

The Economic Thickness of Insulation for Steam Process Distribution Pipelines

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Abstract
Steam pipes are very important in engineering application and are widely used. Thermal insulation is one of the most effective energy-conservation measures in hot pipes. One of the primary purposes of insulation is to conserve energy and increase plant profitability by reducing operating expenses. In existing plants, the planned and conscientious maintenance of insulated hot pipes is required to minimize financial and thermal losses. This seems like a statement of the obvious, and it is. Although an increase in the amount of insulation applied will raise the initial installed cost, but it will reduce the rate of heat loss through the insulation. This paper aims to confirm whether there is an optimal insulation thickness appropriate to the minimum total cost, and to see what the values and facts affecting the value of the minimum cost are. An optimization model is performed depending on Life Cycle Cost analysis. For this purpose, a computer program has been prepared based on the flow chart of the operation procedure overviewed in this paper. The results of Calculations carried out by the computer have given a new concept that is termed as “the critical thermal conductivity of insulation material”, the exceeding of which makes the insulation of pipe a factor that contributes to increase of total cost (ΣC) but not the opposite. The study carried out on steam pipe with outside diameter of 0.1m, steam temperature of 120 °C, steam price of 0.005 \$/kg and insulation material price of 175 \$/m^3 shows that the critical thermal conductivity of insulation material is 0.21 w/(m. °C), the exceeding of which will not cause decrease in the expected total cost of steam pipe insulation and the optimal insulation thickness can not be achieved. When the thermal conductivity of the insulation material used is less than that of the critical thermal conductivity by 0.10 w/(m.°C), the total cost drops from 9.69 \$/(m.year) without insulation to minimum total cost of 5.184 \$/(m.year) with the thermal insulation thickness of 0.092m. The outside temperature of insulation material drops from 117 to 34.4 °C. The effect of the price of steam generation, the price of insulation material, pipe diameter and temperature of steam on the optimal insulation thickness and critical thermal conductivity of insulation material are overviewed in this paper.
Keywords: Optimum insulation thickness, steam pipe insulation, thermal conductivity

1. Introduction

Steam is used in a wide range of industries. Common applications for steam are, for example, steam heated processes in plants and factories and steam driven turbines in electric power plants, but the uses of steam in industry extend far beyond this. Here are some typical applications for steam in industry: Heating/sterilization, propulsion/drive, motive, atomization, cleaning, moisturization, and humidification, .[1]. In modern conditions necessary factor cost-effective functioning of industrial enterprises, as well as companies that supply heat to various customers, primarily utilities is the rational use of heat energy by reducing heat loss . The most important role in reducing heat loss during transport hot fluids (steam) belongs to thermal insulation.[2].

One of the primary purposes of insulation is to conserve energy and increase plant profitability by reducing operating expenses. In existing plants, the planned of insulated steam process distribution pipelines is required to minimize financial and thermal losses. This seems like a statement of the obvious, and it is.[3]. Lack of proper insulation results in large energy losses which in turn cost a lot of money over time. Without proper insulation, the amount of energy lost can be 10 times greater than the energy being delivered through those pipes. 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:

1. Conserve energy by reducing heat loss or gain.
2. Control surface temperatures for personnel protection and comfort.
3. Facilitate temperature control of a process.
4. Prevent vapor flow and water condensation on cold surfaces.
5. Increase operating efficiency of heating/ventilating/cooling, plumbing, steam, process and power systems found in commercial and industrial installations
6. Prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres.

The temperature range within which the term "thermal insulation" applies is from –73.3°C (–100°F) to 815.6°C (1500°F). All applications below –73.3°C (–100°F) are termed "cryogenic" and those above 815.6°C (1500°F) are termed "refractory". In analogy to electrical resistance, the overall effect of an insulator can be described in terms of its “thermal resistance”. The higher the thermal resistance the less the heat flow for a given temperature difference across the insulator, just as the higher the electrical resistance the less the current flow for a given potential difference across a resistor [4]. Till a few years ago, insulation was never designed. Insulation was applied only to reduce surface temperature. Even when designed on a scientific basis in a few progressive plants, the design was based on the then fuel costs. Existing insulation systems in almost every plant, therefore, are obsolete and ineffective. The pressing need is to assess the existing insulation systems, identify the critical energy loss areas and upgrade the insulation systems of such areas on priority basis [5]. The November 2007 Insulation Outlook article “Multiple Choice, Part One” discussed the paradox of the past several years of energy prices more than doubling while thermal insulation thicknesses for hot piping and equipment have not increased. Most insulation thickness tables for hot service industrial piping and equipment were written before 2000, and most of these tables have not been upgraded to reflect the higher energy prices [6]. In this paper, the question of how insulation thicknesses should be selected was addressed. The thicknesses that balance energy savings with lost energy cost plus insulation cost of the installed insulation system.

2. Mathematical model

The increase in thickness of insulation will raise the initial cost of the installation of steam pipes., but it will lead to a reduction in heat loss through the insulation layer. This reduction in heat loss leads to a decrease in the cost of steam regeneration which had been turned into water because of those losses. The total cost under certain conditions could be reduced. To reach the optimum (economic) thickness of insulation, appropriate to the minimum total cost. (insulation plus heat loss), the heat loss cost, insulation cost and the total cost are calculated. The obtained results will be put in tables and then converted into line graphs illustrating thickness and cost. The minimum total cost will be specified on these line graphs, and the insulation thickness appropriate to the minimum total cost is considered as the optimum (economic) thickness of insulation. The data required for the complete analysis of the economic thickness can be summarized:

Price of the insulation material C''_{ins}, ($/m^3$), the investment life of insulation material n,(years), the outside diameter of pipe d_p, (m), the thickness of insulation layer δ_{ins}, (m), length of pipe $L_p=1$, (m), The thermal conductivity of insulation material K_{ins}, (W/(m.°C)), price of steam generation C''_{st}, ($/kg), annual operating period of steam pipes τ_{ins}, (hours), steam temperature t_{st}, (°C), Ambient temperature t_{air}, (°C).

The annual total cost $/(m.year) includes the annual cost of insulation per meter run of pipe and the annual cost of heat loss per meter run of pipe are calculated by the following formulas:

$$\sum C = C_{INS} + C_{ST} \qquad (1)$$

Where C_{INS} the annual cost of insulation per meter run of pipe $/(m.year).

$$C_{INS} = a\, C'_{ins} \qquad (2)$$

Where (a) is the value of depreciation

$$a = \frac{1}{n}$$

(n) is investment life of insulation material, (years).

C'_{ins} is The cost of the insulation of one meter length of the pipeline, $/m

$$C'_{ins} = C''_{ins}\, V_{ins} \qquad (3)$$

Where C''_{ins} is the price of the insulating material, $/m^3$

V_{ins} is the volume of insulation onto one meter length of pipe, m^3

$$V_{ins} = \pi \left[\left(d_p + 2\, \delta_{ins} \right)^2 - d_p^2 \right] \frac{L_P}{4} \qquad (4)$$

or

$$V_{ins} = \pi\, \delta_{ins} \left(d_p + \delta_{ins} \right) L_P$$

Where: d_p is the outside diameter of the pipe, m

δ_{ins} is the thickness of the insulation layer, m

L_p is the length of pipe, ($L_p=1$), m

The annual cost of heat loss per meter run of pipe $\mathbf{C_{ST}}$, $/(m.year) is calculated by the following formula:

$$C_{ST} = C''_{ST}\, \tau_{ins}\, \frac{q}{r}\, 3600 \qquad (5)$$

Where:

C''_{st} is the price of steam generation , ($/kg)

τ_{ins} is the annual operating period of steam pipes, (hours)

r is the latent heat of condensation of steam, r=2207. 10^3 J/kg

q is the heat loss through the insulation layer, w

$$q = \frac{\pi\, L_P\, (t_{st} - t_{air})}{\left[\left[\left(\frac{1}{2 K_{ins}} \right) Ln\left(\frac{d_{ins}}{d_p} \right) \right] + \frac{1}{d_{ins}\, h_o} \right]} \qquad (6)$$

Where:

t_{st} is the temperature of steam. °C

t_{air} is the ambient temperature (air), °C

K_{ins} is the thermal conductivity of insulation material**,** W/(m.ºC)
d_{ins} is the external diameter of insulation layer , m

$$d_{ins} = d_p + (2\delta_{ins}) \qquad (7)$$

h_o is the convection heat transfer coefficient on the outer surface of insulation, w/(m². ºC)

$$h_o = C\left[\frac{t_{ins}-t_{air}}{d_p}\right]^{0.25} \qquad (8)$$

where C is is a coefficient which can be obtained from the table given below according to the average temperature (t_{av}) of the insulation surface (t_{ins}) and air (t_{air}).

$$t_{av} = \frac{t_{ins}+t_{air}}{2} \qquad (9)$$

To find coefficient (C) from table 1, it is necessary to provide the surface temperature of insulation (t_{ins}). It is considered to be 40 degrees.

Table 1. values of the coefficient (C) according to t_{av}

t_{av}	0	50	100	200	300	400	500
C	1.22	1.14	1.10	1.05	0.95	0.85	0.70

Then, the true surface temperature of insulation (t_{ins}) is calculated by the following formula**.**

$$t_{ins} = \left[\frac{q}{h_o\, d_{ins}\pi\, Lp}\right] + t_{air} \qquad (10)$$

In accordance with the safety requirements, the surface temperature of the thermal insulation layer at economic thickness not greater than 150 mm should not exceed 50 °C.
As stated above in the equation (6), the value of $1/(d_{Ti}.\ h_i)$ is not included. The reason of that, this value is considered small compared to the other two thermal resistances.
Where d_{Ti} is inside diameter of the pipe and and h_i is the coefficient of heat transfer from the condensing steam to the internal surface of the pipe.
The importance while searching for economic thickness of insulation is to determine the conditions, where the rate of heat transfer through the steam pipe when adding insulation material is decreased. These conditions are determined as follows:
for insulation of pipe of outer diameter (d_p), a material of insulation should be chosen such that:

$$d_p \geq d_{crins} \qquad (11)$$

where d_{crins} is the critical diameter of insulation.
Note that the critical diameter of insulation (d_{crins}) depends on the thermal conductivity of the insulation k_{ins} and the external convection heat transfer coefficient h_o. The rate of heat transfer through the insulation layer decreases with the addition of insulation when the following conditions are met:

$$d_p \geq d_{crins}$$

$$d_{crins} = \frac{2\,K_{ins}}{h_o} \qquad (12)$$

thus:

$$d_p \geq \frac{2K_{ins}}{h_o} \qquad (13)$$

$$K_{ins} \leq \frac{d_p h_o}{2} \qquad (14)$$

In accession to that, preliminary calculations made by the computer shows that the total cost is only decreasing and reaches the minimum value at a specific value of the thermal conductivity of insulation. This new concept that is termed as "the critical thermal conductivity of insulation material". The optimum insulation thickness appropriate to the minimum total cost (insulation cost plus cost of heat loss through the insulation) only occurs when the thermal conductivity of insulation used is equal or less than that of the critical thermal conductivity (K_{inscr}).

$$K_{ins} \leq \frac{d_p h_o}{2}$$

3. Optimizing procedure

In formulas (3) and (5), it is clear that any change in the price of insulation material or the price of steam generation or both of them, significantly affect the value of the annual total cost of insulation and heat loss as shown in formula one. In connection with the changes that may occur in the value of the annual total cost, which is calculated by the formula (1), the economic thickness of insulation will change indirectly or it might not achieve at all. Jordan is one of the countries that import insulation material or it produces the steam from imported gas.

Over the past ten years, a big change in the price of insulation material occurred as well as in the price of steam generation, and it is expected that the change will continue in the coming years. Moreover, any change in thermal conductivity of insulation or diameters of pipes and steam temperature will change the value of the annual total cost of insulation and heat loss significantly, and will inevitably change the economic thickness of insulation or it might not achieve at all as mentioned above. To estimate the annual total cost of insulation, in a fast and better way to industrial facilities and to specify the value of the economic thickness of insulation (optimal) in light of changes in the price of insulation material, and that of steam generation, a computer program was prepared, assimilating the formulas that do the calculations of the annual cost of insulation per meter run of pipe, the annual cost of heat loss per meter run of pipe, and the annual total cost (insulation plus heat loss), in addition to the optimal thickness of insulation (economic) if it occurs. The flow chart operation procedure as shown in figure (1) comprises the following steps:

After entering the data for price of the insulation material C''_{ins}, ($/m^3$),), the investment life of insulation material n,(years), the outside diameter of pipe d_p, (m), length of pipe L_p=1, (m), The thermal conductivity of insulation material K_{ins}, (W/(m.^oC)), price of steam generation C''_{st}, ($/kg), annual operating period of steam pipes τ_{ins}, (hours), steam temperature t_{st}, (^oC), Ambient temperature t_{air}, (^oC), the thickness of insulation layer δ_{ins}, (m), is given in form of (δins =0.01 to 0.15 step 0.01). By utilizing this form, the computer program will execute the calculation for δ_{ins} =0.01m to .015m with step 0.01m, simulating the process of increasing the thickness of insulation material 0.01m each cycle of calculation. The process of calculation will be repeated until the value of insulation thickness reaches the limited value of 0.15m. After that, the value of the convection heat transfer coefficient on the outer surface of insulation (ho) is identified according to the formula (8). Then the critical thermal conductivity of insulation material (**k_{inscr}**) is calculated by using the formula (15).

Determine which value of thermal conductivity of insulation material to use (**k_{ins}** or **k_{inscr}**) to obtain the economic insulation thickness ($\delta_{ins.ec}$), a conditional statement comprising the thermal conductivity has been put in flow chart. After that, the volume of insulation onto one meter length of pipe **(V_{ins})** is determined by using formula (4), the cost of the insulation of one meter length of the pipeline (**C'_{ins}**) according to formula (3) and the annual cost of insulation per meter run of pipe **(C_{INS})** from formula (2). By using formulas (6) and (5), and respectively, the heat loss through the insulation layer (q**)** and the annual cost of heat loss per meter run of pipe (**C_{ST}**) are calculated. Then, the true surface temperature of insulation (t_{ins}) is calculated by the formula (10). Finally The annual total cost **(ΣC)** in $/(m.year) that comprises the annual cost of insulation per meter run of pipe and the annual cost of heat loss per meter run of pipe are calculated according to formula (1). The obtained results are entered in tables at different values of thickness of the insulation layer, thermal conductivity of insulation material, diameter of the pipe, price of the insulation material, and the price of steam generation.

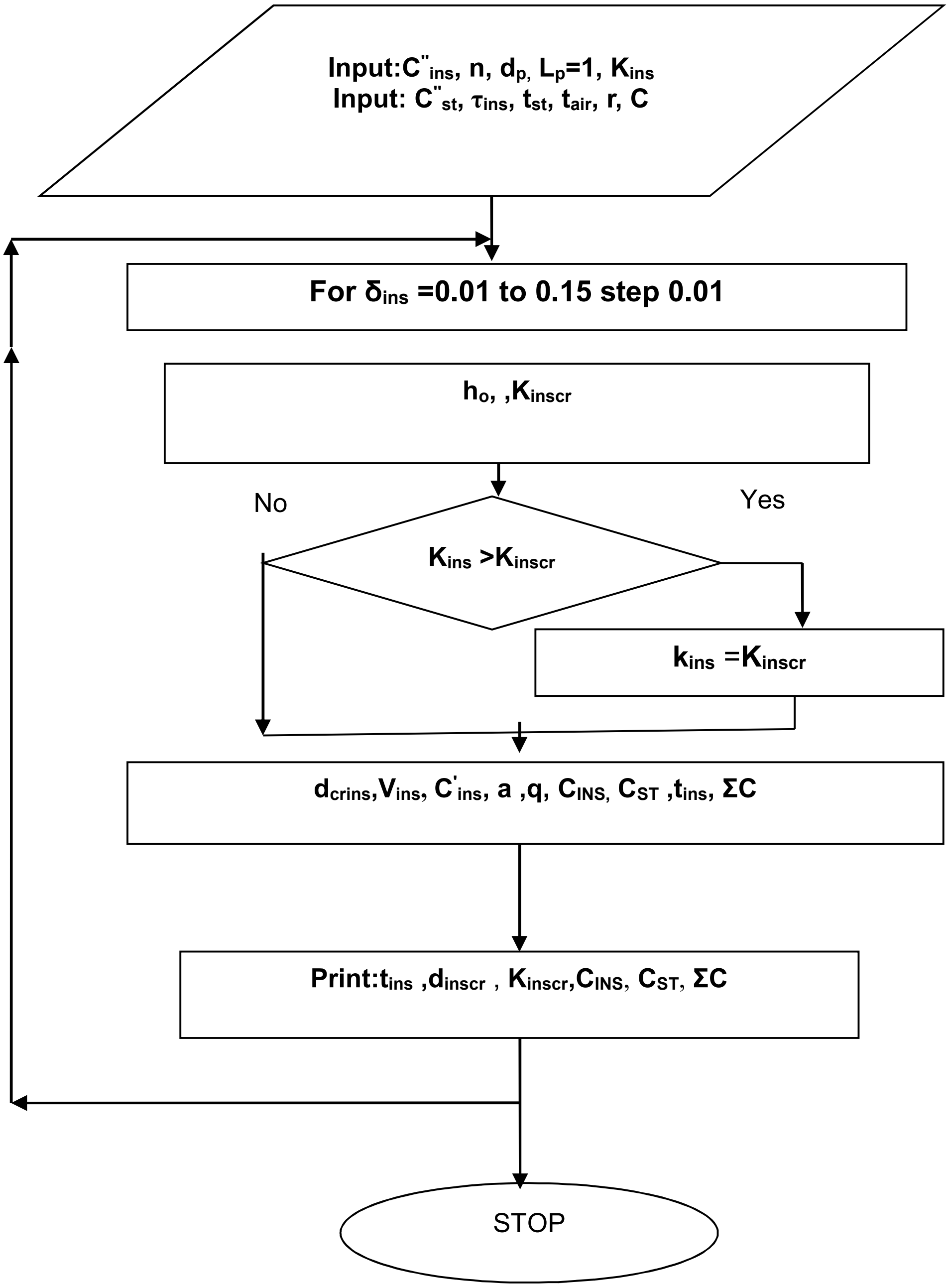

Figure 1. flow chart

4.Results and discussion:

Price of the insulation material C''_{ins}, ($/m^3) price of steam generation C''_{st}, ($/kg) pipes diameters d_p, (m) thermal conductivity of insulation material Kins, (W/(m.ºC)), steam temperature t_{st}, (ºC) and ambient temperature t_{air}, (ºC) are adopted as variable values to determine the extent of effect they produce on the economic (optimal) thickness of insulation layer, appropriate to the minimum total cost, and this is done by changing one of the variables each time and keeping the other values constant.

The computer program is utilized to obtain the present results:

The increase in the thickness of the insulation without restrictions ultimately leads to a reduction in heat loss from the steam pipes, even under conditions of (K_{ins}=0.31m)>(K_{inscr}=0.22), ($K_{inscr}=d_p.h_o/2$) Which is evident On figure (1). This chart shows that the loss of heat from the steam pipe increases with increasing thickness of the insulation. While continuing to increase the thickness of the insulating layer after reaching the maximum value which is higher than that of the heat loss from pipe without thermal insulation, the heat loss is gradually reduced to any desired value. The most important task is not to reduce heat loss per se but the transfer of steam to the consumer at the lowest cost represented by the minimum total cost, (insulation plus heat losses). The results of the calculation performed in this paper under the conditions of (K_{ins}=0.31m)>($K_{ins.cr}$=0.22), ($K_{ins.cr}=d_p.h_o/2$) which are illustrated

in Figure (2) that reflects the values present in table (2) show that the total cost with increasing the thickness of thermal insulation layer is never reduced less than the total cost level of bare pipe. In this case, the lack of pipe insulation is less expensive unless thermal insulation with a suitable thermal conductivity is used. The results of the study, that conducted later under the new conditions of (K_{ins}=0.11) < (K_{inscr}=0.22), ($K_{ins} \leq K_{ins.cr}$), ($K_{ins.cr} = d_p.h_o/2$) show that reduction occurs in each of the heat loss (figure 3) and total cost (Figure 4 that reflects the values present in table 3) immediately after placing a thermal insulation layer with a thickness not exceeding Millimeters. The total cost will continue to decline with the increasing thermal insulation layer thickness to reach the minimum and then begins to rise again. The thickness of the thermal insulation layer that meet the lowest total cost was adopted as economic insulation thickness, that will not be achieved unless ($K_{ins} \leq d_p.h_o/2$).
The results have given a new concept that is termed as "the critical thermal conductivity of insulation material ", ($K_{ins.cr} = d_p.h_o/2$) the exceeding of which makes the insulation of pipe a factor that contributes to increase of total cost (ΣC) but not the opposite. Table (4) shows the effect of change of pipe diameter on, the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation . Here, if the pipe diameter is decreased from 0.3m to 0.05m will in turn reduces the percentage reduction of the total cost [($\Sigma C_{at\ \delta ins=0}$- $\Sigma C_{at\ \delta ins=\delta ins.ec}$)/ $\Sigma C_{at\ \delta ins=0}$] from 73 % to 68.8% ,heat losses [($q_{at\ \delta ins=0}$- $q_{at\ \delta ins=\delta ins.ec}$)/ $q_{at\ \delta ins=0}$] from 83% to 76% , and the economic insulation thickness goes down from to 0.08m to 0.059m. It is also shown that the critical thermal conductivity of insulation decreases from 0.5 to 0.13 w/(m.k). In addition , the results in table (4) show that changing the pipe diameter from 0.3m to 0.05m reduces the surface temperature of economic insulation layer from 30.8 ^oC to 27 ^oC. Table (5) presents the changes that occur in the values of the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation with the change of thermal conductivity of insulation. Here, if the thermal conductivity of insulation is decreased from 0.10 to 0.02w/(m.k) will in turn increases the percentage reduction of the total cost from 50 % to 82% ,heat losses from 61% to 88% , and the economic insulation thickness goes down from to 0.088m to 0.053m. It is also shown that the value of the critical thermal conductivity of insulation has not changed. As well, this table show that the surface temperature of economic insulation layer is reduced from 33.9 ^oC to 25.7 ^oC. Table (6) presents the results of the study of the effect of the change in the price of the insulation on each of the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation. It is clear that reducing the price of insulation from 475 \$/m3 to 75 \$/m3 leads to increase the percentage reduction of the total cost from 63 % to 78%, heat losses from 74% to 84%, the economic insulation thickness goes up from to 0.042m to 0.097m and the surface temperature of economic insulation layer is reduced from 33.9 ^oC to 25.4 ^oC. The value of the critical thermal conductivity of insulation has not changed. Table (7) demonstrates the results of the effect of the steam generation price change on the total cost values, heat losses, economic insulation thickness, surface temperature of economic insulation layer and the critical thermal conductivity of insulation. It turns out that raising the price of steam generation from 0.005 \$/kg to 0.013 \$/kg leads to increase the percentage of the decline in the total cost from 72% to 79%, heat losses from 80% to 84% and the economic insulation thickness goes up from to 0.067m to 0.10m. In addition it seems that the surface temperature of economic insulation layer is reduced from 28.4 ^oC to 25 ^oC and the value of the critical thermal conductivity of insulation has not changed. Table (8) shows the effect of the change of ambient temperature on, the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation. This results indicate that increasing the temperature of air from 5 ^oC to 35 ^oC reduces the percentage reduction of the total cost from 77 % to 60% ,heat losses from 84% to 71% , and the economic insulation thickness goes down from to 0.072m to 0.059m. It is also shown that the critical thermal conductivity of insulation decreases from 0.255 to 0.154 w/(m.k) while the surface temperature of economic insulation layer rises from 13 ^oC to 46 ^oC.
Table (9) lists the change on each of the total cost, heat loss, economic insulation thickness ,critical thermal conductivity of insulation and the surface temperature of economic insulation layer in the case of rising the temperature of steam from 120 to 300 ^oC. It is indicated that the percentage reduction of the total cost goes up from 72% to 83%, heat loss from 80% to 87%, the economic insulation thickness from 0.067m to 0.145m and the surface temperature of economic insulation layer from 28.3 ^oC to 29.1 ^oC. In the meantime, the critical thermal conductivity of insulation remains constant.
Based on the results of all tables, the factors that lead to a rise in the proportion of the economy in the total costs [($\Sigma C_{at\ \delta ins=0}$- $\Sigma C_{at\ \delta ins=\delta ins.ec}$)/ $\Sigma C_{at\ \delta ins=0}$] were collected as follows:
Pipes with great diameters (d_p, m) , low thermal conductivity of insulation material (k_{ins}, w/(m.k)), low price of insulation (C''_{ins}, \$/m^3), high price of steam generation (C''_{st}, \$/kg), low ambient temperature (tair, ^oC) and high temperature of steam (t_{st}, ^oC). By reference to the data in the tables and in accordance with the above it was found that at [d_p=0.3m, k_{ins}=0.02w/(m.k), C''_{ins}=75 \$/m3, C''_{st}=0.013\$/kg, t_{air}=5 ^oC and t_{st}=300 ^oC] the percentage decline in the total cost at the economic insulation thickness reached 85% where the total cost decreased from 69.71 \$/(year.m) without insulation to 10.75 \$/(year.m) at $\delta_{ins.ec}$ which means saving up to (472 000 \$) when length of pipes is 1000 m and 8 years of investment life of insulation.

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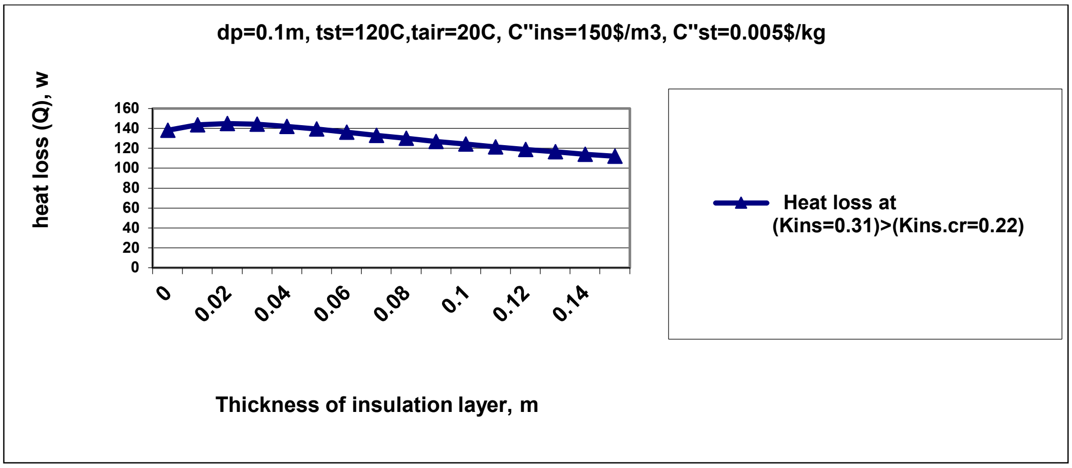

Figure 1. The relationship between the thickness of the insulation layer and heat loss at (K_{ins}=0.31)>(K_{inscr}=0.22) .

Table 2: The influence of the thickness of the insulating layer on the total cost at conditions of (K_{ins}=0.31)>(K_{inscr}=0.22).

K_{ins}=0.31 w/(m.k), d_p =0.1m , t_{st} =120 °C, t_{air}=20 °C, C''_{ins} = 150 \$/m^3, C''_{st}=0.005\$/kg										
Thickness of insulation layer, m										
	0	**0.01**	**0.02**	**0.03**	**0.05**	**0.07**	**0.10**	**0.12**	**.15**	**(K_{ins}=0.31)>(K_{inscr}=0.22)**
C_{INS}	**0.0**	**.007**	**.164**	**.267**	**.515**	**.817**	**1.37**	**1.81**	**2.57**	
C_{ST}	**9.69**	**10.06**	**10.16**	**10.11**	**9.77**	**9.33**	**8.70**	**8.33**	**7.85**	
ΣC	**9.69**	**10.14**	**10.33**	**10.37**	**10.28**	**10.15**	**10.08**	**10.14**	**10.43**	

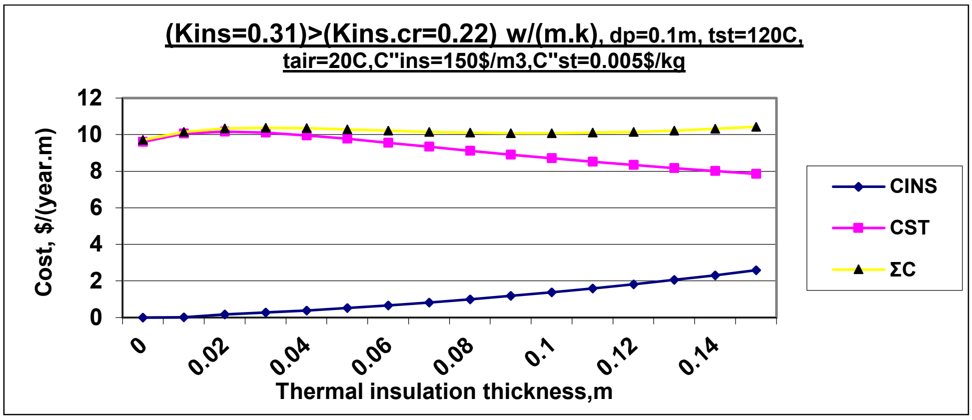

Fig.2. The relationship between the thickness of the insulation layer and the cost of steam generation, the cost of thermal insulation and total cost at (K_{ins}=0.31)>($K_{ins.cr}$=0.22).

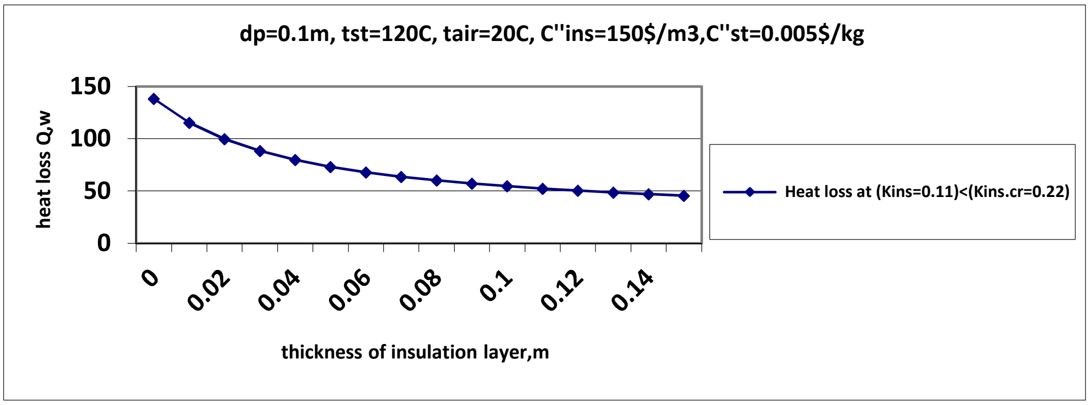

Fig.3. The relationship between the thickness of the insulation layer and heat loss at (K_{ins}=0.11)<(K_{inscr}=0.22).

Table.3.The influence of the thickness of the insulating layer on the total cost at conditions of (K_{ins}=0.11) < (K_{inscr}=0.22).

K_{ins}=0.11 w/(m.k), d_p =0.1m, t_{st} =120 °C, t_{air}=20 °C, C''_{ins} =150 \$/m³,C''_{st}=0.005\$/kg										
Thickness of insulation layer, m										
	0	.02	.05	.07	.09	.11	.13	.14	.15	**(K_{ins}=0.11)<(K_{inscr}=0.22)**
C_{INS}	0.0	.164	.513	.817	1.17	1.58	2.05	2.3	2.57	
C_{ST}	9.69	6.98	5.13	4.47	4.07	3.67	3.41	3.3	3.20	
ΣC	9.69	7.15	5.65	5.29	5.18	5.26	5.46	5.6	5.78	

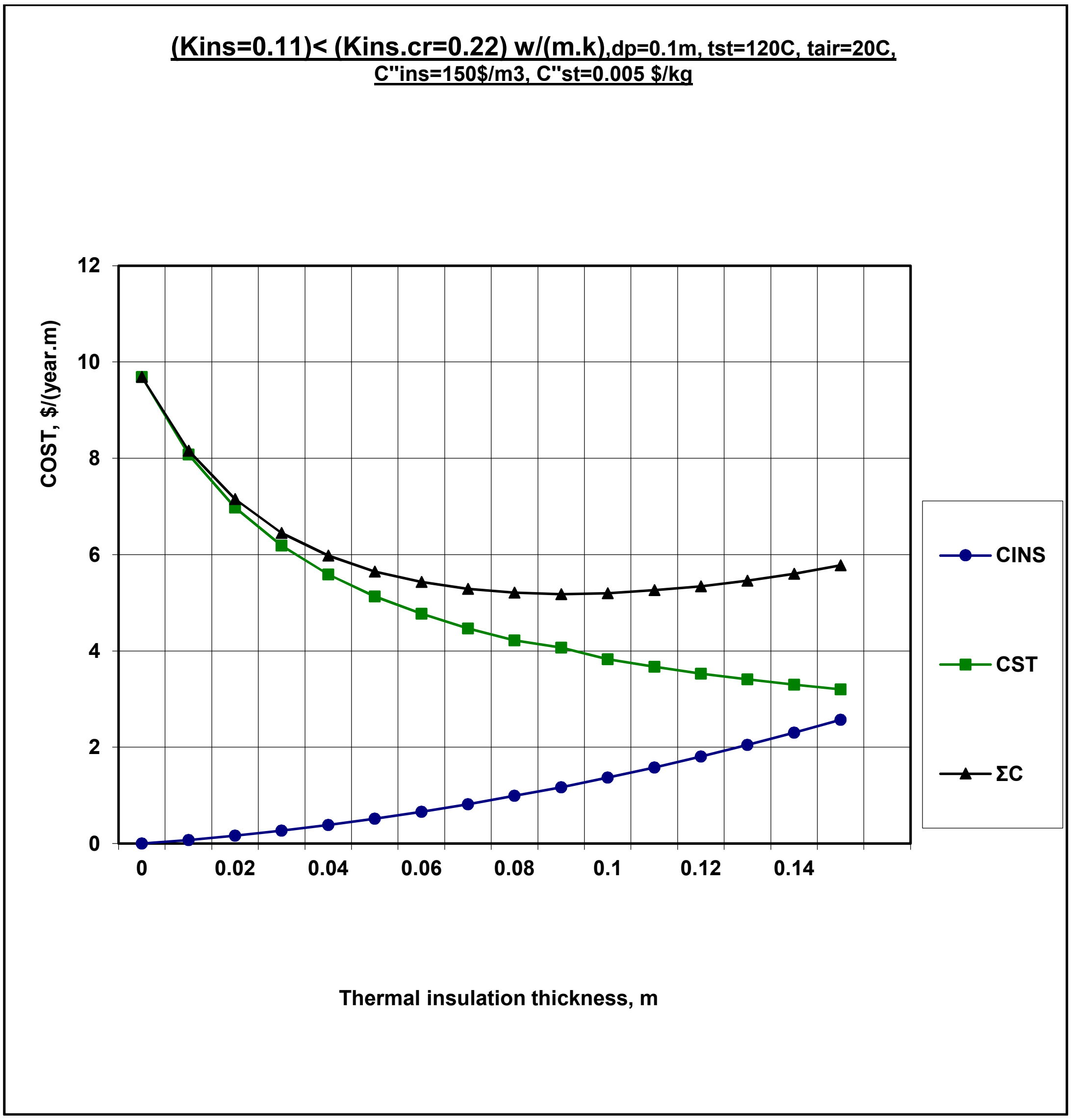

Fig.4: The relationship between the thickness of the insulation layer and the cost of steam generation, the cost of thermal insulation and total cost at (K_{ins}=0.11) < ($K_{ins.cr}$=0.22).

Table 4: The effect of change of pipe diameter on, the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation

t_{st} =120 ºC, C''_{st}=0.005$/kg , C''_{ins} =150 $/m³,$K_{ins}$=0.04w/(m.k) , t_{air}=20 ºC ,L_P=1m					
		t_{sf} ,ºC	Q ,w	ΣC ,$/(year.m)	K_{inscr} , w/(m.k)
d_p=0.05m	δ_{ins}=0	120	82.14	5.76	0.13
	δ_{ins}.ec=0.0589m	27.12	19.44	1.793	
d_p=0.1m	δ_{ins}=0	120	138.15	9.69	0.2199
	δ_{ins}.ec=0.0667m	28.37	27.07	2.667	
d_p=0.15m	δ_{ins}=0	120	187.25	13.13	0.29
	δ_{ins}.ec=0.0719m	29.23	33.88	3.47	
d_p=0.2m	δ_{ins}=0	120	232.35	16.297	0.369
	δ_{ins}.ec=0.0759m	29.801	40.08	4.252	
d_p=0.25m	δ_{ins}=0	120	274.68	19.266	0.437
	δ_{ins}.ec=0.0779m	30.40	46.414	5.012	
d_p=0.3m	δ_{ins}=0	120	314.929	22.08	0.5014
	δ_{ins}.ec=0.0799m	30.849	52.39	5.762	

Table 5: The changes that occur in the values of the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation with the change of thermal conductivity of insulation.

t_{st} =120 °C, C''_{st}=0.005$/kg , C''_{ins} =150 $/m³, d_p=0.1m, t_{air}=20 °C ,L_P=1m					
		t_{sf} ,°C	Q ,w	ΣC ,$/(year.m)	K_{inscr} , w/(m.k)
K_{ins}=0.10	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.088m	33.958	53.2237	4.869	
K_{ins}=0.08	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.0829m	32.26	45.0569	4.2036	
K_{ins}=0.06	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.07599m	30.4822	36.4944	3.4785	
K_{ins} =0.04	δ_{ins}=0	120	138.15	9.69	0.2199
	δ_{ins}.ec=0.0667m	28.37	27.07	2.667	
K_{ins} =0.02	δ_{ins}=0	120	138.15	9.69	0.2199
	δ_{ins}.ec=0.0529m	25.755	16.378	1.7058	

Table 6: The effect of the change in the price of the insulation on each of the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation

t_{st} =120 °C, C''_{st}=0.005$/kg , K_{ins}=0.04 w/(m.k), d_p=0.1m, t_{air}=20 °C ,L_P=1m					
		t_{sf} ,°C	Q ,w	ΣC ,$/(year.m)	K_{inscr} , w/(m.k)
C''_{ins}=475$/m³	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.0419m	33.945	35.4511	3.598	
C''_{ins}=375$/m³	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.04699m	32.390	33.2094	3.3462	
C''_{ins}=275$/m³	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.05599m	30.24	30.005	3.0475	
C''_{ins}=175$/m³	δ_{ins}=0	120	138.15	9.69	0.2199
	δ_{ins}.ec=0.0669m	28.37	27.073	2.6674	
C''_{ins}=75$/m³	δ_{ins}=0	120	138.15	9.69	0.2199
	δ_{ins}.ec=0.097m	25.423	22.030	2.1077	

Table 7: The effect of the steam generation price change on the total cost values, heat losses, economic insulation thickness, surface temperature of economic insulation layer and the critical thermal conductivity of insulation.

t_{st} =120 °C, K_{ins}=0.04 w/(m.k), C''_{ins} =175 $/m³, d_p=0.1m, t_{air}=20 °C ,L_P=1m					
		t_{sf} ,°C	Q ,w	ΣC ,$/(year.m)	K_{inscr} , w/(m.k)
C''_{st}=0.005$/kg	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.0669m	28.374	27.073	2.6674	
C''_{st}=0.007$/kg	δ_{ins}=0	120	138.15	13.566	0.2199
	δ_{ins}.ec=0.0779m	27.024	24.845	3.393	
C''_{st}=0.009$/kg	δ_{ins}=0	120	138.15	17.442	0.2199
	δ_{ins}.ec=0.089m	26.176	23.382	4.069	
C''_{st}=0.011$/kg	δ_{ins}=0	120	138.15	21.318	0.2199
	δ_{ins}.ec=0.095m	25.561	22.2812	4.710	
C''_{st}=0.013$/kg	δ_{ins}=0	120	138.15	25.195	0.2199
	δ_{ins}.ec=0.102m	25.104	21.439	5.325	

Table 8: the effect of the change of ambient temperature on, the total cost, heat losses, economic insulation thickness and critical thermal conductivity of insulation.

t_{st} =120 ºC, K_{ins}=0.04 w/(m.k), C''_{ins} =175 \$/m³, d_p=0.1m, C''_{st}=0.005\$/kg ,L_P=1m					
		t_{sf} ,ºC	Q ,w	ΣC ,\$/(year.m)	K_{inscr} , w/(m.k)
t_{air}=5 ºC	δ_{ins}=0	120	184.30	12.926	0.255
	δ_{ins}.ec=0.0719m	12.72	30.21	2.969	
t_{air}=10 ºC	δ_{ins}=0	120	169.623	11.897	0.245
	δ_{ins}.ec=0.0709m	17.78	29.053	2.871	
t_{air}=15 ºC	δ_{ins}=0	120	154.698	10.850	0.234
	δ_{ins}.ec=0.0689m	23.01	28.097	2.771	
t_{air}=20 ºC	δ_{ins}=0	120	138.15	9.690	0.219
	δ_{ins}.ec=0.0669m	28.37	27.073	2.667	
t_{air}=25 ºC	δ_{ins}=0	120	122.141	8.567	0.204
	δ_{ins}.ec=0.0649m	33.79	25.999	2.560	
t_{air}=30 ºC	δ_{ins}=0	120	104.55	7.333	0.184
	δ_{ins}.ec=0.0629m	39.45	24.815	2.445	
t_{air}=35 ºC	δ_{ins}=0	120	82.328	5.774	0.154
	δ_{ins}.ec=0.0589m	46.25	23.76	2.311	

Table 9: the change on each of the total cost, heat loss, economic insulation thickness ,critical thermal conductivity of insulation and the surface temperature of economic insulation layer in the case of rising the temperature of steam from 120 ºC to 300 ºC..

K_{ins}=0.04 w/(m.k), C''_{ins} =175 \$/m³, d_p=0.1m, t_{air}=20 ºC ,L_P=1m					
		t_{sf} ,ºC	Q ,w	ΣC ,\$/(year.m)	K_{inscr} , w/(m.k)
t_{st} =120ºC r=2207.10³J/kg C''_{st}=0.005\$/kg	δ_{ins}=0	120	138.15	9.690	0.2199
	δ_{ins}.ec=0.0669m	28.374	27.073	2.667	
t_{st} =200ºC r=1939.10³J/kg C''_{st}=0.006\$/kg	δ_{ins}=0	200	248.68	23.824	0.2199
	δ_{ins}.ec=0.099m	29.525	39.218	5.1103	
t_{st} =300ºC r=1403.10³J/kg C''_{st}=0.007\$/kg	δ_{ins}=0	300	386.834	59.754	0.2199
	δ_{ins}.ec=0.145m	29.194	49.79	10.158	