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Minimisation of Exergetic Cost of Steam Pipeline Insulation

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Abstract

This paper presents the optimization study of steam pipeline insulation with three materials: EPS, XPS and rockwool. The steam pipelines considered were single straight pipe, two-branch and three-branch networks with effects of pipe length and multilayered insulation on exergy loss, thickness and its attendant cost of insulation. Scaled exergetic cost model was developed and minimized to determine the optimum insulation thickness for pipeline carrying steam at inlet temperature of 200°C. For the same thickness of layer in composite insulation, preliminary analysis indicated that the best order of arrangement from the pipe outside surface is XPS-EPS-Rockwool. The optimum thickness of insulation and associated cost decreased with increase in flow rate of the steam but they increased with the pipe length. For different pipe lengths, the multilayer composite gave fairly smaller optimum insulation thicknesses and costs as compared with monolithic insulation of pipe with each of the insulation materials. The study also showed that each pipe in the multiple pipe networks had its own peculiar optimum thickness for each insulation layer in the multilayered composite to ensure pipe-end thermal quality of the steam pipeline.

Keywords:scaled exergetic cost, optimum insulation thickness, thermal insulation, exergy loss, steam pipeline.

I. INTRODUCTION

Steam is one of the most energy efficient and reliable means to transfer heat within industrial processing operations. The flexible characteristics of steam provide endless possibilities to many industries like electricity generation, district heating, and sterilization in manufacturing and so on. Steam is used in food and beverage process industries for cooking, drying, sterilizing, humidifying and other heating applications [1,2]. In systems where steam is required to be transported through pipelines then material properties and heat transfer by conduction and convection are involved in the transportation process which affect efficiency of the system. In order to minimize the heat loss from steam pipes it is essential that they are lagged with a suitable insulation material that delivers the best thermal insulation properties [3,4]. Uninsulated steam distribution and condensate return lines are a constant source of wasted energy and to reduce the heat loss efficiently in such a heating system, proper insulation should be selected by accounting for the purpose, environment, ease of handling, and installation cost [5,6].

Energy saving has been the focus of every country because it is a crucial factor that determine the economics development of any country. Piping system which is the major conveyor to transfer steam from one place to another contribute greatly to energy loss. Uninsulated pipe carrying steam or distributing it is a constant source of wasted energy, and to reduce the heat loss efficiently proper insulator must be put in place [5]. Heat insulation is a way of preventing heat loss or gained, or conserving heat within material (especially fluid) transfer from one point to another. It is installed in building, mechanical installations and in various industrial plants [7].

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There have been a number of research studies on thermoeconomic optimization of thermal insulation of piping systems, most especially using the life cost analysis for improving steam transportation through pipelines. Wang et al. [4] worked on the possibilities of getting the exact amount of mass, pressure, density and temperature of the steam transported from one point to another. Başoğul and Keçebas[5] also evaluated the energy, environmental and economic effects of thermal insulation in pipelines with the life cycle cost (LCC) analysis using the $P_1 - P_2$ method, which considers the life cycle energy and life cycle expenditures. Their results showed that there was decrease in fuel cost as the thickness of insulation increases and the best pipe size with the optimum insulation thickness and maximum energy saving were calculated. Ertürk[7] determined the optimum insulation thickness with the use of expanded polystyrene (EPS) and extruded polystyrene (XPS) as insulation materials and various fuels. The results show that the annual fuel and insulation cost fall with the use of insulation material but increase after a certain insulation thickness which are 7.38 cm and 11.70 cm for 50 mm and 1000 mm pipes, respectively. Kruczek[1] investigated the annual heat loss from overhead pipelines into the environment using thermo vision cameras for a one-off infrared examination of pipelines under various weather conditions and theoretical analysis algorithms showed that the mean cost of a pipeline insulation can be reduced by segmenting in order to reconstruct only those pipeline that satisfy economic factors instead of modernizing the whole pipeline network.

Thus, the previous studies have indicated some of the various factors that contribute to the determination of optimum insulation thickness of steam pipelines such as the fuel cost, pipe diameter, cost and thermal properties of the insulation material. Nevertheless, studies on the effect of multilayered composite, pipe length and multiple pipe network systems on pipe-end thermal quality of steam, piping insulation and its attendant cost have not been widely reported. Thus, in this study, these factors will be considered in the exergy-cost minimization of piping system to determine the optimum thickness of insulation.

II. MATERIALS AND METHOD

2.1 Materials

The heat loss or gained from transporting steam through a pipeline are usually influenced by a number of factors, such as the piping structure, piping environment, insulation materials, among others. Thus, the following assumptions were taken in the course of this study.

i. Constant ambient temperature
ii. Flow resistances at pipe bends and joints are negligible
iii. Flow is assumed to be at steady state
iv. Insulation materials are tightly fitted to the pipe with perfect thermal contact

The optimization study was carried out on three different pipe networks: single straight pipe, two-branch network (see Figure 1) and three-branch network (see Figure 2). The pipes are of commercial steel type with thermal conductivity and roughness of 45 W/mK and 0.046 mm, respectively. The geometrical sizes of the pipes in each of the networks are as given in Table 1.

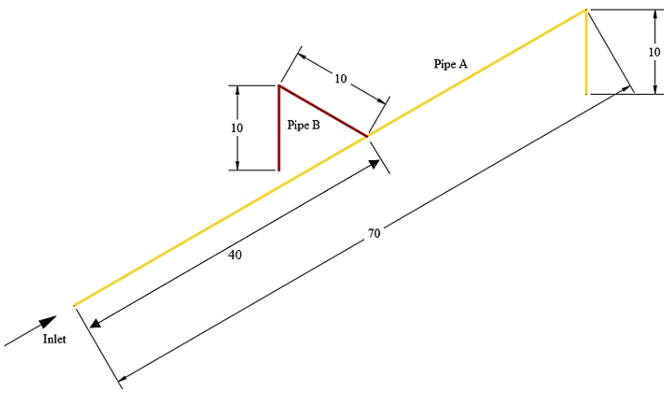

Figure 1. The two-branch pipe network

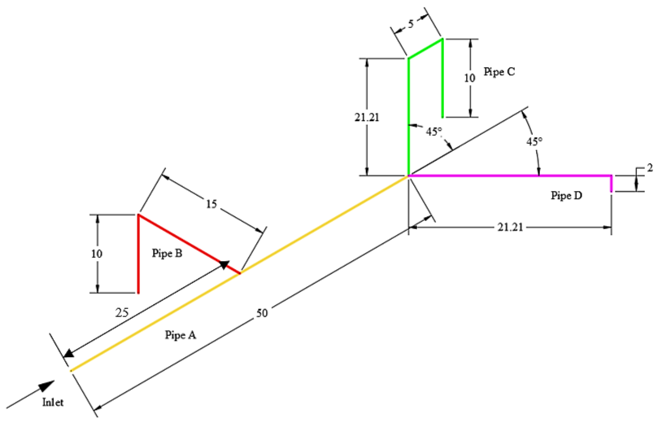

Figure 1. The three-branch pipe network

Table 1. Sizes of pipes in the steam pipeline

	Straight Pipe (mm)	Two-Branch Network (mm)		Three-Branch Network (mm)			
		Pipe A	Pipe B	Pipe A	Pipe B	Pipe C	Pipe D
Nominal Diameter	200	200	100	200	125	100	100
Outer Diameter	219.1	219.1	114.3	219.1	141.3	114.3	114.3
Thickness	8.18	8.18	6.02	8.18	6.55	6.02	6.02

The selected insulation materials for the piping system under this study are expanded polystyrene (EPS), extruded polystyrene (XPS) and rockwool. The thermal conductivity and cost per unit volume of these insulation materials were taken to be 0.039 W/mK and 120 $/m^3, 0.031 W/mK and 180 $/m^3, and 0.040 W/mK and 95 $/m^3, respectively [8][2]. Other parameters used in the study are as given in Table 2.

Table 2. Parameters used for analysis

Parameters	Value
Surrounding air velocity	5 m/s
Surrounding air temperature, T_a	30°C
Steam inlet temperature, T_s	200°C
Steam volumetric flow rate	3000 m^3/h
Density Steam	0.4682 kg/m^3
Specific heat capacity of steam	1976 J/kgK

2.2 Energy Analysis

The heat loss from the steam inside the pipe network to the surrounding air of the pipe network is determined from the rate of heat transfer as [9]

$$Q = \frac{T_s - T_a}{R} \tag{1}$$

where$R$ is the total thermal resistance between the steam and surrounding air, and it is defined as

$$R = \frac{1}{2\pi r_i L h_i} + \frac{\ln(r_{i+1}/r_i)}{2\pi k_p L} + \frac{1}{2\pi L}\sum_{j=i+1}^{n-1}\frac{\ln(r_{j+1}/r_j)}{k_j} + \frac{1}{2\pi r_n L h_n} \tag{2}$$

From equation (2), the third term accounts for the summation of thermal resistances offered by n - j, ($n>j$) insulation materials, L is the pipe length, and r represents the respective inside/outside radius of pipe or insulation material.

Thus, the convective heat transfer coefficient inside the piping system was determined from Gnielinski correlation as [9]

$$h_i = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3}-1)}\left(\frac{k_s}{d_i}\right) \tag{3}$$

where Haaland's equation for friction factor, f is given as [10]

$$\frac{1}{\sqrt{f}} = -1.8\log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon/d_i}{3.7}\right)^{1.11}\right] \tag{4}$$

Also, the convective heat transfer coefficient for outer surface of the piping system was calculated from Churchill and Bernstein as [9]

$$h_o = \left[0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+(0.4/\mathrm{Pr})^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right]^{4/5}\right]\left(\frac{k_a}{d_o}\right) \tag{5}$$

2.3 Exergy Analysis

The net work transfer rate for steady flow exergy balance of steam flowing through pipeline from the first and second laws of thermodynamics is determined as [11,12]

$$\dot{W}_{net} = \dot{m}c_{p,e}(T_{in} - T_{out}) - \dot{m}T_e c_{p,e}\ln\frac{T_{out}}{T_{in}} - \dot{X} \tag{6}$$

To increase the net work transfer rate as defined in equation (6) the last term of the equation, which is the exergy loss due to irreversibility or lost available work in transporting the steam through the pipeline must be reduced and can further be expressed as

$$\dot{X} = T_e\dot{S}_g \tag{7}$$

where T_e is the temperature of the environment and $\dot{S}_g$, which is the entropy generation rate due to the finite temperature difference and fluid friction in the steam pipeline, is given as [13]

$$\dot{S}_g = -\dot{m}c_p\ln\frac{T_{out}}{T_{in}} - \dot{m}_c R\ln\frac{p_{out}}{p_{in}} \tag{8}$$

Thus from equations (w) and (a), the exergy loss is then given as

$$\dot{X} = -T_e\left(\dot{m}c_p\ln\frac{T_{out}}{T_{in}} + \dot{m}R\ln\frac{p_{out}}{p_{in}}\right) \tag{9}$$

The cost of single layer of insulation of a pipe length has been defined to be calculated from [7,8]

$$C_{i,ins} = c_i V_i \tag{10}$$

where i is the number of insulation layer, c_i is insulation material cost per unit volume and the volume of the insulation material is estimated from

$$V_i = \pi(r_i^2 - r_{i+1}^2)L \tag{11}$$

The total cost of multilayered pipe insulation is then expressed as

$$C_{t,ins} = \sum_{i=1}^{n} C_{i,ins} \tag{12}$$

For optimal design of pipe insulation system, trade-off between the high cost of insulation that may result from zero exergetic loss and the excessive loss of exergy for pipe without insulation must be established, and this has led to the development of the scaled exergetic cost of insulation, having it value ranges from zero to one, and is given as

$$C = \frac{\dot{X}}{\max(\dot{X})\big|_{t_{ins}=0}} + \frac{C_{t,ins}}{\max(C_{t,ins})\big|_{T_{out} \square T_{in}}} \tag{13}$$

Therefore, to obtain the optimum thickness of insulation for the pipe transporting the steam, the scaled exergetic cost of insulation is taken as objective function to be minimized, then we have

$$Min \quad f(x) = C \tag{14}$$

Thus, for either the monolithic or multilayer pipe insulation, the constraint for the optimization procedure was set to that none of the insulation material will have its thickness to be less than zero, that is

$$t_{mat,i} \geq 0 \tag{15}$$

The constraint was handled with the penalty method and the whole optimization procedure was resolved using the Nelder-Mead Optimization solver within the COMSOL Multiphysics software.

III. RESULTS AND DISCUSSION

In order to have a suitable arrangement of the three insulation materials for multilayer insulation around the piping system, the materials were arranged into six (REX, RXE, ERX, EXR, XRE and XER), from the inner one next to the pipe to the outer one exposed to the surrounding air. The R stands for rockwool, E for EPS and X for XPS, and the thickness of each insulation layer was 30 mm, making a total of 90 mm. The result obtained as shown in Figure 3 indicates that XER gave the best arrangement for contributing to the higher outlet temperature of steam. This is due to the thermal conductivities of the insulation materials, the XPS having the lowest value and positioned next to the pipe could have increase the conduction resistance of the of the insulation layers.

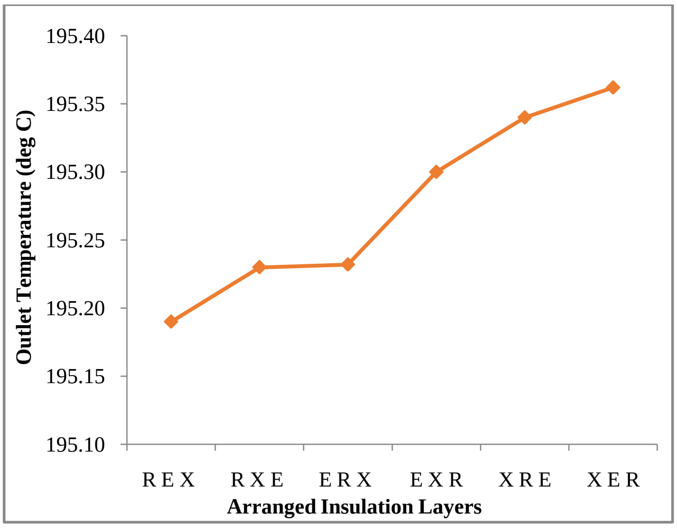

Figure 3. Outlet temperature of steam with different arrangements of insulation

Preliminary investigations were further carried out on the effect of thickness of insulation on straight pipe length of 70 m transporting steam at 3000 m^3/h and inlet pipe temperature of 200°C with only EPS as insulation material. As shown in Figure 4, it was observed that there was sharp reduction in temperature from the inlet and outlet of the pipe when there is no or very small insulation thickness. This is due to the heat loss to the surrounding air. The drop in temperature reduces asymptotically to zero as the insulation thickness increases to approximately 4 m. It could also be seen that the pressure drop increases sharply from no insulation at 850 Pa and rises asymptotically to 955 Pa. This shows that insulation contributes to rise in pumping power to a maximum limit. The similar trend observed between the two intensive properties of steam shows that the steam obeys the ideal gas law.

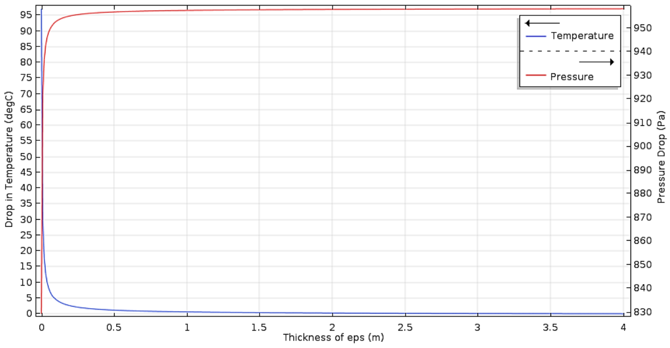

Figure 4. Change in temperature and pressure drop as against the insulation thickness

The sharp drop in temperature due to heat loss through the pipe contributed to very high exergy loss in the piping system at very small thickness or no insulation while there was precipitous decrease as the thickness increases (see Figure 5). The cost of insulation also increases with the thickness. Figure 6 also shows the plot of the scaled exergy loss, scaled insulation cost and scaled exergetic loss. The corresponding insulation thickness to the lowest point on the scaled exergetic loss curve is considered as the optimum thickness, which was found to be 0.296 m. However, the optimum insulation thickness

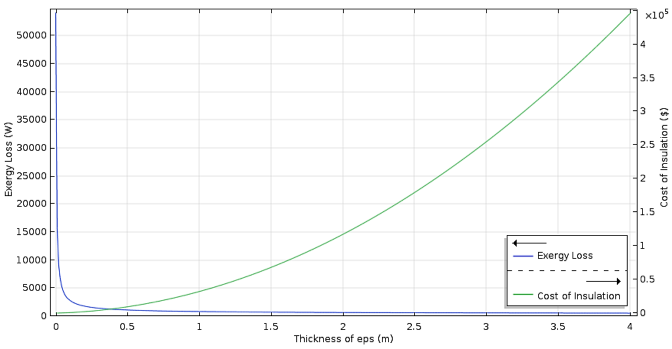

Figure 5.Exergy loss and cost of insulation versus insulation thickness

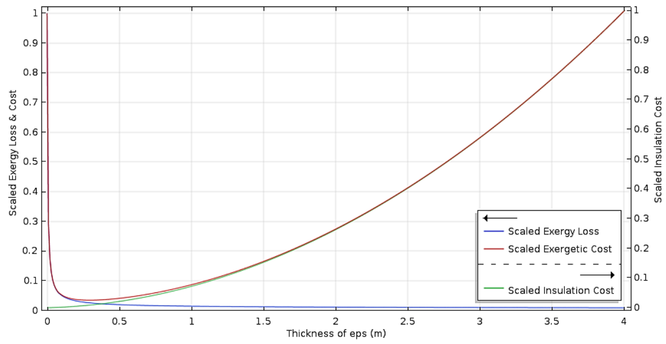

Figure 6. Scaled exergy loss, scaled insulation cost and scaled exergetic cost versus insulation thickness

Table 3 accounts for the effect of the steam flow rate on the steam properties and EPS insulation for pipe length of 70 m. From this table the optimal value results are at the minimum scaled exergetic cost (SEC) while the results at minimum exergy loss indicate the same steam inlet temperature and outlet temperature of steam, which can only be achieved with very large insulation. It can be seen that as the steam flow rate increases, the required thickness of insulation reduces. This obviously implies that it requires high cost of insulation to transport steam at lower steam velocity.

Table 3. The thickness and cost of insulation at various steam flow rates for single straight pipe with EPS

Flow Rate (m^3/h)	ΔP (Pa)			Temperature (K)			Thickness (m)		Cost of Insulation ($)	
	@ No Insulation	@ *Min*Exergy Loss	@ SEC	@ No Insulation	@ *Min*Exergy Loss	@ SEC	@ *Min*Exergy Loss	@ SEC	@ *Min*Exergy Loss	@ SEC
2500	575	685	675	94	200	198	7.0167	0.4700	1339800.00	8547.80
3000	825	955	955	103	200	198	2.3532	0.2960	447460.00	4023.70
3500	1125	1285	127	110	200	197	0.9997	0.099	32155.00	832.53

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			5					1		
4000	1465	1655	164 5	117	200	195	0.4129	0.049 0	6886.40	347.00
4500	1865	2075	205 5	123	200	193	0.2193	0.030 0	2536.20	197.19

The plot of exergy loss at minimum scaled exergetic cost for the straight piping system transporting steam at 3000 m^3/h is as shown in Figure 7. This was obtained for each of the three insulation materials and their composite (XPS-EPS-Rockwool, XER) at varying pipe length. It was observed that the exergy loss in the system increases generally with the pipe length, and this could be attributed to the increase in fluid friction with pipe length. Figure 8 also indicates that the optimum thickness of insulation increases with the varying pipe length except for the multilayer insulation which remains almost the equal for all the pipe length, and this could be ascribed to the tendency for compensation of layer thickness of the composite insulation. The XPS insulation averagely gave small insulation thickness, which could be due to its lower thermal conductivity. Table 4 depicts thicknesses of each layer of the composite insulation, however the selection from optimization was not favourable to EPS. In Figure 9, it is evident that the EPS recorded the highest cost of insulation as a monolithic insulation while the multilayer insulation had the lowest cost of insulation.

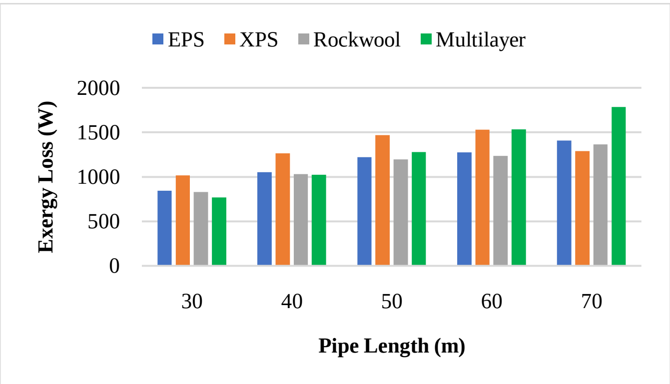

Figure 7. The exergy loss versus pipe length for various insulation materials

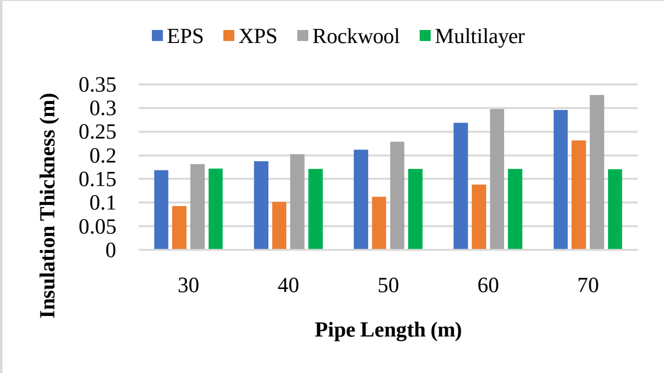

Figure 8. The optimum insulation thickness versus pipe length for various insulation materials

Table 4. The thickness and cost of insulation at various pipe lengths for single straight pipe with composite insulation

Pipe Length (m)	Insulation Thickness (m)				Cost of Insulation ($)
	XPS	EPS	Rockwool	Total	
30	0.0511	0.0000	0.1208	0.1718	711.85
40	0.0511	0.0000	0.1204	0.1715	947.05
50	0.0510	0.0000	0.1201	0.1711	1180.40
60	0.0508	0.0000	0.1202	0.1710	1414.60
70	0.0507	0.0000	0.1201	0.1709	1647.70

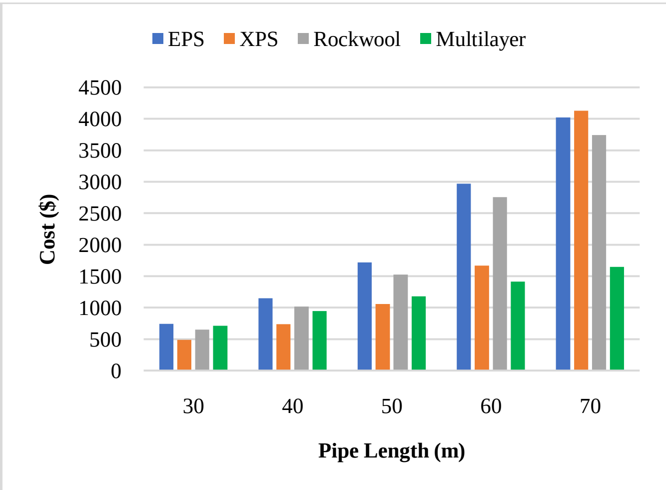

Figure 9. The cost at optimum insulation thickness versus pipe length for various insulation materials

The results of optimization of multilayered (XER) pipe insulation for two-branch and three-branch piping systems transporting steam at 3000 m^3/h are as depicted in Tables 5 and 6, respectively. The tables present the thickness of each layer of insulation materials in the multilayered composite for optimization analyses at minimum exergy loss and minimum scaled exergetic cost. The results in these tables indicated that insulation thicknesses of the pipes in the networks are not the same but each pipe require a specific thickness to obtain the optimal outlet steam temperatures from the pipes. The total capital investment costs of insulating the piping systems at the minimum exergy loss are considerably much higher than optimal costs at the minimum scaled exergetic cost.

Table 5. The thickness and cost of insulation for two-branch pipe network with composite insulation

	@ *Min*Exergy Loss					@ *Min* Scaled Exergetic Cost (SEC)				
	Insulation Thickness (m)				Cost of Insulation ($)	Insulation Thickness (m)				Cost of Insulation ($)
	XPS	EPS	Rockwool	Total		XPS	EPS	Rockwool	Total	
Pipe A	3.8881	0.2395	1.2886	5.4162	2424600.00	0.2159	0.0000	0.2447	0.4606	13945.00
Pipe B	6.7615	4.3296	1.6118	12.7029		0.3801	0.0000	0.3266	0.7066	

Table 6. The thickness and cost of insulation for three-branch pipe network with composite insulation

	@ *Min*Exergy Loss					@ *Min* Scaled Exergetic Cost (SEC)				
	Insulation Thickness (m)				Cost of Insulation ($)	Insulation Thickness (m)				Cost of Insulation ($)
	XPS	EPS	Rockwool	Total		XPS	EPS	Rockwool	Total	
Pipe A	15.6070	6.7331	4.8933	27.2334	38202000.00	0.3009	0.0696	0.2035	0.5740	16706.00
Pipe B	0.0000	6.4483	6.6717	13.1200		0.0207	0.0559	0.0598	0.1363	
Pipe C	18.2210	7.5376	8.4708	34.2294		0.2299	0.1319	0.1358	0.4976	
Pipe D	12.9700	5.6842	2.4197	21.0739		0.1678	0.2317	0.0903	0.4898	

IV. CONCLUSION

In this study, the exergetic cost optimization of thermal insulation on steam pipe network have been carried out. The effect of the pipe length, multilayered insulation and multiple pipe network was considered in determining the optimum insulation thickness. Three insulation materials: EPS, XPS and rockwool were used in the multilayered composite for single straight pipe, two-branch and three-branch networks. Results indicated that the best order of arrangement for the multilayer insulation from the pipe outside surface, given the same thickness of the insulation materials is XPS-EPS-Rockwool. The thickness and cost of insulation decreased with increase in flow rate of the steam but they increased with the pipe length. The optimum thickness and its incidental cost of insulation for the multilayer composite are relatively small as compared with monolithic insulation with each of the insulation materials. Results have also shown that different material layer thicknesses in the composite would be required to obtain the optimum insulation thickness for each pipe in any of the multiple pipe networks.

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