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THERMAL LOADS AT TRANSPARENT STRUCTURES INTEGRATED IN TROMBE WALLS

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Abstract

This contribution presents thermal load stress analysis of insulating glass units (IGU) integrated in Trombe walls. It is based on modelling and numerical simulation of the heat transfer processes occuring in the construction. The boundary conditions are based on experimental data, obtained from an existing Trombe wall test module, situated at the Technical University of Sofia. The investigations are performed for different cases of IGU fixing in the Trombe wall. The temperature fields and the ensuing thermal stresses in the IGU at winter conditions, obtained from the simulations, are used to analyze the possibility of glass failure due to the internal pressure loads.

Keywords: *heat transfer, insulating glass units, Trombe wall, thermal loads, mathematical modelling, CFD*

Introduction

The Trombe wall is a relatively simple passive solar system prone to easy integration in the building envelope. It is simultaneously a collector and accumulator of solar energy. In suitable climatic conditions it can be utilized to substantially reduce the building energy demand, compared with more common design approaches [1, 2]. The typical construction is consisted of a transparent (glass) unit and an opaque thermal storage wall with an external surface coating of high solar absorptivity (and preferably low infrared emissivity). Various configurations are shown in Fig. 1. In an unvented Trombe wall, the absorbed solar heat is transferred through the opaque wall and exchanged between the internal wall surface and the indoor environment via convection and radiation.

In a vented Trombe wall the primary mode of heat transfer is convection in the air gap between the wall and the glazing – heat is transferred from the absorber to the air flow, producing a buoyancy effect which allows for implementation of different ventilation modes.

The most significant factors, influencing the energy performance of an unvented Trombe walls, are the type of absorber coating on the opaque wall and the type of transparent unit [1 - 4]. Insulating glass units (IGU) can be used to decrease the heat losses from the absorber to the outdoor environment, thereby improving the energy performance of the Trombe wall.

The thermal stresses occurring in the IGU of a Trombe wall are expected to be different than those occurring in the IGU of typical window systems and facades, due to the specific features of the heat transfer processes in the passive solar system. This reflects on the mechanical behavior of the transparent unit, which is influenced by the unsteady temperature fields and the differences between the pressure in the hermetized gas cavity of the IGU and the ambient pressure (Fig. 2). The latter is caused by changes of the temperature of the hermetized

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gas, ΔT, altitude, ΔH, and ambient barometric pressure, Δp_m, with respect to those at the time of manufacturing of the IGU [4].

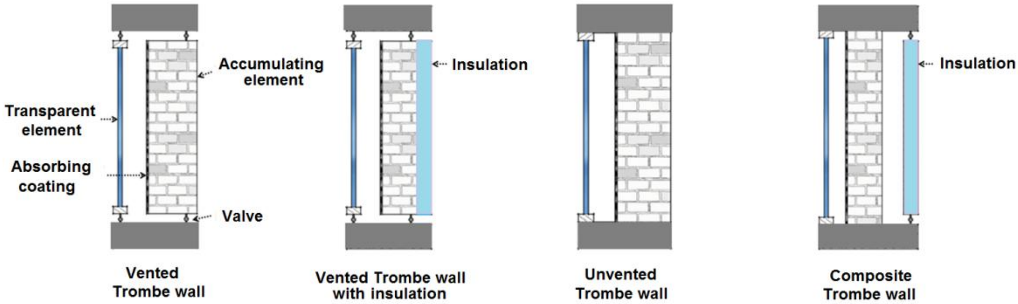


Fig. 1. Various Trombe wall configurations [1, 2]

These internal loads result in deformations of the glass panes, which in combination with the thermo-mechanical processes can lead to glass failure. If the glass panes are not deformed and the volume of the gas cavity of the IGU is not changed, the difference between the internal and ambient pressure is equal to the so called isochoric pressure:

$$\Delta p_{is} = C_1 \Delta T + C_2 \Delta H + \Delta p_m \text{, kPa} \quad (1)$$

Where: C_1 = 0.34 kPa/K and C_2 = 0.012 kPa/m.

Glass is an elastic material and the glass panes are deformed by the presence of internal loads. Therefore, the absolute value of the gauge pressure in the IGU cavity is lower than Δp_{is}, but the latter is used for sizing the IGU [4 - 6]. The terms in equation (1), depending on the changes of the ambient barometric pressure and the altitude, can be predicted according to the locations of the IGU manufacturing site and the place of installation. They do not depend on the IGU construction and the type of fixing to the façade. The pressure difference due to gas temperature change depends on these factors and varies with the ambient temperature and incident solar radiation.

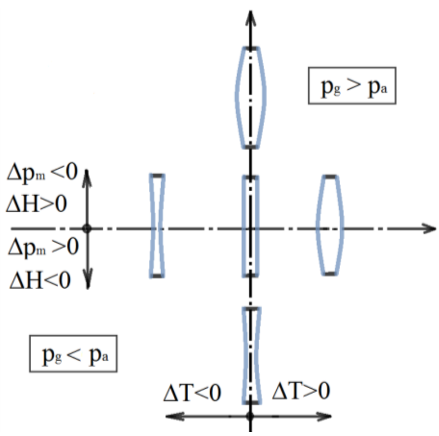


Fig. 2. Deformations occurring in the glass panes of an IGU due to differences between the pressure of the hermetized gas p_g and the local ambient pressure p_a

Based on detailed information about the daily variation of the heat transfer rates and the ensuing mechanical behaviour of the glass panes of a double-glazed IGU, integrated in a curtain wall in Sofia, for the months with the lowest and highest ambient temperatures (January and July), it has been established that the internal load due to temperature differences will not cause defects in the glass if they are not combined with other loads [7]. This contribution presents a model-based study of the heat transfer processes and temperature fields, and the ensuing thermo-mechanical behaviour of the same IGU, integrated in an unvented Trombe wall. Results of the study are also published in [8].

Object of investigation

The thermal stress analysis concerns an actual IGU, integrated in a south-oriented unvented Trombe wall, situated on a test site of the Technical University of Sofia (Fig. 3). It is equipped with a weather station and a monitoring system, which measures temperatures and air velocities in the Trombe wall construction.

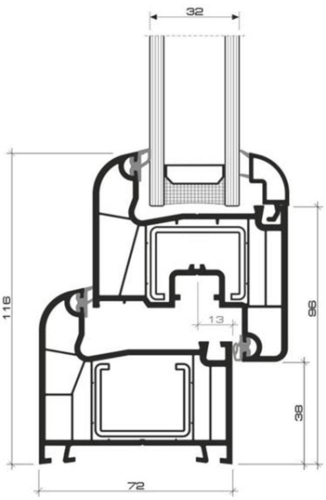
Fig. 3. Test site at the Technical University of Sofia. Adapted from Stankov [4]

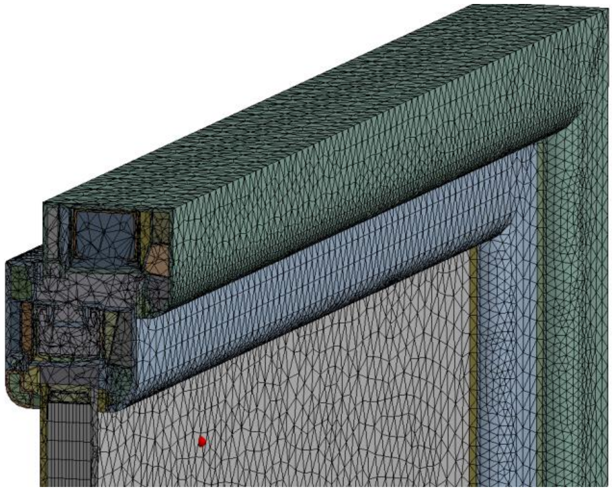
The 1088 mm x 1288 mm IGU consists of an aluminum spacer and two four-millimeter-thick uncoated glass panes, separated by a 24 mm air cavity. Numerical simulations of the heat transfer in the IGU are performed for two types of fixing to the construction of the Trombe wall:

Case 1: Fixation by a PVC or metal frame with relatively small apparent width. It can be assumed that the frame does not influence heat transfer and can be excluded from the geometrical model.

Case 2 (corresponding to the real situation): Fixation in a window system by a five-chamber PVC frame with relatively high thermal resistance (Fig. 4). The influence of the frame on heat transfer in the IGU can't be neglected a priori.

During the warmer seasons (outside of the heating period), the transparent parts of the Trombe wall are shaded in order to avoid overheating of the building. For that reason, the elements of the IGU are maximally loaded due to internal loads at the minimal expected temperature in the construction. The minimal measured temperatures in the experimental module are observed in January (Stankov, 2015). The numerical simulations are performed for two separate instances in that period when the maximal and minimal vacuum pressures in the gas cavity are expected: the hour with the lowest measured temperature (7 am) and the hour with the highest measured solar irradiance (1 pm). The average hourly values of the temperatures in the unvented air space and the coated surface of the thermal storage wall, the heat transfer coefficients and the solar irradiance, obtained from the measurements [3], are used as boundary conditions for the model.





a) b)

Fig. 4. PVC window system with a double-glazed IGU: a)Cross-section of the frame b) Finite volume mesh

CFD analysis

Detailed information about the three-dimensional temperature, pressure and velocity fields in the IGU can be obtained by a coupled finite-volume solution of the equations below at quasi-equilibrium steady state (Penkova et al., 2017).

Fluid domain (hermetized gas cavity in the IGU): continuity equation, momentum equations, energy equation, turbulence model, boundary layer model.

Solid domain (glass panes, spacer elements, sealants, solid parts of the frame): energy equation for non-moving media.

The air in the cavities of the window frame can be modeled as solid domain with an effective thermal conductivity, representing the convective and radiative heat transfer in the construction [9]. The absorbed solar heat flux by the solid elements of the window is modeled as heat source in the energy equation. The surface-to-surface radiation heat transfer between the internal planes of the IGU is computed using the Radiosity solver method of ANSYS/CFX.

The boundary conditions reflect the convective and radiative heat transfer between the surfaces of the window system, external environment, air space and opaque wall.

Heat flux on the external surfaces:

$$\dot{q}_{se} = h_{c,se}\left(T_e - T\right) + \sigma\varepsilon_{se}\left(T_{r,me}^4 - T^4\right) + A_{se} I_s \text{, Wm}^{-2} \quad (2)$$

Where: $h_{c,se}$, $Wm^{-2}K^{-1}$ is the convection heat transfer coefficient between the window and the outdoor environment with temperature T_e; A_{se} – absorptance of the element. It is equal to the total absorptance of the external glass pane $\hat{A}_1$. I_s, Wm^{-2} is the incident solar irradiation; ε_{se} - emissivity of the external surfaces; $T_{r,me}$, K – mean radiation temperature of the external environment(Kumar, 2010).

Heat flux on the internal surfaces:

$$\dot{q}_{si} = h_{c,si}\left(T_i - T\right) + \sigma\varepsilon_{si}\left(T^4_{r,mi} - T^4\right), \text{Wm}^{-2} \tag{3}$$

Where: $h_{c,si}$, $Wm^{-2}K^{-1}$ is the convection heat transfer coeffitent between the window and the air space in the Trombe wall; T_i, K – mean temperature of the air space in the Trombe wall; ε_{si} - effective emissivity, accounting for the emissivity of the internal window surfaces and the absorbing surface of the opaque (thermal storage) wall; $T_{r,mi}$, K - average temperature of the absorbing surface of the opaque wall.

Heat flux on the external surfaces of the internal glass pane of the IGU

$$\dot{q}_g == \hat{A}_2 I_s \text{ , Wm}^{-2} \tag{4}$$

Where: $\hat{A}_2$ is the total absorptance of the internal glass.

The absorptances of the solid elements of the construction are: PVC frame (white): A_{se}=ε_{se}= ε_{si} =0.95; uncoated glass panes: ε_{se}=0.84; $\hat{A}_1$=0.13; $\hat{A}_2$=0.10; effective internal emissivity ε_{si} =0.75 (at emissivity of the absorbing coating 0.87).

The detailed boundary conditions are shown in Table 1. They are used for numerical simulation of the heat transfer processes in the transparent unit for the examined cases. The results obtained for the internal loads are given in the same table. The temperature changes of the hermetized air in the IGU are computed with an assumed temperature of 293 K at the time of manufacturing of the unit. Pi_s is computed according to ΔT at zero ΔH and Δp_m.

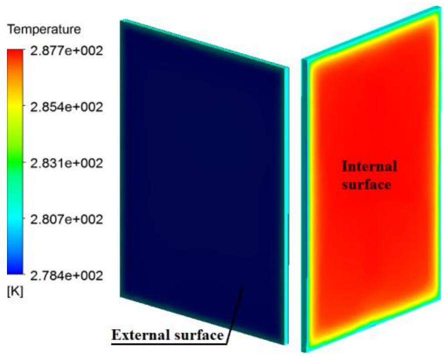
Table 1. Conditions and results

Conditions	Case 1. IGU	Case 2. IGU in window system
January, 7:00 am. T_e=271 K; $T_{r,me}$=260 K; I_s=0 Wm^{-2} T_i=280 K; $T_{r,mi}$=282 K; h_{si}=1 $Wm^{-2}K^{-1}$; h_{se}=20 $Wm^{-2}K^{-1}$	Average temperature of the hermetized air: T=274 K ΔT= -19 K; Δp_{is}= - 6.41 kPa	Average temperature of the hermetized air: T=275 K ΔT= -18 K; Δp_{is}= -6.18 kPa
January, 1:00 pm. T_e=276 K; $T_{r,me}$=265 K; I_s=500 Wm^{-2} T_i=283K; $T_{r,mi}$=286 K; h_{si}=1 $Wm^{-2}K^{-1}$; h_{se}=20 $Wm^{-2}K^{-1}$	Average temperature of the hermetized air: T=283 K ΔT= -10 K; Δp_{is}= -3.44 kPa	Average temperature of the hermetized air: T=284 K ; ΔT= -9 K; Δp_{is}= -3.03 kPa

Visualizations of the temperature fields in the investigated objects are shown in Fig. 5. The differences in surface temperature are negligible for all cases. The average air temperature in the IGU cavity and the corresponding Δp_{is} are almost equal for the examined cases. The changes of air temperature and isochoric pressure are negative. The maximal computed vacuum pressure at zero volume change of the IGU cavity is 6.41 kPa for the single unit and 6.18 kPa for the unit in window system (difference below 4 %). That will cause deformations of the glass panes and reduction of the cavity volume. This effect is expected to be more pronounced at a lack of solar radiation. The vacuum is accordingly reduced after the glass deformation.

Data from a previous analysis can be used for estimation of the expected effects [7]. It has been established that if the same IGU is part of a curtain wall in a building situated in Sofia, Δp_{is} equals -4,56 kPa at the lowest ambient temperatures. On the basis of a FEM analysis of the mechanical behavior of the structure, it is found that the resulting internal load does not jeopardize the integrity of the glass panels: the maximal tension stresses (approximately 13 MPa) are more than 5 times lower than the tensile strength of the glass (70 MPa). The absolute value of Δp_{is}, found in this study, is 1.4 times lower than the value of Δp_{is} established in Ivanov

[7]. If the maximal tensile stress in the glass panels increases with the same ratio, it will be approximately 4 times lower than the tensile stress in the gasss of the IGU in a curtain wall.



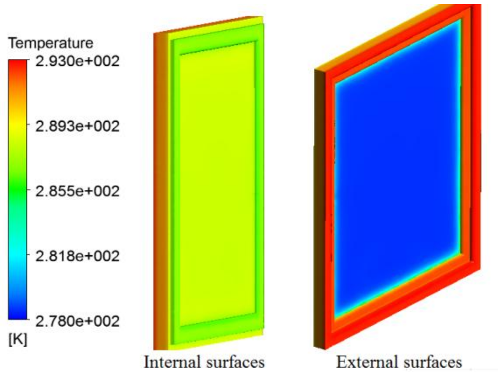


Fig. 5. Temperature fields in a single IGU (a) and window system (b) in January, 1:00 pm

Conclusions

The average temperatures of the elements of insulating glass units, integrated in unvented Trombe walls, are lower and the internal loads due to temperature differences of the hermetized gas are higher, in comparison with those of IGUs in the transparent parts of building envelopes. In the climatic conditions of Sofia this internal load does not jeopardize the integrity of the glass, unless it is combined with additional internal and external loads.

Acknowledgments

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