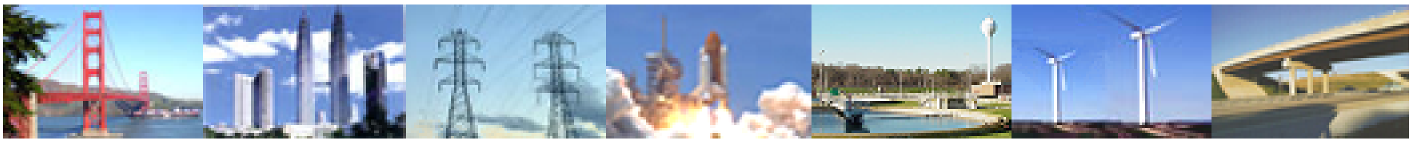

PDHonline Course M157 (3 PDH)

Insulation Audit and the Economic Thickness of Insulation

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Insulation Audit and the Economic Thickness of Insulation

Course Content

Overview

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 steam, chilled water and other process distribution pipelines is required to minimize financial and thermal losses. This seems like a statement of the obvious, and it is.

However, the maintenance and upgrade of thermal insulation is generally regarded as a low priority, or on a "do it later" basis. What eventually transpires is that pipeline insulation maintenance issues tend to accumulate, until major repairs are required, and more importantly, extensive financial losses have been incurred.

The Part -1 of the course titled "Process Plant Insulation & Fuel Efficiency" focused on the type, properties, application and installation guidelines of insulation material and finishes. Brief recap is as follows:

Insulation is used to perform one or more of the following functions:

- Reduce heat loss or heat gain to achieve energy conservation.
- Protect the environment through the reduction of CO_2, NO_x and greenhouse gases.
- Control surface temperatures for personnel and equipment protection
- Control the temperature of commercial and industrial processes.
- Prevent or reduce condensation on surfaces.
- Increase operating efficiency of heating/ventilation/cooling, plumbing, steam, process and power systems.
- Prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres.
- Reduce noise from mechanical systems.

Other than the application of insulation, the selection aspects of the insulation material are also very important. The following design & installation considerations must be noted:

- Type of insulation – rigid, flexible, ease of handling, installation and adjustment
- Easy to modify, repair and alter
- Requirement of skilled and unskilled labor
- Safety & environment considerations
- Weight and density of insulation material

- Ease of removal and replacement
- Type of vapor retarder and insulation finishes
- Thermal performance

This part of the course material focus on the assessment of thermal heat losses and include examples of savings than can be realized using the systematic approach of insulation audit, economics and acceptable thickness of insulation.

In studying heat transfer; we study energy in motion – through a mass by conduction, from a solid to a moving liquid by convection, or from one body to another through space by radiation. Heat transfer always takes place from warmer to colder. Heat transfer for conduction and for convection is directly proportional to the driving temperature differential ($T_1 – T_2$). Heat transfer by radiation is proportional to the fourth power of the temperature difference ($T_1^4 – T_2^4$). Small changes in temperature can create relatively large changes in radiation heat transfer. Quantitative heat transfer is proportional to the heat transfer surface area.

Identifying the rate of thermal energy (heat) loss from an inadequate or uninsulated surface is the starting point for understanding the incentive for installing thermal insulation.

Let's look at some basic thermodynamic equations that govern the heat transfer principles.

Heat Gain / Loss from Flat Surfaces

The heat loss (in Btu/ hr) under a steady-state energy balance through a homogeneous material is based on the Fourier equation Q = k * A * dt/dx. In practice the equation is modified to include film resistance at its surfaces.

$Q = A \times U \times (T_1 - T_2)$

For flat surface covered with insulation,

$$U = 1 / R = \frac{1}{L/k}$$

$Q = A \times (T_1 - T_2) / (L/k)$

Q = heat transfer from the outer surface of insulation in Btu/hr

T_1 = the hot face temperature, °F

T_2 = the cold face temperature, °F

T_a = the surrounding air temperature, °F

U = Overall coefficient of heat transfer per degree of temperature difference between the two fluids which are separated by the barrier

L = thickness of insulation

k = thermal conductivity of insulation, Btu/h ft ^{0}F

$\frac{L}{k}$ = "R", is called thermal resistance of insulation

For unit area, the heat transfer in Btu/ft^2 hr is

$$Q = \frac{T_1 - T_2}{\frac{L}{k}}$$

$$Q = (T_2 - T_a) f$$

$$Q = \frac{(T_1 - T_a)}{\frac{L}{k} + \frac{1}{f}}$$

The surface temperature may be calculated from the equation:

$$T_2 = \frac{Q}{f} + T_a$$

Where f is the surface coefficient, Btu in/ft^2 hr °F

The lower the thermal conductivity (k-value), higher shall be the R-value or greater shall be the insulating power.

The thermal conductivity of insulation changes as the difference in temperature between hot surface and the ambient temperature changes. *The thermal conductivity value of a material is taken at the mean temperature* ($T_1 + T_2$)/2 °F and it varies *with mean temperature, material density and with moisture absorption.*

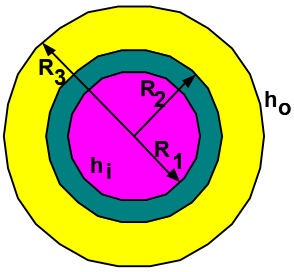
Heat Gain / Loss from Cylindrical Surfaces like Pipes

Unlike flat surfaces, the inner and outer surface areas for pipes are different and therefore the heat transfer equation is different. The pipe wall surface shall gain heat directly by conduction from the fluid flowing through it. The heat is then dissipated to the atmosphere or it flows at a restricted rate through the insulation, if the pipe is insulated. The exact rate of heat loss is very complicated to calculate on theoretical grounds alone, since it shall be affected by:

- Color, texture and shape of the casing
- Vertical or horizontal orientation of the casing
- Air movement (wind speed) over the casing
- Exposure to thermal radiation (e.g. sunlight) - all these in addition to the temperature parameters, etc

Because of the number of complicating factors, generalizations have to be utilized. The theoretical methods for calculating heat transfer for pipe or any other cylindrical objects like tanks is based upon the equivalent thickness of insulation and the area of outer surface of insulation.

The most basic model for insulation on a pipe is shown below.



R_1 and R_2 show the inside and outside radius of the pipe.

R_2 and R_3 shows the inside and outside radius of the insulation.

The equivalent length of insulation is given by equation:

$$\text{Equivalent length} = R_3 \log_e(R_3 / R_2)$$

Considering the other factors viz. the pipe thickness, the overall thermal conductivity (U) value shall be defined by

$$U = \frac{1}{\frac{R_3}{R_1 h_i} + \frac{R_3 \log_e(R_2/R_1)}{k_{pipe}} + \frac{R_3 \log_e(R_3/R_2)}{k_{insulation}} + \frac{1}{h_o}}$$

Where

h_i is the heat transfer coefficient inside pipe (air /liquid film conductance inside) in Btu/ft^2 hr F

h_o is the air film conductance on the outer surface in Btu/ft^2 hr F

k_{pipe} is the thermal conductivity of pipe material

$k_{insulation}$ is the thermal conductivity of the insulation

The heat loss shall be defined by equation

$$Q = A \times U \times (T_{inside\ pipe} - T_{ambient})$$

Or the heat loss per unit of area shall be given by:

$$Q = \frac{T_{inside\ pipe} - T_{ambient}}{\frac{R_3}{R_1 h_i} + \frac{R_3 \log_e(R_2/R_1)}{k_{pipe}} + \frac{R_3 \log_e(R_3/R_2)}{k_{insulation}} + \frac{1}{h_o}}$$

Typically when dealing with insulations, engineers must be concerned with linear heat loss or heat loss per unit length.

$$\frac{Q}{L} = \frac{2\pi R_3 \left[T_{inside\ pipe} - T_{ambient} \right]}{\dfrac{R_3}{R_1\ h_i} + \dfrac{R_3 \log_e (R_2 / R_1)}{k_{pipe}} + \dfrac{R_3 \log_e (R_3 / R_2)}{k_{insulation}} + \dfrac{1}{h_o}}$$

The surface temperature may be computed from the equation:

$$T_{surface} = \left(\frac{Q}{f} \times \frac{R_2}{R_3} \right) + T_{ambient}$$

f is the surface coefficient, Btu in/ft^2 hr °F

For simplicity, the temperature difference is shown as ($T_{inside\ pipe} - T_{ambient}$).

In actual practice log mean temperature difference is to be taken. The heat transfer shall be defined by

$$Q = 2\pi R_3 L\ U\ \Delta T_{LM}$$

Where

$$\Delta T_{LM} = \frac{(T_2 - T_{amb}) - (T_1 - T_{amb})}{LN\left(\dfrac{T_2 - T_{amb}}{T_1 - T_{amb}} \right)}$$

Depending on the complexity of the system it may be necessary to make more than one calculation to arrive at mean temperatures and the losses in different parts of the system.

The heat transfer coefficient of ambient air is 7.0 Btu/h ft^2 °F (40 W/m^2 K). This coefficient shall increase with wind velocity if the pipe is outside. A good estimate for an outdoor air coefficient in warm climates with wind speeds less than 15 mph is around 8.8 Btu/h ft^2 °F (50 W/m^2 K).

Since heat loss through insulation is a conductive heat transfer, there are instances when adding insulation actually increases heat loss. The thickness at which insulation begins to decrease heat loss is described as the '*critical thickness*.' This is discussed further in subsequent section.

Insulation Audit

Thermal insulation audit is a service oriented towards bringing existing shortcomings and unrealized opportunities of saving energy through insulation to the attention of energy managers and engineers, on whom lies the onus of achieving higher and still higher plant energy efficiency.

Concept

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 asses the existing insulation systems, identify the critical energy loss areas and upgrade the insulation systems of such areas on priority basis.

It is essential to know precisely the heat loss/gain from the hot pipelines and equipments in operation. Annual heat losses in terms of money are then worked out. A new insulation system, with upgraded insulation materials is then designed, separately for each and every plant piping and equipment. An economic analysis is then carried out to study the economic viability of this technically superior proposal. The installed cost of the proposed insulation system and the payback period of this investment are worked out. Also, the anticipated reduction in plant fuel consumption due to saving in heat loss is estimated.

Instrumentation

The instrumentation required to make the necessary measurement are:

1) Electronic temperature indicator
2) Surface contact and point contact type thermocouple probes compatible to the temperature indicator
3) Pyrometer, non contact type infrared thermometer (for extremely hot and remote surfaces)
4) Whirling hygrometer for relative humidity (RH) measurement or ordinary dry bulb (DB) and wet bulb (WB) thermometers also serve the purpose
5) Anemometer for wind speed measurement, with a range of zero to 15m/s

Methodology

Following operational parameters and drawing office data are collected from the plant authorities:

1) Type of fuel used (coal, fuel oil, natural gas, LNG etc)
2) Landed cost of fuel, calorific value, boiler efficiency for arriving at the unit heat cost
3) Number of plant operating hours per year
4) Operating temperatures of the pipelines and equipments, individually
5) Pipe nominal bore, outer diameter and pipe lengths
6) Equipment dimensions
7) Existing insulation thickness

Obtain the insulation design basis & data

1) Ambient temperature

2) Maximum permissible surface temperature
3) Wind speed
4) Emissivity of insulation system surface
5) These data are arrived at in consultation with plant authorities as also any available meteorological data.
6) Design of upgraded insulation system

Measurements

Following parameters are measured and recorded at site:

1) Insulation system surface temperature measured at regular intervals over the whole pipeline/equipments, circumferentially and longitudinally by physical contact between thermocouple sensor and insulation system surface
2) Ambient temperature measure at 1meter distance from the insulation system surface. This temperature is measured separately against each reading of the insulation system surface temperature. The ambient temperature is measured by holding and swaying the thermocouple probe in air.
3) Wind speed is measured once in a particular location near the insulated system by an anemometer.
4) Observed emissivity of insulation system surface. Emissivity is read from standard tables, against the material, state of polish, color of paint of the final finish of insulating system.
5) Relative humidity measured near the insulated system by a hygrometer, only for cold system.

Care should be taken to ensure that:

1) Both wind speed and relative humidity of only the immediate atmosphere enveloping the insulated systems are measured.
2) Radiation from a hot surface like unlagged valves, flanges etc do not lead to error in insulation system surface temperature and ambient air temperature measurements.
3) Insulation system surface temperature is measured with the surface contact type thermocouple probe.

Apart from the above measurement, the following parameters are inspected and recorded:

1) Location and dimension of unlagged areas of piping/equipment
2) Condition, whether final finish is Aluminum, GI cladding, plaster etc., state of polish (bright, dull, coated with dust/dirt deposit etc of cladding, color of paint on final finish etc.
3) If insulation and/or cladding is damaged or ruptured, extent and location of it

At least six readings of surface temperature and ambient temperature are taken at a particular location. Surface temperature readings need to be normalized i.e. modified to be made compatible to the design ambient temperature, so that comparison between the existing insulation system and the new, upgraded insulation system to be designed and proposed may be made based on the same datum.

Analysis

The data collected during plant audit are than analyzed systematically and calculations are performed on present value to arrive at the quantity of energy losses both in thermal and dollar values. Usually a software program is used to estimate the heat losses.

Computations

Once the data is collected, the heat loss can be computed for the un-insulated surface and from the surface with the proposed insulation.

Energy savings shall than be calculated as follows:

$E_{savings} = Q_{uninsulated} - Q_{insulated}$ -- **1**

Heat loss from the <u>uninsulated</u> surfaces

Hot surfaces lose heat to the surroundings via convection and radiation. The equation for heat loss, Q, to the surroundings at ambient temperature Ta, from a hot surface at Ts, with area A is:

$Q_{Total} = Q_{Convection} + Q_{Radiation}$

$Q_{uninsulated} = h \times A \times (Ts - Ta) + y \times A \times E \times (Ts^4 - Ta^4)$ -------------------------- **2**

Where

$Q_{uninsulated}$ is a total heat loss in Btus/ft^2

Ta is the ambient temperature in degrees absolute (°F + 460)

Ts is hot surface temperature in degrees absolute (°F + 460)

A is the area (ft^2)

h is the convection coefficient (Btu/ft^2 hr °F)

y is the Stefan-Boltzman constant (0.1714 x 10^{-8} Btu/ft^2-hr-R^4)

E is the emissivity factor that depends on color and texture of the surface varying from about 0.1 for aluminum to 0.9 for dark surfaces

For warm surfaces, the value of the convection coefficient h is about 1.5 Btu/ft^2-hr-F. For hot surfaces, the value of the convection coefficient should be calculated as a function of the orientation of the surface and the temperature difference between the surface and the surrounding air. First verify if the flow is laminar or turbulent. Flow is

Laminar if: $D^3\ \Delta T < 63$

Turbulent if: $D^3\ \Delta T > 63$

Empirical relation of convection coefficient (h) is than calculated as follows:

Horizontal Surfaces Loosing Heat Upwards: $h_{Lam} = 0.27 \times (\Delta T/L)^{0.25}$; $h_{Tur} = 0.22 \times (\Delta T)^{0.33}$--------**3**

Tilted / Vertical Surfaces: $h_{Lam} = 0.29 \times (\Delta T \times (\sin B)/L)^{0.25}$; $h_{Tur} = 0.19 \times (\Delta T \times (\sin B)/L)^{0.33}$-------**4**

Horizontal Pipes and Cylinders: $h_{Lam} = 0.27 \times (\Delta T/D)^{0.25}$; $h_{Tur} = 0.18 \times (\Delta T)^{0.33}$--------------------------**5**

Using these relations for convection coefficient, Equation 2 can be solved for $Q_{uninsulated}$ to estimate the current heat loss.

In all relations,

1) L is the characteristic length (ft),
2) ΔT is temperature difference between the surface and the surrounding air (F),
3) D is characteristic diameter (ft),
4) B is tilt angle of the surface from horizontal, and
5) h is convection coefficient (Btu/ft^2 hr °F).

Dimensional approximations for convection coefficients are listed in ASHRAE Fundamentals, 1989.

Once h is calculated as above, the heat loss equation can be solved for $Q_{uninsulated}$.

Heat loss from the Insulated surfaces

Heat loss estimation from the insulated surfaces is little tricky. When calculating the heat loss or gain from an uninsulated surface, one has to equate Q_{Total} to the sum of $Q_{Convection} + Q_{Radiation}$ (Refer to equation 2). When insulation is considered over bare surface, the heat loss/gain equation is modified as:

$Q_{insulated} = h \times A \times (T_{os} - T_a) + y \times A \times E \times (T_{os}^{\ 4} - T_a^{\ 4})$ ---**6**

Unfortunately the value of outside surface temperature Ts is not known and therefore the equation has two unknown variables namely h and Ts. To solve this equation, another equation is written for a steady-state energy balance for the surface of the insulation. The heat lost through the insulation must balance with the heat lost (or gained) via the surrounding air.

$Q_{insulated} = A * (T_{is} - T_{os})/ R = A * (T_{os} - T_a)* f = A * (T_{is} - T_a) / (R + 1/f)$ -----------------------------**7**

Where

1) A is the area (ft^2)
2) T_{is} is the hot face or inner surface temperature (°F) of the insulation. The hot face temperature of insulation is equivalent to the uninsulated surface temperature T_s used in equation 2 above.
3) T_{os} is the cold face or outer surface temperature (°F) of the insulation
4) T_a is the ambient temperature (°F)
5) h is the convection coefficient (Btu/ft^2 hr °F)
6) y is the Stefan-Boltzman constant (0.1714×10^{-8} Btu/ft^2-hr-R^4)
7) E is the emissivity factor that depends on color and texture of the surface varying from about 0.1 for aluminum to 0.9 for dark surfaces
8) R is the resistance of insulation (R = L/k), where L is thickness of insulation in inches and k is thermal conductivity of insulation in Btu/h ft °F.

   For cylindrical surfaces such as pipes

   $R = \ln (R_o / R_i) / 2\pi k$, where R_i = internal radius of insulation = ½ diameter of pipe (ft) and R_o = outer radius of insulation = ½ diameter of pipe (ft) + insulation thickness (ft)
9) f is the surface coefficient (Btu in/ft^2 hr °F); (generally, the heat transfer coefficient of ambient air is 7.0 Btu/h ft^2 °F (40 W/m^2 K). This coefficient shall increase with wind velocity if the pipe is outside. A good estimate for an outdoor air coefficient in warm climates with wind speeds less than 15 mph is around 8.8 Btu/h ft^2 °F (50 W/m^2 K).

Equating equations 6 & 7;

$$h \times A \times (T_{os} - T_a) + y \times A \times E \times (T_{os}^{\ 4} - T_a^{\ 4}) = A * (T_{is} - T_{os}) / R$$

OR

$$h \times A \times (T_{os} - T_a) + y \times A \times E \times (T_{os}^{\ 4} - T_a^{\ 4}) - A * (T_{is} - T_{os}) / R = 0 \text{-------------------------------} \mathbf{8}$$

One of the easiest ways to solve this system of nonlinear equations is successive substitution.

In the successive-substitution method the following methodology is adopted:

Step #1: An initial value for T_{is} (hot face temperature) is used to determine whether the flow is laminar or turbulent.

Step #2: Than depending on the flow and the type of surface, either of applicable equation 3, 4 or 5 is chosen and the h value is substituted in equation 8 to determine a new value of T_{os}.

Step#3: The final values of T_{os} and h can then be substituted into Equation 6 to find $Q_{insulated}$.

(Refer to illustrations 1 and 2 as practical examples)

Evidently, the estimation of heat losses at varying operating temperatures involve large scale, laborious and repetitive calculations, which increases manifold depending on the number of pipelines, equipments, vessels, tanks, furnaces, boilers etc. surveyed in a plant. Such large scale calculations could utilize standard pre-calculated tables, charts and insulation software programs available with manufacturers and various handbooks.

Surface temperature of the insulation is a good indicator of insulation effectiveness and the following norm may be adopted to evaluate the use of improving the insulation levels.

As a rule of thumb, for quick check for the performance of insulation, the ΔT (temperature difference between the surface temperature of insulation and ambient air) should be less than the values indicated in the table below:

FOR	Δ T ($T_{surface} - T_{ambient}$)
Operating Temperature <= 200°C (392°F)	**7°C (12.6°F)**
Operating Temperature >200°C (392°F) and <= 400°C (752°F)	**10°C (18°F)**
Operating Temperature >400°C (752°F) and <= 600°C (1112°F)	**15°C (27°F)**
Operating Temperature >600°C (1112°F)	**20-25°C (36-45°F)**

These values ensure that apart from a tolerable insulation system surface temperature, the heat losses are within limits, payback of investment on insulation is excellent and workspace temperature around insulated system is comfortable.

Economics

The economic benefits of insulation shall vary according to application and the method of financial appraisal. One of the simplest methods of financial appraisal is the "Pay back" analysis where costs are compared with savings and the result is expressed in terms pay back period. Process plant will almost certainly be insulated to give a payback of less than two years. The payback period actually increases with insulation thickness – such incremental thickness having an increased time of payback. The final increment should pay for itself well within the life of the plant or that of the insulation whichever might be deemed the shorter. Simple payback period is calculated as follows:

1) IC = Installed cost including cost of insulation material, freight, taxes, ancillary & supporting materials, cladding, labor etc of insulation system
2) SHC = Savings in cost of heat lost per annum

3) PB = Payback period of investment on new upgraded insulation system

4) PB = IC * 12/SHC months

Illustration # 1

Energy audit data on a 3" hot water pipe distributing to various process equipment indicate an average surface temperature of 180° F. An average temperature of air is 78° F. The pipe length is 250 ft. Calculate the present heat losses and the savings possible, if the pipe is insulated with 2" thick fiberglass insulation having conductivity (k-value) of about 0.30 Btu-in/hr ft^2 F. What will be the simple payback, if the total cost of providing the insulation is $2000? Consider the hot water generation is through a gas fired boiler operating at 60% efficiency and using natural gas @ $ 4 per mcf?

Solution

Step # 1 (Check whether the convection flow is laminar or turbulent)

Dimensional approximations for convection coefficients are checked in accordance with ASHRAE Fundamentals, 1989.

Flow is Laminar if $D^3 \Delta T < 63$

Flow is Turbulent if $D^3 \Delta T > 63$

Substituting the values :

$D^3 \Delta T = (3/12)^3 * (180 – 78) = 1.6$ which is < 63

Therefore the flow is Laminar.

Step # 2 (Find the convection coefficient)

For laminar flow, the convection coefficient (again using dimensional units of ft and degrees F) is about:

The convection coefficient for laminar flow from a pipe; $h_{Lam} = 0.27 \times (\Delta T/D)^{0.25}$

Or $h_{Lam} = 0.27 \times (180 - 78)^{0.25} / (3/12)^{0.25} = 1.21$ Btu/ft^2 F hr

Step # 3 (Find the heat loss for uninsulated surface)

Assuming emissivity E = 0.90, the heat loss from the pipe is given by equation:

$Q_{uninsulated} = h \times A \times (Ts – Ta) + y \times A \times E \times (Ts^4 – Ta^4)$

Area A per unit length = $\pi * D = 3.14 * (3/12) = 0.785\ ft^2$

$Q_{uninsulated} = 1.21 * 0.785 * (180 – 78) + (0.1714 \times 10^{-8}) * 0.785 * 0.9 * ((180 + 460)^4 – (78 +460)^4)$

$Q_{uninsulated}$ = 199 Btu/hr per ft length of pipe

Total heat loss for 250 length of uninsulated pipe $Q_{uninsulated}$ = 49750 Btu/hr

Step # 4 (Find the resistance value of insulation)

Conductivity of the insulation; k = 0.30 Btu in / hr ft^2 F = 0.025 Btu/hr ft F.

The thermal resistance of two inches of insulation would be about:

$R_{insulation} = \ln (R_o / R_i) / 2\pi k$, where

R_i = internal radius of insulation = ½ diameter of pipe = 0 .125 ft and

R_o = outer radius of insulation = ½ diameter of pipe + insulation thickness (ft) = 0.29 ft

Therefore $R_{insulation} = \ln (0.29 / 0.125) / 2 * 3.14 * 0.025 = 5.4$ hr F ft / Btu

Step # 5 (Find the heat loss from an insulated surface)

Assuming steady state conditions, the heat loss through the insulation would equal the heat loss from the insulation surface by convection and radiation.

$h \times A \times (T_{os} - T_a) + y \times A \times E \times (T_{os}{}^4 - T_a{}^4) = A * (T_{is} - T_{os}) / R$

The above equation can be rearranged and solved for the temperature of the outer surface of the insulation T_{os}:

$0 = \mathbf{h} * (\pi * D) * (T_{os} - T_a) + y * (\pi * D) * E * (T_{os}{}^4 - T_a{}^4) - (T_{is} - T_{os}) / R_{insulation}$

$0 = \mathbf{\{0.27 \times (T_{os} - 78)^{0.25} / (3/12)^{0.25}\}} * (\pi * D) * (T_{os} - T_a) + y * (\pi * D) * E * (T_{os}{}^4 - T_a{}^4) - (T_{is} - T_{os}) / R_{insulation}$

Where $(\pi * D)$ is $3.14 * 3/12 = 0.785$

$0 = 0.27 * (T_{os} - 78)^{0.25} * 0.785 + (0.1714 \times 10^{-8}) * 0.785 * 0.9 * ((T_{os} + 460)^4 - (78 + 460)^4) - (180 - T_{os}) / 5.4$

Or T_{os} = ~90°F

The heat loss through per feet length of the distribution piping would be about:

$Q = (T_{is} - T_{os}) / R_{insulation} = (180 - 90) / 5.4 = 16.7$ Btu / hr /ft

Total heat loss for 250 length of pipe $Q_{Total\ insulated}$ = 4175 Btu/hr

Step # 6 (Estimate Savings)

Assuming the efficiency of the boiler is 60%, 8760 hours operation per year the energy savings (natural gas) would be about:

$E_{savings} = (Q_{uninsulated} - Q_{insulated}) / ή_{boiler} = (49750 - 4175)/ 0.6 \times 8760 = 665.39 \times 10^6$ Btus / yr

Heat value of natural gas = 1 m Btus per mcf

Savings in Natural Gas = ~666mcf per annum

Step # 7 (Estimate Simple Payback /Return on Investment)

Cost of providing the insulation	= \$ 2000
Savings in Natural Gas @ 4 per mcf`	= \$ 2664 per annum
Simple Payback Period	= \$ 2000 * 12 / \$ 2664 per year = ~ 9 months

Illustration # 2

Energy audit data on a hot water condensate tank indicate an average surface temperature of 170° F and an average temperature of air and the surrounding walls is 78° F. The tank dimensions are about 2.5 feet diameter and 6 feet length. Calculate the heat losses and the savings possible if the tank is insulated with 2" thick fiberglass insulation having conductivity (k-value) of about 0.30 Btu-in/hr ft^2 F.

Solution

Step # 1 (Check whether the convection flow is laminar or turbulent)

Dimensional approximations for convection coefficients are checked in accordance with ASHRAE Fundamentals, 1989.

Flow is Laminar if $D^3 \Delta T < 63$

Flow is Turbulent if $D^3 \Delta T > 63$

Substituting the values :

$D^3 \Delta T = (2.5)^3 * (170 – 78) = 1437.5$ which is > 63

Therefore the flow is turbulent.

Step # 2 (Find the convection coefficient)

The convection coefficient for turbulent flow from a horizontal cylinder; $h_{tur} = 0.18 \times (\Delta T)^{0.33}$

Or $h_{tur} = 0.18 \times (170 - 78)^{0.33} = 0.81$ Btu/ft^2 F hr

Step # 3 (Find the heat loss for uninsulated surface)

Assuming emissivity E = 0.90, the tank heat loss from the tank is given by equation:

$Q_{uninsulated} = h \times A \times (Ts – Ta) + y \times A \times E \times (Ts^4 – Ta^4)$

$$A = L\pi D + \frac{\pi}{2}D^2 = 6 * 3.14 * 2.5 + 3.14 * (2.5)^2 = 56.9 \text{ ft}^2$$

$Q_{uninsulated} = 0.81 * 56.9 * (170 – 78) + (0.1714 \times 10^{-8}) * 56.9 * 0.9 * ((170 + 460)^4 – (78 + 460)^4)$

$Q_{uninsulated} = 10714$ Btu/hr

Step # 4 (Find the resistance value of insulation)

Conductivity of the insulation; k = 0.30 Btu in / hr ft^2 F = 0.025 Btu/hr ft F.

The thermal resistance of two inches of insulation in the radial direction would be about:

$R_{insulation} = \ln (R_o / R_i) / 2\pi k$, where

R_i = internal radius of insulation = ½ diameter of tank = 1.25 ft and

R_o = outer radius of insulation = ½ diameter of tank + insulation thickness (ft) = 1.42 ft

Therefore $R_{insulation}$ = ln (1.42 / 1.25) / 2 * 3.14 * 0.025 = 0.81 hr F ft / Btu

Step # 5 (Find the heat loss from an insulated surface)

Assuming steady state conditions, the heat loss through the insulation would equal the heat loss from the insulation surface by convection and radiation.

$h \times A \times (T_{os} - T_a) + y \times A \times E \times (T_{os}^{\,4} - T_a^{\,4}) = A * (T_{is} - T_{os}) / R$

Or

$Q/L = h * (\pi * D) * (T_{os} - T_a) + y * (\pi * D) * E * (T_{os}^{\,4} - T_a^{\,4}) = (T_{is} - T_{os}) / R_{insulation}$

The above equation can be rearranged and solved for the temperature of the outer surface of the insulation T_{os}:

$0 = h * (\pi * D) * (T_{os} - T_a) + y * (\pi * D) * E * (T_{os}^{\,4} - T_a^{\,4}) - (T_{is} - T_{os}) / R_{insulation}$

$h_{tur} = 0.18 \times (\Delta T)^{0.33} = 0.18 \times (T_{os} - T_a)^{0.33}$

$0 = 0.18 \times (T_{os} - T_a)^{0.33} * (\pi * D) * (T_{os} - T_a) + y * (\pi * D) * E * (T_{os}^{\,4} - T_a^{\,4}) - (T_{is} - T_{os}) / R_{insulation}$

Where (π * D) is 3.14 * 2.5 = 7.85

$= 0.18 * (T_{os} - 78)^{1/3} * 7.85 + (0.1714 \times 10^{-8}) * 7.85 * 0.9 * ((T_{os} + 460)^{4} - (78 + 460)^{4}) - (170 - T_{os}) / 0.81$

Or T_{os} = 88°F

The heat loss through the cylindrical walls of an insulated tank would be about:

$Q = L * (T_{is} - T_{os}) / R_{insulation}$ = 6 * (170 – 88) / 0.81 = 607 Btu / hr

The heat loss through the two flat ends would be about:

$Q = A * (T_{os} - T_a) / (R + 1/f) = 2 * 3.14 * (2.5)^2 / 4 * (88 - 78) / (2 / 0.3 + 1/1.1) = 13$ Btu / hr

The total heat loss = Heat loss from walls + Heat loss from 2 ends = 607 + 13 =620 Btu / hr

Step # 6 (Estimate Savings)

Assuming the efficiency of the boiler is 60%, 8760 hours operation per year the energy savings (natural gas) would be about:

$E_{savings} = (Q_{uninsulated} - Q_{insulated}) / ή_{boiler} = (10714 - 620) / 0.6 \times 8760 = 147.4 \times 10^6$ Btus / yr

Heat value of natural gas = 1 m Btus per mcf

Savings in Natural Gas = 147.4 mcf per annum

Illustration # 3

Standard Reference Tables of Heat Losses in Steam Distribution Piping

Consider for example the following set of conditions for steam distribution piping downstream of boiler:

1) Pipe steel emmitance - 0.8
2) Wind Speed- 0 mph
3) Ambient Temperature- 75°F
4) 8 760 Hours/Year operation
5) Conversion Efficiency- 75%
6) #6 grade Fuel Oil,
7) Heat Content per Gallon 138,700 BTU's,
8) Cost per gallon- $0.60

The effect of un-insulated piping v/s insulated piping; operating under same set of conditions is illustrated below in Table 1 & Table 2:

Table -1

Uninsulated Steam Line Losses

Steam Pressure (PSI)	Pipe Diameter 2 Inches	Pipe Diameter 4 Inches	Pipe Diameter 6 Inches	Pipe Diameter 8 Inches	Pipe Diameter 10 Inches
100	452.5 Btu/ft/hr 3,964,000 Btu/ft/yr $22.68 Loss/ft/yr.	794.7 Btu/ft/hr 6,959,000 Btu/ft/yr $40.14 Loss/ft/yr	1131 Btu/ft/hr 9,908,000 Btu/ft/yr $57.15 Loss/ft/yr	1434 Btu/ft/hr 1.256 x10^7 Btu/ft/yr $72.44 Loss/ft/yr.	1751 Btu/ft/hr 1.534 x10^7Btu/ft/yr $88.46 Loss/ft/yr
150	533.2 Btu/ft/hr. 4,671,000 Btu/ft/yr $26.94 Loss/ft/yr	938.1 Btu/ft/hr. 8,218,000 Btu/ft/yr $47.40 Loss/ft/yr	1337 Btu/ft/hr. 1.171 x10^7 Btu/ft/yr $67.56 Loss/ft/yr	1697 Btu/ft/hr. 1.486 x10^7Btu/ft/yr $85.72 Loss/ft/yr	2073 Btu/ft/hr. 1.816 x10^7Btu/ft/yr $104.70 Loss/ft/yr
200	602.6 Btu/ft/hr. 5,279,000 Btu/ft/yr $30.45 Loss/ft/yr	1062 Btu/ft/hr. 9,302,000 Btu/ft/yr $53.65 Loss/ft/yr	1515 Btu/ft/hr. 1.327 x10^7 Btu/ft/yr $75.56 Loss/ft/yr	1923 Btu/ft/hr. 1.685 x10^7 Btu/ft/yr $97.18 Loss/ft/yr	2351 Btu/ft/hr. 2.060 x10^7 Btu/ft/yr $118.80 Loss/ft/yr
250	660.6 Btu/ft/hr. 5,787,000 Btu/ft/yr $33.38 Loss/ft/yr	1166 Btu/ft/hr. 1.021 x10^7 Btu/ft/yr $58.90 Loss/ft/yr	1665 Btu/ft/hr. 1.458 x10^7 Btu/ft/yr $84.11 Loss/ft/yr	2114 Btu/ft/hr 1.852 x10^7 Btu/ft/yr $106.80 Loss/ft/yr	2585 Btu/ft/hr. 2.265 x10^7 Btu/ft/yr $130.60 Loss/ft/yr

The table below provides loss data for the same parameters as above with a difference that the pipelines are insulated and aluminum jacketed for external protection. The insulation material considered is Perlite pipe block conforming to ASTM C610-99 and the aluminum cladding is considered to be 0.1 emissive. The insulation thickness considered is sufficient to limit the surface temperature to 120°F or less.

Table - 2

Insulated Steam Line Savings

Steam Pressure (PSI)	Pipe Diameter 2 Inches	Pipe Diameter 4 Inches	Pipe Diameter 6 Inches	Pipe Diameter 8 Inches	Pipe Diameter 10 Inches
100	2.5 inches insulation 477,700 Btu/ft/Yr $20.10 ft/yr saving	3.0 Inches Insulation 634,600 Btu/ft/yr $36.48 ft/yr saving	3.0 Inches Insulation 835,800 Btu/ft/yr $52.33 ft/yr saving	3.0 Inches Insulation 981,100 Btu/ft/yr $66.78 ft/yr saving	3.5 Inches Insulation 1,064,000 Btu/ft/yr $82.32 ft/yr saving
150	2.5 inches insulation 544,100 Btu/ft/yr $23.80 ft/yr saving	3.0 Inches Insulation 722,700 Btu/ft/yr $43.23 ft/yr saving	3.5 Inches Insulation 852,400 Btu/ft/yr $62.64 ft/yr saving	3.5 Inches Insulation 1,021,000 Btu/ft/yr $79.83 ft/yr saving	4.0 Inches Insulation 1,115,000 Btu/ft/yr $98.27 ft/yr saving
200	3.0 Inches Insulation 552,300 Btu/ft/yr $27.26 ft/yr saving	3.5 Inches Insulation 734,500 Btu/ft/yr $49.41 ft/yr saving	4.0 Inches Insulation 870,900 Btu/ft/yr $71.54 ft/yr saving	4.0 Inches Insulation 1,038,000 Btu/ft/yr $91.19 ft/yr saving	4.5 Inches Insulation 1,138,000 Btu/ft/yr $112.20 ft/yr saving
250	3.0 Inches Insulation 593,000 Btu/ft/yr $29.96 ft/yr saving	3.5 Inches Insulation 788,600 Btu/ft/yr $54.35 ft/yr saving	4.0 Inches Insulation 935,000 Btu/ft/yr $78.72 ft/yr saving	4.5 Inches Insulation 1,039,000 Btu/ft/yr $100.80 ft/yr saving	5.0 Inches Insulation 1,145,000 Btu/ft/yr $124.00 ft/yr saving

Using tables 1 & 2, the reader should note that one foot of uninsulated 10" steam line operating at 250 PSI would consume approximately 217 gallons of fuel. The data & calculations are as follows:

Uninsulated 10" steam line @ 250 PSI, Refer table # 1

1) Heat loss = 2.265×10^7 Btu/ft/yr
2) Heat content of fuel per gallon = 138,700 BTU's
3) Conversion Efficiency- 75%
4) Fuel consumption = Heat loss/ (Heat content of fuel * Conversion efficiency)
5) Or fuel consumption = 2.265×10^7 / (138,700 * 0.75) = 217 gallons
6) Cost of fuel = $ 0.6 per gallon
7) Total cost of fuel = 217 * 0.6 = $130.6

With 5" of Perlite Insulation applied to 10" pipeline operating @250 PSI, Refer table# 2,

1) Heat loss = 1,145,000 Btu/ft/yr
2) Heat content of fuel per gallon = 138,700 BTU's,
3) Conversion Efficiency- 75%
4) Fuel consumption = Heat loss/ (Heat content of fuel * Conversion efficiency)
5) Or fuel consumption = 1,145,000 / (138,700 * 0.75) = 11 gallons
6) Cost of fuel = $ 0.6 per gallon
7) Total cost of fuel = 11 * 0.6 = $6.6
8) *Potential savings $130.6 - $ 6.6 = $ 124 per ft per year*

Similarly the savings can be computed for un-lagged valves and fittings. The heat losses from un-insulated gate valves are tabulated below:

Table - 3

Heat Energy Losses from Un-insulated Gate Valves in Btu/hr

Operating Temp. (^oF)	3"Valve	4" Valve	6" Valve	8" Valve	10" Valve	12" Valve
200	1,690	2,020	3,020	4,030	4,790	6,050
300	3,630	4,340	6,500	8,670	10,300	13,010
400	6,260	7,470	11,210	14,940	17,750	22,420
500	9700	11,680	17,575	23,170	27,510	34,750
600	14,150	16,900	25,340	33,790	40,130	50,690

Consider a 6" gate valve on a 400^{o}F line.

Considering yearly total hours of plant operation on 8760 hours basis (24/7/365 continuous operation), the heat loss amounts to (8760 x 11,210)/0.75 = **130.9 MM/Btu Year**

We can now estimate the savings achievable by insulating this valve with a Perlite block valve cover from the table-2.

Considering the fuel oil cost of $0.6 USD per gallon, the calorific value of the fuel as 138,700 Btu/Gallon, and the conversion factor is 75%. Then the cost per MM/Btu will be:

Cost of fuel per MM Btu = (10^6/138,700) x 0.6 = *$4.32 USD per MM/Btu*

Yearly financial losses due to un-insulated 6" gate valve on 250PSI steam line = 130.9 x 4.32 = *$565.49 USD per Year*

Note that the financial loss incurred is for a single valve only. The total losses incurred shall be much higher on numerous valves in the facility. *As a rule of thumb, the heat loss from un-insulated flange would have the heat loss as about 0.5 m of same size uninsulated pipe and an un-insulated valve could have more than twice this.*

Factors that affect Heat Loss/Gain

Quantitative heat transfer is proportional to the heat transfer surface area, temperature differential and the thermal conductivity (k-value) of the insulation material. Other than these, the other important factors that affect heat gain/loss through the surface are:

Insulation Finishes & Emissivity

With insulation systems, the surface finish or emissivity of the cladding (jacketing) over insulation needs to be considered.

Emissivity is defined as the relative power of a surface to emit heat by radiation. The emissivity (E) of a surface material is measured on a scale 0 to 1. In practice both the values 0 and 1 are unachievable. The emittance of 0.1 is considered to be representative of aluminum jacketing. An emittance of 0.8 is considered to be representative of non-metallic surfaces.

A dull finish increases the emissivity and thereby allows more heat to radiate from the system. A reflective metal finish decreases the emissivity and retains more heat within the system. Depending on the particular temperature requirement of the process, the amount of heat transferred can be controlled by both insulation thickness and the emissivity of the jacketing.

Surface Resistance

With dull finish of plain fabric, the resistance to heat loss is low or it allows more heat to radiate from the system.

Table below shows the variations of surface resistances (resistance to heat loss) for still air with different finishes.

Values for Surface Resistances for Still Air in ft^2 °F / Btu				
$T_{SURFACE} - T_{AMBIENT}$		Plain Fabric Dull Metal	Stainless Steel	Aluminum
°F	°C	E = 0.95	E = 0.4	E = 0.2
10	5	0.53	0.81	0.90
25	14	0.52	0.79	0.88
50	28	0.50	0.76	0.86
75	42	0.48	0.75	0.84
100	55	0.46	0.72	0.80

Table below illustrates the effect of surface coefficient on heat losses and surface temperature for a 6" (150 mm) pipe in ambient air at 86°F (30° C) for different operating temperature values.

Reference is for Aluminum (E = 0.2), Stainless Steel (E = 0.4) and Cloth (E = 0.95). Surface temperature Ts is in °C. Q is heat loss in Kcal/hr/meter run; and k is thermal conductivity in Kcal/hr/m/°C (For conversion 1Kcal = 3.56 BTU)

Temperature	Insulation	Cloth		Galvanized Steel		Aluminum	
Deg C		Q	Ts	Q	Ts	Q	Ts
100	25mm; k= 0.041	85.9	41	87.9	43	78.8	46
100	50mm; k= 0.041	42.0	36	42.0	37	40.0	39
300	50mm; k= 0.052	205.5	53	203	57	196.6	63
300	100mm; k= 0.052	94.1	42	91.5	44	91.2	48
500	100mm; k= 0.067	206.5	53	204.9	57	201.3	64
500	150mm; k= 0.067	127.9	45	126.4	48	124.3	53

Wind Speed

Increased air movement has greater effect on heat loss from bare piping than from insulated piping.

Table below shows the effects of wind velocity on heat loss from bare and insulated surfaces.

Reference is for 150 mm pipe at 300°C, ambient temperature 30°C, Insulation k = 0.0515 kcal/m/hr/°C and finish galvanized mild steel.

Effect of wind velocity on heat loss (kcal/m/hr)					
Wind Velocity (m/sec)	Bare	Insulation Thickness			
		25mm	50mm	75mm	100mm
0	3415	507	307	232	191
1	4197	537	319	238	198
5	7086	572	330	247	205
10	10490	576	336	248	206

Factors that contribute to pipeline insulation degradation:

1) Failure to repair or replace damaged pipe insulation after repairs to pipeline components or fittings
2) Steam leaks and moisture contaminate insulating material
3) Failure to correctly prioritize maintenance tasks and resources
4) Lack of awareness concerning cost of steam and the potential financial losses incurred
5) Production constraints
6) Failure of engineering personnel and management to prioritize and manage available resources
7) Magnitude of potential financial losses not understood at engineering and production management level.
8) For reasons of their shape; valves and fittings tend to be overlooked in pipeline insulation projects.
9) Access difficulties; "Out of site, out of mind."

Practices for effective maintenance of insulation

Insulation systems must be inspected and maintained to ensure that the system continues operation according to design. Periodic inspections are needed to determine the presence of moisture, which will lower the insulation thermal efficiency, often destroying the insulation system. Further, corrosion may develop on the exterior surface of the pipe, if moisture is present and the temperature is above 25°F (-4°C).

The Frequency of inspection should be determined by the critical nature of the process, the external environment and the age of the insulation system. The following practices are suggested for O&M personnel:

1) Regular and timely energy audits.
2) Regular use of thermographic equipment to isolate areas of concerns.
3) Follow-up for completion of audits findings on regular basis.

4) Heat balance of the system on routine basis.
5) Communication to all concerned departments of heat losses and increase in fuel consumption.
6) Computing specific energy consumption i.e. developing energy use pattern per unit of production.
7) The extent of moisture present within the insulation system and (or) the corrosion of the pipe will determine the need to replace the insulation. Replace all soaked / compressed insulation.
8) Routing examination of the pipe & equipment surfaces for corrosion, if the insulation is physically wet.
9) Addition of insulation based on the revised temperature conditions.
10) Ensuring fresh insulation material receipts as per specifications given by the licensor.
11) Regular maintenance of insulation systems. The practices include:
    - Look for jacketing integrity and open seams around all intersecting points such as pipe transitions, branches and tees.
    - Look for signs of moisture or ice on the lower part of horizontal pipe, at the bottom elbow of a vertical pipe, and around pipe hangers/saddles as moisture may migrate to low areas.
    - Look for bead caulking failure especially around flange and valve covers.
    - Look for cloth visible through the mastic or finish if the pipe is protected by a reinforced mastic weather barrier.
    - Additionally, as the line operates, it must be continuously inspected for any breaches in the vapor and/or weather barrier to protect the insulation from moisture infiltration. If any damage is sighted, it is imperative to take action immediately and repair it.

Quality of Insulation Job

Five distinct components characterize a quality insulation job. It is important to define and distinguish each one.

1) **Insulation Material**

   The insulation itself should be a low thermal conductivity material with low water vapor permeability and it should be non-wicking.

2) **Insulation Joint Sealant**

   All insulations particularly those operating at below ambient conditions should utilize a joint sealant. The joint sealant should be applied as a full bedding coat to all sealant joints. A properly designed and constructed insulation/sealant/insulation joint will retard liquid water and water vapor migration through the insulation system.

3) **Vapor Retarders**

Vapor retarders function to prevent water vapor infiltration, thus keeping the insulation dry. Closed-cell insulation materials have lower tendency to absorb water. But typically most of the insulation material will absorb a certain amount of water. Care should be taken to either use low permeance (water vapor permeability less than 0.1 perm-inches) insulation materials or use a continuous and effective vapor retarder system. The vapor retarder application along with closed-cell insulation material should be considered for cold surfaces to prevent surface condensation.

The service life of the insulation and pipe depends primarily on the in-place water vapor permeance of the vapor retarder. Therefore, the vapor retarder must be free of discontinuities and penetrations. The insulation and the vapor retarder will expand and contract with ambient temperature cycling. The vapor retarder system must be installed with a mechanism to permit this expansion and contracting without compromising the integrity of the vapor retarder.

4) **Jacketing**

The purpose of jacketing on the pipe and vessel surfaces is to prevent weather and abrasion damage to vapor retarder and insulation. Protective jacketing is also required whenever piping is exposed to wash downs, physical abuse or traffic. Various plastic and metallic products are available for this purpose.

The jacketing must be of the band type, which holds and clamps the jacketing in place circumferentially. Pop rivets, sheet metal screws, staples or any other item that punctures should not be used because they will compromise the vapor retarder.

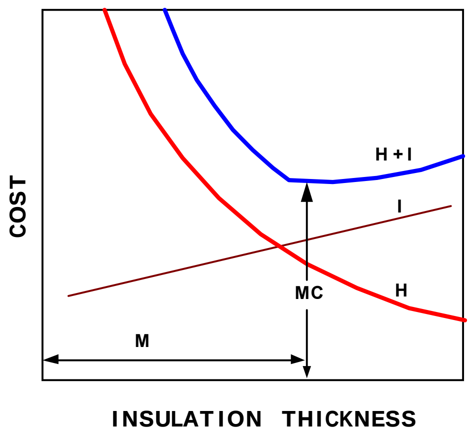
5) **Weather Barrier Joint Sealant**

All metal-jacketed insulation systems operating at below ambient conditions should utilize a weather barrier joint sealant. The joint sealant should be a liquid water resistant elastomeric material available to bond to the specified metal surface. The joint sealant is applied to all joints to prevent driven water from migrating through the joints, accumulating within the insulation system.

Section II- Acceptable levels of Insulation

Insulation of any thermal system means capital expenditure. Therefore, one of the most important factors in any insulation system is to analyze the thermal insulation with respect to cost.

The effectiveness of insulation follows the law of diminishing returns. The reciprocal of the amount of insulation used, for instance, 1, ½, 1/3, 1/4… the first insulation is most valuable, with every succeeding increment less so. There is a definite economic limit to the amount of insulation, which is justified, i.e. there is a thickness below which the insulation is insufficient and the loss of heat is more. An increased thickness is wasteful in terms of cost, and cannot be recovered through small heat savings. This limiting value, termed economic thickness of insulation is that thickness of insulation at which the costs of heat loss, plus the installed cost of insulation is at a minimum, over a given period of time. The figure below demonstrates this principle.



Where

I = Cost of Insulation

H = Cost of Heat Loss

I + H = Total Cost

M = Economic Thickness

MC = Minimum Cost

The determination of economic thickness requires the attention to the following factors:

1) Value of fuel (fuel cost plus cost of labor, maintenance etc)
2) Annual hours of operation
3) Heat content of fuel
4) Efficiency of combustion of fuel
5) Average exposure ambient still air temperature
6) Required exterior surface temperature (120^{o}F default)

7) Pipe diameter/thickness of surface

8) Type of insulation material

9) Estimated cost of insulation installed

10) Amortization (repayment) period

11) Heat loss per linear meter (or square meter, if a flat surface is used)

Assessment of Insulation Thickness

Broadly speaking, the exercise to select the economic thickness and type of insulation is influenced by three important factors;

1. Economics
2. Safety
3. Process Conditions

The first part is facilitated by comparing the heat losses vis-à-vis the possible savings and the investment on the total installed cost of insulation over a period of time.

The second part is the safety. One of the invaluable rules of thumb refers to limit the surface temperature to less than 130^{o}F.

The third part of the assessment pertains to the effect of heat losses on the physical state of the fluid being transported. Excessive long run of pipes shall deliver working fluids at comparatively lower temperatures and in the case of steam; it could be delivered in a very wet saturated condition.

Bearing these provisos in mind, the exercise to select the economic thickness and type of insulation varies with the particular application.

Economics

Economic thickness of insulation is a well-documented calculation procedure. The calculations typically take in the entire cost of installing the insulation including plant depreciation. When we say the total cost, it includes the material, labor and installation cost of finishing materials as well. This is particularly relevant when comparing high performance insulation with more conventional materials. If a 2” diameter pipe is insulated with 1” of high performance insulation instead of the 3” of conventional insulation then the surface area is reduced by a factor of 3. If the surface cladding is stainless steel then the cost savings would go a long way towards paying for the higher cost of the high performance insulation.

It must also be borne in mind that insulation takes up space, for example an adequate gap is required between pipes to accommodate insulation. The space constraint in some locations for instance in routing of air-conditioning ducts over false ceiling is sometime a limiting factor. The low thickness high performance insulation shall be less taxing on the space.

The insulation adds to the weight implying that the higher thickness of insulation can mean higher stress and additional supports which will all add to the capital cost. The loading on the insulation material is a function of its compressive strength. ASME B31 standards establish basic stress allowances for the piping material.

Standard data charts for calculating the economic thickness of insulation are widely available. Below are the economic thickness tables that have been adapted from Perry's Chemical Engineers' Handbook:

Table- 1

ECONOMIC THICKNESS OF INDOOR INSULATION AT VARIOUS PIPE TEMPERATURES IN °F

(At 80° F Still Ambient Air for Aluminum Clad Calcium Silicate Insulation)

Pipe Diameter (Inches)	Insulation Thickness (Inches)	Energy Costs, $ per million BTU							
		1	2	3	4	5	6	7	8
0.75	1.5	950	600	550	400	350	300	250	250
	2				1100	1000	900	800	750
	2.5				1750	1050	950	850	800
	3								1200
1	1.5	1200	800	600	500	450	400	350	300
	2			1200	1000	900	800	700	700
	2.5					1200	1050	1000	900
	3						1100	1150	950
1.5	1.5	1100	750	550	450	400	400	350	300
	2			1000	850	700	650	600	500
	2.5				1050	900	800	750	650
	3						1150	1100	1000
2	1.5	1050	700	500	450	400	350	300	300
	2			1050	850	750	700	300	600
	2.5			1100	950	1000	750	700	650
	3				1200	1050	950	850	800
4	1.5	950	600	500	400	350	300	300	250
	2		1100	850	700	600	550	500	450
	2.5			1200	1000	850	750	700	650
	3				1050	900	800	750	700
	3.5							1150	1050
6	1.5	600	350	300	250	250	200	200	200
	2		1100	850	700	600	550	500	500
	2.5			900	800	650	600	550	550
	3			1150	1000	850	750	700	600
	3.5						1100	1000	900
	4								1200
10	2		1100	850	700	650	550	500	450
	2.5		1200	900	750	700	600	550	500
	3			1050	900	750	700	600	550
	3.5					1200	1050	950	900
	4								1200
16	2	950	650	500	400	350	300	300	300
	2.5		1000	800	700	600	550	500	450
	3		1200	950	800	700	600	550	500
	3.5					1150	1050	950	850
	4					1200	1100	1000	900
	4.5						1150	1050	950

Table- 2

ECONOMIC THICKNESS OF OUTDOOR INSULATION AT VARIOUS PIPE TEMPERATURES IN °F

(At 60° F Average Speed 7.5 mph for Aluminum Clad Calcium Silicate Insulation)

Pipe Diameter (Inches)	Insulation Thickness (Inches)	Energy Costs, $ per million BTU 1	2	3	4	5	6	7	8
0.75	1	450	300	250	250	200	200	150	150
	1.5	800	500	400	300	250	250	200	200
	2			1150	950	850	750	700	650
	2.5			1100	1000	900	800	750	700
1	1	400	300	250	200	200	150	150	150
	1.5	1000	650	500	400	350	300	300	250
	2			1100	900	800	700	700	600
	2.5				1200	1050	950	850	800
	3					1100	1000	900	850
1.5	1	350	250	200	200	150	150	150	150
	1.5	900	600	450	350	300	300	250	250
	2		1000	850	700	600	550	500	450
	2.5			1150	950	800	750	700	600
	3					1200	1050	1000	900
2	1	350	250	200	150	150	150	150	150
	1.5	900	550	450	400	300	300	250	250
	2		1150	900	750	650	600	550	550
	2.5			1000	850	750	650	600	600
	3				1050	950	850	750	700
4	1	250	200	150	150	150	150	150	150
	1.5	750	500	350	300	250	250	200	200
	2		950	750	600	500	450	400	350
	2.5		1150	950	750	650	600	500	500
	3			1150	1000	850	750	650	600
	3.5								1150
6	1	250	150	150	150	150	150	150	150
	1.5	450	300	200	200	150	150	150	150
	2		900	700	600	500	450	400	350
	2.5		1050	800	650	600	500	450	400
	3			1050	900	750	700	600	550
	3.5					1150	1050	950	850
	4							1200	1150
	4.5								1200

Example-1:

Consider a 6" pipe at 500 ^{0}F temperature in an indoor setting. With an energy cost of $5.00/million Btu, what is the economic thickness?

Answer: From the table-1 above for indoor insulation, corresponding block to 6.0 in pipe and $5.00/million Btu energy costs; we see temperatures of 250 ^{0}F, 600 ^{0}F, 650 ^{0}F, and 850 ^{0}F. Since our temperature does not meet 600 ^{0}F, we use the thickness before it. In this case, 250 ^{0}F corresponds to 1.5" of insulation. At 600 ^{0}F, we would increase to 2.0" of insulation.

Economic thickness charts from other sources will work in much the same way as this example.

Economic Thickness and the Present Energy Cost

As discussed above, the thermal insulation thickness that satisfies an economic assessment of the minimal cost of owning and operating a thermal system is called the economic thickness. The economic thickness pays for itself besides earning a return over its original cost. From this definition, any changes occurring in the prices of fuel or in the insulation cost will tend to shift the economic thickness to another value. Therefore the insulation levels, which were uneconomical in the year 70's, may be quite lucrative now due to drastic increase in fuel prices in the recent years. Based on the prevailing cost structure one has to review the entire insulation system and assess if additional insulation is necessary to achieve optimum economy.

Find below are the generic tables- 3 & 4, indicating the economic thickness of insulation in inches with surface exposed to 10 mph wind. The tables have been calculated using surface emittance of 0.1 and ambient temperature of 70°F. Notice that the thickness increases when the energy cost is higher.

Given the importance of cost of energy as a factor, two levels of energy cost were considered: $3 per million BTUs and $6 per million BTUs. These costs are for energy delivered to the system being considered including energy conversion efficiency and other losses.

Table- 3

Insulation Thickness when energy cost is $3 per million BTUs

Nom. Pipe Diameter (inches)	Process Temperature (°F)					
	200	400	600	800	1000	1200
½	1	1	1.5	2.5	2.5	3
1	1	1.5	2	2.5	3	3
2	1	1.5	2	3	3	4
3	1	2	2.5	3	4	4
4	1	2	2.5	3	4	4
5	1	2	3	4	4	4
6	1.5	2	3	4	4	4
8	1.5	2.5	3	4	4	4
10	1.5	2.5	3	4	4	4
12	1.5	2.5	4	4	4	4
16	1.5	2.5	4	4	4	6
20	1.5	2.5	4	4	4	6
24	1.5	2.5	4	4	4	6

Source: U.S. Department of Energy; Energy Efficiency and Renewable Energy Office of Industrial Technologies Washington, D.C. 20585 from September, 1995 ORNL/M-4678

Table- 4
Insulation Thickness when energy cost is $6 per million BTUs

Nom. Pipe Diameter (inches)	Process Temperature (°F)					
	200	400	600	800	1000	1200
½	1	1.5	2.5	3	3	3
1	1	2	3	3	4	4
2	1.5	2.5	3	4	4	4
3	1.5	2.5	4	4	4	4
4	1.5	3	4	4	4	6
5	1.5	3	4	4	4	6
6	1.5	3	4	4	6	6
8	1.5	3	4	4	6	6
10	1.5	4	4	4	6	6
12	2	4	4	4	6	6
16	2	4	4	6	6	8
20	2	4	4	6	6	8
24	2	4	4	6	6	8

Source: U.S. Department of Energy; Energy Efficiency and Renewable Energy Office of Industrial Technologies Washington, D.C. 20585 from September 1995 ORNL/M-4678

Methodology of computing economic thickness

Step #1 Compute the heat loss per year on 100 ft of surface

Step #2 Compute the installed insulation cost per year. This figure is equivalent to cost of 100 linear feet of insulation divided by the amortization period* (years of repayment).

Step #3 Add the cost of heat to the insulation cost.

Step #4 Plot this summation for various values of insulation thickness, the lowest point on the curve indicates economic thickness.

Mathematical analysis for determining optimum thickness is as under:

Cost of heat loss per year = $q * N * P / (n * H)$ in $ per year

Where

N = Number of hours of operation of plant per year

P = Price of fuel in $ per gallon

n = Efficiency of generation or conversion

H = Gross calorific value of fuel in BTU per gallon

q = Heat loss in BTUs per hour

Annual Cost of Insulation = c/a

Where

c = Cost of insulation including outer protective covering

a = Amortization period

Amortization period is defined by

$a = 1/ (r/100 + 1/z)$

Where

r = Percentage return on capital

z = Plant life in years

The cost of heat losses per year is computed for a range of insulation thickness at ½" intervals and tabulated. These costs are added to each thickness and from that the minimum cost becomes apparent.

The following case shall illustrate the computation of economic thickness.

A process industry has a package boiler using furnace oil as fuel. Efficiency of the package boiler is 80%. The plant operates for 6000 hours each year. It is now required to calculate the economic thickness of insulation for a cylindrical surface (steam pipe) whose hot face temperature is 300°F.

Insulation material being used is the mineral wool with a density of 120 kg/cum. The outer surface of insulation is covered with thin aluminum sheet of 0.56mm thickness.

Cost of fuel = $ 0.60 per gallon

Calorific value of fuel = 138,700 BTU's per gallon

Boiler efficiency = 75%

Plant operational hours = 6000 hours per year

Rate of capital required = 20%

Assume plant life = 5 years

Average ambient temperature = 75°F

Cost of useful heat = 0.60 / 0.75 * 138700 = $ 0.0000058 per BTU

Cost of useful heat per annum = $ 0.035 per BTU per annum

Amortization period (yrs of repayment) = 1/ (.2 + 1/5) = 2.5 years

Tabulation of heat losses and insulation cost for cylindrical surface at 300°F

Insulation Thickness (inches)	Heat loss / year (Btu per 100 ft length)	Annual Cost ($ / 100 ft) of		
		Heat Loss (Btu) (a)	Insulation * (b)	Total Cost ($ / 100 ft) (a) + (b)
1"	4120	144	80	224
1½"	3460	121	92	213
2"	3140	110	100	210
2½"	2800	98	108	206
3"	2650	93	122	215
3½"	2450	86	134	220
4"	2400	84	142	226

* Annual cost of insulation = Total cost of insulation / Amortization period

Per definition, the economic thickness is a thickness at which cost of heat loss plus the installed cost of insulation is minimum. Therefore the economic thickness in example above is 2½".

The data reflected in the table are for guidance only. The purpose of above example is to provide a direction regarding proper use of application of such data, so that engineer and designer involved in selection of economical thickness can make the appropriate decision and/or apply proper engineering judgment. In real situations the total cost of insulation should be estimated from the supplier's data and the heat loss figures could be quantified from standard tables.

For quicker evaluation of insulation levels, the tables 1 to 4 above could be utilized.

Safety

Pipes and surfaces that are readily accessible by workers are subject to safety constraints. The recommended safe "touch" temperature range is from 130 ^{0}F to 150 ^{0}F (54.4 ^{0}C to 65.5 ^{0}C). Insulation calculations aim to keep the outside temperature of the insulation around 120 to 140 ^{0}F (60 ^{0}C). An additional tool employed to help meet this goal is aluminum covering wrapped around the outside of the insulation. Aluminum's thermal conductivity of 209 W/m K (390 Btu/h ft ^{0}F) does not offer much resistance to heat transfer, but it does act as another resistance while also holding the insulation in place. Typical thickness of aluminum used for this purpose ranges from 0.2 mm to 0.4 mm.

When considering safety, engineers need a quick way to calculate the surface temperature that will come into contact with the workers. Using heat balance equations is certainly a valid means of estimating surface temperatures, but it may not always be the fastest. Charts are available that utilize a characteristic called "equivalent thickness" to simplify the heat balance equations.

Since the heat loss is constant for each layer, calculate Q for the bare pipe, and then solve equation below for $T_{surface}$ (surface temperature). If the economic thickness results in too high a surface temperature, repeat the calculation by increasing the insulation thickness by 1/2 inch each time until a safe touch temperature is reached.

$$\textbf{Equivalent Thickness} = k\,R\,\frac{T_{inside\ pipe} - T_{surface}}{T_{surface} - T_{ambient}}$$

Where

k = is the thermal conductivity of insulation at mean average temperature

R = surface resistance

The equation above can be used to easily determine how much insulation will be needed to achieve a specific surface temperature.

Example-2:

A 16" pipe contains a heat transfer fluid at 850 ^{0}F (454 ^{0}C) and it needs to be covered with insulation so that the surface temperature does not exceed 130 ^{0}F. The design ambient temperature is 85 ^{0}F (29.4 ^{0}C). Assume the pipe shall be provided with calcium silicate insulation with aluminum cladding. Find the equivalent thickness of the insulation.

Step # 1: For $T_{surface} – T_{ambient}$ = 130 ^{0}F - 85 ^{0}F = 45 ^{0}F, determine the R_s value for aluminum. From standard tables R_s = 0.865 h ft^2 ^{0}F/Btu.

Step # 2: For average mean temperature of ($850\ ^0F + 85\ ^0F$)/2 = $467.5\ ^0F$, select the thermal conductivity of calcium silicate insulation (k_{ins} = 0.0365 Btu/h ft ^0F) from manufacture's tables.

Step # 3: Compute the Equivalent thickness using the relation

$$\text{Equivalent Thickness} = k\,R\,\frac{T_{\text{inside pipe}} - T_{\text{surface}}}{T_{\text{surface}} - T_{\text{ambient}}}$$

$$\text{Equivalent Thickness} = (0.0365\ \text{Btu/h ft}\ ^0\text{F})(0.865\ \text{h ft}^2\ ^0\text{F/Btu})\ \frac{850\ ^0\text{F} - 130\ ^0\text{F}}{130\ ^0\text{F} - 85\ ^0\text{F}}$$

Equivalent Thickness = 6.1 in (155 mm)

The equivalent thickness is a baseline. The manufacturer data charts show the actual thickness corresponding to the equivalent thickness. For instance, for calcium silicate material equivalent thickness of 6.1" corresponds to nearly 5" of insulation (Refer to manufacturer's catalogues).

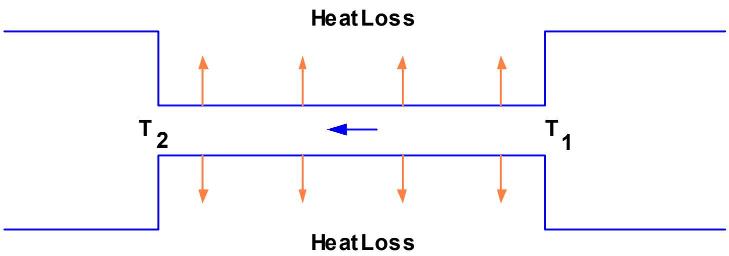
As a standard practice, the table below provides data for the insulation thickness required to obtain surface temperature below 125°F with Zero Wind and calculated using emittance 0.1 and ambient temperature 80°F.

Nom. Pipe Diameter (inches)	Process Temperature (°F)					
	200	400	600	800	1000	1200
½	1	2	3	5	7	10
1	1	2	3.5	6	8	>10
2	1	2.5	4.5	7	9	>10
3	1	2.5	5	8	>10	>10
4	1	3	5	8	>10	>10
5	1	3	6	9	>10	>10
6	1	3	6	9	>10	>10
8	1	3.5	6	10	>10	>10
10	1	3.5	7	10	>10	>10
12	1	3.5	7	10	>10	>10
16	1	4	8	>10	>10	>10
20	1	4	8	>10	>10	>10
24	1	4	8	>10	>10	>10

Source: U.S. Department of Energy; Energy Efficiency and Renewable Energy Office of Industrial Technologies Washington, D.C. 20585 from September, 1995 ORNL/M-4678

Process Conditions

The temperature of a fluid inside an insulated pipe is an important process variable that must be maintained from one node to another in most situations. Consider the length of pipe connecting two pieces of process equipment shown below:



The fluid is flowing from equipment 1 at temperature T_1 to equipment 2. In order to predict T_2 for a given insulation thickness, we first make the following assumptions:

1. Constant fluid heat capacity over the fluid temperature range
2. Constant ambient temperature
3. Constant thermal conductivity for fluid, pipe, and insulation
4. Constant overall heat transfer coefficient
5. Turbulent flow inside pipe
6. 15 mph wind for outdoor calculations

For pipe surface the heat transfer is governed by equation:

$$Q = 2\pi R_3 L\ U\ \Delta T_{LM}$$

Where

$$U = \frac{1}{\dfrac{R3}{R1\ h_i} + \dfrac{R3\ \log_e(R2/R1)}{k_{pipe}} + \dfrac{R3\ \log_e(R3/R2)}{k_{insulation}} + \dfrac{1}{h_o}}$$

$$\Delta T_{LM} = \frac{(T_2 - T_{amb}) - (T_1 - T_{amb})}{LN\left(\dfrac{T_2 - T_{amb}}{T_1 - T_{amb}}\right)}$$

$$h_i = \frac{0.023 * C_p * m}{A\left(\dfrac{C_p \mu}{k_{fluid}}\right)^{2/3}\left(\dfrac{2\ R1\ m}{A\ \mu}\right)^{0.2}}$$

k = thermal conductivity of fluid

μ = viscosity of fluid

C_p = heat capacity of fluid

h_i = heat transfer coefficient inside pipe

h_o = 7.0 Btu/h ft^2 °F indoors and 8.8 Btu/h ft^2 °F outdoors

A = internal area of pipe

m = mass flow rate of fluid

Another heat balance equation at steady state condition yields:

$$Q = m\,C_p\,(T1 - T2)$$

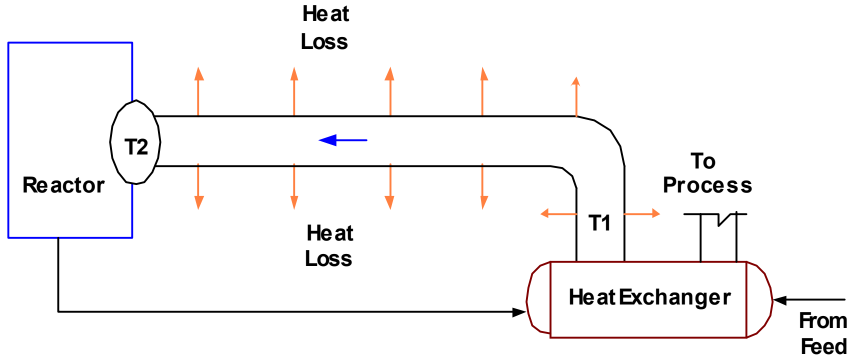
Solving the two heat transfer equations above for T_2 yields:

$$T2 = (T1 - T_{amb})\,\exp\left(\frac{-2\pi R3\,U\,L}{m\,C_p}\right) + T_{amb}$$

This equation is very useful in analyzing insulation and its impact on a process. The example below illustrates this.

Example- 3

Consider a typical process having an uninsulated length of 100-meter pipe connected to heat exchanger and a reactor. With the data indicated below, check whether insulating this piece of pipe provides opportunity for energy savings. Calculate what is the current reactor entrance temperature (T2) compared with the entrance temperature after applying the economic insulation thickness to pipe?



Data:

a. Calcium silicate insulation

b. Temperature of stream exiting the heat exchanger (T1) is 400 ^{0}C (752 ^{0}F)

c. Ambient temperature is 23.8 ^{0}C (75 ^{0}F)

d. Mass flow = 350,000 kg/h (771,470 lbs/h)

e. $R_{inside\ pipe}$ = R1 = 101.6 mm (4.0 in)

f. $R_{outside\ pipe}$ = R2 = 108.0 mm (4.25 in)

g. Thermal conductivity of pipe = k_{pipe} = 30 W/m K (56.2 Btu/h ft ^{0}F)

h. Ambient air heat transfer coefficient = ho = 50 W/m^2 K (8.8 Btu/h ft^2 ^{0}F)

i. Fluid heat capacity = $C_{p\ fluid}$ = 2.57 kJ/kg K (2.0 Btu/lb ^{0}F)

j. Fluid thermal conductivity = k_{fluid} = 0.60 W/m K (1.12 Btu/h ft ^{0}F)

k. Fluid viscosity = u_{fluid} = 5.2 cP

l. Energy costs = $3.79/million kJ ($4.00/million Btu)

m. Equivalent length of pipe = 100 meters (328 feet)

Solution

Corresponding to energy cost of $3.79/million kJ ($4.00/million Btu), pipe outside radius 101.6mm (4.0”), the economic thickness of insulation for outdoor location is 63.5 mm (2.5”). [Refer to economic thickness table above, example 1]

Therefore outside radius of pipe after insulation, R3 = 108.0 mm + 63.5 mm = 171.5mm

Average mean temperature of (400 ^{0}C + 23.8 ^{0}C)/2 = 211.9 ^{0}C or 413 ^{0}F

Thermal conductivity of calcium silicate @ 211.9 ^{0}C or 413 ^{0}F, k_{ins} = 0.070 W/m K or (0.13 Btu/h ft ^{0}F)

$$h_i = \frac{0.023 * C_p * m}{A\left(\frac{C_p \mu}{k_{fluid}}\right)^{2/3}\left(\frac{2\ R1\ m}{A\ \mu}\right)^{0.2}} \quad \text{or } h_i = \frac{0.023 * 2.57 * 350000}{0.0324\left(\frac{2.57 * 5.2}{0.60}\right)^{2/3}\left(\frac{2 * 0.101 * 350000}{0.0324 * 5.2}\right)^{0.2}}$$

Or h_1 = 1400 W/m^2 K or 247 Btu/h ft^2 °F

$$U = \frac{1}{\frac{R3}{R1\ h_i} + \frac{R3 \log_e(R2/R1)}{k_{pipe}} + \frac{R3 \log_e(R3/R2)}{k_{insulation}} + \frac{1}{h_o}}$$

$$U_{bare\ pipe} = \frac{1}{\frac{0.1715}{0.1016 * 1400} + \frac{0.1715\ LN\left(\frac{0.108}{0.1016}\right)}{30} + \frac{1}{50}}$$

Or $U_{bare\ pipe}$ = 46 W/m^{2}K or 8.1 Btu/h ft^2 °F

$$U_{insulated} = \frac{1}{\frac{0.1715}{0.1016 * 1400} + \frac{0.1715\ LN\left(\frac{0.108}{0.1016}\right)}{30} + \frac{0.1715\ LN\left(\frac{0.1715}{0.108}\right)}{0.07} + \frac{1}{50}}$$

Or $U_{insulated}$ = 0.87 W/m^{2}K or 0.15 Btu/h ft^2 °F

With bare pipe the temperature of fluid at node 2 at the entrance of reactor shall be given by equation

$$T2 = (T1 - T_{amb})\ \exp\left(\frac{-2\pi R3\ U\ L}{m\ C_p}\right) + T_{amb}$$

$$T2 = (400 - 23.8)\ \exp\left(\frac{-2\pi\ 0.1715 * 46 * 100}{350000 * 2.57}\right) + 23.8$$

T2 (bare pipe) = 398°C (748.4°F)

Similarly calculating with insulation:

$$T2 = (400 - 23.8)\ \exp\left(\frac{-2\pi\ 0.1715 * 0.87 * 100}{350000 * 2.57}\right) + 23.8$$

T2 (with insulation) = 399. 96°C (752°F)

Temperature difference with insulation is nearly 2 ^{0}C (3.6°F).

Annexure-A

Key Data Specification for Insulation Systems in Industrial Projects

Insulation Class	Insulation Material	Jacket Material	Remarks
Class 1 Heat Conservation	Calcium Silicate, Cellular glass, Mineral wool at temperature > 420°C	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	
Class 2 Cold Service Insulation	Cellular glass	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	Vapor Barrier
Class 3 Personnel Protection	Either of class 1-9 or perforated sheet metal guards	In accordance with classes 1-9 as applicable	Perforated guards to be Stainless steel. If insulation is used, it should be designed so that the jacket temperature do not exceed 70°C
Class 4 Frost Proofing	Cellular glass	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	Vapor Barrier
Class 5 Fire Proofing	Cellular glass + ceramic fiber or mineral wool when necessary	Stainless Steel	Insulation requirements are dependent on protection requirements and must be accepted by authority having jurisdiction.
Class 6 Acoustic Insulation – 10dB	Cellular glass, Ceramic fiber or Mineral wool	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	30mm cellular glass + 25mm fibers + metallic jacketing (or aluminum foil + non-metallic jacketing)
Class 7 Acoustic Insulation – 20dB	Cellular glass, Ceramic fiber or Mineral wool	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	30mm cellular glass + 38mm fibers + heavy synthetic sheets + metallic jacketing (or aluminum foil + non-metallic jacketing)
Class 7 Acoustic Insulation – 30dB	Cellular glass, Ceramic fiber or Mineral wool	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	30mm cellular glass + 38mm fibers + 2 x heavy synthetic sheets + 25mm fibers + 2 x heavy synthetic sheets + metallic jacketing (or aluminum foil + non-metallic jacketing)
Class 9 External Condensation	Cellular glass	Non metallic weather proofing membrane or metallic Stainless Steel or Aluminum	Vapor Barrier