HEAT PIPES FOR HEATING AND COOLING THE GROUND

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Uninterrupted, year-round operation of greenhouses and assurance of required conditions in liquid-water complexes requires additional heating of the ground and air during the cold period of the year. Removal of snow and ice from roads requires heating of the road surface. The ground must be heated during wintertime construction, since frozen earth has a higher mechanical strength. The problem of unloading and loading frozen bulk materials onto railroad cars and ships is well known. Heating of the soil in greenhouses enables strawberry production of up to 50 tons/ha, i.e., 400% higher than with unheated soil, potatoes ripen one month earlier with a yield of up to 30 tons/ha and the deviation of the sizes of the potatoes from the standard is not greater than 8% [1].

The problem of ensuring the required conditions for operation of temporary roads in swampy locations in the northern regions of the country during the spring-winter period requires rapid freezing of the ground employing the cold from the atmosphere. Freezing and cooling of the soil is also desirable from the standpoint of creating underground cold stores, used during the summer months in air-conditioning and ventilation systems.

Analysis of nontraditional (alternative) sources of energy, such as the sun, heat in the ground, ground water, biomass, etc. [2], shows that they can provide the required temperature regime in greenhouses throughout the year, with the exception of a short period when the temperature of the environment drops to −15-20°C. During these periods additional heating of the ground and air with the use of fossil fuel is required [3].

The seven-year plan for the Unified Energy System, starting in 1980, provides for the building of large commercial greenhouses, intended for year-round agricultural production with subsoil heating with the combined use of alternative sources of energy, VÉR, and fossil fuel [1]. A similar program was undertaken in the Hungarian People's Republic also [4].

Heat pipes (HP), which are efficient heat transmission device, whose internal thermal resistance equals 0.005-0.01 K/W, can be employed together with heat pumps in order to utilize the solar energy, heat stored in the soil, biomass, and commercial VÉR. It is also desirable to use them for cooling and freezing of the soil employing the cold in the atmosphere. Heat pipes not only make it possible to transport heat over a significant distance without losses, but they also permit collecting together scattered low-density energy sources and transform them into a local high-density source and vice versa. It is especially important to combine alternative energy sources, VÉR, and classical heaters together with heat pipes [5]. Such combined heating systems with economical consumption of fossil fuel permit solving the problem of heating protected soil over a large part of the territory of the USSR [6].

1. Heat Pipes for Heating and Cooling the Ground. Gravitational heat pipes and thermosiphoning systems are employed for the purpose mentioned above. In these systems the liquid from the condenser is returned to the evaporator both by means of a porous wick and by stream flow under the action of gravity along the bottom generatrix of the pipe surface. In order to ensure that the excess liquid from the stream is uniformly distributed over the entire surface of the evaporator, screw inserts [7] or spirals [8] are placed into the evaporator, which permits lowering the thermal resistance of the evaporator. In gravity heat pipes the thickness of the wick is reduced to a minimum, and its role reduces to distributing liquid along the perimeter of the evaporator, which significantly reduces the thermal resistance. In such heat pipes the axial limit of heat transport Q_{crit} is determined by the hydrodynamic interaction of oppositely moving liquid-vapor flows.

To determine the thermal resistance of gravity heat pipes and the heat-transport limit one usually studies the equation of hydrodynamics for a liquid and vapor under the assumption that their flow is stratified, and the flow regime of the liquid is laminar, and the amount of liquid in the pipe is small ($V_\ell = 0.6\text{-}0.7\ V_{evap}$) [9]:

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$$\nu_l\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\left(\frac{\partial u}{\partial z}\right)_{\mathrm{av}}=\frac{1}{\rho_l}\frac{dP_l^n}{dz}+g\sin\varphi, \tag{1}$$

$$u_{\omega_1}=0;\ \left.\frac{\partial u}{\partial y}\right|_{\omega_2=0}=-f_v\frac{\rho_v\bar{u}_v^2}{8\mu_v},$$

$$\frac{d}{dz}\left(P_v+\rho_v\beta_v\bar{u}_v^2\right)=-f_v\frac{\rho_v\bar{u}_v^2}{2D_{hv}}. \tag{2}$$

The equation of pressure balance for any section of the heat pipe has the form

$$\frac{dP_l}{dz}-\frac{dP_v}{dz}=\rho g\cos\varphi\left(\frac{dH'}{dz}-\mathrm{tg}\,\varphi\right), \tag{3}$$

where the coordinate z is measured from the condenser side. For an inclined or horizontal heat pipe the liquid moves under the action of the hydrostatic head, arising as a result of the change in the level of the stream along the heat pipe. The heat flux Q is related with the average velocities of the liquid and vapor by the relation

$$Q(z)=\bar{u}_vS_v\rho_vr=\bar{u}_lS_l\rho_lr.$$

The equation of conservation of mass for boundary conditions of the third kind on the surface of the heat pipe for known coefficients of heat transfer in the evaporator a_e and condenser α_c is

$$\frac{dQ(z)}{dz}=-\frac{\alpha_{\mathrm{ex}}(T_{\mathrm{ex}}-T_v)2\pi R_{\mathrm{ex}}}{1+\alpha_{\mathrm{ex}}/\alpha_c};\ Q(0)=0,\ Q(L)=0. \tag{4}$$

The method for solving the system of equations (1)-(4) is described in [9]. A properly chosen geometry of the heat pipe and capillary structure permits obtaining R_{HP} = 0.005-0.01 K/W.

2. Formulation of the Problem of Heating Protected Soil. We shall study the problem of heating the surface of a layer of soil with the help of heat pipes buried in the soil. It is well known [5] that diurnal temperature oscillations propagate to a depth of less than 1 m, while seasonal oscillations propagate to a depth of about 10 m. Regarding the soil as a semibounded body and its surface as a plane with the coordinate x = 0 with a periodically varying temperature

$$t=T_0+\sum_{n=1}^{\infty}T_n\cos(n\omega\tau-\varepsilon_n), \tag{5}$$

in accordance with the solution presented in [10] we write the law of variation of the temperature of the soil at a depth x from the surface in the form

$$t=T_0+\sum_{n=1}^{\infty}T_ne^{-K^*x\sqrt{n}}\cos(n\omega\tau-\varepsilon_n-K^*xn^{1/2}), \tag{6}$$

where k* = (ω/2x) and T_0 is the starting temperature of the soil. According to the data of [5], the heat flux transported by the heat pipe from deep within the layer to its surface also varies in time according to a harmonic law, since the heat pipe operates as an automatic system and transports the heat flux only when the temperature on the surface of the earth drops below the temperature deep in the layer.

The problem of two-dimensional axisymmetric nonstationary heat transfer from a heat pipe buried in the ground is formulated in the form

$$\frac{\partial t}{\partial\tau}=a\left(\frac{1}{r}\frac{\partial t}{\partial r}+\frac{\partial^2 t}{\partial r^2}\right),\ r_0\leqslant r<\infty. \tag{7}$$

$$\lambda\left.\frac{\partial t}{\partial r}\right|_{r=r_0}=\alpha\left(t|_{r=r_0}-t_{\mathrm{B}}\right), \tag{8}$$

$$t|_{\tau=0}=t_{\mathrm{M}}. \tag{9}$$

The problem (7)-(9) is solved in [10] with the help of the Laplace transformation. To determine the heat flux transported by the heat pipe the improper integral of a complicated combination of Bessel functions with singularities of the first and second kind must be calculated. Because of the complexity of such calculations approximate methods for solving the problem (3)-(5) of [11] have been developed. Owing to the low inertia the transient processes in heat pipes occur much more rapidly than do changes in the external conditions of heat transfer. It can therefore be assumed that heat pipes operate in a nearly stationary regime. In [11] it is assumed that the temperature distribution in the soil mass, right up to the boundary of the thermal effect R(τ), corresponds to the stationary case. The law for the motion of the boundary of the thermal effect is assumed to have the form

$$R(\tau)=\sqrt{r_0^2+4a\tau}. \tag{10}$$

The procedure for calculating nonstationary heat transfer between the heat pipe and the soil is studied in detail in [12].

Heat pipes placed in the soil operate like thermal diodes and transport the heat flux upwards in accordance wth the law of variation of the temperature in the surface layer of the soil. Thus with the help of heat pipes the diurnal and seasonal oscillations of the temperature near the soil surface can be reduced, in a definite approximation, to a minimum and a nearly stationary temperature distribution as a function of the coordinate x can be achieved in the form

$$\frac{d^2t}{d\xi^2}=-AK,\ \text{where}\ \xi=\int_0^x\frac{dx}{K}, \tag{11}$$

whose solution [10] for A = 0 has the form

$$t=T_0+F\xi, \tag{12}$$

where T_0 is the temperature of the earth's surface and F is the heat flux. The value of T_0 depends both on the intensity of the heat transfer between the earth's surface and the surrounding medium and on the heat transfer between the heat pipe and the soil. The total heat flux (thermal losses) from the earth's surface to the surrounding medium is given by

$$\Sigma Q_n=Q_{\text{conv}}+Q_{\text{rad}}+Q_{\text{evap}} \tag{13}$$

Under conditions of forced ventilation of greenhouses [3]

$$Q_{\text{vent}}=m[C_{pA}(T_A-T_i)+W_A(h_w+C_{pm}T_A)-W_i(h_w+C_{pw}T_i)]. \tag{14}$$

Heat flows to the earth's surface in a greenhouse are given by

$$\Sigma Q_i=Q_{\text{s.r}}+Q_{\text{r}}+Q_{\text{h}} \tag{15}$$

where $Q_{\text{s.r}}$ is the heat flux due to solar radiation, Q_{r} is the heat flux accompanying the respiration of plants, and Q_{h} is the heat flux owing to the heat conduction in the soil. The difference $\Sigma Q_n - \Sigma Q_i \le Q_{\text{hp}}$ must be compensated by the heat flux transported along the heat pipe:

$$Q'_{\text{hp}}=K_{\text{hp}}A'(T_e-T_c). \tag{16}$$

The number of heat pipes per unit area of the surface in the greenhouse is given by

$$n=Q_{\text{hp}}/Q'_{\text{hp}}.$$

According to the data of [5], the heat losses ΣQ_n to the surrounding medium during the spring-winter period in the central band across Europe equal 100-200 W/m², and the heat flux taken up by the evaporating part of the heat pipe, oriented vertically in the soil down to a depth of 15-20 m, equals 10-15 W for each meter of depth. Thus with an evaporator 20 m long it is possible to extract from deep dry soil up to 200 W and to compensate the heat losses indicated above. If the soil is saturated with warm ground water, the heat flux extracted from the soil by one heat pipe can be increased by a factor of two to three. Figures 1 and 2 show the temperature profile along a heat pipe lying in a heat reservoir in the ground, the rate of growth of leaves and the height of the plants heated by the heat pipe [14].

3. Heating of Soil in Greenhouses with the Use of Heat from the Ground, Groundwater, the Sun, and Biomass. Low-grade heat is accumulated in the soil primarily during the summer, when solar radiation heats the soil and the ground water. This process can be intensified and a significant amount of energy can be stored with the help of solar collectors and spe-

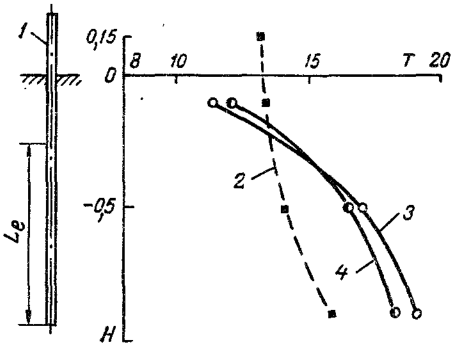

Fig. 1

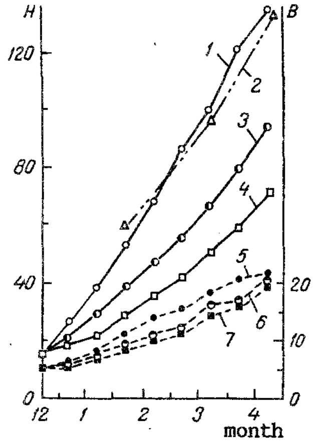

Fig. 2

Fig. 1. Temperature field in the soil in the presence of an underground heat reservoir [11]: 1) heat pipe; 2) temperature field along the side surface of the heat pipe; 3, 4) temperature field in the soil around the heat pipe at a distance of 5 and 15 cm. T, °C; H, m.

Fig. 2. Rate of growth of plants and increase in the number of leaves on them as a function of time in a film greenhouse: 1, 5) with underground heat storage and heat pipe; 3, 6) with heat storage; 4, 7) without heat storage and heating; 2) greenhouse heated by burning fossil fuel (1-4: rate of growth of plants; 5-7: rate of increase in the number of leaves). H (cm) is the height of the leaves; B is the number of leaves.

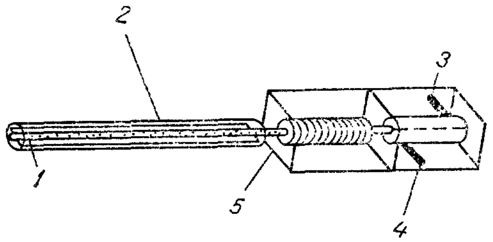

Fig. 3. Heat pipe with heat storage and a liquid heat exchanger: 1) heat pipe evaporator, element of a solar collector; 2) glass envelope; 3, 4) water in and out; 5) heat storage reservoir.

cial heat storage systems. It is well known that heat flows from deep within the earth up to earth's surface increase substantially, if underground heat networks, electrical cables, sources of underground fires, etc., in other words, local sources of heat, are present. A number of heat and cold storage systems for compensating the diurnal and seasonal variations of the temperature have now been built [12, 13]. The storage systems required for diurnal temperature changes are small; such systems often employ a phase-change material as the heat-storing medium (paraffin, Glauber's salt, etc.). Figure 3 shows a module for a diurnal heat storage system combined with a heat pipe, which is an element of a solar collector. The heat reservoir is filled with hermetically sealed polyethylene spherical capsules 20-30 mm in diameter, filled with a phase-change material $C_{18}H_{38}$, which with a melting temperature of 28°C stores 140 J/cm^3 of heat. Hot water, heated in a solar collector with heat storage, is pumped through polyethylene pipes underground and heats the ground [5].

Water reservoirs and enclosures filled with gravel, pebbles, or sand are used for large-scale seasonal heat storage systems, intended for long-term storage of low grade heat. Figure 4 shows a diagram of a water heat-storage reservoir with a volume of 6000 m^3 [8]. It is 50 m long, 16 m wide, and 7.5 m deep. The heat stored in such a reservoir during the summer can heat during the winter a greenhouse with an area of 20,000 m^2.

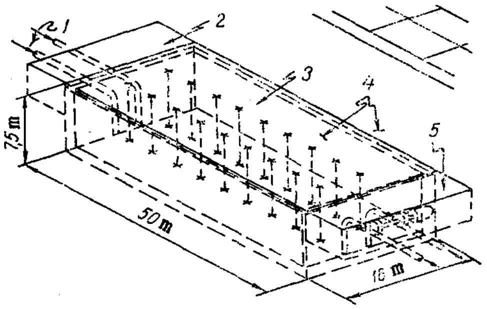

Fig. 4

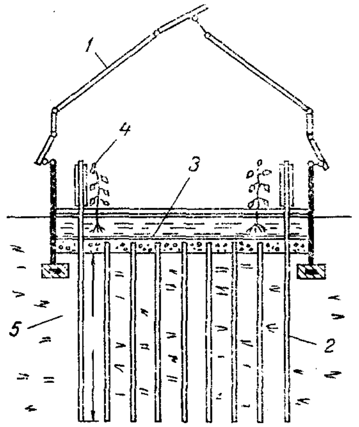

Fig. 5

Fig. 4. Diagram of an underground water reservoir for seasonal heat storage: 1) hot water in; 2) water distribution zone; 3) reservoir; 4) water level indicator; 5) pumps.

Fig. 5. Transverse section of a greenhouse with heat pipes, placed in an underground heat-storage reservoir: 1) film roof; 2) heat pipes; 3) zone in which the roots of the plants are heated; 4) plant; 5) soil.

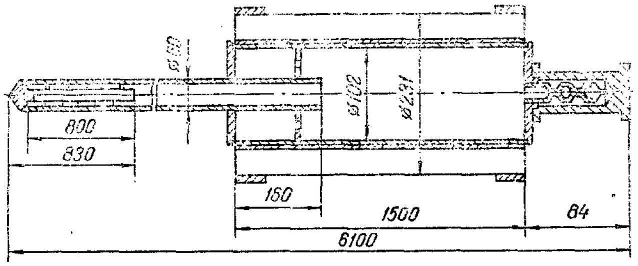

Fig. 6. Diagram of heat pipe for heating protected soil by redistribution of heat flows from deep underground to the surface of the earth.

Enclosures filled with biomass, into which polymer tubes are inserted, should also be included amongst seasonal heat-storage systems. Reservoirs for biomass are filled with agricultural wastes – manure, residue from grapes, plums, apples, etc. Twenty tons of compost are required to heat 200 m^2 of protected soil in a greenhouse over a heating period of 500 h, and in this case, the heat released is sufficient to maintain a positive soil temperature even when the outdoor temperature is −15°C. Utilization of solar energy and the energy stored in biomass makes it possible to create autonomous establishments which are not tied to commercial enterprises [3].

Figure 5 shows the transverse section of a film greenhouse 1, under which there is a heat-storage reservoir 4, perforated by heat pipes 3. The heat in the heat reservoir is supplied either by a solar collector (Fig. 9) or a biomass reservoir (Fig. 7). Figure 7 shows a section of a heat-storage reservoir filled with biomass lying next to the greenhouse. The heat from the reservoir is fed into the protected soil by heat pipes. The results of studies of the growth of tomatoes in hot houses with protected soil heated with heat pipes, lying in an underground heat-storage reservoir, to which heat is supplied by a solar collector, are described in [12]. Experimental data on the extraction of heat over an area of 1500 m^2 from soil with the help of a heat pipe 33.8 mm in diameter, an evaporator 18.6 m long, and a long horizontal condenser in the surface layer of the earth 4.9 m long and 33.8 mm in diameter are presented in [14]. A total of 1213 heat pipes are buried in the soil.

Heat pipes were placed in the ground with a spacing of 610 mm and heat the surface, transmitting a heat flux of 150 W/m^2. The pipes are made of steel, and the heat-transfer

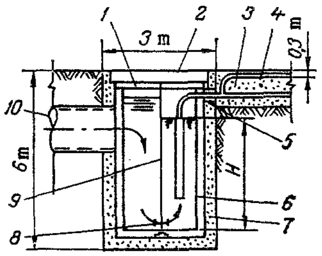

Fig. 7

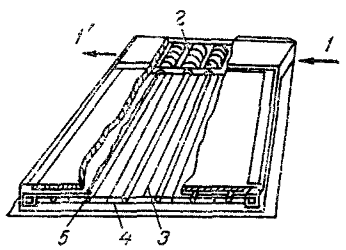

Fig. 8

Fig. 7. Heat-storage reservoir — a tank for biomass or warm water: 1) thermal insulation; 2) tank cover; 3) soil; 4) heat-pipe condenser, placed horizontally in the soil; 5) packing; 6) thermal insulation; 7) concrete wall; 8) opening; 9) barrier; 10) pipe.

Fig. 8. Flat, heat-pipe based solar collector: 1, 1') water in and out; 2) finned condensers of the heat pipe; 3) radiation panel; 4) thermal insulation; 5) heat-pipe evaporators.

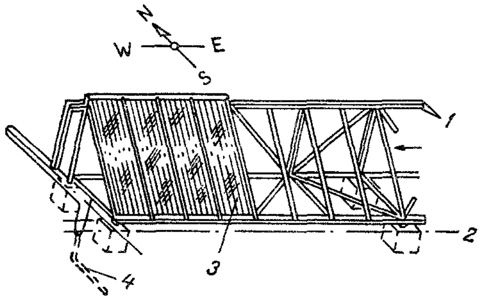

Fig. 9

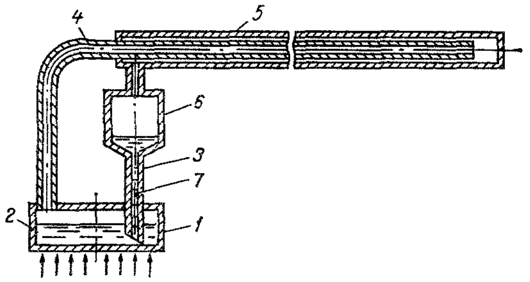

Fig. 10

Fig. 9. Frame with flat solar collectors: 1, 4) water in and out; 2) foundation bearing; 3) solar collectors.

Fig. 10. Diagram of heat pipe for heating the surface of the ground (the heat source is a thermoelectric heater): 1) heat pipe evaporator; 2) heat-transfer agent; 3) overflow pipe; 4) steam channel; 5) heat pipe condenser; 6) auxiliary heat pipe condenser.

agent is ammonia. A greenhouse in which 31 heat pipes were installed over an area of 36 m^2 is described in [12]. The heat pipes maintained the temperature of the protected soil equal to 25°C during the winter. The average temperature of the underground heat-storage reservoir equalled 30°C, while the outdoor air temperature during the winter equalled −6°C. This example indicates the possibility of growing vegetables the year round. Copper heat pipes 150 cm long with an outer diameter of 44.5 mm and an inner diameter of 42.1 mm were buried in the ground at a depth of 120 cm, and the heat-transfer agent was water. The heat-pipe condensers had 24 fins 25 mm high, 0.8 mm thick, and 200 mm long. The heat-storage reservoir was heated by a solar collector of the north-south type. The hot water flowing along pipes buried 1.5 m underground heated it to 28-30°C.

Heat pipes and solar collectors for heating protected soil in greenhouses have been developed at the Institute of Heat and Mass Transfer of the Belorussian SSR Academy of Sciences (IHMT) [5]. Figure 6 shows a diagram of the heat pipes with the following parameters: length L_{hp} = 6100 mm, evaporator length ℓ_e = 4500 mm, outer diameter of the evaporator d_{out} = 60 mm, outer diameter of the condenser d_c = 102 mm, thickness of the pipe wall δ = 3 mm, the pipe material is steel, and the heat transfer-agent is ammonia. The condenser has 12 fins 60 mm high, 1500 mm long, and 3 mm thick. A screw setup which twists the film of liquid and improves the wetting of the inner surface of the evaporator, which intensifies heat exchange, is placed in the evaporator.

Figure 8 shows a diagram of a flat solar collector developed at IHMT. The collector is made of aluminum heat pipes, with longitudinal finning, or thermosiphons. The heat-transfer agent is ammonia or freon-12. The heat-pipe condensers have transverse finning and are placed in a liquid heat exchanger; cold water flows into the inlet 1 and hot water flows out of the outlet 1'. The area of the surface exposed to solar radiation equals 1 m^2 [15].

TABLE 1. Data from Tests of Heat-Pipe Based Heater for Railroad Switches Under Natural Conditions

Point at which temp. is measured	Heater No. 1 (T, °C)			Heater No. 1 (T, °C)		
	tongue	foot plate	rail	pipe	tongue	rail
I. Tongue positioned to left; T_{air} = −1.5°C, snow, wind, overcast weather						
1	—5,6	3,6	8,3	124	15,7	23,6
2	—7,0	2,2	3,6	120	10	15,7
3	—5,6	2,2	2,9	123	7,9	12,9
4	—5,6	2,2	3,3	123	4,3	6,9
5	—5,6	2,2	3,6	122	4,3	4,3
6	—4,9	2,2	2,9	116	2,2	7,9
7	—5,6	2,2	4,3	115	2,2	5,7
II. Tongue positioned to right; T_{air} = −4°C, light wind, sunny						
1	5,1	23,8	14,5	102,5	27,5	27,5
2	7,1	15,7	12,7	109	16,8	18,5
3	7,2	26,8	11,1	130,4	20,7	18,5
4	7,5	21,1	10,7	131,1	13,5	23,2
5	7,1	18,5	10	120,4	14	16,8
6	6,4	12,1	8,5	118	11,4	17,1
7	6,1	8,1	7,5	131,1	11,4	15,4
8	4,7	7,5	7,5	142	8,2	14,2

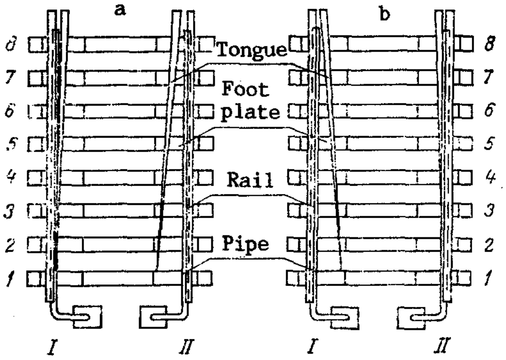

Fig. 11

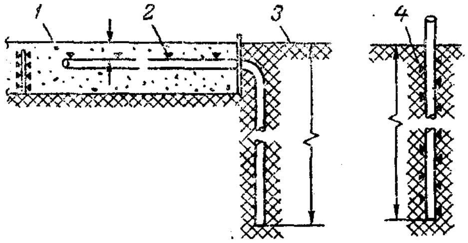

Fig. 12

Fig. 11. Diagram of heat-pipe-based heaters for railroad switches: a) position of switch to the left; b) to the right: I and II) heaters Nos. 1 and 2.

Fig. 12. Diagram illustrating the heating of the road bed with the help of heat pipes buried in the ground: 1) road surface; 2) heat pipe; 3) surface of the ground; 4) temperature sensors.

4. Heating of Ground by Heat Pipes from Organic Sources of Heat. In those cases when the ground cannot be heated with the help of alternative energy sources or VÉR, it is desirable to employ heat-pipe-based heaters, whose heat sources are thermoelectric heaters or gas burners. Figure 10 shows a diagram of a vapor-dynamic thermosiphon developed at IHMT [16]. Such a heater is capable of heating a protected layer of soil 40 to 60 cm wide and up to 40 m long, maintaining its temperature at a level of 20°C. A characteristic feature of such heat-pipe-based heaters is that they automatically heat the coldest sections of the ground, since it is precisely at these locations that intensive heat exchange between the heat pipe and the soil occurs. Heaters which actively heat the soil are also useful from the standpoint of disinfecting the cultivated layer of soil and in the fight against harmful insects and bacteria, since they make it possible to raise rapidly the soil temperature under the film up to 60-65°C. They are very effective in protecting plants from seasonal frosts. Vapor-dynamic thermosiphons were employed in the experimental greenhouse of the Central Botanical Garden of the Academy of Sciences of the Belorussian SSR for heating protected soil when growing lilacs propagated by cuttings. Thermosiphons were placed horizontally at a depth of 20 cm from the surface of the soil. They were 6 m long and had an outer diameter of 16 mm; the heat source was a 0.7 kW thermoelectric heater. The maximum temperature of the surface of the thermosiphon in dry soil reached 60°C. With the help of a temperature regulator it is possible to regulate smoothly the soil temperature over a wide range depending on the weather.

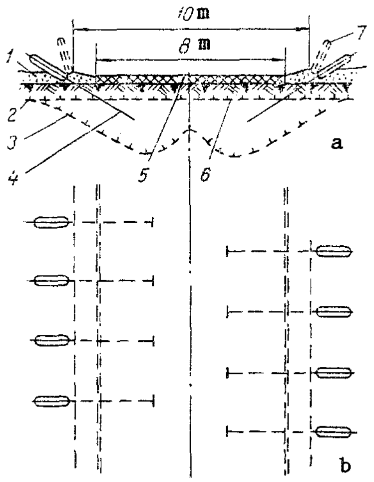

Fig. 13

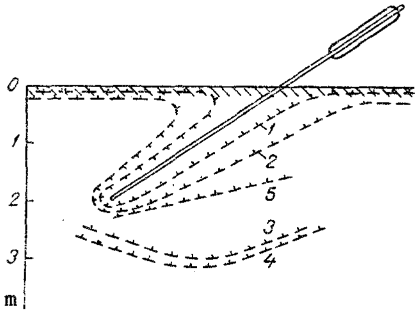

Fig. 14

Fig. 13. Transverse section of a road with two-way traffic, whose bed is frozen with the help of heat pipes during the winter: 1) snow cover; 2) depth of natural freezing of the ground; 3) freezing front after installment of heat pipes; 4) heat pipes; 5) layer of brushwood; 6) layer of compacted snow; 7) condensers [18] (a: transverse section of the road; b: view from the top).

Fig. 14. Region of freezing of the soil around the heat pipe with aluminum fins on the condenser: 1) November 17, 1978; 2) December 2, 1978; 3) April 5, 1979; 4) June 1, 1979 [18].

Heaters based on analogous thermosiphons for railroad switches were developed at IHMT, and they were tested under natural conditions. Figure 11 shows a diagram of the installation of a thermosiphon in a switch. The heat pipe is 4500 mm long and 16 mm in diameter. The heat source is a 2 kW thermoelectric heater. The tests were performed during snowy weather with a moderate wind, and the air temperature fluctuated from −5 to −1.5°C. During the tests the position of the rail tongue changed to the left (Fig. 11a) or to the right (Fig. 11b). The results of the temperature measurements are presented in Table 1. During the tests the temperature of the heat-pipe condenser equalled 110-120°C, which indicates the large margin available in the power of the heater. One-and-a-half hours after the heaters were switched on the switch was dry and free of snow; the falling snow immediately evaporated. The tests performed confirmed the suitability of this design of a heater for railroad switches in order to fight against snow and ice.

In the European regions of our country the problem of fighting against snow and ice during the winter on essential roads, bridges, streets, etc., is an important problem. The use of heat pipes, buried in the ground and transmitting heat from underground to the surface in order to heat the road bed (Fig. 12), has the following advantages over other methods of heating involving the burning of fossil fuel: 1) it is not necessary to use fuel; 2) high reliability and long operating lifetime (10-15 years) of the heating system are guaranteed, since the heat pipes are used independently of one another, there is a large number of heat pipes, and the efficiency equals 95-97%; and 3) there is no danger of destroying the asphalt or concrete because of thermal stresses, since the pavement on the road is guaranteed to be isothermal to a high degree. The heat flux transmitted by the heat pipes is inversely proportional to R_{hp} and directly proportional to ΔT. When the temperature of the road bed drops, the difference of the temperatures ΔT at the ends of the heat pipe increases, and the magnitude of the heat flux transmitted along the heat pipe increases, i.e., the pipe operates in an automatic mode. The energy expended on heating the road during the winter is compensated during the summer by solar radiation.

5. Cooling and Freezing of Soil with the Help of Heat Pipes. Heat pipes have the unique property that they can be used with any spatial orientation, and they do not require energy consumption and special equipment. Their thermal resistance is two to three orders of magnitude lower and less metal is required to make them than in the case of single-phase liquid or air thermosiphons. Figure 13 shows an example of the application of heat pipes for freezing the road bed in order to increase its mechanical strength. The heat pipes,

designed at IHMT, were installed at an angle of 30° on the shoulders of a two-lane highway [5, 12].

A profile of the heat pipe is shown in Fig. 6. Natural tests of seven experimental heat pipes were performed under the conditions of the northern region of the Ob' River in order to check their efficiency for freezing thawed soils using the natural cold of the atmosphere. Figure 14 shows isotherms of the region of freezing of the soil around the heat pipes, placed along the road. The most reliable results on freezing of the soil around heat pipes were obtained when the air temperature became positive (April-May). The maximum depth of freezing around the heat pipes was 3.5 m, and the frozen zone was 4-5 m wide. Analogous heat pipes [17, 18] can be used to freeze reservoirs and rivers in the northern regions of the country for the construction of temporary passages. The ice columns formed around the heat pipes substantially reduce the construction time, and they reduce the cost of the project and increase the load capacity of the passage.

Thus heat pipes are self-regulating heat-exchange systems, which, being buried in the ground at a depth of 10-20 m, make it possible to smooth temperature gradients in the soil without consumption of fossil fuel, which makes it possible either to maintain a positive temperature on the surface of the protected soil in greenhouses, the floor in animal complexes, road beds, and bridges or, by employing the cold stored in the atmospheric air, to freeze soil deeply during the winter in order to increase its mechanical strength.

Heat pipes combined with alternative energy sources and VÉR at commercial enterprises make it possible to save substantial amounts of fossil fuel in a number of industrial and economic sectors with economic heating of protected soil in greenhouses and hot houses and heat treatment of soil and other bulk loads.

NOTATION

τ, time; t and T, temperature; x, y, and z, coordinates; u, velocity; ρ, density; g, acceleration of gravity; ϕ, angle; P, pressure; r, latent heat of vaporization; λ, coefficient of thermal conductivity; β_v, coefficient of momentum flux; ν and μ, kinematic and dynamic viscosity; f, coefficient of friction; D_h, hydraulic diameter; S, area; Re, Reynolds number; α, heat transfer factor; R, radius; Q, heat flux; K, dimensionless tangential stress; H', height of the stream of liquid; M, mass of the heat-transfer agent; L, length of the pipe; ω, frequency; a, coefficient of thermal diffusivity; m, mass flow rate; C_{pA} and C_{pw}, heat capacity of air and water vapor; h_w, enthalpy of water vapor; W, moisture content; and H, height of the tank. Indices: v, vapor; ℓ, liquid; ex, external; max, maximum; e, evaporator; δ, film of liquid; c, condenser.

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