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Thermo-economic analysis of pipe insulation for district heating piping systems

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ABSTRACT

In this study, the 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 (LCC) analysis via P_1–P_2 method. Rock wool as insulation material and a system of pipelines (50–200 mm nominal sizes) with flow of hot water are considered. The results show that optimum insulation thicknesses vary between 0.085 and 0.228 m, energy savings vary between 10.041 $/m and 175.171 $/m, and payback periods vary between 0.442 and 0.808 years depending on the nominal pipe sizes and the fuel types. The highest value of energy savings is reached in 250 mm nominal pipe size for fuel-oil fuel type, while the lowest value is obtained in 50 mm for geothermal energy. Considering the economical and environmental advantages, the geothermal energy is a better choice and then natural gas.

1. Introduction

Energy is considered as a major key in the generation of wealth and an important factor in economic development. Every country should develop energy policies in order to use their own resources efficiently, considering the decreasing fossil fuel sources and increasing prices. On the other hand, environmental pollution associated with fossil fuels has a serious threat on ecosystem and human health. Thus, in the design stages of fossil power and heating systems main objective should be maximizing energy saving with minimum energy consumption.

With the increase in the cost of the energy and the high energy consumed by some areas such as industrial, building, transportation and agriculture, these sectors especially building have recently received considerable attention on energy consumption because of heat losses. In building sector, the energy consumption of space heating is approximately two times more than that of the other consumption sources (such as water heating, cooking, food refrigeration and freezing) [1]. Space heating can be provided on a building-by-building basis or increasingly through a district heating network that supplies the needs of multiple consumers by means of an underground piping network connected to one or multiple wells or down hole heat exchangers. And, the heat losses in space heating occur from envelope of dwellings or during transmission of hot water for district heating. Therefore, use of proper insulation in buildings and piping systems is quite important for both energy savings and reducing undesirable emissions from the burning of fossil fuels.

Insulation is defined as those materials or combinations of materials which retard the flow of heat energy by performing one or more of the following functions: i) conserve energy by reducing heat loss or gain, ii) control surface temperatures for personnel protection and comfort, iii) facilitate temperature control of a process, iv) prevent vapor flow and water condensation on cold surfaces, v) increase operating efficiency of heating/ventilating/cooling, plumbing, steam, process and power systems found in commercial and industrial installations, and vi) prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres [2]. Also, the thickness of an insulation material is chosen by considering the average ambient temperature of the region, thermal conductivity of the insulation material and its price. Increasing the thickness of the insulation material will not only decrease air pollution but also increase energy saving. However, an insulation thickness allowing zero heat loss is neither practical nor economical. A balance point should be determined between the insulation material cost and the savings obtained. The balance point indicates the optimum insulation thickness [3].

Various thermal insulation systems taking advantages of different types of thermal insulation materials on both organic

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(expanded plastics, wood wool, cork, straw, technical hemp) and inorganic basis (foamed glass, glass and mineral fibers) are being designed and tested [4]. Besides, most of the available studies focus on insulating buildings [5–7] and cold stores [8,9], because of the large potential for energy savings. These studies consider the flat plate or slab as the geometric configuration, presenting the large areas of roofs and façades. On the other hand, studies to improve thermal insulation for cylindrical geometry are few in spite of the extensive use of pipelines and cylindrical heat exchangers in refineries, chemical industry, district heating/cooling, and power plants. For example, Zaki and El-Turki [10] studied the optimization of multi-layer thermal insulation for pipelines. Wechsatol et al. [11] 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. In a more recent work [12], they studied the optimization of a tree-shaped system of insulated pipes for the distribution of a stream of hot water over an area which is covered uniformly by users who must receive the same flow rate of hot water. They showed that the geometry of the insulated tree structure is relatively insensitive to how the insulation is distributed over all the pipes. The thermal performance of the structure is also found to be relatively insensitive to how finely the distribution of pipe sizes and insulation radius is optimized. Kalyon and Sahin [13] studied the optimum insulation thickness of a pipe subjected to convective heat transfer that minimizes the heat loss using the control theory approach and steepest descent method. Sahin [14] studied the optimal insulation of ducts subjected to external thermal radiation. He found the optimal insulation thickness variation along the tube using a limited amount of insulation material in order to minimize the heat transfer. Due to the convenience of implementation, the thickness function of the insulation in his analysis is considered to be linear along the duct. In further their study [15], critical radius of insulation for a circular tube subjected to radiative and convective heat transfer was studied analytically. They found that a critical insulation thickness may exist such that the heat transfer between the fluid and the radiative environment becomes a maximum. Öztürk et al. [16] presented four different thermo-economic techniques for optimum design of hot water piping systems. Their study was carried out for a hot water pipe segment, and the differences and merits of each method were discussed. Karabay [17] studied a thermo-economic optimization method for a hot-water distribution pipe. The method used by his was based on the second law of thermodynamics. Both the optimum pipe diameter and the insulation thickness were determined simultaneously, considering exergy destruction due to friction and exergy loss due to heat losses as the operation cost, while the piping and insulation costs were considered as an investment.

Life-cycle cost (LCC) analysis is often applied to energy technologies and building projects. A life-cycle cost analysis can show that spending more initially on additional building or piping system insulation can produce a net savings over the lifetime of a building or piping system. The concept of life-cycle cost is used to determine the optimum insulation thickness in order to take effects of the change in interest and inflation that directly affect both the cost of insulation materials and fuels. In this study, for the insulation economy an optimization model based on the life-cycle cost analysis via P_1–P_2 method is developed. Using the optimization model, the optimum insulation thicknesses for piping system of district heating are calculated for four different types of fuel, namely, coal, natural gas, fuel-oil and geothermal fluid in the city of Afyonkarahisar/Turkey. Also, the energy savings and payback periods resulting from the use of insulation material such as rock wool are calculated.

2. Modeling and analysis

2.1. The structure of the piping system

A district heating system is composed of many elements, building a chain from the heat source to the heated buildings. The sole purpose of a district heating system is to supply adequate heat to its customers. The consumer uses the heat to maintain indoor temperature at a reasonably constant level and counter for building heat loss to the surroundings. Most district heating systems use conventional fuel (coal, natural gas or fuel-oil) as the heat source. But, in some areas (i.e., Afyon Geothermal District Heating System [18]) geothermal heat is used as the district heating source. The heat distribution in district heating systems is carried out by the use of either hot water or steam through a closed loop network, where the hot water or steam is piped to each consumer in the supply network, cooled down by the heat consumer, piped back to the heat center and re-heated [19].

Heat gain, heat loss and temperature change of transfer pipelines for district heating systems are significantly influenced by (i) insulation, (ii) surrounding environment – ambient air for above ground pipe or soil for underground pipe, and (iii) pipe structure. The hot water piping system considered in this study is shown in Fig. 1 for unit length. It is a long straight conduit segment, installed in an environment at temperature and pressure, which are also identical to those of the dead state. The assumptions are a constant environmental temperature and constant thermodynamic properties at an appropriate mean temperature. Besides, the hot water for a district heating system is pumped through the pipe with a constant velocity under steady-state steady-flow control volume conditions. Pressure drops due to the liquid flow friction and hot water fluid of intermingling molecules of different species through molecular diffusion are neglected in this study.

2.2. The heat loss calculation for the piping system

Heat losses occurred from pipe through piping system for a district heating system can generally be calculated by the following equation.

$$Q_p = UA(T_{ad} - T_o) = UA\Delta T \tag{1}$$

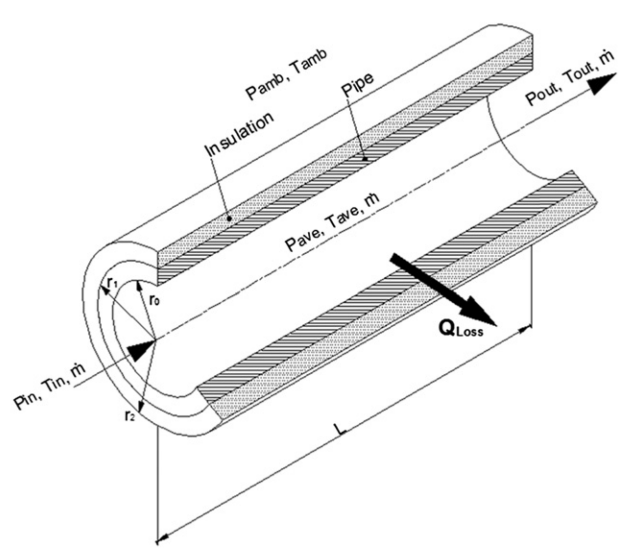

Fig. 1. The hot water pipeline with insulation and definition of various parameters.

where A is the total surface area of pipe, T_o is the temperature of outside air, T_{ad} is the average design temperature of inside fluid, and U is the overall heat transfer coefficient.

The total internal resistance of any piping system, R_p, is equal to the summation of the surface resistances of convective heat transfer over the inside and outside surfaces of the pipe and the total internal resistance of all layers of piping system is given as

$$R_p = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k_2} + \ldots \frac{\ln\left(\frac{r_n}{r_{n-1}}\right)}{2\pi L k_n} + \frac{1}{h_o A_o} \tag{2}$$

where k_1, k_2, etc. are thermal conductivities of layers of piping system, and r_1, r_2, etc. are their radiuses. And, the inside surface area of pipe is $A_i = 2\pi L r_0$ while the outside surface area of the last layer of piping system is $A_o = 2\pi L r_n$.

In this study, the total internal resistance of un-insulated piping system is

$$R_{p,un-ins} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{1}{h_o A_o} \tag{3}$$

and the total internal resistance of insulated piping system is the following form.

$$R_{p,ins} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k_{ins}} + \frac{1}{h_o A'_o} \tag{4}$$

Here, k_{ins} is the heat transfer coefficient of insulation material 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 [20]

$$\frac{h_i D}{k_i} = 0.023 Re^{0.8} Pr^{0.4} \tag{5}$$

and

$$h_o = 11.58(1/d)^{0.2}\left[2/((T_{ms} - T_o) - 546.3)\right]^{0.181} \times (T_{ms} - T_o)^{0.266}(1 + 2.86V_{air})^{0.5} \tag{6}$$

where k_i is the heat transfer coefficient of fluid in the inside of pipe. Eq. (6) is a general equation of ASTM Standard C680 for computer calculations [21]. In here, $d = D + 2\delta$, 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

$$\Delta U = U_{un-ins} - U_{ins} = \frac{1}{R_{p,un-ins}} - \frac{1}{R_{p,ins}} \tag{7}$$

The effect of the outside radius of insulated piping system on the thermal transmission efficiency can be obtained by differentiating Eq. (7) and the result is as follow

$$\frac{\partial(\Delta U)}{\partial r_2} = -\frac{\frac{1}{2\pi L k_{ins} r_2} - \frac{1}{2\pi L h_o r_2^2}}{\left(\frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k_{ins}} + \frac{1}{h_o A'_o}\right)^2} \tag{8}$$

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

$$Q_{save} = Q_{un-ins} - Q_{ins} = \Delta U \Delta T = (U_{un-ins} - U_{ins})\Delta T \tag{9}$$

2.3. Calculation of the insulation economy

An analysis of annual energy consumption and cost usually accompanies the design heat load calculations and plays an important role in the selection of a heating system. There are various methods for calculation of annual energy consumption. The simplest and most intuitive way of estimating the annual energy consumption of a building is the degree-days method, which is a steady-state approach. The number of annual heating degree-days (HDD) using hourly data is determined from

$$HDD = (1\ \text{year}) \sum_{1}^{365} (T_b - T_{sa})^* \tag{10}$$

where T_b is the base temperature and T_{sa} is the solar-air temperature for each hour. The * sign above the parenthesis indicates that only positive values are to be counted, and the temperature difference is to be taken to be zero when $T_b < T_{sa}$. The base temperature is the outdoor temperature below which heating is needed. In this study, the base temperature is taken as 18 °C and the hourly data given by Buyukalaca et al. [22] is used for more accurate results.

The annual heat loss, Q_A, can be determined using the heating degree-days, HDD as given by the following equation.

$$Q_A = 86,400\ HDDU \tag{11}$$

The annual energy requirement for heating can be calculated by dividing heat loss to the efficiency of the heating system, η_s,

$$E_w = \frac{86,400\ HDDU}{\eta_s} \tag{12}$$

and the annual fuel consumption for heating is

$$m_f = \frac{86,400\ HDDU}{H_u \eta_s} \tag{13}$$

where H_u is lower heating value of the fuel given usually in J/kg, J/m^3 or J/kW h depending on the fuel type.

The annual total energy cost for heating, C_f, is given

$$C_f = \frac{86,400\ HDDUC_F}{H_u \eta_s} \tag{14}$$

where C_F is fuel cost in \$/kg, \$/m^3, or \$/kW h depending on the fuel type.

The total cost of insulation (C_{ins}) depends on the cost of insulation material per unit volume (C_I) can be calculated by the following equation

$$C_{ins} = C_I V \tag{15}$$

where C_I is the cost of insulation material in \$/m^3 and $V = \pi/4(r_2^2 - r_1^2)L$ is the volume of material used in insulation (in m^3).

To calculate insulation economy, it is necessary to identify the ratio of life-cycle energy (P_1) and the ratio of life-cycle expenditures incurred to the initial investment (P_2) because of the additional capital investment. P_1 has relation with increase rate (or inflation rate) (d), discount rate (interest rate) (i), and lifetime (N) as expressed by the following

$$P_1 = \frac{1}{(d-i)}\left[1-\left(\frac{1+i}{1+d}\right)^N\right] \quad \text{if} \quad i \neq d \tag{16}$$

If the increase rate (d) is equal to discount rate (i), P_1 is calculated from

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

P_2 is the ratio of the life-cycle expenditures incurred because of the additional capital investment to the initial investment. P_2 is defined by

$$P_2 = 1 + P_1 M_s - \frac{R_v}{(1+d)^N} \tag{18}$$

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.

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

$$C_t = P_1 C_f + P_2 C_{ins} \tag{22}$$

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

$$S = \frac{86,400 \ P_1 \mathrm{HDD} U C_F}{H_u \eta_s} - P_2 C_I V \tag{23}$$

The outside radius of insulated piping system can be determined by minimizing Eq. (23) or maximizing Eq. (22). 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 MATLAB optimization Toolbox. Selecting P_1 from cases of $i \neq$ d (Eq. (16)) or $i = d$ (Eq. (17)), the selected P_1 into Eq. (23) is inserted and set equal to zero, then payback period (N_p) can be calculated.

3. Results and discussion

In the present study, an economic analysis (LCC analysis) is performed in order to estimate the optimum thickness, saving and payback period which minimizes the total cost including the pipe insulation material and the energy consumption costs. This analysis is most use in insulation applications. Thus, the optimum thickness for different diameters of pipe materials are calculated in heating loads of Afyonkarahisar which is the coldest city of Turkey by using the parameters shown in Tables 1, 2 and 3, and Eqs. (22) and (23). In addition, the energy savings and payback periods resulting from the use of insulation such as rock wool are investigated. In these calculations, the values given in Table 1 such as fuel prices, lower heating values and heating systems efficiencies are used, and rock wool is chosen for the insulation of the piping system. The pipe materials for piping system of district 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. Furthermore, fixed parameters are such as average hot water temperature, $T_{ad} = 80$ °C [(70 + 90)/2], temperature of outside air, T_o, 15 °C and mean outside surface temperature of piping system, T_{ms}, 93 °C. The velocities of fluid and outside air are taken as constant parameters, 0.8 and 0.2 m/s, respectively. The results of our calculations for pipes used in district heating pipeline networks are compared and discussed under subtitles as given below.

3.1. The annual costs and energy savings for different pipe sizes and fuel types

The annual cost of fuel and insulation cost against insulation thickness by using rock wool as insulation material is given in Fig. 2. It is seen that the cost of the fuel decreases with increasing insulation thickness. The total cost is the sum of the cost of fuel and insulation material. On the other hand, the insulation cost increases linearly with insulation thickness for flat wall insulation applications. But, this phenomenon could not be seen in the graphic mentioned in Fig. 2 due to cylindrical geometry in pipe insulation applications. The insulation thickness at the minimum total cost is taken as the optimum insulation thickness. For 150 mm pipe size, the optimum insulation thickness is 0.112 m by using geothermal energy while it is 0.202 m by using fuel-oil.

The comparison of energy savings over the lifetime versus insulation thickness for various fuels in 150 mm pipe size is shown in Fig. 3. In Afyonkarahisar, the energy saving for fuel-oil is 114.358 $/m, whereas energy saving for geothermal energy is 26.063 $/m. Also, Fig. 4 shows the comparison of energy savings for all nominal pipe sizes by using geothermal and fuel-oil. The optimum insulation thickness is achieved when the savings start to drop as the thickness of insulation material is increased. The energy savings is maximum at optimum insulation thickness. The energy savings is also dependent upon the insulation thickness. For instance in geothermal

Table 1
Prices and lower heating values of fuels, and efficiencies of heating systems [23].

Fuels	Price[a]	H_u	η
Coal	0.3926 ($/kg)	29.260 × 10^6 J/kg	65%
Natural gas	0.5022 ($/m^3)	34.485 × 10^6 J/m^3	93%
Fuel-oil	1.3202 ($/kg)	41.278 × 10^6 J/kg	80%
Geothermal[b]	0.3044 ($/m^3)	80.928 × 10^6 J/m^3	38%

[a] Assuming 1 $ = 1.4392 Turkish Liras (TL) as of October 2010.
[b] The values for geothermal energy is from Ref. [18].

Table 2
Some properties of stainless steel pipe used in district heating systems.

Nominal pipe size (mm)	Nominal pipe size (inch)	Outer diameter, r_1 (mm)	Wall thickness, t (mm)	Weight class	Sch No	Unit weight (kg/m)
50	2	60.3	3.91	STD	40	5.44
100	4	114.3	6.02	STD	40	16.07
150	6	168.3	7.11	STD	40	28.26
200	8	219.1	8.18	STD	40	42.55
250	10	273	9.27	STD	40	60.29

Note: For stainless steel pipe (ANSI B 36.10), the density, melt temperature and conductivity are 7.99 g/cm^3, 1371–1399 °C and 16.2 W/m K, respectively.

Table 3
Parameters used in calculation.

Parameters	Values
Heating degree-days (HDD)	2828 °C days
Fuels	See Table 1
Pipes	See Table 2
Insulation	Rock wool
Conductivity (k_{ins})	0.040 W/mK
Cost (C_I)	95 $/m^3
Discount rate (i)	4%
Increase rate (d)	5%
Lifetime (N)	10 years

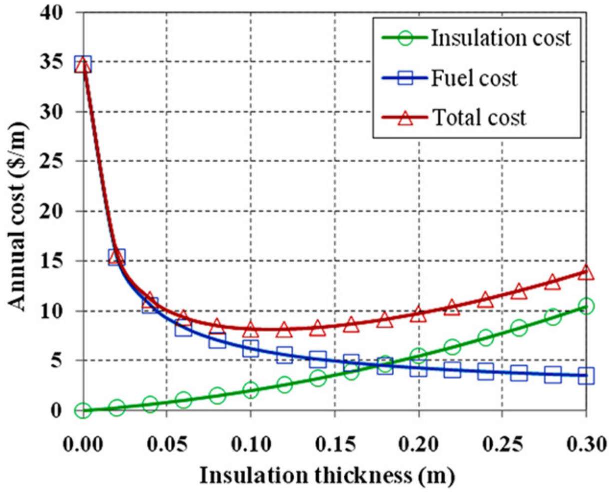

Fig. 2. Effect of insulation thickness on the annual cost in a nominal pipe size of 150 mm for geothermal energy.

(see Fig. 4(a)) the energy savings is 10.041 $/m at a certain thickness for 50 mm nominal pipe size, whereas the energy savings for 250 mm is 39.803 $/m. The energy savings in fuel-oil (see Fig. 4(b)) reaches maximum value which is 175.171 $/m for 250 mm nominal pipe size at the optimum insulation thickness.

3.2. Effect of nominal pipe sizes on LCC analysis for different fuel types

Fig. 5 presents the effect of optimum insulation thickness on nominal pipe size for different fuels. It is seen that the optimum insulation thickness increases with increasing nominal pipe size. From graphic, the highest optimum insulation thickness is obtained from 250 mm nominal pipe size and from fuel-oil as a fuel. From Fig. 6, the comparison of energy savings over the lifetime versus nominal pipe size types is shown for different fuel types. In this city (Afyonkarahisar), energy saving values increase for costly fuels such as fuel-oil, coal, natural gas and geothermal energy. It appears that the highest value of the energy savings of all nominal pipe size types is reached by using fuel-oil as an energy source, whereas the lowest energy saving is obtained by using geothermal energy. As can be seen in Fig. 6 for fuel-oil, the energy saving rates for 50, 100, 150, 200 and 250 mm are respectively 44.139, 80.134, 114.358, 144.562 and 175.171 $/m, while the 250 nominal pipe size has the highest value of the energy savings.

In Fig. 7, the variation of the payback period due to nominal pipe size types is shown for various fuel types. In this figure, the highest payback period is from geothermal energy, followed by the natural

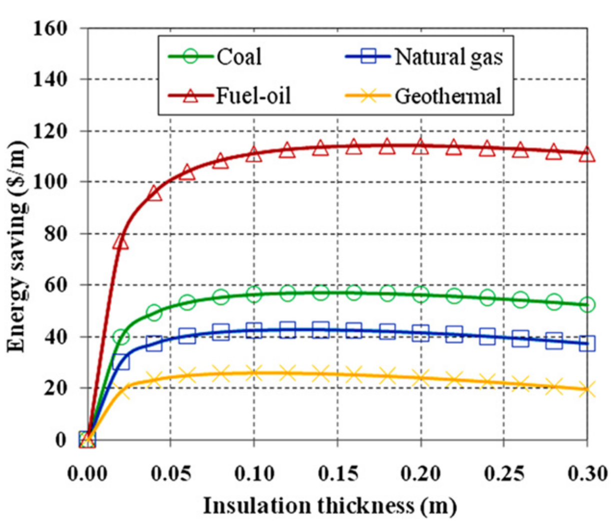

Fig. 3. Comparison of energy savings over the lifetime versus insulation thickness for selected fuels in 150 mm nominal pipe size.

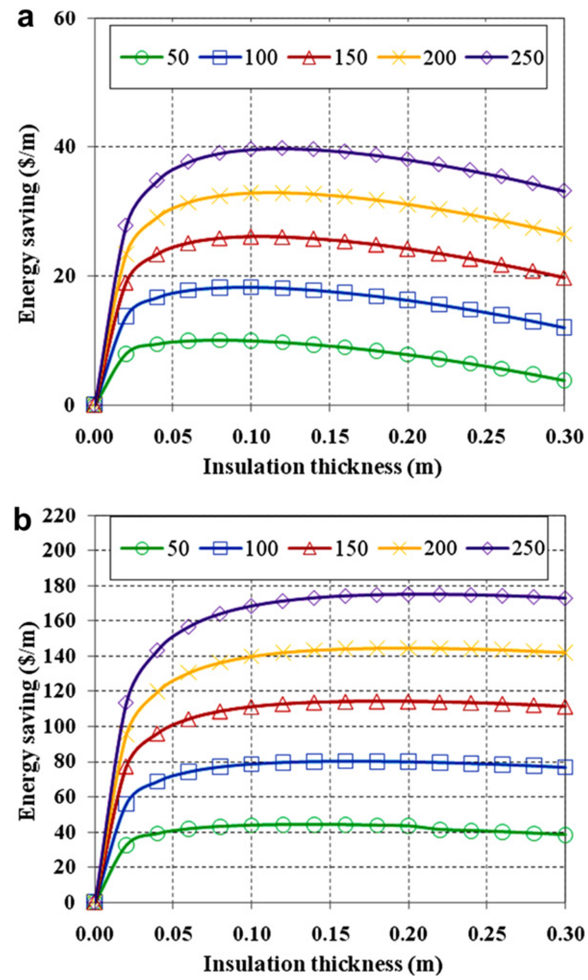

Fig. 4. Comparison of energy savings for all nominal pipe sizes by using (a) geothermal and (b) fuel-oil as an energy source.

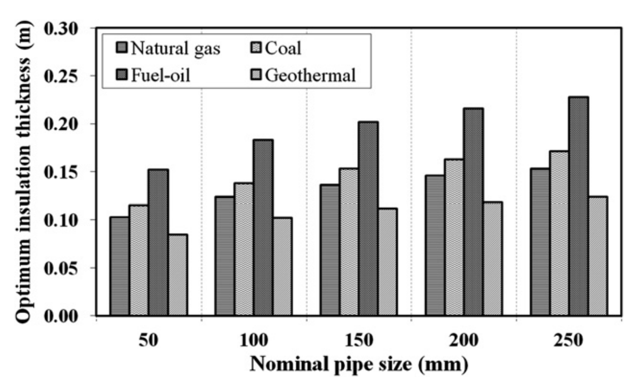

Fig. 5. Effect of optimum insulation thickness on nominal pipe size types for different fuel types.

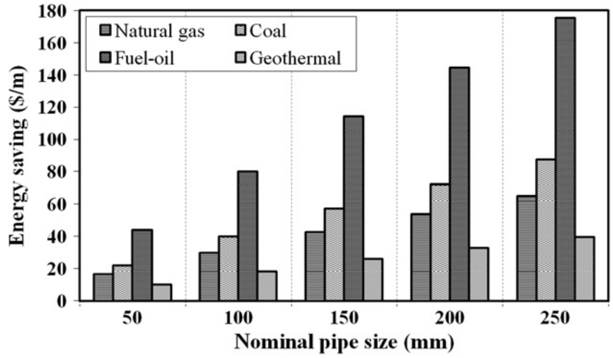

Fig. 6. Comparison of energy savings over the lifetime versus nominal pipe size types for different fuel types.

gas, coal and fuel-oil. For instance, the highest payback period value with 0.789 years (for 150 pipe size) in Afyonkarahisar found by using geothermal energy as an energy source for heating, while the lowest value (0.442 years for 200 mm) is reached by using fuel-oil as an energy source. It can be seen that the payback periods obtained from 150 mm nominal pipe size are found lower than others.

3.3. *Effect of degree-days on LCC analysis for different pipe sizes and fuel types*

The LCC analysis is performed for Afyonkarahisar which is the coldest city in Turkey. However, the nominal pipe sizes used in the study can also be used in other countries having different climatic zones (degree-days). For this reason, analysis results were extended. Thus, for these types of pipe, the optimum thickness can be selected in similar climatic zones on world.

In a nominal pipe size of 150 mm, Fig. 8 shows variation of the optimum insulation thickness versus degree-days for various fuels. It is clearly seen from the figure that the insulation thickness take higher values for more severe climate conditions and also for higher fuel costs. But, the optimum insulation thickness increases by diminishing increments with increasing degree-days. So, a region where the energy requirement is more, the optimum insulation thickness does not increase at the same rate with its energy requirement. Because of a considerably change between the maximum and the minimum values of the degree-days in Turkey and World, optimum insulation thickness varies significantly one region to another. It appears that the highest value of the optimum insulation thicknesses is reached by using fuel-oil as an energy source, whereas the lowest optimum insulation thickness is obtained by using geothermal energy as the energy source.

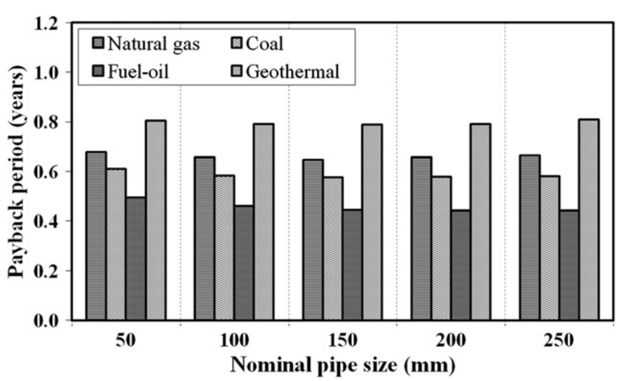

Fig. 7. Comparison of payback period versus nominal pipe size types for different fuel types.

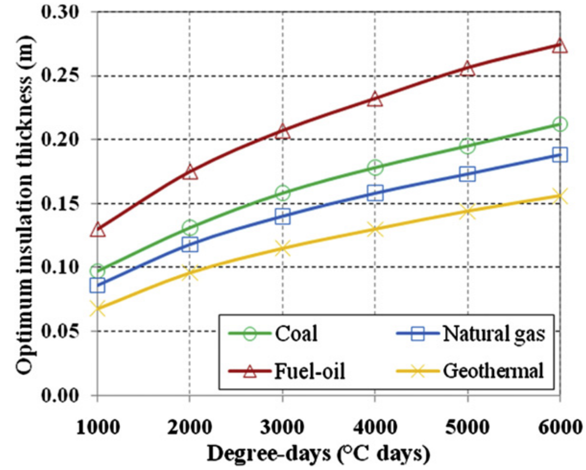

Fig. 8. Optimum insulation thickness versus degree-days for various fuels in a nominal pipe size of 150 mm.

The effect of degree-days on energy savings for different insulating materials is shown in Fig. 9. From figure, it can be seen that the energy savings are directly proportional to the cost of fuel and degree-days. Energy savings become more significant in cold regions. In all nominal pipe sizes, energy savings value increases for costly fuels such as fuel-oil, coal and natural gas. The energy savings over the lifetime of 10 years increases for increasing degree-days. It is seen that energy cost savings vary between 3.185 $/m and 248.960 $/m depending on the fuels and pipe sizes.

The effect of degree-days on the payback period for different fuel types in 150 mm nominal pipe size is shown in Fig. 10. It is seen that the payback periods depend on degree-days and fuel types. The payback period decreases as the degree-days increase. This clearly indicates that the application of insulation in cold climates is more advantageous. For instance, the highest payback period value with 1.220 years in Afyonkarahisar found by using geothermal as an energy source for 150 mm pipe size, while the lowest value is reached by using fuel-oil as an energy source.

In different climate zones, the optimum insulation thicknesses are shown for geothermal from Fig. 11(a) and fuel-oil from Fig. 11(b). It is clear that the insulation thicknesses take higher values for more severe climate conditions and for higher pipe sizes.

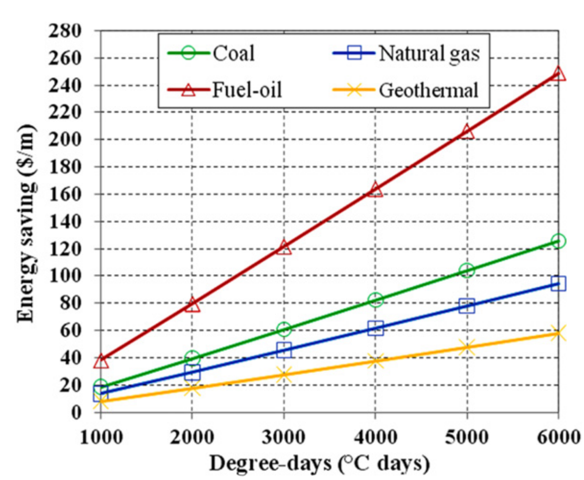

Fig. 9. Effect of degree-days on energy savings for different fuels in 150 mm nominal pipe size.

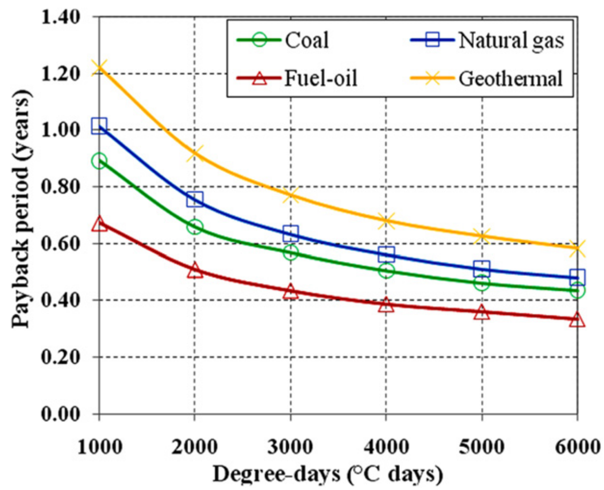

Fig. 10. Effect of degree-days on payback period for different fuel types in a nominal pipe size of 150 mm.

In Fig. 12, the effect of degree-days on energy saving is shown for various nominal pipe sizes. Here, the graphics for nominal pipe size types are given separately. From graphics, it is obvious that the savings increase linearly with degree days and savings is directly proportional to degree days indicating in cold weather (higher degree-day values). The more savings can be made by making 250 mm pipe size. Besides, it can be also noted that the energy saving values of nominal pipe sizes for geothermal gas (see Fig. 12(a)) remained under the values of those for remainder fuels. The highest energy saving is obtained from fuel-oil (see Fig. 12(b)).

The effect of degree-days on payback period for different fuel types is shown in Fig. 13. It is seen that the payback periods depend on degree-days and fuel types such as geothermal (from Fig. 13(a)) and fuel-oil (from Fig. 13(b)). The payback period is shortened while degree-days increase. This clearly indicates that the payback period is shorter, whereas costs of applying insulation thickness in colder regions increases. Therefore, the application of insulation in cold climates is more advantageous.

3.4. The evaluation of the calculations for different pipe sizes and fuel types

The optimum insulation thickness, energy saving and payback period of the selected insulation material with different nominal

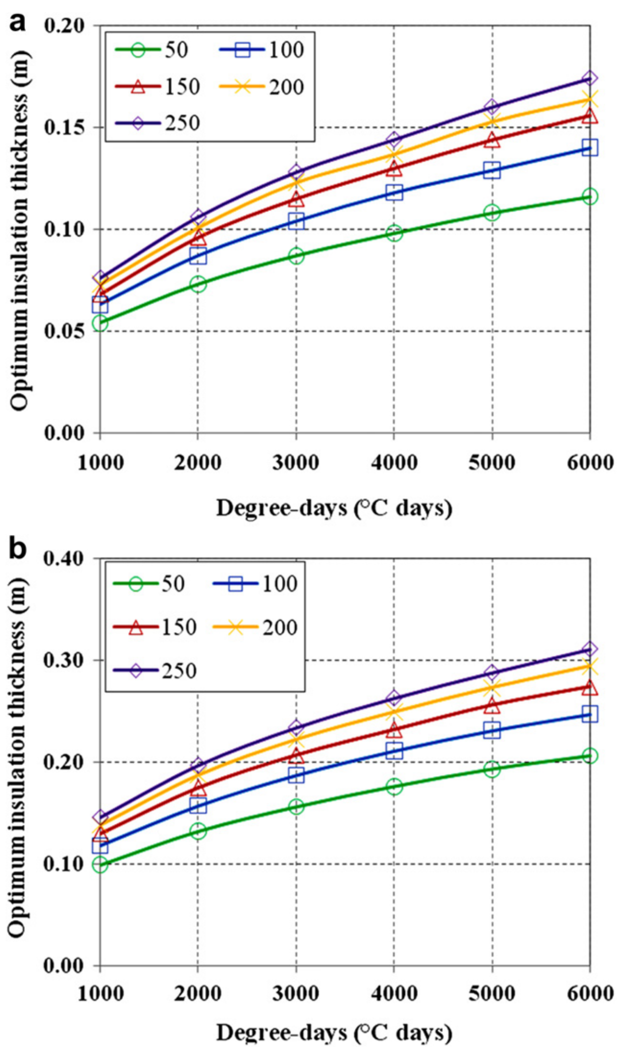

Fig. 11. Optimum insulation thickness versus degree-days for various nominal pipe sizes by using (a) geothermal and (b) fuel-oil.

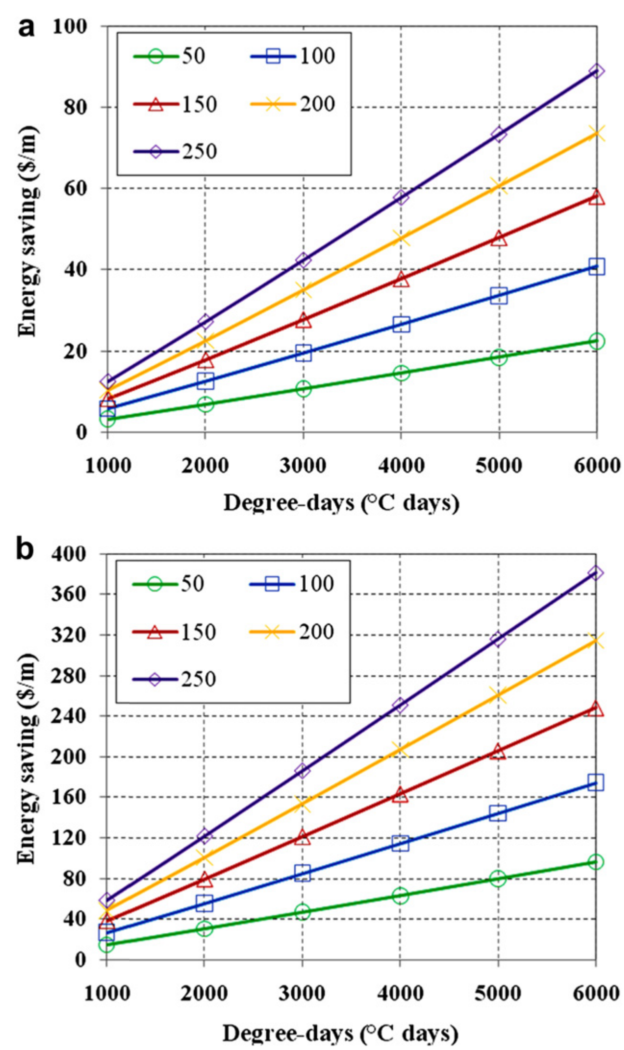

Fig. 12. The effect of degree-days on energy saving for various nominal pipe sizes in different fuel types such as (a) geothermal and (b) fuel-oil.

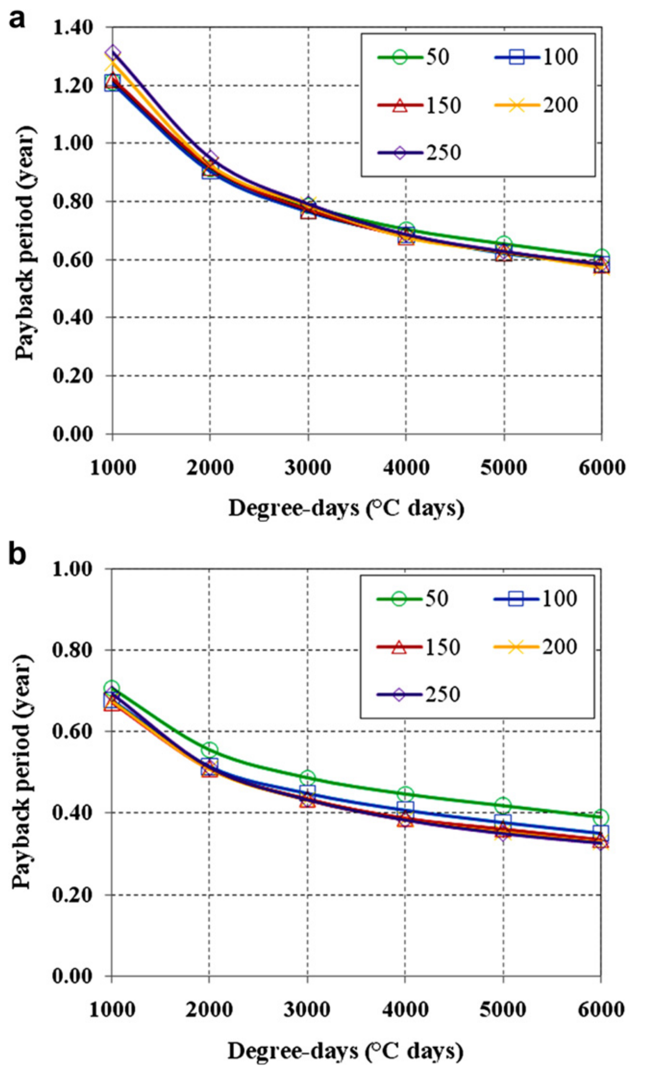

Fig. 13. Effect of degree-days on payback period for different pipe size types by using (a) geothermal and (b) fuel-oil.

sizes of pipe in the piping system for various fuels are illustrated in Table 4. It appears that the optimum insulation thicknesses vary between 0.085 and 0.228 m, the energy savings vary between 10.041 and 175.171 $/m, and the payback periods vary between 0.442 and 0.808 years depending on the type of fuel and nominal

Table 4
Optimum insulation thickness, energy savings and payback periods for various fuels and pipe sizes (Rock wool insulation material).

	Fuel types	Nominal pipe sizes				
		50	100	150	200	250
Optimum insulation thickness (m)	Coal	0.115	0.138	0.153	0.163	0.171
	Natural gas	0.103	0.124	0.136	0.146	0.153
	Fuel-oil	0.152	0.183	0.202	0.216	0.228
	Geothermal	0.085	0.102	0.112	0.118	0.124
Energy saving ($/m)	Coal	22.039	40.067	57.183	72.262	87.519
	Natural gas	16.430	29.881	42.651	53.875	65.228
	Fuel-oil	44.139	80.134	114.358	144.562	175.171
	Geothermal	10.041	18.268	26.063	32.906	39.803
Payback period (years)	Coal	0.611	0.582	0.576	0.578	0.581
	Natural gas	0.679	0.657	0.645	0.657	0.663
	Fuel-oil	0.494	0.461	0.444	0.442	0.443
	Geothermal	0.804	0.791	0.789	0.792	0.808

pipe sizes. In general, the optimum insulation thickness increases with increasing pipe size. The table shows that, geothermal energy with a thickness of 0.085 m, natural gas with a thickness of 0.103 m and coal with a thickness of 0.115 m, the rest of the fuels has an optimum insulation thickness of 0.152 m when there is 50 mm nominal pipe size in the piping system. In the city of Afyonkarahisar, energy saving values increase for costly fuels such as fuel-oil, coal, natural gas and geothermal energy. It appears that the highest value of the energy savings of all nominal pipe sizes is reached by using fuel-oil as an energy source, whereas the lowest energy saving is obtained by using geothermal. For fuel-oil, it has energy savings of 44.139 $/m with 50 mm in the piping system and gradually increases with increasing pipe size to 175.171 $/m with a size of 250 mm. When compared to an un-insulated piping system, pipe with 250 mm installed at its optimum insulation thickness has the greatest energy savings. In this table, the highest payback period is from geothermal, followed by the natural gas, coal, and fuel-oil. For instance, the highest payback period value with 0.808 years (for 250 mm pipe size) in Afyonkarahisar found by using geothermal energy as an energy source for heating, while the lowest value (0.442 years for 200 mm) is reached by using fuel-oil. It can be seen that the payback periods obtained from 200 mm pipe size wall material are found lower than others.

4. Conclusions

Modeling piping systems' thermal performance is important for understanding and predicting thermal behaviors of piping systems in order to provide techniques for designing and analyzing problems such as energy conservation, energy demands, environmental comfort and the response of control in a piping system. The insulation in the hot water distribution pipelines is performed with a view to minimize heat losses from constructional elements such as pipe and its layers. In this study, the optimum insulation thickness of pipes used in district heating pipe 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. In the calculations, LCC analysis is used. The results obtained show that energy savings are directly proportional to the cost of fuel, insulation material, nominal pipe sizes and climatic conditions. The energy savings vary between 10.041 $/m and 175.171 $/m depending on the nominal pipe sizes and fuel types. The highest value of energy savings is reached for a nominal pipe size of 250 mm and the lowest energy savings is also obtained for the 50 mm pipe size. Here, an energy saving of about 400% results by making 250 mm nominal pipe instead of 50 mm. Within this value there are no fees in the pumping process, so it has been so high. And the highest value of optimum insulation thicknesses is reached as 0.228 m (for 250 mm) by using fuel-oil as an energy source, whereas the lowest optimum insulation thickness is obtained as 0.085 m (for 50 mm) by using geothermal energy. In addition, the highest payback period value with 0.808 years for 250 mm pipe size found by using geothermal energy as an energy source, while the lowest value is reached as 0.442 years for a nominal pipe size of 200 mm by using fuel-oil. Considering the economical and environmental advantages, the geothermal energy is a better choice and then natural gas. Consequently, this study will be an efficient guide for the people working in the area for better design, analysis and operation of pipe insulation. The proper insulation materials at optimum insulation thickness provide the economical and environmental advantages with decreasing heat transmission from pipes. This can be achieved by only using the most suitable and simple methods.

Nomenclature

Q_p	heat losses occurred from pipe (W)
Q_{save}	pipe heat load between un-insulated and insulated piping systems (W)
Q_A	the annual heat loss (W)
R_p	total internal resistance of piping system (K/W)
$R_{p,un-ins}$	internal resistance of un-insulated pipe (K/W)
$R_{p,ins}$	internal resistance of insulated pipe (K/W)
U	overall heat transfer coefficient (W/m K)
U_{ins}	overall heat transfer coefficient of insulated pipe (W/m^2 K)
U_{un-ins}	overall heat transfer coefficient of un-insulated pipe (W/m^2 K)
ΔU	difference between overall heat transfer coefficients of un-insulated and insulated pipes
T_{ad}	average design temperature of inside fluid (K)
T_o	design temperature of outside air (K)
T_{ms}	the mean outside surface temperature of piping system (K)
T_b	the base temperature (K)
T_{sa}	the solar-air temperature for each hour (K)
h_i	convection heat transfer coefficient for inside of pipe (W/m^2 K)
h_o	convection heat transfer coefficient for outside of pipe (W/m^2 K)
k_i	the heat transfer coefficient of fluid in the inside of pipe (W/m K)
k_{ins}	thermal conductivity of insulation material (W/m K)
HDD	heating degree-days (°C-days)
η_s	the efficiency of the heating system
H_u	lower heating value of the fuel (J/kg, J/m^3, J/kW h)
C_I	cost of insulation material per unit volume ($/m^3)
C_F	fuel cost ($/kg, $/m^3, $/kW h)
C_f	annual energy cost ($)
C_{ins}	total insulation cost ($)
V	the volume of insulation material (m^3)
C_t	total cost of heating ($)
LCC	life cycle cost
E_w	total annual energy requirement for heating
m_f	the annual fuel consumption for heating
P_1	life cycle energy
P_2	life cycle expenditures
d	increase rate (%)
i	discount rate (%)
N	lifetime (years)
ΔT	difference between inside and outside design temperature (K)
δ_{ins}	optimum insulation thickness (m)
L	length of pipe (m)
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)
A'_o	outside surface area of nth layer of pipe (m^2)
S	energy savings ($)
N_p	payback period (years)

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