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A new approach and results of wall and air temperature dynamic analysis in underground spaces

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ABSTRACT

In this paper our primary aim is to define the changes of air and internal wall temperature in underground spaces in time domain. As an additional aim the change of heat flux through the wall in time domain has been calculated. Based on the heat balance, the dynamic basic equation of the space has been defined. The basic equation is a differential equation which contains the internal heat sources and the heat capacity of the space. For solving the basic equation, the initial condition, the time-varying boundary condition of the third kind and the Fourier's conductivity differential equation are necessary. The convolution integral of the solution function has been obtained by the use of the integral-differential equation acquired by substituting the temperatures and heat fluxes into the basic equation. The solution of the acquired equation can be obtained in a numerical way. Our new mathematical approach to the solution of the physical model makes it possible to investigate the air and wall temperatures, as well as the heat flow through the wall in underground spaces.

1. Introduction

In Europe the buildings' energy use is 40% of the total energy consumption. The reduction of energy use and the emission of carbon dioxide can be achieved mainly by limiting the energy used by buildings, as the valid national and international regulations suggest. This process was initiated by the Directive 2002/91/EC of the European Parliament and Council, which deals with the energy performance of buildings. Later in 2010 the European Parliament and Council adopted the EPBD recast directive, replacing the former building energy performance directive. It describes the further actions to be taken, among them introduces the requirements on "nearly zero energy buildings" by 2018 and 2020. In the process, the member states, Hungary among them, developed the calculation method of the energy performance of buildings (decree No. 7/2006 (V.24) TNM), and its revision in line with the recast (decree No. 40/2012. (VIII. 13.) BM and decree No. 20/2014. (III. 7.)).

The history of underground spaces suitable for human occupancy coincides with the history of humans. These residential spaces provide shelter against hot weather, storms and nomadic roving tribes. Examples can be found in almost all continents: in Tunisia, China, Ghana, America and Turkey. The constant temperature of 8–12 °C in underground spaces provides reliable protection against both cold winter and hot summer [1–6]. An important feature of underground spaces is the higher protection against the climatic influences. The soil temperature follows the external changes with phase delay and significant attenuation. As a result, the heating and cooling thermal loads are remarkably lower. A pleasant thermal comfort can be ensured with less energy in underground spaces [7–14]. The history of humanity proves that building underground spaces is not only advantageous for the protection against environmental effects but also considering energy aspects. By now, technical practice has proven this with both measurements and dimensioning procedures.

In this paper the dimensioning model is presented and a solution method is proposed for the determination of the air and wall temperature in an underground space, as well as the heat flux through the wall. The developed method can be used for the thermal dimensioning of spaces located underground.

The primary aim of investigation was to develop the dimensioning method which is suitable for determining time dependent changes in the expected air and wall temperature in underground spaces. In addition, the parameters of the heat flux through the wall

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can be calculated based on the air and wall surface temperature in the underground space.

The new numerical process was performed by sixth order Adams–Moulton, seventh order embedded Dormand–Prince and composite Simpson formulas. The obtained new results are numeric, they are arranged into matrices, and presented graphically. The mathematical-numerical process will be presented due to space limitations in a coming article.

At developing the physical and mathematical model it was assumed that the underground space is not bordered by walls, but by semi-infinite spaces. The soil temperature varies in annual cycles.

The proposed new mathematical-numerical approach to analyse the physical model makes it possible to investigate the dynamic behaviour and sizing of the air, internal wall temperatures, as well as the heat flow through the wall in underground spaces.

By simulation obtained and graphically presented new results are also available regarding the heat transfer properties and thermal comfort in operating underground spaces.

2. Aims and expected results

In scientific literature combined analysis of the air and wall temperature and the heat flux through the wall is not to be found for underground spaces. In contrast, we offered a new approach: applying time-varying boundary condition of the third kind which corresponds to the real process. In the framework of study a new software tool for the numerical simulation was developed. The new results obtained by the method were presented in general diagrams.

The primary aim of investigation was to develop the dimensioning method which is suitable for determining time dependent changes in the expected air and wall temperature in underground spaces.

In addition, the parameters of the heat flux through the wall can be calculated based on the air and wall surface temperature in the underground space. In this way, it is possible already during the dimensioning process to determine the most important indicators of the thermal comfort, the values of PMV and PPD [15,16].

3. Physical and mathematical model

The physical model of the considered underground space consists of the ventilation system, the heating-cooling system and the soil surrounding the underground space. The combined effects of the thermal load influence the room air temperature. Heat transfer media are the mass of the moist air and surrounding soil. Important thermal components of this system are the heat fluxes and the thermal parameters of the system, see Fig. 1.

During the development of the mathematical model the heat balance equation with initial and boundary conditions has been defined. The components of the heat transfer equation have been defined which play a role in the heat transfer process, such as the air, the soil and the wall of the underground space. While developing the mathematical model it was assumed that the underground space is not only bordered by walls, but by semi-infinite spaces. The soil temperature varies in annual cycles.

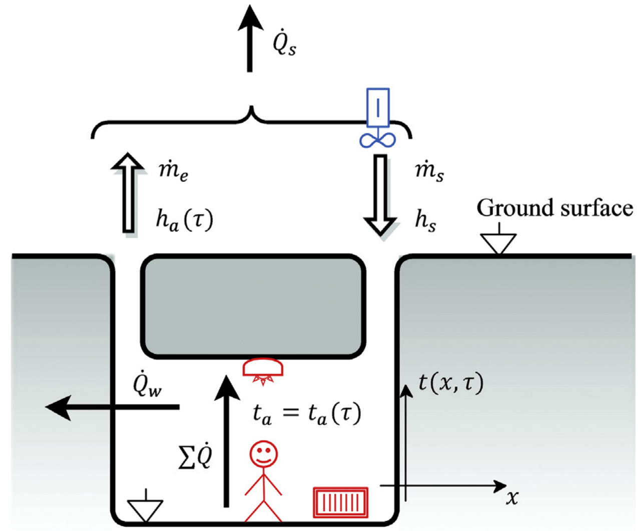

Fig. 1. Underground spaces with energy sources, heat fluxes and system parameters.

The basic equation is the heat balance equation Eq. (1), which contains the heat transport of the space. The heat balance is defined by the internal heat load, the energy flow of the ventilation and the heat flow through the wall.

$$\left[\sum \dot{Q} - \dot{Q}_w(\tau) - \dot{Q}_s(\tau)\right] d\tau = c_{p,a} \cdot \rho_a \cdot V \cdot dt_a \tag{1}$$

The internal heat load includes human, light, electrical equipment components and also mechanical cooling and heating loads.

$$\sum \dot{Q} = \dot{Q}_{heating} + \dot{Q}_{cooling} + \dot{Q}_{human} + \dot{Q}_{lighting} + \dot{Q}_{electrical\ \ equipment} \tag{2}$$

The heat flows in Eq. (2) can be calculated according to heat transfer equations. The detailed description can be found in our previous paper [17]. Eq. (3) describes the change of temperature in the wall of the underground space:

$$t(x,\tau)|_{x=0} = \int_0^\tau [t_a(\tau-u) - t_a(0)] \cdot \left\{ H \cdot \sqrt{\frac{a}{\pi u}} - aH^2 e^{aH^2 u} \cdot erfc\left[H\sqrt{au}\right] \right\} du + t(x,\tau)|_{\tau=0,\ x=0} \tag{3}$$

where:

$$H = \frac{\alpha}{\lambda} \tag{4}$$

$$a = \frac{\lambda}{\rho \cdot c} \tag{5}$$

After substituting the wall surface temperature increment Eq. (3) in the heat balance equation Eq. (1) the result is the differential equation of the underground space in time domain:

$$\frac{dt_a(\tau)}{d\tau} + k_1 t_a(\tau) + k_2 \cdot \left[\int_0^\tau [t_a(\tau-u) - t_a(0)] \cdot g(u)|_{x=0}\ du + t(x,\tau)\Big|_{\tau=0,\ x=0} \right] + k_3 = 0 \tag{6}$$