UNDERGROUND HOT WATER TRANSMISSION LINES IN PERIODIC OPERATION

By

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Preface

Technical development, improving indices of the specific consumption of condensing power stations and the gradual transformation of the structure of energy carriers have introduced a new concept and new trends in district heating systems. The production of heat by the individual plants has once more become an attractive solution and new modern heating systems have been developed. Not only urbanisation, the provision of public utilities and the evolution of the infrastructure but communal and industrial consumers, too, require more up-to-date, more hygienic and better heat supply. It is necessary, therefore, to study whether or not the existing heating power stations can be operated more economically and under what conditions could new plants be built to produce both heat and energy. In addition, with a higher standard of development and better public supplies, the disproportion between power consumption during the daytime and the night hours has increased, causing difficulties in the satisfaction of the need for electric power during peak periods.

It was the study of these two major problems which has given birth to the idea of operating heating power stations to cover peak consumption.

"The running of heating stations to meet demand during consumption peaks is a régime in which, making use of the heat storage capacity of the network and of the heated plant, the station supplies the possible maximum electric energy during the period of consumption peaks [1—4]."

This meant parting with the previous concept according to which a heating power station's only function is to meet the demand for heat. An optimum method of operation had to be developed which serves the interests of both the power generating plant and the heated object.

Up to recently our examinations extended to the effect of periodic operation (to cover peak loads) upon the inside temperature of heated rooms [5, 6], and to pipe systems carrying hot water from the plant, routed above the surface [7, 8]. In the latter case, i.e. with free standing lines above ground ambient temperature can be assumed to be constant and this assumption simplifies the examinations.

In the present paper, however, we intend to take consideration also of the heat storage capacity of the soil and of the temperature variations close to the heated pipe.

1. The method applied

We approached the problem in several steps.

a) In the experimental rig we measured the heat loss, respectively the set of isotherms suitable to calculate it in both stationary and periodic operation;

b) We elaborated a general solution to formulate and compute the equation of the isotherms.

c) We substituted the geometry and the thermodynamic features of the measuring device into the calculation formulas and checked upon the agreement between measured and calculated values.

d) In the said manner we confirmed the correctness of the calculation method and determined the pattern of the heat losses likely to occur in a full-size equipment.

e) We confirmed the process qualitatively by the findings of a previous model experiment.

f) On the basis of the above we have established that reasonably safe conclusions may be drawn for the effects of periodic operation also for underground transmission lines.

And now let us describe the process in greater detail.

2. The experiment. Measurement results

For the purposes of measurements a large wooden box had been provided, filled with clean sand. In its centre a pair of pipes — forward and return — were fitted, the latter provided with cut-off facilities. This arrangement enabled the determination of the set of isotherms forming around one, or both, pipes as required (see Fig. 1). To measure the rate of the cooling down of hot water, thermometers were fixed to either end of the box. In the mid-line of the box, mounted to wooden frames, very small resistance thermometers made of Ni wire were positioned, each connected to a compensograph, for the recording of the temperatures around the pipes. Hot water was delivered to the set-up from a heat exchanger heated with saturated steam the volume of which was controlled by a suitable valve. To cool down the water between the forward and return pipes a calorifer was available.

First stationary operation was studied. At a forward water temperature of 110 °C we measured the set of isotherms around the pipes then, manipulating the steam valve "2" of Figure 1 according to a present programme, we

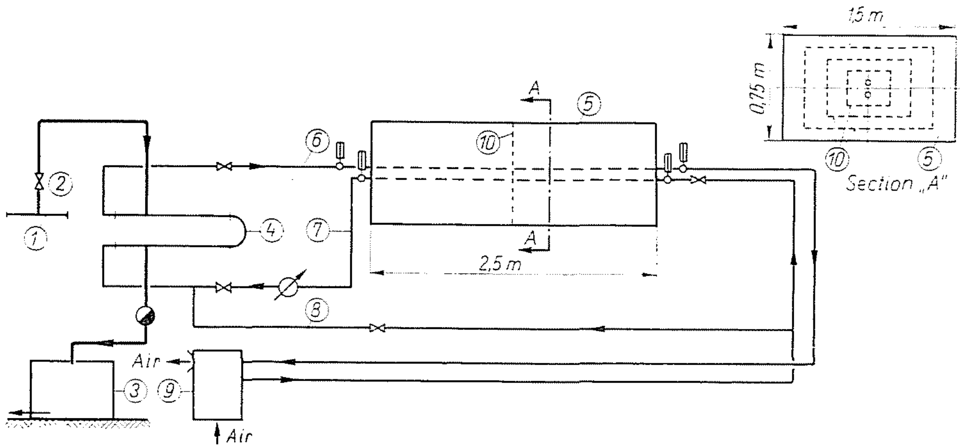

Fig. 1. Arrangement of a heat loss measuring apparatus. 1: Steam distribution; 2: Steam control value; 3: Condensing tank; 4: Steam–Hot water heat exchanger; 5: Measuring case; 6: Hot water forward conduit; 7: Hot water return conduit; 8: Hot water trunk conduit; 9: Thermal ventilator for water cooling; 10: Measuring frames

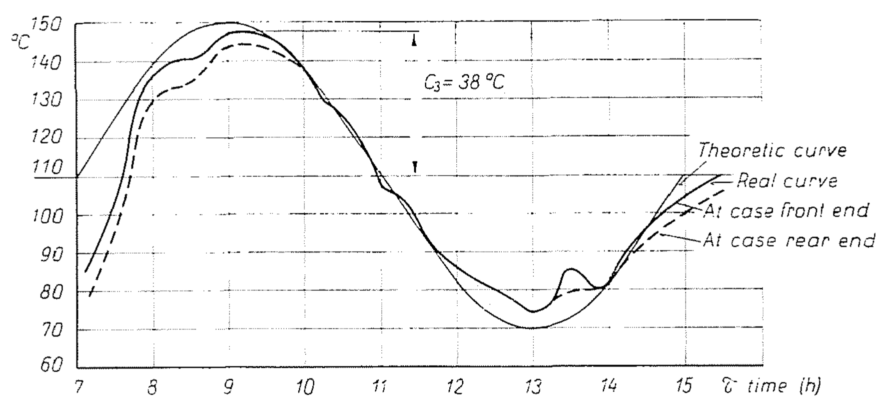

Fig. 2. Periodical change of the temperature of the forward streaming water

cause the temperature to vary periodically (Fig. 2). The function so measured fairly approximated the sine function considered in the calculation. The pattern of the isotherms was again recorded. Fig. 3 shows the curves plotted during stationary and periodic operation, respectively, i.e. the temperatures measured on different radii starting out from the midline of the pipe, in function of time.

Here follows the description of the calculation process.

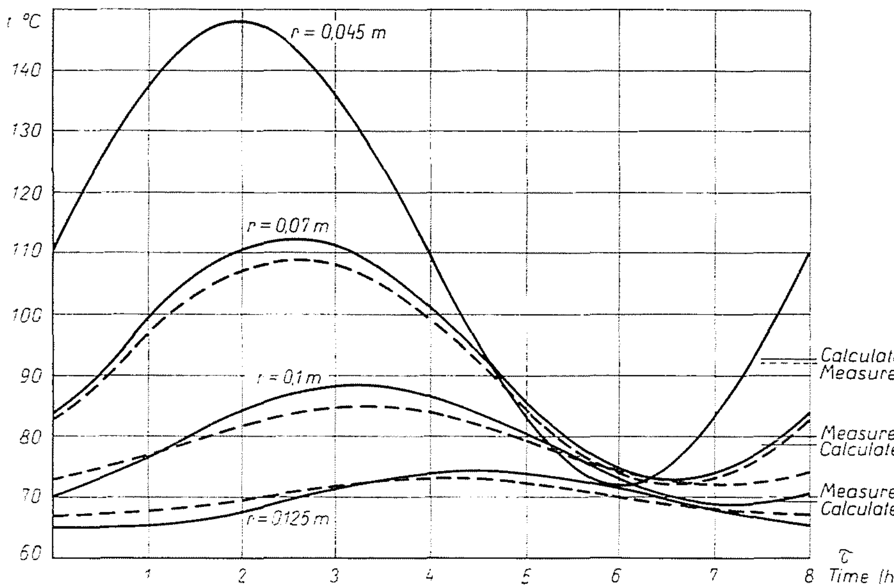

Fig. 3. Isotherms around a heated tube (conduit). ——— Curves of calculated values; - - - - - Curves of measured values

3. The equation of the isotherms

We set out from the differential equation

$$\frac{\partial^2 \vartheta}{\partial r^2} + \frac{1}{r}\frac{\partial \vartheta}{\partial r} = \frac{1}{a}\frac{\partial \vartheta}{\partial \tau} \tag{1}$$

which describes the temperatures arising around a cylindrical body [9] where

ϑ designates the excess temperature (the temperature above that of the surroundings) in °C

r the radii in m

τ time in hours

a the heat conduction factor of the soil around the pipe in m^2/h, $a > 0$

Assuming a radius of $r_1 \leqq r < \infty$ which, in our case, is equal to the outer circumference of the pipe, temperature will vary according to a given periodic function

$$\vartheta(r_1, \tau) = f(\tau) \tag{2}$$

In infinity excess temperature becomes zero, i.e. the temperature around the pipe, in infinity, is the same as that of the surroundings.

Note: In the present chapter peak operation has always been substituted with a sine function. As proved above, measurements too had been performed with such substitution, in order to simplify calculations.

The problem has no initial conditions, the solution assumes the form of

$$\vartheta = e^{i\omega\tau} R(r) \tag{3}$$

where $\omega = \frac{2\pi}{\tau_0}$, τ_0 stands for the length of the period (h).

Substituting the value of ϑ according to (3) into the differential equation (1) we arrive at

$$e^{i\omega\tau}\left(R'' + \frac{1}{r}R'\right) = \frac{i\omega}{a} R e^{i\omega\tau} \tag{1a}$$

whence we obtain

$$R'' + \frac{1}{r}R' - \frac{i\omega}{a}R = 0 \tag{1b}$$

differential equation of the Bessel type. Resolved it yields

$$R = C_1 J_0\left(i^{3/2}\sqrt{\frac{\omega}{a}}r\right) + C_2 K_0\left(\sqrt{i\frac{\omega}{a}}r\right) \tag{1c}$$

To select C_1 and C_2 the following conditions may apply: If $r \to \infty$ then the first member, too, tends toward infinity. Therefore, in conformity with the boundary condition, C_1 may be equal to 0; since C_2 is arbitrary, let it, for the time being, be equal to 1.0.

Accordingly:

$$\begin{aligned}\vartheta &= e^{i\omega\tau} K_0\left(\sqrt{i\frac{\omega}{a}}r\right) = (\cos\omega\tau + i\sin\omega\tau)\cdot\\ &\cdot\left[\operatorname{ker}\left(\sqrt{\frac{\omega}{a}}r\right) + i\operatorname{kei}\left(\sqrt{\frac{\omega}{a}}r\right)\right] =\\ &= \cos\omega\tau\cdot\operatorname{ker}\left(\sqrt{\frac{\omega}{a}}r\right) - \sin\omega\tau\cdot\operatorname{kei}\left(\sqrt{\frac{\omega}{a}}r\right) +\\ &+ i\left[\sin\omega\tau\cdot\operatorname{ker}\left(\sqrt{\frac{\omega}{a}}r\right) + \cos\omega\tau\cdot\operatorname{kei}\left(\sqrt{\frac{\omega}{a}}r\right)\right]\end{aligned} \tag{3a}$$

where "ker" and "kei" denote the real and imaginary parts of Kelvin's function [10, 11].

Both the real and the imaginary parts provide a resolution to the differential equation.

Let ϑ' be the real, ϑ'' the imaginary part and let C' and C'' be arbitrary constants. If so, then

$$\vartheta' = C'\left[\cos\omega\tau\cdot\ker\left(\sqrt{\frac{\omega}{a}}\,r\right) - \sin\omega\tau\cdot\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}\,r\right)\right] \tag{3b}$$

$$\vartheta'' = C''\left[\sin\omega\tau\cdot\ker\left(\sqrt{\frac{\omega}{a}}\,r\right) + \cos\omega\tau\cdot\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}\,r\right)\right] \tag{3c}$$

Since both ϑ' and ϑ'' represent a solution to the equation, their sum, too, is one and:

$$\begin{aligned}\vartheta = \vartheta' + \vartheta'' = &\left[C'\ker\left(\sqrt{\frac{\omega}{a}}\,r\right) + C''\,\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}\,r\right)\right]\cos\omega\tau + \\ &+\left[C''\ker\left(\sqrt{\frac{\omega}{a}}\,r\right) - C'\,\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}\,r\right)\right]\sin\omega\tau\end{aligned} \tag{3d}$$

The determination of the C' and C'' constants is as follows: if the pipe radius r_1 is a definite number and the period time of τ_0 is known then a heat conduction factor of the sand around the pipe

$$\Gamma = \ker\left(\sqrt{\frac{\omega}{a}}\,r_1\right) \qquad \Lambda = \mathrm{kei}\left(\sqrt{\frac{\omega}{a}}\,r_1\right) \tag{4}$$

can be calculated. The boundary condition

$$f(\tau) = C_3 \sin\omega\tau = \vartheta(r_1, \tau)$$

is the periodic time — temperature function taking place around the outer circumference of the pipe. Likewise

$$\lim_{r\to\infty} \vartheta(r, \tau) = 0$$

which means that in infinity the ambient temperature will be attained.

It may be written that

$$\left.\begin{aligned}\Gamma C' + \Lambda C'' &= 0\\ -\Lambda C' + \Gamma C'' &= C_3\end{aligned}\right\} \qquad \Lambda^2 + \Gamma^2 \neq 0 \tag{4a}$$

whence

$$C' = \frac{-\Lambda C_3}{\Lambda^2 + \Gamma^2} \qquad C'' = \frac{\Gamma C_3}{\Lambda^2 + \Gamma^2} \tag{4b}$$

Substituting them into the relationship (3d), a correlation well suited for the calculation will be obtained:

$$\vartheta(r,\tau)=\left[\frac{\Gamma C_3}{\Gamma^2+\Lambda^2}\ker\left(\sqrt{\frac{\omega}{a}}r\right)+\frac{\Lambda C_3}{\Gamma^2+\Lambda^2}\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}r\right)\right]\sin\omega\tau+ \tag{3e}$$

$$+\left[\frac{-\Lambda C_3}{\Gamma^2+\Lambda^2}\ker\left(\sqrt{\frac{\omega}{a}}r\right)+\frac{\Gamma C_3}{\Gamma^2+\Lambda^2}\mathrm{kei}\left(\sqrt{\frac{\omega}{a}}r\right)\right]\cos\omega\tau$$

Now let us substitute the measurement results.

4. Calculation with the geometric and thermodynamic features of the measuring rig

The pipe diameter is N dia 80 mm. Therewith the outer radius will be 0.045 m (Fig. 3).

In an eight-hour period the value of ω will be

$$\omega=\frac{2\pi}{\tau_0}=\frac{\pi}{4}=0.995/\mathrm{h}$$

Substituting the thermodynamic properties according to [12] the heat conduction factor of sand is

$$a=\frac{\lambda}{c\varrho}=\frac{1.0}{0.44\cdot1400}=1.623\,10^{-3}\ \mathrm{m^2/h}$$

The value of $\sqrt{\frac{\omega}{a}}r_1$, accordingly, will be:

$$\sqrt{\frac{\omega}{a}}r_1=\sqrt{\frac{0.995}{1.623\cdot10^{-3}}}\cdot0.045=1.115$$

$$\Gamma=\ker 1.115=\quad 0.2147 \qquad \Gamma^2=0.046$$

$$\Lambda=\mathrm{kei}\,1.115=-0.4550 \qquad \Lambda^2=0.207$$

As verified by calculations (Fig. 2):

$$C_3=38\ ^\circ\mathrm{C}$$

therefore, on the basis of equation (4b) we may write that

$$C' = \frac{(-0.455)\cdot 38}{0.046+0.207} = 68.2$$

$$C'' = \frac{0.2147\cdot 38}{0.046+0.207} = 32.3$$

Now the r radii may be substituted into Eq. (3e). Obviously, the "measured" values in Fig. 3 will be chosen. The following values will be calculated:

$$r = 0.07 \text{ m}$$

$$r = 0.1 \text{ m}$$

$$r = 0.125 \text{ m}$$

As an example, let

$$r \text{ be } 0.07 \text{ m}$$

This would mean that the wave is examined at a distance of

$$r - r_1 = 0.07 - 0.045 = 0.025 \text{ m}$$

away from the pipe wall.

Substituting this into Eq. (3e):

$$\vartheta(r, \tau) = [68.2 \operatorname{ker}(24.8 \cdot 0.07) + 32.3 \operatorname{kei}(24.8 \cdot 0.07)] \cos \omega\tau +$$
$$+ [32.3 \operatorname{ker}(24.8 \cdot 0.07) - 68.2 \operatorname{kei}(24.8 \cdot 0.07)] \sin \omega\tau$$

from the table functions ker and kei will be [10, 11]

$$\operatorname{ker}(24.8 \cdot 0.07) = -0.0036$$

$$\operatorname{kei}(24.8 \cdot 0.07) = -0.2649$$

and thereby

$$\vartheta(r, \tau) = 8.795 \cos \omega\tau + 17.984 \sin \omega\tau$$

In this manner the pattern of the function $\vartheta(r, \tau)$ can be determined for each radius. The problem still awaiting solution is to find the isotherms in stationary operation around which the so calculated periodic function would fluctuate. These isotherms must obviously be established from the heat loss.

The heat loss during the measurement is as follows:

$$\dot{Q} = (t_e - t_a) \frac{2\pi \cdot L \cdot \lambda}{\ln \frac{d_a}{2r_1}} = (110 - 26) \frac{2\pi \cdot 2.5 \cdot 1.0}{\ln \frac{0.75}{2 \cdot 0.045}} = 620 \text{ kcal/h} \tag{5a}$$

where, in addition to the previous symbols

t_e denotes the mean forward going water temperature and, according to our conditions, also the temperature of the pipe circumference (110 °C);

t_a the external surface temperature of the box: 26 °C;

L the length of the box;

d_a the outer diameter which corresponds to the external dimensions of the box (m).

On the basis of (5a) the equation of the isotherms will assume the following form:

$$t_r = t_e - \frac{\dot{Q}}{2\pi L\lambda} \ln \frac{2r}{2r_1} \tag{5b}$$

Illustrating it with the previous example of $r = 0.07$ m:

$$t_{r=0.07} = 110 - \frac{620}{2 \cdot 2.5 \cdot 1.0} \ln \frac{2 \cdot 0.07}{2 \cdot 0.045} = 92.6 \text{ °C}$$

Performing this calculation for each radius we will be able to tally the measured and calculated data. Fig. 3 accordingly includes two-two (measured and calculated) sets of lines, namely, the pattern of soil temperature along various r radii away from the pipe circumference first at constant then at periodically varying water temperatures (or, in our case at constant and periodically varying temperature of the pipe circumference). As seen from the figure the measured and calculated values show a fair agreement, proving that the calculation process may safely be accepted and used to study the problem and elucidate the variations of the isotherms in underground pipe systems during periodic peak operation in full size equipment.

5. Calculating the heat loss and the pattern of the isotherms in full size equipment

When studying this problem we followed this train of thoughts:

a) We assumed a harmonic function which approximates the actual conditions of peak operation under extreme conditions, i.e. a maximum temperature of 150 °C, a trough temperature of 70 °C. Since no such fluctuations of the forward flowing water temperature have ever been encountered in power stations, this case may be regarded as the theoretically most unfavourable. To approximate actual conditions (on peak run a day) we chose twenty-four-hour periods. This gave a 40 °C amplitude of the function and a period duration of eight hours.

b) We studied the temperature pattern around pipes of 100, 200, 500 and 600 mm diameter. The fact that no thermal insulation had been assumed again shifted the calculations towards the least favourable case. The temperature field was calculated and established at 2.5—5.0 and 10.0 cm away from the pipe circumference. It was found that the periodic function subsides very rapidly in the coil.

c) In the next step we sought for that radius (respectively that distance from the pipe wall) at which the amplitude of the temperature fluctuations due to intermittent — peak — operation went below 2 °C. These distances were measured and plotted in function of the pipe diameters.

Since the distances were very small, it was proved that underground the effect of peak running would subside within a very short distance even in extremely unfavourable cases, which never occur in practice. Thereafter the heat loss can be readily calculated in the same way as in traditionally operated transmission lines, i.e. systems ran at constant temperature round the clock.

Some more essential numerical steps in the calculation had been:

$$\omega = \frac{2\pi}{24} = 0.2615/\text{h}$$

The heat conduction factor a of the soil was taken to be identical with the previous value of a_{sand}. Therefore

$$\sqrt{\frac{\omega}{a}} = 12.7/\text{m}$$

Taking into consideration the different pipe diameters the values of

$$\sqrt{\frac{\omega}{a}}\, r_1$$

of C' and C'' were compiled in Table I.

Table I

Complementary values for the application of relationship (3e)

Nominal pipe diameter [mm]	External pipe radius [m]	$\sqrt{\frac{\omega}{a}}\, r_1$	C'	C''
100	0.054	0.685	34.4	32.9
200	0.108	1.371	101.0	26.3
500	0.2605	3.31	259.0	−561.0
600	0.311	3.95	−25.08	−1060

The values substituted consecutively into relationship (3e) yield the pattern of periodic waves.

In Table II the values of r and of

$$\sqrt{\frac{\omega}{a}}\, r$$

were compiled as a function of distances measured from the pipe wall while Table III indicates the distances at which amplitude drops to < 2 °C.

Table II

The values of r and of $\sqrt{\frac{\omega}{a}}\, r$

Pipe diameter [mm]	Distance from pipe wall measured in cm					
	2.5		5.0		10.0	
	r [m]	$\sqrt{\omega/a}\, r$	r [m]	$\sqrt{\omega/a}\, r$	r [m]	$\sqrt{\omega/a}\, r$
100	0.079	1.003	0.104	1.32	0.154	1.956
200	0.133	1.69	0.158	2.01	0.208	2.645
500	0.2855	3.625	0.3105	3.945	0.3605	4.58

Table III

The distances where amplitude is less than 2 °C

Pipe diameter [mm]	Distance from pipe wall [cm]	r [m]	$\sqrt{\frac{\omega}{a}}\, r$
100	25	0.304	3.86
200	27	0.378	4.81
500	30	0.5605	7.11
600	30	0.611	7.76

Having substituted the figures of Tables I, II and III into the relationship (3e) we obtained the equations of the periodic waves. For the graphic illustration it was necessary also to determine the temperature of the isotherms along the radii r for the case if the pipes would carry water at a constant temperature of $110\ °C = \frac{150+70}{2}\ °C$.

For the calculation of the isotherms we found information in Reference [13]:

$$t = \frac{\dot{q}}{4\pi\lambda} \ln \frac{u^2+(h-v)^2}{u^2+(h+v)^2} \quad [°C] \tag{6}$$

where

$\dot{q}$ designates the heat losses along the pipe-line [kcal/rm, h]
λ the heat conduction factor of the soil [kcal/m, h, °C]

while the designations of u, v, h are seen in Fig. 4 which indicates, in actual figures, the geometry of the isotherms and the arrangement of the 100 mm diameter pipe.

On the basis of [14] soil temperature of 6 °C had been assumed for the calculation. According to Fig. 4 the heat loss per running metre in a pipe of 100 mm diameter amounts to

$$\dot{q} = \frac{(110-6)\cdot 4\pi \cdot 1.0}{\ln \frac{0.054^2+(2\cdot 1.5)^2}{0.0542}} = 162.5 \text{ kcal/rm, h}$$

Other heat loss values and isotherms are shown in Table IV.

Table IV

The heat loss per running metre and the numerical value of the isotherms

Pipe diameter [mm]	$\dot{q}$ [kcal/rm, h]	Distance from pipe wall in terms of cms					
		2.5	5	10	25	27	30
100	162.5	100.1	92.9	82.9	65.5	—	—
200	200.0	103.5	98.1	89.5	—	75.0	—
500	267.0	105.4	102.6	96.4	—	—	78.0

The figures designate the temperature of the isotherms in degrees centigrade (°C)

Thereafter the function $\vartheta(r, \tau)$ could be plotted without any difficulty whatsoever (Fig. 5). It clearly shows the effect of the pipe diameter and the "subsidence" of the periodic function.

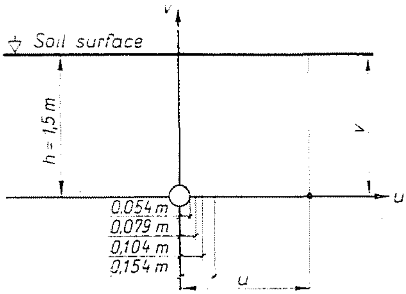

Fig. 4. Determination of the isotherms: symbols and dimensions

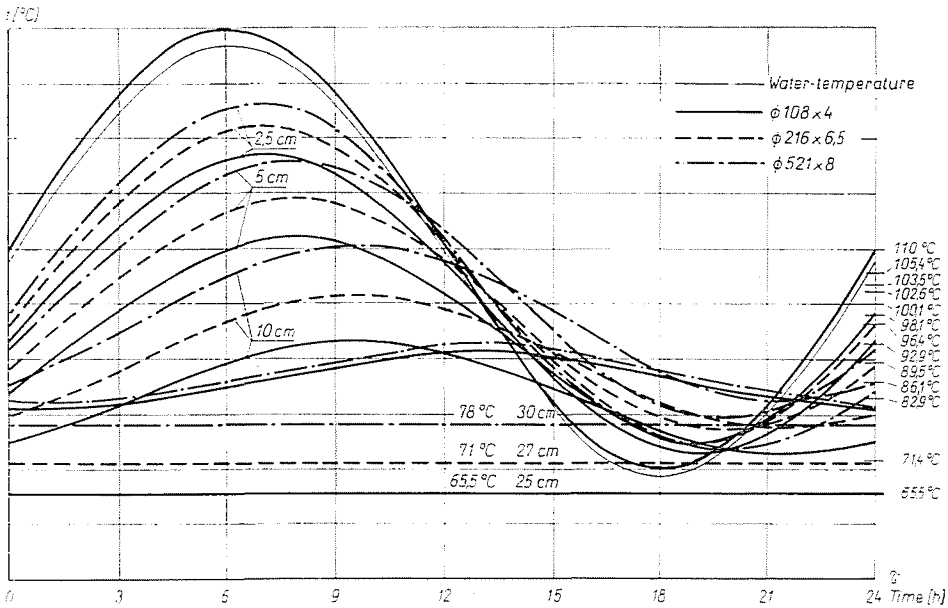

Fig. 5. Isotherms around a heated tube

Fig. 6 indicates the distance at which the effect of peak operation has completely subsided, for different pipe diameters.

The calculation eloquently proves that assuming even an extreme case — 500 mm diameter non-insulated pipe and peak running between 150 and 70 °C — the fluctuations will subside within a ring of 30 cm thickness. This in fact confirms that for the determination of heat losses we may safely account with constant ambient temperature also in pipes routed underground.

We could qualitatively verify this statement also on the basis of a model experiment we had carried out earlier.

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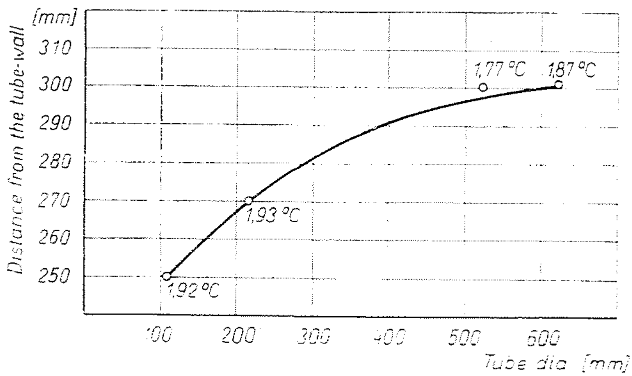

Fig. 6. Distance from the tube-wall, at which the temperature oscillation is less than 2 °C

6. The model experiment

In a previous article we described the electric model composed to simulate the electric time function for peak operation, in which the isotherms had been substituted by lines of constant voltage. The measured and calculated data showed close agreement. The electric time function represented extremely unfavourable conditions for peak operation with a 50 °C difference in the forward-going water temperature during peaks and troughs, respectively, and four-hour peak running periods. In this particular case differences were observed at the 35 °C isotherm only while the 25 °C isotherm showed no longer any effect of intermittent operation. Since the 35 °C isotherm was at a distance of approximately 25 cm from the wall of the 300 mm diameter pipe, the model proved beyond doubt that the experiment supported our theory.

Summary

The paper proves that in conformity with an evaluation of the effects of peak operation by measurements, calculations and a model experiment, the temperature close to pipelines routed underground may be assumed to be constant. Authors, accordingly, succeeded in elucidating the pattern of heat losses in transmission pipes led both on the surface and underground, as well as the heat losses in the inside temperature of heated premises, due to peak operation. This, ultimately, enables the consideration and calculation of every possible factor relating to this novel type of operation.

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