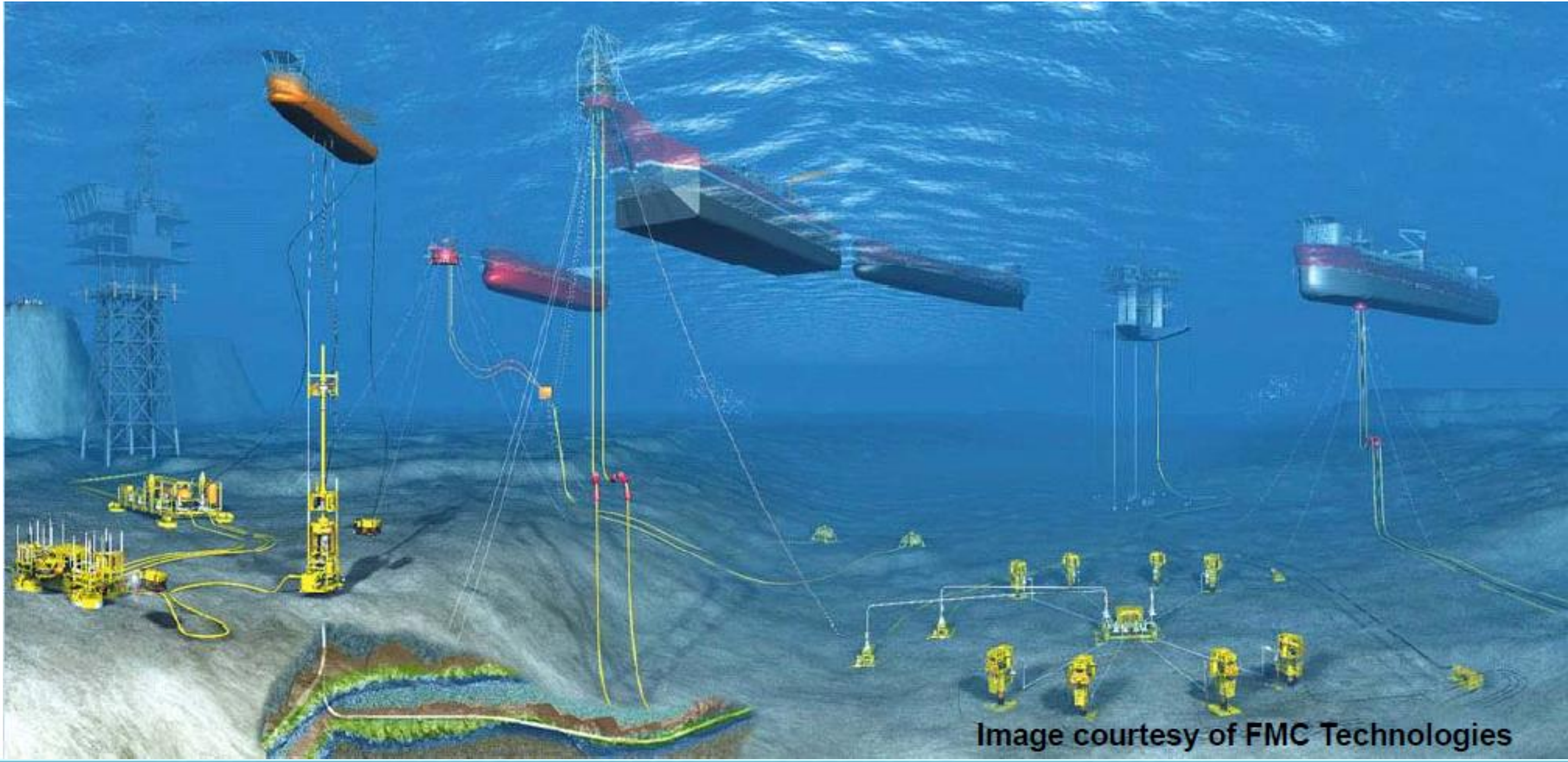


Subsea Engineering

Yutaek Seo

Thermal analysis

- Thermal analysis or design predicts the temperature profile along the pipeline
- It is important parts of pipeline design, because this information is required for pipeline analysis including expansion analysis, buckling, corrosion protection, hydrate prediction, and wax deposition analysis.
- In most cases, the management of the solids produced determines the hydraulic and thermal design requirements.
- To maintain a minimum temperature of fluid to prevent hydrate and wax deposition in the pipeline, insulation layers may be added to the pipeline.

k and U

- Thermal Conductivity (k) is the property of a material which defines its ability to transfer heat.
- Overall Heat Transfer Coefficient (U-value) determines the heat transfer through a pipe system, incorporating the thermal conductivity of the materials as well as the geometry of the system.

Thermal design

- Thermal design includes both steady-state and transient heat transfer analyses.
- Steady-state heat transfer

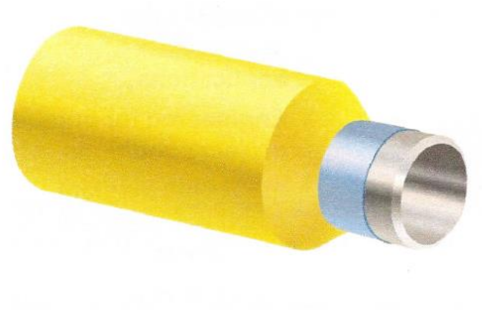
  : The production fluid temperature decreases as it flows along the pipeline due to the heat transfer through the pipe wall to the surrounding environment.

  : The temperature profile in the whole pipeline system should be higher than the requirements for prevention of hydrate and wax formation during normal operation and is determined from steady-state flow and heat transfer calculations.
- Transient

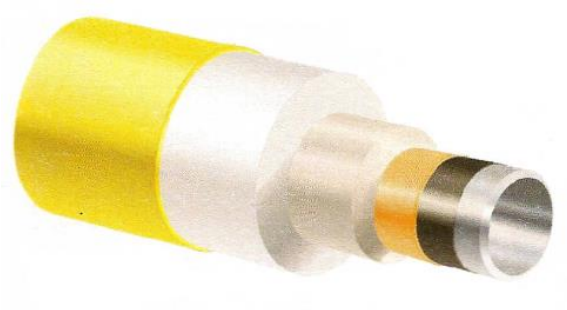
  : If the steady flow conditions are interrupted due to a shutdown or restarted again during operation, the transient heat transfer analysis for the system is required to make sure the temperature of fluid is out of the solid formation range within the required time.

Thermal management

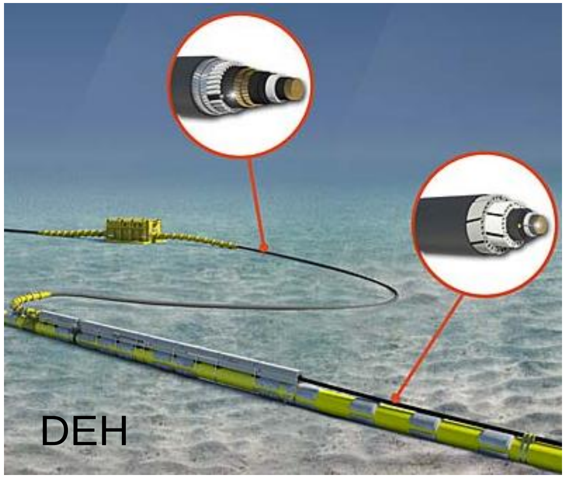
- It is necessary to consider both steady-state and transient analyses in order to ensure the performance of the insulation coatings will be adequate in all operational scenarios.
- The thermal management strategy for pipelines can be divided into passive control and active heating.
- Passive control includes pipelines insulated by external insulation layers, pipe-in-pipe (PIP), bundle and burial, and active heating includes electrical heating and hot fluid heating.



Single layer

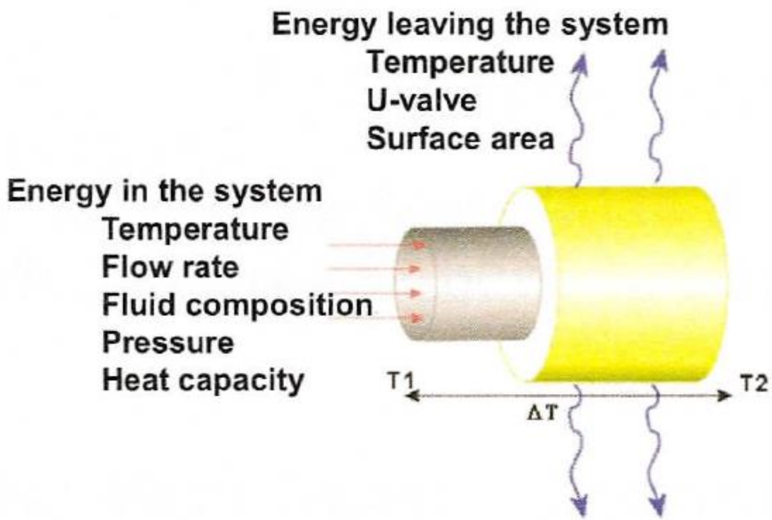


Multi layer

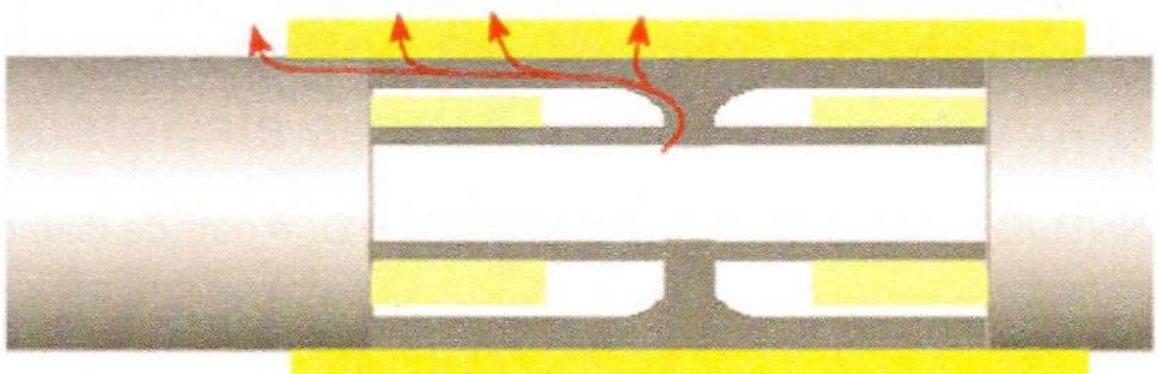


DEH

Heat transfer during steady state flow



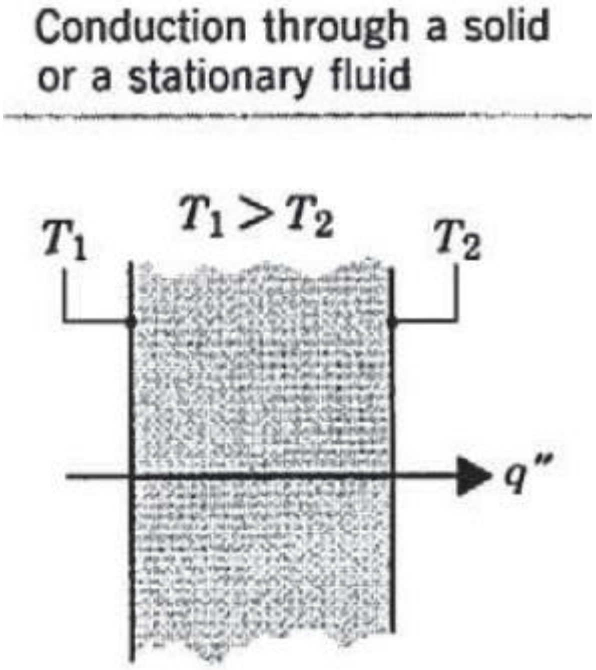
Main section of pipe



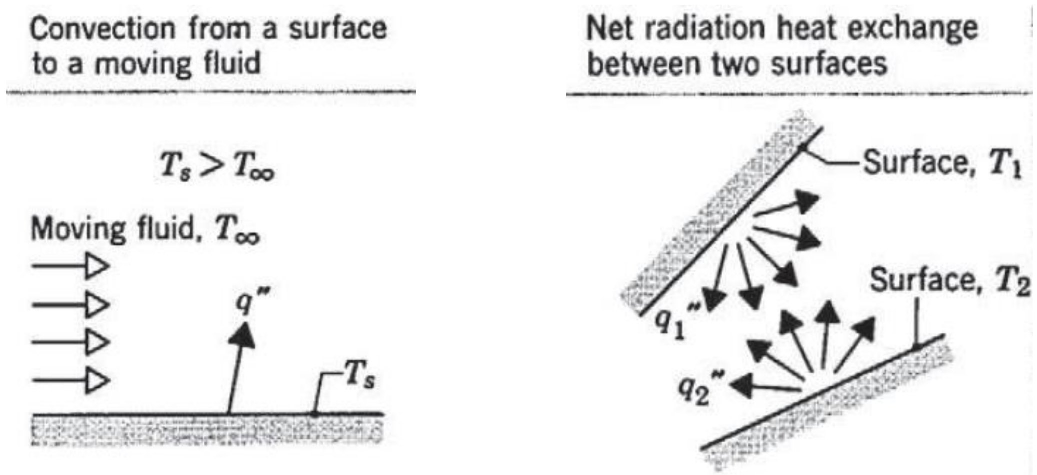
Thermal Leakage from a Bulkhead or Field Joint

Heat transfer fundamentals

- Heat is transferred by any one or a combination of the three heat transfer modes: conduction, convection, and radiation.
- When a temperature gradient exists in a stationary medium, which may be gas, liquid, or solid, the conduction will occur across the medium.



- If a surface and a moving fluid have a temperature difference, the convection will occur between the fluid and surface.
- All solid surfaces with a temperature will emit energy in the form of electromagnetic waves, which is called radiation



- Although these three heat transfer modes occur at all subsea systems, for typical pipelines, heat transfer from radiation is relatively insignificant compared with heat transfer from conduction and convection.

Heat conduction

- For a one-dimensional plane with a temperature distribution T(x), the heat conduction is quantified by the following Fourier equation:

$$q'' = -k \cdot \frac{dT(x)}{dx} \qquad (14\text{-}1)$$

Where,

q'': heat flux, Btu/(hr ft^2) or W/m^2, heat transfer rate in the x direction per unit area;

k: thermal conductivity of material, Btu/(ft hr ^{o}F) or W/(m K);

dT/dx: temperature gradient in the x direction, ^{o}F/ft or ^{o}C/m.

- When the thermal conductivity of a material is constant along the wall thickness, the temperature distribution is linear and the heat flux becomes:

$$q'' = -k \cdot \frac{T_2 - T_1}{x_2 - x_1} \qquad (14\text{-}2)$$

- By applying an energy balance to a 3D differential control volume and temperature boundary condition, the temperature distribution may be acquired from the heat diffusion equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q} = \rho c_p\frac{\partial T}{\partial t} \qquad (14\text{–}3)$$

Where,

q : heat generation rate per unit volume of the medium, Btu/(hr ft3) or W/m3;

r: density of the medium, lb/ft^3 or kg/m^3;

c_p: specific heat capacity, Btu/(lb ^{o}F) or kJ/(kg K);

x,*y*,*z*: coordinates, ft or m;

t: time, sec.

- For cylindrical coordinates, the heat diffusion equation may be rewritten as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \quad (14\text{–}4)$$

Where,

r, z: radius and axial directions of cylindrical coordinates;

ϕ : angle in radius direction.

- For most flowline systems, the heat transfer along the axial and circumferential directions may be ignored and, therefore, transient heat conduction without a heat source will occur in the radial direction of cylindrical coordinates.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)=\rho c_p\frac{\partial T}{\partial t} \quad (14\text{–}5)$$

- For a steady heat transfer, the right side of equation is equal to zero.
- The total heat flow per unit length of cylinder is calculated by following equation:

$$q_r = -2\pi k \frac{T_2 - T_1}{\ln(r_2/r_1)} \qquad (14\text{-}6)$$

Where,

r_1, r_2: inner and outer radii of the cylinder medium, ft or m;

T_1, T_2: temperatures at corresponding points of r_1, r_2, ^oF or ^oC;

q_r: heat flow rate per unit length of cylinder, Btu/(hr ft) or W/m.

Convection

- Both internal and external surfaces of a subsea pipeline come in contact with fluids, so convection heat transfer will occur when there is a temperature difference between the pipe surface and the fluid.
- The convection coefficient is also called a film heat transfer coefficient in the flow assurance field because convection occurs at a film layer of fluid adjacent to the pipe surface.

Internal convection

- Internal convection heat transfer occurs between the fluid flowing in a pipe and the pipe internal surface; it depends on the fluid properties, the flow velocity, and the pipe diameter.
- For the internal convection of pipelines, Dittus and Boelter proposed the following dimensionless correlation for fully turbulent flow of single-phase fluids:

$$Nu_i = 0.0255 \cdot Re_i^{0.8} \cdot Pr_i^n \qquad (14\text{-}7)$$

Where,

Nu_i : Nusselt number, $Nu_i = (h_i D_i) / k_f$

Re_i : Reynolds number, $Re_i = (D_i V_f \rho_f) / \mu_f$;

Pr_i : Prandtl number, $Pr_i = C_{pf} \mu_i / k_f$;

n: 0.4 if the fluid is being heated, and 0.3 if the fluid is being cooled;

h_i, internal convection coefficient, D_i, pipeline inside diameter, k_f, thermal conductivity of the fluid, V_f, velocity of the fluid, ρ_f , density of the fluid, C_{pf}, specific heat capacity of the fluid, μ_i, viscosity of the fluid

- Therefore,

$$h_i = 0.0255\ Re_i^{0.8}\ Pr_i^{n}\ k_f / D_i$$

which will be used to calculate U-value

- If the flow is laminar (i.e., $Re_i < 2100$), h_i may be calculated using Hausen's equation as follows:

$$Nu_i = 3.66 + \frac{0.0668\left(\frac{D_i}{L_o}\right)Re_i Pr_i}{1 + 0.4\left[\left(\frac{D_i}{L_o}\right)Re_i Pr_i\right]^{2/3}} \qquad (14\text{-}8)$$

where, L_o is the distance from the pipe inlet to the point of interest.

- In most pipeline cases, $D_i/L_o \approx 0$, therefore Equation (14-8) becomes:

$$Nu_i = 3.66 \qquad (14\text{-}9)$$

- For the transition region ($2100 < Re_i < 104$), the heat transfer behavior in this region is always uncertain because of the unstable nature of the flow, especially for multiphase flow in pipeline systems.
- A correlation proposed by Gnielinski may be used to calculate h_i in this region:

$$Nu_i = \frac{(f/8)(Re_i - 1000)Pr_i}{1 + 12.7(f/8)^{1/2}(Pr_i^{2/3} - 1)} \quad (14\text{–}10)$$

where the fiction factor f may be obtained from the Moody diagram

- Typical ranges for internal convection coefficients for turbulent flow.

Table 14-1 Typical Internal Convection Coefficients for Turbulent Flow [5]

	Internal Convection Coefficient, h_i	
Fluid	**Btu/(ft^2·hr·°F)**	**W/(m^2 K)**
Water	300–2000	1700–11350
Gases	3–50	17–285
Oils	10–120	55–680

- Thermal conductivities and specific heat capacities for a variety of typical oils and gases.

Table 14-2 Typical Thermal Conductivities for Crude Oil/Hydrocarbon Liquids [5]

Temperature	0°F (−18°C)		200°F (93°C)	
API Gravity	Btu/(ft·hr·°F)	W/(m·K)	Btu/(ft·hr·°F)	W/(m·K)
10	0.068	0.118	0.064	0.111
20	0.074	0.128	0.069	0.119
30	0.078	0.135	0.074	0.128
40	0.083	0.144	0.078	0.135
50	0.088	0.152	0.083	0.144
60	0.093	0.161	0.088	0.152
80	0.103	0.178	0.097	0.168
100	0.111	0.192	0.105	0.182

Table 14-4 Typical Specific Heat Capacities for Hydrocarbon Liquids [5]

Temperature	0°F (−18°C)		100°F (38°C)		200°F (93°C)	
API Gravity	Btu/(lb·°F)	kJ/(kg·K)	Btu/(lb·°F)	kJ/(kg·K)	Btu/(lb·°F)	kJ/(kg·K)
10	0.320	1.340	0.355	1.486	0.400	1.675
30	0.325	1.361	0.365	1.528	0.415	1.738
50	0.330	1.382	0.370	1.549	0.420	1.758
70	0.335	1.403	0.375	1.570	0.430	1.800

Table 14-3 Typical Thermal Conductivities for Hydrocarbon Gases [5]

Temperature	50°F (10°C)		100°F (38°C)		200°F (93°C)	
Gas Gravity	Btu/(ft·hr·°F)	W/(m·K)	Btu/(ft·hr·°F)	W/(m·K)	Btu/(ft·hr·°F)	W/(m·K)
0.7	0.016	0.028	0.018	0.031	0.023	0.039
0.8	0.014	0.024	0.016	0.028	0.021	0.036
0.9	0.013	0.022	0.015	0.026	0.019	0.033
1.0	0.012	0.021	0.014	0.024	0.018	0.031
1.2	0.011	0.019	0.013	0.022	0.017	0.029

Table 14-5 Typical Specific Heat Capacities for Hydrocarbon Gases [5]

Temperature	0°F (−18°C)		100°F (38°C)		200°F (93°C)	
Gas Gravity	Btu/(lb·°F)	kJ/(kg·K)	Btu/(lb·°F)	kJ/(kg·K)	Btu/(lb·°F)	kJ/(kg·K)
0.7	0.47	1.97	0.51	2.14	0.55	2.30
0.8	0.44	1.84	0.48	2.01	0.53	2.22
0.9	0.41	1.72	0.46	1.93	0.51	2.14
1.0	0.39	1.63	0.44	1.84	0.48	2.01

External convection

- The correlation of average external convection coefficient suggested by Hilpert is widely used in industry:

$$Nu_o = C\,Re_o^{\,m}\,Pr_o^{\,1/3} \qquad (14\text{–}12)$$

Where,

Nu_o : Nusselt number, $Nu_o = (h_o D_o) / k_o$

Re_o : Reynolds number, $Re_o = (D_o V_o \rho_o) / \mu_o$;

Pr_o : Prandtl number, $Pr_o = C_{po} \mu_o / k_o$;

h_o, external convection coefficient, D_o, pipeline outer diameter, k_o, thermal conductivity of the surrounding fluid, V_o, velocity of the surrounding fluid, ρ_o , density of the surrounding fluid, C_{po}, specific heat capacity of the surrounding fluid, μ_o, viscosity of the surrounding fluid,

C, *m*: constants, dependent on the Re number range

Table 14-6 Constants of Correlation

Re_o	*C*	*m*
$4 \times 10^{-1} - 4 \times 10^{0}$	0.989	0.330
$4 \times 10^{0} - 4 \times 10^{1}$	0.911	0.385
$4 \times 10^{1} - 4 \times 10^{3}$	0.683	0.466
$4 \times 10^{3} - 4 \times 10^{4}$	0.193	0.618
$4 \times 10^{4} - 4 \times 10^{5}$	0.027	0.805

- When the velocity of surrounding fluid is less than approximately 0.05 m/s in water and 0.5 m/s in air, natural convection will have the dominating influence and the following values may be used:

$$h_o = \begin{cases} 4 \ \ \mathrm{W/(m^2K)}, & \text{natural convection in air} \\ 200 \ \ \mathrm{W/(m^2K)}, & \text{natural convection in water} \end{cases} \qquad (14\text{–}13)$$

- Many of the parameters used in the correlation are themselves dependent on temperature. Because the temperature drop along most pipelines is relatively small, average values for physical properties may be used.
- The analysis of heat transfer through a wall to surrounding fluid does not address the cooling effect due to the Joule-Thompson expansion of a gas. For a long gas pipeline or pipeline with two-phase flow, an estimation of this cooling effect should be made.

U-value

- Figure 14-4 shows the temperature distribution of a cross section for a composite subsea pipeline with two insulation layers.

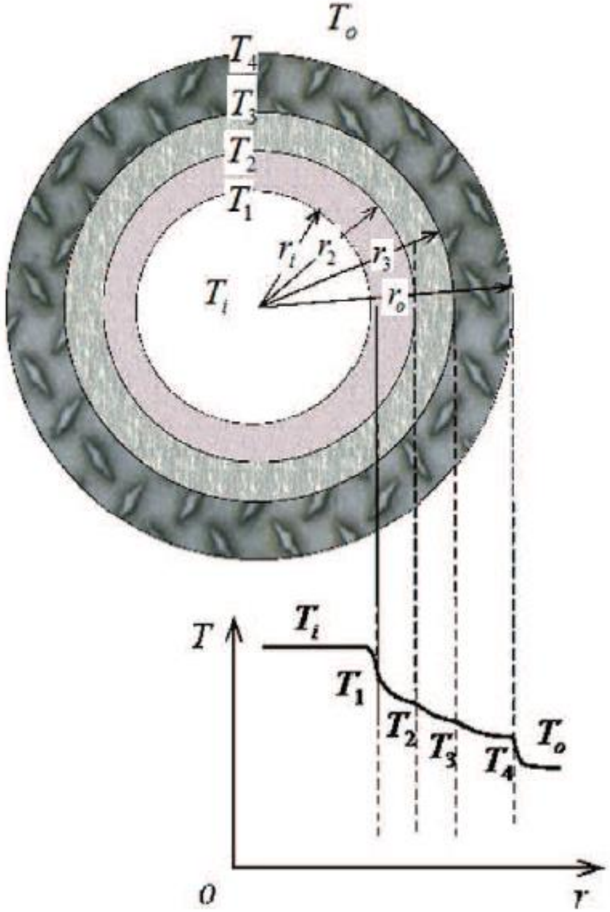


Figure 14-4 Cross Section of Insulated Pipe and Temperature Distribution

- Radiation between the internal fluid and the pipe wall and the pipeline outer surface and the environment is ignored because of the relatively low temperature of subsea systems.
- Convection and conduction occur in an insulated pipeline as follows,
  : Convection from the internal fluid to the pipeline wall;
  : Conduction through the pipe wall and exterior coatings, and/or to the surrounding soil for buried pipelines;
  : Convection from flowline outer surface to the external fluid

- For internal convection at the pipeline inner surface, the heat transfer rate across the surface boundary is given by the Newton equation:

$$Q_i = A_i \cdot h_i \cdot \Delta T = 2\pi\, r_i\, L\, h_i\, (T_i - T_1) \qquad (14\text{-}18)$$

where

Q_i : convection heat transfer rate at internal surface, Btu/hr or W;

h_i : internal convection coefficient, Btu/(ft^2 hr ^{o}F) or W/(m^2 K);

r_i : internal radius of flowline, ft or m;

L: flowline length, ft or m;

A_i : internal area normal to the heat transfer direction, ft^2 or m^2;

T_i : internal fluid temperature, ^{o}F or ^{o}C;

T_1: temperature of flowline internal surface, ^{o}F or ^{o}C.

- For external convection at the pipeline outer surface, the heat transfer rate across the surface boundary to the environment is:

$$Q_o = A_o \cdot h_o \cdot \Delta T_o = 2\pi \, r_o \, L \, h_o \, (T_4 - T_o) \qquad (14\text{-}19)$$

where

Q_o : convection heat transfer rate at outer surface, Btu/hr or W;

h_o : outer convection coefficient, Btu/(ft^2 hr ^{o}F) or W/(m^2 K);

r_o : outer radius of flowline, ft or m;

L: flowline length, ft or m;

A_o: outer area normal to the heat transfer direction, ft^2 or m^2;

T_o : environment temperature, ^{o}F or ^{o}C;

T_4: outer surface temperature of flowline, ^{o}F or ^{o}C.

- Conduction in the radial direction of a cylinder can be described by Fourier's equation in radial coordinates:

$$Q_r = -2\pi\, r\, L\, k \frac{\partial T}{\partial r} \qquad (14\text{-}20)$$

where

Q_r : conduction heat transfer rate in radial direction, Btu/hr or W;

r: radius of cylinder, ft or m;

k: thermal conductivity of cylinder, Btu/(ft hr ^oF) or W/(m K);

$\partial T/\partial r$: temperature gradient, ^oF/ft or ^oC/m.

- Integration of Equation (14-20) gives:

$$Q_r = \frac{2\pi\, L\, k(T_1 - T_2)}{\ln(r_2/r_1)} \qquad (14\text{-}21)$$

- The temperature distribution in the radial direction can be calculated for steady-state heat transfer between the internal fluid and pipe surroundings, where heat transfer rates of internal convection, external convection, and conduction are the same.
- The following heat transfer rate equation is obtained:

$$Q_r = \frac{T_i - T_o}{\dfrac{1}{2\pi r_i L h_i} + \dfrac{\ln(r_1/r_i)}{2\pi k_1 L} + \dfrac{\ln(r_2/r_1)}{2\pi k_2 L} + \dfrac{\ln(r_o/r_2)}{2\pi k_3 L} + \dfrac{1}{2\pi r_o L h_o}} \qquad (14\text{-}22)$$

- The heat transfer rate through a pipe section with length of L, due to a steady-state heat transfer between the internal fluid and the pipe surroundings, is also expressed as follows:

$$Q_r = UA(T_i - T_o) \qquad (14\text{-}23)$$

where

U: overall heat transfer coefficient based on the surface area A, Btu/ (ft^2 hr ^oF) or W/ (m^2 K);

A: area of heat transfer surface, A_i or A_o, ft^2 or m^2;

T_o : ambient temperature of the pipe surroundings, ^oF or ^oC;

T_i : average temperature of the flowing fluid in the pipe section, ^oF or ^oC.

Multilayer insulation

- The U-value for a multilayer insulation coating system is easily obtained from an electrical-resistance analogy between heat transfer and direct current.
- The steady-state heat transfer rate is determined by:

$$Q_r = UA(T_i - T_o) = (T_i - T_o)/\sum R_i \qquad (14\text{–}27)$$

where UA is correspondent with the reverse of the cross section's thermal resistivity that comprises three primary resistances: internal film, external film, and radial material conductance.

- The relationship is written as follows:

$$\frac{1}{UA} = \sum R_i = R_{film,in} + R_{pipe} + \sum R_{coating} + R_{film,ext} \qquad (14\text{–}28)$$

- The terms on the right hand side of the above equation represent the heat transfer resistance due to internal convection, conduction through steel well of pipe, conduction through insulation layers and convection at the external surface.
- They can be expressed as follows.

$$R_{film,in} = \frac{1}{h_i A_i} \qquad (14\text{-}29)$$

$$R_{pipe} = \frac{\ln(r_l/r_i)}{2\pi L k_{pipe}} \qquad (14\text{-}30)$$

$$\sum R_{coating} = \frac{\ln(r_{no}/r_{ni})}{2\pi L k_n} \qquad (14\text{-}31)$$

$$R_{film,ext} = \frac{1}{h_o A_o} \qquad (14\text{-}32)$$

- Therefore, the U-value based on the flowline internal surface area A_i is:

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{r_i ln(r_1/r_i)}{k_1} + \frac{r_i ln(r_2/r_1)}{k_2} + \frac{r_i ln(r_o/r_2)}{k_3} + \frac{r_i}{r_o h_o}}$$

and the U-value based on the flowline outer surface area A_o is:

$$U_o = \frac{1}{\frac{r_o}{r_i h_i} + \frac{r_o ln(r_1/r_i)}{k_1} + \frac{r_o ln(r_2/r_1)}{k_2} + \frac{r_o ln(r_o/r_2)}{k_3} + \frac{1}{h_o}}$$

- U-value is a function of many factors, including the fluid properties and fluid flow rates, the convection nature of the surroundings, and the thickness and properties of the pipe coatings and insulation.
- Insulation manufacturers typically use a U-value based on the outside diameter of a pipeline, whereas pipeline designers use a U-value based on the inside diameter.
- The relationship between these two U-values is:

$$U_o \times \mathrm{OD} = U_i \times \mathrm{ID} \tag{14-26}$$

Achievable U-Values

- The following U-values are lowest possible values to be used for initial design purposes:
  - : Conventional insulation: 0.5 Btu/ft^2 hr ^{o}F (2.8 W/m^2 K);
  - : Polyurethane pipe-in-pipe: 0.2 Btu/ft^2 hr ^{o}F (1.1 W/m^2 K);
  - : Ceramic insulated pipe-in-pipe: 0.09 Btu/ft^2 hr ^{o}F (0.5 W/m^2 K);
  - : Insulated bundle: 0.2 Btu/ft^2 hr ^{o}F (1.1 W/m^2 K).
- Insulation materials exposed to ambient pressure must be qualified for the water depth where they are to be used.

Insulation design for flowlines

Flowline	Layers	WT mm	OD mm	ID mm	K W/m°K	Cp j/kg°K	Density kg/m³	U-Valve W/m^2-°K
6″ ID PIP Production Well Jumper WD = 1880m	Fluid (Methane)	–	152.4	–	–	3550	170	1.14 (0.200 Btu/hr-ft^2-deg F)
	Steel	12.7	177.8	152.4	45	461	7865	
	FBE	0.30	178.4	177.8	0.30	1500	1300	
	PUF	29.8	238.0	178.4	0.025	900	64	
	Steel	15.9	269.8	238.0	45.000	461	7865	
8″ ID Flexible Flowline WD = 1880m	Fluid (Methane)	–	203.2	–	–	3550	170	3.82 (0.673 Btu/hr-ft^2-deg F)
	316 SS	10.0	223.2	203.2	14.00	470	4491	
	PA 11	12.00	247.2	223.2	0.27	2000	1050	
	Polyester	2.20	251.6	247.2	0.13	450	800	
	Carb. Steel	18.00	287.6	251.6	56.00	450	7860	
	PP Foam	50.0	387.6	287.6	0.16	2180	700	
	PA 11	10.0	407.6	387.6	0.27	2000	1050	
8″ ID Wet Insulation Production Flowline WD = 1760m	Fluid (Methane)	–	203.2	–	–	3550	170	2.70 (0.476 Btu/hr-ft^2-deg F)
	Steel	15.9	235.0	203.2	45	461	7865	
	FBE	0.30	235.6	235.0	0.300	1500	1300	
	PP Adhesive	0.30	236.2	235.6	0.215	2000	900	
	PP Solid	6.00	248.2	236.2	0.220	2000	900	
	TDF	105.0	458.2	248.2	0.185	2000	740	
	PP Solid	4.0	466.2	458.2	0.220	2000	900	
8″ ID PIP Production Flowline WD = 1840m	Fluid (Methane)	–	177.8	–	–	3100	87	1.14 (0.200 Btu/hr-ft^2 deg F)
	Steel	15.9	209.6	177.8	45	461	7865	
	FBE	0.30	210.2	209.6	0.30	1500	1300	
	PUF	28.5	267.2	210.2	0.025	900	64	
	Steel	16.7	300.6	267.2	45.000	461	7865	

U-value for Buried pipe

- The U-value of pipelines can be described as:

$$U_i = \frac{1}{\sum \frac{r_i \ln(r_{no}/r_{ni})}{k_n} + \frac{r_i \cosh^{-1}(2Z/D_o)}{k_{soil}}} \qquad (14\text{-}33)$$

where the first term in the denominator represents the thermal resistance of the radial layers of steel and insulation coatings, and the second term in the denominator represents the thermal resistivity due to the soil and is valid for H > $D_o/2$.

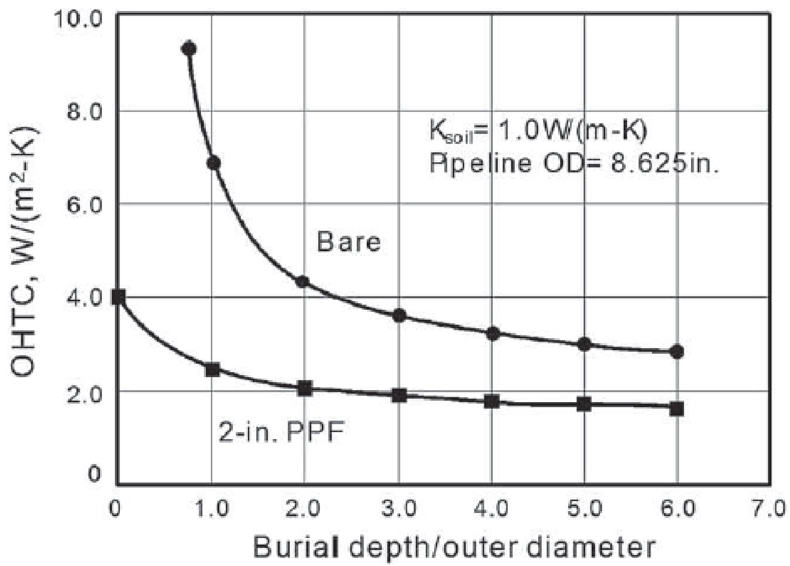


Figure 14-5 U-Value versus Burial Depth for Bare Pipe and 2–In. PPF-Coated Pipe [13]