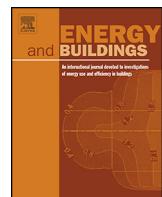




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Determination of energy saving and optimum insulation thicknesses of the heating piping systems for different insulation materials



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ABSTRACT

Large amounts of heat losses occur in pipelines of district heating system. If these lines become insulated, a significant energy savings would be obtained. In this study, by using life cycle cost analysis (LCCA) method, the optimum insulation thickness, energy savings, annual costs and payback period were estimated for various pipe diameters and insulation materials of the heating systems in Isparta/Turkey and in the regions with different degree-day values. As a fuel, natural gas was used in the study. In consequence of the calculations, the optimum insulation thickness was found vary between 0.048 and 0.134 m, the energy-saving was found vary between 10.84 and 49.78 \$/m; and the payback period was found vary between 0.74 and 1.29 years. According to these results, EPS insulation material with a nominal diameter (DN) of 250 mm provides the highest energy savings, while the lowest value was found to be in fiberglass insulation material with DN 50 mm. As a result, heating systems, selection of suitable pipe diameters and insulation materials with optimum thicknesses provide significant economic advantages and savings.

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1. Introduction

In many countries, the energy required for space heating in buildings has the highest share of all which is about 40% of total energy consumed in the residential sector and this energy transport with pipe networks. Increasing energy demand and environmental consciousness all over the world have made it imperative that energy sources should be used a lot more efficiently. The most important part of the energy strategy of any country is energy saving. Because of the limited energy-sources and environmental pollution arising from the use of fuels, energy saving has become compulsory [1]. It is clear from the above data that effective thermal protection in residential sector plays an important role toward the reduction of energy consumption for space heating. Using proper insulation in pipe network is perhaps the most effective way of energy conservation in district heating applications. Insulation reduces fuel consumption, undesirable emissions from the burning of fossil fuels. Insulation as a single investment pays for itself many times over during the life cycle of a pipe network.

Most of the available studies focus on insulating heating and cooling buildings [2–5] and insulated piping line [6–14], because of the large potential for energy savings. However, most of these studies consider uniform insulation thickness. For example, Öztürk and Karabay [10] presented a computer code that calculates

optimum pipe diameters and insulation thickness for district heating networks. The code includes a thermo economic optimization model. In this model, exergy destruction and exergy loss costs of piping network are considered as operation cost and piping and insulation costs considered as investment costs. Kalyon and Şahin [11] optimum insulation thickness of a pipe subjected to convective heat transfer that minimizes the heat loss is studied using the control theory approach and steepest descent method. As a constraint to the problem, the amount of insulation material is assumed to be fixed. A circular pipe through which fluid is transported from one end to the other is considered. Variations of the bulk temperature of the fluid as well as the temperatures of the outer surface of the insulation are evaluated. Keçebaş et al. [12] presented, optimum insulation thickness of pipes used in district heating pipeline networks, energy savings over a lifetime of 10 years, and payback periods are calculated for the five different pipe sizes and four different fuel types in the city of Afyonkarahisar/Turkey. For this reason, an optimization model is performed depending on Life Cycle Cost Analysis (LCCA) via P_1-P_2 method. Wechsolt et al. [13] investigated the optimal geometric layout of schemes for distributing hot water uniformly over an area. The amount of insulation material, the volume of all the pipes, and the amount of pipe wall material were the main constraints in their work. Zaki and Al-Turki [14] calculated the optimum thickness of insulation material for a pipeline using different layers of material of different properties and cost.

Turkey is divided into four climatic zones depending on average temperature degree-days of heating. Climatic conditions are the

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Nomenclature

A'_o	Outside surface area of n th layer of pipe (m^2)
A	Total surface area of pipe (m^2)
A_i	Inside surface area of pipe (m^2)
A_o	Outside surface area of last layer of pipe (m^2)
C_f	Annual energy cost (\$)
C_F	Fuel cost ($\$/\text{m}^3$)
C_I	Cost of insulation material per unit volume ($\$/\text{m}^3$)
C_{ins}	Total insulation cost (\$)
C_t	Total cost of heating (\$)
d	Increase rate (%)
E_w	Total annual energy requirement for heating
HDD	Heating Degree-Days ($^\circ\text{C}$ -days)
h_i	Convection heat transfer coefficient for inside of pipe ($\text{W}/(\text{m}^2 \text{K})$)
h_o	Convection heat transfer coefficient for outside of pipe ($\text{W}/(\text{m}^2 \text{K})$)
H_u	Lower heating value of the fuel (J/m^3)
i	Discount rate (%)
k_f	The heat transfer coefficient of fluid in the inside of pipe ($\text{W}/(\text{m} \text{K})$)
k_{ins}	Thermal conductivity of insulation material ($\text{W}/(\text{m} \text{K})$)
L	Length of pipe (m)
LCCA	Life Cycle Cost Analysis
m_f	The annual fuel consumption for heating
N	Lifetime (years)
N_p	Payback period (years)
Q_A	The annual heat loss (W)
Q_p	Heat losses occurred from pipe (W)
Q_{save}	Pipe heat load between un-insulated and insulated piping systems (W)
R_p	Total internal resistance of piping system (K/W)
$R_{p,\text{ins}}$	Internal resistance of insulated pipe (K/W)
$R_{p,\text{un-ins}}$	Internal resistance of un-insulated pipe (K/W)
S	Energy savings (\$)
T_f	Average design temperature of inside fluid (K)
T_b	The base temperature (K)
T_{ms}	The mean outside surface temperature of piping system (K)
T_o	Design temperature of outside air (K)
T_{sa}	The solar-air temperature for each hour (K)
U	Overall heat transfer coefficient ($\text{W}/(\text{m} \text{K})$)
U_{ins}	Overall heat transfer coefficient of insulated pipe ($\text{W}/(\text{m}^2 \text{K})$)
$U_{\text{un-ins}}$	Overall heat transfer coefficient of un-insulated pipe ($\text{W}/(\text{m}^2 \text{K})$)
V	The volume of insulation material (m^3)
δ_{ins}	Optimum insulation thickness (m)
ΔT	Difference between inside and outside design temperature (K)
ΔU	Difference between overall heat transfer coefficients of un-insulated and insulated pipes
η_s	The efficiency of the heating system

major factors governing the heat load requirements of the buildings. Valid for a base temperature of 15°C and an interior ambient temperature of 20°C , HDD values are less than 1500 for the first region, and greater than 4500 for the fourth region [15]. Isparta is third climatic zone in Turkey [16].

In this study is to provide a methodology for predicting thermal performance of five different insulation materials used in heating pipe systems. Firstly, the thickness, energy saving, payback

Table 1
Thermal conductivity and price values of insulation materials [3,17].

Insulation materials	Conductivity ($\text{W}/(\text{m} \text{K})$)	Price ($\$/\text{m}^3$)
Foam board	0.027	193
XPS	0.031	224
Rockwool	0.040	95
EPS	0.028	155
Fiberglass	0.033	350

Table 2
Some properties of stainless steel pipes (ANSI B 36.10) used in heating pipelines.

Nominal diameter	Outer diameter, r_1	Wall thickness, t	Unit weight	Conductivity	
			mm	inch	W/m K
50	2	60.3	3.91	5.44	54
100	4	114.3	6.02	16.07	54
150	6	168.3	7.11	28.26	54
200	8	219.1	8.18	42.55	54
250	10	273.1	9.27	60.24	54

period, annual fuel consumption for insulation in heating pipelines is determined depending on LCCA analysis via P_1-P_2 method by considering the heat conductivity and price of the insulation material, average temperature in the region, fuel price for the heating and factors related to regulations, and the results obtained are evaluated.

2. Analysis

2.1. The structure of the heating system pipes

Heat gain, heat loss and temperature change of transfer pipe lines for heating systems are significantly influenced by insulation, surrounding environment–ambient air for above ground pipe or soil for underground pipe, and pipe structure. Consider the circular pipe through which a given fluid is transported from one end to the other as shown in Fig. 1 for unit length. The assumptions are a constant environmental and hot fluid temperature and constant thermodynamic properties at an appropriate mean temperature. Besides, the hot fluid for a heating system is pumped through the pipe with a constant velocity under steady-state steady-flow control volume conditions.

In this study, the insulation materials properties given in Table 1 such as foam board, XPS, rock wool, EPS and fiberglass as insulation materials are chosen for the heating piping system. The pipe materials for piping system of heating are taken as stainless steel pipe, the properties of which are given in Table 2. Another parameters used in calculation are given in Table 3.

2.2. Heat loss through heating system pipe network

I calculate optimum heating system pipe insulation thickness considering heat losses from throughout pipe surface. Heat loss

Table 3
The parameters used in calculations.

Parameter	Value
Heating degree-days	2607 $^\circ\text{C}$ -days
Fuel	Natural gas
Price, C_F	0.5022 $\$/\text{m}^3$
H_u	$34.485 \times 10^6 \text{ J/kg}$
Insulation materials	See Table 1
Pipes	See Table 2
Interest rate, i	4%
Inflation rate, d	5%
Lifetime, N	10 years

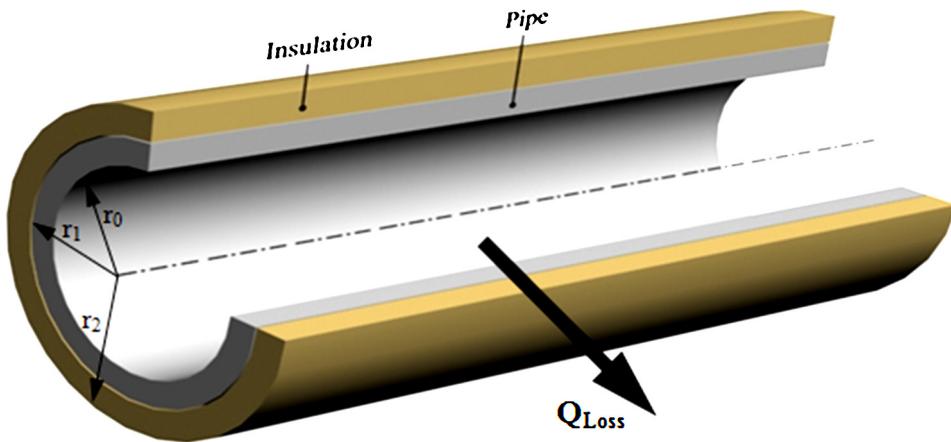


Fig. 1. Heating systems pipe cross section.

from heating system pipe can be calculated by the following heat conduction equation.

$$Q_p = UA(T_f - T_o) = UA\Delta T \quad (1)$$

where U is the overall heat transfer coefficient of pipe layers, T_o is the temperature of ambient air, T_f is the average design temperature of inside hot fluid. The annual heat loss can be determined by

$$Q_A = 86,400 \text{ HDDU} \quad (2)$$

where HDD is the heating degree days of analyzed city. The annual energy requirement for heating can be calculated by dividing heat loss to the efficiency of the heating system, η_s ,

$$E_w = \frac{86,400 \text{ HDDU}}{\eta_s} \quad (3)$$

The total internal resistance of un-insulated heating piping system is giving by

$$R_{p,\text{un-ins}} = \frac{1}{h_i A_i} + \frac{\ln(r_1/r_0)}{2\pi L k_1} + \frac{1}{h_o A'_o} \quad (5)$$

and the total internal resistance of insulated heating piping system is giving by

$$R_{p,\text{ins}} = \frac{1}{h_i A_i} + \frac{\ln(r_1/r_0)}{2\pi L k_1} + \frac{\ln(r_2/r_1)}{2\pi L k_{\text{ins}}} + \frac{1}{h_o A'_o} \quad (6)$$

Here, k_{ins} is the heat transfer coefficient of insulation materials and it must be kept in mind that the outside surface area of the last layer of piping system is $A'_o = 2\pi L r_2$. Furthermore, the convection heat transfer coefficients for the inside and outside surfaces of piping system, respectively, h_i and h_o are calculated as [18].

$$\frac{h_i D}{k_f} = 0.023 Re^{0.8} Pr^{0.4} \quad (7)$$

and

$$h_o = 11.58 \left(\frac{1}{d} \right)^{0.2} \left[\frac{2}{(T_{ms} - T_o) - 546.3} \right]^{0.181} (T_{ms} - T_o)^{0.266} \times (1 + 2.86 V_{\text{air}})^{0.5} \quad (8)$$

where k_f is the heat transfer coefficient of fluid in the inside of pipe. In this equation, $d = D + 2\delta$, and T_{ms} the mean outside surface temperature of piping system.

The difference between the overall heat transfer coefficients of un-insulated and insulated piping systems can be written as

$$\Delta U = U_{\text{un-ins}} - U_{\text{ins}} = \frac{1}{R_{p,\text{un-ins}}} - \frac{1}{R_{p,\text{ins}}} \quad (9)$$

The effect of the outside radius of insulated piping system on the thermal transmission efficiency can be obtained by differentiating Eq. (9) and the result is as follow

$$\frac{\partial(\Delta U)}{\partial r_2} = - \frac{(1/2\pi L k_{\text{ins}} r_2) - (1/2\pi L h_o r_2^2)}{((1/h_i A_i) + (\ln(r_1/r_0)/2\pi L k_1) + (\ln(r_2/r_1)/2\pi L k_{\text{ins}}) + 1/h_o A'_o)^2} \quad (10)$$

Besides, the heat loss load between the un-insulated and insulated piping systems may be obtained from following equation

$$Q_{\text{save}} = Q_{\text{un-ins}} - Q_{\text{ins}} = \Delta U \Delta T = (U_{\text{un-ins}} - U_{\text{ins}}) \Delta T \quad (11)$$

2.3. Optimization of hot fluid pipe insulation thickness and energy saving

In this study, determination of the amount energy cost calculated using P_1-P_2 method. This method is a practical and can be used for optimization the insulation thickness of hot fluid pipe system. The annual total energy cost, C_f , is given

$$C_f = \frac{86,400 \text{ HDDU} C_F}{H_u \eta_s} \quad (12)$$

where H_u is lower heating value of the fuel given J/m³ and C_F is fuel cost in \$/m³. The annual fuel consumption is

$$m_f = \frac{86,400 \text{ HDDU}}{H_u \eta_s} \quad (13)$$

There m_f is annual fuel consumption in m³/m year [12]. The total investment cost of insulation is given by the following equation

$$C_{\text{ins}} = C_I V \quad (14)$$

where C_I is the cost of insulation material in \$/m³ and V , in m³ is the volume of material used in insulation.

The first cost of insulation may be treated as capital investment. It is possible to calculate the present worth of the net amount of energy savings via insulation using a well known method known as the P_1-P_2 method [19]. P_1 has relation with inflation rate d , interest rate i , and lifetime N . P_2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment. The equations for P_1 is defined as [20]

$$P_1 = \frac{1}{(d - i)} \left[1 - \left(\frac{1+i}{1+d} \right)^N \right] \quad \text{if } i \neq d \quad (15)$$

$$P_2 = 1 + P_1 M_s - R_v (1+d)^{-N} \quad (16)$$

where M_s is the ratio of the annual maintenance and operation cost to the original first cost, R_v is the ratio of the resale value to the first cost. P_2 can be taken as 1 if the maintenance and operation cost is

zero. If the increase rate is equal to discount rate, P_1 is calculated from

$$P_1 = \frac{N}{1+i} \quad \text{if } i = d \quad (17)$$

The total cost of heating with the insulated piping system can be calculated by the following equations

$$C_t = P_1 C_f + P_2 C_{ins} \quad (18)$$

The net energy cost savings over the lifetime for heating from using insulation material, S , can be formulated with P_1-P_2 method as

$$S = \frac{86,400 P_1 H D D U C_F}{H_u \eta_s} - P_2 C_l V \quad (19)$$

The outside radius of insulated piping system can be determined by maximizing Eq. (18) or minimizing Eq. (19). So the differential of S or C_t with respect to r_2 is taken and set equal to zero, then the optimum insulation thickness $\delta_{ins} = r_2 - r_1$ is obtained using MAPLE technical computing software. Selecting P_1 from cases of $i \neq d$ (Eq. (15)) or $i=d$ (Eq. (17)), the selected P_1 into Eq. (19) is inserted and set equal to zero, then pay-back period N_p can be calculated [12].

3. Results and discussion

In heating system pipe insulation applications, the energy transmission requirement does not decrease the same rate as well since the overall heat transfer coefficient does not direct proportionally change with insulation thickness. Especially in cylindrical geometries, insulation thickness and insulation cost increased non-linearly, while it caused small decreases in the fuel cost. The total cost decreases initially and then increased gradually, depending on the increases in the cost of insulation material. The insulation thickness that gives the minimum value of the total cost curve is referred to as the optimum insulation thickness. The changes in the fuel costs, insulation costs and total costs of a fiberglass insulation material with a DN of 100 mm, depending on insulation thickness, are given in Fig. 2. As shown there, the optimum insulation thickness for a fiberglass material a DN of 100 mm was found to be 5.7 cm. Since the fuel costs are high in Turkey, optimum insulation thicknesses usually increase depending on fuel costs. For DN 100 mm,

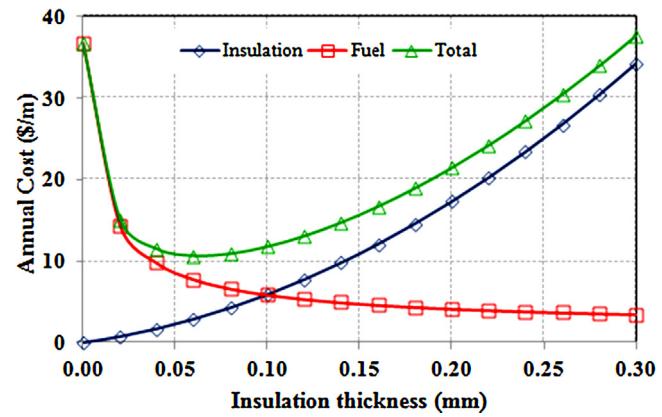


Fig. 2. Effect of insulation thickness on the costs for the fiberglass insulation material at the NPS 100 mm.

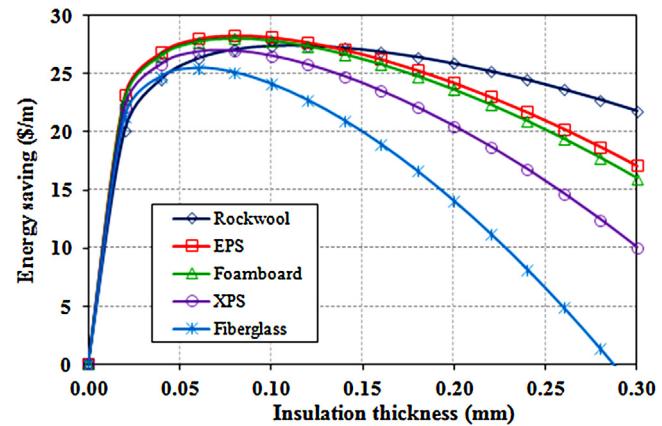


Fig. 3. The comparison of energy savings in all the insulation material for 100 mm of NPS.

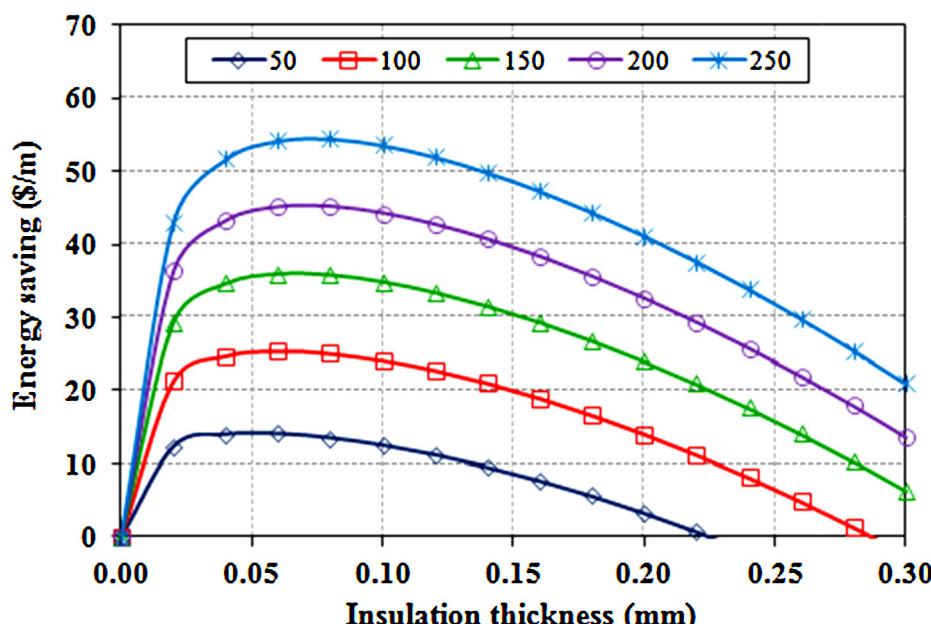


Fig. 4. The comparison of energy saving according to insulation thickness for all the NPS by using fiberglass as insulation materials.

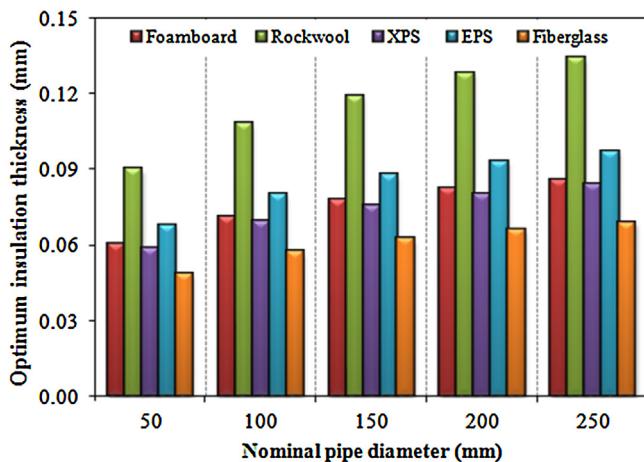


Fig. 5. Effect of optimum insulation thickness on nominal pipe size types for different insulation materials.

the changes in total lifetime energy savings of different insulation materials, depending on insulation thickness, are shown comparatively in Fig. 3; where, the energy saving for fiberglass insulation is 25.96 \$/m, while the energy saving for EPS insulation is 28.45 \$/m.

Total cost depends on insulation thickness, when it is minimum with a certain thickness. Energy saving is also dependent on the thickness of insulation. Increase in insulation thickness that exceeds investment cost provides increases in energy saving from fuel costs. In case of thicknesses more than a certain value, costs would exceed the saving, i.e. the additional thickness of the insulation material would be no longer economic. With the increase in insulation thickness, the optimum insulation thickness was obtained from the point, at which the saving begins to decrease. The changes in the energy savings depending on insulation thicknesses, which were obtained throughout life cycle by use of different insulation materials with all DN values, are shown in Fig. 4. As clearly seen in the chart, energy savings increase in parallel with the increase in DN thickness; and the highest gain for a total life of 10 years was obtained at DN 250 mm.

Changes in optimum insulation thicknesses of different insulating materials, depending on DN, are shown in Fig. 5. With the increase in nominal pipe thickness, the optimum insulation thickness increased as well. As clearly seen in the chart, the maximum insulation thickness was obtained from DN 250 mm, when mineral wool was used as an insulation material. This is because the heat transfer coefficient of the insulation material consisting of mineral wool was high. Changes of energy savings for different insulation materials are shown in Fig. 6, according to the DN values. In parallel with the increase in DN, the amount of savings for all insulation materials increased. The greatest saving was obtained by use of EPS insulation material. When EPS insulation material is used, DN 50, 100, 150, 200 and 250 mm provided savings in the amount of 12.22, 22.28, 32.01, 40.75 and 49.78 \$/m respectively. In addition, increases in energy saving are observed in parallel with increases in pipe diameters. Form the figure, it can be understood that greater energy savings can be obtained by means of pipes with big diameters in comparison with small diameters. For different insulation materials, changes in payback period at optimum insulation thicknesses are shown in Fig. 7, according to DN values. Payback period varies depending on the initial investment cost of the system. The longest payback period was found to be 1.29 years, for DN 250 mm and fiberglass insulation material.

There are four different degree-day regions in Turkey, and the coldest one is the 4th degree-day region. The calculations were made for the city of Isparta with the degree-day value of 2607. Isparta is located in the 3rd degree-day region, and has a cold

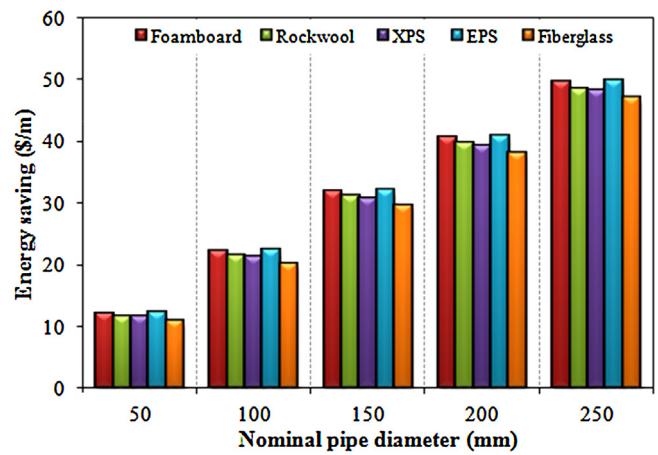


Fig. 6. Comparison of energy savings over the lifetime versus nominal pipe size types for different insulation materials.

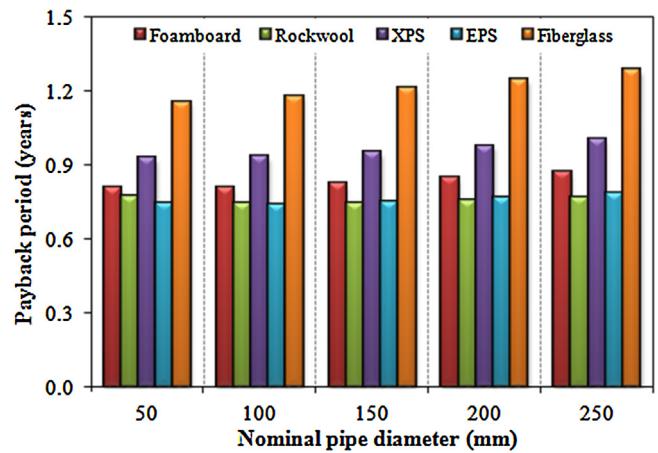


Fig. 7. Comparison of payback period versus nominal pipe size types for different insulation materials.

climate. In order to enable the data obtained during the study to be used in different regions, the calculations were expanded by using different degree-day values. For different insulation materials, changes in optimum insulation thicknesses that depend on degree-day values are shown in Fig. 8. The optimum insulation thickness increased in parallel with the increase in the degree-day values and insulation cost. Energy saving is directly proportional to fuel cost and climate conditions. Therefore, energy saving becomes

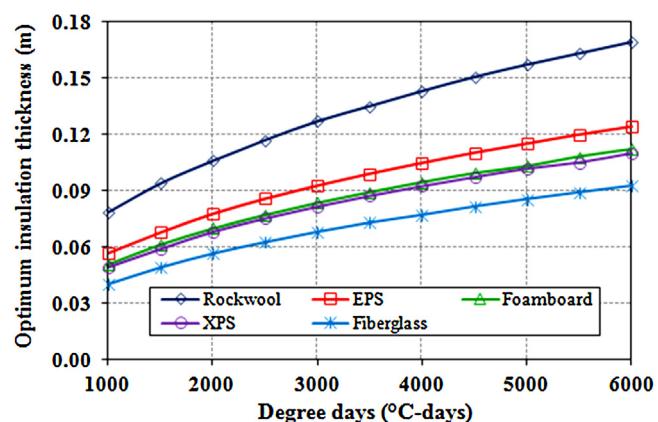


Fig. 8. Optimum insulation thickness of heating piping versus DD values for different insulation materials.

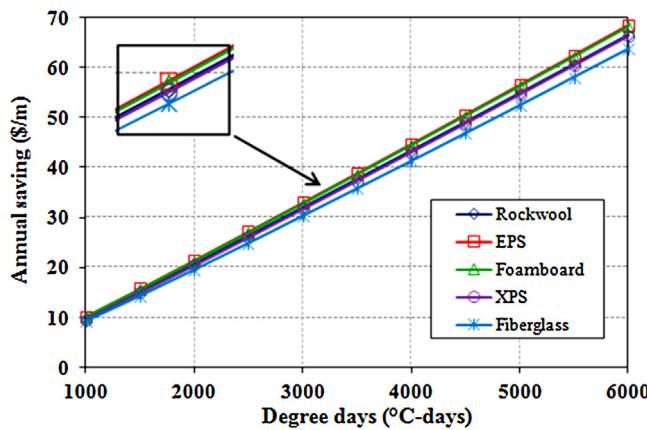


Fig. 9. Annual saving of heating piping versus DD values for different insulation materials.

more important in cold climates. For different insulation materials, the effect of degree-day values on energy saving is shown in Fig. 9. Annual saving increases with degree-day values, while insulation cost and insulation heat transfer coefficient decrease. For different materials, the effect of degree-day values on payback period is shown in Fig. 10. As shown in the figure, payback period decreases according as degree-day values increases. It seems clearly that the payback period becomes shorter in cold regions, by means of insulation cost. In order to prevent thermal energy loss in heating system pipeline, and to reduce fuel consumption, the fluid must be kept in the pipe. Thermal insulation is one of the most important ways to do this. As shown in Fig. 11, the annual fuel consumption decreased with the insulation application. The effect of insulation thickness of insulating material on fuel consumption is clearly seen in the figure. Using thermal insulation reduces use of energy and provides a significant fuel saving. When the optimum insulation thickness was used in the pipelines, the fuel consumption increased depending on the insulation thickness. For example, the fuel consumption for DN 100 mm was found between 0.607 and 7.607 m³/m, depending on the insulation thickness. For all pipe diameters, the highest fuel consumption occurred when rockwool insulation material was used; and this material was followed by XPS, EPS and foamboard. The optimum insulation thickness, energy saving and payback period values for different insulation materials with different pipe diameters are given in Table 4. As shown in the table, the optimum insulation thickness was found vary between 0.048 and 0.134 mm, depending on DN and the insulating material, while the energy savings were found vary between 10.84 and 49.78 \$/m. The lowest

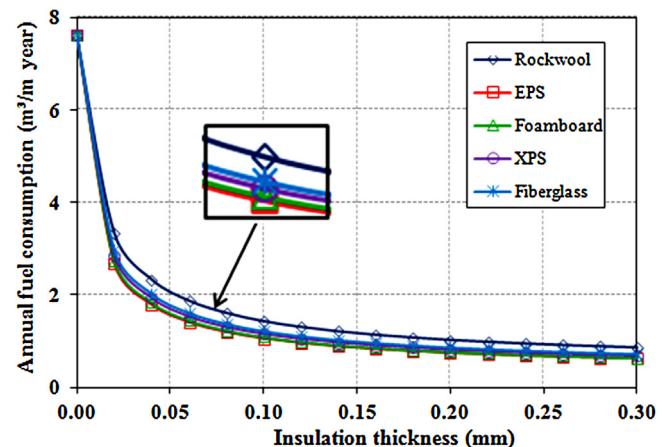


Fig. 11. The effect of the insulation thickness on the annual fuel consumption by insulation materials for a nominal pipe size of 100 mm.

Table 4

Optimum insulation thickness, energy saving and payback period for different insulation materials and DN (natural gas fuel).

	Insulation	Nominal pipe sizes (mm)				
		50	100	150	200	250
Optimum insulation thickness (m)	Rockwool	0.090	0.108	0.119	0.128	0.134
	EPS	0.068	0.080	0.088	0.093	0.097
	Foam board	0.060	0.071	0.078	0.082	0.086
	XPS	0.058	0.069	0.076	0.080	0.084
	Fiberglass	0.048	0.057	0.063	0.066	0.069
Energy saving (\$/m)	Rockwool	11.63	21.49	31.03	39.56	48.32
	EPS	12.22	22.28	32.01	40.75	49.78
	Foam board	12.08	22.05	31.74	40.48	49.56
	XPS	11.53	21.24	30.71	39.30	48.25
	Fiberglass	10.84	20.18	29.45	37.98	47.01
Payback period (years)	Rockwool	0.77	0.75	0.75	0.76	0.77
	EPS	0.74	0.75	0.75	0.77	0.79
	Foam board	0.81	0.81	0.83	0.85	0.87
	XPS	0.93	0.93	0.95	0.98	1.01
	Fiberglass	1.15	1.18	1.21	1.25	1.29

energy saving was found at DN 50 mm for fiberglass insulation material, while the highest energy saving was obtained when EPS insulation material with the value of DN 250 mm was used.

4. Conclusion

In this study the optimum insulation thickness of the heating system pipe, energy savings over a lifetime of 10 years and payback periods are calculated for the five different insulation materials for Isparta city of Turkey. The degree-days used in the study can also be used in other countries having different degree-days. And this reason analysis results were extended for this insulation materials can be chosen in different climatic zone on world. These results show that energy cost savings are directly proportional to the cost of fuel, insulation material and climatic conditions. It is seen that energy savings vary between 10.84 and 49.78 \$/m depending on pipe DNs and insulation materials. The highest value of optimum insulation thicknesses is reached by using rock wool as insulation in 250 mm DN, whereas the lowest optimum insulation thickness is obtained by using fiberglass as insulation in 50 mm DN. The highest payback period value with 1.29 years in 250 mm DN found by using fiberglass as insulations, while the lowest value with 0.74 years by using EPS as insulation in 50 mm DN. These results show that energy saving is more significant when a costly fuel is used for heating system pipe network. The fiberglass is a better choice when the optimum

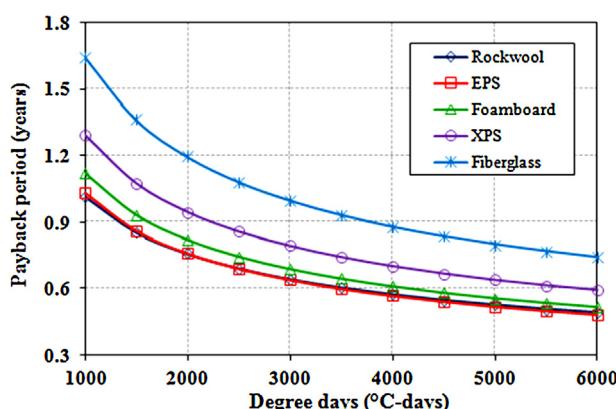


Fig. 10. Payback period of heating piping versus DD values for different insulation materials.

insulation thickness is an important consideration. The insulation material installed at its optimum insulation thickness in the heating pipelines will not only reduce the heat loss from the heating pipeline but also has economical and environmental advantages.

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