PDHonline Course K115 (3 PDH)

Making Decisions with Insulation

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Making Decisions with Insulation

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COURSE CONTENT

In the chemical industry, the most common insulators are various types of calcium silicate or fiberglass. Calcium silicate is generally more appropriate for temperatures above 225 °C (437 °F), while fiberglass is generally used at temperatures below 225 °C. Below are charts showing the thermal conductivity for calcium silicate insulation and fiberglass insulation.

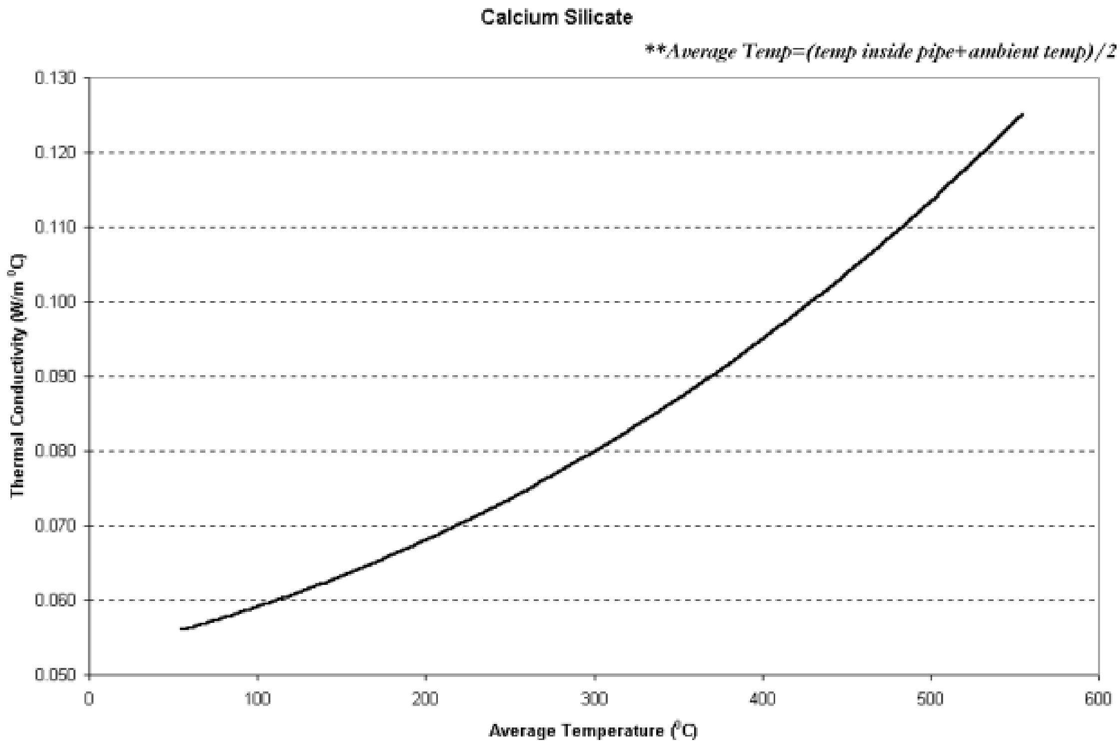


Figure 1.

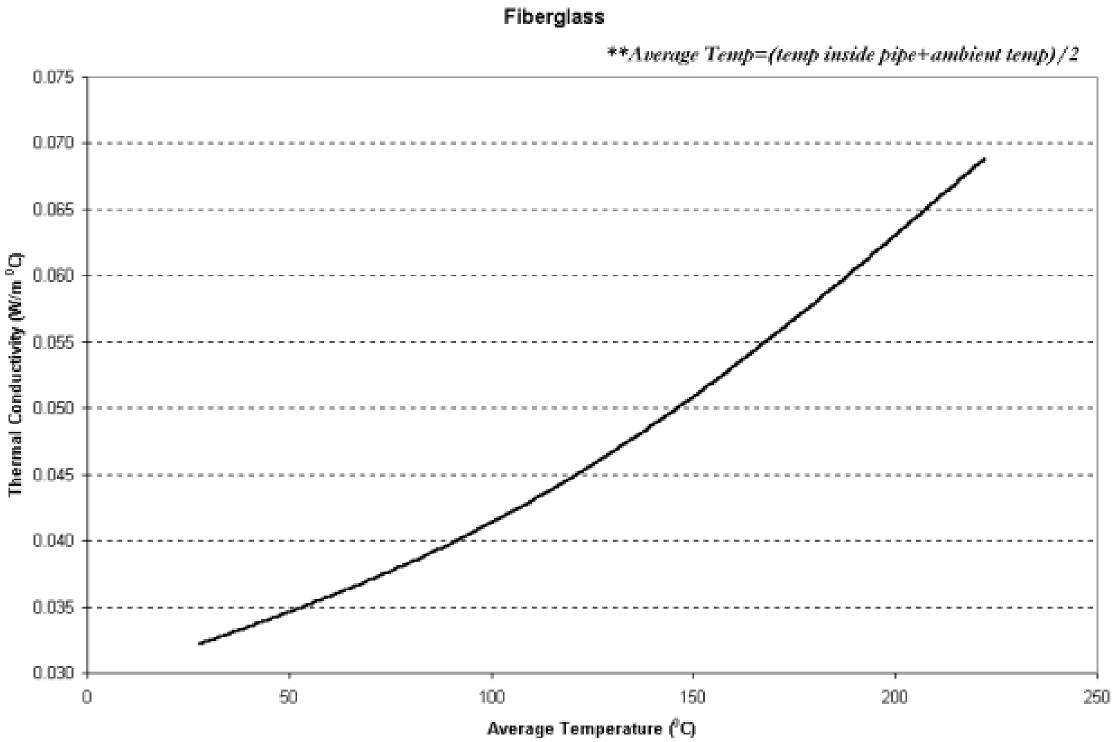
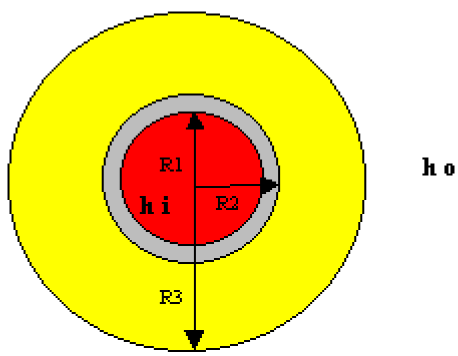


Figure 2.

A Brief Look at Theory

The most basic model for insulation on a pipe is shown below. R1 and R2 show the inside and outside radius of the pipe respectively. R3 shows the radius of the insulation. Typically when dealing with insulations, engineers must be concerned with linear heat loss or heat loss per unit length.

$$U = \frac{1}{\frac{R3}{R1\,hi} + \frac{R3\ \mathrm{LN}(R2/R1)}{k_{pipe}} + \frac{R3\ \mathrm{LN}(R3/R2)}{k_{insulation}} + \frac{1}{ho}} \quad \textbf{(1)}$$



Generally, the heat transfer coefficient of ambient air is 40 W/m^2 K (7 Btu/h ft2 °F). This coefficient can of course increase with wind velocity if the pipe is outside.

A good estimate for an outdoor air coefficient in warm climates with wind speeds under 15 mph is around 50 W/m^2 K (8.8 Btu/h ft2 °F). The total heat loss per unit length can then be calculated by:

$$\frac{Q}{L} = 2\pi R3\, U\, \Delta T \qquad \textbf{(2)}$$

$$\text{where } \Delta T = T_{insidepipe} - T_{ambient}$$

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. Since the critical thickness is almost always a few millimeters, it is seldom (if ever) an issue for piping. Critical thickness is a concern however in insulating wires. **Figure 3** shows the heat loss vs. insulation thickness for a typical insulation. It's easy to see why wire insulation is kept to a minimum as adding insulation would increase the heat transfer.

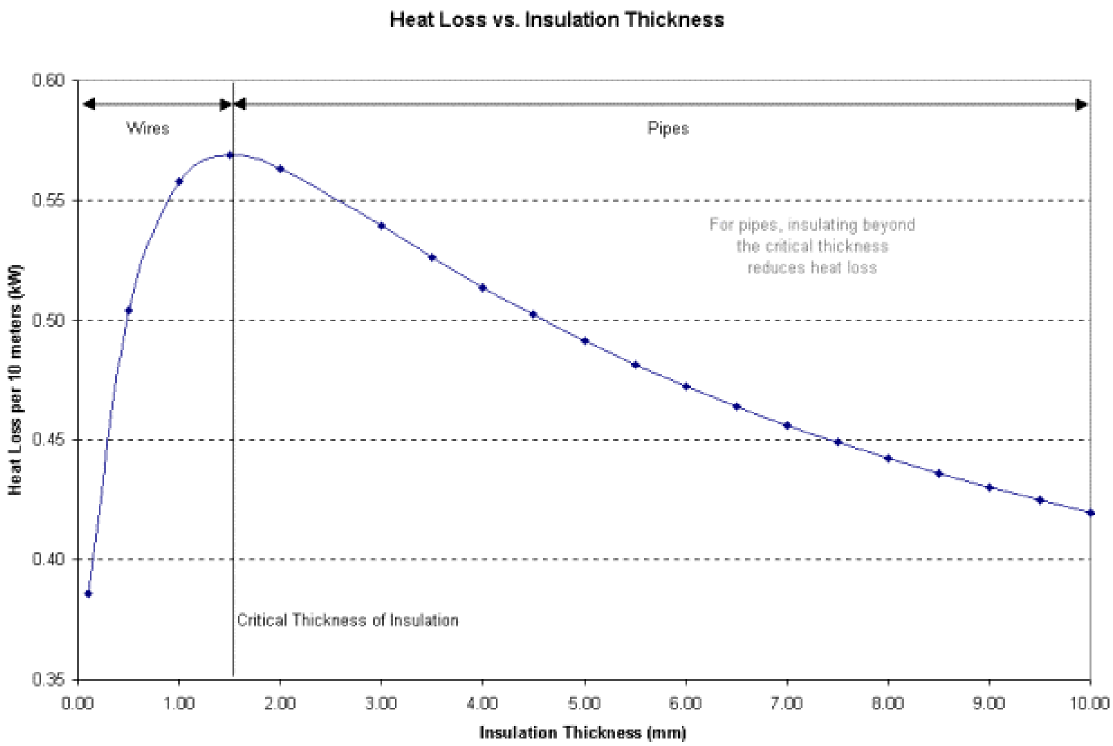


Figure 3.

Thinking About Insulation from All Sides

Three major factors play an important role in determining insulation type and thickness. Here, we'll focus on resolving the thickness issue since many manufacturing facilities have a "standard" type of insulation that they use. The three key factors to examine are:

1. Economics
2. Safety
3. Process Conditions

Each situation must be studied to determine how to meet each one of these criteria. First, we'll examine each aspect individually, then we'll see how to consider all three for an example.

Economics

Economic thickness of insulation is a well documented calculation procedure. The calculations typically take in the entire scope of the installation including plant depreciation to wind speed. Data charts for calculating the economic thickness of insulation are widely available. Below are economic thickness tables that have been adapted from Perry's Chemical Engineers' Handbook:

Economic Thickness of Indoor Insulation

Adapted from Perry's Chemical Engineers' Handbook		Minimum pipe temperature (°F)							
		Energy Costs, $/million Btu							
Pipe Size (in)	Insulation Thickness (in)	1	2	3	4	5	6	7	8
0.75	1.5	950	600	560	400	350	300	250	250
	2				1100	1000	900	800	750
	2.5				1750	1050	950	860	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
3	1.5	950	650	500	400	350	300	300	250
	2		1100	900	700	600	550	500	450
	2.5			1050	850	750	650	500	500
	3				1050	950	800	750	700
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	4	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
8	2		1000	800	650	550	500	450	400
	2.5		1050	850	700	600	550	500	450
	3				1050	900	800	750	700
	3.5					1200	1100	1000	900
	4							1150	1100
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
12	2	1150	750	600	500	400	400	350	300
	2.5		1000	800	650	550	500	450	400
	3			1200	1000	900	800	700	650
	3.5					1200	1100	1000	900
	4						1150	1050	950
	4.5						1200	1100	1000
14	2	1050	650	550	450	400	350	300	300
	2.5		1000	800	650	550	500	450	400
	3			1100	950	800	700	650	600
	3.5					1150	1000	950	850
	4					1200	1050	1000	900
	4.5						1200	1100	1000
14	2	1050	650	550	450	400	350	300	300
	2.5		1000	800	650	550	500	450	400
	3			1100	950	800	700	650	600
	3.5					1150	1000	950	850
	4					1200	1050	1000	900
	4.5						1200	1100	1000
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
18	2	1000	650	500	400	350	350	300	300
	2.5		950	750	600	550	600	450	400
	3		1150	900	750	650	550	500	500
	3.5					1200	1100	1000	900
	4						1150	1050	950
	4.5						1200	1100	1000
20	2	1050	700	550	450	400	350	350	300
	2.5		1000	800	600	550	500	450	400
	3		1150	900	750	650	550	50	500
	3.5						1100	1000	950
	4						1150	1050	1000
	4.5							1200	1100
24	2	950	60	500	400	350	300	300	250
	2.5		1150	900	750	650	550	500	450
	3			1050	900	750	700	600	550
	3.5					1100	1000	900	800
	4					1150	1050	950	850
	4.5						1150	1050	950

** 80 ^{0}F Still Ambient Air, Aluminum jacketed calcium silicate insulation

Economic Thickness of Indoor Insulation

Adapted from Perry's Chemical Engineers' Handbook		Minimum pipe temperature (°C)							
		Energy Costs, $/million KJ							
Pipe Size (mm)	Insulation Thickness (mm)	0.948	1.896	2.844	3.792	4.74	5.688	6.636	7.584
19.05	38.1	510.0	315.6	287.8	204.4	176.7	148.9	121.1	121.1
	50.8				593.3	537.8	482.2	426.7	398.9
	63.5				954.4	565.6	510.0	454.4	426.7
	76.2								648.9
25.4	38.1	648.9	426.7	315.6	260.0	232.2	204.4	176.7	148.9
	50.8			648.9	537.8	482.2	426.7	371.1	371.1
	63.5					648.9	565.6	537.8	482.2
	76.2						593.3	621.1	510.0
38.1	38.1	593.3	398.9	287.8	232.2	204.4	204.4	176.7	148.9
	50.8			537.8	454.4	371.1	343.3	315.6	260.0
	63.5				565.6	482.2	426.7	398.9	343.3
	76.2						621.1	593.3	537.8
50.8	38.1	565.6	371.1	260.0	232.2	204.4	176.7	148.9	148.9
	50.8			565.6	454.4	398.9	371.1	148.9	315.6
	63.5			593.3	510.0	537.8	398.9	371.1	343.3
	76.2				648.9	565.6	510.0	454.4	426.7
76.2	38.1	510.0	343.3	260.0	204.4	176.7	148.9	148.9	121.1
	50.8		593.3	482.2	371.1	315.6	287.8	260.0	232.2
	63.5		-17.8	565.6	454.4	398.9	343.3	260.0	260.0
	76.2				565.6	510.0	426.7	398.9	371.1
101.6	38.1	510.0	315.6	260.0	204.4	176.7	148.9	148.9	121.1
	50.8		593.3	454.4	371.1	315.6	287.8	260.0	232.2
	63.5			648.9	537.8	454.4	398.9	371.1	343.3
	76.2				565.6	482.2	426.7	398.9	371.1
	88.9							621.1	565.6
152.4	101.6	315.6	176.7	148.9	121.1	121.1	93.3	93.3	93.3
	50.8		593.3	454.4	371.1	315.6	287.8	260.0	260.0
	63.5			482.2	426.7	343.3	315.6	287.8	287.8
	76.2			621.1	537.8	454.4	398.9	371.1	315.6
	88.9						593.3	537.8	482.2
	101.6								648.9
203.2	50.8	-17.8	537.8	426.7	343.3	287.8	260.0	232.2	204.4
	63.5		565.6	454.4	371.1	315.6	287.8	260.0	232.2
	76.2				565.6	482.2	426.7	398.9	371.1
	88.9					648.9	593.3	537.8	482.2
	101.6							621.1	593.3
254	50.8	-17.8	593.3	454.4	371.1	343.3	287.8	260.0	232.2
	63.5		648.9	482.2	398.9	371.1	315.6	287.8	260.0
	76.2			565.6	482.2	398.9	371.1	315.6	287.8
	88.9					648.9	565.6	510.0	482.2
	101.6								648.9
304.8	50.8	621.1	398.9	315.6	260.0	204.4	204.4	176.7	148.9
	63.5		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	76.2			648.9	537.8	482.2	426.7	371.1	343.3
	88.9					648.9	593.3	537.8	482.2
	101.6						621.1	565.6	510.0
	114.3						648.9	593.3	537.8
355.6	50.8	565.6	343.3	287.8	232.2	204.4	176.7	148.9	148.9
	63.5		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	76.2			593.3	510.0	426.7	371.1	343.3	315.6
	88.9					621.1	537.8	510.0	454.4
	101.6					648.9	565.6	537.8	482.2
	114.3						648.9	593.3	537.8

355.6	50.8	565.6	343.3	287.8	232.2	204.4	176.7	148.9	148.9
	63.5		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	76.2			593.3	510.0	426.7	371.1	343.3	315.6
	88.9					621.1	537.8	510.0	454.4
	101.6					648.9	565.6	537.8	482.2
	114.3						648.9	593.3	537.8
406.4	50.8	510.0	343.3	260.0	204.4	176.7	148.9	148.9	148.9
	63.5		537.8	426.7	371.1	315.6	287.8	260.0	232.2
	76.2		648.9	510.0	426.7	371.1	315.6	287.8	260.0
	88.9					621.1	565.6	510.0	454.4
	101.6					648.9	593.3	537.8	482.2
	114.3						621.1	565.6	510.0
457.2	50.8	537.8	343.3	260.0	204.4	176.7	176.7	148.9	148.9
	63.5		510.0	398.9	315.6	287.8	260.0	232.2	204.4
	76.2		621.1	482.2	398.9	343.3	287.8	260.0	260.0
	88.9					648.9	593.3	537.8	482.2
	101.6						621.1	565.6	510.0
	114.3						648.9	593.3	537.8
508	50.8	565.6	371.1	287.8	232.2	204.4	176.7	176.7	148.9
	63.5		537.8	426.7	315.6	287.8	260.0	232.2	204.4
	76.2		621.1	482.2	398.9	343.3	287.8	10.0	260.0
	88.9						593.3	537.8	510.0
	101.6						621.1	565.6	537.8
	114.3							648.9	593.3
609.6	50.8		15.6	260.0	204.4	176.7	148.9	148.9	121.1
	63.5		621.1	482.2	398.9	343.3	287.8	260.0	232.2
	76.2		-17.8	565.6	482.2	398.9	371.1	315.6	287.8
	88.9					593.3	537.8	482.2	426.7
	101.6					621.1	565.6	510.0	454.4
	114.3						621.1	565.6	510.0

** 80 ^{0}F Still Ambient Air, Aluminum jacketed calcium silicate insulation

Economic Thickness of Outdoor Insulation

Adapted from Perry's Chemical Engineers' Handbook		Minimum pipe temperature (°F)							
		Energy Costs, $/million Btu							
Pipe Size (in)	Insulation Thickness (in)	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	600	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	60	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	500
	2.5			1000	850	750	650	600	550
	3				1050	950	850	750	700
3	1	300	200	150	150	150	150	150	150
	1.5	750	500	400	300	250	250	250	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
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			1050	900	700	650	600	550
	3			1100	950	750	700	650	600
	3.5						1200	1100	1000
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
8	1	250	200	150	150	150	150	150	150
	2		850	650	550	450	400	350	350
	2.5		900	700	600	500	450	400	400
	3			1100	950	800	750	700	600
	3.5					1150	1000	950	850
	4							1050	1000
10	2	200	150	150	150	150	150	150	150
	2.5		1000	800	650	550	500	450	400
	3		1200	950	800	700	600	550	500
	3.5					1100	1000	900	800
	4							1150	1050
	4.5							1200	1100
12	1.5	250	150	150	150	150	150	150	150
	2	950	600	500	400	350	300	250	250
	2.5		900	700	550	500	400	400	350
	3			1100	900	800	700	650	550
	3.5					1100	1000	900	850
	4					1150	1050	950	900
	4.5					1200	1100	1000	950
14	1.5	250	150	150	150	150	150	150	150
	2	850	550	400	350	300	250	250	250
	2.5		850	650	550	500	400	400	400
	3			1000	850	700	650	550	500
	3.5				1200	1000	950	850	800
	4					1050	1000	900	850
	4.5						1100	1000	950

16	1.5	250	150	150	150	150	150	150	150
	2	800	500	350	300	300	250	250	200
	2.5		900	700	550	500	450	400	350
	3		1000	850	700	600	500	450	400
	3.5				1200	1000	950	850	800
	4					1100	1000	900	850
	4.5					1150	1000	950	900
18	1.5	250	150	150	150	150	150	150	150
	2	850	550	400	350	300	250	250	200
	2.5		800	650	500	450	400	350	350
	3		1000	800	650	550	500	450	400
	3.5					1100	1000	900	850
20	1.5	150	150	150	150	150	150	150	150
	2	900	550	450	350	300	300	250	250
	2.5		850	650	550	450	400	350	350
	3		1000	800	650	550	500	450	400
	3.5					1150	1050	950	900
	4					1200	1100	1000	950
	4.5						1200	1100	1050
24	1.5	150	150	150	150	150	150	150	150
	2	800	500	400	300	250	250	200	200
	2.5		950	750	650	550	500	450	400
	3		1150	950	750	650	600	550	500
	3.5				1150	1000	900	800	750
	4				1200	1050	950	850	800
	4.5						1050	950	850

** 60 °F Average wind speed of 7.5 mph, Aluminum jacketed calcium silicate insulation

Economic Thickness of Outdoor Insulation

Adapted from Perry's Chemical Engineers' Handbook

Pipe Size (mm)	Insulation Thickness (mm)	Minimum pipe temperature (°C) — Energy Costs, $/million KJ: 0.948	1.896	2.844	3.792	4.74	5.688	6.636	7.584
19.05	25.4	232.2	148.9	121.1	121.1	93.3	93.3	65.6	65.6
	38.1	426.7	260.0	204.4	148.9	121.1	121.1	93.3	93.3
	50.8			621.1	510.0	454.4	398.9	371.1	343.3
	63.5			593.3	537.8	482.2	426.7	398.9	371.1
25.4	25.4	204.4	148.9	121.1	93.3	93.3	65.6	65.6	65.6
	38.1	537.8	343.3	260.0	204.4	176.7	148.9	148.9	121.1
	50.8			593.3	482.2	426.7	371.1	315.6	315.6
	63.5				648.9	565.6	510.0	454.4	426.7
	76.2					593.3	537.8	482.2	454.4
38.1	25.4	176.7	121.1	93.3	93.3	65.6	65.6	65.6	65.6
	38.1	482.2	315.6	232.2	176.7	148.9	148.9	121.1	121.1
	50.8		537.8	454.4	371.1	15.6	287.8	260.0	232.2
	63.5			621.1	510.0	426.7	398.9	371.1	315.6
	76.2					648.9	565.6	537.8	482.2
50.8	25.4	176.7	121.1	93.3	65.6	65.6	65.6	65.6	65.6
	38.1	482.2	287.8	232.2	204.4	148.9	148.9	121.1	121.1
	50.8		621.1	482.2	398.9	343.3	315.6	287.8	260.0
	63.5			537.8	454.4	398.9	343.3	315.6	287.8
	76.2				565.6	510.0	454.4	398.9	371.1
76.2	25.4	148.9	93.3	65.6	65.6	65.6	65.6	65.6	65.6
	38.1	398.9	260.0	204.4	148.9	121.1	121.1	121.1	93.3
	50.8		510.0	398.9	315.6	260.0	232.2	204.4	176.7
	63.5		621.1	510.0	398.9	343.3	315.6	260.0	260.0
	76.2			621.1	537.8	454.4	398.9	343.3	315.6
	88.9								621.1

101.6	25.4	121.1	93.3	65.6	65.6	65.6	65.6	65.6	65.6
	38.1	398.9	260.0	176.7	148.9	121.1	121.1	93.3	93.3
	50.8		510.0	398.9	315.6	260.0	232.2	204.4	176.7
	63.5			565.6	482.2	371.1	343.3	315.6	287.8
	76.2			593.3	510.0	398.9	371.1	343.3	315.6
	88.9						648.9	593.3	537.8
152.4	25.4	121.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	38.1	232.2	148.9	93.3	93.3	65.6	65.6	65.6	65.6
	50.8		482.2	371.1	315.6	260.0	232.2	204.4	176.7
	63.5		565.6	426.7	343.3	315.6	260.0	232.2	204.4
	76.2			565.6	482.2	398.9	371.1	315.6	287.8
	88.9					621.1	565.6	510.0	454.4
	101.6							648.9	621.1
	114.3								648.9
203.2	25.4	121.1	93.3	65.6	65.6	65.6	65.6	65.6	65.6
	50.8		454.4	343.3	287.8	232.2	204.4	176.7	176.7
	63.5		482.2	371.1	315.6	260.0	232.2	204.4	204.4
	76.2			593.3	510.0	426.7	398.9	371.1	315.6
	88.9					621.1	537.8	510.0	454.4
	101.6							565.6	537.8
254	50.8	93.3	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	63.5		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	76.2		648.9	510.0	426.7	371.1	315.6	287.8	260.0
	88.9					593.3	537.8	482.2	426.7
	101.6							621.1	565.6
	114.3							648.9	593.3
304.8	38.1	121.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	510.0	315.6	260.0	204.4	176.7	148.9	121.1	121.1
	63.5		482.2	371.1	287.8	260.0	204.4	204.4	176.7
	76.2			593.3	482.2	426.7	371.1	343.3	287.8
	88.9					593.3	537.8	482.2	454.4
	101.6					621.1	565.6	510.0	482.2
	114.3					648.9	593.3	537.8	510.0
355.6	38.1	121.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	454.4	287.8	204.4	176.7	148.9	121.1	121.1	121.1
	63.5		454.4	343.3	287.8	260.0	204.4	204.4	204.4
	76.2			537.8	454.4	371.1	343.3	287.8	260.0
	88.9				648.9	537.8	510.0	454.4	426.7
	101.6					565.6	537.8	482.2	454.4
	114.3						593.3	537.8	510.0
406.4	38.1	121.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	426.7	260.0	176.7	148.9	148.9	121.1	121.1	93.3
	63.5		482.2	371.1	287.8	260.0	232.2	204.4	176.7
	76.2		537.8	454.4	371.1	315.6	260.0	232.2	204.4
	88.9				648.9	537.8	510.0	454.4	426.7
	101.6					593.3	537.8	482.2	454.4
	114.3					621.1	537.8	510.0	482.2
457.2	38.1	121.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	454.4	287.8	204.4	176.7	148.9	121.1	121.1	93.3
	63.5		426.7	343.3	260.0	232.2	204.4	176.7	176.7
	76.2		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	88.9					593.3	537.8	482.2	454.4
508	38.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	482.2	287.8	232.2	176.7	148.9	148.9	121.1	121.1
	63.5		454.4	343.3	287.8	232.2	204.4	176.7	176.7
	76.2		537.8	426.7	343.3	287.8	260.0	232.2	204.4
	88.9					621.1	565.6	510.0	482.2
	101.6					648.9	593.3	537.8	510.0
	114.3						648.9	593.3	565.6
609.6	38.1	65.6	65.6	65.6	65.6	65.6	65.6	65.6	65.6
	50.8	426.7	260.0	204.4	148.9	121.1	121.1	93.3	93.3
	63.5		510.0	398.9	343.3	287.8	260.0	232.2	204.4
	76.2		621.1	510.0	398.9	343.3	315.6	287.8	260.0
	88.9				621.1	537.8	482.2	426.7	398.9
	101.6				648.9	565.6	510.0	454.4	426.7
	114.3						565.6	510.0	454.4

** 60 °F Average wind speed of 7.5 mph, Aluminum jacketed calcium silicate insulation

Example of Economic Thickness Determination:

Using the tables above, assuming a 6.0 in pipe at 500 ^{0}F in an indoor setting with an energy cost of $5.00/million Btu, what is the economic thickness?

Answer: Finding the 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 or 1 1/2 inches of insulation. At 600 ^{0}F, we would increase to 2.0 inches of insulation.

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

Safety

Pipes that are readily accessible by workers are subject to safety constraints. The recommended safe "touch" temperature range is from 130 $^\circ$F to 150 $^\circ$F (54.4 $^\circ$C to 65.5 $^\circ$C). Insulation calculations should aim to keep the outside temperature of the insulation around 140 $^\circ$F (60 $^\circ$C). An additional tool employed to help meet this goal is aluminum covering wrapped around the outside of the insulation to keep the insulation in place.

Aluminum's thermal conductivity of 209 W/m K 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. The addition of aluminum adds another resistance term to Equation 1 when calculating the total heat loss:

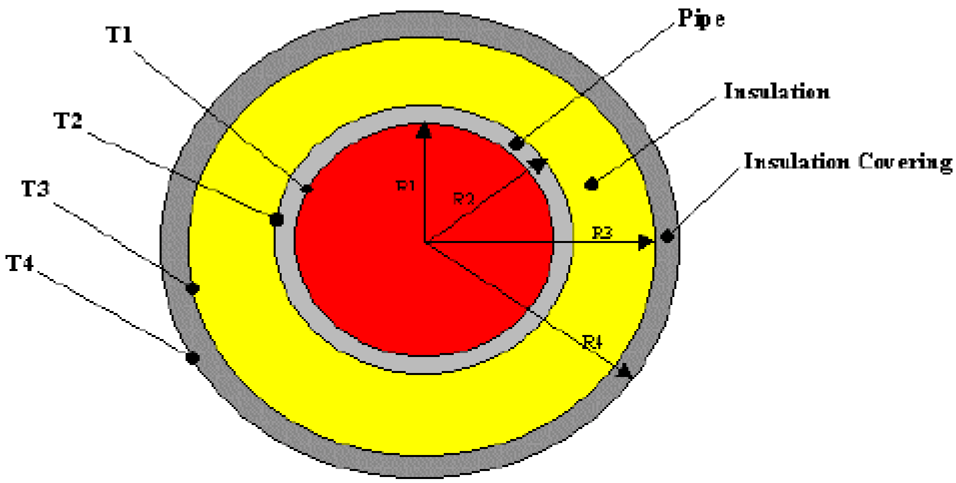
$$U = \frac{1}{\frac{R4}{R1\,hi} + \frac{R4\ LN(R2/R1)}{k_{pipe}} + \frac{R4\ LN(R3/R2)}{k_{insulation}} + \frac{R4\ LN(R4/R3)}{k_{aluminum}} + \frac{1}{ho}} \quad \textbf{(3)}$$

and Equation 2 becomes :

$$\frac{Q}{L} = 2\pi R4\ U\ \Delta T$$

where R4 is the radius of the pipe, insulation , and aluminum cover combined.

However, when considering safety, engineers need a quick way to calculate the surface temperature that will come into contact with the workers. This can be done with equations or the use of charts. We start by looking at another diagram:



At steady state, the heat transfer rate will be the same for each layer:

$$Q = \frac{T1 - T2}{(R2 - R1)/(k_{pipe} ALM_{pipe})} = \frac{T2 - T3}{(R3 - R2)/(k_{ins} ALM_{ins})} = \frac{T3 - T4}{(R4 - R3)/(k_{inscover} ALM_{inscover})} \quad \textbf{(4)}$$

where :

$$ALM_{pipe} = \frac{(2\pi\ R2\ L) - (2\pi\ R1\ L)}{LN\left(\frac{2\pi\ R2\ L}{2\pi\ R1\ L}\right)},$$

$$ALM_{ins} = \frac{(2\pi\ R3\ L) - (2\pi\ R2\ L)}{LN\left(\frac{2\pi\ R3\ L}{2\pi\ R2\ L}\right)},$$

$$ALM_{inscover} = \frac{(2\pi\ R4\ L) - (2\pi\ R3\ L)}{LN\left(\frac{2\pi\ R4\ L}{2\pi\ R3\ L}\right)}$$

Rearranging Equation 4 by solving the three expressions for the temperature difference yields:

$$Q = \frac{T1 - T4}{\left(\frac{R2 - R1}{k_{pipe} ALM_{pipe}}\right) + \left(\frac{R3 - R2}{k_{ins} ALM_{ins}}\right) + \left(\frac{R4 - R3}{k_{inscover} ALM_{inscover}}\right)} \quad \textbf{(5)}$$

Each term in the denominator of Equation 5 is referred to as the "resistance" of each layer. We will define this as Rs and rewrite the equation as:

$$Q = \frac{T1 - T4}{Rs_{pipe} + Rs_{ins} + Rs_{inscover}} \quad \textbf{(6)}$$

Since the heat loss is constant for each layer, use Equation 4 to calculate Q from the bare pipe, then solve Equation 6 for T4 (surface temperature). Use the economic thickness of your insulation as a basis for your calculation, after all, if the most affordable layer of insulation is safe, that's the one you'd want to use. 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.

As you can see, 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. This correlation also uses the surface resistance of the outer covering of the pipe. Figure 4 shows the equivalent thickness chart for calcium silicate insulation. Table 5 shows surface resistances for three popular covering materials for insulation:

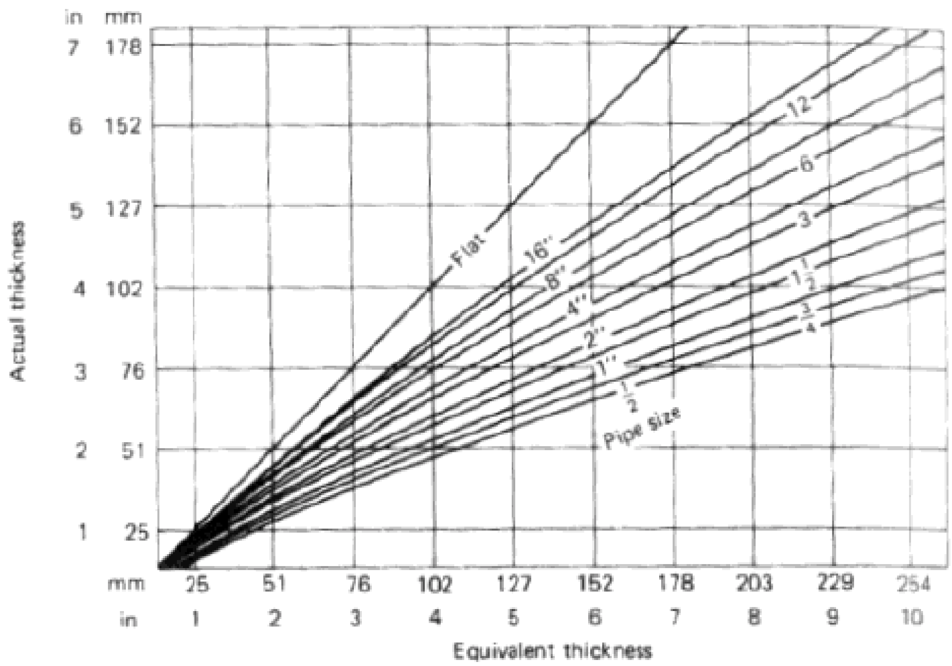


Figure 4: Equivalent Thickness Chart for Calcium Silicate Insulation

Table 5: Values for Surface Resistances
$h\ ft^2\ ^0F/Btu \quad (m^2\ ^0C/W)$

R_s Values for still air

Tsurface-Tambient °F	Tsurface-Tambient °C	Plain, fabric dull metal $\varepsilon = 0.95$	Aluminum $\varepsilon = 0.2$	Stainless steel $\varepsilon = 0.4$
10	5	0.53 (0.093)	0.90 (0.158)	0.81 (0.142)
25	14	0.52 (0.091)	0.88 (0.155)	0.79 (0.139)
50	28	0.50 (0.088)	0.86 (0.151)	0.76 (0.133)
75	42	0.48 (0.084)	0.84 (0.147)	0.75 (0.132)
100	55	0.46 (0.081)	0.80 (0.140)	0.72 (0.126)

R_s Values with wind velocities

Wind velocity		Plain, fabric dull metal		Aluminum		Stainless steel	
mi/h	km/h	mi/h	km/h	mi/h	km/h	mi/h	km/h
5	8	0.35	0.06	0.41	0.07	0.40	0.07
10	16	0.30	0.05	0.35	0.06	0.34	0.06
20	32	0.24	0.04	0.28	0.05	0.27	0.05

With the help of Figure 4 and Table 5 (or similar data for another material you may be dealing with), the relation:

$$\text{Equivalent Thickness} = k_{ins} R_s \frac{T_{pipe} - T_{surface}}{T_{surface} - T_{ambient}} \quad \textbf{(7)}$$

can be used to easily determine how much insulation will be needed to achieve a specific surface temperature. Let's look at an example to illustrate the various uses of this equation.

Example of Outer Surface Temperature Determination:

Your supervisor asks you to install insulation on a new pipe in the plant. Recently, two workers suffered severe burns while accidentally touching the new piping so safety is of primary concern. He instructs you to be sure that this incident does not repeat itself. The pipe contains a heat transfer fluid at 850 °F (454 °C). The ambient temperature is usually near 85 °F (29.4 °C). After checking the supplies that you have available, you notice that you have calcium silicate insulation and aluminum available for covering. You would like to insulate the 16 inch pipe for a surface temperature of 130 °F.

$$\text{Equivalent Thickness} = k_{ins} R_s \frac{T_{pipe} - T_{surface}}{T_{surface} - T_{ambient}}$$

Tsurface - Tambient = 130 °F - 85 °F = 45 °F, from Table 5 we estimate a Rs value for aluminum at 0.865 h ft^2 °F/Btu .

Taverage = (850 °F + 85 °F)/2 = 467.5 °F (242 °C), from Figure 1 we estimate a thermal conductivity of 0.0365 Btu/h ft °F (0.0703 W/m °C) for calcium silicate insulation.

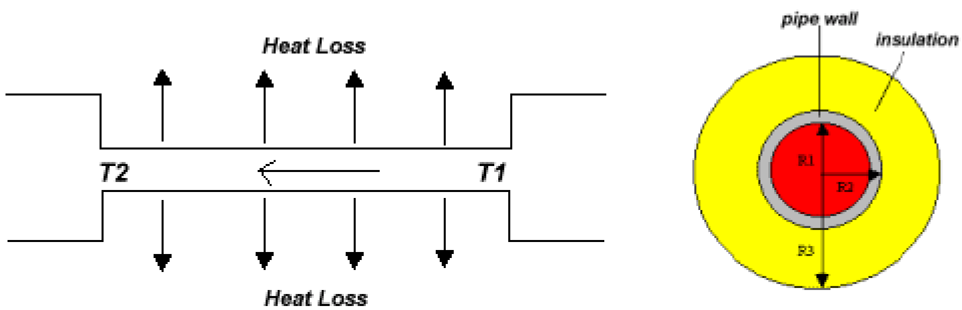
$$\text{Equivalent Thickness} = (0.0365\ \text{Btu/h ft}\ ^0\text{F})(0.865\ \text{h ft}^{2\,0}\text{F/Btu})\ \frac{850\ ^0\text{F} - 130\ ^0\text{F}}{130\ ^0\text{F} - 85\ ^0\text{F}}$$

Equivalent Thickness = 6.1 in (155 mm)

From Figure 4 above, an equivalent thickness of 6.1 in corresponds to an actual thickness of nearly 5.0 in of insulation.

Process Conditions

The temperature of a fluid inside an insulated pipe is an important process variable that must be considered in many situations. Consider the length of pipe connecting two pieces of process equipment shown below:



In order to predict T2 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

$$Q = 2\pi \, L \, R3 \, U \, \Delta T_{LM}$$

where:

$$U = \cfrac{1}{\cfrac{R3}{R1\,hi} + \cfrac{R3\,LN(R2/R1)}{k_{pipe}} + \cfrac{R3\,LN(R3/R2)}{k_{ins}} + \cfrac{1}{ho}} \qquad \textbf{(8)}$$

$$hi = \frac{0.023\, C_p\, \dot{m}}{A_x \left(\frac{C_p \mu_{fluid}}{k_{fluid}}\right)^{\frac{2}{3}} \left(\frac{2\,R1\,\dot{m}}{A_x\, \mu_{fluid}}\right)^{0.2}}$$

k = thermal conductivity

μ = viscosity

C_p = heat capacity of fluid

hi = heat transfer coefficient inside pipe

ho = 7.0 Btu/h ft^2 ^0F (40 W/m^2 K) indoors

ho = 8.8 Btu/h ft^2 ^0F (50 W/m^2 K) outdoors

$$\Delta T_{LM} = \frac{(T2 - T_{amb}) - (T1 - T_{amb})}{LN\left(\frac{T2 - T_{amb}}{T1 - T_{amb}}\right)}$$

Another heat balance equation yields:

$$Q = \dot{m}\, C_p (T1 - T2) \qquad \textbf{(9)}$$

where:

$\dot{m}$ = mass flowrate of fluid

Setting Equation 8 equal to Equation 9 and solving for T2 yields:

$$T2 = (T1 - T_{amb}) \exp\left(\frac{-2\pi\, R3\, U\, L}{\dot{m}\, C_p}\right) + T_{amb} \qquad \textbf{(10)}$$

Equation 10 provides another useful tool for analyzing insulation and its impact on a process. Equation 10 has been incorporated into the "Insulated Pipe Temperature Prediction Spreadsheet" available at later in the course.

One example may be the importance of designing insulation thickness to prevent condensation on cold lines. Usually, when we hear the word "insulation" we instantly think of hot lines. However, there are times when insulation is used to prevent heat from entering a line. In this situation, the dew point temperature of the ambient air must be considered. Table 6 and Table 7 show dew point temperatures as a function of relative humidity and dry bulb temperatures.

Dew-Point Temperatures (^{0}F)

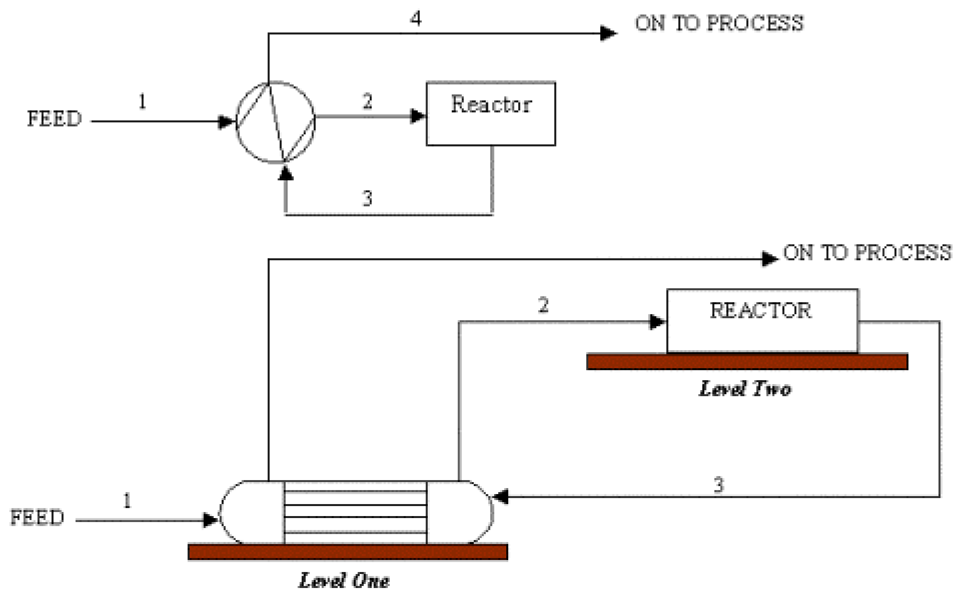
Dry Bulb Temp. (^{0}F)	Percent Relative Humidity																	
	10	15	20	25	30	35	40	45	50	60	65	70	75	80	85	90	95	100
5	-35.0	-30.0	-25.0	-21.0	-17.0	-14.0	-12.0	-10.0	-8.0	-5.0	-4.0	-2.0	-1.0	1.0	2.0	3.0	4.0	5.0
10	-31.0	-25.0	-20.0	-16.0	-13.0	-10.0	-7.0	-5.0	-3.0	0.0	2.0	3.0	4.0	5.0	7.0	8.0	9.0	10.0
15	-28.0	-21.0	-16.0	-12.0	-8.0	-6.0	-3.0	-1.0	1.0	5.0	6.0	8.0	9.0	10.0	12.0	13.0	14.0	15.0
20	-24.0	-16.0	-11.0	-8.0	-4.0	-2.0	2.0	4.0	6.0	10.0	11.0	13.0	14.0	15.0	16.0	18.0	19.0	20.0
25	-20.0	-15.0	-6.0	-4.0	0.0	3.0	6.0	8.0	10.0	15.0	16.0	18.0	19.0	20.0	21.0	23.0	24.0	25.0
30	-15.0	-9.0	-3.0	2.0	5.0	8.0	11.0	13.0	15.0	20.0	22.0	23.0	24.0	25.0	27.0	28.0	29.0	30.0
35	-12.0	-5.0	1.0	5.0	9.0	12.0	15.0	18.0	20.0	24.0	26.0	27.0	28.0	30.0	32.0	33.0	34.0	35.0
40	-7.0	0.0	5.0	9.0	14.0	16.0	19.0	22.0	24.0	28.0	29.0	31.0	33.0	35.0	36.0	3.0	39.0	40.0
45	-4.0	3.0	9.0	13.0	17.0	20.0	23.0	25.0	28.0	32.0	34.0	36.0	38.0	39.0	41.0	43.0	44.0	45.0
50	-1.0	7.0	13.0	17.0	21.0	24.0	27.0	30.0	32.0	37.0	39.0	41.0	42.0	44.0	45.0	47.0	49.0	50.0
55	3.0	11.0	16.0	21.0	25.0	28.0	32.0	34.0	37.0	41.0	43.0	45.0	47.0	49.0	50.0	52.0	53.0	55.0
60	6.0	14.0	20.0	25.0	29.0	32.0	35.0	39.0	42.0	46.0	48.0	50.0	52.0	54.0	55.0	57.0	59.0	60.0
65	10.0	18.0	24.0	28.0	33.0	38.0	40.0	43.0	46.0	51.0	53.0	55.0	57.0	59.0	60.0	62.0	63.0	65.0
70	13.0	21.0	28.0	33.0	37.0	41.0	45.0	48.0	50.0	55.0	57.0	60.0	62.0	64.0	65.0	67.0	68.0	70.0
75	17.0	25.0	32.0	37.0	42.0	46.0	49.0	52.0	55.0	60.0	62.0	64.0	66.0	69.0	70.0	72.0	74.0	75.0
80	20.0	29.0	35.0	41.0	46.0	50.0	54.0	57.0	60.0	65.0	67.0	69.0	72.0	74.0	75.0	77.0	78.0	80.0
85	23.0	32.0	40.0	45.0	50.0	54.0	58.0	61.0	64.0	69.0	72.0	74.0	76.0	78.0	80.0	82.0	83.0	85.0
90	27.0	36.0	44.0	49.0	54.0	58.0	62.0	66.0	69.0	74.0	77.0	79.0	81.0	83.0	85.0	87.0	88.0	90.0
95	30.0	40.0	48.0	54.0	59.0	63.0	67.0	70.0	73.0	79.0	82.0	84.0	86.0	88.0	90.0	91.0	93.0	95.0
100	34.0	44.0	52.0	58.0	63.0	68.0	71.0	75.0	78.0	84.0	86.0	88.0	91.0	92.0	94.0	96.0	98.0	100.0
105	38.0	48.0	56.0	62.0	67.0	72.0	76.0	79.0	82.0	88.0	90.0	93.0	95.0	97.0	99.0	101.0	103.0	105.0
110	41.0	52.0	60.0	66.0	71.0	77.0	80.0	84.0	87.0	92.0	95.0	98.0	100.0	102.0	104.0	106.0	108.0	110.0
115	45.0	56.0	64.0	70.0	75.0	80.0	84.0	88.0	91.0	97.0	100.0	102.0	106.0	107.0	109.0	111.0	113.0	115.0
120	48.0	60.0	68.0	74.0	79.0	85.0	88.0	92.0	96.0	102.0	105.0	107.0	109.0	112.0	114.0	116.0	118.0	120.0
125	52.0	63.0	72.0	78.0	84.0	89.0	93.0	97.0	100.0	107.0	109.0	111.0	114.0	117.0	119.0	121.0	123.0	125.0

Dew-Point Temperatures (^{0}C)

Dry Bulb Temp. (^{0}C)	Percent Relative Humidity																	
	10	15	20	25	30	35	40	45	50	60	65	70	75	80	85	90	95	100
-15.0	-37.2	-34.4	-31.7	-29.4	-27.2	-25.6	-24.4	-23.3	-22.2	-20.6	-20.0	-18.9	-18.3	-17.2	-16.7	-16.1	-15.6	-15.0
-12.2	-35.0	-31.7	-28.9	-26.7	-25.0	-23.3	-21.7	-20.6	-19.4	-17.8	-16.7	-16.1	-15.6	-15.0	-13.9	-13.3	-12.8	-12.2
-9.4	-33.3	-29.4	-26.7	-24.4	-22.2	-20.6	-19.4	-18.3	-17.2	-15.0	-14.4	-13.3	-12.8	-12.2	-11.1	-10.6	-10.0	-9.4
-6.7	-31.1	-26.7	-23.9	-22.2	-20.0	-18.9	-16.7	-15.6	-14.4	-12.2	-11.7	-10.6	-10.0	-9.4	-8.9	-7.8	-7.2	-6.7
-3.9	-28.9	-26.1	-22.2	-20.0	-17.8	-16.1	-14.4	-13.3	-12.2	-9.4	-8.9	-7.8	-7.2	-6.7	-6.1	-5.0	-4.4	-3.9
-1.1	-26.1	-22.8	-19.4	-16.7	-15.0	-13.3	-11.7	-10.6	-9.4	-6.7	-5.6	-5.0	-4.4	-3.9	-2.8	-2.2	-1.7	-1.1
1.7	-24.4	-20.6	-17.2	-15.0	-12.8	-11.1	-9.4	-7.8	-6.7	-4.4	-3.3	-2.8	-2.2	-1.1	0.0	0.6	1.1	1.7
4.4	-21.7	-17.8	-15.0	-12.8	-10.0	-8.9	-7.2	-5.6	-4.4	-2.2	-1.7	-0.6	0.6	1.7	2.2	-16.1	3.9	4.4
7.2	-20.0	-16.1	-12.8	-10.6	-8.3	-6.7	-5.0	-3.9	-2.2	0.0	1.1	2.2	3.3	3.9	5.0	6.1	6.7	7.2
10.0	-18.3	-13.9	-10.6	-8.3	-6.1	-4.4	-2.8	-1.1	0.0	2.8	3.9	5.0	5.6	6.7	7.2	8.3	9.4	10.0
12.8	-16.1	-11.7	-8.9	-6.1	-3.9	-2.2	0.0	1.1	2.8	5.0	6.1	7.2	8.3	9.4	10.0	11.1	11.7	12.8
15.6	-14.4	-10.0	-6.7	-3.9	-1.7	0.0	1.7	3.9	5.6	7.8	8.9	10.0	11.1	12.2	12.8	13.9	15.0	15.6
18.3	-12.2	-7.8	-4.4	-2.2	0.6	3.3	4.4	6.1	7.8	10.6	11.7	12.8	13.9	15.0	15.6	16.7	17.2	18.3
21.1	-10.6	-6.1	-2.2	0.6	2.8	5.0	7.2	8.9	10.0	12.8	13.9	15.6	16.7	17.8	18.3	19.4	20.0	21.1
23.9	-8.3	-3.9	0.0	2.8	5.6	7.8	9.4	11.1	12.8	15.6	16.7	17.8	18.9	20.6	21.1	22.2	23.3	23.9
26.7	-6.7	-1.7	1.7	5.0	7.8	10.0	12.2	13.9	15.6	18.3	19.4	20.6	22.2	23.3	23.9	25.0	25.6	26.7
29.4	-5.0	0.0	4.4	7.2	10.0	12.2	14.4	16.1	17.8	20.6	22.2	23.3	24.4	25.6	26.7	27.8	28.3	29.4
32.2	-2.8	2.2	6.7	9.4	12.2	14.4	16.7	18.9	20.6	23.3	25.0	26.1	27.2	28.3	29.4	30.6	31.7	32.2
35.0	-1.1	4.4	8.9	12.2	15.0	17.2	19.4	21.1	22.8	26.1	27.8	28.9	30.0	31.1	32.2	32.8	33.9	35.0
37.8	1.1	6.7	11.1	14.4	17.2	20.0	21.7	23.9	25.6	28.9	30.0	31.1	32.8	33.3	34.4	35.6	36.7	37.8
40.6	3.3	8.9	13.3	16.7	19.4	22.2	24.4	26.1	27.8	31.1	32.2	33.9	35.0	36.1	37.2	38.3	39.4	40.6
43.3	5.0	11.1	15.6	18.9	21.7	25.0	26.7	28.9	30.6	33.3	35.0	36.7	37.8	38.9	40.0	41.1	42.2	43.3
46.1	7.2	13.3	17.8	21.1	23.9	26.7	28.9	31.1	32.8	36.1	37.8	38.9	40.6	41.7	42.8	43.9	45.0	46.1
48.9	8.9	15.6	20.0	23.3	26.1	29.4	31.1	33.3	35.6	38.9	40.6	41.7	42.8	44.4	45.6	46.7	47.8	48.9
51.7	11.1	17.2	22.2	25.6	28.9	31.7	33.9	36.1	37.8	41.7	42.8	43.9	45.6	47.2	48.3	49.4	50.6	51.7

It is crucial that sufficient insulation is added so that the outer temperature of the insulation remains above the dew point temperature. At the dew point temperature, moisture in the air will condense onto the insulation and essentially ruin it.

Practical Example



In the figure above, a typical reactor feed preheater (interchanger) is shown. The heat exchanger resides on the first level of the structure while the reactor is on the second level. During construction, stream 2 was not insulated because it runs from the exchanger directly to the ceiling away from workers so it posed no safety risk. The reaction is endothermic, so heat is supplied by a Dowtherm jacket surrounding the vessel. The equivalent length of the pipe containing stream 2 is 100 meters. A recent rise is fuel oil costs (which is used to heat the Dowtherm) has prompted the company to search for ways to conserve energy. With the data provided below, you recognize an opportunity for energy savings. Any increase in the reactor feed temperature will reduce the reactor duty and save money. What is the current reactor entrance temperature compared with the entrance temperature after applying the economic insulation thickness to the pipe?

Data:

Calcium silicate insulation

Temperature of stream 2 exiting the heat exchanger is 400 $^{\circ}$C (752 $^{\circ}$F)

Ambient temperature is 23.8 $^{\circ}$C (75 $^{\circ}$F)

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

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

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

Thermal conductivity of pipe = k_{pipe} = 30 W/m K (56.2 Btu/h ft $^{\circ}$F)

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

Fluid heat capacity = Cp_{fluid} = 2.57 kJ/kg K (2.0 Btu/lb $^{\circ}$F)

Fluid thermal conductivity = k_{fluid} = 0.60 W/m K (1.12 Btu/h ft $^{\circ}$F)

Fluid viscosity = u_{fluid} = 5.2 cP

Energy costs = \$4.74/million kJ (\$5.00/million Btu)

Equivalent length of pipe = 100 meters (328 feet)

Calculations:

$$T_{inreactor} = (T_{outexchanger} - T_{ambient}) \exp\left(\frac{-2\pi\ R3\ U\ L}{\dot{m}\ C_p}\right) + T_{ambient}$$

$$U = \frac{1}{\frac{R3}{R1\ hi} + \frac{R3\ LN(R2/R1)}{k_{pipe}} + \frac{R3\ LN(R3/R2)}{k_{insulation}} + \frac{1}{ho}}$$

From Table 2, economic insulation thickness is 63.5 mm (2.5 in), R3 = 171.5 mm

From Figure 1, $k_{insulation} = 0.070$ W/m K

$$hi = \frac{0.023\ C_p\ \dot{m}}{A_x\left(\frac{C_p\ \mu_{fluid}}{k_{fluid}}\right)^{\frac{2}{3}}\left(\frac{2\ R1\ \dot{m}}{A_x\ \mu_{fluid}}\right)^{0.2}} = \frac{(0.023)(2.57)(350000)}{(0.0324)\left(\frac{(2.57)(5.2)}{(0.60)}\right)^{\frac{2}{3}}\left(\frac{(2)\qquad(0.1016)(350000)}{(3.6)(0.0324)(5.2)}\right)^{0.2}}$$

$$hi = 2171\ W/m^2K = 382\ Btu/h\ ft^2\ {}^0F$$

$$U_{Bare\ Pipe} = \frac{1}{\frac{0.1715}{(0.1016)(2171)} + \frac{0.1715\ LN(0.108/0.1016)}{30} + \frac{1}{50}} = 47\ W/m^2K = 8.3\ Btu/h\ ft^2\ {}^0F$$

$$U_{Insulated} = \frac{1}{\frac{0.1715}{(0.1016)(2171)} + \frac{0.1715\ LN(0.108/0.1016)}{30} + \frac{0.1715\ LN(0.1715/0.108)}{0.07} + \frac{1}{50}}$$

$$U_{insulated} = 0.87\ W/m^2K = 0.15\ Btu/h\ ft^2\ {}^0F$$

With bare pipe,

$$T_{inreactor} = (400\,^0C - 23.8\,^0C)\exp\left(\frac{-2\pi\ (0.1715)(47)(100)}{(350000)(2.57)}\right) + 23.8\,^0C = \underline{398\,^0C}$$

With insulation,

$$T_{inreactor} = \underline{399.96}\ {}^0C$$

Temperature difference with insulation is nearly 2 °C (3.6 °F). While this doesn't sound too dramatic, consider the energy savings over one year with the insulation:

Q = mass flow x Cpfluid x temperature difference

Q = (350,000 kg/h)(2.57 kJ/kg K)(2.0K) = 1799000 kJ/h

1799000 kJ/h x 8760 hours/year = 15,760 million kJ/year

15,760 million kJ/year x \$4.74/million kJ = <u>\$74,700 per year</u>

By insulating the pipe, energy costs have decreased by nearly \$75,000 per year