Determination of economic optimum insulation thickness of indoor pipelines for different insulation materials in split air conditioning systems

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Abstract

This paper presents investigation of optimum insulation thickness, energy savings and payback periods for gas pipeline and liquid pipeline under the heating and cooling modes of a split air conditioning system using R-407C as refrigerant. Analyses are performed for four different insulation materials indicated as extruded polystyrene, foamboard, rockwool and expanded polystyrene. In consequence of the calculations, the optimum insulation thickness of gas pipeline vary from 45 to 50 mm, the energy saving vary between 78 and 83%; and the payback period vary from 0.025 to 0.468 years, whereas, the optimum insulation thickness of liquid pipeline vary from 28 to 45 mm, the energy saving vary between 40 and 79%; and the payback period vary from 0.044 to 0.289 years. Finally, for both gas and liquid pipeline, the expanded polystyrene is a better choice when the optimum insulation thickness is an important consideration.

Key words : Optimum insulation thickness, Life-cycle cost analysis, Insulation material, R-407C, Split air conditioning system

1. Introduction

The split air conditioning systems are commonly used as thermal comfort for residential and commercial buildings. A split air conditioning system comprises of the indoor and outdoor units. The outdoor unit is assembled on or near the wall outside of the room. While the outdoor unit contains the compressor, condenser and the expansion valve, the indoor unit involves blower, the cooling coil, and air filter. The indoor unit is connected to the outdoor unit by refrigerant pipes collaterally.

The statistics show that more than 50% of the electricity bill in a commercial building and more than 30% of total electricity bills in residential areas are contributed by the operating cost of air conditioning systems (Yau and Pean, 2014). Therefore, the insulation of split air conditioning system pipelines reduces energy consumption of the system. The insulation thickness for the pipelines is needed to be optimized in respect to economical so as to minimize the energy and insulation costs in addition to reducing the heat loss to the surroundings. The concept of economical thermal insulation thickness considers the initial cost of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation (Kaynaklı, 2012).

A number of studies focused on the economic optimum insulation thickness for the hot water or air service pipelines. The annual energy demand is determined by degree-day method in the many studies. The method is a simple procedure evaluating static conditions. Zaki ve Al-Turki (2000) studied economic analysis of thermal insulation for pipelines with flow of superheated steam, furfural, crude oil, and 300-distillate. In the analysis, rockwool and calcium silicate as insulation materials and a system of pipelines (0.1–0.273 m nominal size) was employed and external heat transfer coefficient value was assumed constant. Li and Chow (2005) studied the optimum insulation thickness for water pipes of different diameters varying from 0.02 m to 0.2 m based on a life-cycle cost analysis. They investigated the effects of outdoor air conditions and design parameters on the optimum thickness. Öztürk et al. (2006) presented four different thermo-economic techniques for optimum design of hot water piping systems. They were as follows: the

first one was a sequential optimization of pipe diameter based on minimization of total cost without considering heat losses and then of insulation thickness based on minimization of cost of insulation and heat losses. The second was simultaneous optimization of pipe diameter and insulation thickness based on the first law of thermodynamics and cost. The third was simultaneous determination of pipe diameter and insulation thickness based on maximization of exergy efficiency without considering cost. Finally, the fourth was simultaneous determination of pipe diameter and insulation thickness based on maximization of exergy efficiency and cost minimization. A case study was carried out for a hot water pipe segment, and the differences and merits of each method were discussed. Important parameters such as annual operation time, depreciation period, interest rate, fuel and electricity prices, and the thermo-physical parameters were assumed to be the same and constant for all methods. Soponpongpiat et al. (2010) conducted the optimum thickness analysis of air conditioning duct's insulation by means of thermo-economics method. In the analyses, circular galvanized steel duct with duct diameter of 0.5 m as pipe materials and rubber and fiberglass as insulation materials were employed. The effects of heat transfer coefficient at inside and outside of duct on the optimum thickness of these insulators were studied. They demonstrated that the variation of inside and outside duct convective heat transfer coefficient does not affect optimum thickness but net saving increases when inside and outside duct convective heat transfer coefficient increases. Keçebaş et al. (2011) calculated the optimum insulation thickness of pipes used in district heating pipeline networks, energy savings over a lifetime of 10 years, and payback periods for the five different pipe sizes and four different fuel types determined as natural gas, coal, fuel-oil and geothermal in the city of Afyonkarahisar/Turkey depending on life cycle cost (LCC) analysis via P_1 - P_2 method. Rockwool as insulation material and a system of pipelines (50-200 mm nominal sizes) with flow of hot water were considered. The results showed that optimum insulation thicknesses varied between 0.085 and 0.228 m, energy savings varied between 10.041 \$ m⁻¹ and 175.171 \$ m⁻¹, and payback periods varied between 0.442 and 0.808 years depending on the nominal pipe sizes and the fuel types. The highest value of energy savings was 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 economic and environmental advantages, the geothermal energy was a better choice and then natural gas. Başoğlu and Keçebaş (2011) studied the energy, economic and environmental evaluations of thermal insulation in district water heating pipeline. The optimum insulation thickness, energy saving over a lifetime of 10 years, payback period and emissions of CO, CO₂ and SO₂ are determined for nominal pipe sizes and fuel types determined as natural gas, coal, fuel-oil, geothermal and LPG based on heating loads in Afyonkarahisar/Turkey. They used the life cycle cost analysis to determine the optimum insulation thickness of the pipeline material. The highest value of optimum insulation thickness, energy savings, emissions and the lowest payback period are obtained for a nominal pipe size of 200 mm. Keçebaş (2012) optimized insulation thickness by using exergy method and life-cycle cost concept for the case of using various fuels such as coal, natural gas and fuel-oil. They determined that combustion parameters such as excess air, stack gas temperature, and combustion chamber parameters were much more effective on optimum insulation thickness. The optimum insulation thickness decreased with the increasing of inlet temperature of fuel, and with the decreasing of excess air coefficient, temperatures of stack gases and combustion chamber. Under this effects, the optimum insulation thicknesses were determined as 0.065, 0.071, 0.099 m with a rate of 68.27%, 71.54% and 77.85% in the exergetic saving for natural gas, coal and fuel-oil fuels, respectively. The optimum insulation thickness, total annual exergetic cost, exergy saving, and exergy losses depending on heat transfer increased with the increase of heating degree-days, while they decreased by increasing the temperature of outside air (reference state). In addition, the optimum insulation thickness for the exergoeconomic optimization was higher than that of energoeconomic optimization. Kayfeci (2014) estimated the optimum insulation thickness, energy savings, annual costs and payback period for various pipe diameters and insulation materials of the heating systems with flow hot water in Isparta/Turkey and in the regions with different degree-day values by using Life Cycle Cost Analysis (LCCA) method. In the analyses, natural gas as a fuel and EPS, foamboard, XPS, fiberglass and rockwool as insulation material were used. The highest energy saving was found to be in EPS insulation material with nominal diameter (DN) of 250 mm, while the lowest value was found to be in fiberglass insulation material with DN 50 mm. Kayfeci et al. (2014) used the artificial neural networks (ANNs) to predict optimum insulation thickness and life cycle costs (LCC) for pipe insulation applications. Data were collected from insulation markets and some data were calculated by using LCC analysis. They developed a three-layer feed forward ANN model based on a back propagation algorithm and calculated the optimum insulation thickness, total cost, cost saving and payback period. Kaynaklı (2014) carried out a literature review on the optimum economic thickness of the thermal insulation on a pipe or duct with different geometries used in various industries. The heat transfer

equations, the basic results, the optimization procedures and the economic analysis methods used in the studies were presented comparatively. Additionally, a practical application example based on optimizing the insulation thickness on a pipe was performed, and the effective parameters of the optimum insulation thickness were investigated. Yıldız and Ersöz (2016) presented the investigation into optimum insulation thickness of HVAC ducts and the effect of wind speed on it. Optimum insulation thickness, energy savings over a lifetime of 10 years and payback periods were determined for the four different energy types as coal, fuel-oil, LPG and natural gas and two different insulation materials as fiberglass and rockwool. The results indicated that the application of insulation in high wind speeds is more advantageous. Yıldız and Ersöz (2015) determined economical optimum insulation thickness of pipe network of VRF systems. Optimum insulation thickness, energy savings over a lifetime of 10 years and payback periods were investigated for high pressure gas pipelines, low pressure gas pipelines and low pressure liquid pipelines under the heating-only and cooling-only modes of the three-pipe VRF system using R-410A as refrigerant.

On the other hand, only a limited number of analytical techniques were applied to analyze the optimization of the pipes. Sahin (2004) optimized numerically the variation in the thermal insulation thickness of a pipe for space applications to minimize the radiative heat loss to the ambient. In this study, the thickness of the insulation was assumed to be linearly varying along the pipe and was determined the suitable slope of the insulation thickness along the pipe, which maximizes the fluid outlet temperature (thus minimizes the heat loss). Sahin and Kalyon (2005) studied an analytical solution for the insulation thickness variation over a pipe to maintain a uniform outer surface temperature. They considered heat losses by convection and radiation from the outer surface of the insulation to the surrounding and obtained an explicit analytical solution of the profile for the insulation thickness variation. It was shown that the insulation thickness variation that provides uniform surface temperature was independent of the convection and radiation heat transfer coefficients. Bahadori and Vuthaluru (2010a) developed a simple correlation for optimum economic thickness of thermal insulations as a function of steel pipe and equipment diameter for different thermal conductivity of insulation and the correlation was generalized for wide range of surface temperatures. Bahadori and Vuthaluru (2010b) formulated simple correlations for the estimation of heat flow through insulation, thermal resistance and thermal insulation thickness for flat surfaces, ducts and pipes. The accuracy of the proposed method was tested and it was found to be in excellent agreement with the reported data for the wide range of conditions.

There are many studies in the literature dealing with on economic thermal insulation thicknesses of hot water or air service pipelines by means of heating degree day and analytical optimization techniques. In those studies, it is investigated that the effect of different parameters such as pipe diameter, working fluid, interest rate inflation rate, energy source, fuel type, insulation materials on economic optimum pipe insulation. In this study, economic optimum insulation thickness analysis is applied to indoor pipelines of split air condition systems using R-407C under the heating and cooling modes for four different insulation materials as extruded polystyrene (EPS), foamboard, rockwool and expanded polystyrene (XPS).

2. Description of split air conditioning system

The A split air conditioning system typically supplies climatized air to a single room of a building and comprised of a compressor, condenser, evaporator and a thermostatic expansion device. The indoor unit (located in room) is connected to the outdoor unit in parallel with the refrigerant pipes.

The split air conditioning systems have two-pipe configurations which are a gas pipeline (GP) and a liquid pipeline (LP) and can be used for cooling or heating depending on the season as shown Figures 1 and 2.

In heating mode, indoor unit of the split air conditioning system operates as condenser. The refrigerant enters the condenser as superheated vapor and it leaves as saturated liquid on ideal vapor-compression heat pump cycle.

When it comes to cooling mode, indoor unit of the split air conditioning system operates as evaporator. The refrigerant enters evaporator as saturated mixture and it leaves the evaporator as saturated vapor in the in the ideal vapor-compression refrigeration cycle.

Fig. 1. Schematic view of the split air conditioning system under heating mode

In this study, thermo-economically optimum insulation thickness is analyzed for heating and cooling modes of split air conditioner using R-407C refrigerant as working fluid.

Fig. 2. Schematic view of the split air conditioning system under cooling mode

3. Analyses

3.1 Thermodynamic analysis of split air conditioning system

In this study, thermodynamic analysis of split air conditioning system using R-407C as refrigerant is evaluated under steady-state conditions. While the indoor unit services condenser in the heating mode, it services evaporator in the cooling mode.

In the thermodynamic analysis of split air conditioning system, mass flow rates values are firstly calculated. Since indoor unit capacity values are known, refrigerant mass flow rates in both gas and liquid pipeline for heating and cooling conditions are calculated respectively from Equations (1) and (2),

$$\dot{m}_{R,hm} = \frac{\dot{Q}_{hl}}{(h_{cond,in} - h_{cond,out})} \quad (1)$$

$$\dot{m}_{R,cm} = \frac{\dot{Q}_{cl}}{(h_{evap,out} - h_{evap,in})} \quad (2)$$

In Equation (1), $\dot{Q}_{hl}$ is the heating load, h_2 is the enthalpy value of condenser inlet and h_3 is the enthalpy value of condenser outlet. $\dot{Q}_{cl}$ is the cooling load, h_1 is the enthalpy value of evaporator inlet and h_4 is the enthalpy value of evaporator outlet. It is assumed that the split air conditioning system under heating mode operates on an ideal vapor-compression heat pump cycle, whereas, the system under cooling mode operates on an ideal vapor-compression refrigeration cycle. Besides, the evaporation and condensation temperatures are assumed 280 K and 320 K, respectively.

Secondly, the pipe diameters for each of gas and liquid pipelines of the split air conditioning system are determined from manufacturer catalogs. Finally, the velocities of R-407C refrigerant in each of gas and liquid pipeline are calculated by,

$$V_R = \frac{\dot{m}_R}{\rho_R A_c} \quad (3)$$

where, ρ_R is the density of R-407C and A_c is the cross section area of the pipes.

The thermodynamic properties of the R-407C refrigerant are calculated by means of REFPROP 9.0 and operation parameters and these properties are given in Table 1.

Table 1. The system operation parameters and thermodynamic properties correspond to the parameters

Parameters	T (K)	P (kPa)	h (kJkg ⁻¹)	k (Wm ⁻¹ K ⁻¹)	$\mu \cdot 10^{-6}$ (Pa.s)	Pr
Evaporation condition	280	705.39	-	-	-	-
Condensation condition	320	2060.00	-	-	-	-
Evaporator inlet	280	705.39	271.79	0.069198	139.86	2.4078
Evaporator outlet	280	705.39	419.80	0.012697	11.83	0.9810
Condenser inlet	343.03	2060.00	450.84	0.019207	14.69	0.9418
Condenser outlet	320	2060.00	271.79	0.073769	115.26	2.7166

The selected pipes dimensions and the values calculated by Equations (1) and (3) for gas and liquid pipelines of both heating and cooling modes of the split air conditioning system are summarized in Table 2.

Table 2. The pipe dimensions, mass flow rates and velocity values for heating and cooling of the split air conditioning system

Operation mode	Pipeline	Q (kW)	m (kg s ⁻¹)	d _o (mm)	t (mm)	V (m s ⁻¹)
Heating mode	GP	8.0	0.045	15.88	1.0	3.18
	LP	8.0	0.045	6.35	0.8	1.79
Cooling mode	GP	7.1	0.229	15.88	1.0	46.41
	LP	7.1	0.229	6.35	0.8	10.98

3.2 Heat loss through pipelines of the split air conditioning system

The heat losses from pipeline surface of the systems are calculated by Equation (4). The properties of the insulation and pipe materials for piping network of the split air conditioning system are given in Table 3.

$$\dot{Q} = UA_s(T_{R,m} - T_a) \quad (4)$$

where U is the overall heat transfer coefficient of pipe layers, A_s is the total surface area of pipe, $T_{R,m}$ is the average working fluid temperature of inside pipe and T_a is the ambient temperature of the pipelines networked inside building and the value for the heating and cooling modes is assumed as 293 K and 303 K respectively. U is calculated from;

$$U = \frac{1}{R_t} \quad (5)$$

where R_t are the total thermal resistances, which are calculated by Equations (6) and (7) for uninsulated and insulated pipe systems.

$$R_{t,un-ins} = \frac{1}{h_i A_{s,i}} + \frac{l \hat{q} \frac{r_o}{r_i}}{2\pi L_{pipe} k_{pipe}} + \frac{1}{h_o A_{s,o}} \quad (6)$$

$$R_{t,ins} = \frac{1}{h_i A_{s,i}} + \frac{l \hat{q} \frac{r_o}{r_i}}{2\pi L_{pipe} k_{pipe}} + \frac{l \hat{q} \frac{r_{ins}}{r_o}}{2\pi L_{pipe} k_{ins}} + \frac{1}{h_o A_{ins,o}} \quad (7)$$

where, k_{ins} is the thermal conductivity of insulation material, $A_{ins,o}$ is the outside surface area of the insulated pipe which equals to $A_{ins,o} = 2\pi L r_{ins}$ and L is the pipe length which is assumed as 1 m.

The convection heat transfer coefficients for the inside and outside surface of piping system h_i and h_o are calculated as (Incropera and Dewitt, 1996);

$$h_i = \frac{0.023 Re^{0.8} Pr^{0.4} k_R}{D_{pipe}} \quad (8)$$

and

$$h_o = Nu_o \frac{k_{air}}{D_{pipe}} \quad (9)$$

$$Nu_o = 0.3 + \frac{k_{air} \sqrt{Re} Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}} [1 + (Re/282000)^{5/8}]^{4/5} \quad (10)$$

In Equations (8) and (10), Reynolds number (Re) is calculated by;

$$Re = \frac{\rho V D}{\mu} \quad (11)$$

where, ρ is the density of working fluid or ambient air, D is the pipe diameter, μ is the dynamic viscosity and V is the speed of working fluid or of ambient air. The velocity of ambient air is assumed of 0.2 ms^{-1} in these analyses.

Table 3. The properties of pipelines and insulation materials (Incropera and Dewitt, 1996).

Material	Properties	Value
Insulation	Extruded polystyrene (EPS)	$k_{eps} = 0.028 \text{ Wm}^{-1}\text{K}^{-1}$, $155 \text{ \$m}^{-3}$
	Foamboard	$k_{fb} = 0.027 \text{ Wm}^{-1}\text{K}^{-1}$, $193 \text{ \$m}^{-3}$
	Rockwool	$k_{rw} = 0.039 \text{ Wm}^{-1}\text{K}^{-1}$, $90 \text{ \$m}^{-3}$
	Expanded polystyrene (XPS)	$k_{xps} = 0.039 \text{ Wm}^{-1}\text{K}^{-1}$, $224 \text{ \$m}^{-3}$
Pipe	Seamless copper pipe	$k_{pipe} = 52 \text{ Wm}^{-1}\text{K}^{-1}$
	GP Diameter	$D_o = 15.88 \text{ mm}$, $t = 1.0 \text{ mm}$,
	LP Diameter	$D_o = 6.35 \text{ mm}$, $t = 0.8 \text{ mm}$,

3.3 Life Cycle Cost Analysis and optimization of insulation thickness

Life cycle cost analysis is a method used to evaluate the economic performance of energy systems over their entire life. The interest and inflation rates effecting insulation material costs are considered in the LCCA of the optimum pipe insulation thickness. In this study, the method is used for optimization the insulation thickness of pipelines of the split air conditioning system.

The annual total energy cost, C_f , is calculated by,

$$C_f = \frac{\dot{Q} \Delta t}{H_u \eta_{electricity} COP} C_F \quad (12)$$

where, Δt is annual operation time of the split air conditioning system under heating mode or cooling mode, H_u is lower heating value of energy source and C_F is fuel cost. The annual fuel consumption is

$$m_{f,an} = \frac{UA(T_{R,m} - T_a) \Delta t}{H_u \eta_{electricity} COP} \quad (13)$$

The total investment cost of insulation is given by the following equation

$$C_{t,ins} = C_{ins} V_{ins} \quad (14)$$

where, C_{ins} is the cost of insulation material and V_{ins} is the volume of the insulation materials.

P_1 - P_2 method is well-known method in the LCCA analysis. While the P_1 is a present worth factor which changes 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. In the insulation applications, the initial investment is the

insulation material cost and the design parameters used in the analyses are given in Table 4.

P_1 and P_2 are calculated by Equations (15) and (16), respectively,

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

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

where, M_s is ratio of maintenance, insurance, and other incidental costs in the first year to the first costs, R_v is ratio of the resale value at the end of the economic period to the first costs. P_2 are taken as 1.0 since M_s and R_v values are assumed zero.

The total cost of heating or cooling with the insulated piping can be calculated by Equation (17),

$$C_t = P_1 C_f + P_2 C_{t,ins} \quad (17)$$

Energy savings (\$ m⁻¹) obtained during the lifetime of insulation material can be calculated as follows [20]:

$$ES = C_{t,un-ins} - C_{t,ins} \quad (18)$$

where, $C_{t,un-ins}$ and $C_{t,ins}$ are the total heating or cooling costs when insulation is not and is applied, respectively.

Energy savings can be expressed as % by the following equation:

$$\frac{ES}{C_{t,un-ins}} \times 100 \quad (19)$$

Then, pay-back period, PP is calculated by solving the following equation for PP:

$$\frac{C_{t,ins}}{ES} = \frac{1}{d-i} \left[1 - \left(\frac{1+i}{1+d} \right)^{PP} \right] \quad (20)$$

Table 4. The design parameters used in economical analyses (The Central Bank of the Republic of Turkey, 2014), (Incropera and Dewitt, 1996).

Parameters	Values
Energy source (Electricity)	
H_u	$3.599 \times 10^6 \text{ JkW}^{-1}\text{h}^{-1}$
C_F	$0.1059 \text{ \$ kWh}^{-1}$
$\eta_{\text{electricity}}$	0.99
Operation time (hours)	
Heating mode	2100
Cooling mode	0.99
System performance (COP)	
Heating mode	5.77
Cooling mode	4.77
Interest rate (%)	4.5
Inflation rate (%)	9.4
Life time (years)	10

4. Results and discussion

The thermo-economical optimization analysis of hot water and hot air heating pipe networks is widely investigated in the literature. In this study, the thermo-economical optimization analysis is applied to the gas and liquid pipelines of the split air conditioning system operated under heating and cooling conditions. Thermo-economical insulation thickness optimization is carry out for four different insulation materials as expanded polystyrene (EPS), foamboard, rockwool and extruded polystyrene (XPS).

The variations of the insulation thickness, fuel and total costs with respect to both gas and liquid pipelines insulated

with EPS under heating mode of the split air conditioning system are demonstrated on the left side of Figure 3 one after another, whereas, variations of these costs with respect to both gas and liquid pipelines insulated with EPS under cooling mode of the split air conditioning system are shown on the right side of this figure.

Fig. 3. Effects of insulation thickness on the total cost for GP and LP insulated with EPS under heating (left side) and cooling (right side) modes of the split air conditioning system

As shown in Figure 3, the cost of the fuel decreases as insulation thickness increases. However, the insulation cost increases linearly with insulation thickness. The total cost is the sum of the cost of fuel and insulation material. The insulation thickness at the minimum total cost is determined as the optimum insulation thickness.

When it comes to energy savings, the variations emerging for all insulation materials of GP and LP under both heating and cooling modes of the split air conditioning system are presented successively on the Figure 4.

The optimum insulation thickness is achieved when the energy savings start to drop thanks to the increased thickness of insulation material. The energy savings is at maximum level under optimum insulation thickness. The energy savings depend upon the insulation thickness, insulation material unit costs and heat load values on the pipelines. Insulating the pipelines up to optimum insulation thickness increases energy savings; however, over insulation more than optimum insulation thickness decreases energy saving.

As witnessed in Figure 4, in the heating mode of the split air conditioning system which its gas and liquid pipelines are insulated with EPS, foamboard, rockwool and XPS while the energy saving values vary from 61% to 83% for the gas pipeline, these values vary from 47% to 79% for the liquid pipeline. When it comes to the cooling mode of the split air conditioning system which its gas and liquid pipelines are insulated with EPS, foamboard, rockwool and XPS while the energy saving values vary from -65% to 49% for the gas pipeline, these values vary from -121% to 45% for the liquid pipeline. Here, negative values for energy saving shows that energy saving is not obtained because the payback periods become too long and sometimes even longer than the lifetime of the insulation material. For example, under the cooling mode, the insulation thickness more than 0.07 m for LP with EPS is loss of money because it does not provide energy savings.

Equation (18) is minimized or Equation (20) is maximized and then the outside radius of insulated piping system is found. ES or C_t is differentiated with regard to r_o and founded set is equalized to zero, then the optimum insulation thickness is determined from $x_{opt} = r_{ins} - r_o$. MATLAB optimization toolbox is used to determine the optimum insulation thickness.

Fig. 4. Comparison of energy savings for both GP and LP insulated with determined insulation materials under heating and cooling modes of the split air conditioning system

The variations of the optimum insulation thicknesses with respect to each of the gas and liquid pipelines for analyzed all insulation material under both heating mode and cooling mode of the split air conditioning system are represented in the Figure 5. As seen in Figure 5, under heating mode of the split air conditioning system, while the optimum insulation thickness varies between 45 and 50 mm for gas pipeline depending on the analyzed insulation materials, whereas, it varies from 28 mm to 45 mm for the liquid pipeline.

Fig. 5. Optimum insulation thicknesses of gas and liquid pipelines for different insulation materials under heating and cooling modes

Besides, as seen in Figure 5, under cooling mode of the split air conditioning system, while the optimum insulation thickness varies between 26 and 41 mm for the gas pipeline depending on the analyzed insulation materials, whereas, it varies from 22 mm to 33 mm for the liquid pipeline.

While the highest optimum insulation thicknesses are obtained on gas pipeline insulated with both EPS and rockwool under heating mode, the lowest values of optimum insulation thicknesses are obtained on liquid pipeline insulated with XPS under cooling mode.

The optimum insulation thicknesses of GP and LP have different values for heating and cooling modes. Therefore, the highest value calculated for the heating and cooling modes must be selected as the optimum insulation thickness. As a result, optimum insulation thicknesses for GP and LP of the investigated split air conditioning system are determined as, 50 and 32 mm for EPS, 45 and 29 mm for foamboard, 50 and 45 mm for rockwool, 45 and 28 mm for XPS, respectively.

Fig. 6. Energy savings obtained by optimum insulation of gas and liquid pipelines for different insulation materials under heating and cooling modes

The variations of the energy savings with respect to each of the gas and liquid pipelines for analyzed all insulation material under both heating mode and cooling mode of the split air conditioning system are represented in the Figure 6. As seen in Figure 6, under heating mode of the split air conditioning system, while the energy saving varies between 78% and 83% for gas pipeline depending on the analyzed insulation materials, whereas, it varies from 40% to 79% for the liquid pipeline. Besides, as seen in Figure 6, under cooling mode of the split air conditioning system, while the energy savings varies between 49% and 79% for the gas pipeline depending on the analyzed insulation materials, whereas, it varies from 33% to 45% for the liquid pipeline. While the highest energy savings are obtained on gas pipeline insulated with EPS under heating mode, the lowest values of energy savings are obtained on liquid pipeline insulated with rockwool under cooling mode.

The variations of the payback period for each of pipelines insulated with EPS, foamboard, rockwool and XPS is shown in Figure 7 for both heating mode and cooling mode of the split air conditioning system. Under heating mode of the split air conditioning system, while the payback periods vary between 0.025 and 0.468 years for gas pipeline depending on the insulation materials, whereas, they vary from 0.041 to 0.312 years for the liquid pipeline. Besides, again, as seen in Figure 7, under cooling mode of the split air conditioning system, the payback periods vary between 0.041 and 0.213 years for the gas pipeline depending on the insulation materials, whereas, they varies from 0.203 to 0.301 years for the liquid pipeline. While the shortest payback periods are determined at gas pipeline insulated with rockwool under heating mode, the longest payback periods are carried out at the gas pipeline insulated with XPS under heating mode.

Fig. 7. Payback periods vs optimum insulation thicknesses of gas and liquid pipelines for different insulation materials under heating and cooling modes

The optimum insulation thickness, energy savings and payback periods based on analyzed insulation materials for gas and liquid pipelines of given the split air conditioning system are summarized in Table 5 for heating and cooling modes.

Table 5. The optimum insulation thickness, energy savings and payback periods for heating and cooling modes of the split air conditioning system

Insulation material	Pipeline	Heating mode			Cooling mode		
		x_{opt} (mm)	ES (%)	PP (years)	x_{opt} (mm)	ES (%)	PP (years)
EPS	GP	50	83	0.038	29	49	0.213
	LP	32	79	0.041	25	45	0.203
Foamboard	GP	45	82	0.040	26	79	0.041
	LP	29	48	0.233	22	45	0.221
Rockwool	GP	50	78	0.025	41	74	0.049
	LP	45	40	0.289	33	33	0.301
XPS	GP	45	80	0.468	26	76	0.048
	LP	28	40	0.312	22	37	0.299

5. Conclusions

In literature, many studies are presented on the optimum insulation thickness computations in the pipe performed based mainly on the heating load and other parameters such as the costs of the insulation material and energy, efficiencies of the heating system, the lifetime, and the current inflation and discount rates. In this study, the economical optimum insulation thickness is studied for the gas and liquid pipelines of the split air conditioning system. Analyses are carried out for four different insulation materials determined as EPS, foamboard, rockwool and XPS. Considering the results of the analyses, the following main conclusions can be drawn from the present study:

- (1) While the cost of the fuel decreases as insulation thickness increases, the insulation cost increases with insulation thickness.
- (2) While the highest energy savings are obtained on gas pipeline insulated with EPS under heating mode, the lowest values of energy savings are obtained on liquid pipeline insulated with rockwool under cooling mode.
- (3) While the highest optimum insulation thicknesses are obtained on gas pipeline insulated with both EPS and rockwool under heating mode, the lowest values of optimum insulation thicknesses are obtained on liquid

pipeline insulated with XPS under cooling mode.

- (4) While the shortest payback periods are determined at gas pipeline insulated with rockwool under heating mode, the longest payback periods are carried out at the gas pipeline insulated with XPS under heating mode.
- (5) The highest optimum insulation thicknesses calculated for each of GP and LP must be selected because GP and LP of the split air conditioning system are used under both heating and cooling modes.

Finally, for both gas and liquid pipeline of the split air conditioning system, the expanded polystyrene (XPS) is a better choice when the optimum insulation thickness is an important consideration.

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