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Influence of cavities geometric and emissivity properties on the overall thermal performance of aluminum frames for windows

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ABSTRACT

The increasing attention to energy saving in buildings has led to more accurate analysis of the thermal performance of windows. In particular, the use of aluminum frames has known a rapid development; thanks to the installation of thermal break systems, the performance of aluminum frames is nowadays comparable to the one wooden frames. The numerous air cavities inside aluminum frames suggest a deep investigation of the heat exchange process; the paper, therefore, analyzes the effect of the geometric and surface characteristics of the cavities on the overall performance of the profile. The attention was focused on the emissivity properties of the cavity inner surfaces, since they play a fundamental role on radiation heat transfer; furthermore, the frame thermal performance was evaluated when the geometries of some cavities are changed with the insertion of rubber gaskets.

All the analysis were conducted with two different approaches: numerical and experimental, obtaining a good match between the methods; the validation of the CFD model makes it a quick and user-friendly tool for the preliminary design and optimization of aluminum window frames with a high thermal resistance.

1. Introduction

Windows represent the component which mostly affects the energy demand of buildings. They consist of opaque and transparent elements that have to ensure together a high thermal performance, in order to minimize the overall component heat losses. Therefore, the design of each single component of a window becomes strategic to achieve the energy savings objectives, reducing the overall energy demand of a building, and more and more advanced windows are being designed and proposed on the market. A high thermal performance windows analysis, for example, was conducted by Larsson et al. [1] who studied the temperature pattern in a triple low-emissivity glazing, whose cavities were filled with krypton. The study was conducted in steady-state conditions, through experimental tests, analytical and numerical methods for four different boundary conditions.

At the aim of reducing the window dispersions, particular attention has to be reserved to metal frames, which, by their own nature, are composed of structural materials with high thermal conductivity. The aluminum, for instance, has very low thermal resistance, but the thermal performance of the frame could be improved using thermal breaks and introducing air gaps. The air cavities are characterized by complex mechanisms of heat exchange that have been studied with different approaches. Gustavsen et al. [2] analyzed the profiles of air cavities with rectangular geometries using CFD simulations in natural convection, comparing the results with infrared thermography surveys, to assess the temperature trend of the cavity outer surfaces. This comparison showed an excellent correspondence between experimental and numerical results. In general, the numerical study of window frames can be carried out with 2-D simulations, defining an equivalent conductivity of the air gap which is a function of the heat exchange that occurs mainly by natural convection and radiation. The equations that define the equivalent conductivity are described in the Standards EN ISO 10077-2 [3] and ISO 15099 [4], characterized by two different approaches with regard to the way the air gaps convection coefficient is evaluated. Gustavsen et al. [5] compared the two procedures, identifying strengths and weaknesses of the methods; Noyé et al. [6] evaluated the effective conductivity of aluminum and PVC window frames with both Standards, comparing the results with experimental measurements. The ISO 15099 is considered to be more accurate, even if the proposed equations appear more complex. Gustavsen et al. [7] conducted a study on air cavities with different geometries, considering only the natural convection with both a CFD simulation technique and the equations proposed by ISO 15099.

In the present paper, the procedures proposed by the EN ISO 10077-2 are analyzed, with particular reference to the influence of the emissivity properties of the surfaces facing the cavities of the

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Nomenclature

b	cavity length, m
C_1	constant for the evaluation of the convective coefficient, W/mk
C_2	constant for the evaluation of the convective coefficient, W/m^2 K$^{4/3}$
d	cavity depth, m
E	emittance
EPDM	ethylene–propylene diene monomer
F	view factor
h_a	conduction and convection coefficient, W/m^2 K
h_{bc}	heat exchange coefficient (boundary condition), W/m^2 K
h_r	radiation coefficient, W/m^2 K
q_{bc}	thermal flux, W
R_s	total thermal resistance of cavity, m^2 K/W
T	temperature, K
T_{amb}	ambient temperature (boundary condition), K
T_m	average temperature inside the cavity, K
T_w	wall temperature (boundary condition), K

Greek symbols

ε_1	emissivity of surface 1
ε_2	emissivity of surface 2
ΔT	temperature difference between the inner surfaces of the cavity, K
λ	conductivity, W/m K
λ_{eq}	equivalent conductivity, W/m K
σ	Stefan–Boltzmann constant, W/m^2 K^4

aluminum frame. The two terms which contribute to the definition of the equivalent conductivity (convective heat transfer coefficient and radiation heat transfer coefficient) were examined individually: both coefficients were subjected to a sensitivity analysis to find the parameters with a bigger influence on their values. In order to assess the performance of the real layout in window frames, the study of gaps connected in series was also performed, searching for an optimized depth value of each air gap with low-emissive surfaces, as a compromise between the need of high thermal resistance and the necessity of limited dimensions, to reduce the global thickness of the frame. The study of some commercial aluminum frames was also carried out, at the aim of evaluating the influence of the shape and the number of seals and thermal breaks on window thermal performance. Experimental tests in a hot box setup (according to the EN 12412-2 [8]), and numerical simulations (following the indications of EN ISO 10077-2) were finally performed and compared, at the aim of evaluating the influence of seals and thermal breaks on the overall window thermal performance, trying to understand, at the same time, the degree of approximation of the CFD analysis.

2. Theoretical analysis of the heat transfer in cavities

The process that governs the heat transfer through a gas contained inside a cavity includes both natural convection and radiation, depending therefore by several factors: the geometry of the cavity, its position (vertical, horizontal or inclined), the solid surfaces emissivities, and the thermophysical properties of the gas: density, thermal conductivity, specific heat capacity, thermal expansion coefficient and dynamic viscosity. At the aim of simplifying the analysis if the entire window frame, it is useful to introduce an equivalent conductivity of the gap, so treating the cavity as a solid component.

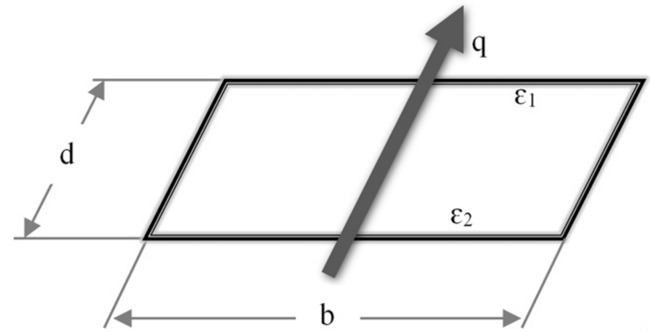

Fig. 1. Section of a generic cavity.

According to the EN ISO 10077-2, the equivalent conductivity (λ_{eq}) could be expressed as follows:

$$\lambda_{eq} = \frac{d}{R_s}$$

where

$$R_s = \frac{1}{h_a + h_r}$$

and d represents the cavity depth (Fig. 1).

Therefore, the heat transfer analysis was focused on the definition of the coefficients h_a and h_r, determining the characteristics that most influence their numerical values.

2.1. Convective heat transfer coefficient

The coefficient h_a describes the heat transfer occurring by conduction and convection inside the cavity, according to the following function:

$$h_a = \max\left\{\frac{C_1}{d}; C_2 \Delta T^{1/3}\right\}$$

where C_1 = 0.025 W/m K and C_2 = 0.73 W/m^2 K$^{4/3}$.

The maximum has to be chosen between a value that depends on the depth d of the cavity (resistance by conduction), and another proportional to the temperature difference ΔT between the inner surfaces (resistance by convection). Fig. 2 shows the trend of the convection coefficient as a function of the depth for several temperature differences ΔT, ranging from 1 °C to 25 °C. The latter values have been selected taking into account of the real working conditions of the window frames.

It is worth noting that for low values of the depth d (about 13–15 mm) the heat exchange is driven by the conduction resistance, therefore, it does not depend by the temperature of the cavity inner surfaces. When the cavity depth increases, the heat transfer becomes a function of ΔT (convection resistance), remaining constant as the cavity shape changes. Fixing the depth, the heat transfer mechanism follows the conduction thermal exchange for low values of ΔT, while, with the increasing of the temperature difference between the faces, the natural convection drives the process.

2.2. Radiation heat transfer coefficient

The radiation heat transfer coefficient h_r is defined as follows:

$$h_r = 4\sigma T_m^3 EF$$

where