1.277	0.02416	1008	1.711×10^{-5}
10	1.232	0.02496	1008	1.761×10^{-5}
20	1.189	0.02576	1008	1.811×10^{-5}

2. CFD modeling of the glazing examples

2.1. Geometries and materials

The first set of simulated glazing examples consisted of two 4 mm soda-lime glass panes mounted together into the glazing spacer. Air filled the gap which was 16 mm thick. The gap of 16 mm thickness is quite common in the EU market for double pane windows with air or argon/air 90%/10% fillings.

The total thickness of the glazing was 24 mm. The glazing external dimensions were 700 mm × 700 mm.

2D modeling has been used in first step calculations, but 3D modeling appeared to be more convergent with measurement results. That is why 3D models were finally introduced.

The cross sections of part of the modeled glazing is shown in Fig. 2. Two glazing examples are given in the figure: vertical glazing (cavity inclined at $\alpha = 90^\circ$) and horizontal glazing (cavity inclined at $\alpha = 180^\circ$ – upper warm side).

Ansys Fluent CFD program was used to perform the calculations [11]. The heat exchange through the glazing was simulated for different glazing angles, i.e. different heat flow directions. It was assumed that the angle 90° stands for the glazing in a vertical position (horizontal heat flow direction) and the angle 180° stands for the glazing in a horizontal position and upper warm side (downward heat flow direction). Various angles between 90° and 180° were analyzed.

Glass thermal properties were set to be constant and can be seen in Table 1. Glass specific heat and density are not taken into account in steady state calculations. Air properties were assumed to be piecewise linear and are given in Table 2.

2.2. Mesh

The segment of mesh cross section of 3D glazing model is presented in Fig. 3.

In order to reduce the number of cells and simulation time the grid independency test was performed. A few mesh configurations for each model were generated: a refined grid consisting

Fig. 1. Office building in Austria and shopping mall in Germany (photo by A. Lechowska).