QUALITY ASSESSMENT OF THERMAL INSULATION OF PIPELINES WITHIN THE DISTRICT HEATING SYSTEMS

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Abstract - The paper comes under the major concern for the growth of energy efficiency within the centralized supply systems with thermal energy (CSSTE). In the paper there is presented a model for evaluating the loss of heat through insulation. Thus the identified loss of heat is used for evaluating the quality of thermal insulation for the transport and distribution networks within CSSTE. Also there are presented the results of applying this evaluating model for a primary thermal network area belonging to CSSTE in Oradea municipality. On the basis of the results obtained, which are presented under the form of a table and graphics, there are drawn conclusions regarding the factors that have an influence on the loss of heat and the directions in which one should act in order to reduce them.

Keywords: heat power plant, energy efficiency, thermal insulation.

1. INTRODUCTION

CSSTE represents a unitary technological and functional assembly consisting of the following main subsystems: the source, the primary thermal networks (PTN), substation/ mini substation (SB), secondary thermal networks (STN).

In order that CSSTE as an assembly to be competitive from the energetic point of view each of the subsystem components should reach certain compulsory requirements.

In rating the PTN and STN the knowledge of the loss of heat is of a major importance. For evaluating them there were created several models [1, 2, 3, 4, 5, 6].

An important component of the loss of heat is represented by the loss through thermal transfer, from the heat carrier to the environment which leads to a drop of temperature within the heat carrier flowing along the pipe, having also a direct influence on the outer surface temperature of the thermal insulation. In the CSSTE case, the subject of the present paper, the heat carrier is the boiling water, with a maximum temperature of 125°C.

In the framework Regulation of the public service for thermal power supply [7] as well as in the rule I13 [8] the minimum value of the efficiency which the thermal insulation associated with the heat carriers needs to assure is set at 80%.

For the insulation of the new pipes in [7, 8] the values in table 1, are set for the minimum thickness of the insulation coat, according to the nominal diameter (DN) related to a permeability multiplier of the insulation of 0,035W/mK.

Table 1. Thickness of the insulation coat, according to the pipe's diameter [7, 8]

No.crt.	Nominal diameter [mm]	Thickness of the insulation coat [mm]
1.	<20	20
2.	20 - 35	30
3.	40-100	=DN
4.	≥100	100

These provisions represent a case study, the results of which are presented in the paper.

2. THE MODEL USED FOR ASSESSMENT

The analyzed thermal network is of dendritic type with a sequencing of serial and paralleled connected sections, the loss of heat consisting in the summation of the loss of heat for the component sections. The total loss of heat comprises the loss due to leaking and the loss through thermal transfer from the fluid to the environment. The calculation model developed below refers to the second category, loss through thermal transfer, also known as loss through insulation.

Used notes:

- t_i – the temperature of the heat carrier [°C];
- t_{ir} – the temperature of the heat carrier according to the adjuster scheme [°C];
- t_e – the temperature of the exterior air [°C];
- θ – the temperature at the interior surface of the insulation [°C];
- θ_e – the temperature at the exterior surface of the insulation [°C];
- α_i – the coefficient of heat transfer through convection, starting from fluid to the interior surface of the pipe $\left[\frac{W}{m^2 \cdot grd}\right]$;
- α_e – the coefficient of heat transfer through convection and radiation, from insulated pipe to the environment $\left[\frac{W}{m^2 \cdot grd}\right]$;
- α_r – the coefficient of heat transfer through radiation from pipe to the environment $\left[\frac{W}{m^2 \cdot grd}\right]$;

α_c – the coefficient of heat transfer through convection from pipe to the environment $\left[\frac{W}{m^2 \cdot grd}\right]$;
λ – thermal conductivity of the pipe [W/m·K];
λ_j – thermal conductivity of the insulation coat „j'' [W/m·K];
η_{iz} – the efficiency of the insulation;
q_0 – the unitary loss of heat in case of uninsulated pipe [W/m];
q_{iz} – the unitary loss of heat in case of insulated pipe [W/m];
v – the speed of wind [m/s];
γ – air density [kg/m^3];
λ_a – thermal conductivity of the air [W/m·K];
c_p – caloric power of the air [J/kg·K].

The efficiency of the insulation

According to [3, 6], the efficiency of insulation is defined through the ratio (1):

$$\eta_{iz} = (q_0 - q_{iz})/q_0 \qquad (1)$$

Starting with this definition we explain further on q_0 and q_{iz}, using the notes in fig.1.

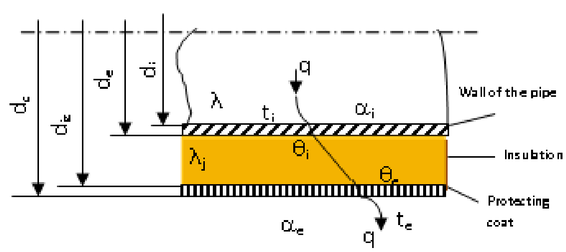

Fig. 1. Heat transmission through the pipes

2.1. Specific heat loss in case of uninsulated pipes

For calculating the heat loss through the walls of the pipes, as seen in [1, 2, 3], one can apply the ratio (2):

$$q_0 = k\pi(t_i - t_e) \qquad (2)$$

where:

$$k = \frac{1}{\frac{1}{\alpha_i d_i} + \frac{1}{2\lambda}\ln\frac{d_e}{d_i} + \frac{1}{\alpha_e d_e}} \qquad (3)$$

is the coefficient of heat transfer from fluid to the environment, related to a line meter pipe.

Because the thickness of the pipes walls is reduced, and the thermal conductivity of the steel is pretty high, the thermal resistance of the pipe's wall is neglected. Also, the convection coefficient α_i on the interior surface of the pipe being very high in comparison with the heat transfer coefficient on the exterior surface of the pipe α_e, the resistance $1/\alpha_i d_i$ is neglected. Thus the ratio (2) and (3) become:

$$q_0 = \alpha_e \pi d_e (t_i - t_e) \qquad (4)$$

$$k \approx \alpha_e d_e \qquad (5)$$

The heat transfer coefficient on the exterior surface α_e defined in [2], given by the formula (6), sums up the effects of convection and radiation:

$$\alpha_e = \alpha_c + \alpha_r \qquad (6)$$

The value of the exchange coefficient through radiation transfer on the surface of the pipe is:

$$\alpha_r = bC \qquad (7)$$

where: C – is the radiation constant of the pipe [W/m^2·grd^4];

b = $[(T/100)^4 - (T_e/100)^4] / (T - T_e)$ – is the temperature factor;

$T = \theta_e + 273$ is the absolute temperature of the surface;

$T_e = t_e + 273$ is the absolute temperature of the environmental air.

In the case of horizontal pipes in calm air, the coefficient α_c depends in special on the difference of temperature $\theta = \theta_e - t_e$, between the exterior surface of the pipe and the environmental air and is given by the formula:

$$\alpha_c = 1{,}86 \cdot \theta^{0,24} \qquad (8)$$

If the environmental air is in motion, then the convection coefficient α_c is mainly influenced by the speed v of the air. In this case, the value α_c is given by the formula:

$$\alpha_c = 0{,}107 \cdot \left(\frac{v d_e \gamma c_p}{\lambda_a}\right)^{0,75} \cdot \frac{\lambda_a}{d_e} \qquad (9)$$

Exchanging in the formula (5) α_e, given in the formula (6), (7), (8), (9), one will obtain the loss of heat of the uninsulated pipes, into calm air:

$$q_0 = (1{,}86 \cdot \theta^{0,24} + bC)\pi d_e(t_i - t_e) \qquad (10)$$

respectively at different speeds of the air:

$$q_0 = \left(0{,}107 \left(\frac{v d_e \gamma c_p}{\lambda_a}\right)^{0,75} \frac{\lambda_a}{d_e} + bC\right)\pi d_e (t_i - t_e) \qquad (11)$$

2.2. Heat loss in case of insulated pipes

In the case of insulated pipes, we also apply equation (2), as we did for uninsulated pipes, with the specification that this time the convection coefficient k includes as well the resistance of the insulating coat. In case of an insulation composed of n coats:

$$k = \frac{1}{\frac{1}{\alpha_i d_i} + \frac{1}{2\lambda}\ln\frac{d_e}{d_i} + \sum_{j=1}^{n}\frac{1}{2\lambda_i}\ln\frac{d_{iz_j}}{d_{iz_{j-1}}} + \frac{1}{2\lambda}\ln\frac{d_c}{d_{iz_n}} + \frac{1}{\alpha_e d_c}} \qquad (12)$$

As in case of uninsulated pipes, in practical calculation, thermal resistance on the interior surface, the resistance of the wall and of the protection coat is neglected and the result is:

$$k = \frac{1}{\frac{1}{2\lambda_1}\ln\frac{d_{iz_1}}{d_e} + \frac{1}{2\lambda_2}\ln\frac{1}{\alpha_e d_c}} \qquad (13)$$

The approximation made by neglecting the resistance on the interior surface and the resistance of the pipe's wall is much reduced in case of insulated pipes, than in uninsulated ones, because in case of insulated pipes the thermal resistance of the insulation represents [2] about 85% from the total resistance, and the rest of 15% belongs to the resistance at superficial heat transfer on the exterior surface.

For also taking into account the heat loss through radiation, in this case in ratio (13) the coefficient α_e from ratio (6), will be introduced, where α_r is given by ratio (7), and α_c by (8) or (9).

Likewise, for the calculation of the thermal transfer coefficient through convection and radiation α_e, in case of exterior pipes, one can use after [3] the ratio:

$$\alpha_e = 9{,}28 + 0{,}046\,\theta_e + 6{,}96 v^{1/2} \qquad (14)$$

the loss of heat through insulated pipes can be obtained:

$$q_{iz} = \frac{\pi(t_i - t_e)}{\sum_{j=1}^{n} \frac{1}{2\lambda_i} \ln \frac{d_{iz_j}}{d_{iz_{j-1}}} + \frac{1}{\alpha_e \cdot d_c}} \qquad (15)$$

Where $d_{iz_{i-1}} = d_e$, for i = 1. In ratio (15), we mark with:

$$R_{iz} = \sum_{j=1}^{n} \frac{1}{2\pi\lambda_j} \ln \frac{d_{iz_j}}{d_{iz_{j-1}}} \qquad (16)$$

The insulation resistance, and with:

$$R_e = \frac{1}{\pi \cdot \alpha_e \cdot d_c} \qquad (17)$$

The thermal transfer resistance at the exterior surface of the last coat at environmental air.

Provided that temperature at the surface of the insulation is known, the specific loss of heat can be determined [3] with the aid of the ratio:

$$q_{iz} = (\theta_e - t_e)/R_e \qquad (18)$$

From the equality between equations (15) and (18), with the notes in (16) and (17), there can be obtained the ratio for calculating the temperature at the surface of the insulation:

$$\theta_e = t_i - \frac{t_i - t_e}{R_{iz} + R_e} \cdot R_{iz} \qquad (19)$$

The value of thermal conductivity λj is specific to each of thermal insulation materials used, being named in the instruction sheet by the trade company. For the networks built before 1990, the insulation coat was made mainly out of mineral wool or glass wool with an exterior protection made out of millboard and sheet-metal, for those built over the earth, or of millboard only for those constructed under earth. The thermal conductivity according to the nature of insulation and the medium temperature of it t_{miz} can be calculated [3], with the following ratios:

- $\lambda_j = 0{,}059 + 0{,}000186 t_{miz}$ - mineral wool shells;
- $\lambda_j = 0{,}051 + 0{,}00016 t_{miz}$ - mineral wool mattress;
- $\lambda_j = 0{,}047 + 0{,}00031 t_{miz}$ - for glass wool.

As t_{miz} is the arithmetic mean a t_i and θ_e, the calculation is made through successive iterations. Values are attributed to θ_e, with which λ_j and α_e is calculated, up to the point where the attributed value reaches a deviation from the calculated value of the ratio (19) under the limit imposed deviation.

3. CASE STUDY. THE CALCULATION OF HEAT LOSS THROUGH INSULATED PIPES BUILT OVER THE EARTH, IN AN AREA OF CSSTE IN ORADEA MUNICIPALITY

3.1. General considerations

CSSTE in Oradea municipality was developed into stages, in the interval (1966÷1989) along with the development of the industrial sector and the enlargement of the dwelling areas.

Within CSSTE, fig.2, there were two thermal power supply sources represented by the two central-heating and power plants (CHP), situated one in the N–W of the town (CHP 1) and the other in the S–E of the town (CHP 2).

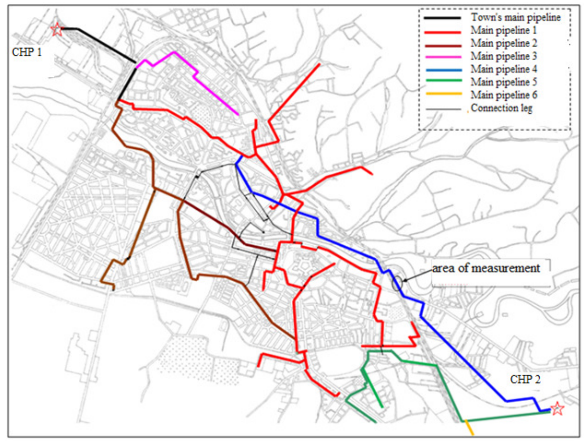

Fig.2. Primary thermal network in Oradea municipality –Principle Scheme

In order to supply the urban consumers, there has been developed, in several stages, a primary thermal network. Thus, a mains pipe which starts from CHP 1 and goes up to the entrance of the town, where is split into main pipe 1, 2, 3 that supply the north-west and the central part of the town was built.

Once the dwelling area of the town increased towards S-E and CHP 2 was built (1986÷1989), the main pipe 4 and 5 became operative for supplying that area.

After 1990 there ceased the assets scheduled for industrial objectives in CHP 2 area, which were taken into account when the power plant was constructed from the point of view of steam release. Furthermore several economical agents, that used thermal energy supplied by CHP 1, ceased or reduced their activity. Thus the use of thermal energy in Oradea municipality became very low, and the energy could be supplied by a single power plant through cogeneration. In such conditions in 2003, the entire urban usage of thermal energy was taken over by CHP 1. For putting this into practice, the capacity of the thermal networks within the district heating power plant was increased up to the connection with main pipeline 1 and 2. Also a connection of high capacity between main pipeline 1 and 4 was created, which had the role of supplying main pipe 5 as well, assuring thus the necessary flow of the heat carrier for the consumers initially supported by CHP 2.

Functioning in new conditions, with a single supply source, implied some changes in pressure regimes, the flows and implicitly temperature drops in certain areas of the network.

The present paper shows the results of a study made on the condition of the insulation for a section of main pipe 4, with DN 800, built over the earth. The total length of the over the earth network with DN 800, from which the section in discussion belongs, is of 6092m. Through this network there are supplied consumers with a necessary maximum power of 101MW, which can be provided with a flow rate of heat carrier of 1341t/h at a turn and return difference temperature of 65°C.

The application of calculating models lead to some results which provide an evaluation of the heat loss through insulation of the over the earth thermal networks of power supply in the analyzed area, as well as the measures that are to be taken in order to decrease them

3.2. Results and discussions

The calculating model presented above was put into practice for the flow pipe of the primary thermal networks built over the earth, which register the highest heat loss. In the analyzed area the pipes have DN 800, and the thermal insulation on the supply pipe was realized with mineral wool mattress with a thickness of 100mm, protected at the exterior surface with black painted sheet-metal.

On the basis of specific heat loss of the pipe, for wind speeds of 0m/s, respectively 5m/s, without insulation (q_0, q_{0v}) and with insulation (q_{iz}, q_{izv}), the theoretic efficiency of the over the earth pipes' insulation was determined (η_{iz}, η_{izv}). The temperature on the surface of the insulation for the theoretical project conditions, without wind θ_{eo} and with wind θ_{ev} was also calculated. The temperature of the primary heat carrier t_{ir}, was considered to be the one from the calibration sheet.

The results of the calculation are presented in table 2.

Table2. Specific heat loss and the efficiency of the insulation

t_e	t_{ir}	q_0	q_{0v}	q_{iz}	q_{izv}	η_{iz}	η_{izv}	θ_{eo}	θ_{ev}
°C	°C	W/m	W/m	W/m	W/m	%	%	°C	°C
8	90	2434	6363	130	136	94,7	97,9	13,2	9,7
7	91	2501	6519	133	140	94,7	97,9	12,4	8,7
6	92	2568	6675	136	143	94,7	97,9	11,5	7,8
5	94	2676	6917	141	148	94,7	97,9	10,8	6,8
4	96	2786	7159	146	153	94,8	97,9	10,0	5,9
3	98	2896	7401	151	159	94,8	97,9	9,2	5,0
2	100	3007	7645	156	164	94,8	97,9	8,4	4,0
1	102	3119	7889	161	169	94,8	97,9	7,7	3,1
0	104	3233	8134	166	174	94,9	97,9	6,9	2,2
-1	106	3347	8379	171	180	94,9	97,9	6,1	1,3
-2	108	3463	8625	176	185	94,9	97,9	5,4	0,3
-3	110	3580	8872	181	190	94,9	97,9	4,6	-0,6
-4	112	3697	9120	186	195	95,0	97,9	3,8	-1,5
-5	114	3816	9368	191	201	95,0	97,9	3,1	-2,5
-6	116	3936	9617	196	206	95,0	97,9	2,3	-3,4
-7	118	4057	9867	201	212	95,0	97,9	1,6	-4,3
-8	120	4179	10118	206	217	95,1	97,9	0,8	-5,2
-9	122	4303	10369	211	222	95,1	97,9	0,1	-6,2
-10	123	4378	10531	214	226	95,1	97,9	-0,8	-7,1
-11	124	4454	10692	217	229	95,1	97,9	-1,6	-8,1
-12	125	4531	10853	221	233	95,1	97,9	-2,4	-9,0

For determining the actual status of the insulation a series of measurements were made. Hence, the temperature at the surface of the insulation was measured with the aid of a thermal imager. In fig.3. there are presented images of the pipe taken with the aid of camera and thermal imager.

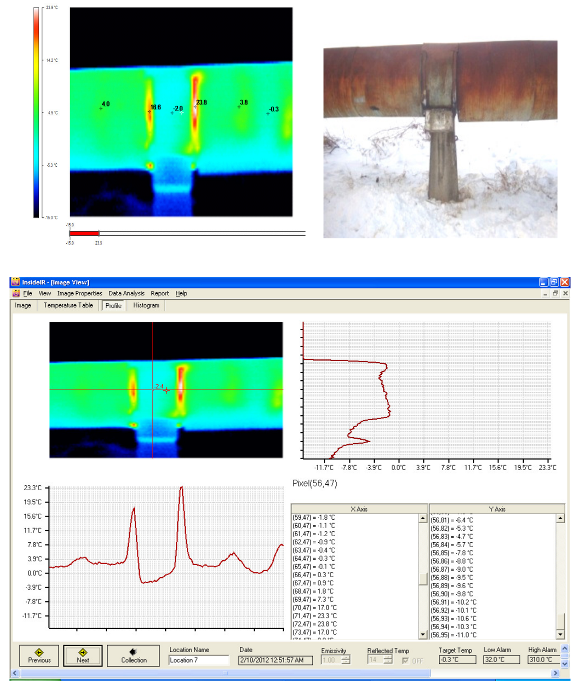

Fig.3. Section of pipe from the analysed area

The temperature of the primary heat carrier in the analyzed area was considered to be equal with the one measured in SB 836, both with local instruments as well as with a measurement instrument with a recording diagram assembled especially for this purpose. This substation is connected in the trunk area, the lay-out of the connection pipes being under earth and having a length of 134m. The relative short length and the good condition of the insulation leads to a minor heat loss for this connection, reason for which it was neglected in the calculation made.

On the basis of taken measurements, at an exterior temperature of -11°C, and a speed of wind at 2m/s, the real specific heat loss $q_{izr,}$ respective the real efficiency, η_{izr} was determined, for a medium temperature at the surface of the pipe of 1°C.

The results of the measurements and the calculation made, starting with these measurements are presented in table 3.

Table 3.The insulation parameters determined on the basis of project data and the taken measurements

Data from:	t_e	v	t_i	θ_e	q_{iz}	η_{iz}
	°C	m/s	°C	°C	W/m	%
project	-11	2	124	-7,2	228	96,5
measurement	-11	2	116	1	726	90,5

From the comparative analysis of the values determined with the aid of project data with the measured ones, presented in table 3, it results that the actual status of the insulation leads to specific heat loss of more than 3 times (considering the fact that during measurement the temperature of heat carrier was under the adjuster value), corresponding to a diminishing of efficiency of more than 6 %.

The theoretic efficiency according to the outer temperature, as well as the resulted efficiency after measurement are graphically represented in fig. 4.

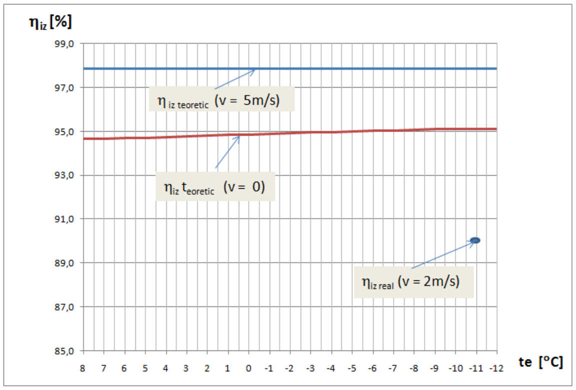

Fig.4. The theoretic and real efficiency of the insulated flow pipe PTN

From the data presented in table 2 and chart in fig. 4, it results that the speed of wind significantly influences the heat loss in case of uninsulated pipes, it's effects decreasing with the growth of the thermal insulation efficiency. One can notice that the real efficiency of the insulation is much under the theoretic one, being damaged by over 25 years of usage.

The variation of temperature at the outer surface of the insulation according to the temperature of the heat carrier and the outer air, for speeds of wind of 0m/s, respectively 5m/s is presented in fig.5.

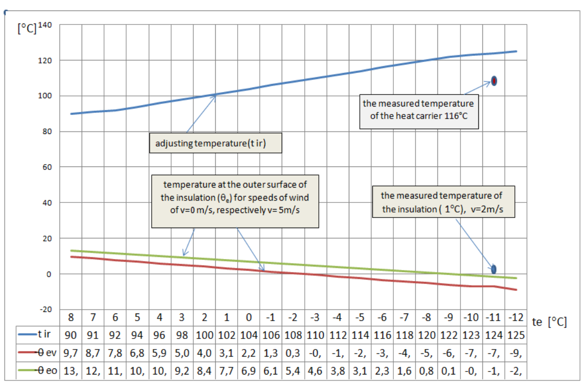

Fig.5. The temperature at the surface of insulation (θ_e) according to the calibration temperature of heat carrier (t_{ir}) and the outer temperature (t_e)

It can be also noticed that the temperature at the surface of the insulation is influenced by the speed of wind, the difference up against the outer air decreasing with the growth of wind speed. For real conditions the temperature at the surface of the insulation (1°C) is higher than the theoretic one (-8,1÷-1,6)°C, hence another element that describes the degradation of the insulation in time.

For the analyzed pipe sector, with DN 800, the actual maximum flow rate of the heat carrier is of only 1341t/h. For this flow rate the medium speed of the heat carrier is of 0,73m/s. For DN 600 and DN 500 at the same flow the speeds are 1,29m/s and 1,84m/s. The recommended speed [2] on pipes which carry water is comprised between 0,5m/s and 3m/s, thus a reduction of the pipe's section won't lead to an overrun of the recommended speeds.

For seeing the effect of the section reduction over the heat loss through insulation, the specific loss of heat for pipes DN 600 and DN 500, with a mineral wool insulation of 100mm thickness, as well as for the pipe DN 800, the speed of wind of 5m/s and the fluid temperature corresponding to the outer temperature were calculated. The results are graphically illustrated in fig. 6.

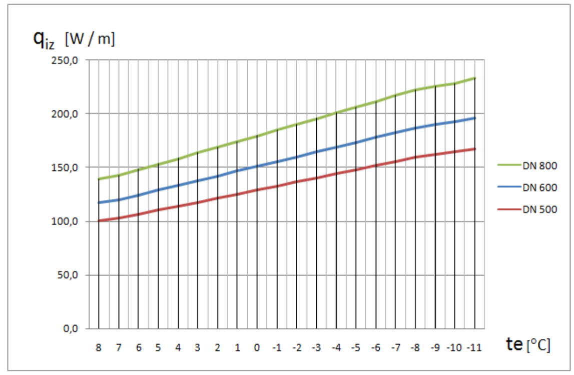

Fig.6. Specific heat loss on DN 800, DN 600, DN 500 pipes

It can be easily seen that the specific heat loss on DN 500 are 30% lower than in the case of DN 800 pipes.

5. CONCLUSIONS

One of the factors which has an influence on the global efficiency of CSSTE is the heat loss through insulation. The calculating model presented in the paper allows the evaluation of these loss for the pipes built over the earth. The mathematical model shows the effects of some factors such as the temperature of primary thermal heat carrier, the exterior temperature, the speed of wind and the diameter of the pipe, on the efficiency of the insulation and heat loss.

The measurements confirm the results obtained through calculation and highlight the degradation of insulation. The temperatures at the surface of the insulation recorded with the thermal imager on the network section studied can be ranged into a wide table of values, which shows that the insulation coat is uneven along the pipe. There are areas where the insulation has a good condition and the temperature at the surface of the insulation is closer to the one indicated in the calculus, but also areas with a much higher temperature.

In calculating the specific loss a medium value of these temperatures was considered. The value of the insulation efficiency thus determined is with over 6% lower than the theoretic one and the specific heat loss of more than 3 times higher than values resulted from theoretic calculations, a thing which highlights the ample degradation of the insulation in more than 25 years of service.

High temperatures in the areas of holders are also put into light. These high temperatures lead to significant heat loss which needs to be considered when evaluating in assembly the loss of the entire network.

A special attention needs to be paid on sizing the pipe. Choosing the optimum diameter of the pipe can lead to significant shortage of heat loss through insulation. In the analyzed case, the reduction of the diameter from DN 800 to DN 500 has the effect of reducing the loss with cca.30%.

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