EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER FROM PIPES BURIED IN THE GROUND

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This paper gives the results of experimental investigations of heat transfer from underground pipelines in unsteady-state thermal conditions by means of a physical model in which the thermal conductivity of the soil and the diameter and depth of burial of the pipes were varied. The experimental data are compared with known theoretical results and the range of validity of previously proposed design equations are determined.

Sound heat calculations of pipelines require reliable values of the coefficients of heat transfer from the moving medium to the soil. Yet the literature known to us [1–6] does not give sufficiently reliable values of the heat transfer coefficients (K). By its very nature K is a quantity which depends on the technology of conveyance of the gas or liquid, the depth of burial and diameter of the pipe, the thermophysical characteristics and moisture content of the soil, the heat transfer conditions at the surface of the soil, and other factors.

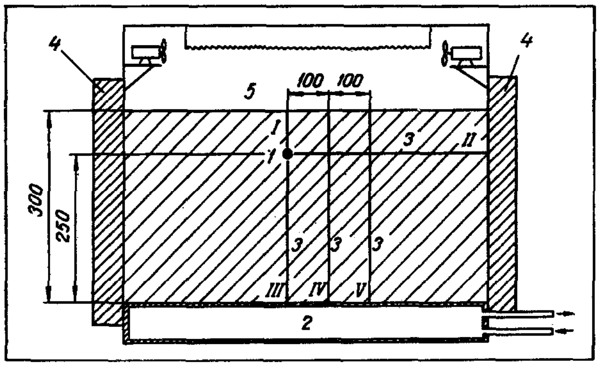

Fig. 1. Diagram of experimental apparatus: 1) heater; 2) tank; 3) thermocouple assemblies I–V; 4) heat insulation; 5) air chamber for regulating air temperature.

Despite the numerous experimental investigations, it is usually impossible to analyze the values of K recommended in the literature in the case of operating pipelines, since the authors of these works usually fail to give complete data characterizing the experimental conditions.

The inadequate study of the thermal interaction of a pipeline and the soil is due both to the complexity of the heat transfer process itself, especially in waterlogged ground, and to the difficulty of experimental investigation, particularly the simulation of heat transfer from the pipe to the soil in field conditions.

Strictly speaking, K should be determined separately for each specific gas pipeline. Since this is impossible in practice, heat calculations are made from the Forchheimer, Arons-Kutateladze, Gröber, and other formulas, which are based on premises which do not correspond to actual conditions.

Despite their fundamental faults, the possibility of practical application and the limits of application of these formulas can be determined only by a compraison of calculated and experimental data.

In view of the fact that earlier experimental investigations failed to include an important practical range of depths of burial, pipe diameters, and thermophysical properties of soil, we carried out experiments in which the heat loss of underground pipes was simulated physically.

If similarity conditions are to be secured, the following factors in the model and in the real case must be similar: geometric properties, physical constants, time course of process, and conditions of interaction of the system and surroundings.

In addition to geometric similarity ($l' = \nu_l l$; $t' = \nu_t t$; $a' = \nu_a a$), the Fourier numbers of the model and the real case must be the same ($a\tau/l^2 = a'\tau'/(l')^2 = \mathrm{Fo}$ or $\nu_a \nu_\tau / \nu_l^2 = 1$).

From an analysis of the boundary conditions for the real case and the model we find: $\nu_T/\nu_l = 1$ from the initial condition; $\nu_q/\varphi(\nu_T, \nu_l) = 1$ from the boundary condition of the second kind with due regard to the restriction usually imposed in similarity theory, viz., homogeneity of the functions of the real case and the model for heat flux (q).

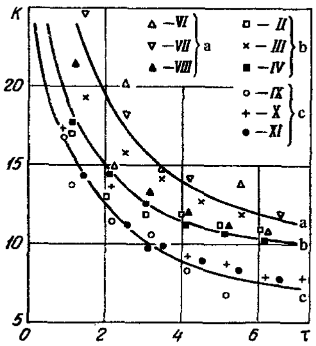

Fig. 2. Change in heat transfer coefficient (K, W/m, deg) with time (τ, hr) on heating of soil (λ_s = 0.29 W/m · deg): a) h/D = 2.2; D = 3.0 cm; experiment VI—q = 30.6 W/m; VII—286; VIII—123; b) h/D = 3.0, D = = 2.0 cm, experiment II—q = 38.0 W/m, III—152, IV—267; c) h/D = 1.28, D = = 5.1 cm; experiment IX—q = 18.1 W/m, X—68.0, XI—120.0.

In our investigations we used real soil (sand), i. e., $\nu_a = 1$. Hence, $\nu_\tau = \nu_l^2$, i. e., the time scale is equal to the square of the linear dimension scale.

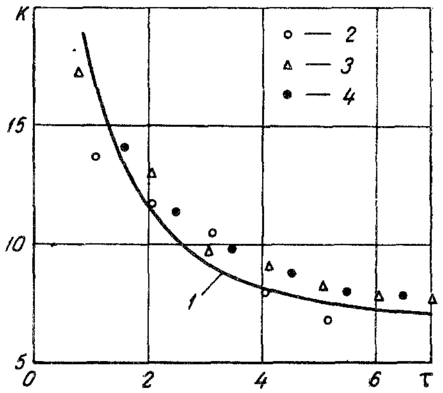

Fig. 3. Comparison of experimental data with solution of [8]: 1) From [8]; 2) experiment IX; 3) X; 4) XI (2–4—h/D = 1.28; D = 5.1 cm).

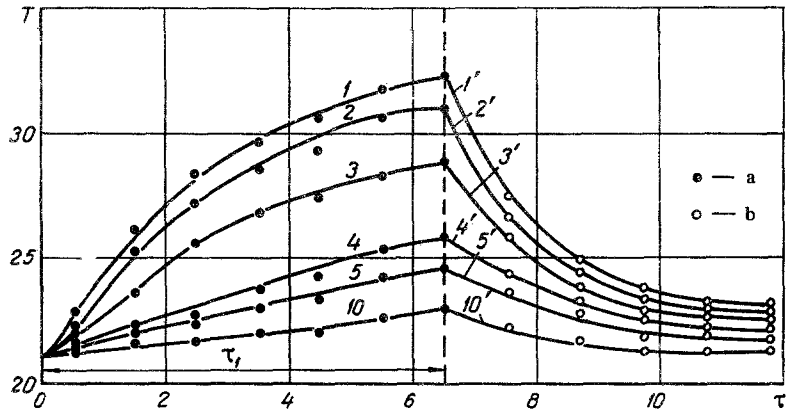

Fig. 4. Plots of source temperature (T, °C) against time (τ, hr) at different points in soil at depth of burial of pipe: 1, 1') Source; 2, 2', 3, 3', 4, 4', 5, 5', 10, 10') distance from source in mm, respectively; a) heating; b) cooling. The soil consisted of wet sand (w = 9.2%, λ_g = 0.50 W/m·deg).

Table 1

Comparison of Experimental and Calculated Values of Heat Transfer Coefficients

Soil	D, mm	h, mm	h/D	q, W/m	Heat transfer coefficients, W/m · deg: experimentally obtained	calculated from formula: Forchheimer (1)	calculated from formula: Arons-Kutateladze (2)	calculated from formula: Tugonov-Yablonskii (3)	Deviation (%) from formulas: (1)	(2)	(3)
Dry sand	20	60	3.0	38.1	12.5			8.8	6.1	9.3	29.5
				268.0	12.1	11.7	11.3		2.4	5.8	27.0
	30	65	2.17	123.0	14.6				38.0	40.5	55.0
				28.7	13.9	9.0	8.8	6.6	35.0	37.6	61.6
	51	65	1.28	68.1	9.6				26.5	28.8	37.2
				120.0	9.5	7.1	6.8	6.0	25.6	28.0	36.6
Damp sand	51	65	1.28	33.2	11.3	12.2	12.0	7.1	−7.2	−5.1	37.9
				68.1	9.2				−33.0	−30.5	21.8
	30	65	2.17	107 0	12.3	14.4	13.9	9.3	−17.0	−13.2	24.6

Proceeding from the above principles of physical simulation we designed an experimental apparatus for the investigations. It consisted of a chamber (80 × × 80 × 60 cm) filled with sand (Fig. 1). The boundary condition $dt/dx = 0$ when $x \to \infty$ on the side surfaces of the model was secured by thermal insulation with PSD-4 foam plastic 10 cm thick. On the bottom of the chamber there was a tank with circulating water to secure the boundary condition t_0 = const on the bottom of the model. During the experiments the water temperature was kept constant by a U-8 ultrathermostat. The heat transfer conditions at the soil—atmosphere boundary were as close as possible to actual conditions.

As heat sources we used electric heaters consisting of coils of 0.5 mm manganin wire wound on porcelain or glass tubes of various diameters. Movement of the wires during heating was prevented by covering them with epoxy resin. We used three heaters with the following parameters: D = 20, 30, and 51 mm; l = 80, 74, and 73 cm; R = 118, 152, and 263 ohm.

During the experiment a constant voltage was maintained on the heater terminals and this ensured that the heat flux from the source was constant. The heat flux was determined from the Joule-Lenz formula.

To measure the temperatures at different points in the soil we used TMK copper-constantan thermocouples and GZP-47 galvanometers. The thermocouples were grouped together in assemblies (10 thermocouples in each). The base of the thermocouple assembly consisted of 0.3 mm PESHOK constantan wire, to which 0.5 mm copper wires in PVC insulation were soldered at fixed distances. The thermocouples enabled us to measure the increase in temperature of the working junctions over the temperature of a reference junctions. The latter was measured in a Dewar vessel by a mercury thermometer with scale divisions of 0.1° C. The thermocouples were calibrated beforehand at several temperatures in the range from 0–10° C. The temperature of the soil was measured at 50 points.

The thermal conductivity of the soil was determined by two independent methods: by the flat heat-probe method and by the regular heat regime method. In the first method a flat probe (with a guard frame of dimensions 30 × 30 × 2 cm) was buried in the soil. The measurements were made by the cooling plate procedure with a liquid in the probe as a heat source. To check the measurements we determined the thermal diffusivity (a) with an a-calorimeter by G. M. Kondrat'ev's method. For dry sand we obtained the following results: λ_s = 0.280 and 0.312 W/m · deg, a = 0.73 and $0.81 \cdot 10^{-3}$ m²/hr (the first values by the regular heat regime method); for moist sand (w = 9.2%), λ_s = 0.50 and $a = 1.20 \cdot 10^{-3}$.

Before being put into the chamber all the sand was passed through a 2 mm sieve; the bulk density of the dry sand was γ = 1540 kg/m³, and that of the damp sand (w = 9.2%), γ = 1620 kg/m³.

Observations were made with different values of h/D, λ_s, and q. During the experiments the distance from the heater to the tank was kept constant at 25 cm. To obtain the required values of h/D we altered the height of the sand above the pipe. To eliminate the systematic error we took two readings—direct and reverse—from the galvanometer. We carried out eleven experiments with dry sand and ten experiments with most sand (w = 9.2%).

The experiment was continued until the change in temperature with time became equal to (or less than) the accuracy of temperature measurement.

From the present heat fluxes, which were altered during the investigation from 15–290 W/m², and the measured temperature heads we determined the coefficient of heat transfer from the source to the soil (Fig. 2). It should be noted that this graph can be used for practical calculations if the required parameters lie within the investigated range.

Figure 3 shows a comparison of the theoretical Tugunov-Yublonskii solution [8] with our experimental data. The figure shows that the greatest difference between them does not exceed 10–15%. This can be attributed to the slightly different premises of theory and experiment and the errors of the latter. In the deviation of the equation of [8] it was assumed that the temperature throughout the soil mass was constant. In the conduction of our experiment we made the vertical temperature gradient in the ground correspond to real conditions.

We evaluate the error of the experiment. Using the heat transfer coefficient given by the formula

$$K = \frac{q}{t_н - t_0}, \quad (1)$$

and also the known relationships from the theory of errors, we obtain

$$\delta_k = \sqrt{4\delta_u^2 + \delta_\tau^2 + \delta_R^2 + \delta_D^2 + \delta_l^2 + \delta_{(t_н - t_0)}^2}. \quad (2)$$

In accordance with the accuracy of the instruments used in our model, the maximum possible absolute errors of measurement are: σ_u = 0.1 V; σ_τ = 1 min; σ_R = 1 ohm; σ_D = 1.0 mm; σ_l = 5 mm; $\sigma_{(t_H - t_0)}$ = 0.1° C. The minimum values of the measured parameters are: U_{min} = 15 V; τ_{min} = 1 hr; R_{min} = 118 ohm; D_{min} = = 20 mm; l_{min} = 730 mm; $(t_H - t_0)_{min}$ = 1° C. The maximum relative error in the determination of K will be 0.115 (or 11.5%). Since in the majority of experiments $(t_H - t_0) \gg 1.0$, and δ_k is determined mainly by $\delta_{(t_H - t_0)}$, the former will be less than 11.5%.

Returning to the analysis of the agreement between our experimental data and the Tugunov-Yablonskii formula for the unsteady heat regime, we can show that the differences are within the limits of experimental error. Our data also agree well with Chernikin's formula [4], which ignores heat transfer at the soil-air boundary. This formula for the conditions of our model agrees with [7] (curve 1 in Fig. 3). Hence, we can conclude that within the limit of the accuracy of the practical calculations of underground pipes heat loss to the atmosphere can be neglected.

The heating of the pipe-soil system when the pipe becomes operative depends mainly on the rate of heating of the soil. Figure 4 shows plots of temperature against time at different points in the soil (thermocouple assembly No. 2; see Fig. 1) on heating to the steady state and subsequent cooling. As these data show, the temperature of the pipe during heating reaches the quasi-steady state [4] much more rapidly than that of the soil.

The rate of change of temperature, which is rapid at the start of the heating process, subsequently becomes slower and at the end is very slow (1–2° C in 50–100 hr); it appears as if the system has reached the steady state. An analysis of the experimental data (see curves 4–10 in Fig. 4) indicates that the front of the heat wave due to the source moves very slowly through the soil: after 600 hr the soil temperature at a distance of 39 cm (8D) from the heater rises by approximately 0.5° C. Arons and Polyak obtained similar results in field investigations of a pipe 220 mm in diameter, laid at a depth of 0.7 m.

Figure 4 also shows the results of one of the experiments on the cooling of heated soil when the heat source is cut off (curves 1'–5', 10'). An analysis of these curves shows that the source temperature decreases much more rapidly than the soil temperature, especially at large distances from the source (curves 5' and 10'). An analysis of the experimental data indicates that the thermal effect of the source extends into the soil to distances equal to five or six radii of the pipe.

The results obtained can be used to evaluate the time of heating of the pipe. In our experiments the quasi-steady state was attained in 6–7 hr. Calculations from the Arons-Kutateladze formula give τ = 7.7 hr (for D = 5.1 cm; h/D = 1.28), and from the Tugunov-Yablonskii formula [8] τ = 8.5 hr, i.e., both these formulas agree well with our experimental data.

Since calculations of gas pipes are usually based on steady-state conditions, it is of interest to compare the existing theoretical solutions of Forchheimer, Arons and Kutateladze, and Tugunov and Yablonskii [7] with our experimental data.

In Table 1 we have selected the experimental values of the heat transfer coefficients which correspond to the quasi-steady state and the values calculated from the above-mentioned formulas. Table 1 shows that the differences between the results calculated from the theoretical formulas and the experimental data are -30 to +60%. In the case of most practical interest for gas-pipe calculations (h/D = 1.28) the differences do not exceed -30 to +37%. Since the experimental error is about 10% we can regard this as a quite satisfactory agreement.

In view of the contradictory recommendations regarding the choice of K (the values of K obtained by different authors differ considerably from one another) and the fact that in the design of gas pipes the value of K is chosen irrespective of D, h/D, and λ_s, we can recommend for practical calculations the simplest of the above formulas—the Forchheimer formula.

NOTATION

h is the depth of burial of pipe (heater); D is the diameter of pipe (heater); l is the length of pipe (heater); γ is the bulk density of soil; w is the moisture content of soil; λ_s is the thermal conductivity of soil; a is the thermal diffusivity of soil; q is the heat flux ($q = 0.24 \cdot 3.6U^2/\pi DlR$); K is the coefficient of heat transfer from pipe to soil; t is the temperature (t_H is the source, t_0 is in natural conditions, outside the region of thermal influence of the pipe); R is the ohmic resistance of heater; U is the voltage applied to heater; Fo is the Fourier number; ν is the modeling scale; δ is the relative error of measurement, σ is the absolute error; τ is the time; τ_1 is the heating time.

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