Expected thermal comfort in underground spaces

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Abstract — **In this paper a method is presented for dimensioning underground spaces in terms of heat transfer characteristics and thermal comfort. 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. 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.**

Keywords: *PMV, PPD, underground space, simulation, modelling*

I. 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], [2], [3].

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 [4], [5], [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 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 [7], [8], [9].

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 [10]. 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.

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 correspond 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

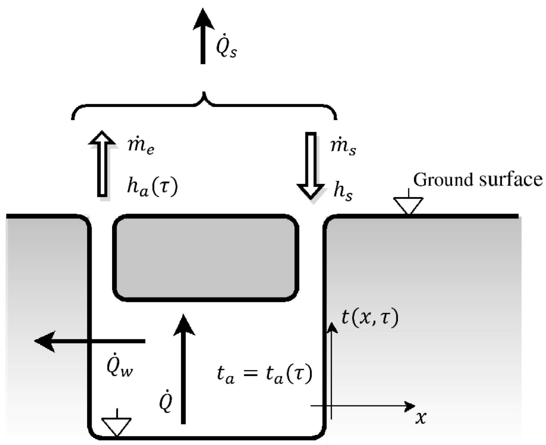

Figure 1. Underground spaces with energy sources, heat fluxes, system parameters and working mediums (air and soil)

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* [11], [12].

II. Physical Model

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.

III. Dynamic Mathematical Model

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, therefore 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 [13]. The heat conduction through the soil mass over the time domain is described by Fourier's parabolic partial differential equation. The convection heat transfer from the air to the wall of the underground space is defined by integrating the differential equation.

A. *The dynamic heat balance equation*

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 (1).

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

Where:

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

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

Convective heat transfer from the air to the wall:

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

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

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

B. *The dynamic heat transfer through the soil*

The dynamic heat transfer through the soil is described by one dimension Fourier partial differential equation of the heat conduction equation (5), as seen Fig. 2 [14], [15]:

$$\frac{\partial t(x,\tau)}{\partial \tau} = a \cdot \frac{\partial^2 t(x,\tau)}{\partial x^2} \tag{5}$$

Boundary conditions:

$$\text{at } x = 0\,;\ -\lambda \cdot \frac{\partial t(0,\tau)}{\partial x} + \alpha \cdot [t_a(\tau) - t(0,\tau)] = 0 \tag{6}$$

$$\text{at } x = \infty\,;\ t(\infty,\tau) = const. \tag{7}$$

Initial condition:

$$\text{at } \tau = 0\,;\ t(x,0) = t_a(0) = const. \tag{8}$$

IV. Dynamic Mathematical Model

The partial differential equation (5) is easier to solve, if in the conditional equations (6), (7) and (8) the constants equal zero. This means, shifting the zero point of the temperature scale to the initial soil or air temperature. The transformed coordinate axis of temperature is distinguished by a comma (Fig. 2).

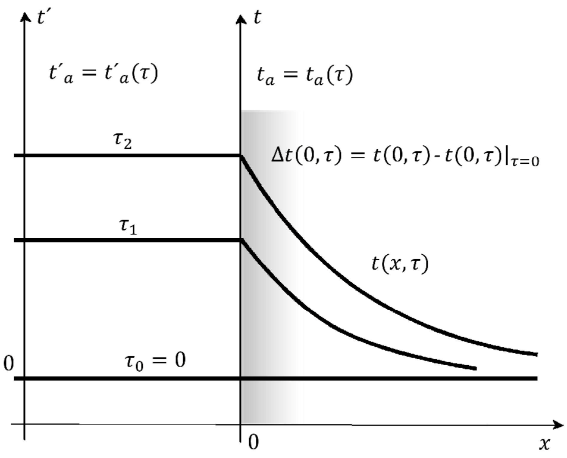

Figure 2. Temperature distribution of the air, and soil in the semi-infinite space depending on x-coordinate and τ-time

One type of the equations, which satisfies the one-dimension Fourier partial differential equation of heat conduction (5) is:

$$t = A + Bx + \frac{C}{\sqrt{\tau}} \cdot e^{\frac{-(q-x)^2}{4 \cdot a \cdot \tau}} \tag{9}$$

The constants in the equation above (A, B, C, a, q) can be determined based on the conditional equations.

If the boundary condition varies in time, the differential equation of the heat conduction can be solved using Laplace transformation or by the Duhamel’s method [16]. The Duhamel’s method can be conveniently used when the initial temperature distribution is arbitrary or when the temperature of the surrounding medium (air) depends on time and distance. In this case the temperature of the surrounding medium (air) depends only on time, so the Laplace transformation is preferred [17].

Based on the equations (5), (6), (7), (8) the obtained solution (10) is a convolution integral as a function of time (τ) and distance (x).

In fact, physically, the solution is the modified temperature increment of the soil from the wall surface at time (τ) and distance (x).

The solution is a convolution integral:

$$\Delta t(x,\tau) = \int_0^{\tau} t_a'(\tau - u) \cdot g(u) \cdot du \tag{10}$$

Where:

$$g(u) = H \cdot \sqrt{\frac{a}{\pi \cdot u}} \cdot e^{-\frac{x^2}{4 \cdot a \cdot u}} - a \cdot H^2 \cdot e^{H \cdot x + a \cdot H^2 \cdot u} \cdot erfc\left[\frac{x}{2 \cdot \sqrt{a \cdot u}} + H \cdot \sqrt{a \cdot u}\right] \tag{11}$$

$$H = \frac{\alpha}{\lambda} \tag{12}$$

After substituting the function (11) and (12) in equation (12), we can get the wall surface or modified soil temperature increment. After substituting the before determined wall surface temperature increment in heat balance equation (1) the result is the differential equation of the underground space in the time domain:

$$\frac{dt_a}{d\tau} + k_1 \cdot t_a + k_2 \cdot \left[\int_0^{\tau} t_a'(\tau - u) \cdot g(u)|_{x=0} \cdot du + t(0,\tau)|_{\tau=0}\right] + k_3 = 0 \tag{13}$$

Where:

$$k_1 = \frac{A \cdot \alpha + \dot{m}_s \cdot (c_{p,a} + x_a \cdot c_{p,s})}{c_{p,a} \cdot V \cdot \rho_a} \tag{14}$$

$$k_2 = -\frac{A \cdot \alpha}{c_{p,a} \cdot V \cdot \rho_a} \tag{15}$$

$$k_3 = \frac{\dot{Q} - \dot{m}_s \cdot (x_a \cdot r_0 + h_s)}{c_{p,a} \cdot V \cdot \rho_a} \tag{16}$$

Initial condition:

$$\text{at} \quad \tau = 0\,; \; t_a(0) = t(x,0) = const. \tag{17}$$

Comments:

- At the start of heating the soil temperature is considered as resultant temperature. The soil and the air temperature are equal in all points of space.
- The temperatures of various surface parts could be different, if these are justified. Then the heat loss of the wall has to be calculated separately for each part of surface, which should be substituted in the equation (1).
- The absolute humidity of the air in the underground space is included in the constants of equation (13). If the humidity load is not significant, the absolute humidity of the supply air is equal to the room air absolute humidity. This is the usual case for comfort spaces.
- If the absolute humidity of the air varies in time, the variables k_1 and k_3 of equation (13) will also vary in time.

V. Numerical Solution Of The Mathematical Model

Equation (13) is an integro-differential equation, which contains convolution integral. The differential equation can be solved by means of finite difference methods. For this purpose, the differential equation (13) was converted into a difference equation. The convergence of the numerical procedure can be ensured if the studied temperature and heat flux are monotonous functions of time and no sudden changes occur. Within the simulation process the optimum time step was accordingly investigated and selected [19].

An algorithm is worked out and a software tool is designed for the numerical solution of differential equation (13). The algorithm of the dimensioning procedure of underground spaces is illustrated in Fig. 3.

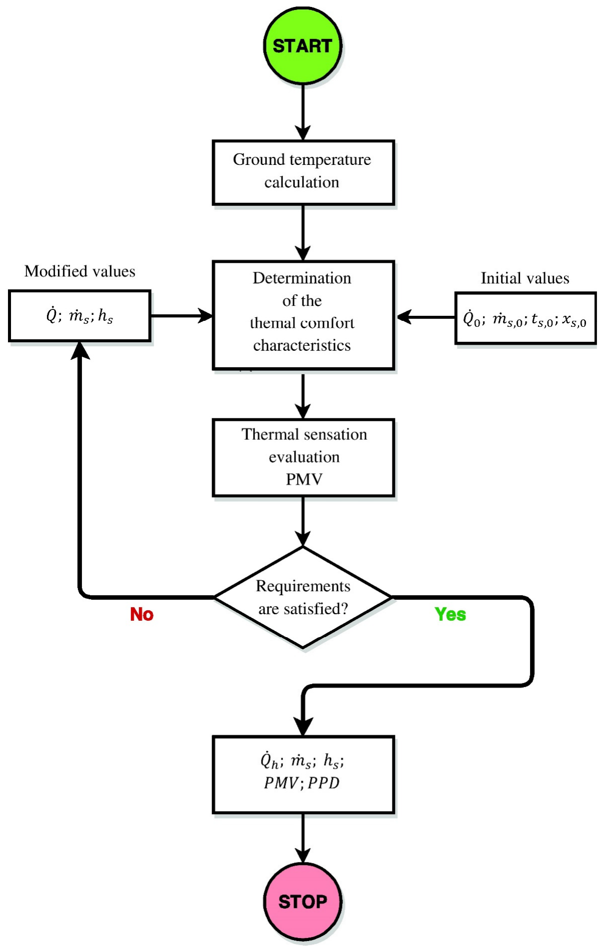

Figure 3. Algorithm for the dynamic thermal dimensioning of an underground space

A. *Initial values and data for simulation*

The dimensions of the studied underground space are: 8 m width, 40 m length and 3 m height.

The thermal sensation of human is influenced by activity and clothing. The base values of these parameters are:

$\frac{M}{A_{Du}} = 1[\text{met}] = 58[\text{W/m}^2]$ (sedentary activity level)

$I_{clo} = 1[\text{clo}] = 0.155[\text{m}^2\text{K/W}]$ (typical working clothes)

Characteristics of the soil:

ρ= 1 800 kg/m^3

λ= 1.5 W/m K

c = 0.84 kJ/kg K

t = t (0, 0) = 12°C (x = 0, τ= 0)

VI. REULTS

In the study, the heat load, the enthalpy of the supply air and the air exchange rate were taken into account. The basic data of the respective versions are shown in Table 1.

TABLE I.
INPUT DATA AND RESULTS OF CERTAIN SIMULATION VERSIONS AFTER 70 HOURS (SEE FIG. 4.)

№		(1)	(2)	(3)	(4)	(5)	(6)
Input data	δ ; [cm]	3	0	5	3	3	3
	$\frac{\sum \dot{Q}}{V}$; $\left[\frac{W}{m^3}\right]$	17	17	17	48	17	17
	n ; [1/h]	3	3	3	3	6	3
	t_S ; [°C]	24	24	24	24	24	30
	x_S ; [g/kg]	8	8	8	8	8	8
	$t(0,0)$; [°C]	12	12	12	12	12	12
Results	$\dot{Q}_h$; $[kW]$	10	10	10	30	10	10
	$\dot{Q}_h + \dot{Q}_s$; $[kW]$	48,1	48,1	48,1	68,1	86,1	52,1
	$\dot{q}_w$; $[W/m^2]$	11,2	19,8	8,9	18,8	10,9	12,9
	PMV ; [-]	0,07	-1,39	0,48	2,20	0,00	0,59

Table 1 also contains the results obtained after 70 hours.

We transferred the results of heat transfer characteristics and the thermal comfort dimensioning process into diagrams. Thermal load and ventilation

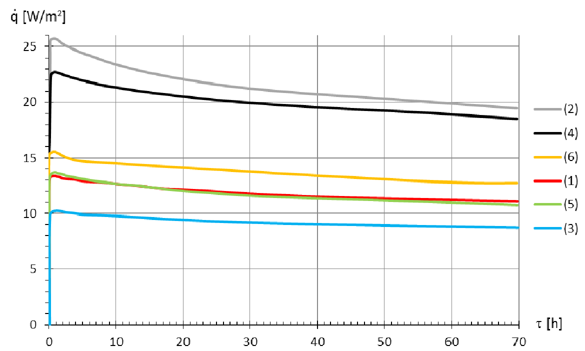

Figure 4. Graphics of the heat fluxes through the wall as a function of time

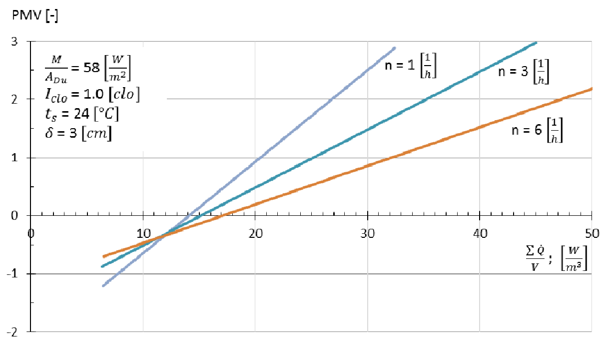

Figure 5. Thermal comfort in the underground space (τ = 70 hour)

figures were converted into specific values, so that the results obtained can be used also for dimensioning tasks.

Fig. 4. shows the change of heat flux through the wall of the underground space.

Fig. 5 shows the thermal comfort improvement in the respective cases.

The influence of thermal insulation thickness can be seen in Fig. 6 and Fig. 7 at various air exchange rates (n=1 and 3 1/h) and internal heat load.

The basic values considered for the dimensioning can be reliably used in general cases too. The conclusions summarised can be obtained from the evaluation of the results. Version (1) from the previously presented Table 1. can be considered as a reference.

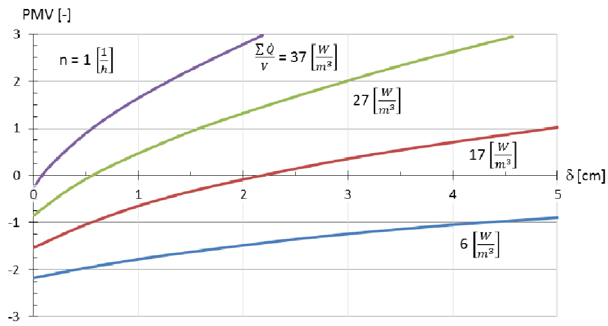

Figure 6. Influence of the thickness of thermal insulation on the *PMV* value (n = 1 h^{-1}, τ = 70 hour)

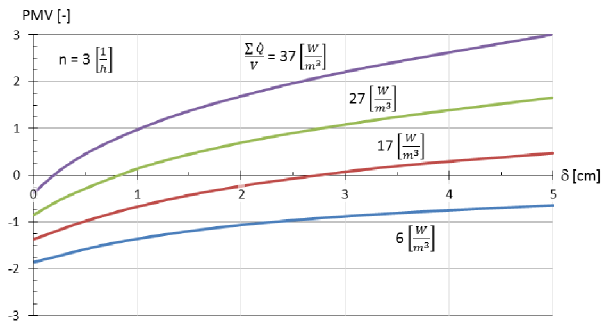

Figure 7. Influence of the thickness of thermal insulation on the *PMV* value (n = 3 h^{-1}, τ = 70 hour)

VII. DISCUSSION

The heat flux through the wall of an underground space can be reduced significantly by the use of a 3 cm thick thermal insulation /Versions (1) and (2)/.

The increase of the thermal insulation thickness over 5 cm (Fig. 6 and Fig. 7) has minor impact, thus not recommended.

If the resultant heat balance (people, lighting, technology) of the underground space does not exceed the value of 15-18 W/m^3 and the thermal insulation thickness is at least 3 cm it is not required to use mechanical cooling (Fig. 5).

If thermal insulation of 3 cm thickness is used, then the initial maximum heat loss is reduced to 16 W/m^2 and after 70 hours it reduced to 13 W/m^2. (Fig. 4).

If the thickness of the thermal insulation is 5 cm, the heat loss is reduced to 10.5 W/m^2 (Fig. 4).

VIII. CONCLUSIONS

We developed a dimensioning method for underground spaces. The physical model is capable for the analysis of dynamic processes, the temperature change of the wall and the air, as well as the thermal sensation characteristics (*PMV*, *PPD*) determined in the underground space. According to our investigations the thermal comfort characteristics have been considered permanent after 70 hours. From these data we developed generally applicable dimensioning diagrams for sizing underground spaces. These help to determine the required heating power, ventilation air flow, and thermal comfort characteristics. By using a finite-element model we could get more detailed results. However, these results required long time or great software and hardware needs. The applied algorithm and dimensioning charts could give quick and useful results.

Summary of conclusions

- The older scientific literature of dimensioning methods are not suitable for complex calculation of heating, cooling performance and thermal comfort in underground spaces.
- During the investigation of the non-steady state process, the change of air temperature after 70 hours was less than 0.00001°C/s (0.036°C/h).
- Heating and cooling are significantly affected by the internal heat load of the underground space. In case of 15-18 W/m^3 resultant heat balance, it is not required to use mechanical cooling or heating.
- It is recommended to use 3-5 cm thick thermal insulation on the surrounding surfaces of the underground space.
- The supply air flow must be dimensioned according to the required fresh air need. From the energy point of view it is not recommended to increase the temperature and the volume flow of the supply air.
- 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.

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