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Physical and Mathematical Conditions of Non-Stationary Thermal Conditions of the Underground Air Channels

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Abstract

The article presents the research of changes of operational conditions of the non-stationary underground air channels. When making the research, the authors use physico-mathematical conditions, based on the fact that there are two identical underground air channels along the left and right side of an inhabited building. Each air channel has the same length, diameter and depth below the ground level. An air channel plan of non-stationary heat exchange has been made. It is necessary to supply the cooled air into the inhabited building to maintain the normal in-door climate conditions in the summer. Mathematical analysis of the physical conditions includes the equation of the temperature thermal field of the channel wall and the equation of convective heat transfer from the wall surface towards the moving air current. To calculate the thermal conditions of the underground air channels the following assumptions were made:

- radiant heat transfer is too small in underground air channels, so it can be neglected and heat transfer can be considered convective;

- heat transfer by conduction in the flow direction can be neglected.

Keywords: energy efficiency of the heating system, the specified and the actual heat carrying agent flow rate, specified and actual temperature of the heat carrying agent, the pressure of the heat carrying agent in a heating system, piezometer chart.

INTRODUCTION

Mathematical dependences allowing to calculate the average value of surface coefficient of convection heat transfer and the resulting thermal balance has been obtained.

Let us consider the general formulation of the problem. There are two identical underground air channels along the left and right side of a inhabited building. Each air channel has the length L, m and diameter d, m, and is located at the depth of h, m, from the ground level. Figure 1 shows an air channel plan to illustrate the problem formulation of non-stationary heat exchange.

It is necessary to supply cooled air into the inhabited building to maintain the normal in-door climate in the summer [1].

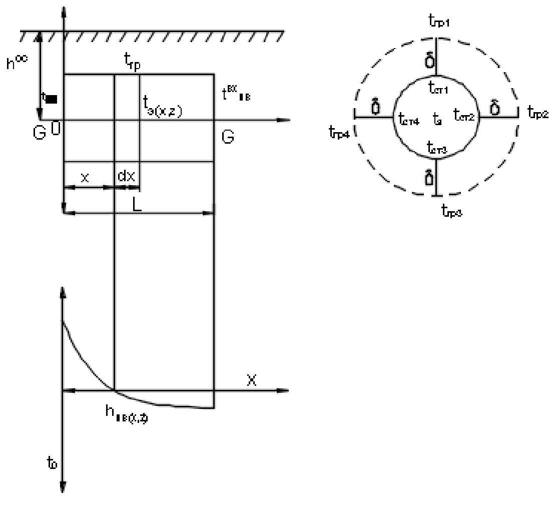

Figure 1: Air channels plan of non-stationary heat exchange (composed by [1, p.64])

The air inlet temperature **$t_{н.в.}$**, °C enters the air channel with constant velocity ω, m/s. It flows round the inner walls of the air channel. Air enters the channels by means of rarefaction during the fan operation of the air conditioning system. The change of the outdoor air temperature (**$t_{н.в.}$**,°C) during the design day is described by the dependence [10]:

$$t_{н.в.} = t^{m}_{н.в.} + At_{н.в.} + \cos\frac{2\pi}{\tau_0}(z - z^{\max}_{н.в.}) \qquad (1)$$

where $t^{m}_{н.в.}$,°C is the mean value of the outdoor air temperature; $At_{н.в.}$ °C is the outdoor temperature swing or its maximum outdoor temperature deviation; t_0 is the period of temperature variations, h; $z^{\max}_{н.в.}$ is the daytime with the maximum outdoor temperature, h.

Heat transfer in air channels depends on the temperature variation of the outdoor air entering the channels and the soil temperature variation [8]. The volume of channels does not contain foreign objects.

The operation conditions of the underground heat air channels is periodic and the theory of the heat stability for the cylindrical wall can be used for heat calculation.

When formulating the problem the mathematical analysis of the physical conditions includes the equation of the wall temperature field and the equation of convective heat transfer from the wall surface towards the moving airflow.

THE RESULTS OF THE SERIES OF EXPERIMENTS AND THEIR ANALYSIS

The following assumptions were used to calculate the thermal conditions of underground air channels:

– radiant heat transfer in underground air channels is too small, so it can be neglected and heat transfer can be considered convective;

– heat transfer by conduction in the flow direction can be neglected [5];

– numerical analysis showed that the left side of the equation [5] is a lot less than the second addend in the right side.

The accepted assumptions allow to make the system of equations of heat transfer in the cross-section of the underground air channel. This system by Yu. Tabunschikov is a physico-mathematical condition.

The equation system comprises the equation of the convective heat balance in an elementary volume of length dx in the underground air channels according to the law of conservation of energy. Therefore, the equation of the thermal conditions of underground air channels becomes [4]:

$$(V_в \cdot C_в \cdot \rho_в)\frac{dt_в}{dx} = (t_i - t_в)\cdot \alpha_i \cdot d_i \cdot dx \qquad (2)$$

where $V_в$ is the air flow rate, m^3/s; $C_в$ is air specific heat j/(kg•K); $\rho_в$ is the air density, kg/m^3; t_i is the temperature of the inner surface of the air channel, °C; $t_в$ is the mean air temperature of the air channel, °C; α_i is the coefficient of convective surface heat transfer of the inside surface, W/(m^2•K); d_i is he cross-sectional diameter of one of the air channel, m.

The heat balance of the inner surface of one of the air channels without taking into account radiant heat transfer [9] becomes:

$$\lambda_{гр}\frac{\partial t_{cm}}{\partial n} = \alpha_k (t_{cm} - t_в) \qquad (3)$$

where $\lambda_{гр}$ is coefficient of soil thermal conductivity W/(m·K); t_{cm} is the surface temperature of the wall of the air channel, °C; n is the normal to the wall of the air channel; $\alpha_к$ is convection surface heat transfer coefficient W/(m^2·K).

This equation considers the heat flow into the depth of the soil along the normal to the inner surface of the air channel. In this case convective heat transfer occurs between the inner surface of the air channel and the air moving along the air channel.

The temperature of the inner surface of the air channel [9] along its length changes faster compared with a negli-gible change of the temperature of the walls of the air channel diameter. The wall temperature ( ) of the air channel can be defined as follows, °C:

- temperature t_{ct} is determined by the temperature value

$$t_{гр.i} = t^{год}_{cp} + 0{,}5\Delta t + \frac{h_{гр}}{30} - \frac{h_{гр}}{200} \pm \frac{At_{год}}{e^{h_{гр}} \cdot \sqrt{\dfrac{\pi\cdot\rho_{гр}\cdot C_{гр}}{\lambda_{гр}\cdot T'}}} \cdot \cos\left(\frac{2\pi}{T'}\cdot z - h_{гр}\cdot\sqrt{\frac{\pi\cdot\rho_{гр}\cdot C_{гр}}{\lambda_{гр}\cdot T'}}\right) \qquad (4)$$

where $t_{ср}^{год}$ is the mean soil temperature of the study area, °C; Δt is the temperature difference between the soil temperature on the axis of the air channel depth and the air temperature inside the channel, °C; $h_{гр}$ is the distance from the soil surface to the axis of the air channel, m; $\frac{h_{гр}}{30}$ is the value that takes into account the constant heat influx from the earth's center (the mean soil temperature increases as descending deep into the earth by about 1°C for every 30m); $\frac{h_{гр}}{200}$ is the correction for the geodetic mark of the area; $At_{год}$ is the annual temperature swing of the surface of the soil, °C; $\rho_{гр}$ is the soil density, kg/m^3; $C_{гр}$ is specific soil heat, j/kg•K; $\lambda'_{гр}$ is the coefficient of soil thermal conductivity, W/m•K; T'= 8760 h is annual period of temperature variation; z is the time interval, h.

The proportion of the components of soil being known the coefficient of soil thermal conductivity can be determined. Coefficient of thermal conductivity heavily depends on soil temperature and moisture content (ratio of water volume filling the pores W_v to the porosity volume of the soil W, that is $w_{в л} = \frac{W_v}{W}$ for the fertile and sandy soils. The heat capacity of the soil is defined as the sum of the heat capacities of its constituent elements. The value of the soil heat capacity changes little. When soil moisture content is average it equals to 1 j/(kg·K). To determine the thermal conductivity coefficient $\lambda_{гр}$, W/m·K, the following formulas can be used [7]:

$$\lambda_{гр} = D_i \cdot C_{гр}, \tag{5}$$

where $D_i = 2\rho_{гр}^{0,8} - 0,0039(w_{вл} - 17)^2.\ C_{гр}$

Specific heat capacity $C_{гр}$, j/(kg•K) was determined based on the soil moisture content and soil density according to the formula [7]:

$$C_{гр} = (C_{сп} + \frac{w_{вл}}{100}) \cdot \rho_{гр}, \tag{6}$$

Where $C_{сп} = \frac{0,714 + 0,798}{2} = 0,756\, j/(kg \cdot K)$ - specific heat capacity of different soils in dry condition [7], and its magnitude varies within very small limits 0,714÷0,798 j/(kg•K). The mean value of surface heat transfer coefficient of convective heat exchange α_K, W/(m2·K) for air along the channel length equals [6]:

$$\alpha_к = (0,896 + 1,51 \cdot 10^{-3} t) \frac{(\omega_в \cdot \rho_в) \cdot \Delta t^{0,1}}{d^{0,5}} \xi_1 \tag{7}$$

where t is the mean air temperature, °C; $\omega_в$ is air speed, m/s; $\rho_в$ is the air density, kg/m^3; Δt is the difference between the air temperature and the channel surface temperature, °C; $d_{вн}$ is the internal diameter of the channel, m; ξ1 is the coefficient of hydraulic resistance of the underground air channel obtained from the formula $\frac{l}{d}$ [6, 11]. For very long channels the value of Nu becomes almost constant:

$$Nu = 4 \cdot \left(\frac{\Pr}{\Pr_{cm}} \right)^{0,25} \tag{8}$$

For air at Pr=$\Pr_{ст}$ heat transfer coefficient of the convective surface heat exchange is:

$$\alpha_к\text{, Вт/(м}^2\text{·К)}: \alpha_к = \frac{4\lambda_в}{d} \tag{9}$$

For air at Pr = 0,703 and $\frac{\Pr}{\Pr_{cm}} \approx 1$ the expression (8) becomes:

$$Nu = 0,0018 \cdot \mathrm{Re}^{0,8} \cdot \xi_1 \tag{10}$$

The mean value of surface heat exchange coefficient of the convective heat transfer α_K, W/(m2·K) [3] is defined by the formula:

$$\alpha_к = 4,08 \cdot \omega_в^{0,8} \cdot D^{0,2} \cdot \xi_1 \tag{11}$$

where $\omega_в$ is the air velocity in the channel, m/s; D is the diameter of the channel, m.

The above equations are valid for the air moving in the hydraulic smooth surface channel. The heat balance equation [2, 6] is:

$$Q = W_1 \Delta\tau = kF\Theta_m\text{,W} \tag{12}$$

where $W_1 = M_в C_в$ is the heat capacity rate of the chilled air, W/K; $\Delta\tau = \tau_2 - \tau_1$ is the temperature change of the cooling air; k is of heat transfer coefficient of the underground air channel, W/m^2·K; F is the surface of the heat exchange with the underground soil, м²; θ_m is the medium logarithmic temperature difference (K) of the heat exchange process. It is determined according to the equation:

$$\theta_m = \frac{\Delta\tau}{\ln \frac{t_{гр} - \tau_1}{t_{гр} - \tau_2}} \tag{13}$$

where $t_{\text{гр}} = t_{cm}$ is the ground temperature, which is constant and equal to the channel wall temperature, °C; τ_1, τ_2 are, respectively, the air temperatures at the entrance and exit of the underground channel, °C.

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