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EVALUATION OF THE THERMAL PART OF THE CODE SAFIR BY COMPARISON WITH THE CODE TASEF.

D. Pintea¹, J. M. Franssen²

SUMMARY

A thorough analysis has been performed to evaluate SAFIR release 1.3, through a set of examples presented by Wickström and Borås in the paper "An evaluation scheme of computer codes for calculating temperature in fire exposed structures – two dimensional analysis". The results of SAFIR 1.3 have been compared with the results obtained by TASEF, or to analytical solution when available. The results of SAFIR 1.3 compare well with the analytical solutions and, with few exceptions, with those of TASEF.

INTRODUCTION

Most of the cases concern a square 2D section, a quarter of which is analysed using a refining mesh of 4, 16, 64 or 256 elements, see Figure 1 for the 16 elements mesh. Only some of the analysed cases have constant thermal properties and an analytical solution. During the first comparisons, some differences appeared between SAFIR 1.3 and TASEF results, specially with coarse discretisations, with SAFIR 1.3 leading to more severe spatial oscillations. This behaviour could be traced to the fact that the capacity matrix in SAFIR 1.3 results directly from the numerical integration of the shape functions and has therefore a complete pattern, with diagonal terms. The results obtained with this complete capacity matrix are labelled as SAFIR 1.3 in the text. The absence of spatial oscillations in the TASEF results are probably due to the fact that a diagonal capacity matrix is used in this code. In order to evaluate the effect of this approximation, the possibility has been introduced in SAFIR 1.3 to use a diagonal capacity matrix obtained by equation 1.

$$C_d(i,i) = \frac{C(i,i) \sum_{i=1}^N \sum_{j=1}^N C(i,j)}{\sum_{i=1}^N C(i,i)} \quad (1)$$

$$C_d(i,j) = 0 ; i \neq j.$$

with C the complete matrix,
C_d the diagonal matrix,
N number of nodes of the element.

The results obtained with this scheme are labelled as SAFIR diagonal in the text.

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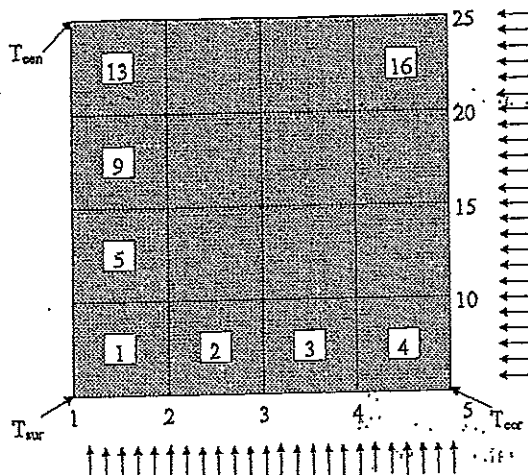


Figure 1 : 16 elements mesh

LEVEL 1- COMPARISON AGAINST ANALYTICAL RESULTS

The considered cross section is a square of $2l$ by $2l$, therefore only a quadrant was modelled due to the symmetry. Constant material properties were considered:

- half side length $l = 1$ m
- conductivity $k = 1$ W/mK
- specific heat $c = 1$ J/kgK
- density $\rho = 1$ kg/m³

The square cross section initially at 1000°C is afterward subjected to a constant ambient gas temperature of $T=0^\circ\text{C}$ during 1 second. In this case the heat transfer at the boundary is given by:

$$Q = h(T_g - T_s) \quad (2)$$

with h – the net heat flux, T_g , T_s – the gas and surface temperature.

In all four cases (the meshes of 4, 16, 64 and 256 elements) 2000 time steps of 0.0005 seconds were used and two Gauss points in each direction of the finite element. Reasonable solutions can be obtained with a larger time step, but this small value is the one beyond which the results are not modified by further refining of the time step. The temperatures calculated in the centre of the square are listed in Table 1, as well as the analytical solution.

The graphical presentation of the temperature in the centre as a function of time for different number of elements is displayed in Figure 2.

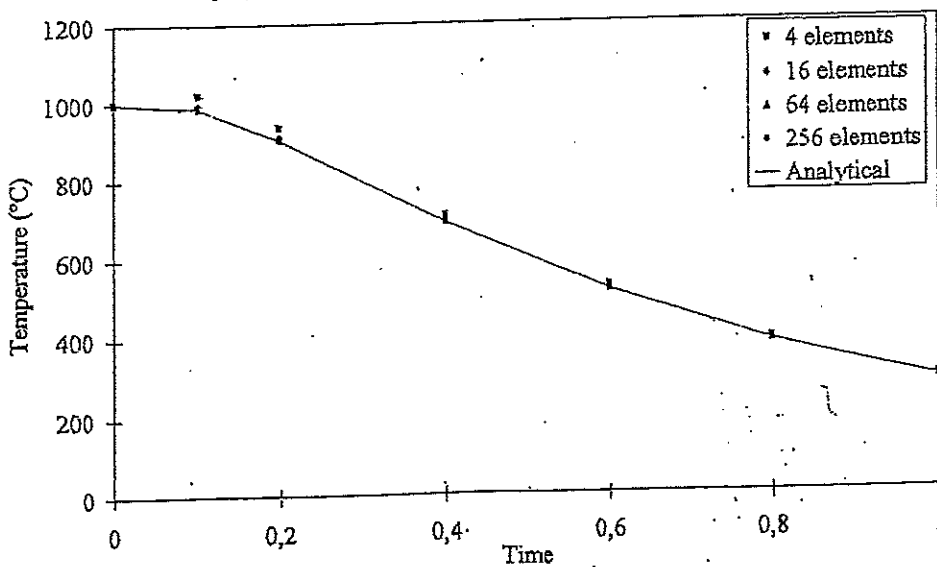
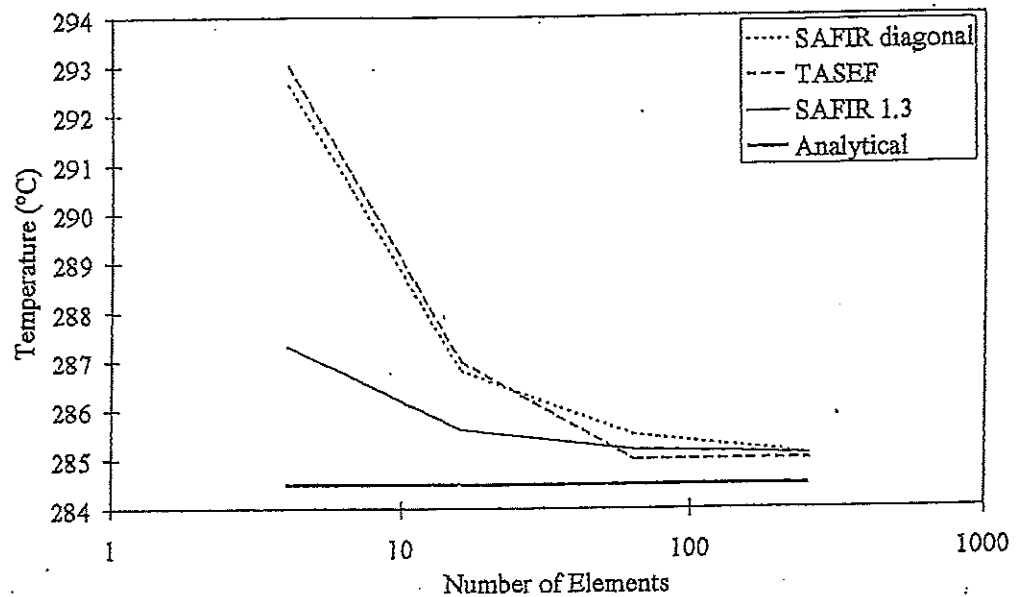


Figure 2 : SAFIR 1.3 results against analytical solution

Table 1 : *SAFIR 1.3* results against analytical solution

Time	4 elements	16 elements	64 elements	256 elements	Analytical
0.0	1000	1000	1000	1000	1000
0.1	1020.8	993.8	987.9	986.5	986.4
0.2	937.0	911.9	905.6	904.1	903.8
0.4	707.2	694.7	691.5	690.7	690.2
0.6	524.1	517.3	515.6	515.2	514.7
0.8	388.1	384.4	383.5	383.3	382.7
1.0	287.3	285.6	285.2	285.1	284.5

An extremely good match with the analytical solution can be noticed even for the 4 elements mesh. If a comparison is made for the results after 1 second between *SAFIR 1.3*, *SAFIR diagonal* and *TASEF* (Figure 3), it can be noticed that *SAFIR 1.3* converges faster toward the analytical solution when the complete capacity matrix is used. The spatial oscillation is present on Figure 2 only during the first 0.1 second and for a very coarse mesh (temperature at 0.1 sec greater than 1000°C). The *SAFIR diagonal* and *TASEF* produce virtually the same results.

Figure 3 Temperature at center point T_{cen} after 1 minute vs. the number of elements

LEVEL 2 - SIMPLE NON-LINEAR BOUNDARY PROBLEM

In the second case, the same cross section has been considered, but with a concrete type material, having the following properties:

half side length	$l = 0.10 \text{ m}$
conductivity	$k = 1 \text{ W/mK}$
specific heat	$c = 1000 \text{ J/kgK}$
density	$\rho = 2400 \text{ kg/m}^3$
relative emissivity	$\epsilon = 0.8$
convection coefficient	$\alpha = 10 \text{ W/m}^2\text{K}^4$

In this case the heat transfer Q by radiation and convection to the boundaries is:

$$Q = \epsilon \sigma (T_s^4 - T_i^4) + \alpha (T_s - T_i) \quad (2)$$

The initial temperature was 0°C and the cross section is afterward subjected to a constant temperature of 1000°C. The temperatures were calculated at 30, 60, 90, 120, 150 and 180 minutes, using a constant time step of 5 seconds. The center temperature plot after 30 minutes is displayed in Figure 4 and after three hours in Figure 5.

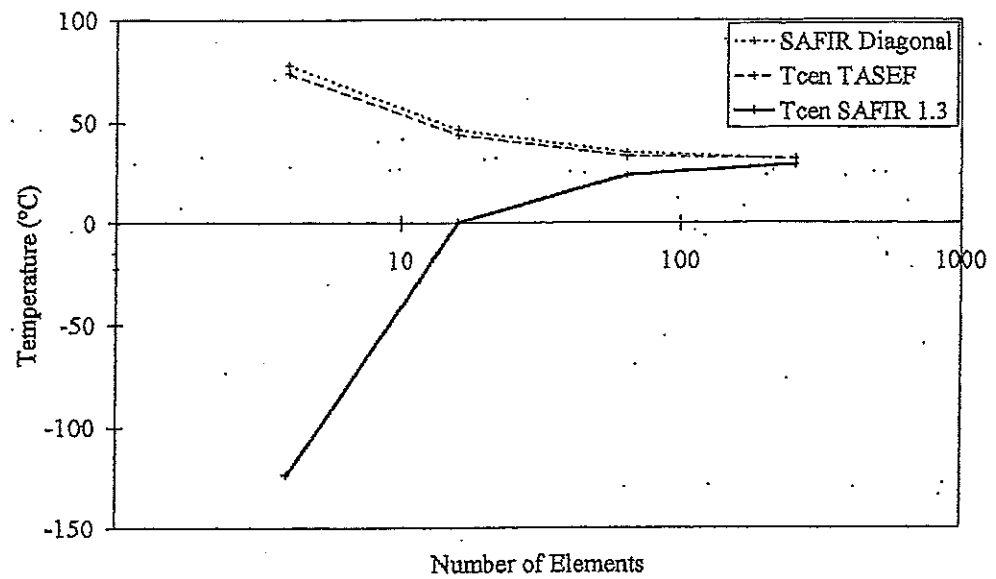


Figure 4 Center temperature after 30 minutes vs. number of elements

It can again be noticed that the spatial oscillations appear during the first minutes and with coarse meshes, see Figure 4, but that the convergence with the number of elements is faster if the results after a longer duration are considered, see Figure 5.

As an example of convergence of the solution with the time step, a study was carried out with different time steps on the 16 elements model. The nodal temperatures at center, surface and corner were computed after three hours of exposure, this time to the ISO curve, using different time steps. The plot of the center temperature after three hours is displayed in Figure 6.

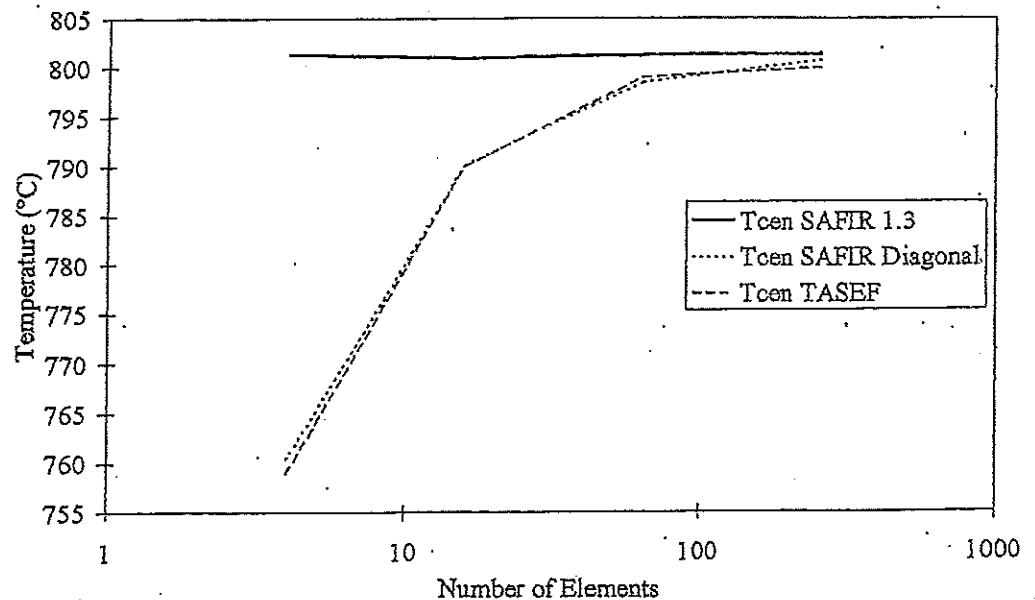


Figure 5 Center temperature after 3 hours vs. number of elements

It can be noticed that *SAFIR 1.3* has a faster convergence toward the solution than *TASEF*. This is probably due to the fact that *SAFIR* uses an implicit time integration scheme whereas *TASEF* uses an explicit scheme. Each time step cost therefore less time for *TASEF* than for *SAFIR* and Figure 6 does not allow to draw any conclusion on the total CPU time required by the two codes to solve the problem. The required CPU time is anyway very short for the kind of 2D problems analyzed in this

paper, in the order of magnitude of some tens of seconds.

A difference between the two temperature solutions was detected, due to the fact that in the *TASEF* examples the starting temperature was 0°C, while *SAFIR 1.3* uses the standard ISO 834 temperature curve, starting from the room temperature of 20°C.

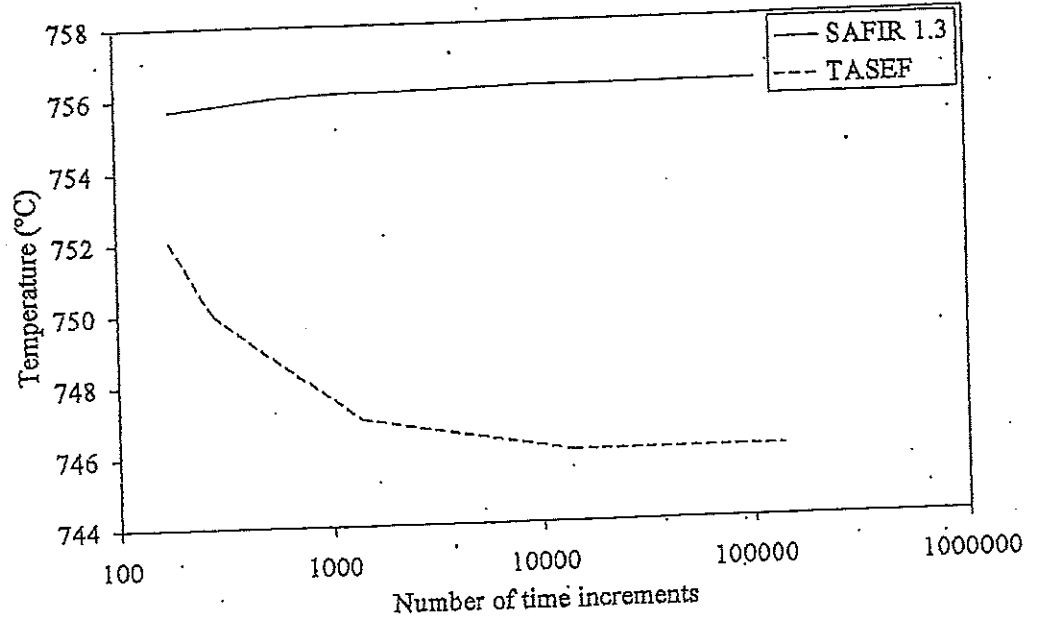


Figure 6 : Center temperature after 3 hours of ISO exposure vs number of time increments

The same example, but with a temperature dependent thermal conductivity, was analyzed as LEVEL 3 and lead to the same kind of conclusions as the LEVEL 2 example. The following values define the 3 points on which the bi-linear variation is based :

$$\begin{aligned} k(T=0) &= 1.5 \text{ W/mK} \\ k(T=200) &= 0.7 \text{ W/mK} \\ k(T=1000) &= 0.5 \text{ W/mK} \end{aligned}$$

LEVEL 4 - LATENT HEAT DUE TO WATER CONTENT

Level 4 has the same characteristics as level 3 but a water content of 5% by weight was considered. After 30 minutes of ISO fire exposure the results for the centre temperature are very similar for *SAFIR diagonal* and *TASEF*, see (Figure 7), because here the initial temperature of the ISO curve was set to 0°C in *SAFIR diagonal*. After 30 minutes of exposure, the nodal temperatures in the majority of nodes are less than 100°C.

After three hours of ISO fire exposure (Figure 8) a larger difference has been detected due to two reasons.

The first one is that *TASEF* considers the water evaporation in the range 100°C to 120°C, while in *SAFIR 1.3* and *SAFIR diagonal* the temperature range for water evaporation is between 100°C to 200°C (as stated in EUROCODE).

The second reason could lead in the way that the two programs handle the water vapour. *SAFIR* considers that after the 200°C the water has been evaporated and that the vapour has left the section, and no further energy is consumed. This situation corresponds with what is observed during tests on unconfined concrete assemblies. The colder results of *TASEF* may be due (although it has to be confirmed) to the fact that the water vapour remains in the section after evaporation and consumes energy to be heated. This corresponds to the situation of confined concrete, like in concrete filled

hollow sections for example.

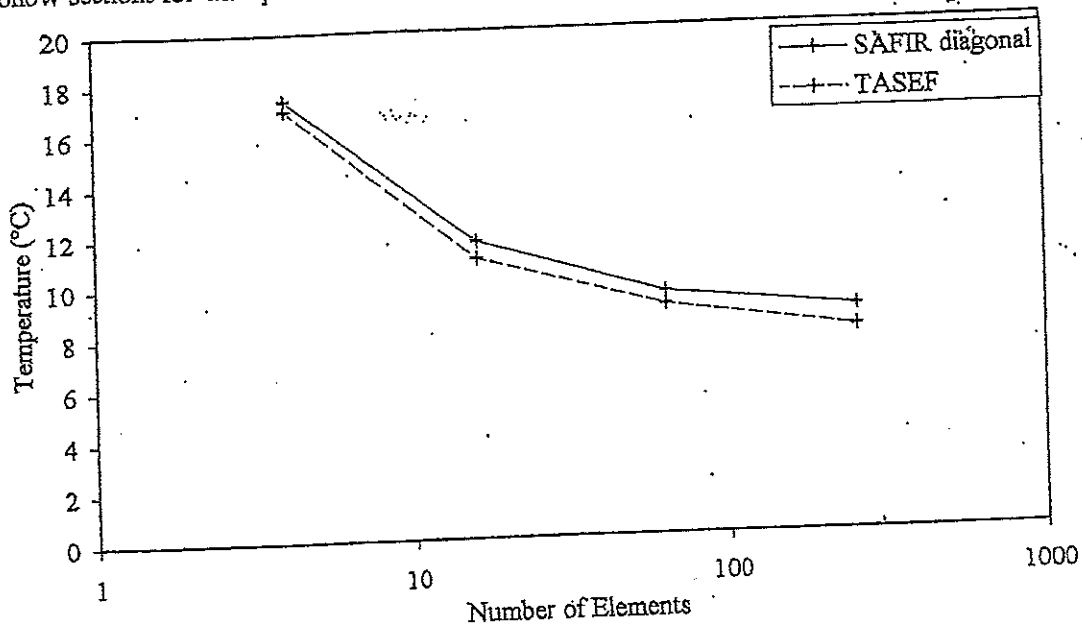


Figure 7 : Center temperature after 30 minutes ISO fire exposure vs. number of elements
Other example were analyzed, in which the square core is surrounded by a 10 mm steel tube. The core is made of the same wet concrete material in LEVEL 5, and of mineral wool in LEVEL 6. Similar conclusions as in the previous examples could be drawn.

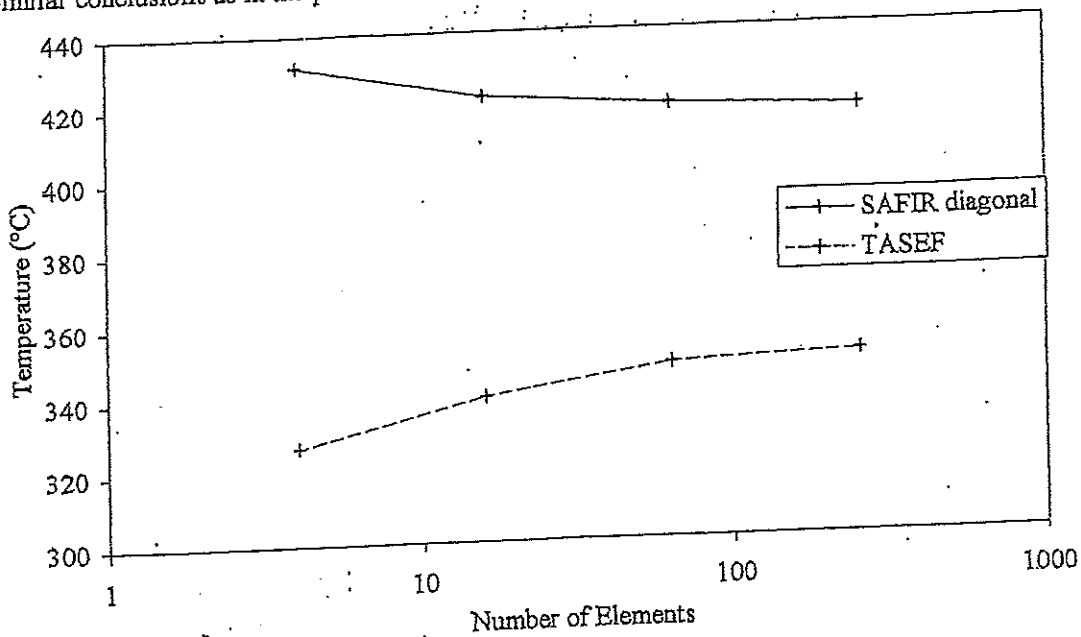


Figure 8 Center temperature after 3 hours ISO fire exposure vs. number of elements
LEVEL 7 - HEAT TRANSFER IN INTERIOR CAVITIES

In the Level 7 example the problem of heat transfer in internal cavities was studied through two sets of case studies:

- a. a one dimensional heat transfer problem
- b. a two dimensional heat transfer problem.

In both cases a rectangle of 110 by 20 mm with 5 mm thick wall was considered, see Figure 9, with the following thermal properties in the walls:

conductivity $k = 1 \text{ W/mK}$
 specific heat $c = 1000 \text{ J/kgK}$
 density $\rho = 1000 \text{ kg/m}^3$

In the first one dimensional problem, the initial temperature is 0°C and suddenly increased to 1000°C on side A, while side B is maintained at 0°C . Sides C and D are perfectly insulated (adiabatic boundaries). In this case the heat is transferred by conduction through the lower and upper wall, and by radiation through the void. The heat transfer through the left and right walls are negligible. Three meshes were used with various number of elements along the 100 mm walls, a two elements mesh, a four elements mesh and an eight elements mesh, see Figure 9.

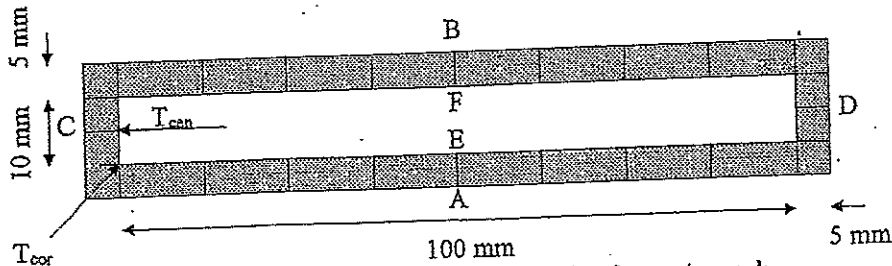


Figure 9 : Structure with a void, eight elements mesh.

The results of the calculations are presented in Table 2. A very good match between analytical results and the results from both programs can be noticed.

Table 2 : Void problem SAFIR 1.3 vs. TASEF and Analytical solution

Number of Elements	Side E	Side E	Side E	Side F
	SAFIR 1.3	TASEF	SAFIR 1.3	TASEF
2	786.7	789	195.8	198
4	774.3	774	228.9	229
8	778.8	779	219.3	220
Analytical	779.4		220.6	

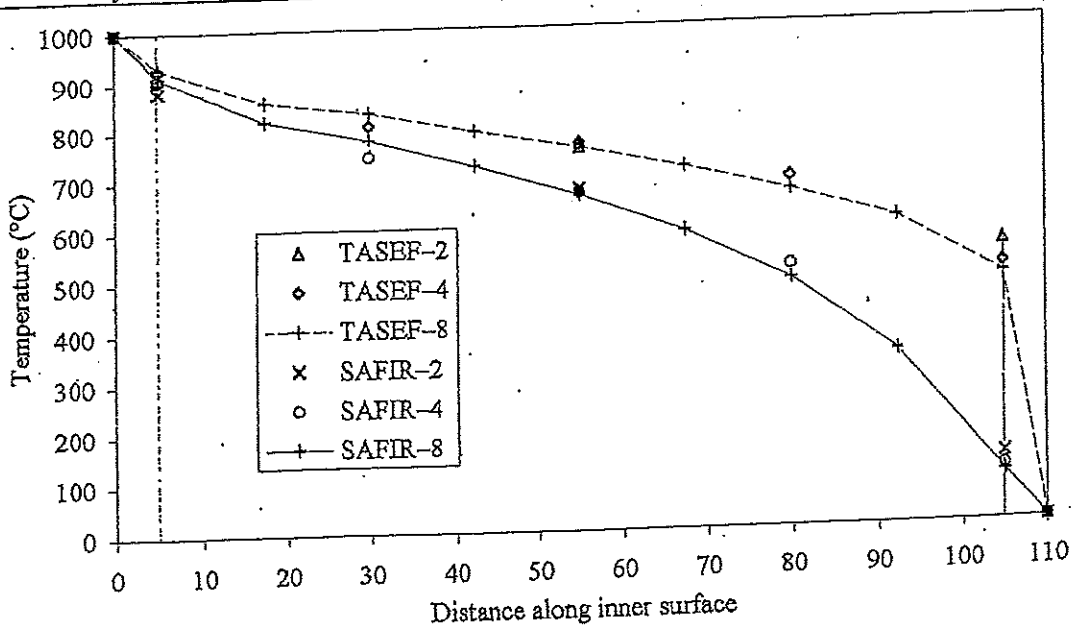


Figure 10 Temperature after 60 minutes along the inner surface of the void

The second problem was a two dimensional problem. In this case sides A and B were considered the adiabatic boundaries, the nodes on side C have their temperature suddenly increased to 1000°C while the nodes on side D are kept at 0°C. Due to the low thermal conductivity of the material in the walls the heat transfer by conduction in the long sides is negligible and the thermal energy is mainly transferred from the warm boundary to the cool one by radiation.

Figure 10 presents the temperature distribution along side E (or F) after 60 minutes of exposure for different discretisations.

Although both programs show a clear convergence as the number of elements is increased, convergence is toward significantly different solutions. It can be observed that, according to *SAFIR*, the temperature drop in the 5 mm walls is almost the same in the left and in the right wall, roughly 90°C, which would be expected because the thermal resistance of both walls is the same and the situation after 60 minutes has reached a steady state condition. The detailed analysis of the *TASEF* results confirm that this program has also virtually reached a steady state condition after 60 minutes, but no explanation could be found by the authors why the temperature drop in the walls is so different. This may be due to a misunderstanding by the authors in the definition of the example, perhaps in the boundary conditions.

CONCLUSIONS

Different examples have been analyzed and comparisons have been made between the results of the computer program *SAFIR* developed at the University of Liège, those of the program *TASEF* developed by Wickström and analytical results, when available.

Both programs show good convergence properties toward exact solutions, when available, or toward the solutions which are most of the time very close to each others. Limited differences have been found and attributed to slightly different formulations of the capacity matrix, to different time integration scheme, or to different definition of the initial temperature for the ISO curve. More significant difference has been observed when evaporation of moisture is involved, probably due to different hypotheses with regard to the behavior of the vapor after it has been created. In one single case involving radiation in a 2D internal cavity, severe differences have been noticed with no explanation found by the authors. This point could probably be solved by deeper contact between the 2 groups of developers.

The kind of exercise described in this paper as well as in the original paper of Wickström is highly valuable for the validation of a thermal computer program, and perhaps even more for the experience it gives to the users performing the exercise because they really learn how their code reacts to different variations of the input parameters. In this sense, the initiative of Wickström who built this series of test cases is highly valuable and has to be recognized. It is hoped that further developers or users will do the exercise in the future.

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1. E. Sterner, U. Wickström, *TASEF - Temperature Analysis of Structures Exposed to Fire - User's Manual*, Borås, SP Report 1990:05.
2. J. M. Franssen - Program *SAFIR* ver. 1.3, *User's Manual*, University of Liège, Dec 1996.