New method for heat loss calculation

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Abstract *- The process of heat transportation by means of heat distribution networks is accompanied by considerable heat losses, which has the impact on the overall operation of a heat distribution network as well as the efficiency of heat supply. Heat losses depend on several factors such as the temperature of transported working fluid, ambient temperature, design of the heat distribution system (channel, directly buried, underground, above-ground...), its length, the thickness and quality of the insulation material used.*

Keywords - heat loss, thermal network, thermal resistance, insulation thickness, balance method.

I. INTRODUCTION

Nowadays, heat loss is most commonly determined by the balance method based on the experimentally measured difference of temperature values on the inlet and outlet of the piping. Determination of total heat loss along a specific network section requires an accurate reading of the temperature of a heat carrier medium at the beginning and end of the studied section. At the same time, it is essential to know the mass flow rate of water within the examined part of the piping.

II. DETERMINING HEAT LOSS BY THE BALANCE METHOD

Presently, the total heat loss (heat capacity, heat flow) of an insulated pipe at a specific time is determined by the following formula (1):

$$P = Q_m \cdot c_{\mathrm{v}} \cdot \Delta t \qquad \text{(W)} \tag{1}$$

where:

Q_m is the water mass flow ($\mathrm{kg \cdot s^{-1}}$),

$Q_m = \rho \cdot Q_V$, kde $Q_V = \upsilon \cdot S$

c_{v} – specific heat capacity of water ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$),

Δt – decrease in the water temperature in the respective section (°C),

ρ – water density ($\mathrm{kg \cdot m^{-3}}$),

Q_V – water flow rate ($\mathrm{m^3 \cdot s^{-1}}$),

υ – speed of the flow ($\mathrm{m \cdot s^{-1}}$),

S – flow area of the pipe ($\mathrm{m^2}$).

The heat loss can be determined on the basis of formula (1), providing the heat transmission medium temperature and water flow rate (or speed) at the inlet and outlet of the examined area are known. The following relation can be used for calculating the total heat (power) loss:

$$P = q \cdot S_{\mathrm{ins}} \qquad \text{(W)} \tag{2}$$

where:

q - heat flow density on the surface of the pipe insulation ($\mathrm{W \cdot m^{-2}}$),

S_{ins} –surface area of the pipe with the insulation ($S_{ins} = \pi \cdot d_3 \cdot l$) ($\mathrm{m^2}$),

l –length of the examined section of a pipe (m),

d_3 - external diameter of the insulation (m)

From the equality of relations (1) and (2), we can determine the specific heat loss (the heat flow density) for direct piping as well as for reverse piping, depending on the increase in the water temperature between the inlet and outlet of the piping, as follows:

$$q = \frac{Q_m \cdot c_{\mathrm{v}} \cdot \Delta t}{\pi \cdot d_3 \cdot l} \qquad (\mathrm{W \cdot m^{-2}}) \tag{3}$$

The relation between heat flow density q and the linear heat flow density q_l is expressed as follows:

where the specific heat loss is expressed as follows:

$$q_l = q \cdot \pi \cdot d_3 \quad (\mathrm{W \cdot m^{-1}}) \tag{4}$$

By inserting relation (3) into (4) we get a formula for calculating the specific heat loss (heat flow density), depending on the decrease in the water temperature at the inlet and outlet of the pipe in the following form:

$$q_{l,\mathrm{BM}} = \frac{Q_m \cdot c_\mathrm{v} \cdot \Delta t}{l} \quad (\mathrm{W \cdot m^{-1}}) \tag{5}$$

or

$$q_{l,\mathrm{BM}} = \frac{Q_V \cdot \rho \cdot c_\mathrm{v} \cdot \Delta t}{l} = Q_V \cdot \rho \cdot c_\mathrm{v} \cdot \Delta T \quad (\mathrm{W \cdot m^{-1}})$$

where:

ΔT – the temperature decrease in a pipe one meter in length ($\mathrm{K \cdot m^{-1}}$),
Q_V – the water flow rate ($\mathrm{m^3 \cdot s^{-1}}$),

The balance method for determining heat losses is suitable only for very long stretches of heat distribution systems, where the measurement error of temperature difference does not cause a significant error in the subsequent determination of heat losses expressed analytically in line with the aforementioned methodology. Measuring the temperature difference of the heat transmission medium within shorter sections with excellent insulation requires highly precise measuring equipment that would enable the temperature difference to be measured with the accuracy of at least two decimal places. However, such devices cannot be permanently installed as a part of every distribution network, especially if a distribution system stretches several tens of kilometres.

The aforementioned disadvantages of using the balance method for determining specific and total heat losses in the secondary heat distribution systems further underscore the need to develop new methods for calculating the values. From the perspective of the producer as well as distributor, such methods should be devised, whose implementation would not require substantial financial resources and, at the same time, would allow for the simple determination of the value of the total or specific heat loss in a distribution network.

III. EXPRESSING UNIT SPECIFIC HEAT LOSS BY ANALYTICAL PROCEDURE

The application of this methodology enables us to determine heat losses for a specific temperature of heat transmission medium and ambient temperature for a distribution network with both direct and reverse piping, known design of the system, the length of pipeline, the dimensions of the distribution network and the thickness of insulation. The calculation of the heat loss as described below requires dividing the heat distribution network into individual sections with similar dimensions and design.

Specific heat loss of piping one meter ($q_{l,AG}$) in length can be expressed as follows [4]:

For the above-ground piping (AG)

$$q_{l,\mathrm{AG}} = q_{l,\mathrm{AG},1} + q_{l,\mathrm{AG},2} = \frac{t_{\mathrm{i},1} - t_\mathrm{e}}{R_{l,1}} + \frac{t_{\mathrm{i},2} - t_\mathrm{e}}{R_{l,2}} \quad (\mathrm{W \cdot m^{-1}}) \tag{6}$$

where:

$q_{l,\mathrm{AG},1}$ – specific heat loss for direct piping ($\mathrm{W \cdot m^{-1}}$),
$q_{l,\mathrm{AG},2}$ – specific heat loss for reverse piping ($\mathrm{W \cdot m^{-1}}$),
$t_{\mathrm{i},1}$ - water temperature in the direct piping (K)
$t_{\mathrm{i},2}$ - water temperature in the reverse piping (K)
t_e – ambient temperature (K),
$R_{l,1}$ – linear specific thermal resistance of the direct piping ($\mathrm{m \cdot K \cdot W^{-1}}$),
$R_{l,2}$ – linear specific thermal resistance of the reverse piping ($\mathrm{m \cdot K \cdot W^{-1}}$),

In relation (6), $R_{l,1(2)}$ is the linear specific thermal resistance and, for the piping with insulation (Fig. 1), can be calculated as follows:

$$R_{l,1(2)} = R_{l,\alpha_{c,1}} + R_{l,\lambda} + R_{l,\lambda_{iz}} + R_{l,\alpha_{c,2}} \quad (m \cdot K \cdot W^{-1}) \tag{7}$$

where:

$R_{l,\alpha_{c,1}}$ – linear specific thermal resistance on the inner surface of the pipe ($m \cdot K \cdot W^{-1}$),

$R_{l,\lambda}$ – linear specific thermal resistance of the pipe wall ($m \cdot K \cdot W^{-1}$),

$R_{l,\lambda_{iz}}$ – linear specific thermal resistance of the insulation ($m \cdot K \cdot W^{-1}$),

$R_{l,\alpha_{c,2}}$ – linear specific thermal resistance on the outer surface of the insulation ($m \cdot K \cdot W^{-1}$),

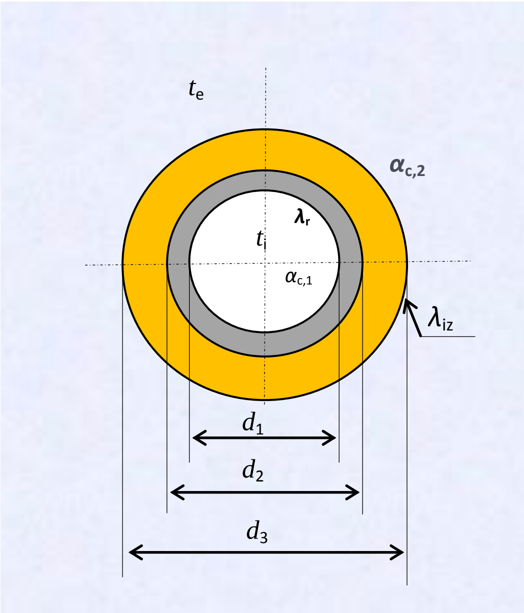

FIG. 1 ABOVE-GROUND PIPING WITH THE INSULATION

The linear specific thermal resistance for heat transfer from the flowing medium to the pipe wall and the linear specific thermal resistance for the heat transferred through the wall of a steel pipe $R_{l,\lambda}$ is insignificant and thus can be ignored in the calculation so the relation for determining linear specific thermal resistance is formulated as follows:

$$R_{l,1(2)} = \frac{1}{2 \cdot \pi \cdot \lambda_{ins}} \cdot \ln\frac{d_3}{d_2} + \frac{1}{\pi \cdot d_3 \cdot \alpha_{c,2}} \quad (m \cdot K \cdot W^{-1}) \tag{8}$$

where:

d_2 - internal pipe diameter (m),

λ_{ins} - thermal conductivity of the insulation ($W \cdot m^{-1} \cdot K^{-1}$),

d_3 – external diameter of the piping with insulation (m),

$\alpha_{c,2}$ – coefficient heat transfer from the flowing medium to the outer environment ($W \cdot m^{-2} \cdot K^{-1}$).

The linear specific thermal resistance of the direct and reverse piping can be considered the same, as the thermal conductivity and the heat transfer coefficient from the surface of an insulated pipe into the outer environment for direct and reverse piping differ minimally. Thus relation (6) can be formulated as follows:

$$q_{l,AG} = \frac{1}{R_{l,1,(2)}} \cdot (t_{i,1} + t_{i,2} - 2.t_e) \quad (W \cdot m^{-1}) \tag{9}$$

or

$$q_{l,AG} = q_{p,AG} \cdot (t_{i,1} + t_{i,2} - 2.t_e) \quad (W \cdot m^{-1}) \tag{10}$$

where:

$q_{p,\mathrm{AG}}$ - specific heat loss unit of the district heating network above ground ($W \cdot m^{-1} \cdot K^{-1}$).

Specific heat loss per unit of a directly buried heat distribution network (DBN) is expressed as follows:

$$q_{l,\mathrm{DBN}} = q_{l,DBN,1} + q_{l,DBN,2} \quad (W \cdot m^{-1}) \tag{11}$$

or

$$q_{l,DBN} = \frac{R_{l,2} \cdot (t_{\mathrm{i},1} - t_{\mathrm{e}}) - R_{\mathrm{z}} \cdot (t_{\mathrm{i},2} - t_{\mathrm{e}})}{R_l} + \frac{R_{l,1} \cdot (t_{\mathrm{i},2} - t_{\mathrm{e}}) - R_{\mathrm{z}} \cdot (t_{\mathrm{i},1} - t_{\mathrm{e}})}{R_l} \quad (W \cdot m^{-1}) \tag{12}$$

where:

$q_{l,\mathrm{DBN},1}$ – specific heat loss for direct piping ($W.m^{-1}$),
$q_{l,\mathrm{DBN},1}$ – specific heat loss for reverse piping ($W.m^{-1}$),

When calculating the total linear specific thermal resistance R_l the linear specific thermal resistance $R_{l,\alpha_{\mathrm{c},1}}$ $R_{l,\lambda}$ can also be ignored for this type of pipeline laying, and only the relation for the linear specific thermal resistance for insulation and soil $R_{l,\mathrm{z}}$ is applied.

The linear specific thermal resistance $R_{l,1}$ ***of a direct pipe is determined as a sum of the thermal heat resistance of insulation and soil as expressed in the following formula [3]:***

$$R_{l,1} = \frac{1}{2 \cdot \pi \cdot \lambda_{\mathrm{iz},1}} \cdot \ln \frac{d_3}{d_2} + \frac{1}{2 \cdot \pi \cdot \lambda_{\mathrm{z}}} \cdot \ln \frac{4.H_{\mathrm{r}}}{d_3} \quad (m \cdot K \cdot W^{-1}) \tag{13}$$

The linear specific thermal resistance $R_{l,2}$ of a reverse pipe is determined as a sum of the thermal heat resistance of insulation and soil, as expressed in the following formula [3]:

$$R_{l,2} = \frac{1}{2 \cdot \pi \cdot \lambda_{\mathrm{ins},2}} \cdot \ln \frac{d_3}{d_2} + \frac{1}{2 \cdot \pi \cdot \lambda_{\mathrm{z}}} \cdot \ln \frac{4.H_{\mathrm{r}}}{d_3} \quad (m \cdot K \cdot W^{-1}) \tag{14}$$

To calculate the soil resistance between two pipes (the rate of mutual interaction) the following formula is used:

$$R_{\mathrm{z}} = \frac{1}{2 \cdot \pi \cdot \lambda_{\mathrm{z}}} \cdot \ln \sqrt{\left(\frac{2.H_{\mathrm{r}}}{C} \right)^2 + 1} \quad (m \cdot K \cdot W^{-1}) \tag{15}$$

where the calculation of the reduced lying depth H of a pipe can be performed as follows:

$$H_{\mathrm{r}} = H_1 + \frac{\lambda_{\mathrm{z}}}{\alpha_0} \quad (m) \tag{16}$$

where:

H_1 (H_2) - lying depth of the piping (direct, reverse) (m)
λ_{z} – thermal conductivity coefficient of soil ($W \cdot m^{-1} \cdot K^{-1}$),
α_0 – heat transfer coefficient between the earth's surface and the outer environment ($W \cdot m^{-2} \cdot K^{-1}$),
C - distance between the axes of pipes (m).

The total thermal resistance can be after adjustment expressed as follows:

$$R_l = R_{l,1} \cdot R_{l,2} - R_{\mathrm{z}}^2 \quad (m \cdot K \cdot W^{-1}) \tag{17}$$

In this case the linear specific thermal resistance of a direct and reverse piping is identical or there is only a marginal difference. Thus, relation (12) can be formulated as follows:

$$q_{l,\mathrm{DBN}} = \frac{R_{l,1,(2)} - R_z}{R_l} \cdot (t_{i,1} + t_{i,2} - 2 \cdot t_e) \quad (\mathrm{W \cdot m^{-1}}) \tag{18}$$

or

$$q_{l,DBN} = q_{p,DBN} \cdot (t_{i,1} + t_{i,2} - 2 \cdot t_e) \quad (\mathrm{W \cdot m^{-1}}) \tag{19}$$

where:

$q_{p,\mathrm{DBN}}$ –specific heat loss unit of the directly buried heating pipeline $(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$.

The aforementioned implies that the formula for the calculation of the specific heat loss of one meter in length can be expressed as follows:

$$q_{l,x} = q_{p,x} \cdot (t_{i,1} + t_{i,2} - 2 \cdot t_e) \quad (\mathrm{W \cdot m^{-1}}) \tag{20}$$

where:

x - specifies the design of a pipeline section (e.g. AG - above round, DBN - directly buried network).

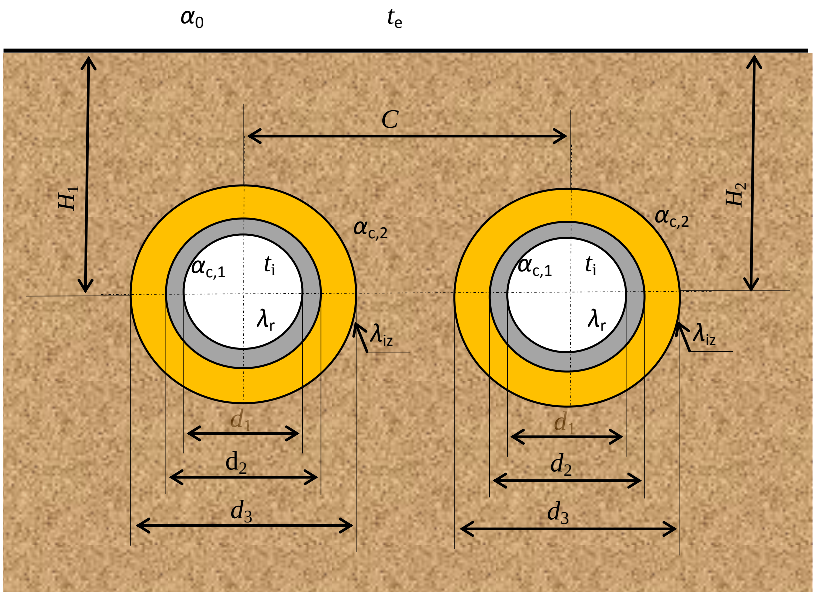

FIG. 2 BURIED PIPELINE WITH THE INSULATION

Fig. 3 and 4 depicts specific heat losses in a pipeline section $q_{p,x}$ $(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$ for individual designs of the distribution network depending on the diameter of the pipe and the thickness of insulation.

To determine the value of specific heat losses by equation (20), the relevant value of $q_{p,x.}$ is read from the diagrams, based on the diameter of a pipe and the thickness of insulation, and the value is then used in formula (20).

The diagrams were obtained taking into account the following conditions:

1. The specific heat loss unit for different designs depending on the diameter of a pipe and the thickness of insulation is calculated from the following relations:

$$q_{p,\mathrm{AG}} = \frac{1}{R_{l,1,2}} \quad (\mathrm{W \cdot m^{-1} \cdot K^{-1}}) \tag{21}$$

$$q_{p,\,\mathrm{DBN}} = \frac{R_{l,1,2} - R_z}{R_l} \quad (\mathrm{W \cdot m^{-1} \cdot K^{-1}}) \tag{22}$$

2. The calculation of the values of specific thermal resistance in point 1 (using formulas 21 and 22) considered the average value of water temperature in the direct and reverse piping obtained from the following variants:

1. variant	2. variant	3. variant	4. variant
t_1/t_2 = 70/60 °C	t_1/t_2 = 65/60 °C	t_1/t_2 = 60/55 °C	t_1/t_2 = 55/50 °C
t_1/t_2 = 70/55 °C	t_1/t_2 = 65/55 °C	t_1/t_2 = 60/50 °C	t_1/t_2 = 55/45 °C
t_1/t_2 = 70/50 °C	t_1/t_2 = 65/50 °C	t_1/t_2 = 60/45 °C	t_1/t_2 = 55/40 °C
t_1/t_2 = 70/45 °C	t_1/t_2 = 65/45 °C	t_1/t_2 = 60/40 °C	
t_1/t_2 = 70/40 °C	t_1/t_2 = 65/40 °C		

The ambient temperature was determined based on the STN EN 12831 [9]. Its value is t_e = -15°C.

PIPO_ALS with all its characteristic properties was considered as an insulating material [8]. The calculations were performed with the mean value of the thermal conductivity coefficient of the insulation λ_{ins} as a function of the temperature of transferred water (λ_{ins} = 0,04 W·m^{-1}·K^{-1}), heat transfer coefficient between the surface of insulation and the ambient environment $\alpha_{c,2}$ = 3 W·m^{-2}·K^{-1}, lying depth H_1 = 1.2 m and the mean value of the thermal conductivity of soil λ_s = 1,3 W·m^{-1}·K^{-1}.

The total heat loss of a heat distribution network P_c is, after determining the specific heat losses for each network design, expressed as follows:

- for the above ground heat transmission network:

$$P_{c,AG} = \sum_{i=1}^{i=n} q_{i,l,AG} \cdot L_{i,AG} \quad \text{(W)} \tag{23}$$

- for the underground heat transmission network:

$$P_{c,DBN} = \sum_{i=1}^{i=n} q_{i,l,DBN} \cdot L_{i,DBN} \quad \text{(W)} \tag{24}$$

where:

$q_{i,l,AG}$ – the specific heat loss in the above ground piping section, one meter in length (W·m^{-1}),
$q_{i,l,DBN}$ – the specific heat loss in the directly buried piping section, one meter in length (W·m^{-1}),
$L_{i,AG}$ - the length of above ground piping (m),
$L_{i,DBN}$ - the length of directly buried piping (m),

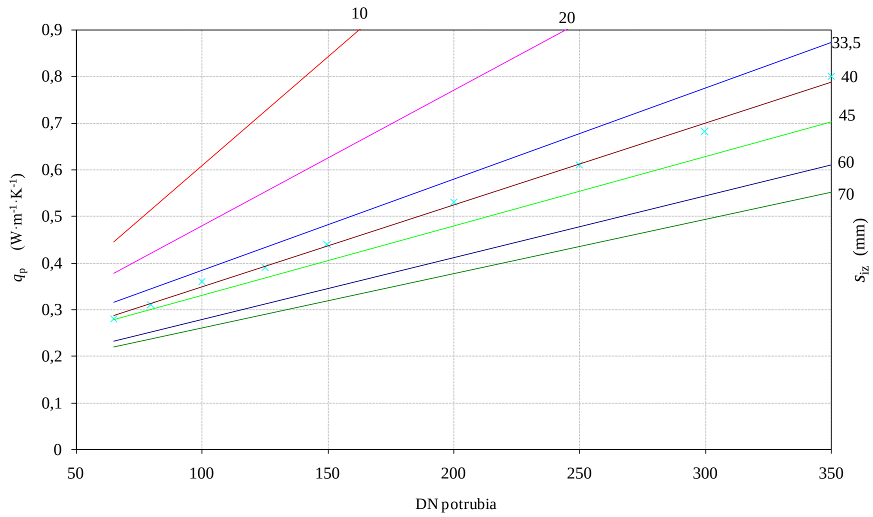

FIG. 3 SPECIFIC HEAT LOSS UNIT OF DIRECTLY BURIED PIPING

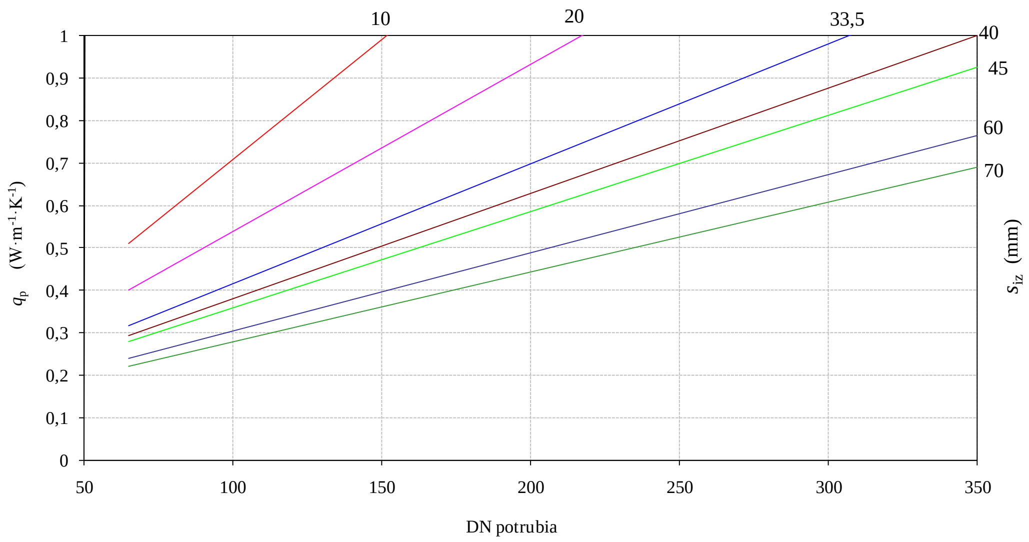

FIG. 4 SPECIFIC HEAT LOSS UNIT OF ABOVE-GROUND PIPING

IV. CONCLUSION

The methodology for determining heat losses of heat distribution networks, as presented in the article, is fairly simple. Based on the actual water temperature in direct and reverse piping and the ambient temperature, the value of specific as well as total heat loss of the examined heat transmission network can be readily determined.

The presented method of calculating heat losses can be practically applied for the purposes of running heat distribution networks as well as assessing their efficiency.

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