AN APPROXIMATE SOLUTION FOR THE INNER-GLASS LONGITUDINAL TEMPERATURE PROFILE IN DOUBLE GLAZED WINDOWS

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Abstract *The window condensation prediction can be included among the most critical issues affecting the design and the maintenance of a building since the 1D temperature approximation turns out to be inadequate. Thus, the numerical approach is almost mandatory wishing to model temperature multidimensional profiles which are essentially due to the coupling of glass and frame. In this connection, the present study aims to introduce an approximate yet accurate analytical model in order to predict longitudinal temperature profiles along the glass, which are of interest for detecting the threshold for condensation. The one-dimensional model is built-up on the parameters featuring the thermal characteristics of the glazing profiles as established by the international standard ISO 10077-2:2012. Moreover, the meaning of the linear thermal transmittance is fully elucidated. Preliminary results show that quite good agreement can be attained between the temperature profiles proposed in the present study and the one arising from the corresponding CFD study.*

1. INTRODUCTION

Energy efficiency is now one of the main goals of building design, in order to reduce carbon dioxide emissions into the atmosphere as well as deal with the gradual exhaustion of natural resources.

The health of the environment and its influence, both on the quality of indoor air as well as the preservation of the finishing elements, is equally important. In both cases, the main cause of degradation is the condensation of the water vapor present in the air, which is manifested in correspondence to the thermal bridges. It is not unusual to witness the disintegration of plaster, swelling of paint films, instability of wooden floors (just to name a few), due to the above-mentioned phenomenon. In some circumstances, the insulating material of the walls be damaged, with it significantly reducing the thermal performance. When it is not dealt with, mould and mildew forms, leading to health problems such as respiratory problems and more frequently, allergies, especially in the more vulnerable members of the population, such as children and the elderly [1].

To overcome these problems, the study of the thermal behaviour of glass doors and windows assumes a primary role, since these items represent the technological envelope in the system/building, a weak area in terms of heat exchange with the external environment.

In relatively recent years, the need to contain the thermal dispersion has facilitated the adoption of indiscriminate frames with excellent air tightness that, in the absence of adequate ventilation has led to a significant worsening of the condensation problem. The phenomenon is accentuated in areas where there is an increased production of steam, such as bedrooms, bathrooms and the kitchen, where there is a higher humidity value that raises the dew point temperature, thus leading to probable condensation [2].

Condensation is formed on the glass inner surface usually a consequence of it cooling. Observing closely the surface of a double glassed window frame, it should be noted that water droplets usually form on the lower edges of the pane, a fact, which can be confirmed by a thermo-graphic analysis and shows a thermal gradient along the longitudinal profile of the inner pane [3],[4],[5]. The characterization of the thermal transmittance, based on the method proposed by UNI EN ISO 10077-2:2012, which assumes a constant value of the temperature of the glass pane. The latter consideration suggests that 1D assumption to feature glass temperatures is inadequate wishing to identify the possible dew-point threshold. Thus, a more accurate analysis is required, which takes into account the uneven distribution in glass [6],[7],[8],[9]. The present study proposes a procedure to quickly estimate temperature profiles in the area close to the frame where thermal bridges are responsible for its departure from the 1D predictions. One of the advantages of the proposed procedure is the possibility to better predict the condensation problem, thus checking the possible onset of condensation and, the subsequent negative effects previously highlighted.

2. THE TEST CASE

A typical cladding unit consisting of a double-glazing unit and a wood frame is considered, Figure 1. The scheme itself is proposed by the ISO 10077-2:2012 [10],[11] as a benchmark to test numerical results obtained by numerical calculations. The window glazing and the end walls form a vertical enclosure of width W = 20 mm and height H = 1 m. The enclosure is filled with a gas with a gas whose equivalent thermal conductivity is 0.034 W/(m·K). The enclosure is confined by two 4mm float glass panes with thermal conductivity of 1.00 W/(m·K). Insolation is absent.

The spacer between the glasses is realized by assembling a structure made of aluminum, polysulfideand silica gel, whose thermal conductivities are 160, 0.13 and 0.13 W/(m·K), respectively. The wood frame exhibits a thermal conductivity of 0.13 W/(m·K), the EDPM employed for the joint between the glass and the frame of 0.40 W/(m·K). Therefore, it is easier for heat to pass through the spacer.

Third kind boundary conditions are given on the outer and inner glazing surfaces: these are bathed by isothermal air with fixed surface thermal resistances, namely R_{se} = 0.04 K m^2/W and R_{si} = 0.13 K m^2/W , while the respective fluid temperatures are 0 and 20°C. An increased thermal resistance, $R_{si,red}$ = 0.20 K m^2/W, is used for the internal edges, according to ISO 10077. The related heat transfer coefficients are for horizontal heat flow, such as across a vertical window.

Three cavities can be identified by inspection of Figure 1, two of which are unventilated (i.e. they are completely closed) while the third one is slightly ventilated (i.e. they are connected either to the exterior or to the interior by a slit greater than 2 mm but not exceeding 10 mm).

3. NUMERICAL SCHEME

The 2D steady governing equations have been solved using the general purpose CFD software COMSOL. The numerical algorithm is based on the direct stationary solver Pardiso.

Conduction takes place in the solid regions according to the Laplace equation,

$$\underline{\nabla}^2 T = 0 \tag{1}$$

According to the ISO 10077 and ISO 10292 suggestions, the buoyancy driven convective heat flow and the radiation taking place in the unventilated space between the glass panes are described by a symplified approach consisting in considering the space between the glass panels filled with a gas whose equivalent thermal conductivity is 0.034 W/(m·K).

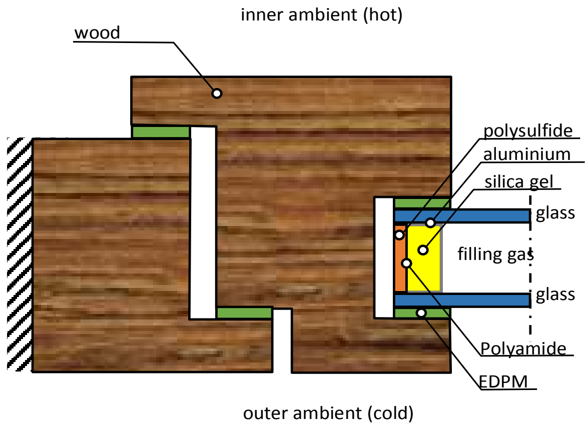

Figure 1. Geometry of the wood frame with glazing.

Such a conductivity is used in the whole cavity, up to the edges, thus the Laplace equation is solved also in the gas region.

Grid sensitivity testing was done to ensure that the numerical results were grid independent. Sample calculations were performed on grids with approximately 3000 and 7000 triangular elements. Results showed that the linear thermal transmittance, selected as a control parameter, did not differ more than 0.1 %. Moreover, the geometry at hand was validated by a benchmark given by the ISO 10077 itself, whose displayed result (0.084 W/(m K)) was recovered within the 1.19% limit.

4. THE MEANING OF THE LINEAR THERMAL TRANSMITTANCE OF THE FRAME

With reference to the internal boundary evidenced in Figure 2, heat loss from a unit comes both from the frame and from the glass. The heat flux coming from the frame may be further subdivided into contributions: the former is orthogonal to the frame boundaries parallel to the x-axis whose length is equal to b_f, $\dot{Q}_{bf} = \dot{q}_{bf} \cdot b_f$; the latter is orthogonal to the frame boundaries parallel to the y-axis whose length is equal to l_f, $\dot{Q}_{lf} = \dot{q}_{lf} \cdot b_f$. In a similar fashion, heat loss related to the glass may be calculated by evidencing the central double-glazing glass panel contribution, where isotherms are parallel to glass surfaces, $q_g^{1D} \cdot b_g$. The complimentary heat loss featuring the glass accounts for the coupling effects of the glass to the frame, $\Delta q_g \cdot b_g$. The latter can be envisioned as the difference between the two-dimensional and the one-dimensional heat fluxes across the inner glass boundary.

It will be shown that it is related to well-known linear thermal transmittance. In summary, the addressed energy balance allows to introduce the glazing thermal conductance $L_{2D\psi}$

$$\dot{Q}_f + \dot{Q}_g = L_{2D\psi}\Delta T = \dot{q}_{bf} \cdot b_f + \dot{q}_{lf} \cdot l_f + \dot{q}_g^{1D} \cdot b_g + \Delta\dot{q}_g \cdot b_g \quad (2)$$

where ΔT = Ti –To, Ti and To are the inner and outer ambient temperatures.
The term related to the 1D heat flux across the glass may be recast as:

$$\dot{q}_g^{1D} \cdot b_g = U_g^{1D} \cdot b_g \cdot \Delta T \quad (3)$$

where U_g^{1D} is the 1D thermal transmittance of the glass. The three remaining terms are encompassed into a single one introducing the thermal transmittance of the frame, U_f ,:

$$U_f \cdot b_f \cdot \Delta T = \dot{q}_{bf} \cdot b_f + \dot{q}_{lf} \cdot l_f + \Delta\dot{q}_g \cdot b_g \quad (4)$$

Thus, $L_{2D\psi}$ results as the sum of two contributions:

$$L_{2D\psi} = U_f \cdot b_f + U_g^{1D} \cdot b_g \quad (5)$$

Since the actual definition of U_f , includes the heat loss from the frame and the extra heat loss from the edge of the glass, it is desired to keep the frame loss practically independent of the type of the glazing unit. To this purpose, a companion reference configuration, identified by apex "*" is introduced. Here, the frame section is completed by a dummy insulating panel replacing the glazing unit. The panel (addressed by apex "p" in what follows) exhibits a known thermal conductivity, i.e. 0.035 W/(m K). Proceeding in a similar fashion as before, the energy balance across the dashed boundary yields:

$$\dot{Q}_f^* + \dot{Q}_p = \Delta T \cdot L_{2D} = \dot{q}_{bf}^* \cdot b_f + \dot{q}_{lf}^* \cdot l_f + \left(\dot{q}_p^{1D} + \Delta\dot{q}_p\right) \cdot b_p \quad (6)$$

where L_{2D} is the thermal conductance of the section. The term related to the 1D heat flux across the panel is recast introducing the 1D-thermal transmittance of the panel U_p^{1D} :

$$q_p^{1D} \cdot b_p = U_p^{1D} \cdot b_p \cdot \Delta T \quad (7)$$

Thus, introducing the last expression into eq. (6), the definition for L_{2D} given by UNI EN 10077, i.e. $L_{2D} = U_f^* \cdot b_f + U_p^{1D} \cdot b_p$, is recovered provided that the thermal transmittance of the frame U_f^* is defined as:

$$b_f \cdot \Delta T \cdot U_f^* = \dot{q}_{bf}^* \cdot b_f + \dot{q}_{lf}^* \cdot l_f + \Delta\dot{q}_p \cdot b_p \quad (8)$$

The definition of U_f^*, includes the heat loss from the frame and the extra heat loss from the edge of the panel which may be expected to be much less than the frame contribution, thus

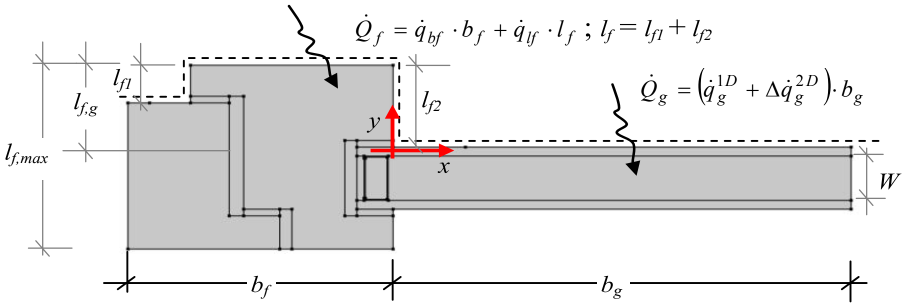

Figure 2. Relevant heat fluxes at the inner interface

making such a parameter practically independent of the glazing.
For such a reason the frame transmittance is properly selected as the one evaluated in the reference configuration, while the one related to the glazed structure differs by a quantity ΔUf $= U_f - U_f^*$. In view of the above positions, the expression for $L_{2D\psi}$ turns out to be:

$$L_{2D\psi} = U_f^* \cdot b_f + \Delta U_f \cdot b_f + U_g^{1D} \cdot b_g \tag{9}$$

Finally, defining ΔUf ·bf as the linear thermal transmittance of the frame, Ψ, the same expression of UNI EN 10077 is recovered while its meaning is elucidated.

5. THE APPROXIMATED TEMPERATURE PROFILE ALONG THE INNER GLASS

Considering that the Biot number related to the glass pane transverse section is typically much lower than the unit, the finned surface model seems to be a proper model to identify the temperature profile along the glass. For such a reason, the shape for the temperature profile along the glass is sought to be an exponential function:

$$T_g^{2D}(x,\delta) = T_g^{1D} + \left(T_{g,x=0} - T_g^{1D}\right)\cdot Exp\left(-\frac{x}{\delta}\right) \tag{10}$$

where T_g^{1D} is the one- dimensional temperature of the internal glass and $T_{g,x=0}$ is the temperature at glass base. The unknown parameter δ expresses the decay rate of the exponential, thus representing a measure of the extension of the 2D-thermal effects due to the glass to frame coupling. The temperature of the glass at $x = 0$ has been estimated considering a linear temperature evolution across the frame; the move is suggested by considering that the isotherms in the frame are almost parallel to the x-axis with the exception of the relatively small region where coupling effects are sensible. Thus, the following expression has been

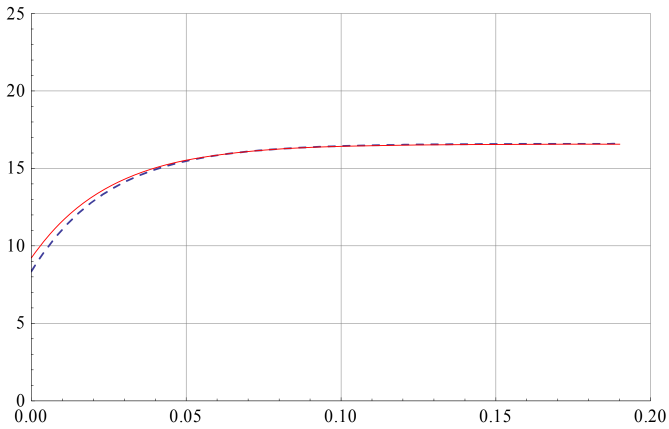

Figure 3. Comparison between the exact and approximate temperature profiles

written:

$$T_{g,x=0} = T_{is} - \left(T_{is} - T_{os}\right) \cdot \frac{l_{f,g}}{l_{f,\max}} \tag{11}$$

where: T_{is} and T_{os} are the internal and external surface temperatures of the frame, respectively; $l_{f,max}$ = 83 mm is the maximum length of the frame boundary parallel to the y axis; $l_{f,g}$ = 39 mm is the distance between the longer internal boundary of the frame and the average line across the glass, both parallel to the x axis. In order to estimate the surface temperatures, the heat flux across the frame, $\dot{q}_f$, was evaluated considering the reference thermal transmittance U_f^* , $\dot{q}_f = U_f^{ref} \cdot \Delta T$; Therefore, the surface temperatures of the frame were obtained as:

$$T_{is} = T_i - q_f \cdot R_{is}; \qquad T_{es} = T_o + q_f \cdot R_{os} \tag{12}$$

R_{is} and R_{os} are the surface resistances of the section, as given by UNI EN 10077. The 1D temperature of the glass is readily evaluated by series resistance argumentations and considering that the knowledge of U_g^{1D} allows the evaluation of the one-dimensional heat flux across the glass.

As observed before, the parameter δ represents a measure of the extension of the two-dimensional effects on the edge of the glass, thus it is expected to be related to the linear thermal transmittance of the frame, Ψ. To this purpose, it is recalled that:

$$\Psi = \Delta U_f \cdot b_f = \left(\frac{\dot{q}_{bf} \cdot b_f}{\Delta T} + \frac{\dot{q}_{lf} \cdot l_f}{\Delta T} + \frac{\Delta \dot{q}_g \cdot b_g}{\Delta T} - U_f^* \right) \cdot b_f \tag{13}$$

The heat fluxes on the II hand can be explicited in terms of the unknown *δ*. In particular, the frame contributions to heat loss are estimated by considering the related surface exchange:

$$\dot{q}_{bf} \cdot b_f + \dot{q}_{lf} \cdot l_f \approx \left(h_{red} \cdot b_{red} + h_{norm} \cdot \left(b_f - b_{red}\right)\right) \cdot \Delta T \tag{14}$$

In a similar fashion $\Delta\dot{q}_g$ has been estimated by integrating the local heat flux along the glass:

$$\Delta\dot{q}_g = \dot{q}_g^{2D} - \dot{q}_g^{1D} = \int_0^{b_{red}} h_{red} \cdot \left(T_i - T_g^{2D}(x,\delta)\right) \cdot dx + \int_{b_{red}}^{b_g} h_{norm} \cdot \left(T_i - T_g^{2D}(x,\delta)\right) \cdot dx - \dot{q}_g^{1D} \tag{15}$$

In the latter equation the unknown parameter *δ* appears explicitly.

6. RESULTS

Substituting the last two equations in eq. (13), the parameter δ can be determined. Thus, a value of 25.6 cm is obtained. Results are shown in Figure 3 where both the approximate and the numerical curves are reported. Both curves increases with increasing the *x* coordinate, till to asimptotically attain a fixed value irrespective of the edge effects due to the coupled frame. The numerical curve, as expected exhibits a quasi exponential increase. The fairly agreement between the two curves is witnessed by the RMSE which turns out to be less than 0.2°C.

7. CONCLUSIONS

An approximate analytical solution has been pointed out for the inner-glass temperature profile of a double paned window. The quick estimation is made possible by employing the thermal features taken by the ISO 10077 rating data. Numerical results have been obtained for the same sample test configuration by the Comsol multiphysics commercial code. Comparative results show a quite satisfying agreement. Thus, the simple one-dimensional model seems to be a quick way to descrive the possible condensation onset. A meaningfull interpretation of the linear thermal transmittance has been given too. Further tests will be carried out with reference to more complex geometry to verify that suitable results can still be attained.

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