SIMULATION OF FRAME CAVITY HEAT TRANSFER USING BISCO v10w

PHYSIBEL

Introduction

In construction elements such as window frames and bricks, the heat transfer through air cavities is often a quite important part of the global heat transfer through them. The heat transfer mechanisms are infrared radiation and conduction (in case of still air) or convection (in the case of flowing air).

Several current European standards apply a heat transfer simplification by replacing the cavity by an imaginary material with an equivalent thermal conductivity. The standard formulas for the equivalent thermal conductivity are based on simplifications of the radiation and conduction or convection. The EN ISO 10077-2:2003 "Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames" is an example of such a standard. This document is referred further as *"the 10077-2:2003 standard"*.
In the Physibel software this simplified method is implemented through the so-called EQUIMAT type.

A revision of the EN ISO 10077-2 prescribing a physically more correct method for cavity heat transfer is in the running now. This document is referred further as *"the 10077-2 revision standard"*.
In BISCO version 10w with the RADCON module this physically more correct method is implemented through the so-called TRANSMAT type.

The simplified method of the 10077-2:2003 standard and the detailed one of the 10077-2 revision standard are discussed and compared to each other using *BISCO version 10w* (released in 2012). Sample frame simulations and detailed cavity simulations help understanding both methods.

Sample frame A

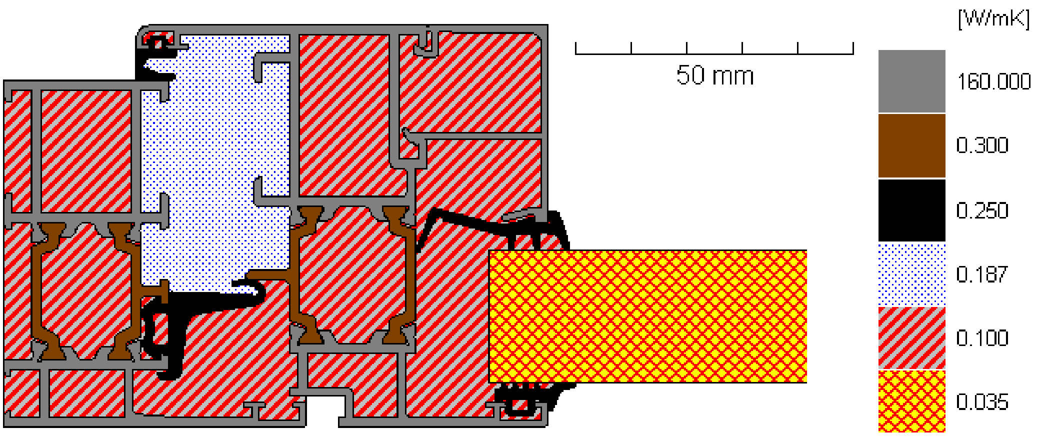
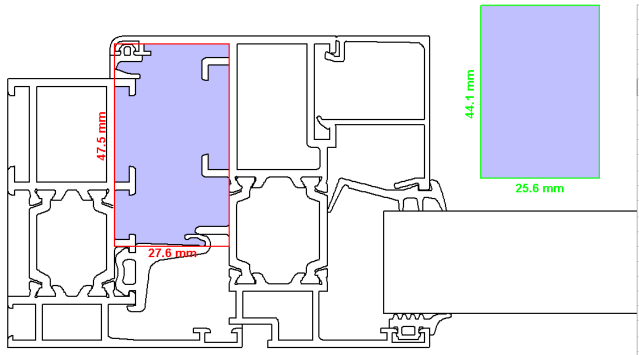


Figure 1. Sample frame A data.

In sample frame A (Figure 1) only one single air cavity is assumed. The other cavities are filled with a material with thermal conductivity $\lambda = 0.1$ W/mK.

Simulation according to the 10077-2:2003 standard using EQUIMAT.

BISCO data Frame_A_EQUIMAT.bsc



geometric data	BISCO		
cavity circumscribing rectangle depth [mm]	47.5		from BISCO
cavity circumscribing rectangle width [mm]	27.6		from BISCO
area of the true cavity [pixels]	113034		from BISCO
pixel width [mm]	0.100000		from BISCO
cavity area [mm^2]	1130.3		
equivalent cavity depth [mm]	44.1		formula from EN ISO 10077-2
equivalent cavity width [mm]	25.6		formula from EN ISO 10077-2
convection			
constant C1 [W/mK]	0.025		constant from EN ISO 10077-2
constant C2 [W/m^{2}K$^{4/3}$]	0.73		constant from EN ISO 10077-2
constant C3 [-]	0.3333333		constant from EN ISO 10077-2
cavity temperature difference [K]	10.0		from BISCO results, if unknown use 10 K
convective heat transfer coefficient [W/m^{2}K]	1.57		formula from EN ISO 10077-2
Nusselt number	2.77		formula derived from EN ISO 10077-2
radiation			
long wave emissivity of side 1 [-]	0.9		default value 0.9
long wave emissivity of side 2 [-]	0.9		default value 0.9
mean cavity temperature [K]	283.0		default value 283
intersurface emittance	0.82		formula from EN ISO 10077-2
view factor	0.63		formula from EN ISO 10077-2
radiative heat transfer coefficient [W/m^{2}K]	2.67		formula from EN ISO 10077-2
equivalent thermal conductivity [W/mK]	**0.187**		formula from EN ISO 10077-2

Figure 2. Calculation of the cavity equivalent conductivity.
(file EN_ISO_10077-2_lambda_eq_frame_A.xls)

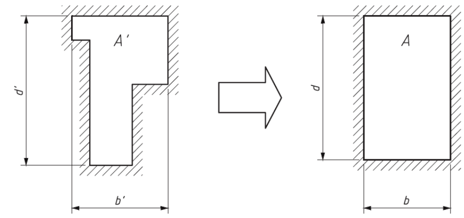
The cavity equivalent conductivity calculation according to the 10077-2:2003 standard requires 4 steps.

Step 1.

For non-rectangular cavities a transformed rectangular cavity is derived (see standard extract at the right).
The transformed rectangular has a depth d and a width b (d = 44.1 mm, b = 25.6 mm for the sample cavity).

6.3.3 Unventilated non-rectangular air cavities

Non-rectangular air cavities (T-shape, L-shape, etc.) are transformed into rectangular air cavities with the same area ($A = A'$) and aspect ratio ($d/b = d'/b'$) (see Figure 5) and then 6.3.2 is applied.



Key
A area of the equivalent rectangular air cavity
d, b depth and width of the equivalent air cavity
A' area of the true cavity
d', b' depth and width of the smallest circumscribing rectangle

Figure 5 — Transformation of non-rectangular air cavities

Step 2.

A convective heat transfer coefficient h_a is calculated (see standard extract at the right).
Using the default temperature difference
h_a = 1.57 W/m^{2}K is found for the sample cavity.

The formula used takes into account that for small cavities (d < 16 mm) conduction occurs (still air) instead of convection.

6.3.2.2 Convective heat transfer coefficient

The convective heat transfer coefficient, h_a, is:

If b < 5 mm where

$$h_a = \frac{C_1}{d} \qquad C_1 = 0{,}025 \text{ W / (m·K)}; \tag{3}$$

otherwise where

$$h_a = \max\left\{\frac{C_1}{d}; C_2\,\Delta T^{1/3}\right\} \tag{4}$$

C_1 = 0,025 W/(m·K);
C_2 = 0,73 W/(m^2·K$^{4/3}$);
ΔT is the maximum surface temperature difference in the cavity.
If no other information is available, use ΔT = 10 K

Step 3.

A radiative heat transfer coefficient h_r is calculated (see standard extract at the right).
Using a default overall emissivity ε = 0.9 and a default mean temperature (10°C)
h_r = 2.67 W/m^{2}K is found for the sample cavity.

6.3.2.3 Radiative heat transfer coefficient

$$h_r = 4\sigma T_m^3\, E\, F \tag{6}$$

where

σ = 5,67 × 10^{-8} W/(m^2·K^4) is the Stefan-Boltzmann constant;

$E = \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)^{-1}$ is the intersurface emittance;

$F = \frac{1}{2}\left(1 + \sqrt{1 + (d/b)^2} - d/b\right)$ is the view factor for a rectangular section;

ε_1 and ε_2 are the emissivities of the surfaces indicated in Figure 4.

The values of the emissivities should be given to two decimal places.
If no other information is available use ε_1 = 0,90 and ε_2 = 0,90.
If no other information is available, use T_m = 283 K for which

$$h_r = C_4\left(1 + \sqrt{1 + (d/b)^2} - d/b\right) \tag{7}$$

where C_4 = 2,11 W/(m^2·K)

Step 4.
The equivalent conductivity is calculated from the convective and radiative heat transfer coefficients h_a and h_r (see standard extract at the right). The depth d is the dimension in the direction of the heat flow.
For the sample cavity λ_{eq} = 0.187 W/mK.

6.3.2.1 Equivalent thermal conductivity

The equivalent thermal conductivity of the cavity is given by Equation (1):

$$\lambda_{eq} = \frac{d}{R_s} \quad (1)$$

where

d is the dimension of the cavity in the direction of the heat flow;

R_s is the thermal resistance of the cavity, given by Equation (2):

$$R_s = \frac{1}{h_a + h_r} \quad (2)$$

Figure 3 shows the results of the frame simulation.
The thermal transmittance is $\mathbf{U_f = 3.085\ W/m^2K}$.

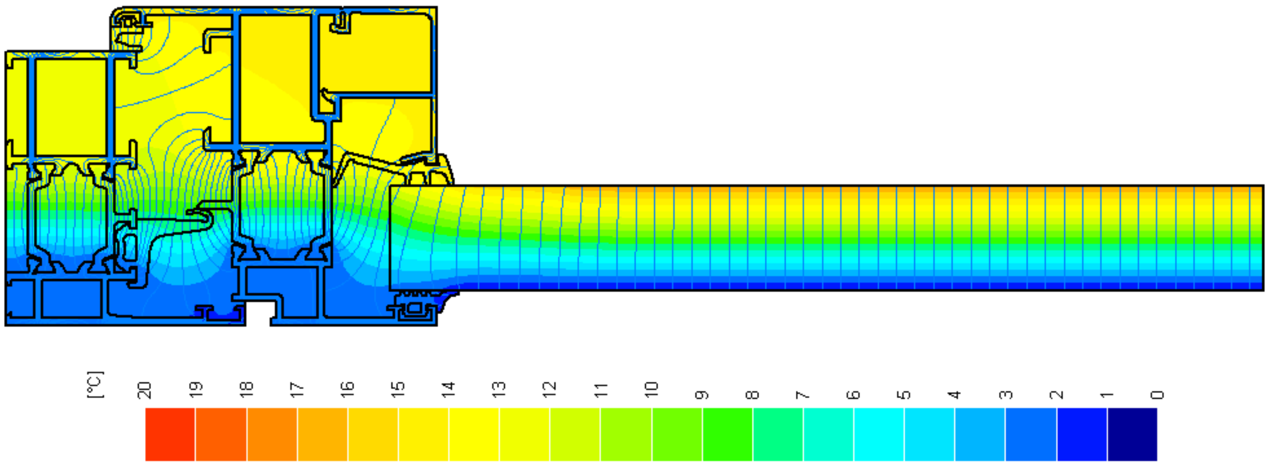


Figure 3. Isotherms and heat flow lines (increment 0.1 W/m) in frame A (using EQUIMAT).

Discussion
Week elements of the 10077-2:2003 standard are the following.
- The method isn't unambiguous as 2 options are available for the temperature difference, both in the radiation and the convection formula.
- Radiation shielding in concave shaped cavities isn't taken into account.
- Nothing is said on how to derive the emissivity of the opposite rectangle sides. In Figure 4 it is false to take e_1 = 0.1. This is an important gap in the standard. In fact this gap implies that considering low emissivity values is unauthorised in standard calculations.
- The direction of the heat flow is not well defined. In a lot of practical case the heat flow direction corresponds less or more to the X- or Y-axis, but in a case as shown in Figure 5 there is a problem. Assuming X being the heat flow direction, different equivalent thermal conductivities are found for the 2 identical cavities.

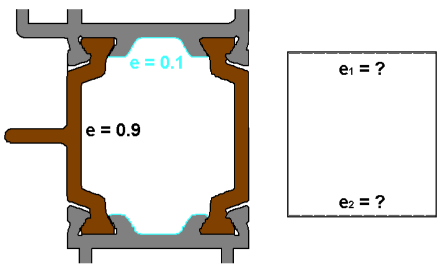


Figure 4. Emissivity problem

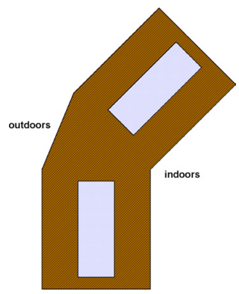


Figure 5. Heat flow direction problem

Simulation according to the 10077-2 revision standard using TRANSMAT.
BISCO data Frame_A_TRANSMAT.bsc

The principles of the 10077-2 revision standard are the following.

1. A detailed radiation model is used.
The radiative heat exchange between the elementary surfaces around the air cavity (resulting from the grid) is calculated using the view factor based radiosity method. This has 2 benefits:
- a rectangular simplification isn't required
- the emissivity can be different for each elementary surface.
Experimental validations show that the detailed radiation model results are very close to reality.

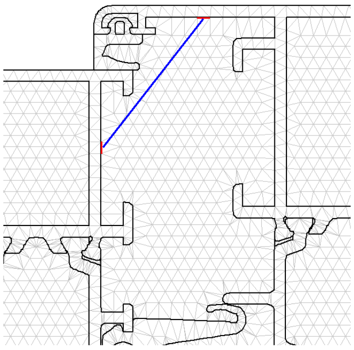


Figure 6. Viewfactor based radiosity method scheme and triangular grid.

2. Conduction or convection are modelled using an equivalent thermal conductivity.
The equivalent thermal conductivity equals

$$\lambda_{eq} = \lambda_{air}\ Nu$$

with λ_{air} thermal conductivity of air at 10°C = 0.025 W/mK
Nu the Nusselt number

Nu = 1 means still air: the heat transfer mechanism is conduction
Nu > 1 means flowing air: the heat transfer mechanism is convection.

3. The equivalent conduction heat flow direction is derived iteratively.

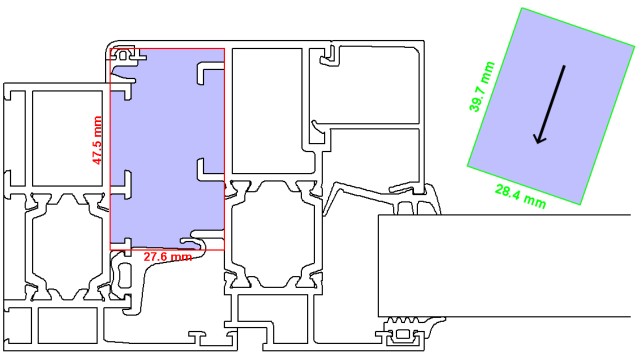


Figure 7. Calculation of an equivalent rectangle: the depth corresponds to the heat flow direction.

The Nusselt number formula requires a depth and width of a rectangle. This rectangle is derived iteratively in order to have the depth corresponding to heat flow direction. In this case the slope is 109° (from the horizontal axis).

4. The Nusselt number is calculated using the formula of the the 10077-2:2003 standard[1].

if b < 5 mm   Nu = 1

otherwise $$Nu = \max\left[1, \frac{d\,C\,\Delta T^{1/3}}{\lambda_{air}}\right]$$

with
- b   rectangle width [m] = 28.4 mm for the sample cavity
- d   rectangle depth [m] = 39.7 mm for the sample cavity
- C $= 0.73\ W/(m^2 \cdot K^{4/3})$
- ΔT the maximum surface temperature difference in the cavity = 8.1 °C for the sample cavity

For the sample cavity the Nusselt number is Nu = 2.33.

5. The reference temperatures shall be 20 °C indoors and 0 °C outdoors.
This condition is required to have an unambiguous temperature difference in the convection formula and in the non-linear radiosity method.

Through these principles the 10077-2 revision standard implements the heat transfer mechanisms physically more correct and meet some shortcomings of the 10077-2:2003 standard.

Figure 8 shows the results of the frame simulation. The heat flow lines in the cavity cannot be drawn. Indeed the cavity heat transfer is a combination of radiation and equivalent conduction. Heat flow lines can only be drawn in case of pure conduction.
The thermal transmittance is $\mathbf{U_f = 2.948\ W/m^2K}$ (4.5 % lower than using EQUIMAT).

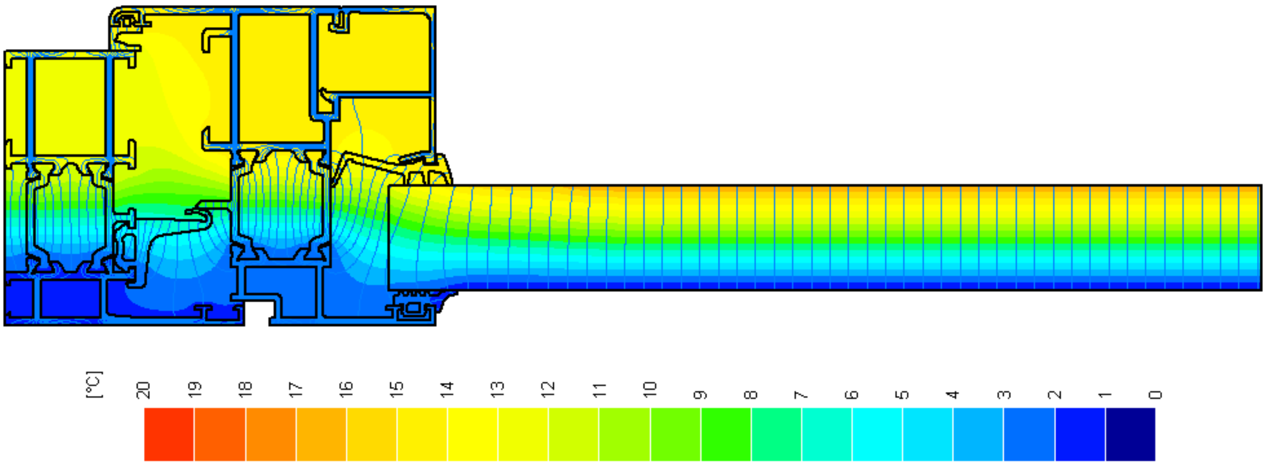


Figure 8. Isotherms and heat flow lines (increment 0.1 W/m) in frame A (using TRANSMAT).

[1] The convection formula is an empirical formula assuming horizontal heat flow. Therefore the standard concerns vertically positioned windows and façades only. The ISO 15099 standard "Thermal performance of windows, doors and shading devices — Detailed calculations" contains convection formulas for upwards and sloped heat flow as well. Also EN 673 "Glass in buildings - Determination of thermal transmittance (U value) - Calculation method" contains such convection formulas. It would be of interest to include or to refer to such formulas in future versions of EN ISO 10077-2. It would allow deriving the thermal transmittance of frames in non-vertical positions, as for example in roofs.

Sample frame B

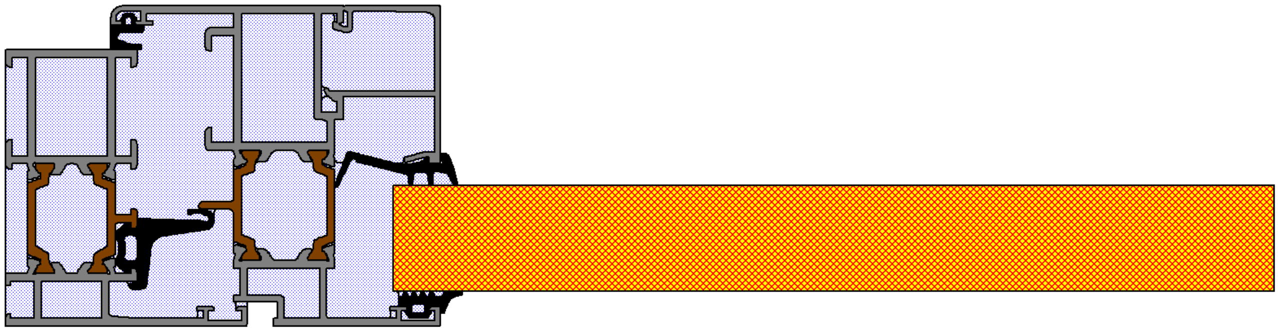


Figure 9. Sample frame B section.

Sample frame B (Figure 9) is identical to sample frame A, but now all cavities are air cavities (and not filled by a material).

Simulation according to the 10077-2:2003 standard using EQUIMAT.
BISCO data Frame_B_EQUIMAT.bsc
The thermal transmisttance of the frame is **U_f = 3.003 W/m^{2}K**.

Simulation according to the 10077-2 revision standard using TRANSMAT.
BISCO data Frame_B_TRANSMAT.bsc
The thermal transmisttance of the frame is **U_f = 2.846 W/m^{2}K** (-5.2 %).

Comparing 4 cavity types

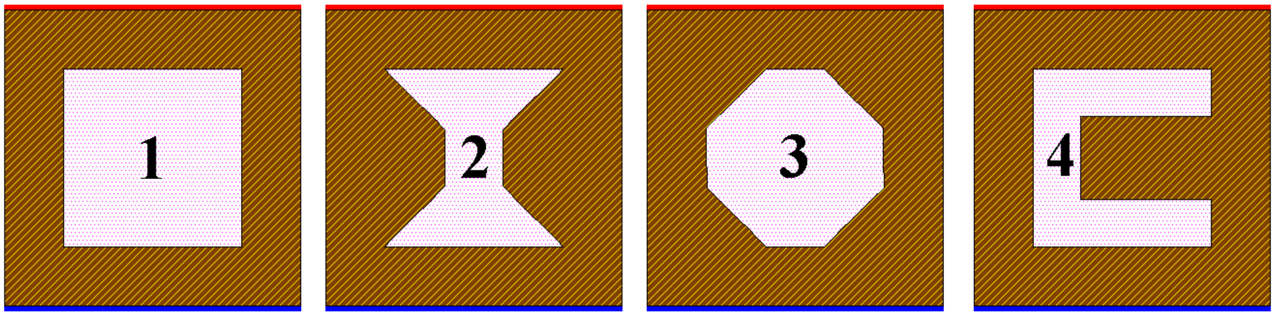


Figure 10. 4 cavity types: (1) rectangular, (2) concave, (3) convex, (4) irregular.

Figure 10 shows 4 cavity shapes. The cavity is embedded in a plastic material layer positioned between an internal and external environment. 2 heights of the cavities are considered:
- h = 15 mm, resulting in still air and thus conduction in the cavity (Nu = 1)
- h = 30 mm, resulting in flowing air and thus in convection in the cavity (Nu > 1).

The heat flow is calculated according to both the 10077-2:2003 standard (using EQUIMAT) and the 10077-2 revision standard (using TRANSMAT). Table 1 refers to the 16 BISCO simulations.

h = 15 mm	EQUIMAT	TRANSMAT
TYPE 1	cavity_15mm_type_1_equimat.bsc	cavity_15mm_type_1_transmat.bsc
TYPE 2	cavity_15mm_type_2_equimat.bsc	cavity_15mm_type_2_transmat.bsc
TYPE 3	cavity_15mm_type_3_equimat.bsc	cavity_15mm_type_3_transmat.bsc
TYPE 4	cavity_15mm_type_4_equimat.bsc	cavity_15mm_type_4_transmat.bsc
h = 30 mm	EQUIMAT	TRANSMAT
TYPE 1	cavity_30mm_type_1_equimat.bsc	cavity_30mm_type_1_transmat.bsc
TYPE 2	cavity_30mm_type_2_equimat.bsc	cavity_30mm_type_2_transmat.bsc
TYPE 3	cavity_30mm_type_3_equimat.bsc	cavity_30mm_type_3_transmat.bsc
TYPE 4	cavity_30mm_type_4_equimat.bsc	cavity_30mm_type_4_transmat.bsc

Table 1. Overview of cavity simulation BISCO data files.

h = 15 mm	EQUIMAT	TRANSMAT	%
TYPE 1	1.3182	1.3279	-0.7%
TYPE 2	1.3914	1.3693	1.6%
TYPE 3	1.3607	1.3720	-0.8%
TYPE 4	1.3565	1.3085	3.7%
h = 30 mm	EQUIMAT	TRANSMAT	%
TYPE 1	2.0550	2.0754	-1.0%
TYPE 2	2.0578	2.0179	2.0%
TYPE 3	2.0510	2.0731	-1.1%
TYPE 4	2.0436	1.9433	5.2%

Table 2. Heat flows through objects [W/m].

Table 2 lists the heat flows through the objects (plastic material + cavity).
The result using the TRANSMAT type for the cavity with height 15 mm can be considered as very reliable in respect to physical reality. Indeed only conduction and radiation occur and these heat transfer mechanisms are simulated according to the governing physical laws (Fourier, Boltzmann). Therefore it can be concluded that the 10077-2:2003 standard (using EQUIMAT) underestimates the heat flow in case of rectangular (type 1) and convex (type 3) cavities. The 10077-2:2003 standard is not conservative for these cavity types as it should be.
For concave (type 2) and irregular (type 4) cavities the 10077-2:2003 standard overestimates the heat flow. This was already illustrated in the sample A frame simulations.

Conclusions

The 10077-2 revision standard meets some important shortcomings of the 10077-2:2003 standard:
- through a physically correct radiation simulation,
- through considering the real heat flow direction in the cavity convection or conduction,
- through fixed reference temperature conditions (20 °C and 0 °C).

In cases as the sample B frame a 5 % lower thermal transmittance U_f is obtained using the 10077-2 revision standard. This cannot be generalised for all frames. Indeed the cavity type comparison shows that for rectangular and convex cavities the 10077-2:2003 standard isn't conservative.