APPLIED INDUSTRIAL ENERGY AND ENVIRONMENTAL MANAGEMENT

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Part III:

FUNDAMENTALS FOR ANALYSIS AND CALCULATION OF ENERGY AND ENVIRONMENTAL PERFORMANCE

Toolbox 10
INDUSTRIAL INSULATION

1. Any surface which is hotter than its surroundings will lose heat. The heat loss depends on many factors, but the surface temperature and its size are dominant. Putting the insulation on a hot surface will reduce the external surface temperature. By insulation, the surface will increase on circular pipes or vessels, but the relative effect of temperature reduction will be much greater and heat loss will be reduced. A similar situation occurs when the surface temperature is lower than its surroundings. In both cases some energy is lost. These energy losses can be reduced by laying the practical and economical insulation on surfaces whose temperatures are quite different than the surrounding one.

2. **Standard pipe outside diameters (mild steel pipe)**

Pipe nominal (in)	¾	1	1¼	1½	2	2½	3	4	5	5	6	8	10	12
Pipe nominal (mm)	20	25	32	40	50	65	80	100	125	125	150	200	250	310
Pipe OD (mm)	26.9	33.7	42.4	48.3	60.3	76.1	88.9	114.3	139.7	141.3	168.3	219.1	273.0	324

3. There are many different types of insulation materials and systems available, each having different thermal performances, handling properties, fire safety and other characteristics.

The details are available from the manufacturers and in the specific technical literature. The cost of insulation differs greatly and this requires detailed attention and the careful selection of insulation materials.

The most important aspect of insulation thermal performance is thermal conductivity. Other factors influencing thermal performance include surface properties which affect losses due to radiation. So, radiation losses can be reduced by the addition of a shiny metallic skin over the insulating layer. The benefit of the implementation of the additional skin can amount to roughly a 10 % reduction in overall heat loss.

The manufacturers of insulation provide information on thermal performance which avoids the need for complex heat transfer calculations. The offered data normally refer to a so-called ***U-value*** and give the heat loss per unit length of pipe for a range of pipe diameters, operating fluid stream temperatures and insulation thickness. These data are used for the estimation of heat loss and are based on specified external conditions, which can be significantly different than those assumed for calculation.

Tables 10.1 and 10.2 show some of the basic characteristics of insulation materials. From Table 10.2, it is possible to see that the thermal conductivity of insulating materials varies significantly according to the type of material, its density and operating temperature.

The operating temperature is an important criterion for the selection of insulation material, but other factors related to the service environment (internal or external use, required surface finish, structural strength constraints and accessibility) must also be taken into account. The selected material has to satisfy all requirements, but the economic thickness of pipe insulation varies according to type because of differences in properties and costs.

Table 10.1: Characteristics of some Insulation Materials

Material	Approximate Maximum Temperature [°C]	Bulk Density [kg/m^3]
Mineral Wool (Glass)	230	15–100
Mineral Wool (Rock)	850	80–150
Magnesia	315	180–220
Calcium Silicate	800	190–260
Polyurethane Rigid Foam	110	30–160
Polyisocyanurate Rigid Foam	140	30–60
Phenolic Rigid Foam	120	35–200
Polyethene	80	30–40
Synthetic Rubber	115	60–100

Table 10.2: Thermal Conductivity of some Insulating Materials

Material	*Density [kg/m^3]*	*Thermal Conductivity [W/(m K)]*		
		50 °C	*100 °C*	*300 °C*
Calcium Silicate	210	0.055	0.058	0.083
Expanded Nitrite Rubber	65–90	0.039		
Mineral Wool (Glass)	16	0.047	0.065	
	48	0.035	0.044	
Mineral Wool (Rock)	100	0.037	0.043	0.088
Magnesia	190	0.055	0.058	0.082
Polyisocyanurate Foam	50	0.023	0.026	

We recommend the use of insulation material characteristics supplied directly by the manufacturers.

The desirable properties of insulating materials are as follows:

– small thermal conductivity;
– water and temperature resistance;
– mechanical and chemical stability.

The manufacturers must always be consulted in order to determine the properties and performance of their products.

4. Where windy conditions prevail, heat loss increases and the estimated value for still air has to be increased, also. Table 10.3 shows roughly the effect of wind speed on heat loss. This affects only a convective heat transfer process.

Table 10.3: Effect of Wind Speed on Heat Loss

Wind Speed [km/h]	Wind Coefficient
Still Air	1.0
5	1.5
10	2.0
14	2.5
19	3.0
26	3.5
34	4.0

5. A non-insulated valve loses about the same amount of heat as approximately 1 m of non-insulated pipe of the same diameter. Non-insulated flanges lose about 50 % as much as a valve. This practical rule makes the estimation of heat loss and the calculation of possible energy saving by insulating an installation whose temperature differs from the ambient one easier.

6. Each plant has different fuel and insulation costs and different boiler efficiency. The criteria for the payback or rate of return, against which proposed capital investments have to be judged, have to be set by management.

A possible method of evaluating insulation projects is as follows:

a. Determine the cost of insulation for different insulation thickness.
b. Determine the heat loss for each level of insulation from the appropriate manufacturers' data.
c. Calculate the corresponding energy savings and cost reductions bearing in mind current boiler efficiency and cost of fuel.
d. Calculate the payback for the lowest level of insulation and compare it with the factory criterion.
e. If the payback is shorter than that which the factory management defines, calculate the incremental cost of insulating the next level and the corresponding incremental value of savings. Calculate the incremental payback and compare it with the factory criteria.
f. If the new payback is still lower than the requirement, the procedure has to be repeated for the next insulation thickness. The final thickness of insulation which meets the management's criteria is acceptable and represents the economic thickness of insulation.

This calculation uses payback as the criterion. Instead of payback, some other techniques can be used depending on company policy.

In addition to the suggested methods, a method for determining the economic thickness of insulation can be developed or found in the available literature.

7. The basic model of insulation on a pipe is shown in Fig. 10.1. The overall heat transfer coefficient of insulated pipe is as follows:

$$U = \frac{1}{\frac{D_3}{D_1 \cdot h_{in}} + \frac{D_3 \cdot \ln\left(\frac{D_2}{D_1}\right)}{2 \cdot k_{PIPE}} + \frac{D_3 \cdot \ln\left(\frac{D_3}{D_2}\right)}{2 \cdot k_{INSULATION}} + \frac{1}{h_{out}}} \qquad (10.1)$$

where, besides the marks in Fig. 10.1, k_{PIPE} and $k_{INSULATION}$ are the thermal conductivities of pipe and insulation, respectively.

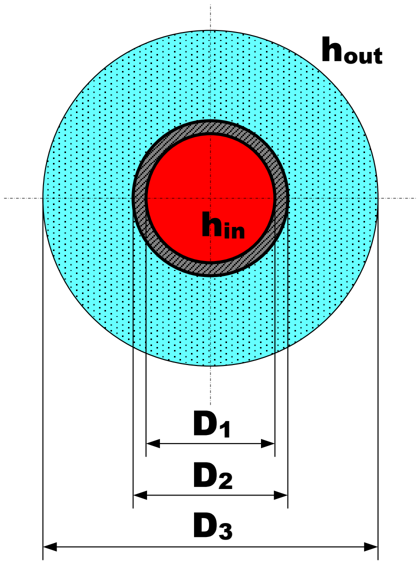


Figure 10.1: Cross Section of Insulated Pipe

Heat loss per one meter of insulated pipe is:

$$\frac{Q}{L} = \pi \cdot D_3 \cdot U \cdot (T_{in} - T_{out}) \tag{10.2}$$

Let us consider the following numerical example.

D_1 = 82.5 mm; D_2 = 89 mm; D_3 = 189 mm (insulation thickness = 50 mm); insulation thermal conductivity = 0.07 W/(m K), thermal conductivity of pipe material = 67 W/(m K). The heat transfer coefficient in the pipe is h_{in} = 1000 W/(m^2 K) and the heat transfer coefficient at the outside insulation surface is h_{out} = 8 W/(m^2 K). The temperature of the fluid within the pipe is 90 ^{o}C and the ambient temperature is 20 ^{o}C.

The overall heat transfer coefficient is:

$$U = \frac{1}{\dfrac{189}{82.5 \cdot 1000} + \dfrac{\frac{189}{1000} \cdot \ln\left(\frac{89}{82.5}\right)}{2 \cdot 67} + \dfrac{\frac{189}{1000} \cdot \ln\left(\frac{189}{89}\right)}{2 \cdot 0.07} + \dfrac{1}{8}} = \tag{10.3}$$

$$\frac{1}{0.00229 + 0.00011 + 1.01670 + 0.125} = \frac{1}{1.1441} = 0.87405 \ W/(m^2 \ K)$$

The first two members of the denominator in Equation (10.3) are much smaller than the next two. Their influence on the result of the final calculation of overall heat transfer coefficient is very small. A similar situation appears in the great majority of cases in practice. This means that the following simplification of Equation (10.3) is possible:

$$U = \frac{1}{\dfrac{D_3 \cdot \ln\left(\frac{D_3}{D_2}\right)}{2 \cdot k_{INSULATION}} + \dfrac{1}{h_{out}}} \tag{10.4}$$

In the case presented in Equation (10.3), the result of this simplification gives the result U = 0.87589 W/(m2 K). This is really negligible bearing in mind that we have to estimate the heat loss of the entire thermal system.

8. The simple software for the calculation of hot pipe heat loss is based on Equation (10.4). A user can select up to five insulation thicknesses and calculate the heat loss. The available nominal pipe diameters are: 1; 1 ½; 2; 2 ½; 3; 4; 5; 6; 8; 10; 12 inches.

The fluid temperature is assumed to be the same as the pipe surface temperature (see Section 6). After inputting this temperature, the ambient temperature, the emissivity of outside insulation (or pipe) surface, the thermal conductivity of the insulation and the wind coefficient (see Section 3), the software will calculate the heat loss for the bare and insulated pipe and present the result in a Table and in a Diagram for all pipe diameters.

The heat transfer coefficients are calculated using the appropriate formulae from Toolbox 7.

An example of the calculation is presented in Fig. 10.2 for the following input data:

– Thermal Conductivity of Insulation (k) 0.05 W/(m K)
– Temperature of Pipe Surface (T_2) 143.6 °C
– Ambient Temperature (T_{out}) 25 °C
– Surface Emissivity 0.95
– Wind Coefficient 1.00

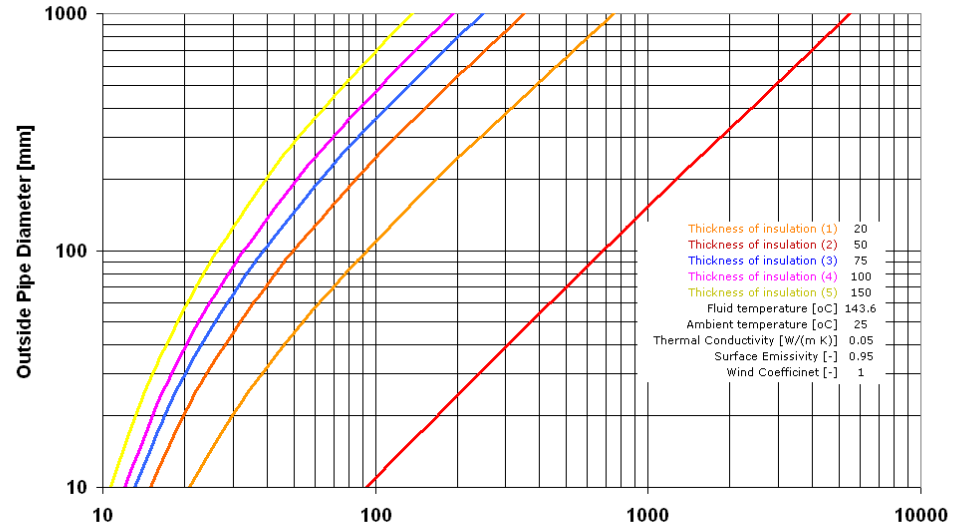


Figure 10.2: Graphical Interpretation of Calculation

9. **Example**

This example gives an estimation of the cost reduction which can be achieved by using insulation for the prevention of heat loss in pipes. The rate of heat loss (for given pipe and process conditions) depends on the thickness of the insulation and its thermal performance. At the same time, it depends on the insulation lagging cost. The main task is to compare the cost of lost energy and installation cost for insulation.

Two pipes (one bare and one insulated) are presented in Fig. 10.3. As both pipes are used for the same purposes, the heat loss which appears has to be calculated and compared.

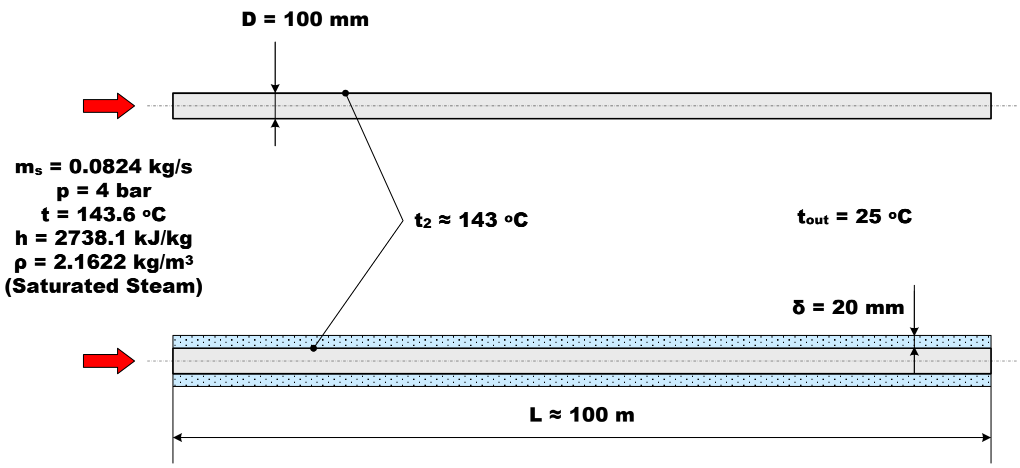


Figure 10.3: Bare and Insulated Pipes

Data

- Mineral wool insulation
- Thermal conductivity of insulation is 0.06 W/(m K)
- Inlet temperature of fluid has to be transported at 143.6 ^{0}C
- Ambient temperature is 25 ^{0}C
- Mass flow rate of saturated steam is 0.0824 kg/s
- Insulation thickness is 32 mm
- Annual number of operating hours is 8760 h/y
- Natural gas cost is 0.0212 US$/kWh
- Insulation cost including installation is 11 US$/m

$$Q_{B-P} = 100 \cdot 774.42 = 77{,}442 \text{ W} \quad (\text{or } 77.42 \text{ kW}) \tag{10.5}$$

$$Q_{I-P} = 100 \cdot 87.54 = 8{,}754 \text{ W} \quad (\text{or } 8.75 \text{ kW}) \tag{10.6}$$

The expected heat energy saving by insulating the pipe is as follows:

$$\Delta Q = Q_{B-P} - Q_{I-P} = 77.42 - 8.75 = 68.89 \text{ kW} \tag{10.7}$$

or, bearing in mind the total number of operating hours, the total expected energy saving is:

$$\Delta Q_{Annual} = 8760 \cdot 68.89 = 601{,}724 \text{ kWh / a} \tag{10.8}$$

The additional fuel consumption for covering this heat loss is as follows:

$$\Delta F_{Annual} = \frac{\Delta Q_{Annual}}{\eta_{Boiler}} = \frac{601{,}724}{0.8} = 752{,}155 \text{ kWh / a} \tag{10.9}$$

The annual cost for this unnecessary expense is:

$$\Delta C_{Fuel} = 0.02125 \cdot 752{,}155 = 15{,}983 \text{ US\$ / a} \tag{10.10}$$

The cost of insulation including installation is:

$$CI = 11 \cdot 100 = 1100 \text{ US\$} \qquad (10.11)$$

By insulating the pipe, energy costs have decreased by nearly 16 000 US$ per year and the installation cost is only 1100 US$.

10. **Plate or Large Cylindrical Surfaces.** Similar problems occur with the various tanks used in industry for storing or collecting various hot fluids. It is essential to estimate losses and calculate the possible effects of insulation on the operating cost of an energy system to which these tanks belong. Figure 10.4 shows the typical shapes of tanks which are found in industry. The problem of determining loss is very similar to the problem of determining loss in pipes. The difference is only in the determination of the heat transfer coefficients for the surfaces of the tanks. These coefficients are also determined based on the relations in Toolbox 7.

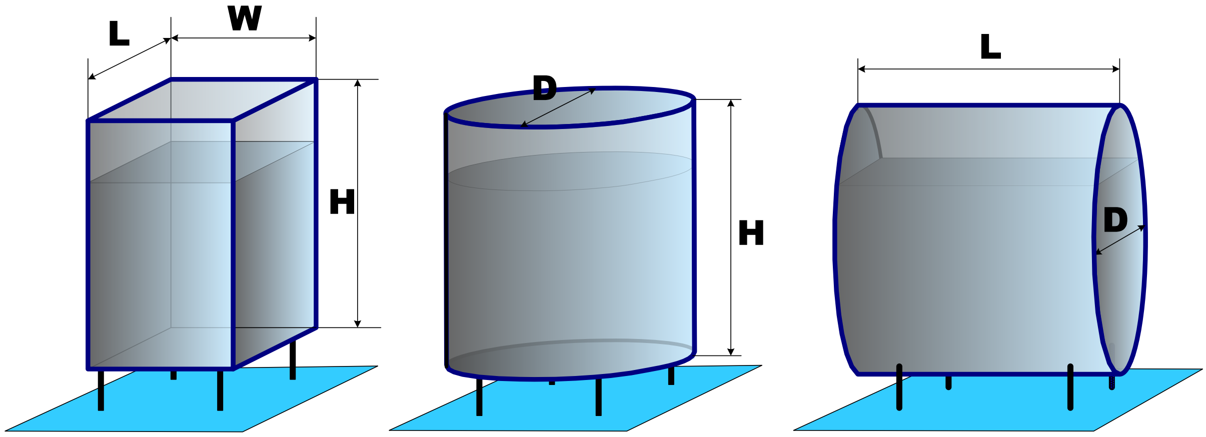


Figure 10.4: Different Types of Tanks in Industry

11. **Software.** Based on the assumptions presented in the previous paragraphs, a program has been prepared which can assess the effects of installing insulation on pipelines and tanks. The software computes the losses for given temperatures and heat transfers which occur when a pipeline or a tank is non-insulated and for several thicknesses of insulation. The thermal characteristics of insulation are also given.

Figure 10.5 shows the starting appearance (FORM). In addition to single pipes and vessels, it is possible to choose an option where loss is estimated in a distribution system composed of pipes with various diameters with an arbitrary number of valves and flanges.

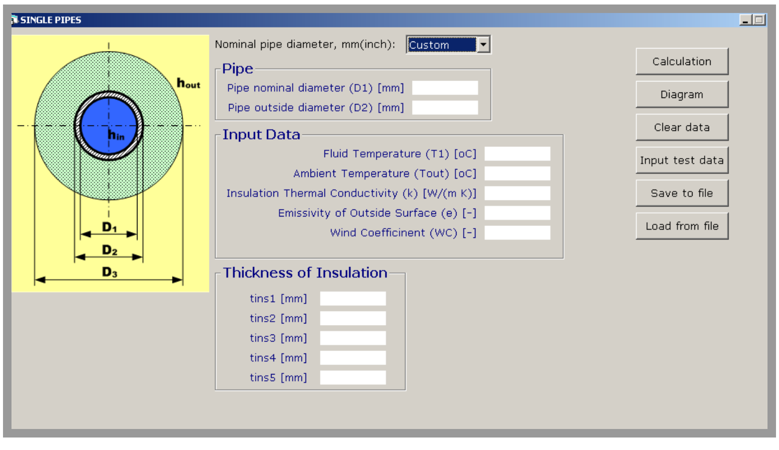


Figure 10.5: Starting Appearance (Options: (1) SINGLE PIPES (2) MORE PIPES AND (3) VESSELS

Figure 10.6 shows the Form for the computation of heat loss in single pipes of various standard diameters. The selectable sizes are given in the Frame: Input Data and the desired insulation thicknesses are provided in the Frame: Thickness of Insulation. In the Frame: Results, there are losses per meter of bare pipe length and all selected insulation thicknesses.

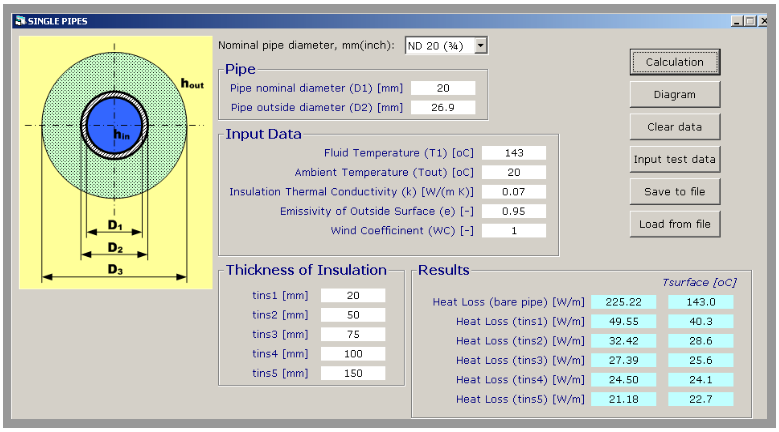


Figure 10.6: Window of Option 1 – Single Pipe

By selecting the Option: Vessel, a window is opened which provides for opportunities to determine heat loss for three typical geometries of tank. The input values are the same as in the case of pipes, however instead of pipe diameters here there are vessel dimensions. It is assumed that the vessel temperature is constant. In the Frame: Results, the total estimate of heat loss is obtained for various insulation thicknesses and given the conditions in the vessel and around it.

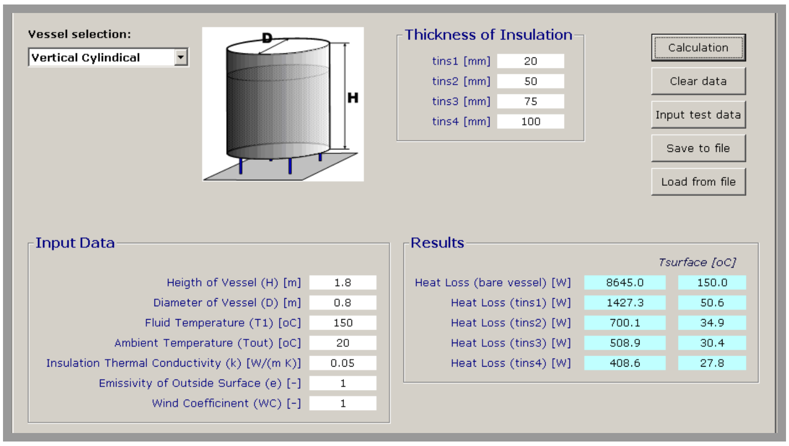
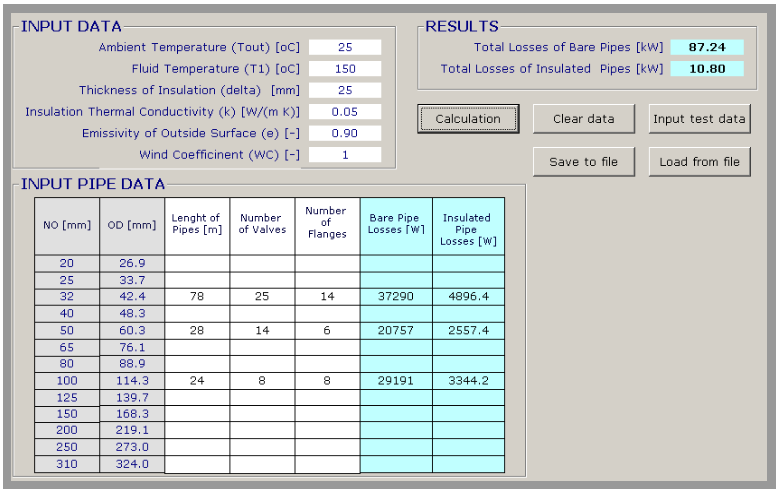


Figure 10.7: Window of Option 1 – Vessel

The most common case in engineering practice concerns the estimation of the total heat loss of one part or the entire distribution network. In order to achieve this, it is necessary to measure the length of certain pipelines and their diameters, count the number of valves and flanges and assess the existing insulation, if any. If the insulation is damaged and should be replaced anyway, it has to be treated as if it does not exist. When these aggregate data are input, as well as other computation parameters, the program (Frame Part of Installation) produces the total heat loss. For different computation parameters, the calculations are repeated and if there are also tanks, vessels or reservoirs in the relevant installation, then separate computations are executed for them, as well. If the unit prices of the insulation and its fitting are known, then it is possible to compute the possible energy saving and its price and energy management will be able to make a very reliable decision regarding the work that is necessary in order to insulate the installation.



NO [mm]	OD [mm]	Lenght of Pipes [m]	Number of Valves	Number of Flanges	Bare Pipe Losses [W]	Insulated Pipe Losses [W]
20	26.9					
25	33.7					
32	42.4	78	25	14	37290	4896.4
40	48.3					
50	60.3	28	14	6	20757	2557.4
65	76.1					
80	88.9					
100	114.3	24	8	8	29191	3344.2
125	139.7					
150	168.3					
200	219.1					
250	273.0					
310	324.0					

Figure 10. 8: Many Pipes forming the Network

References

Eastop, T.D., Croft, D.R. (1990) *Energy Efficiency (for Engineers and Technologists)* Longman Scientific & Technological.

Energy Efficiency Office, Department of the Environment, UK (1993) Fuel Efficiency Booklet No. 8, *The Economic Thickness of Insulation for Hot Pipes*.

www.cheresources.com *Making Decisions with Insulation*.