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Dynamic thermal dimensioning of underground spaces

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ABSTRACT

The accurate dynamic determination of the average energy demand of an underground space is difficult because the soil surrounding the rooms is a semi-infinite space and its temperature varies in annual cycles. In this paper a method is presented for dimensioning underground spaces in terms of heat transfer characteristics and thermal comfort. The dynamic physical and mathematical model with initial and boundary conditions have been developed. Within the procedure of mathematical modelling the heat transfer properties, the heat comfort model and the simulation algorithm of underground spaces have been created. The obtained simulation results are presented in diagrams in favour of the quick sizing of the required heating and cooling performance of underground spaces. The presented diagrams can be used in an effective manner also for the calculation of thermal comfort in underground spaces. These are new in our paper.

1. Introduction

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 [1–4].

Urban development today cannot be imagined without underground spaces. Many spaces with different functions are built underground, including not only parking lots, but also shopping malls, exhibition halls and service facilities. Office buildings, shopping centres can also have levels below the ground floor [5–7].

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 with significant attenuation. As a result, the heating and the cooling thermal loads are remarkably lower. A pleasant thermal comfort can be ensured with less energy in underground spaces [8–16].

An underground space is not bordered by walls, but with semi-infinite spaces. This has to be considered when developing the physical model. The soil temperature varies in annual cycles. The development of physical and mathematical models necessarily requires simplifying assumption. Different methods can be found in the international literature for determining the heating and cooling capacities. Measurement results are also available regarding the heat transfer properties and thermal comfort in operating underground spaces. In this paper the dimensioning model is presented and a solution method is proposed for the determination of heating and cooling performance, supply air properties and thermal comfort parameters. The developed method can be used for the spaces located underground.

Sizing methods of underground spaces can be found in the literature of the 1950s. The starting points of these methodologies are steady state equations, Bogoszlovszkij et al. [17], Macsinszkij [18]. Sizing methods can be found for dynamic processes of the warm-up period and providing constant temperature. Design methods approximate time-varying boundary conditions of the heat conduction differential equation with time constant boundary conditions of the first and second kind: Lakos [19], Barcs [20], Gráber [21], Kokits [22] and Straub [23]. New dimensioning methods found in literature are primarily engaged in the evaluation of thermal comfort and comparison of underground spaces. Yanqiang et al. [24]. developed the thermal comfort evaluation with the development of thermal indices for subway, underground shop and underground hotel. They carried out objective and subjective measurements with thermal questionnaires based on PMV-PPD and the developed new thermal indices. C. van Dronkelaar et al.

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[25]. was engaged in theoretical studies of underground space heating and cooling energy demand.

In scientific literature combined analysis of heating, cooling energy demand and thermal comfort is not to be found. In contrast with the above mentioned results of scientific literature research, we applied time-varying boundary condition of the third kind which is corresponding to the real process. A new software tool for the numerical simulation was developed in the framework of study. The 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 required performances for heating and air handling processes in underground spaces.

In addition, the parameters of thermal comfort can be calculated based on the obtained temperature, humidity of 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 [26–28].

2. Physical model of an underground space

The physical model of an underground space consists of ventilation, heating-cooling system and the soil surrounding the underground space.

Working mediums are the mass of moist air and surrounding soil. Still, important components of this system are the heat fluxes and the parameters of the system, see Fig. 1.

3. Dynamic mathematical model of an underground space

The mathematical model of an underground space describes the heat balance of the underground space including the ventilation and heating-cooling demand, internal thermal load, and the heat flux through the wall. The analysed thermal events in the underground space happen in the space and in the time, there for their mathematical description is possible with partial differential equations. The leading partial differential equation has been obtained on the basis of the heat balance of the underground space [29,30]. The heat conduction through the soil mass over the time domain is described by Fourier's parabolic partial differential

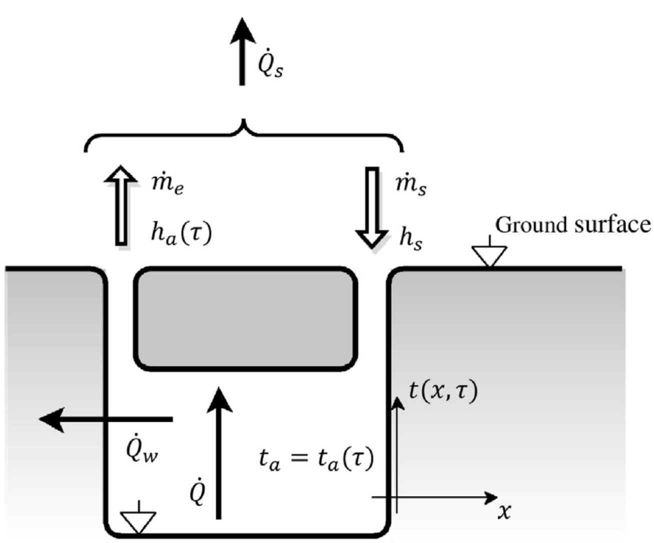

Fig. 1. Underground spaces with energy sources, heat fluxes, system parameters and working mediums (air and soil).

equation. The convection heat transfer from the air to the wall of the underground space is defined by integrating the differential equation.

3.1. The dynamic heat balance equation of the underground space

The heat balance of the underground space means the increment of the sum of heat fluxes, which equals the increment of the air enthalpy filling underground space.

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

where:

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

$$\dot{Q} = \dot{Q}_\mathrm{h} + \dot{Q}_\mathrm{l} + \dot{Q}_\mathrm{e} + \dot{Q}_\mathrm{h,c} \quad (2)$$

Convective heat transfer from the air to the wall:

$$\dot{Q}_w(\tau) = \int_A \alpha\cdot\left[t_a(\tau) - t(x,\tau)|_{x=0}\right]\cdot dA \quad (3)$$

The heat capacity of ventilation is the supply air enthalpy increment:

$$\dot{Q}_s(\tau) = \dot{m}_S\cdot[h_a(\tau) - h_s] \quad (4)$$

Approximations and remarks:

- The temperature of the soil varies according to the change of season. This change shows a certain delay and damping as we consider deeper areas. The amplitude of the temperature change is 0.6 °C in the depth of 8 m and 0.2 °C in the depth of 10 m [28–30]. The location of the underground space under earth the surface defines the sizing soil temperature. Further, the heat capacity of the soil is considerably higher than that of the air. Consequence: according to these aspects, the soil temperature can be considered to be quasi-stationary.
- If underground space is bordered with flat surfaces, we assumed parallel heat flow lines which are perpendicular to the wall. It means that no heat absorption is considered by the corners. By assuming heat penetration depth of 3 m on the basis of practical data, the soil volume neglected at the corners is below 10%, if the circumference of the underground space is more than 85 m. Inference and consequence: the heat flux lines in the soil are considered to be parallel, so the effect of corners at the underground space is neglected.
- The soil is considered to be a homogeneous material in terms of heat transfer properties with its resultant thermal characteristics [28,29,31].
- If the humidity load of the underground space is negligible, the air exchange takes place at constant absolute humidity. In this case, the absolute humidity content can be regarded as equal to the absolute humidity content of the supply air [32–34].
- If the humidity load is not negligible in the underground space, then the enthalpy of the air depends not only on the temperature change but also on the humidity variations in the underground space. This will be discussed later [35].
- In the differential equation Eq. (1) the unknown parameter is air temperature $t_a(\tau)$.
- The surface temperature of the wall can be expressed as a function of the air temperature [36–40].
- The concrete walls are considered to have similar thermal characteristics as the soil [41].