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EXPERIMENTAL AND NUMERICAL ANALYSIS OF A WALLS MADE FROM AERATED CONCRETE BLOCKS EXPOSED TO FIRE

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ABSTRACT

In this paper solution of a non-stationary one dimensional (1D) heat conduction problem has been presented. The finite difference method, i.e. by applying energy balance has been used. The finite difference method has been applied and the partial differential equation of heat conduction has been reduced to an algebraic form. This procedure is also called discretization problem. By solving the system of algebraic equations, temperatures at discrete points - network nodes were obtained. Additional discretization was performed in non-stationary processes over time. Numerical 1D non-stationary calculation was performed on six walls of different thickness made of aerated concrete 50 mm, 75 mm, 100 mm, 120 mm, 150 mm and 250 mm thick are exposed to the developed fire. The developed fire represents the logarithmic dependence of the temperature as a function of time according to the standard SRPS EN 834-1. The period of wall heating was analyzed, i.e. period until the moment when the temperature rise is observed on the non-exposed side of the wall. The paper compares the achieved experimental results with the obtained numerical results

Keywords: numerical one-dimensional (1D) non-stationary calculation; fire condition; autoclaved aerated concrete; thermal behavior; different thicknesses of a wall.

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1. INTRODUCTION

Non-stationary methods of heat conduction are based on the relationship that exists between the change in temperature on a sample exposed to a time-varying heat source and the thermal diffusivity of the substance from which the sample was made [1]. The thermal diffusivity of the sample is ratio of thermal conductivity of material λ and product of bulk density ρ of the material and the specific heat at constant pressure Cp [1].During a fire, there is a large increase in temperature in the materials and structural elements exposed to fire. Temperature change data in fire conditions can be obtained experimentally, analytically and numerically [2].Experimental testing of structures, in this case a walls is performed in a vertical furnace, on samples of standard dimensions 3000 mm x 3000 mm, which simulates a real fire defined by the standard SRPS EN ISO 834-1[3]. Temperatures are measured with thermocouples on the unexposed fire side of the wall. This type of testing is very expensive and is performed only in laboratories for testing the fire resistance of elements of construction. An analytical method for determining the increase in temperature in fire conditions requires solving heat conduction partial differential equations. The numerical approach allows us to easily, with the use of software, get data on the temperature increase over the time in the material or structural element in fire conditions. All software is designed to use the finite difference method, which reduces partial differential equations of heat conduction to an algebraic form. This procedure is also called discretization problem. The application of the finite difference method to boundary elements comes down to setting the energy balance at the physical boundaries of the domain. Boundary conditions at the domain boundaries can be: temperature boundary condition, set heat flux and convective and air (radiation) coefficient of heat transfer.

In this paper the obtained experimental results has been compared with the results achieved computationally and numerically. Experimental and numerical 1D non-stationary calculation and experimental was performed on six walls of different thickness made of the same material (aerated concrete). The analyzed aerated concrete walls 50 mm, 75 mm, 100 mm, 120 mm, 150 mm and 250 mm thick were exposed to the developed fire.

2. NON-STATIONARY ONE-DIMENSIONAL (1D) HEAT CONDUCTION THROUGH A FLAT WALL

The one-dimensional non-stationary heat conduction through a flat wall of thickness L with a heat source$\dot{\boldsymbol{e}}(\boldsymbol{x},\boldsymbol{t})$that is variable in time and space were observed. The thermal conductivity of the wall material is invariable and is$\boldsymbol{k}$. The step of the numerical network is$\Delta \boldsymbol{x} = \boldsymbol{L}/\boldsymbol{M}$ while the nodes of the network are $\mathbf{0}, \mathbf{1}, \mathbf{2}, \ldots, \boldsymbol{M}$as in Figure 1.

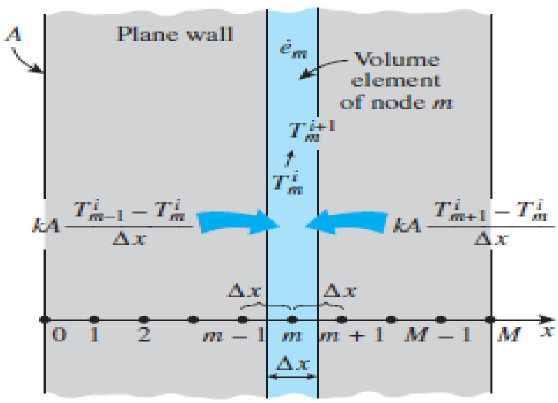

Fig. 1. Non-stationary heat conduction through a flat wall with energy balance of the element$\boldsymbol{m}$

Each inner point$m$, i.e. the inner element of volume $V_{element} = A\Delta x$conducts heat from the left and right sides of the observed element. The energy balance of the internal element in non-stationary heat conduction is given by the following expression:

$$kA\frac{T_{m-1} - T_m}{\Delta x} + kA\frac{T_{m+1} - T_m}{\Delta x} + \dot{e}_m \cdot A \cdot \Delta x = \rho A \Delta x c_p \frac{T_m^{\,i+1} - T_m^{\,i}}{\Delta t} \tag{1}$$

If the previous expression is divided by the area A and multiplied by $\Delta x/k$

$$T_{m-1} - 2T_m + T_{m+1} + \frac{\dot{e}_m \Delta x^2}{k} = \frac{\Delta x^2}{a\Delta t}\left(T_m^{i+1} - T_m^{i}\right) \tag{2}$$

Where $a = k/\rho c_p [m^2/s]$ is the coefficient of thermal diffusion and $\Delta x^2/a\Delta t$is a dimensionless number whose reciprocal value is the Fourier grid numberτ.

$$\tau = \frac{a\Delta t}{\Delta x^2} \tag{3}$$

The energy balance from expression (1) written using the Fourier grid number is given by expression: (4)

$$T_{m-1} - 2T_m + T_{m+1} + \frac{\dot{e}_m \Delta x^2}{k} = \frac{T_m^{\,i+1} - T_m^{\,i}}{\tau} \tag{4}$$

The previous energy balance written in explicit form is given by the following expression:

$$T_{m-1}^{i} - 2T_m^{i} + T_{m+1}^{i} + \frac{\dot{e}_m^{i} \Delta x^2}{k} = \frac{T_m^{i+1} - T_m^{i}}{\tau} \tag{5}$$

The temperature T_m^{i+1} at the point m in the next moment can be simply explicitly expressed from the previous expression for each internal node of the numerical grid:

$$\boldsymbol{T_m^{i+1} = \tau\left(T_{m-1}^{\,i} + T_{m+1}^{\,i}\right) \ + \ (1 - 2\tau)T_m^{i} \ + \tau\frac{\dot{e}_m^{i}\Delta x^2}{k}} \tag{6}$$

The implicit form of the energy balance is given by the following expression:

$$\boldsymbol{T_{m-1}^{i+1} - 2T_m^{i+1} + T_{m+1}^{i+1} + \frac{\dot{e}_m^{i+1}\Delta x^2}{k} = \frac{T_m^{\,i+1} - T_m^{\,i}}{\tau}} \tag{7}$$

The temperature T_m^{i+1} at the point m in the next moment can be simply explicitly expressed from the previous expression. The ordered form of the previous expression is given by the following expression:

$$\boldsymbol{\tau T_{m-1}^{i+1} - (1 + 2\tau)T_m^{i+1} + \tau T_{m+1}^{i+1} + \tau\frac{\dot{e}_m^{i+1}\Delta x^2}{k} + T_m^{\,i} = 0} \tag{8}$$

Applying an implicit or explicit method requires solving the $M - 1$ system of equations for each time moment defined by the counter$i$. An additional two equations are set for the boundary conditions.
An example of additional equations related to boundary conditions is the convective boundary condition as in Figure 2.

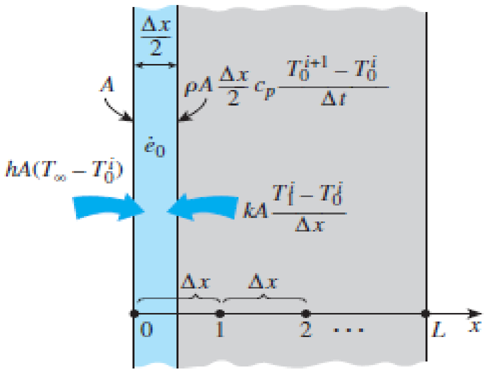

Fig. 2. Convective boundary condition in non-stationary heat conduction through a flat wall

The energy balance for the convective boundary condition by applying the rules of the explicit method is given by the following expression:

$$\boldsymbol{hA\left(T_\infty - T_0^{\,i}\right) + kA\frac{T_1^{\,i} - T_0^{\,i}}{\tau} + \dot{e}_0^{i}A\frac{\Delta x}{2} = \rho A\frac{\Delta x}{2}c_p\frac{T_0^{\,i+1} - T_0^{\,i}}{\Delta t}} \qquad (9)$$

The temperature T_0^{i+1} in the node 0 in the next moment it can be expressed by arranging the previous expression:

$$\mathrm{T}_0^{i+1} = \left(1 - 2\tau - 2\tau\frac{h\Delta x}{k}\right)\mathrm{T}_0^{i} + 2\tau\mathrm{T}_1^{i} + 2\tau\frac{h\Delta x}{k}\mathrm{T}_\infty + \tau\frac{\dot{e}_0^{i}\Delta x^2}{k} \qquad (10)$$

After forming and solving the system of equations at the initial moment, the solution of non-stationary heat conduction is achieved by moving (often the term marching is used) in time based on the defined time stepΔt. The temperature of each point of the numerical network at the initial moment$t = 0$ represents the previous solution at the next moment $t = \Delta t$. The mentioned process of solving the system of equations is repeated as many times depending on the upper limit of the counter.

3. NUMERICAL MODELS OF A WALLS

In this paper the numerical one-dimensional (1D) non-stationary calculation for six walls, different thicknesses, made from autoclaved aerated concrete has been presented. The walls made from autoclaved aerated concrete blocks are thicknesses 50 mm, 75 mm, 100 mm, 120 mm, 150 mm and 175 mm. The walls have been exposed to standard fire. Standard fire curve represent the logarithm dependence temperature in function of time. The next equation represents the standard fire curve[3]:

$$\boldsymbol{T[^\circ C] = 20 + 345\log_{10}(8t + 1)} \qquad (11)$$

Where t is time [min].

The fire curve given by expression (11) is realized within the volume of the furnace, i.e. the temperature of the wall on the side exposed to fire is certainly lower than the temperature inside the volume of the test furnace due to the existence of convective and radiation components during the transfer of heat within the volume of the furnace to the observed wall surface. The heat transfer coefficient in this case is difficult to determine without measuring the heat flux and knowing the change in heat flux along the height of the furnace.

The standard for verification of test furnaces [4] for determining the fire resistance of building structures, stipulates that the temperature on the exposed side of the test sample of the wall is within ± 50 °C. At the beginning of the test, there is a large difference between the temperatures in the furnace and on the wall surface, while after a period of testing; these temperature differences are significantly reduced. Since this paper analyzes the period of wall heating, i.e. the period until the moment when the temperature rise is observed on the non-exposed side of the wall, which in essence does not represent a long period of time. In that reason it can be reasonably considered that there is still a significant temperature difference between the temperature in the furnace and the temperature of the wall on the side exposed to fire. The adopted temperature difference in the numerical calculation is 25^0C. The change in temperature on the surface of the wall exposed to fire is also given by expression (11), where the right side of the expression is reduced by 25^0C.

On the unexposed side of the wall during a fire, the temperature changes over time and its determination is the subject of this paper. Immediately next to the edge of the wall (at a distance that represents a step of the grid that is unchanged and is 5 mm), it is considered that during a short period of testing there is no significant change in temperature, which is the case in practice. In this numerical model, an isothermal boundary condition is set on the wall, where the temperature immediately adjacent to the unexposed wall surface corresponds to the ambient temperature, which corresponds to the initial (initial) temperature.

In Table 1 the thermodynamic and physical characteristics of the analyzed walls with a given initial (initial) temperature of the entire wall has been shown. The initial wall temperatures at the beginning of the experimental tests were taken as the initial temperatures.

Table 1. Thermodynamic, physical characteristics and initial temperature of the analyzed walls

Thickness of the wall [mm]	$\lambda\ [\frac{W}{(mK)}]$	$\rho\ [\frac{kg}{m^3}]$	$c\ [\frac{J}{kg\cdot K}]$	T_{int} [°C]
50	0.119	450	1050	26.1
75	0.119	450	1050	25.2
100	0.119	450	1050	24.25
120	0.119	450	1050	22.27
150	0.119	450	1050	24.10
250	0.106	450	1050	5.9

For easier understanding, a one-dimensional numerical grid is shown in Figure 1 for a 50 mm thick wall, with given temperature limit conditions. The geometric step of the numerical grid is 5 mm for each analyzed wall, while the time step is 0.2 min.

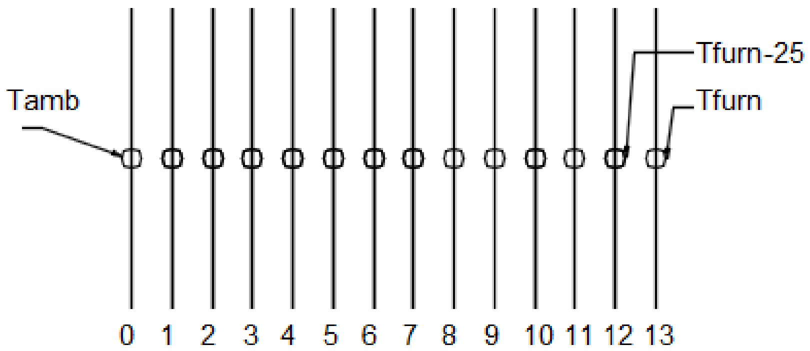

Fig. 3. Numerical wall grid with given boundary conditions

Each of the nodes of the grid represents the internal node of the numerical grid, i.e. for each of the nodes an explicit form of energy balance was applied, which are given by expression (6), where it is also considered that there are no heat sources and abysses in the wall.

After the induction of approximations and drawing a numerical network, the systems of algebraic equations were solved, which are used to determine unknown temperatures in all internal nodes of the grid. Systems of algebraic equations are solved using the Microsoft Excel software package.

The obtained results using the mentioned software package are shown graphically in Figure 4. The Figure shows the heating of the wall in dependence of time and a satisfactory visualization of heat conduction through a fire-prone wall can be seen

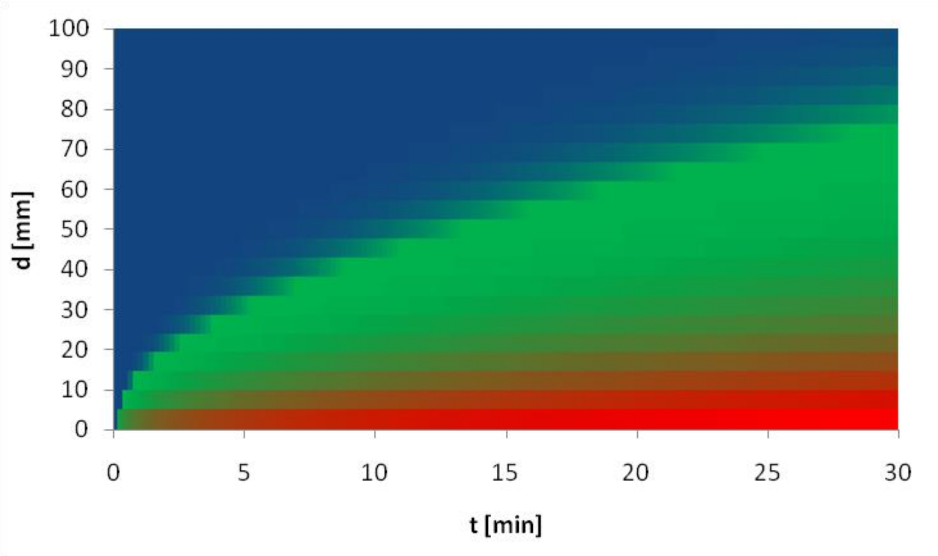

Fig. 4. The results of numerical analysis for a wall thickness 100 mm

4. COMPARATIVE ANALYSIS OF NUMERICAL AND EXPERIMENTAL RESULTS

In the paper of a group of authors [5] the experimental results of testing the fire resistance of aerated concrete walls with different thicknesses has been presented. Considering that after the period of wall heating (occurrence of wall temperature rise is not exposed side) mass transport of water in the wall is dominant, it is difficult to make a reliable numerical model that would describe the behavior of the wall exposed to fire. Therefore, a comparison of the achieved numerical and experimental results was performed until the period of the beginning of wall heating. A graphical representation of the experimental and numerical temperature results on the unexposed side of the wall, for a 50 mm thick aerated concrete wall, is shown in the following Figure 5.

A good match of the achieved results is shown in Figure 5. The time delay of the numerically determined temperatures is approximately 5 min from the moment of the beginning of the wall heating, while the rest of the period of the wall heating using the numerical procedure is similar to the results obtained experimentally. That is, in this way we can consider that the numerical model is valid for thermal analysis of aerated concrete walls that are exposed to the standard fire development curve.
In Figure 6 the experimental and numerical results for a 75 mm thick wall were shown. The similarity of the achieved results before the beginning of wall heating can be noticed with the results shown in Figure 5. Numerical and experimental results do not match after the wall heating period and a significant deviation is noticeable, which is expected due to mass transport of water vapor through the aerated concrete wall. The mentioned deviations between the results of numerical and experimental analysis are greater if the wall is of greater thickness as shown in Figures 7,8,9.For the 250 mm thick wall, the previously mentioned deviations are especially noticeable.

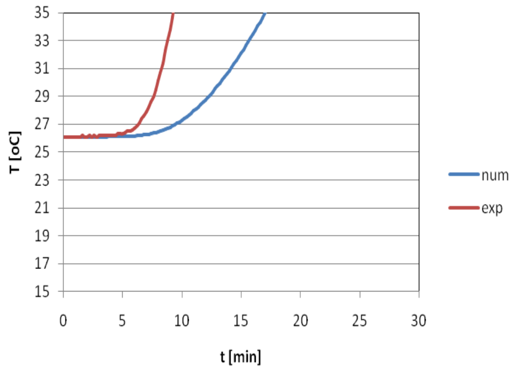

Fig. 5.The temperature results on the unexposed side of a 50 mm thick wall using numerical and experimental procedures

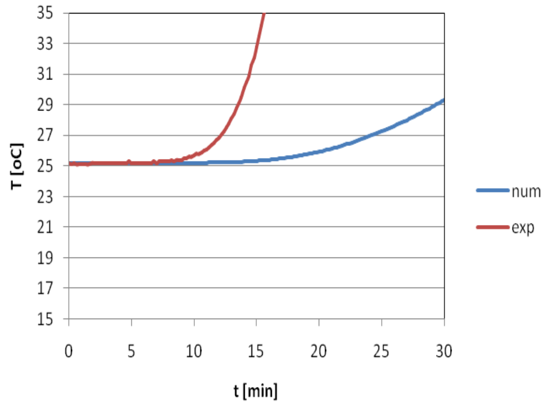

Fig. 6.The temperature results on the unexposed side of a 75 mm thick wall using numerical and experimental procedures

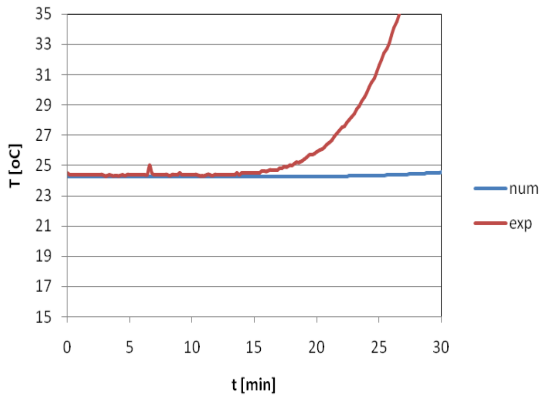

Fig. 7.The temperature results on the unexposed side of a 100 mm thick wall using numerical and experimental procedures

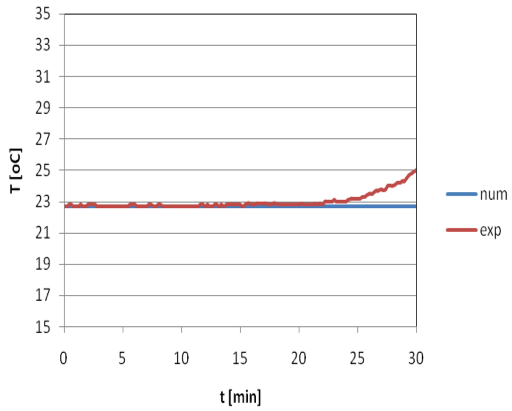

Fig. 8.The temperature results on the unexposed side of a 120 mm thick wall using numerical and experimental procedures

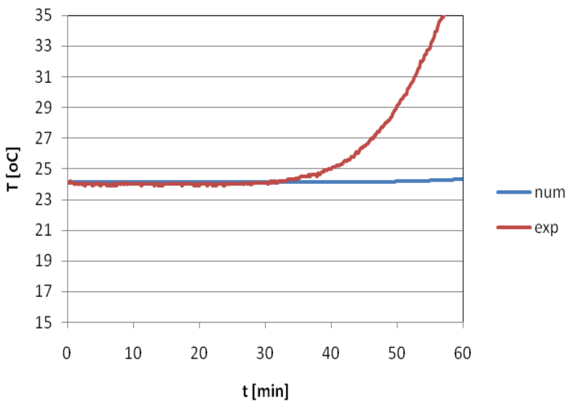

Fig. 9.The temperature results on the unexposed side of a 150 mm thick wall using numerical and experimental procedures

5. CONCLUSION

In this paper numerical one - dimensional (1D) non - stationary calculation for six walls of different thickness made of aerated concrete blocks in fire conditions was performed. Aerated concrete walls with a thickness of 50 mm, 75 mm, 100 mm, 120 mm, 150 mm and 250 mm were analyzed and exposed to the standard fire. One-dimensional (1D) non-stationary calculation of a partial differential equation reduces to an algebraic form. The obtained results were compared with the same results obtained experimentally.

The obtained numerical and experimental results up to the period of the beginning of wall heating are compared, considering that after the period of wall heating (occurrence of wall temperature rise on unexposed side) mass transport of water in the wall is dominant, i.e. it is difficult to make a reliable numerical model a wall exposed to fire. Excellent stacking results were obtained for 50 mm and 75 mm thick walls. For walls with a thickness of 100 mm, 120 mm, 150 mm and 250 mm, there was a larger deviation in the results obtained numerically and experimentally. It was noticed that with the increase of the wall thickness there is a growing discrepancy between the experimental and numerical model, which is expected due to the mass transport of water vapor through the aerated concrete wall.

ACKNOWLEDGEMENTS

The work reported in this paper is a part of the investigation supported by the Ministry of Education, Science and Technological Development, Republic of Serbia, Contract No. 451-03-68/2022-14/200012. This support is gratefully acknowledged.

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