Some critical remarks about the radiative heat transfer in air frame cavities according to EN ISO 10077-2

G Cuccurullo[1], **L Giordano**
Department of Industrial Engineering, University of Salerno,
Via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy

E-mail: gcuccurullo@unisa.it

Abstract. Thermal performances of windows frames are established, in Europe, by the international standard UNI EN ISO 10077-2:2012. The standard introduces an equivalent thermal conductivity for air frame cavities thus simplifying the original combined heat transfer problem to a merely two-dimensional conductive one. The equivalence is referred to a rectangular cavity and is not able to fully recover the same radiative heat flux involved in the original problem. In view of that, the paper is focused on the radiative heat transfer taking place in the air cavities and aims to check if different equivalence criteria could lead to improved results. Thus, numerical tests involving an accurate description of radiative heat transfer in air cavities are compared to the simplified fully-conductive one provided by the standard. Results show that different criteria lead to quite different results. The optimal criterion turns out to depend on both geometrical and surface radiative parameters. It is also shown that, in any case, a proper radiative resistance but not the one suggested by the ISO 10077 should be adopted.

1. Introduction

Actually, energy efficiency is one of the main goals of building design being required to reduce energy consumption and face the gradual exhaustion of natural resources. Moreover, high insulation degrees affect thermal comfort since they influence radiative exchange between inner people and outer walls. In the above connection, the study of the thermal performance of glass doors and windows assumes a primary role, since these items represent a weak area in terms of heat exchange with the external environment [1].

In the last two-decades, the need to contain thermal dispersions through fenestration components has triggered the development of new highly-performant glazing with results that were unimaginable just few years ago. Performances have been greatly enhanced mainly by lowering natural convection effects inside multiple pane windows or selecting special glasses with suitable radiative properties. Since the technological asymptote seems to be very close by now, in the last years researchers have shifted their attention to consider heat transfer through window frames. Consider that, the area occupied by the frame may even weight as much as 20-30% of the total windows area while its impact on the total window heat transfer may be much larger because of the large difference in transmittance featuring other building enclosures. This is the case for aluminum alloys used for windows frames where a 160 W/(m K) thermal reference conductivity is assumed. The latter is at least two magnitude

[1] To whom any correspondence should be addressed.

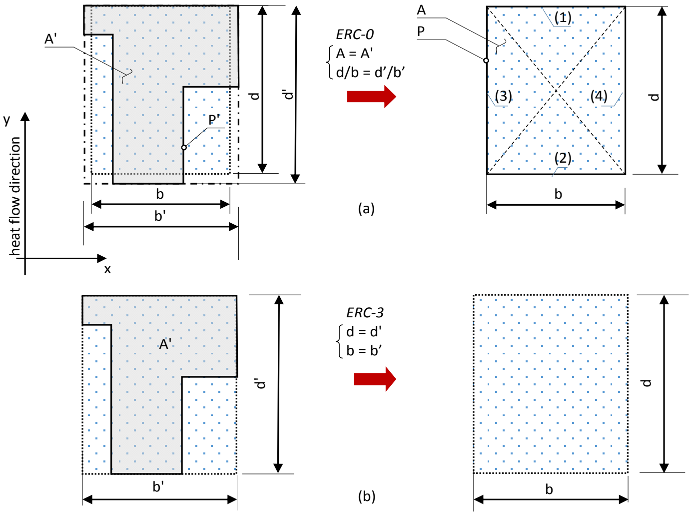

Figure 1. Equivalent rectangular cavities, ERC-0, ERC-1.

order higher than the one related to wood or PVC. This explains why other joining materials (e.g. polyamide) are used than aluminium to realize intermediate junctions. As a matter of fact, reducing the transmittance values for window-frames seems to exhibit wide profit margins wishing to reduce heat loss through the building envelope.

At the same time, determining thermal performances of windows frames in an accurate and repeatable fashion is a primary need triggered by market reasons. It is then advisable to check the accuracy of the procedures involved in featuring the product performance, i.e. the thermal transmittance. To this purpose, numerical procedures based on international standards are often employed whereas some niche options based on the hot box calorimeter can still be adopted (e.g. according to EN ISO 12567 [2]). It is well known and stated by the ISO EN 15099 itself that two different numerical methods of calculating the thermal transmittance are available: the ISO linear method [3-4] and the ASHRAE standard 142P edge method [5]. They treat in a different way the effect of the glazing spacer on the heat transfer through the frame and the glazing unit near the frame [6]. The two methods give sometimes slightly different results [7-8] which are almost contained within the 3% difference. A substantial agreement among 2D-numerical and experimental procedures is found but some improvements can be searched [9-10]. Three dimensional effects are somewhat described [7].

Actually, in Europe, the thermal characteristics of windows, doors and shutters are established by the international standard UNI EN ISO 10077-2:2012. Thus, in the present work attention is focused on such a standard. Nevertheless, with some advices, it is confirmed in what follows that ISO15099 is more accurate than 10077 as claimed by [11, 12]. Also other methods are available, e.g. the one suggested by the National Fenestration Rating Council (NFRC) [13, 14].

Generally speaking, the method proposed by different standards for window frames is based on numerical approaches simplifying the heat transfer problem to a merely two-dimensional conductive one; for such a problem computational efforts strictly required by the combined heat transfer effectively taking place in cavities are strongly reduced. The key parameter for realizing the simplified procedure is the equivalent thermal conductivity which accounts for the radiative-convective heat transfer in the internal frame cavities. The equivalent thermal conductivity doesn't allow to fully recover the radiative heat transfer of the original cavities, thus its introduction is not painless. Then, this paper focuses the attention on the criteria adopted by the standard for realizing the above equivalence. It is aimed to check if new possibilities can be identified in order to attain improved results. To this purpose, numerical tests, carried on by a commercial FEM code (Comsol), act as a reference since it has been involved an accurate description of radiative heat transfer in air cavities. Numerical runs are compared to the corresponding simplified fully-conductive one provided by the

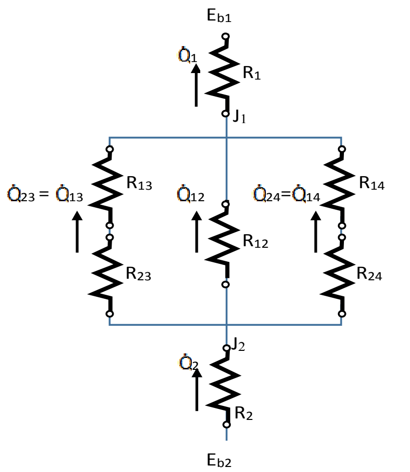

Figure 2. Radiative resistances.

standard. In what follows, it is shown that both the former and the latter approach lead to comparable results in terms of heat fluxes but meaningful improvements can be attained provided that proper corrections are considered with respect to the simplified correlation recommended by the EN ISO10077-2.

2. Basic equations for radiative heat transfer

In order to evaluate the heat flux flowing across the frame, the standard UNI EN ISO 10077-2 states that unventilated non-rectangular air cavities have to be transformed into rectangular cavities filled with a material exhibiting a suitable equivalent thermal conductivity accounting both for radiative and convective contributions.

This approach was early introduced by Standaert [15] and later both by Jonsson [16] and Carpenter [17] which formulated the effective conductivity referred to the rectangular geometry, area $A = d$ x b, perimeter $P = 2(b + d)$, see figure 1. Based on the early approach, several standards, such as ASHRAE 96, ISO 2000a and CEN 2001a, introduce an equivalent thermal conductivity defined as:

$$k_{\mathrm{eq}} = (h_a + h_r)d \; ; \; h_r = 4 \cdot f \cdot \sigma \cdot T_m^3 \tag{1}$$

where h_a and h_r are the convective and radiative heat transfer coefficients, d is the length of the cavity in the heat flow direction, σ is the Stefan-Boltzmann constant, and f is a correcting factor with respect to the black body heat transfer; it has to depend on the cavity geometry and the radiative surface properties assumed as grey ones. In particular, according to the 10077 standard the correcting factor f is given by:

$$\mathrm{f} = \mathrm{E\,F}; \quad F = \frac{1}{2}\cdot\left(1+\sqrt{1+(d/b)^2}-d/b\right); \quad E = \left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)^{-1} \tag{2}$$

where ε_1 and ε_2 are the emissivities of the hot and cold surfaces normal to the heat flow.

In order to apply the previous equations, the transformation of a generic irregular cavity of area A' and perimeter P' into an equivalent rectangular cavity (ERC) has to be performed. After identifying the smallest circumscribing rectangle, dim. b' x d' in figure 1 (a), the transformation can occur according to different criteria. The CEN 2001 a and lately the 10077 standards follow the rule illustrated in figure 1 (a): the ERC saves the same area, $A = A'$, and the same aspect ratio, $d/b = d'/b'$, in order to feature the equivalent rectangle (dim. b x d). In addition to the previous one, identified below with the label "ERC-0", other equivalences can be proposed, for instance:

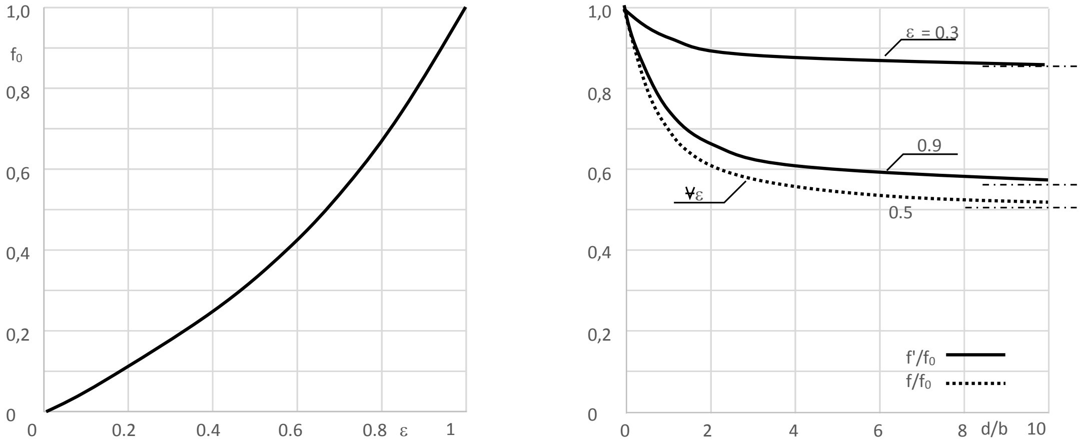

Figure 3. The correcting factors according to the 10077 standard (f) and to this paper (f').

- ERC-1: $A/P = A'/P'$, $d/b = d'/b'$, i.e. the ratio of area to perimeter and aspect ratio are saved;
- ERC-2: $d/d' = A/A'$, $d/b = d'/b'$; the scaling evidences the role of the depth d along which the heat transfer mainly takes place.
- ERC-3→ $d = d'$ and $b = b'$; the smallest circumscribed rectangle is selected, as suggested by the North American National Fenestration Rating Council, figure 1 (b)

After realizing the transformation into a rectangle of the cavity at hand by one of the available criteria, its view factors can be evaluated, as shown in the next paragraph.

3. View factors for rectangular cavity

In order to explicitly evaluate the coefficient h_r for a rectangular cavity, the network method, based on the electrical network analogy by A. K. Oppenheim, has been applied. According to the 10077, the heat transfer essentially takes place along the y-direction since the lateral surfaces (3) and (4) , see figure 1, are sought as adiabatic; for the remaining two surfaces, first-type boundary conditions are given, i.e. $T_1 =$ 0 °C and $T_2 = 20$ °C.

Due to the geometry and load symmetry along the y-axis, the radiosities inherent to the lateral surfaces are equal, $J_3 = J_4$, therefore the related cross flow vanishes. The equivalent electrical network is shown in figure 2; here, the $R_i = (1-\varepsilon_i)/(\varepsilon_i\ w_i)$ are the surface resistances and $R_{ij} = (w_i\ F_{ij})^{-1}$ are the space resistance to radiation, w_i and ε_i being the width and the emissivities of the i-th surface, F_{ij} being the related view factors. Because of symmetry constraints, the view factors between the longitudinal and transverse rectangle surfaces turn out such as $F^* = F_{14} = F_{13} = F_{24} = F_{23}$ and their corresponding resistances are equal.

The radiative heat fluxes can be written in terms of the equivalent resistance, R_{eq}, of the network: $\dot{Q} = \dot{Q}_1 = \dot{Q}_2 = (E_{b2} - E_{b1})/R_{eq}$, where the potentials $E_{b1} = \sigma\cdot T_1^4$ and $E_{b2} = \sigma\cdot T_2^4$ are known, since the corresponding surface temperatures are prescribed.

The only unknown parameters required to evaluate the heat flow along the y-direction are the view factors. These have been calculated using the well known Crossed-Strings Method by Hottel which, in particular, yields:

$$F_{12} = \sqrt{1+\left(\frac{d}{b}\right)^2} - \frac{d}{b}; \qquad F^* = \frac{1}{2}\left[1+\frac{d}{b} - \sqrt{1+\left(\frac{d}{b}\right)^2}\right] \tag{3}$$

Finally, after linearizing, the radiative heat flux between the hot and cold surfaces becomes:

$$\dot{Q} \approx h_r' \cdot A \cdot (T_2 - T_1) \tag{4}$$

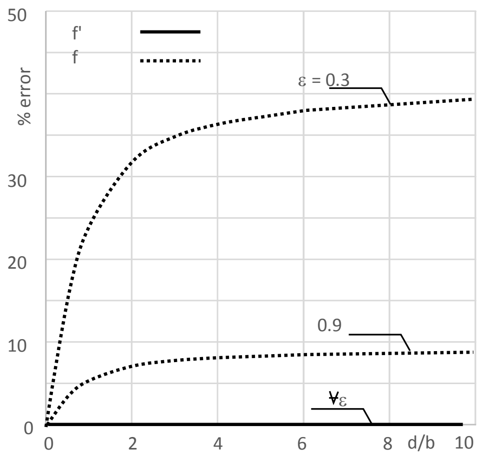

Figure 4. Percentage error for the correcting factors.

where the corrected radiative heat transfer coefficient $h_r' = 4 \cdot \sigma \cdot f' \cdot T_m^3$ is expressed in a similar fashion to eq. (1), the new correcting factor f' being defined as

$$f' = \frac{1}{E^{-1} + F_{34}}; \quad F_{34} = \sqrt{\left(\frac{b}{d}\right)^2 + 1} - \frac{b}{d} \tag{5}$$

The factor f' turns out to be the same of that given by ISO 15099 and formerly introduced by Roth [8], but here it has been expressed in a more compact way.

Finally, by comparing eq. (1) and the (5), it clearly appears that the use of the correction factor f' as an alternative to the corresponding f proposed by the EN ISO 10077-2 gives different results. Both the correcting factors turn out to be decreasing functions of the ratio d/b while selecting the same emissivity ε for both hot and cold surfaces. Considering that both the correcting factors attain the same value $f_0 = \varepsilon/(2-\varepsilon)$ for the ratio d/b being zero, the corresponding normalized curves f/f_0 and f'/f_0 are shown in figure 3 for $\varepsilon = 0.3$ and 0.9. The two selected values for emissivities are typical extreme values of aluminium frames: the former is prescribed by ISO 10077-2, if no other information is available, and is near the one featuring a painted or anodized frame; the latter is characteristic of galvanized or chromed untreated aluminium 6060, not far from the one related to shiny metallic surfaces.

All the normalized curve decrease monotonically attaining different asymptotic values: $f(\varepsilon, d/b\to\infty)/f_0 = 1/2$, independently of ε, while $f'(\varepsilon, d/b\to\infty)/f_0 = (2\text{-}\varepsilon)/2 > 1/2$. Thus, it can be inferred that, for a selected d/b, the factor f turns out to be always lower than f'.

4. Comparison between numerical and simplified results for rectangular cavities

In order to check the analytical expression obtained for the factor f', the radiative heat power leaving the hot surface has been numerically calculated using the software Comsol Multyphisics 5.0, based on the Finite Element Method (FEM). The commercial code allows to evaluate the radiative heat exchange in the cavities according to the diffuse opaque surface model. Thus, a rectangular cavity is singled out and, after building the geometry, the required boundary conditions were imposed: that is, with reference to figure 1, temperatures T_1 and T_2 on (1) and (2) and adiabatic conditions on (3) and (4). The convergence of the solution was verified by increasing the number of elements using the physics controlled mesh. Assuming the numerical solution "to be exact", figure 4 shows the percentage errors committed on the radiative power with respect to the numerical solution: as expected, the correcting factor f' allows to recover numerical results in any case, while the error made

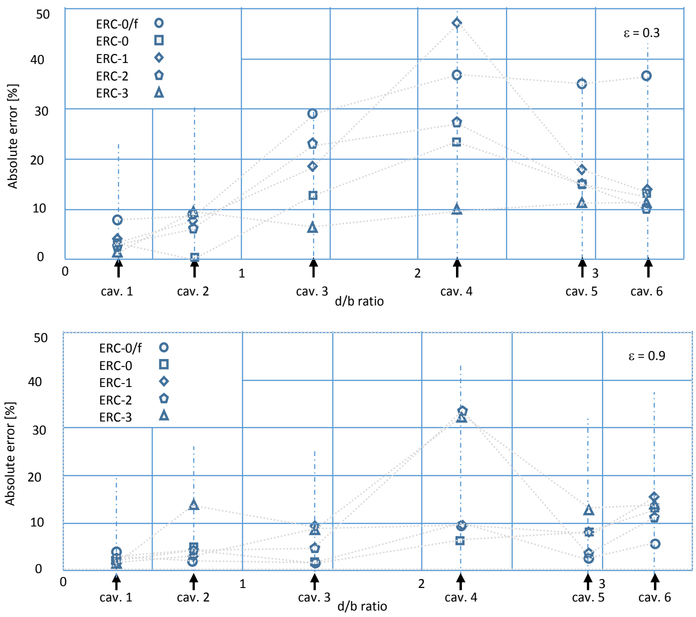

Figure 5. Percentage absolute error on the heat flux.

using the factor f increases with decreasing emissivity and increasing the cavity aspect ratio. Note that for typical emissivity of 0.9 the error made using f is sensibly lower than the one related to low emissivities.
It is then proven that the factor f given by UNI 10077-2 doesn't recover the exact value of radiative heat power even in the most favourable case of a singled out rectangular cavity for which the boundary conditions are strictly applied.

5. Analysis of the equivalence criterion

Six cavities taken from commercial profile (namely, mod. Planet 62 TT (Z), Meral S.p.A, Italy) were analysed in order to check the approximation made by the ERC criteria, see table 1. In view of the conclusion drawn in the previous paragraph, the factor f' is adopted to calculate the equivalent thermal conductivity with the noticeable exception of the case ERC-0 for which, in addition, the correction factor f provided by the 10077 standard is considered as a reference and labelled as ERC-0/f.
The procedure outlined below was followed. After applying the selected ERC criterion to the cavity at hand, its equivalent thermal conductivity was determined, assuming only radiative heat transfer to happen. Then, according to the procedure outlined by the 10077 standard, the original cavity was filled with a fictitious material whose thermal conductivity was the equivalent one. After that, the original shape was surrounded by an additional rectangular frame, the latter being identified by the smallest circumscribing rectangle whose uniform thickness was arbitrarily chosen to be equal to b'/10. Proceeding in such a way, it was allowed to encompass irregularly shaped cavities too by uniquely assigning boundary conditions as already done in the scheme of figure 1. The adjoining frame was assumed to exhibit the already determined equivalent conductivity. Thus, because of the symmetry of the load and geometry, a nearly 1D - heat flux was realized which was easily calculated. Such results were compared with that obtained by using the FEM code to solve the original radiative problem.
Results are summarized in figure 5, where the percentage absolute error on the heat flux leaving the boundary 1 is shown for the two already selected emissivities, i.e. 0.3 and 0.9. As a consequence of what observed in the previous paragraph about the correction factors, lower errors are realized for incresing emissivity. In particular, for ε = 0.3, it can be stated that the criterion ERC-0/f, i.e. the one suggested by the 10077 standard, gives very nearly the worst results for each cavity, whereas the best

results are given by the ERC-3 with the noticeable exception of the most irregular "cavity 2" where ERC-0 prevails. None of the ERC-1 and ERC-2 criteria seem to give advantages. On the contrary, with reference to $\varepsilon = 0.9$, the ERC-3 seems to be the worst case, whereas the ERC-0 is almost the best one for the first four cavities at hand; surprisingly, for the two higher d/b ratio taken under consideration, the criterion proposed by the 10077 standard allows to realize lower errors. In any case, a lower sensitivity to the selected criterion can be appreciated when emissivity decreases.

Finally, it seems that the present work almost entirely confirms that more precise results can be obtained for the heat flux occurring in the cavity by employing the expressions here presented rather than the one suggested by the 10077 standard. Such results were confirmed, for instance, by several authors [6, 11, 12] both from experimental and theoretical point of view. Whilst, due to unpredictable geometrical and emissivity combinations, the criterion suggested by the standard seems to give better results.

Table 1. The six cavity shapes under test.

cav. n.	d/b	shape	cav. n.	d/b	shape
1	0.3		4	2.2	
2	0.72		5	2.92	
3	1.4		6	3.3	

6. Conclusions

In this paper the different methods for calculating the equivalent thermal transmittance for window frame cavities are compared. The reference method is sought to be the one given in the ISO EN 10077. With respect to the latter, both view-factor and geometrical equivalence criteria are compared by processing six typical frame cavities. It has been found that different criteria combinations give different results from the 10077 standard, they almost giving better results depending on the geometry and surface emissivity under consideration. It has been proven that a better description of the heat transfer across the cavity can be realized by using a proper equivalent radiative resistance calculated by the Crossed-Strings Method for the rectangular equivalent shape. Such a result is coherent with that reported by ISO EN 15099 standard, "Thermal Performance of Windows, Doors and Shading Devices Detailed Calculations". Moreover, it is shown that using the geometrical equivalence to a rectangular shape given from the 10077 standard is the best criterion available among that under test for higher emissivities, whereas for lower emissivities the NFRC criteria prevails.

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