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Influence of external conditions on the solidification process in saturated porous flat layers

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ABSTRACT

In the theoretical part of the following work a quasi-stationary model of solidification of moist porous layers saturated water was presented and solved, taking into account the influence of free convection in the unfrozen part of the layer and the thermal resistance of contact between the cold wall and the solidified layer on the solidification process.

In the investigations carried out the phenomenon of water anomaly is also taken into account. Experimental measurements of the thickness of the solidification layer were carried out on a built-in investigation apparatus. The investigation results are presented in the form of diagrams showing the thickness of the solidification layer depending on time.

1. Introduction

The aim of that paper is a theoretical and experimental study of the influence of outside temperature, the location of the porous layer, the thermal resistance of the contact layer and the phenomenon of water anomalies, on the solidification process.

External conditions mentioned in the title of the paper are understood as setting the moist porous layer, overheating the porous layer and thermal resistance of contact between the cold wall and the wet porous layer.

The solidification phenomenon of the moist porous medium, in addition to the properties of this medium and the outside temperature, is influenced by the position of the porous layer with respect to the direction of gravity and the contact layer formed in the solidification process between the cooling wall and the frozen layer. The location of the moist porous layer affects the formation of free convection in the unfrozen moist area of the porous medium and the free convection affects the intensity of heat exchange at the solidification surface, determined by the heat transfer coefficient between liquid and solid areas.

As a result of the research, practically useful formulas were created during work for calculating the solidification process of moist porous media.

Investigation on the solidification process of moist porous materials is extensively reported in the scientific literature [1–7]. However, there are not any works taking into account the thermal resistance of the contact layer and the phenomenon of water anomalies in the process of its solidification.

2. Problem formulation and simple analytical solution

The essence of the proposed model of solidification of a moist porous layer is the use in the theoretical model of the heat transfer coefficient on the solidification surface, determination of which is an additional object of this work.

Thermophysical parameters of the wet and solidified porous medium are assumed to be constants. We assume also that the solidification front is flat and propagates parallel to the surface of the cold wall which take away the heat.

2.1. Solidification model

Fig. 1 shows moist flat horizontal porous layers with porosity φ and thickness H: unlimited (a) and limited (b) adiabatic vertical cylindrical wall with a radius R. The porous layer from the bottom is cooled with a cold wall with a temperature T_W which is lower than water solidification temperature T_F.

The upper surface of the layer is kept at a temperature T_0 which is higher than a solidification temperature $T_0 > T_F$. The water contained in the porous layer undergoes a solidification process, as a result of which the frozen layer is formed with thickness δ.The quasi-stationary solidification process of the moist porous layer is described by the system of heat balance Eq. (1). It follows from them that the sum of heat fluxes supplied to the frozen layer from the unfrozen part of the porous medium with the heat transfer coefficient h on the solidification surface, and the ice that separates

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Nomenclature

c_S	specific heat of ice, J/(kg K)
h	heat transfer coefficient on the solidification front, W/(m^2 K)
h_{CON}	heat transfer coefficient for the contact layer, W/(m^2 K)
k_{ef}	effective heat conductivity moist porous medium, W/(m K)
k_L	heat conductivity of water, W/(m K)
k_S	heat conductivity of ice, W/(m K)
k_{sp}	heat conductivity of frozen layer, W/(m K)
$\dot{q}$	heat flux, W/m^2
t	time, s
H	thickness of the moist porous layer, m
$\tilde{H}$	thickness of the moist porous layer near the solidification surface, m
K	permeability of the porous medium, m^2
L	latent heat of water, J/kg
R	radius of the cylinder, m
T	temperature of the porous layer, °C
T_C	temperature of the contact layer, °C
T_F	solidification temperature, °C
T_0	temperature of the upper surface limiting the moist porous space, °C
T_W	wall temperature, °C
V	volume of porous medium, m^3
V_s	volume of ice, m^3

Greek symbols

β	coefficient of volumetric expansion, 1/K
δ	thickness of frozen layer, m
δ_m	average thickness of frozen layer, m
ν	kinematic viscosity of water, m^2/s
κ_m	thermal diffusion coefficient of a moist porous medium, m^2/s
κ_s	coefficient of temperature compensation of the solid $= k_S/\rho_S c_S$, m^2/s
ρ_s	ice density, kg/m^3
ρ_L	water density, kg/m^3
φ	Porosity

Dimensionless numbers and similarities

$\tilde{\delta}$	dimensionless thickness of frozen layer $= \delta/H$
$\tilde{k}$	ratio of thermal conductivity = k_S/k_{sp}
τ	dimensionless time $= Ste \cdot Fo$
B	overheating parameter $= (T_0 - T_F)/(T_F - T_W)$
Bi	Biot number $= hH/k_{sp}$
Bi_{CON}	Biot number associated with the contact layer $= h_{CON}H/k_{sp}$
F_O	Fourier number $= k_S t/H^2$
Ra	Rayleigh number $= g\beta K(T_0 - T_F)H/(\nu\kappa_m)$
Ra_C	critical Rayleigh number
Nu	Nusselt number $= hH/k_L$
Ste	Stefan number $= c_S(T_F - T_W)/L$

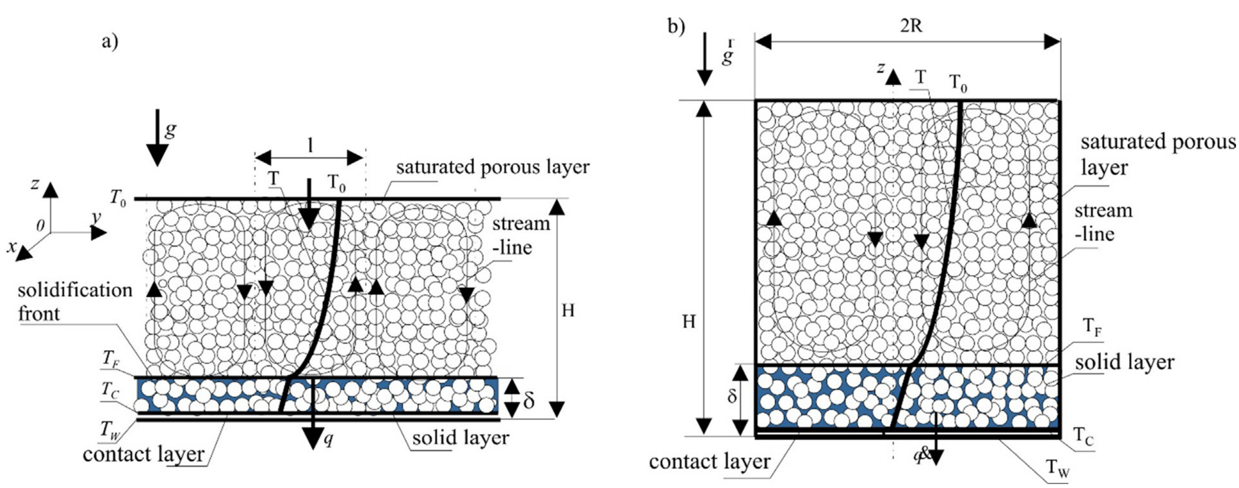

Fig. 1. Saturated horizontal flat porous layers with porosity φ and thickness H: unlimited (a) and limited (b) adiabatic vertical cylindrical wall with radius R.

in the solidification process of water with the solidification velocity $d\delta/dt$ in time t, is equal to the heat flux conducted through the frozen layer with thermal conductivity k_{sp} and the heat flux flowing through the contact layer with temperature T_C, adhering to the cold wall with temperature T_W and heat transfer coefficient for the contact layer h_{CON}. The heat of the phase transformation of water into ice (latent heat) is equal L, and the density of the generated ice ρ_S.

$$h(T_0 - T_F) + \varphi\rho_S L\frac{d\delta}{dt} = \frac{k_{sp}}{\delta}(T_F - T_C) = h_{CON}(T_C - T_W). \tag{1}$$

The contact temperature was determined from the last of the sets of Eq. (1) T_C:

$$T_C = \frac{\frac{k_{sp}}{\delta}T_F + h_{CON}T_W}{\frac{k_{sp}}{\delta} + h_{CON}}. \tag{2}$$

Substituting dimensionless numbers marked as follows: thickness of the frozen layer, time, Stefan number, Fourier number, overheating parameter, Biot numbers associated with the frozen and contact layer, coefficient of temperature compensation of the solid, ratio of thermal conductivity of the solid and frozen porous layer

$$\tilde{\delta} = \frac{\delta}{H}; \quad \tau = Ste \cdot Fo; \quad Ste = \frac{c_S(T_F - T_W)}{L}; \quad F_o = \frac{\kappa_S t}{H^2}; \quad B = \frac{T_0 - T_F}{T_F - T_W};$$

$$Bi = \frac{hH}{k_{sp}}; \quad Bi_{CON} = \frac{h_{CON}H}{k_{sp}}; \quad \kappa_S = \frac{k_S}{\rho_S c_S}; \quad \tilde{k} = \frac{k_S}{k_{sp}},$$