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Analysis of heat transfer mechanisms on hollow concrete masonry units under standardized fire conditions

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Abstract. Concrete structural masonry is widely used on high-rise buildings in Brazil. Through the past decades some effort on research in the topic have been made but there is still a need for research on masonry fire safety. This is reflected in the lack of a Brazilian National Standard regarding masonry under fire conditions. In this context, it is of interest to assess the influence of the cavities present in concrete masonry units (CMU) on thermal behavior. This paper uses ABAQUS software to perform numerical simulations and assess the relative importance of radiation and convection inside cavities in concrete masonry units under standard ISO 834-1:1999 fire condition. Radiation between cavity surfaces and fluid convection are considered using coupled fluid-solid transient heat transfer analysis. The simulation procedure is validated using available experimental data on literature. After validated, parametric analysis is performed through simulations using different concrete emissivity values on cavities. Results show that when concrete cavity surface has high emissivity value the radiation dominates the solution and air flow has negligible effect in the heat transfer inside the cavities.

Keywords: fire safety, concrete masonry, heat transfer

1 Introduction

The ambient on fire transfers heat to structures mainly through convection and radiation while heat transfer within the structure occurs mainly due to conduction. However, it is quite commom that masonry units have internal cavities, thus, there is also heat transfer by radiation and convection inside the cavities. Some authors, such as Russo and Sciarretta [1] and Carvalho [2], use an equivalent thermal conductivity for the cavity air or the masonry material looking forward a good fit between simulation and experimental data without explicitly considering convection and radiation in the cavity. The construction of simplified models is desirable for practical engineering, however, careful assessment must be made about the assumptions in detailed finite element simulations. Although the results of masonry insulation time can easily meet the experimental data, the temperature field can be different due to absence of radiation and convection. This is particularly important in thermostructural analysis when the temperature field influences the failure mechanism. Rodovalho and Corrêa [3] considers the fluid domain inside the CMU's cavities in their thermal simulations under standard fire conditions. However, air thermal conductivity is increased to compensate the absence of radiation consideration. Besides, results do not seem to capture the behavior of natural convection.

This paper contributes to the topic addressing it through a 3D coupled fluid-solid transient thermal simulation. Furthermore, heat transfer by radiation is considered inside the cavities. This allows the assessment of each heat transfer mechanism in the overall results.

2 Heat transfer on structural fire safety

The onset and development of fire in a building is rather a complex process. The temperature field that building components are subjected are uncertain and depends, for example, on combustible type and ventilation conditions [4, 5]. Fire dynamics is the branch that works in modeling and understanding natural fire scenario. However, the fire resistance assessment of building components requires standard verification procedures. Thus, standards for fire testing such as ISO 834-1:1999 [6] are widely used. This standard adopts a temperature-time curve for furnace gases that have rapid heating regime and absence of a cooling phase. The rationale behind this is that critical condition happens when the fire is fully developed after the environment is engulfed in flames in a sudden event called flash-over. The tests are carried out in furnaces where the structure is in contact with hot air, thus, heat transfer occurs through radiation from furnace walls and convection.

Purkiss and Li [4] point the 3 failures criteria evaluated on furnace tests: load bearing capacity, insulation and integrity. This means, respectively, that for an required test duration the building component must have enough strength to support the applied load, the temperature on the unexposed face must remain low enough and the flames can not reach the unexposed face through any failure point of the component. In this way, building components can be classified according to their fire resistance and applied to buildings of different fire resistance requirement.

Furnace tests are the preferred source of fire rating but these tests are expensive. Thus, simulation is an important tool for studying structures under fire condition. Performing simulations of structures under standardized fire have two aspects: heat transfer simulation and structural simulation. For instance, insulation criteria of a wall or slab can be evaluated using heat transfer simulation. Whereas CFD (Computational Fluid Dynamics) should be used on simulation of natural fire conditions, the simulation of furnace test conditions usually does not require it. Instead, boundary conditions on the structure domain are defined to represent the heating regime applied by the furnace. The heat transfer coefficients used in the boundary conditions are usually taken from structural design codes which were calibrated using furnace tests. Then, the temperature field in the solid can be estimated through the Fourier's law which can be solved using finite element method.

On the other hand, temperature rise degrades material and impacts the structure strength [4, 5]. Estimation of resistance can be done using an effective section of the structure that remains at the temperature level which the material still resists. This simplified approach is available in structural design codes [5, 8]. However, a detailed simulation can be carried out where temperature field calculated in the heat transfer analysis is exported to the structural simulation.Then, it considers material's properties dependent on the temperature. Note that, in either approach, heat transfer analysis is a key-factor in the accuracy of load-bearing capacity evaluation.

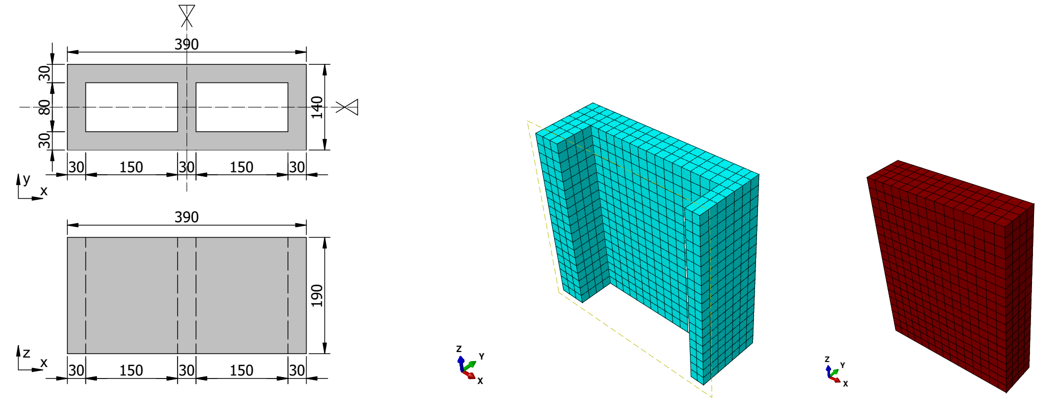
Structural concrete masonry walls, such as slabs, have structural and compartmentation functions. This means that all the 3 failure criteria must be evaluated carefully. Concrete masonry units (CMU) usually have cavities which play a role in the heat transfer within the walls. Rigorous simulation would consider proper mechanisms for heat transfer inside the cavity. Radiation mechanism is described as the heat transfer process between surfaces through electromagnetic waves which do not need a medium to propagate. This mechanism depends on the surface emissivity and the view factor between the surfaces. Emissivity describes the energy emission power compared to a black body emitter and the view factor is calculated based on the relative position of the surfaces. On the other hand, convection mechanism is the heat transfer between a solid surface and adjacent fluid. In this case, heat transfer is influenced by the interaction of fluid motion and conduction. Natural or free convection occurs when the fluid motion is induced by the heat transfer itself because temperature rise makes the fluid expand and move upwards [7, 10].

Therefore, rigorous simulation of the cavity requires two non-conventional procedure in fire simulation of structural elements: radiation exchange between cavity surfaces and CFD analysis of air inside the cavity. Besides, the fluid and solid simulation must be coupled in a way that heat exchange can take place. Implementation of this numerical procedure is a research topic itself that is not addressed in this work. We use the finite element software ABAQUS to perform the coupled simulation which is described in detail in the next section.

3 Simulation setup

Dupim [9] conducted tests on CMUs, 2-block prisms and small walls exposed to fire in a horizontal furnace following ISO 834-1:1999 [6] gas temperature. We use its experimental data from isolated blocks and 2-block prisms to validate our thermal simulation that is performed in the software ABAQUS. The model consist in a hollow concrete masonry unit of the 150 mm x 400 mm group that is exposed to standard fire on all its sides, i.e. the face shells and exterior webs. Figure 1a shows that a simplified prismatic shape is used, it approximates the true truncated cone shape of the cavities. Besides that, the double symmetry of geometry and thermal boundary conditions are considered, thus, only a quarter of the geometry is meshed using 20-node quadratic hexahedron as shown in Fig. 1b. On the other hand, the cavity fluid domain is meshed using 10 mm side 8-node linear hexahedron as shown in Fig. 1c.

Concrete thermal conductivity, density and specific heat are temperature dependent and they are estimated based on EN 1992-1-2:2004 [8]. Concrete thermal behavior depends on its moisture content, thus, 1,5% moisture content in mass is assumed in the simulation. The model uses the specific heat of dry concrete plus the latent heat of water content vaporization in the 100°C to 115°C interval according to Wickström [10] approach.



(a) Simplified geometry dimensions (mm)

(b) Block mesh considering double symmetry

(c) Cavity fluid mesh considering double symmetry

Figure 1. CMU geometry and model's mesh

Air thermal conductivity, specific heat and dynamic viscosity are also functions of temperature and they are taken as the data presented by Çengel and Cimbala [11]. Air thermal expansion coefficient, α, is calculated considering air as an ideal gas. Then, $\alpha = 1/T$ where T is the absolute temperature in Kelvin.

The air temperature on the furnace follows ISO 834-1:1999 [6], that is $T(t) = 345 \log(8t + 1) + 20$ where T is temperature in °C and t is time in minutes. That means that exterior block surfaces perpendicular to x-axis and y-axis (see Fig. 1a) are exposed to hot air. The heat transfer on this boundary occurs through convection and radiation which can be estimated using Newton's law of cooling and Stefan-Boltzmann law, respectively.

The heat transfer coefficients of the surfaces exposed to fire are chosen based on structural fire safety specification in design codes. A constant convective heat transfer coefficient, $\alpha_c = 25$ W/m²K, is used following recommendation of EN 1991-1-2:2002 [12]. The emissivity of concrete surface is taken as $\varepsilon = 0{,}7$ according to EN 1992-1-2:2004 [8]. The surfaces in the symmetry planes are adiabatic as well as the top and bottom surfaces (perpendicular do the z-axis).

Two boundary conditions are used on cavity surfaces: cavity radiation and coupling to fluid simulation. The heat transfer from radiation between the cavity surfaces can be calculated in the simulation assuming diffuse reflection, using the surface emissivity and the calculated view factors of each cavity surface element. Cavity symmetry property is used in the block symmetry plane that crosses the cavity. Total reflection ($\varepsilon = 0$) is assumed on top and bottom face (perpendicular to z-axis) of the cavity. This assumption is reasonable for the isolated CMUs tested which have the top and bottom insulated with fiberglass wool and also for walls that have vertical cavity continuity and uniform heating regime. It must be remembered that the emissivity depends on surface characteristics but also on the temperature and wavelength of the electromagnetic waves [7]. The constant emissivity value in EN 1992-1-2:2004 [8] is calibrated for concrete surface exposed to fully developed fire in a furnace. Thus, this value can not be assumed as a suitable value for emissivity inside the cavity. Considering that, simulations are performed using three cases: $\varepsilon = 0.95$, $\varepsilon = 0.70$ and $\varepsilon = 0.50$. Then, results are compared to assess the sensibility of them to emissivity value.

Air inside the cavity is considered through a coupled fluid-solid thermal analysis. Incompressible flow is assumed and thermal boundary conditions are coupled to the results on solid surfaces of the cavity. Top and bottom faces (perpendicular to z-axis) and cavity surfaces are assigned no-slip and no penetration kinematic boundary conditions. It must be highlighted that this simulation does not include the effects of solid expansion due to temperature rise. In addition, the velocity in the symmetry plane is considered to be 0 in the y-direction. Incompressible flow analysis needs a point of reference pressure, then it is chosen arbitrarily as a corner point in the cavity fluid domain. Natural convection due to fluid thermal expansion is possible using Boussinesq approximation. Thus,the magnitude and direction of gravity's acceleration are specified.

The total time of analysis is chosen according to the experimental data used in the validation, in any case the furnace temperature follows ISO 834-1:1999 equation. The conjugate heat-transfer simulation follows a sequentially staggered methodology which means that solid and fluid equations are solved independently and results at interface are exchanged after a converged time increment. The solid solver exports temperature at the interface to the CFD solver and the CFD solver exports the heat flux in the interface to the solid solver. Time incrementation setup is done in the fluid and solid model, then, the software tries to match the models' time increments following both the rules to achieve the coupled simulation. Fluid analysis is done using implicit Backward-Euler time integration which is unconditionally stable. That way, it is possible to use automatic time incrementation that exceeds the Courant-Friedrichs-Lewy (CFL) stability condition that is applied to explicit integration. In the simulations performed, it was possible to get convergent analysis using initial time increment of 1 s and subsequent increments calculated considering CFL $= 10$. The solid domain analysis used standard Newton-Raphson and automatic time incrementation. However, it must be noted that the fluid analysis usually required smaller time increments, this made the fluid time incrementation setup leads the coupled simulation.

4 Results and discussion

4.1 Model validation

Coupled fluid-solid simulation using $\varepsilon = 0.95$ as cavity surface emissivity is chosen for comparison with experimental data from Dupim [9]. Here, only the results from concrete masonry units of characteristic compressive strength (f_{bk}) equal to 10 MPa are considered. The first batch, "Instrumentation trial batch", was an exploratory one specially to test instrumentation setup, thus, only one specimen was tested. Experimental data and simulation results are presented in Fig. 2. The approximate position of thermocouples are shown in the schematic drawing and line colors are used to group thermocouples of similar position. Details of each thermocouple position and fixing procedure can be found in Dupim [9].

Subsequently, a second batch was performed called "Batch 1", in this case, isolated blocks, 2-blocks prisms and small walls were tested. The results from two isolated blocks are shown in Fig. 3 together with simulation results. Thermocouple position is shown in the drawing.

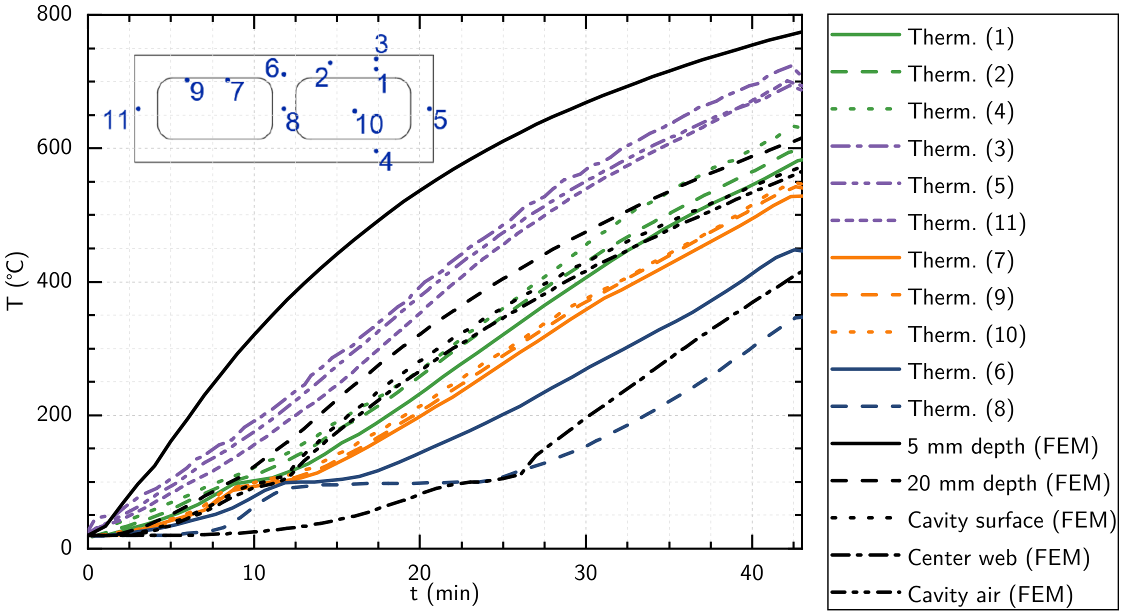


Figure 2. Temperature over time on CMU $f_{bk} = 10$ MPa. All-side fire. Experimental data taken from "Instrumentation trial batch" in Dupim [9]

Figure 2 shows that simulations results overestimates temperature, specially on low depths in the heated surface. However, it should be pointed that some fixing methods and positions are being tested in the "Instrumentation trial batch". That means that experimental position do not match exactly the position sampled on simulation. In addition, temperature variation along the depth is quadratic which means that small differences on simulation and experimental sample position can have great impact in the fit. Thus, this plot is judged on trend basis, that is, the different points sampled on simulation follow reasonably well the trend of similar positions in the experiment. Despite an overall good trend, the result for center web temperature could not reproduce the early heating and long vaporization plateau present in the experimental data. This behavior should be investigated in future research.

Figure 3 shows better fit to experimental data even for low depth thermocouples. However, the experimental scatter in curves for the same depth indicates the difficulty of positioning the thermocouples at the specified depth as related by Dupim [9]. Similar fit is achieved when comparing the simulation results to additional data from Dupim [9].

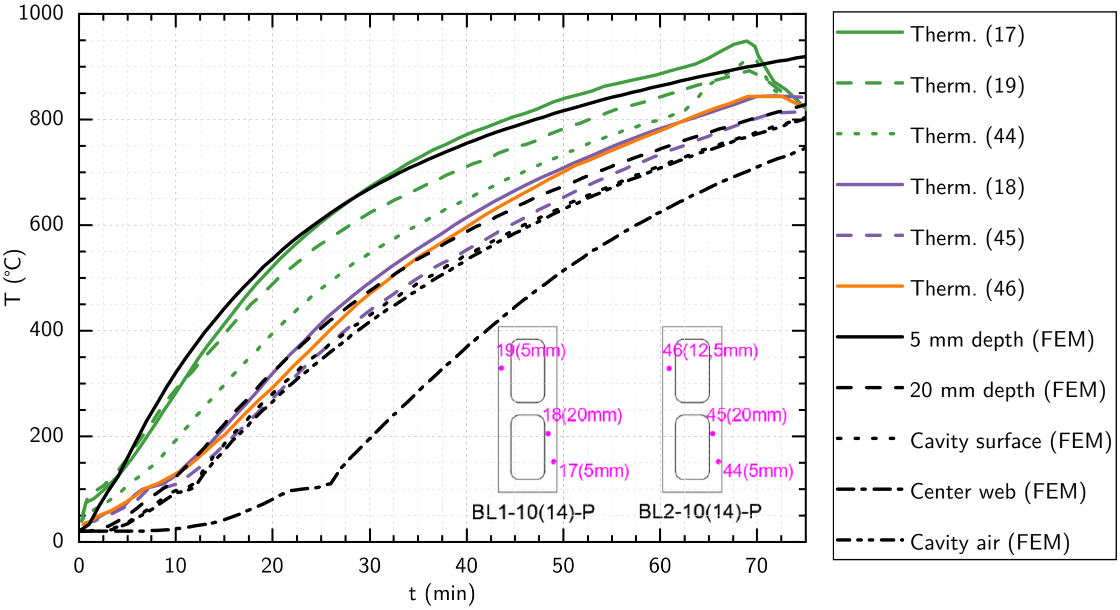
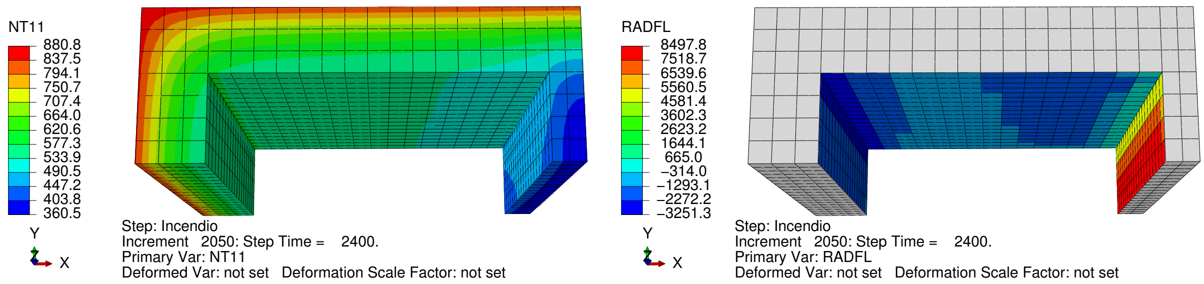


Figure 3. Temperature over time on CMU $f_{bk} = 10$ MPa. All-side fire. Experimental data taken from "Batch 1" in Dupim [9]

In addition to temperature-time plots, inspection of contours plots provides some insight about heat transfer mechanisms. Figure 4 shows the temperature in the block and the radiation flux on the cavity surface at $t = 40$ min. Inspection of the contours shows that heat is transferred by radiation from the heated face shell and exterior web to the central web. Because of this mechanism the surface temperature in the central web is higher than its internal temperature.

On the other hand, Fig. 5 shows the temperature and velocity of air in the cavity at $t = 40$ min. A thin layer of air close to the cavity surface has the same temperature as the surface (shown in Fig. 4a), however, away from cavity surface the air temperature is layered. Hot air remains at the top portion while the cooler air remains in the bottom. Inspection of the velocity vectors shows the convective vortex created by upward motion of air close to the heated surfaces and downward motion of cooler air close to the central web. This convective motion also plays a role in the heating process of the central web.



(a) Temperature (°C)

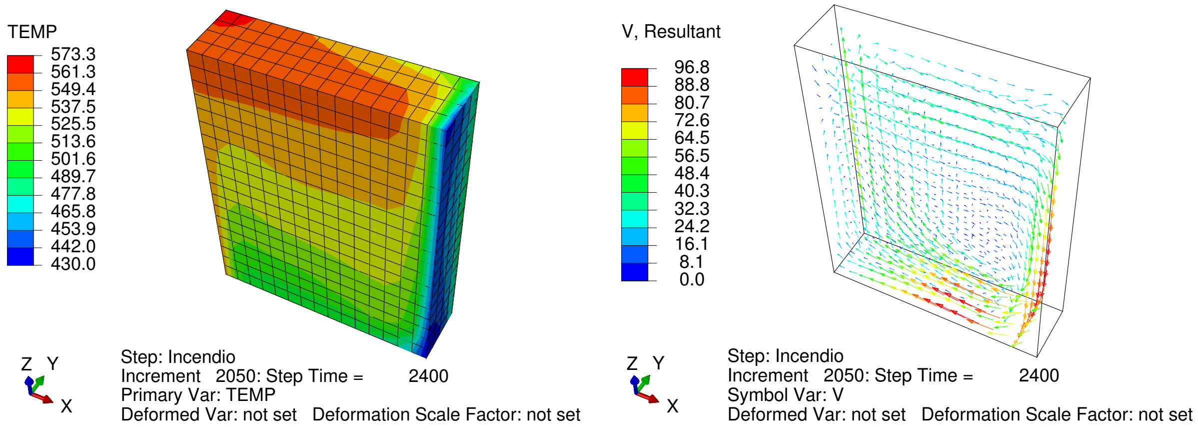
(b) Radiation heat flux on cavity surface

Figure 4. Results of CMU subjected to all-side ISO 834-1:1999 fire at $t = 40$ min

4.2 Assessment of convection and radiation in cavities

Additional simulation results help to assess the importance of convection and radiation inside the cavity for the temperature rise of block during fire. Figure 6 shows the results from the simulations. The influence of air convection is very limited when emissivity is 0.95, that is, black lines (coupled fluid-solid simulation using $\varepsilon = 0.95$) and red lines (solid simulation using $\varepsilon = 0.95$) are almost overlapped.

Further solid simulations using $\varepsilon = 0.70$ and $\varepsilon = 0.50$ show that the changes in results are moderate and the larger changes are seen in the central web. The simulation considering only conduction, that is, no radiation heat



(a) Temperature (°C) (b) Velocity (mm/s)

Figure 5. Results of air domain in CMU cavity subjected to all-side ISO 834-1:1999 fire at $t = 40$ min

transfer inside the cavity, shows huge difference in central web temperature. This shows that radiation plays an important role in heating the cooler areas of the block. However, comparison between high values of emissivity does not show large differences in result. In addition, for high emissivity values the air convection contribution to heat transfer is limited and can be neglected.

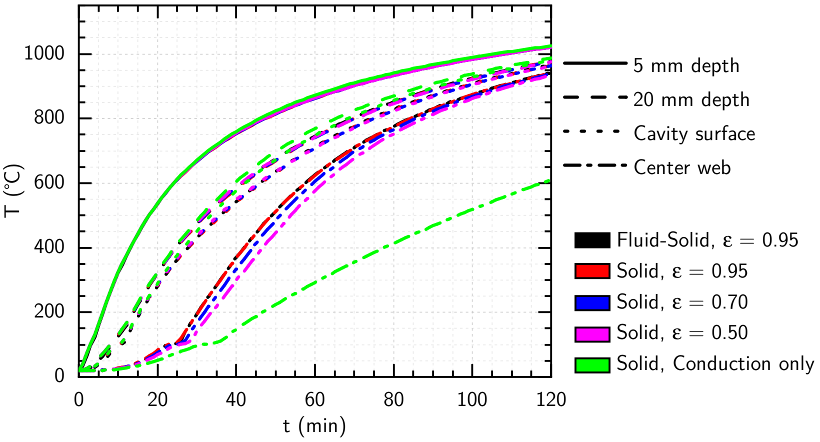


Figure 6. Cavity surface emissivity influence on temperature evolution in different locations of CMU sujected to all-side ISO 834-1:1999 fire

5 Conclusions

This paper showed a simulation methodology to study the heat transfer mechanisms inside the cavity of a concrete masonry unit subjected to standardized fire. Coupled fluid-solid thermal simulation is validated using experimental data available in literature. It was possible to achieve reasonable results using thermal properties of concrete taken from design codes together with proper boundary conditions in the cavity. Additional simulation shows that radiation inside the cavity plays an important role in heating the cooler parts of the block during the fire. Furthermore, the contribution of air convection to heat transfer inside the cavity is negligible when high emissivity values are used on cavity surface. However, it should be pointed that simulations were performed in all-side fire condition and other boundary conditions should be studied such as one-side fire to simulate compartmented fire. In addition, convection influence associated with lower emissivity values should be addressed. Finally, the results presented here as well as others critical analysis of heat transfer mechanisms should be considered in developing simplified analysis of masonry systems such as the use of an effective thermal conductivity.

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