Reducing the Cost of Pumping High Viscosity Fluids for Jordanian Industry

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Abstract:
All industrial facilities have a network of piping that carries liquids. The frictional power required is dependent on rate of flow, pipe size (Diameter), overall length of pipe, pipe characteristics (surface roughness, material, etc.) and properties of the liquid being pumped. Heating high viscosity liquids leads to drop in their viscosity. As a result,   pressure loss resulting from friction deceases, and these pressure losses result in low cost of pumping. But nevertheless, the heating operation demands additional cost that increases progressively with the increase of heating temperature degree. This paper aims to find out the effect of heating temperature degree on cost of pumping and heating, and eventually on the total cost (heating plus pumping). In addition, the paper aims to confirm whether there is an optimal heating degree t_{opt} appropriate to the minimum total cost ΣC_{min}, and to see what the values and facts affecting the value of the minimum cost are. For this purpose, a commuter program has been prepared based on the flow chart of the operation procedure overviewed in this paper**.** Calculations carried out by the computer show the effect of price change of electrical energy \$/(kW.h) on the optimal heating temperature degree**,** and the effect of the price of steam generation demanded   for the heating operation, \$/kg on the optimal heating temperature degree as well , in addition to the effect   of flow rate change of the liquid which will be pumped, kg/s**.** The results also show that the heating optimal degree occurs at the transitional moment from laminar to turbulent flow. When checking the effect of diameters of the used pipe on the optimal heating degree, the results have given a new concept that is termed as "the critical diameter", the exceeding of which makes the heating operation a factor that contributes to increase of total cost, ΣC but not the opposite. The optimal heating degree appropriate to the minimum total cost (heating plus pumping) only occurs when diameters of the pipes used are less than that of the critical diameter. The study carried out on sugar syrup shows that the critical diameter of pipes is $d_{cr}=0.046$ m, the exceeding of which will not cause decrease in the expected total cost of   the heating operation , and the   optimal heating degree can not be achieved. When the diameter of the pipes used is less than that of the critical diameter by 15mm, the total cost drops 1.5 \$/hour with the heating temperature degree increases from 20-29°C when the   liquid flow rate is   6 kg/sec , the electrical energy price is 0.081 \$/kW/h , and the demanded steam price is 0.0055 \$/kg. The effect of the liquid flow, electrical energy price, and diameters of the pipes used on the optimal heating degree and the critical diameter are overviewed in this paper.

Introduction

Industries worldwide depend upon pumping systems for their daily operation. These systems account for nearly 20% of the world's industrial electrical energy demand and range from 25-50% of the energy usage in certain industrial plant operations. Purchase decisions for a pump and its related system components are typically based upon a low bid, rather than the cost to operate the system over its lifetime. This initial cost is a small part of the total cost. Additionally, plant facilities personnel are typically focussed on maintaining existing pumping system reliability rather than optimizing the systems for best energy efficiency.

According to the U.S. Department of Energy study, 16% of a typical facility's electricity costs are for its pumping systems. [1].

Pumping systems in the United States manufacturing industries consume over 142 TWh per year. In the US petroleum industry, for example, 50% of the annual electricity use is for the operation of pumping systems [2].

The power consumed to overcome the static head in a pumping system varies linearly with flow and very little can be done to reduce the static component of the system requirement. On the other hand, several energy and money-saving opportunities exist to reduce the power required to overcome the friction component of the pumping system. The frictional power required is dependent on rate of flow, pipe size (diameter), overall length of the pipe, pipe characteristics (surface roughness, material, etc.) and properties of the liquid being pumped [3].

Pumping High Temperature Liquids, High temperature applications can be found in nearly every industry, There are a number of reasons why a liquid needs to be handled at a high temperature: [4].

Room Temperature Solids	Liquids which are solid or semi-solid at ambient temperature which are heated to permit them to be moved more easily or to be applied, spread, processed, or otherwise utilized.	• Asphalts • Molasses • Roofing Tar • Sulfur • Lead
Heat due to Process	Liquids which are a process by-product or are being used in a product that uses heat as a catalyst to initiate, sustain, accelerate, or complete a reaction.	• Soybean Processing • Refineries (Cracking, Distilling) • Asphalt Blending and Mixing • Polymer Production (Styrene)
Liquids used to Transfer Heat	Liquids used to transfer heat to equipment such as: • Plastic Molders •Snow Removal Equipment • Food & Candy Making Equipment • Chemical Pumps and Equipment	•Dowtherm® (Dow Chemical) •Theminol® (Monsanto) •Mobiltherm® (Exxon Mobil)

At the date of purchase, the quoted price for a pump may seem like the most important matter at hand. In actuallity, the initial purchase price is only a fraction of the pump's total life-cycle-cost (LCC). The chart below represents a pump's total life-cycle-cost over a period of 7 years.
Obviously these percentages vary from pump to pump and application to application, but energy costs typically remain the highest single source of cost over a pump's life [4].
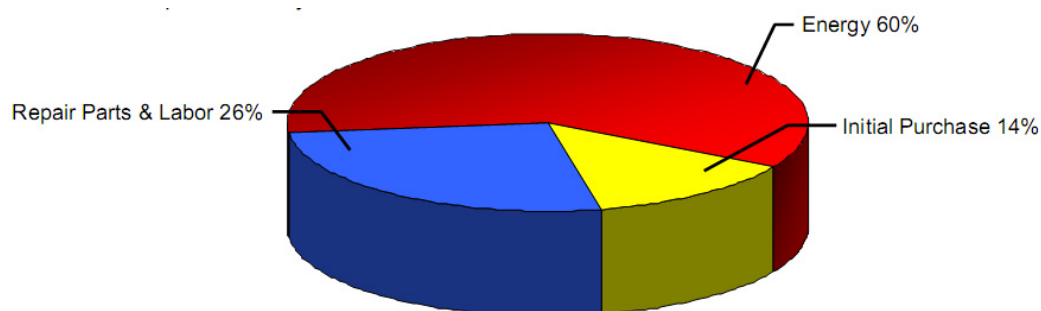
Reducing Energy Costs

Lengthy papers have been written specific to savings from maintenance and parts. And while each should be included in LCC calculations, energy costs remain the largest contributor and yet are often overlooked. Energy savings can be obtained many different ways. Specific to pumps, the three most common means are to alter the system to decrease the input power requirement, to implement controls to maximize pump efficiency, or to replace inefficient pumps with more efficient models for the application [4].

This paper focuses on producing change on liquids characteristics before to pumping operation, and particularly reducing their viscosity through heating. This is because high viscosity food stuff, such as concentrated milk, fats, sugar solutions ….etc are difficult to be pumped in pipes without heating. Viscosity drop resulting from the heating operation decrease losses resulting from friction, the result of which the energy demanded for the pumping operation drops. However, the heating operation also demands additional cost relating to generating the steam necessary for the heating.

The frictional power required is dependent on rate of flow, pipe size (Diameter), overall length of pipe, pipe characteristics (surface roughness, material, etc.) and properties (Viscosity) of the liquid being pumped. Heating operation before to the pumping phase might not be profitable regarding the decreasing pumping total cost at certain conditions relating to pipes diameters and liquid flow rate. Moreover, the existence of an old facility lacking liquid heating system and having specific type of pipes of certain diameters, and technically demanded flow rate is difficult to change. So, it is wrong to recommend that a heating system be added to reduce the total cost, without considering pipes type and pipes diameter, and liquid flow rate.

Accordingly, this paper seeks to study the appropriate design conditions to reduce the total cost (heating plus pumping) in the design phase of facilities intended to be built, and specify whether it is feasible to add a heating system before to pumping operation in the old operating facility, and to get the heating temperature degree that guarantees the minimum cost, if available, by taking into account the effect of liquid

flow rate , diameters and type of pipes used in this facility. As has been mentioned earlier in this paper, if the pipe diameter in the old facility is more than the critical diameter, the optimal temperature degree will not be obtained.

Theory and method of calculation:
To reach the liquid optimal heating degree to reduce their viscosity that will decrease the total cost (heating and pumping) , the heating and pumping cost and the total cost at a heating temperature degree that increases progressively are calculated . The obtained results will be put in tables and then converted into line graphs illustrating heating temperature degree and cost. The minimum total cost will be specified on these line graphs, and the heating temperature degree appropriate to the minimum total cost is considered as the optimal heating temperature degree. Usually, when calculating the total pumping cost , the cost of equipment, buildings, labor , a well as the heating energy cost demanded for the heating, and the electrical energy cost demanded to operate the pumps, which is the largest proportion of the cost, should be taken into account. The total economical cost show that the cost of thermal energy required for the heating operation, and the electrical energy required for operation of pumps are the largest proportion of the total cost. Accordingly, calculations can be simplified by ignoring the cost of equipment, apparatuses, buildings, labor and considering them as items that do not significantly affect calculations results.

It should be noted that most food stuff characteristics might change when heated from 80-90°C. For this reason , when obtaining an optimal heating degree higher than the technically allowed heating degree, the optimal heating temperature degree that will be approved is the technically allowed one.
To calculate the optimal heating temperature degree, the following specific certain data should be provided:
the mass flow rate of the liquid to be pumped m_{Lq}, kg/s,the internal diameter of pipes d_p, m, length of pipes L_p, m, information about the surface roughness of the internal surface of pipe, resistance resulting from friction in pipes, type and number of joints and valves, specific heat of the liquid to be pumped C_{Lq}, J/(kg.k), price of the heating agent (steam) C'_{vep}, \$/kg, electrical energy price C'_{ele}, \$/(kw.hour).

Based on the values of the dynamic viscosity table, and liquid density at different heating temperature degrees , the dynamic viscosity and liquid density will be specified as in the following equations:

$$\mu_{Lq} = f\left(t_{Lq}\right)$$
$$\rho_{Lq} = f\left(t_{Lq}\right)$$

The total cost (\$/hour) that includes the required electrical energy for pumps operation, and the cost of generating steam required for the heating operation are calculated by the following formulas:

$$\sum C = C_{ELE} + C_V \tag{1}$$

Where C_{ELE} is the cost of electrical energy demanded to operate pumps \$/hour.

$$C_{ELE} = C'_{ele} N \tag{2}$$

Where C'_{ele} is the price of electrical energy, \$/(kW.h),
N is the pump power kW

$$N = \frac{m_{Lq}\Delta p}{1000\eta\rho_{Lq}} \tag{3}$$

Where η is the pump efficiency coefficient
Δp is pressure losses in pipes which is obtained from the following formula

$$\Delta p = \frac{\rho_{Lq}w_{Lq}^2}{2}\left[1 + \frac{\lambda L_P}{d_p} + \sum \xi\right] \tag{4}$$

Σξ is loss coefficients can be obtained from the tables according to type of fittings installed on pipe network. (elbows, T-joints and valves)
w_{Lq}- Speed of liquid in pipes (m/s) is calculated by using the following formula:

$$W_{Lq} = \frac{4}{\pi}\frac{m_{Lq}}{d_p^2\rho_{Lq}} = 1.273\frac{m_{Lq}}{d_p^2\rho_{Lq}} \tag{5}$$

the Friction Factor λ, based on the pipe roughness, pipe diameter, and the Reynolds number, can be obtained from engineering handbooks, [5,6,7]. For most applications, the value of this friction factor will be between 0.015 and 0.0225.
for smooth pipes under laminar flow conditions, Re<2300

$$\lambda = \frac{64}{\mathrm{Re}} \tag{6}$$

Under turbulent flow conditions, Re≥2300

$$\lambda = \frac{0.316}{\mathrm{Re}^{0.25}} \tag{7}$$

Re is Reynolds number

$$\mathrm{Re} = \frac{w_{Lq} d_P \rho_{Lq}}{\mu_{Lq}} \tag{8}$$

The cost of steam generation required for heating liquid of high- viscosity ($/hour) is calculated by the following formula:

$$C_V = C'_{vep} p_V 3600 \tag{9}$$

Where

C'_{vep} is the price of the heating agent (steam), $/kg

P_V is the mass flow rate of steam required for heating of liquid, **kg/s**

$$P_V = \frac{Q}{r} \tag{10}$$

r- Latent heat of vaporization of water= 2165.8 kJ/kg

Q is the amount of heat required for heating liquid of high- viscosity from 20°C to the required temperature degree, W

$$Q = m_{Lq} C_{Lq} (t_{Lq} - 20) \tag{11}$$

t_{lq} , the required heating temperature for viscose liquid

Optimizing procedure:

In formulas (2) and (9), it is clear that any change in electrical energy price or the price of steam generation required for the heating operation or both of them, significantly affect the value of the total cost of pumping and heating as shown in formula one. In light of the change that might occur in the value of formula (1), the heating optimal temperature degree will change indirectly or it might not achieve at all. Jordan is one of the countries that import electrical energy or it produces the energy from imported gas. Over the past ten years, big change in electrical energy price occurred as well as in the price of steam generation , and it is expected that change will continue in the coming years. Also, any change in liquid flow rate or pipes diameters, pipes length and type will change the total cost of pumping and heating significantly, and will inevitably change the heating optimal temperature degree. To estimate the cost of pumping, in a fast and better way in industrial facilities and to specify the value of the heating optimal temperature degree in light of changes of electrical energy and that of steam generation   required for the heating operation , a computer program was prepared assimilating the formulas that   do the calculations of the pumping cost, heating cost, and the total cost (heating plus pumping) , in addition to the optimal heating temperature if it occurs.

The flow chart operation procedure as shown in figure (1) comprises the following steps:

After entering the data of pipes diameters d_p , pipe length L_p,the require liquid flow m_{Lq} in addition to the price of electrical energy unit C'_{ele}, price of steam unit required for heating C'_{vep}, fixed values of specific heat of the liquid to be pumped C_{Lq} , pump efficiency η, the latent heat for water evaporation r=2165.8 kJ/kg. Dynamic viscosity μ_{Lq} and intensity ρ_{Lq} of liquid to be pumped are calculated by using the two formulas obtained from the table values of the liquid under study. Here, viscosity values and liquid intensity at the require heating temperature can be entered as data without using a formula. This requires more time and effort that can be reduced by obtaining formulas that connect liquid viscosity and its intensity with the liquid heating temperature degree. After that, the value of the liquid speed in pipes is identified according to formula (5), then Reynolds number is calculated by using formula (8), and according to its value the friction factor (λ) is calculated from formulas (6) and (7). To determine which formula to use , a conditional statement comprising Reynolds number has been put in flow chart. After reaching the friction factor from formulas (6) or (7) , pressure looses value in pipes ΔP are determined by using formula (4) , pump power (N) according to formula (3), and the required electrical energy for operating the pump C_{ELE} from formula (2). By using formulas (9),(10), and (11) respectively, the quantity of heat   required for heating the liquid , steam mass flow rate for heating of liquid (P_V) and the generation cost of the steam required for heating the liquid (C_V) . Finally the total cost in $/hour that comprises electrical energy cost required to operate the pumps, steam production cost for the heating operation are calculated by using formula (1). The obtained results are entered in tables at different heating temperature

degrees t_{Lq}.
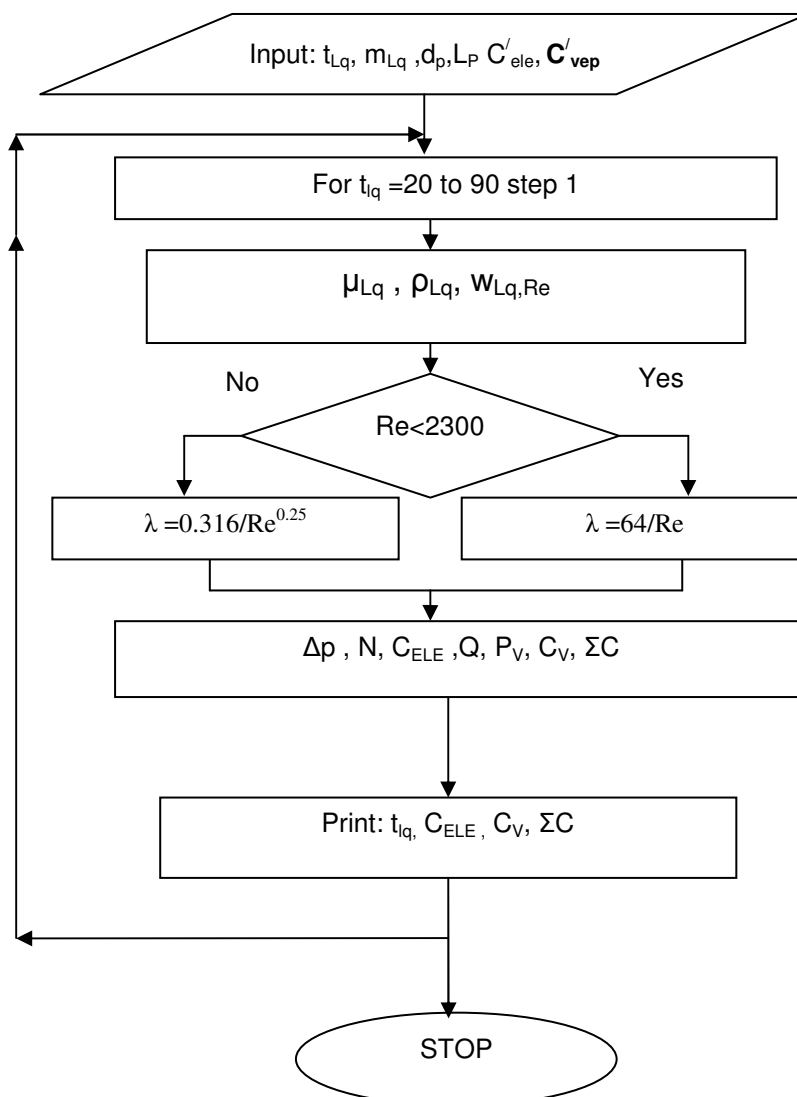

Figure1: flow chart

Results and discussion
The study was conducted on sugar syrup of 65% concentration and specific heat $C_{Lq}=2514$ J/(kg.^{o}k) that flows in smooth pipes of
L_P=200m on which four gate valves and five 90° elbows are installed and the pump efficiency η=0.6 has been adopted.
ξ -loss coefficients for fully open gate valves is 4 and for 90° Elbow is 1, thus Σξ=20
The table values of dynamic viscosity , density are expressed by formulas comprising these values together with the sugar syrup heating temprature:

$$\mu_{Lq} = 278.34 t_{Lq}^{-2.3234} \qquad (12)$$

$$\rho_{Lq} = 0.5679 t_{Lq} + 1327.4 \qquad (13)$$

Electrical energy price $C^{/}_{ele}$, ($/(kW.h)) heating agent price (steam) $C^{/}_{vep}$, ($/kg) pipes diameters d_p, (m) mass flow rate of liquid intended to be pumped m_{Lq}, kg/s are adopted as variable values to determine the extent of effect they produce on the optimal heating temperature degree, 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:

Figures (1and 2) that reflect the values present in table 1 show the change that occurs in the value of the optimal heating temperature degree with the change of electrical energy unit price C'_{ele}, \$/(kW.h). With the decrease of electrical energy price from 0.081 to 0.047 , the total minimum cost of heating and pumping goes down from 4.437 \$/hour to 3.041\$/hour and an optimal heating temperature of the liquid goes down from 29 to 28 °C. In addition , the results in table 1 and diagrams 1 and 2 show that heating the liquid from 20 to t_{opt}=29 °C   before to pumping operation reduces the cost by 30% at the electrical energy unit price 0.081 \$/(kW.h), and by 23% when heating the liquid from 20 to p_{opt}=28 °C at electrical energy unit price 0.047 \$/(kW.h).

Table 2 shows the effect of change of liquid mass flow rate on the optimal heating temperature degree. Here, if the mass flow rate of the liquid to be pumped is decreased from 10kg/s to 4kg/s will in turn   reduces the minimum total cost from 15.35 \$/hour to 2.15 \$/hour, and the optimal heating temperature goes up from to 23 to 30 °C. It is also shown that at flow rate of 6kg/s, the highest level of pumping cost reduction is achieved reaching 36%.

Diagrams 3 and 4 show that the critical diameter of pipes the exceeding of which makes the heating operation before to pumping unbeneficial for   the reduction of pumping cost,   and the cost would   rather increase. This diameter is termed the critical diameter.   Diagram 3 shows the change that occurs in pipe critical diameter with change in electrical energy unit price $\mathbf{C'ele}$, and diagram 4 shows the effect of change of liquid mass flow rate on the critical diameter value . The rise of the electrical energy unit price and the rise of liquid flow rate increase the critical diameter value.

Table 1 : the electrical energy unit price effect on the optimal heating temperature degree corresponding to the total minimum cost.

C'_{ele}=0.081 \$/(kW.h), M_{lq}=6 kg/s, C'_{vep}=0.0055\$/kg, d_p=0.031m									
Heating temperature ,C°									
	20	21	23	25	27	$\mathbf{T_{opt}}$=29	31	33	35
C_v	0	0.13	0.41	0.68	0.96	1.241	1.51	1.79	2.06
C_{ele}	6.86	6.16	5.06	4.23	3.60	3.106	4.59	4.44	4.31
ΣC	6.86	6.30	5.47	4.92	4.56	ΣC= **4.347**	6.10	6.24	6.38
C'_{ele}=0.047 \$/(kW.h), M_{lq}=6 kg/s, C'_{vep}=0.0055\$/kg, d_p=0.031m									
Heating temperature ,C°									
	20	22	24	26	$\mathbf{T_{opt}}$=28	30	32	34	35
C_v	0	0.27	0.55	0.82	1.103	1.37	1.65	1.93	2.06
C_{ele}	3.98	3.23	2.68	2.26	1.937	2.71	2.62	2.54	2.50
ΣC	3.98	3.50	3.23	3.08	ΣC= **3.041**	4.08	4.27	4.47	4.57

Table2: the effect of liquid mass flow rate on the value of optimal heating temperature degree.

| t_{Lq}	M_{Lq}=4kg/s	M_{Lq}=6kg/s	M_{Lq}= 8kg/s	M_{Lq}= 10kg/s
$C^{/}$ele=0.081$/(kW.h), $C^{/}_{vep}$=0.0055$/kg,$d_p$=0.031m				
ΣC, $/hour				
20	3.001	6.862	12.392	19.66
21	2.784	6.305	11.34	17.96
22	2.612	5.849	10.46	16.56
t_{opt}=23	2.477	5.476	9.74	$\Sigma C_{min=}$ **15.35**
24	2.373	5.172	9.14	22.46
25	2.293	4.925	8.64	22.24
t_{opt}=26	2.236	4.726	$\Sigma C_{min=}$ **8.22**	22.05
27	2.196	4.567	12.22	21.88
28	2.171	4.442	12.20	21.74
t_{opt}=29	2.159	$\Sigma C_{min=}$ **4.347**	12.193	21.61
t_{opt}=30	$\Sigma C_{min=}$ **2.158**	6.049	12.195	21.51
31	2.168	6.109	12.207	21.42
32	2.185	6.173	12.22	21.35
33	2.210	6.241	12.25	21.29
34	2.241	6.312	12.29	21.25
35	2.278	6.386	12.33	21.22
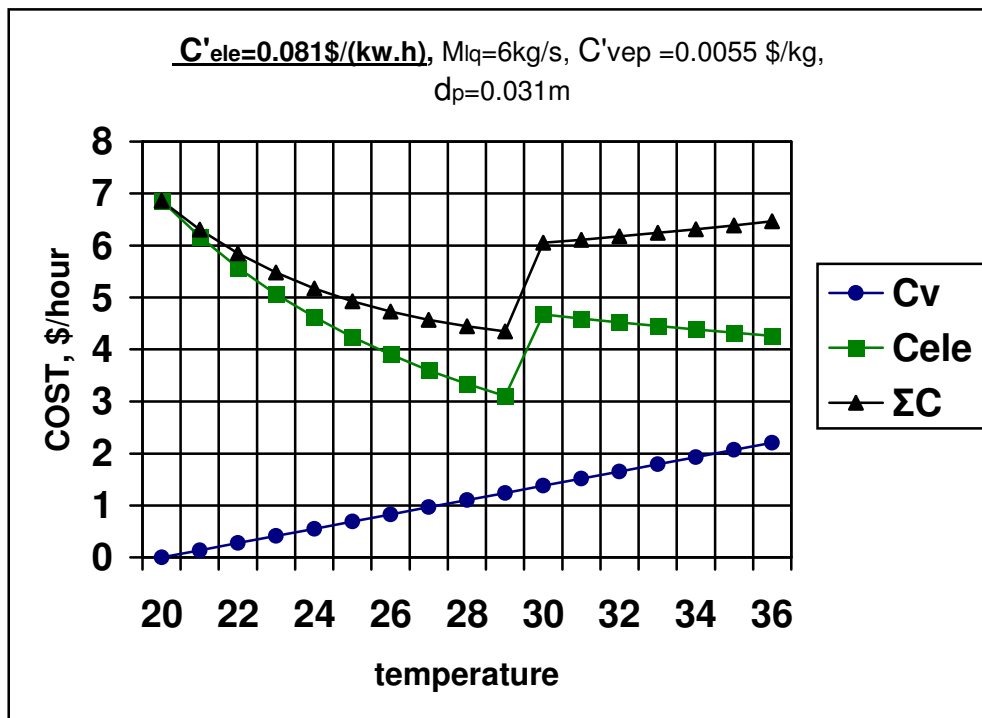
Diagram 1: the relationship between heating temperature degree t_{Lq} of liquid, and the cost of both the steam required for heating the liquid C_v, the electrical energy for pump operation C_{ele}. and the total cost of (heating plus pumping) ΣC at the price of electrical energy unit $C^{/}_{ele}$=0.081 $/(kW.h).
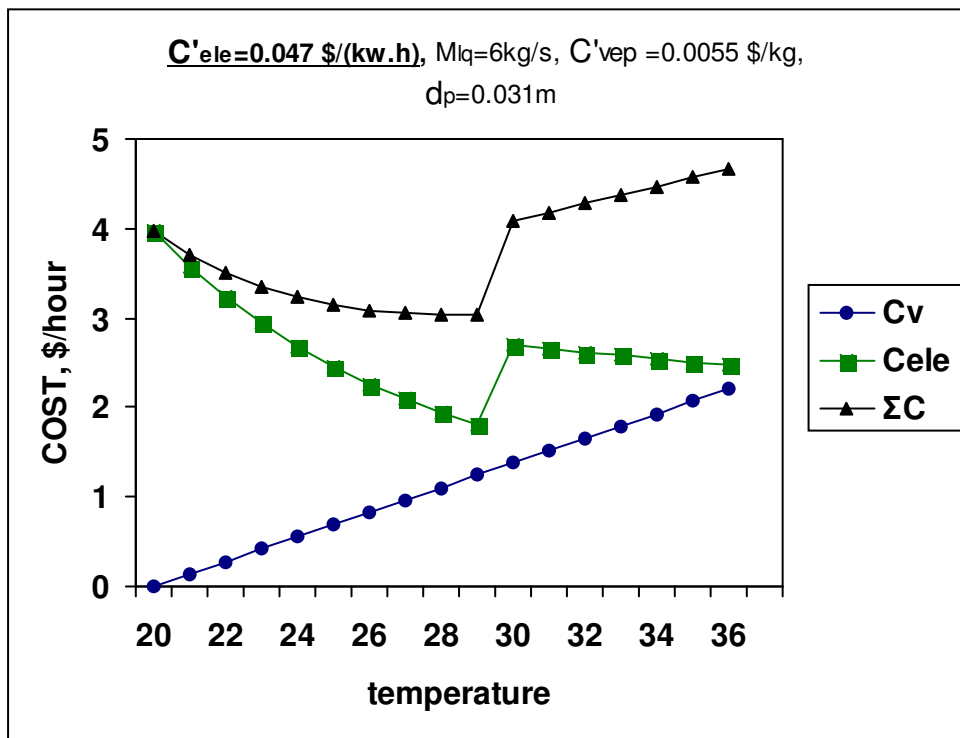
Diagram 2: the relationship between heating temperature degree t_{Lq} of liquid, and the cost of both the steam required for heating the liquid C_v, the electrical energy for pump operation C_{ele}. and the total cost of (heating plus pumping) ΣC at the price of electrical energy unit $C'_{ele}=0.047$ \$/(kW.h).
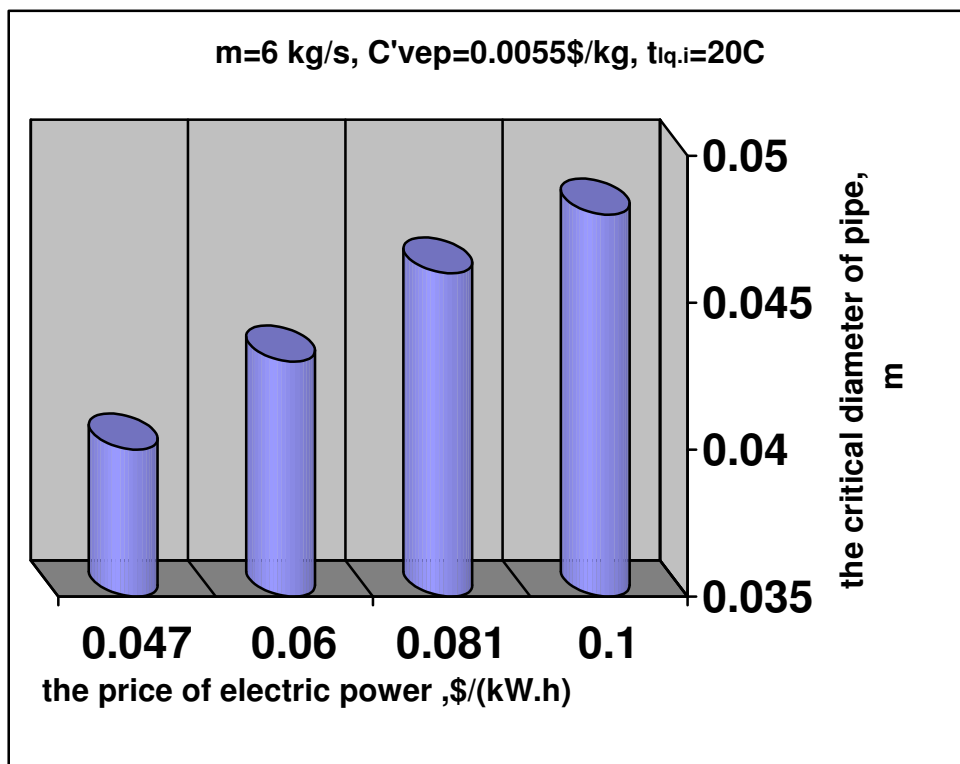

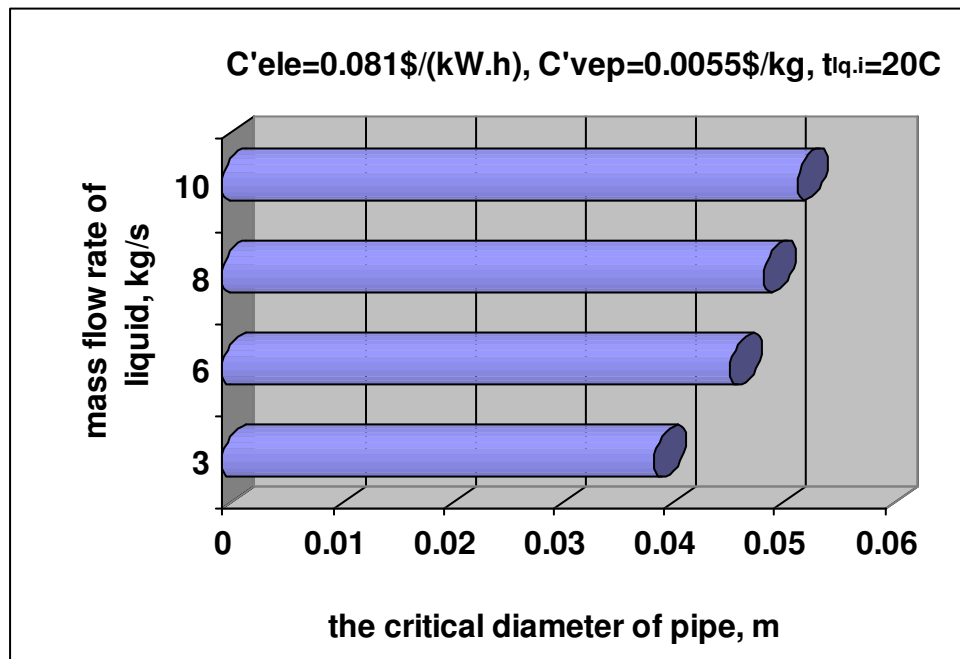Diagram 3 : The effect of electrical energy unit price on pipes critical diameter.

Diagram4 : The effect of liquid flow rate on pipes critical diameter .

Conclusion:

1-Heating high viscosity food stuff or industrial liquids before to pumping reduces pumping cost by 20%-40%.

2- Exceeding pipe critical diameter makes the heating operation unbeneficial for the reduction of pumping cost. This critical diameter is affected by many facts including electrical energy unit price, price of steam production required for the heating of liquid , liquid flow rate and its type. Determining this is done by a computer program that stops the random guessing and provides information that determine whether the heating is needed or not.

3- Calculations indicate that the optimal heating temperature degree is achieved at Reynolds number between Re= 2100-2300 , that is, before changing to turbulent flow.

4- Flow chart provided in this paper can be used not only for the sugar syrup but for any liquid if information about its intensity and viscosity are available.

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