NOTATION

r, radius; t, time; m, Lagrangian coordinate; v, velocity; p, pressure; ρ, density; T, temperature; ε, energy of a unit mass; i, current density; E, H, electric and magnetic field strengths; σ, electrical conductivity; I_ν, spectral intensity of the radiation; I, current; R, resistance; L, inductance; U, voltage; C, capacitance; N^z, density of ions with charge z; N_e, electron density; κ_k, group absorption coefficient; q, Joule heating power; f, ponderomotive force; ν, frequency; r_D, Debye radius.

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GEOTHERMAL ENERGY UTILIZATION WITH HEAT PIPES

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UDC 536.248:536.421.4

Several variants of heat pipes for utilization of geothermal energy and underground rock heat are studied. An original configuration is proposed for a long length vapor-dynamic thermosyphon for such purposes, and experiments performed to test the hypothesis.

Introduction

The planet earth has large energy reserves; however, the thermal flux density per unit surface area is low (0.1-1 kW/m^2). Nevertheless, the earth's surface radiates an energy of $8 \cdot 10^{20}$ J/yr into the surrounding space, which is equivalent to the heat of combustion of $1.9 \cdot 10^{10}$ ton of petroleum.

It is well known that at a depth of 10-20 m the ground temperature is relatively high (10-15°C), independent of seasonal air temperature variations, and increases slowly with depth, reaching 250-300°C at a depth of 4-5 km. The energy stored in the rock strata at such a depth is many times the total heating capability of world reserves of organic fuel. The energy of geothermally heated water within the USSR at temperatures of 30-100°C is about $8.4 \cdot 10^{17}$ J/yr.

Viewed as a heat source, we may arbitrarily divide the earth into three zones having different temperatures: a) surface layers (to 10 m), the temperature of which varies periodically under the action of solar radiation; b) soil and rock of approximately constant temperature, saturated with thermal or ground water; c) deep rock strata.

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The surface layers are of interest primarily to domestic and communal economy, since the energy accumulated from solar radiation in the warm period of the year may be used for heating water and air [1].

Geothermal waters and rock formations are of interest for energetics, but extracton of the energy they contain requires large capital expenditures to drill wells, install heat pipes, and combat intense corrosion and salt precipitation.

1. Utilizaton of Heat in the Surface Layers of the Earth

The A. V. Lykov Heat and Mass Transport Institute of the Academy of Sciences of the Belorussian SSR has developed heat pipes and thermosyphons [2] which allow extraction of energy from the ground at a depth of 10-20 m. Taking the ground to be a semiinfinite body and assuming its surface planar (y = 0) with a periodically varying temperature [3], one can find the temperature change with time at a given depth as

$$T = T_g + \sum_{n=1}^{\infty} T_n \cos(n\omega\tau - \varepsilon_n),$$

where T_g is the ground temperature at y = 0.

With the aid of such devices seasonal and diurnal soil temperature variations can be reduced to a minimum and a temperature field achieved which is described by the system of equations:

$$\frac{d}{dy}\left(K\frac{dT}{d\tau}\right) = -A; \quad \frac{d^2T}{d\varepsilon^2} = -AK; \quad \varepsilon = \int_0^y \frac{dy}{K},$$

the solution of which at A = 0 has the form

$$T = T_g + Q\varepsilon.$$

In dry ground the thermal flux Q reaching the evaporator of a heat pipe usually comprises 10-15 W per 1 m of tube length and is controlled by the thermal resistance of the ground.

To evaluate the possibility of extracting thermal energy from moist soil it is necessary to consider a system of nonlinear differential equations, describing heat and mass transport in the presence of the combined actions of moisture, temperature, and gravitational fields as well as capillary forces [4].

If we make the assumptions of lack of convection in pores, independence of the variable parameters such as temperature, volume moisture content, and gaseous phase pressure, together with constancy of the thermophysical properties of the components [5], then heat and mass transport in a nonisothermal moist capillary-porous body can be described by a system of two nonlinear differential equations in partial derivatives:

the equation of mass transport

$$\frac{\partial x_l}{\partial \tau} = \nabla(D_x\nabla x_l + D_T\nabla T + D_g\nabla y);$$

the equation of energy transport

$$(\rho c)^* \frac{\partial T}{\partial \tau} = \nabla(\lambda_{ef}\nabla T) + \rho_l \Delta h_v [\nabla(D_{xv}\nabla x_l + D_{Tv}\Delta T)].$$

In the given case, we consider as motive forces capillary forces which have an effect on changes in moisture and temperature, molecular diffusion forces which affect the change in vapor pressure with change in temperature, and the gravitational field.

In the gravitational field there may exist certain regions of moist capillary-porous body [6] where the effective thermal conductivity λ_{ef} is more than an order of magnitude greater than that of moist soil due to the presence of evaporation-condensation phase transitions. In this case it is possible to extract thermal fluxes from the soil reaching 100-150 W and more at 1 m depth with the use of heat pipes.

A combination of heat pipes and heat pumps makes possible utilization of scattered low potential heat sources and increase in heat pump condenser temperatures to 50-60°C [7].

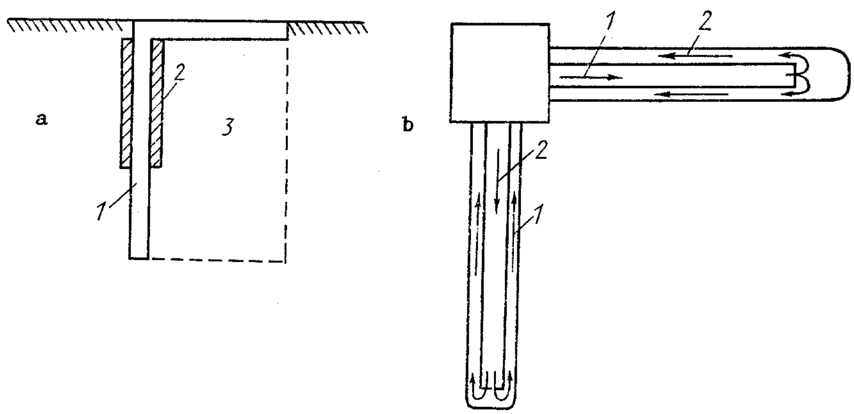

Fig. 1. Vapor-dynamic thermosyphon: a) location in ground (1, thermosyphon; 2, adiabatic zone; 3, thermal effect zone); b) longitudinal section (1, vapor; 2, liquid).

2. Utilization of Heat from Geothermal Water and Deep Layers of the Earth

The heat of geothermal waters can be used by drilling wells into the ground and bringing the water to the surface through tubes, where its heat is extracted in heat exchangers. The used water is then again returned to the ground with pumps. A second method for extracting geothermal water energy, more preferable in our opinion, involves installation within wells of long heat pipes, the condensers of which, located at the surface, are used to heat a second water circuit for a vapor turbine cycle or heating the soil.

This technique eliminates salt stoppage of the surrounding medium and pipes. This same variant is convenient for extraction of energy of deep rock formations.

The Heat and Mass Transport Institute has developed long length vapor-dynamic thermosyphons [8], suitable for this technique. The unique feature of these thermosyphons (Fig. 1) is the use of separate channels for vapor and liquid.

It is well known that in a conventional thermosyphon the critical thermal flux is limited by the interaction of the oppositely directed flows of vapor and liquid, and is inversely proportional to evaporator length. At a thermosyphon evaporator length of 15-20 m the critical thermal flux becomes extremely small, and only the upper portion of the tube is actively used. The vapor-dynamic thermosyphon does not have this shortcoming, so that units hundreds of meters or even kilometers long can be constructed.

Within the coaxial gap of the vapor-dynamic thermosyphon condenser vapor condenses, while in the coaxial gap of the evaporator the two-phase vapor-liquid mixture moving upward boils, with the ratio of the vapor and liquid phases changing as a function of evaporator height.

In the lower part of the thermosyphon the liquid arriving through the central tube is in a supercooled state due to the large pressure of its hydrostatic column.

The maximum moving head which can be produced in such a thermosyphon is determined by the difference between the heights of the liquid columns in the central tube and coaxial gap:

$$\Delta P_{\max} = \rho_l g (H - H_1).$$

The total pressure loss in vapor and liquid over the entire circulation circuit cannot exceed the value $\Delta P_{\max}$ [9]:

$$\sum_i \Delta P_{\text{f}} + \sum_i \Delta P_{\text{ac}} + \sum_i \Delta P_{\text{lr}} \leqslant \Delta P_{\max}.$$

A second condition for stability of operation of a vapor-dynamic thermosyphon is the expression

$$\Delta P_{\max} = \left.\frac{dP}{dT}\right|_{\bar{T}} (T_{\text{ev}}^2 - T_{\text{con}}^2) \cong \frac{2r'\rho_l\rho_v}{\rho_l - \rho_v} \frac{T_{\text{ev}}^2 - T_{\text{con}}^2}{T_{\text{ev}}^2 + T_{\text{con}}^2}.$$

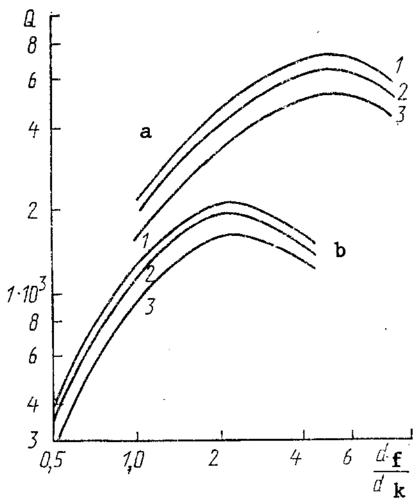

Fig. 2. Limiting thermal flux in vapor-dynamic thermosyphon: a) vapor in inner tube, liquid in gap; b) vapor in inner tube and coaxial gap; 1) tube wall thickness 0.2 mm; 2) 0.5; 3) 1.0; heat transport agent, water. Q, W.

The one-dimensional steady-state problem of hydrodynamics and heat exchange in a vapor-dynamic thermosyphon with separate channels for vapor and liquid in the evaporator with the condition of constancy over channel cross section of pressure, temperature, and velocity for vapor and liquid can be formulated in the following manner:

$$G = G_l + G_v = (\rho_l u_l A_l + \rho_v u_v A_v) A = \text{const}, \quad -dP = G^2 d_l - g\rho_l dy \ \text{(liquid)}$$

$$-dP = G^2 d\,[(1-x^2)/\{\rho_l (1-\alpha)\} + x^2/\rho_2\alpha] + dP_l - g\,[\rho_l (1-\alpha) + \rho_v \alpha]\, dy$$

$$\text{(two-phase flow)}, \quad dh = [q\pi d_2/GA]\, dy.$$

In [10] calculations were performed for the dependence of limiting thermal flux on the ratio of the hydraulic diameters of the channels in the vapor-dynamic thermosyphon condenser, results of which are shown in Fig. 2. Similar calculations must also be performed for the thermosyphon evaporator, in which three zones of heat exchange with the earth through the tube wall may exist: a) developed boiling at the saturation temperature; b) boiling of the underheated liquid; c) convective heat exchange of the underheated liquid located at the pressure of the liquid column in the inner tube.

Aside from external heat exchange in the thermosyphon evaporator, heat exchange occurs through the wall between the cold liquid moving downward in the internal tube and the heated two-phase mixture moving upward under the action of the density difference in the coaxial gap:

$$\Delta Q = kA_{\text{TT}} (T - T) = kd_{\text{ef}} \Delta y\, (T_0 - T_i),$$

where the heat-transfer coefficient k is a function of evaporator height and may vary from 0 to 2000 W/(m·h).

Examples of heat-exchange calculations in these three zones were presented in [11].

For a specified temperature head the critical thermal flux Q_{cr} transferable by a vapor-dynamic thermosyphon depends on the thermal resistances of the evaporation and condensation zones.

CONCLUSIONS

Variants of heat pipes and thermosyphons for utilizing energy of surface soils, geothermal water, and deep rock formations have been considered. The A. V. Lykov Heat and Mass Transport Institute has developed high length vapor-dynamic thermosyphons for this purpose, tested the devices, and compared experimental results to calculations.

NOTATION

T, temperature; τ, time; Q, thermal flux; q, thermal flux density; ω, frequency; x, y, z, coefficients; D, diffusion coefficient; D_g, diffusion coefficient in gravitational field; D_p, diffusion coefficient under action of pressure field; c_p, specific heat; h, enthalpy; x_ℓ, liquid mass per unit volume; ρ, density; H, height; r', latent heat of vapor formation; d, diameter; X, Locart–Martinelli parameter; α, porosity; G, mass flow rate; A, area; d_v, inner diameter of outer tube. Subscripts: ev, evaporator; con, condenser; f, friction; ac, acceleration; l.r., local resistance; k, heat transfer coefficient; ex, external diameter of inner tube; i, inner tube; ℓ, liquid; v, vapor.

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A MATHEMATICAL MODEL OF SOOT FORMATION IN NATURAL GAS COMBUSTION.

1. KINETIC EQUATION AND CRITICAL TEMPERATURE OF THE DEHYDROGENIZATION PROCESS

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UDC 621.43

Elements of a mathematical model are presented for the process of soot formation in natural gas combustion, based on thermal decomposition of the CH_4 methane molecule. The expressions obtained can be used for calculation of the size and concentration of soot particles and their thermal radiation in a natural gas flame.

The thermal radiation produced by a natural gas flame depends significantly upon the size and concentration of soot particles within the flame, which substance, together with the gaseous products of complete combustion (CO_2, H_2O) determine its optical thickness and emissivity [1].

In turn, the soot-formation process depends on the conditions of internal heat-mass exchange between the various zones of the flame, related mainly to the turbulent microstructure. Analysis of well-known expressions for the turbulent mixing time indicates that increase in the scale of turbulent pulsations increases mass exchange within the flame and leads to a reduction in soot-formation time. On the other hand, retardation of the soot-formation process can be achieved by reducing the scale of turbulent pulsations.

It follows from the above that the possibility of controlling the soot-formation process and, thus, the emissivity of a flame rests upon the ability to control the aerodynamic microstructure of the turbulent flame in the segment where that structure is formed, by controlling the processes of fuel and air mixing. It then becomes possible to organize combustion temperature regimes and the dynamics of the soot-formation process.

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