THE COSTS ASSESSMENT ON THE SELECTION OF THE THERMAL INSULATION THICKNESS FOR NETWORKS THERMAL PIPELINES

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Abstract: Thermal energy consumers that provide comfort parameters inside buildings and, in particular, domestic consumers assigned to a centralized heat supply system, are currently affected by the high level of thermal losses on the transport and distribution networks of the heat at source of the actual consuming installations. These losses are incurred to a large extent by consumers and, to a lesser extent, by the heat distributor, which makes the price of heating energy to reach in some localities on the territory of Romania, prohibitive values. This paper presents a study regarding the financial effects of the thermal rehabilitation of a pipeline section for the transport of the heating agent for heating, through the choice of a suitable thermal insulation of the pipes, in order to reduce the heat loss to the external environment.

Key words*:* heat transfer, pipe, insulation, thermal losses, cost.

1. INTRODUCTION

Over the past 15 years, delaying the implementation of programs aimed at centralized heating, continued downgrading of service quality and increasing the value of the heating bill have led to increased mistrust of the population in centralized heating systems and disconnection from the central heating system of approximately 21% of consumers connected to such heat supply systems.
Out of those disconnected, about 70% chose individual heating at block level as a solution, block stair or apartment level using natural gas fuel plants.
This large number of consumers disconnections has led to a large hydraulic imbalances, both in the external distribution networks and especially in the internal hot water supply networks, with serious implications for the quality of the heating of the buildings in the civil buildings.
For these hydraulic imbalances, an aggravating factor in terms of the final price of heat for heating paid by the consumer, is, to an important extent, the heat losses through the thermal networks to the outside environment.
Heat losses related to a centralized heat supply system have lately accounted for about 0.25% of Romania's gross domestic product, or about 112 million EURO.[7]
As a result, it can be said that the centralized heating system is inefficient and expensive due to technical losses and weak market incentives.
In addition, not all household consumers are able to adjust the amount of heat they receive, due to the lack of metering and adjustment systems.
In order to support the heat consumers and to increase the burden of the high energy price on the final consumer's, thermal rehabilitation of thermal energy transmission and distribution networks may be used, which means the reduction of the thermal energy losses through the appropriate choice of the pipe insulation layer.
An assessment of the rehabilitation of centralized heating systems in Romania estimates investments of about 3900 million Euros, but without the effects and efficiency, or if this assessment was based on the real heat demand resulting from the exhaustion of all consumer efficiency measures.

2. THERMAL CALCULATION OF THERMAL TRANSPORT AND DISTRIBUTION NETWORKS

Thermal calculation of piping systems is a particular case of heat transfer between two fluids, between which there is a partition wall formed by one or more layers.
Depending on the temperature of the transported fluid, there are three categories of thermally insulated pipes:
a) *pipelines for hot fluids,* to which thermal insulation aims at reducing heat and temperature losses to the environment and providing outdoor pipe surface temperatures in accordance with occupational safety standards;
b) *thermally insulated refrigerant pipelines* to reduce heat absorption from the environment and avoid condensation of atmospheric humidity on the surface of insulated pipes;
c) *liquid pipelines with temperature close to ambient temperature fitted* with thermal insulation, especially when placed externally to avoid freezing of liquids transported at low ambient temperatures.
The transfer of heat through the pipe wall is mainly carried out by the following processes:
a) through *thermal convection* between the transported fluid and the inner wall of the pipe;
b) through *thermal conduction* through the wall of the insulated pipe, usually made from metallic layer, the basic thermal insulation and an outer protective layer;

c) through *convection* and possibly *thermal radiation* between the outer surface of the pipe and the surrounding environment. More complicated cases of heat transfer through the pipes insulated (pipes buried in the ground with or without channel accompanying hot pipes for pipelines) will be treated separately.
Table 1 presents the main sizes and relationships used to determine the heat transfer between two fluids separated by cylindrical or planar walls [1], [5], [9].
In the table, when calculating the temperature at a point, the plus sign corresponds to the temperature $t_x>t_c$, and minus sign corresponds to temperature $t_x<t_c$.

Table 1. Sizes and basic relations in the calculation of heat transfer between two fluids separated by a cylindrical wall [1], [5]

Name	Measure	Calculation relationship
Thermal resistance to conduction	(m ·°C)/W	$R_{l,cd}=\frac{1}{2\cdot\pi\cdot\lambda}\cdot\ln\frac{d_e}{d_i}$ (1)
Thermal resistance to convection	(m ·°C)/W	$R_{l,cv}=\frac{1}{\pi\cdot d\cdot\alpha}$ (2)
Total thermal resistance	(m ·°C)/W	$R_l=\sum_{i=1}^{n}R_{l,cd,i}+\sum_{i=1}^{n}R_{l,cv,i}$ (3)
Global Heat Exchange Rate	W/(m·°C)	$k_l=\frac{1}{R_l}$ (4)
Unified thermal flow	W/m	$q_l=k_l\cdot\Delta t=\frac{\Delta t}{R_l}=\frac{t_{f1}-t_{f2}}{R_l}$ (5)
Thermal flow	W	$Q=q_l\cdot L$ (6)
Temperature at a point	°C	$t_x=t_c\pm q_l\cdot R_{l,c}\cdot x$ (7)

Heat loss calculation is done by applying custom classical relationships according to specific situations: - type of thermal insulation of the pipes (insulation with mineral wool mattresses or rigid polyurethane foam insulation); - location mode: underground or air; - the thermal regime of operation during the calculation period in correlation with the external climatic parameters; - the state of thermal insulation materialized by the degradation of the physical characteristics that determine the thermal protection of the pipes (degree of degradation of the thermal insulation); - the diameter and length of the various pipe sections.
The general expression of heat loss in pipelines carrying agent is [4]:

$$Q=q_l\cdot(1+K)\cdot L=\frac{t_{m,fl}-t_0}{R_l}\cdot(1+K)\cdot L\ \text{[W]} \tag{8}$$

were: q_l – specific heat loss, [W/m];
$t_{m,fl}$ – average temperature of the heat, [°C];
t_0 – ambient temperature, [°C];
R_l - resistance to heat transfer from fluid to the environment, [(m·°C)/W];
L – the equivalent length of the pipe, [m];
K – correction coefficient that takes into account heat losses through non-insulated pipe supports (Table 2).

Table 2. Coefficient K for determining heat loss through pipe support elements [1], [4]

Pipeline support	Coefficient K for pipelines	
	In the rooms	outdoors
By hanging	0,10	0,15
By leaning	0,15	0,25

For an air-assembled pipe section (Figure 1) the specific heat loss is calculated with the relation:

$$q_l=\frac{t_m-t_e}{R_l}\cdot(1+K)\ \text{[W/m]} \tag{9}$$

were: t_e – outside air temperature, [°C];

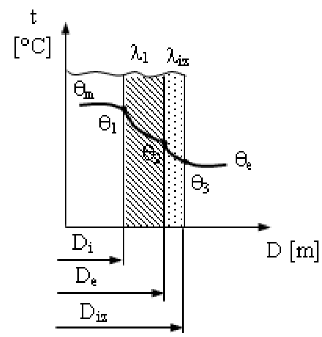

Fig. 1. Temperature variation in a non-homogeneous cylindrical wall

R_l – the heat transfer resistance of the pipe system and the insulation layer, [(m·°C)/W], determined by the relationship:

$$R=R_{l,i}+R_{l,p}+R_{l,iz}+R_{l,e}=\frac{1}{\pi\cdot D_i\cdot\alpha_i}+\frac{1}{2\cdot\pi\cdot\lambda_1}\cdot\ln\frac{D_e}{D_i}+\frac{1}{2\cdot\pi\cdot\lambda_{iz}}\cdot\ln\frac{D_{iz}}{D_e}+\frac{1}{\pi\cdot D_{iz}\cdot\alpha_e} \tag{10}$$

were: α_i – the heat transfer coefficient by convection, from the fluid to the inner surface of the pipe [W/(m^2·°C)];
λ_1 – the thermal conductivity of the pipe material, [W/(m·°C)];
D_e – the outer diameter of the pipe, [m];
D_i – the inner diameter of the pipe, [m];
λ_{iz} – the thermal conductivity of the insulation layer material, [W/(m·°C)], determined by calculation according the insulation type and its average temperature with one of the relations 11, 12 or 13:
- for mineral wool shells:

$$\lambda_{iz}=0{,}059+0{,}000186\cdot t_m\ \text{[W/(m·°C)]} \tag{11}$$

- for mineral wool mattresses:

$$\lambda_{iz}=0{,}051+0{,}00016\cdot t_m\ \text{[W/(m·°C)]} \tag{12}$$

- for glass wool:

$$\lambda_{iz}=0{,}047+0{,}00031\cdot t_m\ \text{[W/(m·°C)]} \tag{13}$$

were: t_m - average temperature of the insulating layer under the assumption of a temperature of 50°C to the insulation surface.
D_{iz} – the outer diameter of the insulating conduit assembly, [m], determined by the relationship:

$$D_{iz} = D_e + 2 \cdot \delta_{iz} \text{ [m]} \quad (14)$$

were: δ_{iz} – the thickness of the insulation layer located on the outside of the pipe, [m];
α_e – heat transfer coefficient by convection, from the isolated pipe to the environment, [W/(m^2·°C)] determined with one of the relationships 15 or 16, depending on the pipeline location:
1. for thermally insulated pipes in enclosed spaces, [3], [5]:

$$\alpha_e = 9{,}4 + 0{,}052 \cdot (t_{m,iz} - t_0) \text{ [W/(m}^2\cdot^\circ\text{C)]} \quad (15)$$

2. for outdoor pipelines (wind speed v, [m/s]):

$$\alpha_e = 9{,}28 + 0{,}046 \cdot t_{m,iz} + 6{,}96 \cdot v^{1/2} \text{[W/(m}^2\cdot^\circ\text{C)]} \quad (16)$$

were: t_0 – the ambient temperature, in this case the temperature of the indoor air, [°C];
$t_{m,iz}$ – average temperature of the outer surface of the pipe insulation, [°C], determined as the arithmetic mean of the heat average temperature, $t_{m,fl}$ and, the temperature of the outer surface of the pipe insulation, t_m:

$$t_{m,iz} = \frac{t_{m,fl} + t_m}{2} \text{ [°C]} \quad (17)$$

For the economic analysis of the thermal rehabilitation measure of the considered section of pipe, are considered the following two indicators:
1. The return on investment, which is the number of years in which the relationship is:

$$t_r = \frac{I}{V_{in} - C} \text{ [ani]} \quad (18)$$

were: I – the value of the investment, [lei];
V_{in} - total revenue generated from receipts, [lei];
C - total expenditure, [lei];

2. Project profitability (accounting rate), which allows for the quicker removal of weaker project variants, established with relationship 19, being considered as eligible projects that fulfil the condition that $R_p>1$:

$$R_p = \frac{V_{in} - C}{I} = \frac{1}{t} \quad (19)$$

3. Calculation of thermal insulation thickness for a given heat loss [1], [2], [3], [8]

The initial calculations for determining the thickness of the thermal insulation layer are as follows:
- location of the pipeline and the state of the environment;
- the temperature of the fluid being transported, t_f, [°C];
- ambient air temperature, t_0, [°C];
- diameter d_e, [mm];
- pipe length, L, [m];
- support module, reinforcement and expansion dampers;
- construction of thermal insulation and characteristics of thermo insulating materials;
- specific heat losses, q_l, [W/m], or total, Q_l, [W].

For pipes with a basic insulation layer and an outer protective layer, total thermal resistance, R_l, [(m·°C)/W], is expressed through mathematical relations 20 şi 21:

$$R_l = R_{li} + R_{lp} + R_{liz} + R_{lp} + R_{le} \quad (20)$$

$$R_l = \frac{(t_f - t_0)}{q_l} \quad (21)$$

Explaining the thermal resistance of the insulation, R_{liz}, [(m·°C)/W] is obtained:

$$R_{liz} = \frac{(t_f - t_0)}{q_l} - (R_{li} + R_{lp} + R_{lsp} + R_{le}) \quad (22)$$

Insulation thickness, δ_{iz}, unknown to the problem, implicitly occurs in thermal resistances R_{liz}, R_{lsp} and R_{le}, equation 20 resolving in two steps:
a) In the first step, the protective layer is neglected, considering it R_{lsp}=0, thermal resistance R_{li} and R_{lp} being determined. With these, equations 20 and 21 show the relation of the insulation dimension:

$$\ln \frac{d_{iz}}{d_e} = 2 \cdot \pi \cdot \lambda_{iz} \cdot \left(\frac{t_f - t_0}{q_l} - R_{li} - R_{lp} - R_{le} \right) \quad (23)$$

Using the logarithm tables' results in the ratio of/to, according to which the value of the thickness of the insulation layer is obtained:

$$\delta_{iz} = 0{,}5 \cdot d_e \cdot \left(\frac{d_{iz}}{d_e} - 1 \right) \text{ [mm]} \quad (24)$$

b) In the second step, taking into account the existence of the protective layer, the thickness of the insulation layer, δiz, [mm], determined with relation 24, with the correction, Δ, [mm], is reduced, obtaining the actual thickness of the thermal insulation:

$$\delta'_{iz} = \delta_{iz} - \Delta \text{ [mm]} \quad (25)$$

If the protective layer is metallic, the value can be admitted for the correction Δ=0.

4. CASE STUDY REGARDING THE COST EVALUATION FOR AN AERIAN CONDUCT TRONSON

The pipeline section chosen for the study is part of the hot water transport network from the source of the thermal agent to the associated thermal points. The transport network is a two-pipe network with a duct (tour) and a return pipe, consisting of several overhead (air) and underground sections (Figure 2).

The total length of the transport network is 6651 m, out of which 4891m (73.54%) in aerial assemblage, respectively 1760m (26.46%) underground, the pipes being buried directly in the soil at a depth of 1 m and a distance between the axes of the two pipes (turn/return) of 0.5 m.
Aerial installation on reinforced concrete pillars consists of 6 sections of pipelines, three of which constitute the airway (section I – CET – connection point A, section II – connection point A – connection point B, section III – connection point B – connection point F22), the other three being the branches of the bus (section IV - connecting point F22 - PT TAGCH, section IX - connecting point A - PT Turceni railway line, section X - connecting point B - PT Colony).

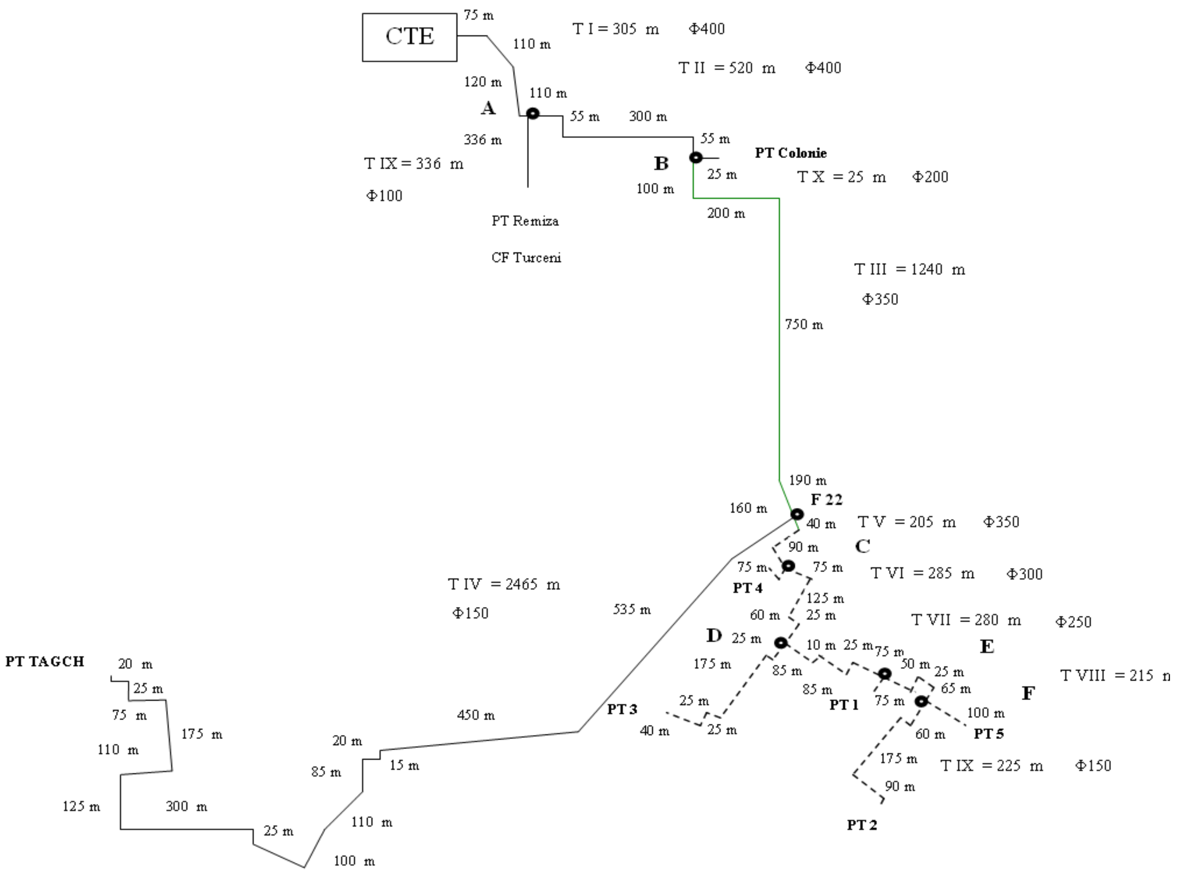

Fig. 2. Thermal transport network scheme of the heat from the source (Turceni) at the point of connection of the consumer (heating point), with green studied section

The underground installation, directly into the ground, comprises 9 sections of pipelines, five of which constitute the underground bus (section V - connection point F22 - connection point C, section VI - connection point C - connection point D, section VII - connection point D - connection point E, section VIII - connection point E - connection point F, section XV - connection point F - PT2), the other four represent the derivations of the bus (section XI - connection point C - PT4 , section XII - connection point D - PT3, section XIII - connection point E - PT1, section XIV - connection point F - PT5).
The transition from the aerial installation to the underground assembly of the transport network is achieved by means of two 90° elbows, and the passages from the pipe sections with larger inner diameters to those with smaller inner diameters are achieved by means of reducers (confusors). Also, taking the efforts of elongation of the pipes 500 is fitted in 500 m of one pound type compensator.

The main thermal energy consumers are supplied by eight thermal points: Thermal point Draw CF Turceni (PT Remiză CF Turceni); - Thermal point TAGCH (PT TAGCH); Thermal Point Colony (PT Colony); Thermal point No. 1 (PT1); Thermal point No. 2 (PT2); Thermal point No. 3 (PT3); Thermal point No. 4 (PT4); Thermal point No. 5 (PT5).
For the case study of the project, one of the six airways (section III - connecting point B - connecting point F22 - with the most damaged layer of the current insulation layer) is considered, for which the thickness of the insulation layer is chosen so that the heat loss is as small as possible. The materials from which the thermal insulation layer of the pipes will be made are: mineral wool (in shells or mattresses), respectively, glass wool.
The application of the calculation formulas presented in section 3 (relations 1 ... 19) for the actual situation of the pipe III, with a very high thermal insulation deterioration (on long sections of the section, the insulation layer is totally missing) leading to the results presented in Table 3.

Table 3. Results on heat losses through the pipeline section studied under real conditions

Determined parameter	Unit	Value
The coefficient of thermal convection of the heating medium inside the pipe wall, α_i	$W/(m^2 \cdot °C)$	3.355,42
Convective thermal resistance inside the pipe, R_{li}	(m·°C)/W	0,000271
Conductive thermal conductivity through pipe, R_{lp}	(m ·°C)/W	0,000153
The coefficient of thermal convection from the external wall of the duct to the outside air, α_e	$W/(m^2 \cdot °C)$	8,005
Convective heat resistance from external pipe wall to outside air, R_{le}	(m ·°C)/W	0,107524
Total thermal resistance	(m ·°C)/W	0,107948
Length of pipe section, L_{cd}	m	1.240,00
The equivalent length of the local resistance elements, $L_{ech,rez.loc}$	m	31,19
Equivalent length of pipe section, $L_{ech.\ cd}$	m	1.271,19
Heat flow unit, q_l	W/m	1.150,83
Correction coefficient that takes into account heat losses through non-insulated pipe supports, K	-	0,25
The heat lost to the outside by the heat, Q	kW	1.828,66
Number of hours of network operation, τ_f	h/an	8.014
Flow rate of heat transfer through pipeline, $m_{ag,t}$	l/s	90,00
The thermal energy flowing through the pipe section, Q_{trsp}	Gcal/an	333.073,32
Loss of thermal energy on the considered pipeline, ΔQ	Gcal/an	12.604,81
The current price of the heat supply from the production source, c_Q	lei/Gcal	76,30
Losses related to heat lost through the pipeline, ΔC	Lei/an	961.747,00

Taking into acount the high level of heat loss on the considered pipeline section, it is necessary to carry out thermal rehabilitation works, which consist in the optimal choice of the thickness of a thermal insulation layer (mineral wool cochils, mineral wool mattresses or glass wool), protected on the outside by a layer of galvanized sheet metal δ_{sp}=2mm, with thermal conductivity λ_{sp}=49,88W/(m·°C). The thermal conductivity of the heat insulation layer taken into account are:

- for mineral wool shells (vmc), $\lambda_{iz}^{vmc} = 0{,}0748\ W/(m\cdot^\circ C)$; - for mineral wool mattresses (vms): $\lambda_{iz}^{vms} = 0{,}0646\ W/(m\cdot^\circ C)$; - for glass wool (vst): $\lambda_{iz}^{vst} = 0{,}0734\ W/(m\cdot^\circ C)$.

The optimal thicknesses of the thermal insulation layer were determined by means of the relation 23, resulting in the following three categories of material: - for mineral wool shells, $\delta_{iz}^{vmc} = 30\ mm$; - for mineral wool mattresses, $\delta_{iz}^{vms} = 25\ mm$; - for glass wool, $\delta_{iz}^{vst} = 29\ mm$.

In order to establish the economic efficiency indicators of the thermal rehabilitation works, prices were considered by the producers and traders of such materials [10], [11], [12], [13] and the results are presented centrally in the table 4.

Table 4. Results on Economic Efficiency Indicators for Thermal Rehabilitation Works of the Pipeline Section Considered

Current no.	Parameter	Insulating / protective material			
		mineral wool shells *	mineral wool mattresses **	glass wool ***	galvanized sheet ****
1.	Thickness, δ_{mat}, [mm]	30,00	25,00	29,00	2,00
2.	Price, c_{mat}	100,00 lei/m	41,50 lei/m^2	9,50 lei/m^2	83,62 lei/m^2
3.	Material Required	1275,00 m	1.441,00 m^2	1.441,00 m^2	1.441,00 m^2
4.	Total material cost, [lei]	127.500,00	59.801,50	13.689,50	120.496,42
5.	Energy saving, ΔQ, [Gcal/an]	$\Delta Q = \Delta Q_{neiz} - \Delta Q_{iz} = 12.604{,}81 - 3.330{,}73 = 9.274{,}08$			
6.	Gcal price, $c_{en,term}$, [lei/Gcal]	76,30			
7.	Financial economy registered by investment, ΔC, [lei]	$\Delta C = \Delta C \cdot c_{en,term} = 9.274{,}08 \cdot 76{,}30 = 707.612{,}30$			
8.	Investment recovery term, [ani]	1,52	0,92	0,66	-
9.	Project profitability	0,6579	1,0870	1,5152	-

5. CONCLUSIONS

For the chosen section of the pipeline, the total heat loss in the case of the constant storage of the flow of the conveying heat agent and its temperature for a whole year is about 4% of the total energy conveyed, under the constant preservation of the outside air temperature.

The choice of the optimum diameter of the insulation layer is made in the same initial calculation assumptions as for the non-insulated pipeline (thermal flow, hot air temperature and outside air temperature, constant), considering that the heat losses will not exceed 1 % from the total heat energy transported, ie, when the specific heat losses are about 304 W/m.

In the case of mineral mattress insulation mattresses and of glass wool, two iterations were needed to determine the optimal thickness of the insulation layer.

The optimum values for the insulation layers are: 30 mm for shells, 25 mm for mattress wool and 29 mm for glass wool.

The results obtained have raised problems in the pricing of the materials used, it is necessary to consult the producers and traders of such products because the pipeline and the insulation layers dimensions are not manufactured and marketed on a large scale, manufacturers making the requested sizes at higher than standard prices.

In the calculation of the investment, for each case, an average price offered by the producers was taken into account, namely: 100 lei/m for the shells of mineral wool, 41,50 lei/m^2 in the case of mineral wool mattresses, respectively 9,50 lei/m^2 in the case of glass wool. It is to be noted that the mineral wool shells are sold in standard lengths of 1 m, for longer lengths, the price increases very much, and the mineral wool mattresses, respectively the glass wool, are sold in packs, according to standard mattress sizes.

In terms of galvanized sheet, used externally to protect the insulation layer, it is sold commercially at a standard price of 82.15 lei/m^2, being sold to a sheet (piece) of standard size of 1250 × 2500 mm, respectively standard price of 83.62 lei/m^2 being sold in standard (piece) sheet of 1000 mm × 2000 mm.

For the economic analysis calculations there were used 1240 sheet metal sheets of 1000 × 2000 mm, at a price of 167.24 lei/sheet, placed on the width (the length of the circle is >1250 mm, because the material losses are smaller.

Regarding the financial savings resulting from the isolation of the pipeline, they lead, for a price of 76,30 lei, to a saving of 707,612.30 lei / year.

Considering the investment costs of the insulation board, in the amount of 207,377.60 lei, the expenses for materials for fixing the insulation layer on the pipe, the ones for execution and assembly, and last but not least the expenses for investments in the thermal insulating material, the total value of investments amounts to: 431,574.78 lei for mineral wool shells case, 345,973.88 lei for mineral wool mattresses case and respectively 288,333.88 lei for glass wool case.

The recovery periods for the insulation of the pipeline with the three types of insulating materials are: 1.52 years for shell coils, 0.92 years for mineral wool mattresses and 0.66 years for glass wool.

As for the rate of return of the project, this economic condition is fulfilled if for this parameter are obtained supra-unit values (condition imposed by relation 19), so that only three variants (mineral mattress insulation mattresses) and the third one (insulation with glass wool) meet the condition from the three insulated piping sections.

As a result, it may be advisable to use 29 mm thick glass wool with a value of 0.0734 W/(m·°C) for the coefficient of thermal conductivity to insulate the considered section of pipe, as it ensures both optimal insulation of the pipeline as well as an optimal regarding the economic and financial parameters.

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