THERMAL SIMULATION OF NON-VENTILATED CAVITIES USING THE RADCON-MODULE

Content

1. Introduction

The heat transfer through gas-filled cavities is often a quite important part of the global heat transfer through building envelope elements such as window frames and brickwork. The cavity heat transfer modes are infrared radiation and conduction (in the case of still gas) or convection (in the case of flowing gas).

Several international standards use the concept of the equivalent thermal conductivity λ_{eq}, integrating radiation and conduction/convection in one equivalent property to describe the heat transfer within cavities. In the Physibel software the type **EQUIMAT** is used for that purpose.

It is important to note that integrating radiation and conduction/convection in a single equivalent thermal conductivity (λ_{eq}) is based on important simplifications.

As an alternative the radiosity method can be used for a more precise heat transfer simulation (taking non-linear heat transfer by radiation into account). It allows a separate analysis of radiation and conduction/convection with less simplification. This method is implemented in the 2D & 3D Physibel software with the type **TRANSMAT (RADCON-module)** (in case the conduction/convection is expressed as an equivalent thermal conductivity) or the type **BC_FREE (RADCON-module)** (in case the conduction/convection is expressed with a convective heat transfer coefficient between the surfaces and a single air node).

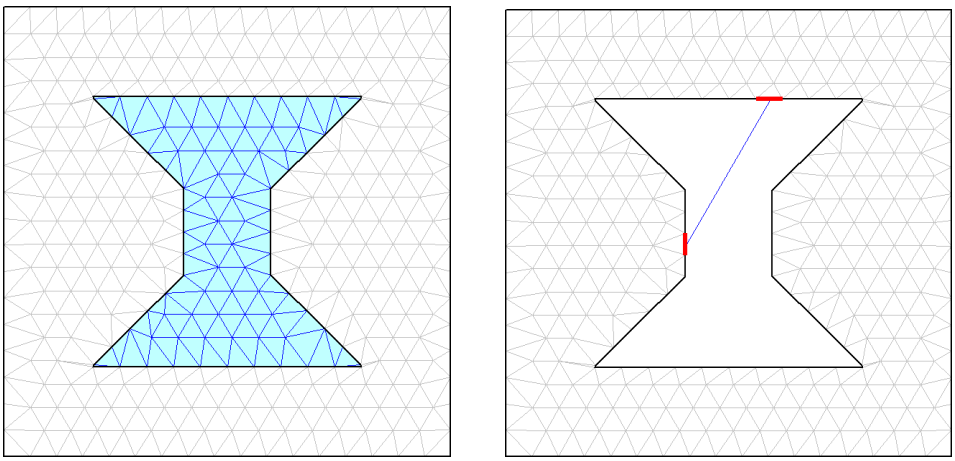


Figure 1. Triangular grid (BISCO): Left) Conduction/convection and Right) radiation (example).

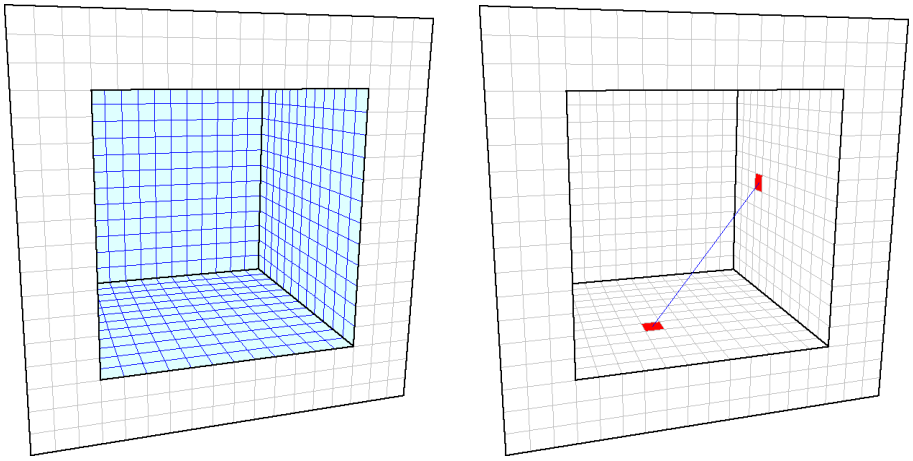


Figure 2. Rectangular grid (TRISCO): Left) Conduction/convection and Right) radiation (example).

2. Cavities with still gas

In cavities with still gas the heat transfer modes are radiation (between the surfaces around the cavity) and conduction (through the still gas). In the Physibel software, the use of the type TRANSMAT allows a correct physical simulation of this coupled heat transfer:

- The conduction finite element algorithm is based on Fourier's laws. A triangular or rectangular grid covering the gas is used to simulate the conduction (left part of Figure 1 and Figure 2).
- The radiation algorithm is based on non-linear or linear view factor based radiation laws (Stefan-Boltzman's law, Lambert's Cosine Law, view factor based heat exchange) (right part of Figure 1 and Figure 2).

3. Cavities with flowing gas

In cavities with flowing gas the heat transfer modes are radiation (between the surfaces around the cavity) and convection (from surface to surface through the flowing gas).

The Nusselt number.

The Nusselt number Nu is a dimensionless heat transfer coefficient expressing the ratio of convection heat transfer to conduction in a fluid (gas) enclosure.

From this definition, a Nusselt number Nu = 1 implies that there is no convection (still fluid). For a Nusselt number Nu > 1 the convection through a gas enclosure can be expressed as conduction through the enclosure filled with a material with a thermal conductivity $\lambda = Nu\ \lambda_{gas}$.

From the above, it is clear that for cavities with still gas, as for cavities with flowing gas the type TRANSMAT can be used provided that the Nusselt number is known.

Empirical relations for the Nusselt number as a function of the configuration, fluid properties and boundary conditions can be found in textbooks on (convective) heat transfer. The formulas listed in standards are derived from such relations, applying some simplifications or being valid only for a specific application.

Some examples of convection formulas according textbooks and standards are implemented in the spreadsheet Cavity_Nusselt.xls.

4. Implementation of convection in European standards

The standard EN ISO 10077-2 contains relations for the Nusselt number within the description of the 'radiosity method' (paragraph 6.4.2.3.2):

in case of b < 5 mm

Nu = 1

otherwise

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

The constant λ_a corresponds to the thermal conductivity of air at 10 °C (λ_{air} = 0.025 W/mK).
In case of Nu = 1, the gas is still.
C is a constant equal to 0,73 W/(m²·K$^{4/3}$).
ΔT is the temperature difference across the air space.
b and d are the width and depth of the (equivalent) rectangular cavity.

EN ISO 10077-2 applies the same formulas to describe convection in the 'single equivalent thermal conductivity method' (paragraph 6.4.3.4.2), although the Nusselt number is there not mentioned explicitly (see APPENDIX B of this document).

It is important to notice that EN ISO 10077-2 always assumes a horizontal heat flow direction and lying frame position (In the Physibel software this corresponds in the Colours window to 'Physical flow direction' = HOR).

The convection formulas according to EN ISO 10077-2 are implemented in the spreadsheet Cavity_Nusselt.xls.

Also the standard EN 673 (Glass in building – Determination of thermal transmittance (U value) – Calculation method) contains relations for the Nusselt number (Figure 3). The formulas are also implemented in the spreadsheet Cavity_Nusselt.xls.

$$Nu = A(Gr\,Pr)^n \quad (6)$$

where

A is a constant;
Gr is the Grashof number;
Pr is the Prandtl number;
n is an exponent.

$$Gr = \frac{9{,}81 s^3 \Delta T \rho^2}{T_m \mu^2} \quad (7)$$

$$Pr = \frac{\mu c}{\lambda} \quad (8)$$

where

ΔT is the temperature difference between glass surfaces bounding the gas space;
ρ is the density;
μ is the dynamic viscosity;
c is the specific heat capacity;
T_m is the mean temperature.

The Nusselt number is calculated from equation (6).

If Nu is less than 1, then the value unity is used for Nu in equation (5).

5.3.1 ***Vertical glazing***

For vertical glazing:

A is 0,035;
n is 0,38.

5.3.2 ***Horizontal and angled glazing***

For horizontal or angled glazing and upward heat flow the heat transfer by convection is enhanced.

This effect shall be considered by substituting the following values of A and n in equation (6).

Horizontal spaces	A = 0,16	n = 0,28
Space at 45°	A = 0,10	n = 0,31

For intermediate angles linear interpolation is satisfactory.

When the direction of heat flow is downward the convection shall be considered suppressed for practical cases and Nu = 1 is substituted in equation (5).

Figure 3. Part of EN 673 on Nusselt number

The standard EN ISO 6946 also contains (implicitly) relations for the Nusselt number taking the heat flow direction into account:

$$Nu = max\left[1, \frac{d\ C_2\ \Delta T^{C_3}}{\lambda_a}\right]$$

The constant λ_a corresponds to the thermal conductivity of air at 10 °C (λ_{air} = 0.025 W/mK).

In case of Nu = 1, the gas is still.
Parameter C_2 is for:

- horizontal heat flow: 0,73
- upward heat flow: 1.14
- downward heat flow: $0.09.d^{-0.44}$

Parameter C_3 is for:

- horizontal heat flow: 1/3
- upward heat flow: 1/3
- downward heat flow: 0.187

ΔT is the temperature difference across the air space.
d is depth of the (equivalent) rectangular cavity.

The convection formulas according to EN ISO 6946 are implemented in the spreadsheet Cavity_Nusselt.xls.

Furthermore, the standard ISO 15099 contains more detailed relations for the Nusselt number.
The physical heat transfer direction is considered and therefore frames in different positions (vertical, horizontal, sloped) can be considered. Distinction between sills and jambs is made.
The convection formulas according to ISO 15099 are also implemented in the spreadsheet Cavity_Nusselt.xls.

5. Numerical simulation of detailed radiation

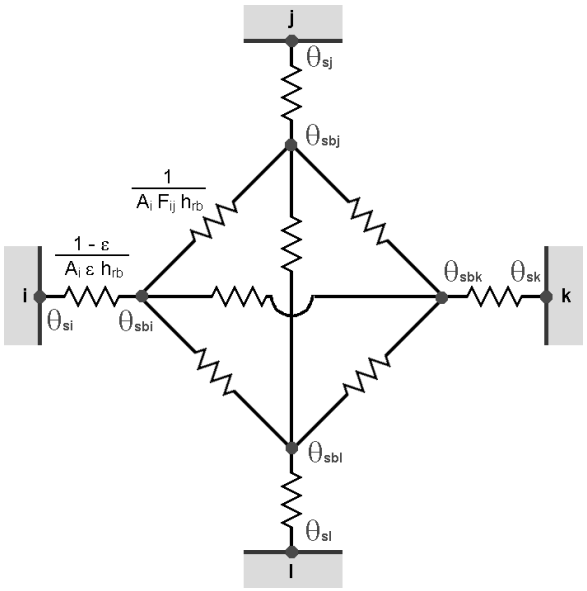


Figure 4 – Radiation thermal resistance network scheme

The radiation heat exchange between the surfaces of an enclosure can be represented by a network of resistances (Figure 4). The potentials in the surface nodes correspond to the surface temperatures (θ [°C] or T [K]).

Each surface node s_i is connected to a so-called black node s_{bi} through a resistance R_i in which a radiation heat flow Q_i occurs.

$$R_i = \frac{1-\varepsilon}{A_i \varepsilon h_{rb}} \quad \text{(Eq. 1)}$$

$$h_{rb} = \sigma \cdot (T_{sb}^2 + T_s^2) \cdot (T_{sb} + T_s) \quad \text{(Eq. 2)}$$

$$Q_i = q_i A_i = \frac{\theta_{sb} - \theta_s}{R_i} \quad \text{(Eq. 3)}$$

Q_i radiative heat flow between real grey surface i and its and black surface [W]

A surface area [m^2]

ε surface emissivity ($0 < \varepsilon < 1$)

h_{rb} black radiation heat transfer coefficient [$W/(m^2.K)$]

θ_{sb} black node temperature [°C]

θ_s surface temperature [°C]

T_{sb} absolute temperature of black node [K]

T_s absolute surface temperature [K]

Each couple of black nodes s_{bi} and s_{bj} are interconnected through a resistance R_{ij} in which a radiation heat flow Q_{ij} occurs:

$$R_{ij} = \frac{1}{A_i F_{ij} h_{rb}} \quad \text{(Eq. 4)}$$

$$h_{rb} = \sigma \cdot (T_{sbi}^2 + T_{sbj}^2) \cdot (T_{sbi} + T_{sbj}) \quad \text{(Eq. 5)}$$

$$Q_{ij} = \frac{\theta_{sbi} - \theta_{sbj}}{R_{ij}} \quad \text{(Eq. 6)}$$

F_{ij} view factor from surface i to surface j

h_{rb} black radiation heat transfer coefficient [$W/(m^2.K)$]

θ_{sbi} temperature of black node connected to surface i [°C]

θ_{sbj} temperature of black node connected to surface j [°C]

T_{sbi} absolute temperature of black node connected to surface i [K]

T_{sbj} absolute temperature of black node connected to surface j [K]

The black radiation heat transfer coefficients depend on the node temperatures. Therefore the equations are **non-linear** (requiring solving them iteratively).
However, the value of the black radiation heat transfer coefficient depends mainly on the mean temperature (see Table 1), and therefore a constant value can often be assumed without too much loss of precision. This is called **linear radiation** heat transfer.
The RADCON module allows both linear and non-linear radiation (according to a setting in the calculation parameters).

black radiation transfer h_{rb} [W/m^2K]		temperature difference between surfaces i and j $\Delta\theta_{ij}$ [°C]										
		0.00	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00
mean tempera θ_m [°C]	-20.00	3.68	3.68	3.68	3.68	3.69	3.69	3.69	3.70	3.70	3.71	3.72
	-15.00	3.90	3.90	3.90	3.91	3.91	3.91	3.92	3.92	3.93	3.93	3.94
	-10.00	4.13	4.13	4.13	4.14	4.14	4.14	4.15	4.15	4.16	4.16	4.17
	-5.00	4.37	4.37	4.37	4.38	4.38	4.38	4.39	4.39	4.40	4.40	4.41
	0.00	4.62	4.62	4.62	4.63	4.63	4.63	4.64	4.64	4.65	4.65	4.66
	5.00	4.88	4.88	4.88	4.88	4.89	4.89	4.90	4.90	4.91	4.91	4.92
	10.00	5.15	5.15	5.15	5.15	5.16	5.16	5.16	5.17	5.17	5.18	5.19
	15.00	5.43	5.43	5.43	5.43	5.43	5.44	5.44	5.45	5.45	5.46	5.47
	20.00	5.71	5.71	5.72	5.72	5.72	5.72	5.73	5.73	5.74	5.75	5.76
	25.00	6.01	6.01	6.01	6.02	6.02	6.02	6.03	6.03	6.04	6.05	6.05
	30.00	6.32	6.32	6.32	6.32	6.33	6.33	6.33	6.34	6.35	6.35	6.36
	35.00	6.64	6.64	6.64	6.64	6.64	6.65	6.65	6.66	6.66	6.67	6.68
	40.00	6.96	6.97	6.97	6.97	6.97	6.98	6.98	6.99	6.99	7.00	7.01
	45.00	7.30	7.30	7.31	7.31	7.31	7.32	7.32	7.33	7.33	7.34	7.35
	50.00	7.65	7.65	7.66	7.66	7.66	7.67	7.67	7.68	7.68	7.69	7.70

Table 1: The black radiation heat transfer coefficient

6. Implementation of radiation in European standards.

Most international standards use **linear** radiation because of its simplicity and because of the reasonable precision in case of a known mean temperature.

For example the standard EN 673 uses **linear** radiation with h_{rb} = 5.1 W/m^{2}K assuming a mean surface temperature of 10 °C. If **non-linear** radiation would be used, the glazing U-value would be a function of environmental temperatures, which would be quite unpractical. In the standard EN 673 the radiation equations as given above are implemented, but these equations are simplified because only parallel surfaces with the equal area need to be considered (factor F_{ij} = 1). Therefore, a thermal simulation of a glazing system with the Physibel software using the TRANSMAT type (RADCON module) with linear radiation is in accordance with EN 673 so far as radiation is concerned.

The standard EN ISO 10077-2:2017 allows 2 methods:

1) 'Radiosity method': using **non-linear** radiation with detailed view factors as discussed in paragraph 5. In the Physibel software this method corresponds to the TRANSMAT type (RADCON module).
2) 'Single equivalent thermal conductivity method': using **linear radiation** assuming a mean temperature of 283 K (Figure 5). Further, this method simplifies the above-mentioned radiation equations in the following way:
   - non-rectangular cavities are transformed into rectangular ones (Figure 6),
   - for the transformed cavity, a simplified form factor formula is used (Figure 5).

   It should be stressed that the standard is unclear on this method on how to apply emissivities different to 0.9 (the default emissivity) in case of non-rectangular cavities[1]. In the Physibel software this method corresponds to the EQUIMAT type (with standard EN 10077).

The radiosity method is physically more precise as the simplifications mentioned are not considered, and therefore its quality can be considered as superior.

6.4.3.4.3 Radiative heat transfer coefficient

$$h_r = 4\sigma T_m^3 \, E \, F \qquad (19)$$

where

σ is the Stefan-Boltzmann constant equal to $5{,}67 \times 10^{-8}$ W/(m^2·K^4);

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

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

ε_1 and ε_2 are the emissivities of the surfaces indicated in Figure 14.

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

$$h_r = C_4 \left(1 + \sqrt{1 + (d/b)^2} - d/b\right) \qquad (20)$$

where C_4 = 2,11 W/(m^2·K).

[1] See also Knowledge base document 'AIR CAVITIES WITHIN EN ISO 10077-2: RADIOSITY METHOD vs. SINGLE EQUIVALENT THERMAL CONDUCTIVITY METHOD.pdf' for more information on this topic.

Figure 5. Part of EN ISO 10077-2 on radiation ('single equivalent thermal conductivity' method)

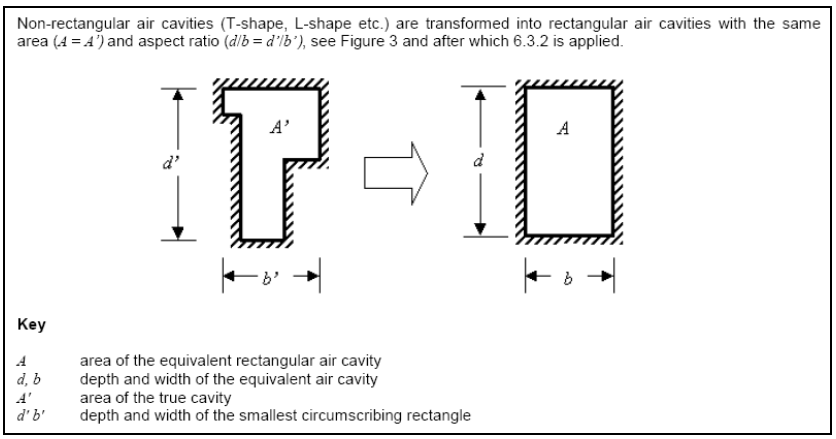


Figure 6. Part of EN ISO 10077-2 on transformation of non-rectangular into rectangular cavities ('single equivalent thermal conductivity' method)

The standard EN ISO 6946 uses a similar approach as the simplified method of EN ISO 10077-2 ('single equivalent thermal conductivity' method) with **linear radiation** with a mean temperature of 283K (10°C) and non-rectangular cavities transformed into rectangular one (as presented in Figure 6). However, the radiative heat transfer coefficient h_r is calculated slightly different (Figure 7). Appendix A illustrates the difference between EN ISO 10077-2 and EN ISO 6946 with an example in BISCO.

In the Physibel software this method corresponds to the EQUIMAT type (with standard EN 6946).

The thermal resistance of the airspace, R_a, is given by:

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

where

R_a is the thermal resistance of the airspace, in m²·K/W.

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{\left(1 + \sqrt{1 + d^2 / b^2} - d / b\right)}}$$

where

h_r is the radiative coefficient, in W/(m²·K);

h_{r0} is the radiative coefficient for a black-body surface (see C.1), in W/(m²·K);

d is the thickness of the airspace, in m;

b is the width of the airspace, in m;

$\varepsilon_1, \varepsilon_2$ are the hemispherical emissivities of the surfaces on the warm and cold faces of the airspace.

Figure 7 - Part of EN ISO 6946 on radiation

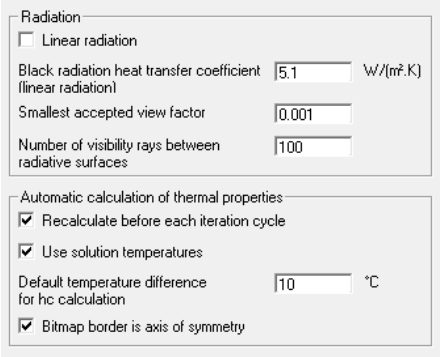
The standard ISO 15099 applies a simplified approach regarding radiation, similar to the 'single equivalent thermal conductivity' method of EN ISO 10077-2 described above.

7. Implementation of detailed radiation in the Physibel software (TRANSMAT).

To simulate non-ventilated gas cavities physically more correctly the RADCON type TRANSMAT can be used as instead of EQUIMAT.

Concerning the radiation, the infrared emissivity of each material (surface) needs to be specified in the Colours windows. The default value is e = 0.9.

To be in line with the 'radiosity' method of EN ISO 10077-2: select within the dialog box Calculation parameters 1) the non-linear radiation model (uncheck 'Linear radiation') and 2) check 'recalculate before each iteration cycle and 3) check 'Use solution temperature'.



For compliance with EN 673, it is recommended to select in the calculation parameters, the linear radiation model with a black radiation heat transfer coefficient h_{rb} = 5.1 W/m2K. An alternative is to use the non-linear model in combination with external / internal temperatures of 0 °C / 20 °C (mean value 10°C).

EN ISO 6946 in fact does not allow to use detailed radiation based on view factors (see above). However, when a more detailed (non-normative) calculation with the convection formulas according to EN ISO 6946 but with detailed radiation is required the type TRANSMAT with standard NIHIL can be used.

Concerning the conduction or convection (with RADCON) the effective thermal conductivity of the gas needs to be defined: $\lambda_{gas\text{-}eff}$ = Nu λ_{gas}. The gas thermal conductivity λ_{gas} and the Nusselt number Nu can be derived from textbooks or standards, e.g EN 673, EN ISO 10077-2 (Cavity_Nusselt.xls).

8. References

EN ISO 10077-2:2017: Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames

ISO 15099:2003: Thermal performance of windows, doors and shading devices — Detailed calculations

EN 673:2011: Glass in building – Determination of thermal transmittance (U value) – Calculation method

EN ISO 6946:2017: Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods

9. APPENDIX A: EXAMPLE

BISCO data

cavity_10077_EQUIMAT.bsc
cavity_6946_EQUIMAT.bsc
cavity_10077_TRANSMAT.bsc
cavity_6946_TRANSMAT.bsc

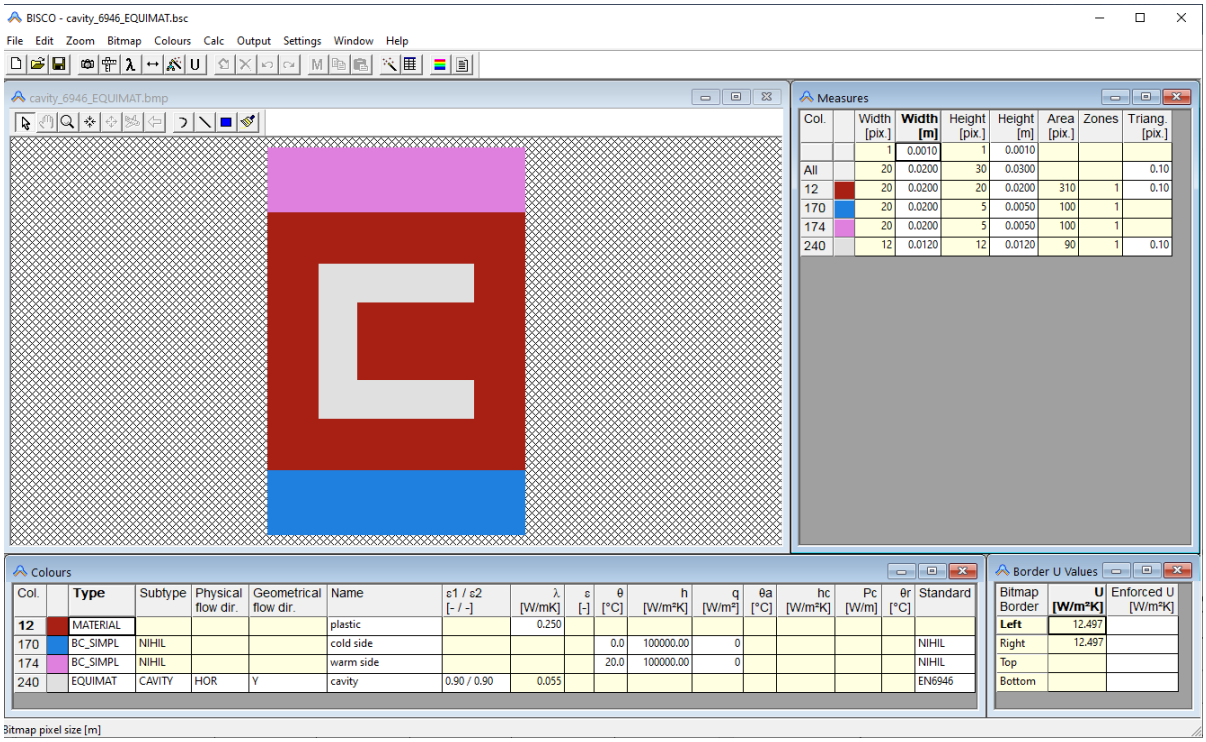


Figure 8 - C-shaped simulated cavity in BISCO

A simple C-shaped non-ventilated cavity is simulated in BISCO both according to EN ISO 10077-2 and to EN ISO 6946 with the EQUIMAT type (single equivalent thermal conductivity method) and the TRANSMAT type of the RADCON module (radiosity method).

The results, presented in Table 2, show in the first row (type EQUIMAT) a small difference between both standards. This related to the different formulation of simplified radiation in these standards (see Figure 5 vs. Figure 7).
Further this table illustrates a (significant) lower heat flow between first and second row (EQUIMAT vs. TRANSMAT). This is because for type EQUIMAT the radiative heat exchange is overestimated (by assuming radiative heat exchange in an equivalent rectangular cavity instead of taking the real cavity's geometry into account).

Table 2 – heat flow (Q) calculated with BISCO

	Q (W/m)	
	EN ISO 10077-2	EN ISO 6946
EQUIMAT (λ_{eq} method)	3.457 (λ_{eq}=0.053 W/mK)	3.480 (λ_{eq}=0.055 W/mK)
TRANSMAT (radiosity method, non-linear radiation)	3.243 (λ_{air}=0.025 W/mK)	3.243 (λ_{air}=0.025 W/mK)

10. APPENDIX B: convection formulas in EN ISO 10077 and EN ISO 6946

6.4.3.4.2 Convective heat transfer coefficient

The convective heat transfer coefficient, h_c, is

if $b < 5$ mm,

$$h_c = \frac{C_1}{d}$$

where

$C_1 = 0{,}025$ W/(m·K);

otherwise

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

where

C_1 = 0,025 W/(m·K);

C_2 = 0,73 W/(m²·K⁴/³);

ΔT is the maximum surface temperature difference in the cavity.

If no other information is available, use $\Delta T = 10$ K for which

$$h_c = \max\left\{\frac{C_1}{d}; C_3\right\}$$

where

C_1 = 0,025 W/(m·K);

C_3 = 1,57 W/(m²·K).

Figure 9. Part of EN ISO 10077-2 on convection ('single equivalent thermal conductivity' method)

Table D.2 — Convective heat transfer coefficient for temperature difference $\Delta T > 5$ K

Direction of heat flow	h_a[a] W/(m²·K)
Horizontal ($\alpha = 90°$)	$0,73 \times (\Delta T)^{1/3}$
Upwards ($\alpha = 0°$)	$1,14 \times (\Delta T)^{1/3}$
Downwards	$0,09 \times (\Delta T)^{0,187}\ d^{-0,44}$

[a] Or, if larger than value from table, $0{,}025/d$.

Figure 10. Part of EN ISO 6946 on convection (convective heat transfer coefficient)