General Heat Transfer and Applications

Heat Rate, Pipe Lagging and Wall Insulations

Process Industry Examples of Processes Using Heat

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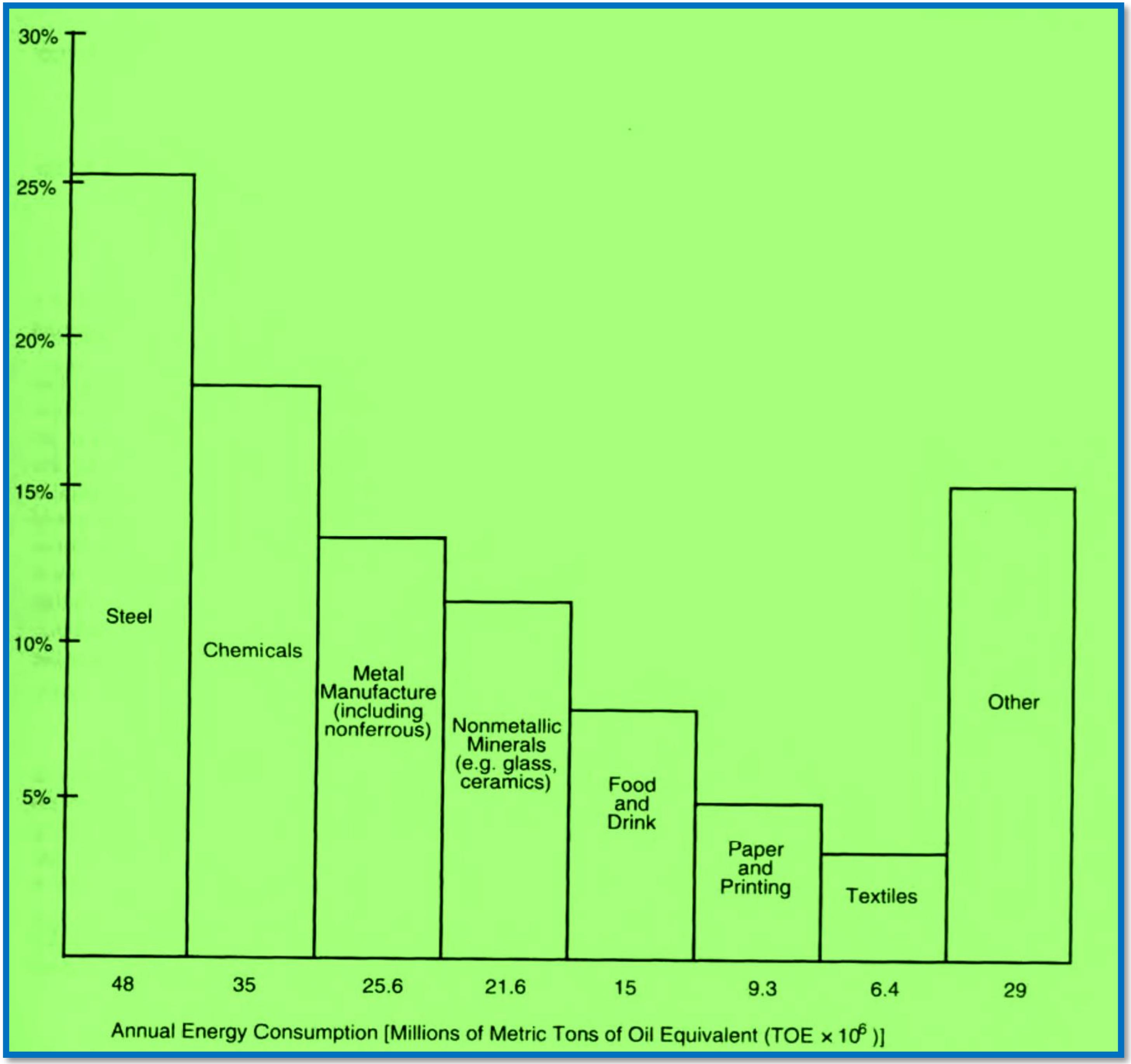
Steel making	Smelting of ores, refining, alloying, melting, casting, forging, rolling, annealing
Chemicals (Includes pharmaceuticals, toilet preparations, soap and detergents, paints, resins and plastics, dye-stuffs and pigments, and fertilizers)	Chemical reactions, hydrogenation, pyrolysis, distillation, purification, evaporation, crystallization, polymerization, drying
Nonmetallic minerals (Includes bricks, pottery, glass, cement, and other refractory materials)	Firing, kilning, drying, calcining, melting, forming (e.g., plate glass), annealing
Metal manufacture (Includes iron and steel, and nonferrous metals)	Blast furnaces and cupolas, soaking and heat treatment, melting, sintering, casting, forging, rolling, annealing
Food and drink (Includes dairy products, brewing, farinaceous products, meat and vegetables, soft drinks, and tobacco)	Milling, blending, drying, forming as liquids, powders, or composite solids, purification, sterilization, pasteurization, fermentation, refrigeration
Paper and printing (Paper, board, stationary, etc.)	Wood pulping and liquification, rolling, drying, coating, and forming
Textiles (Includes fibers and fabrics, rope and net, carpets, and furnishings)	Production of manmade fibers, spinning and weaving, dyeing, and finishing

Note: This list does not include the oil and gas industries, which are also large scale energy users and employ a wide range of heat transfer equipment.

Smelting: the extraction of metal from it
by a process involving heating and melt

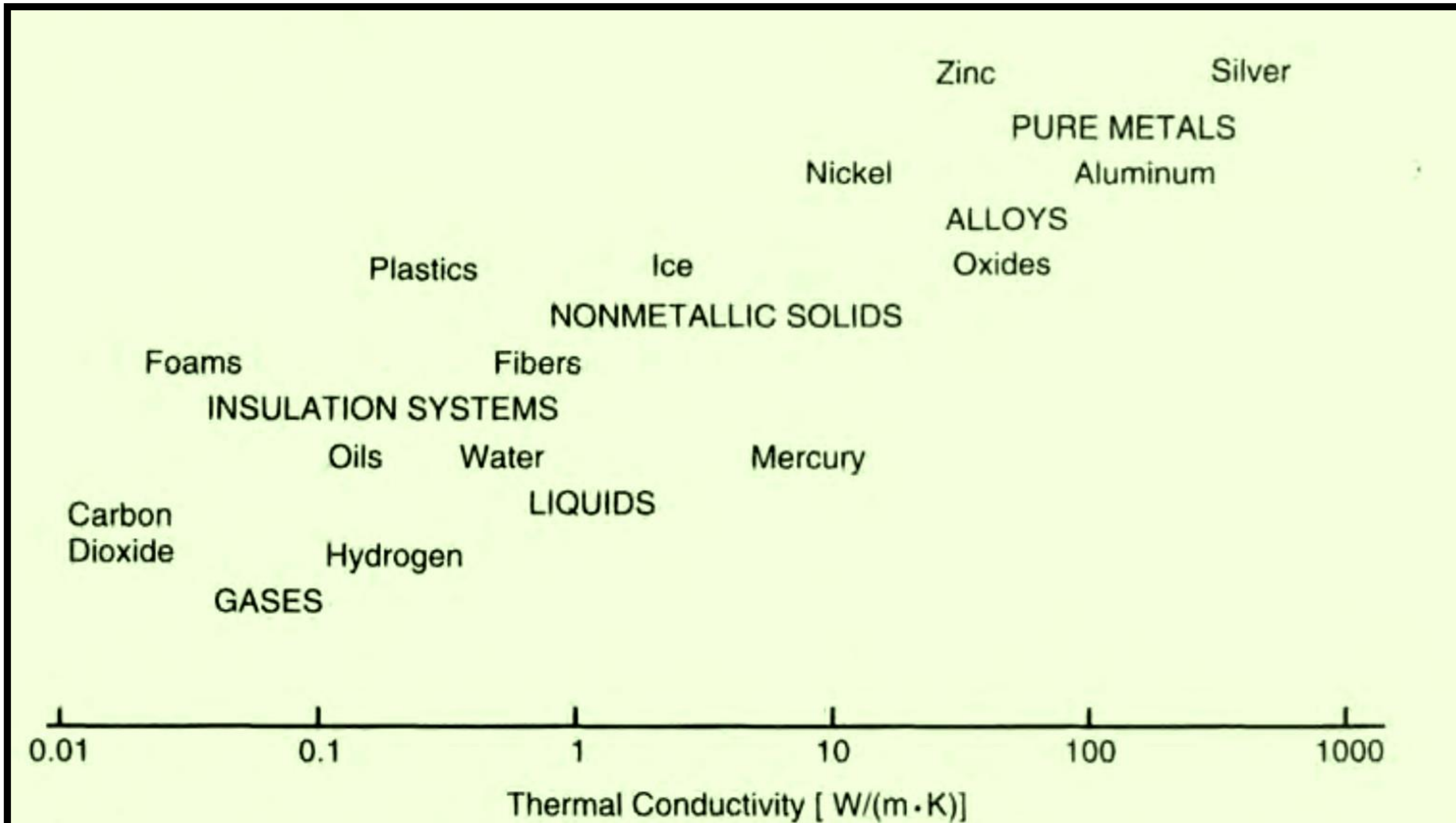
cupola furnace is a melting device


30%
25%
20%
15%
10%
5%
Steel
Chemicals
Metal Manufacture (including nonferrous)
Nonmetallic Minerals (e.g. glass, ceramics)
Food and Drink
Paper and Printing
Textiles
Other
48
35
25.6
21.6
15
9.3
6.4
29
Annual Energy Consumption [Millions of Metric Tons of Oil Equivalent (TOE × 10^6)]

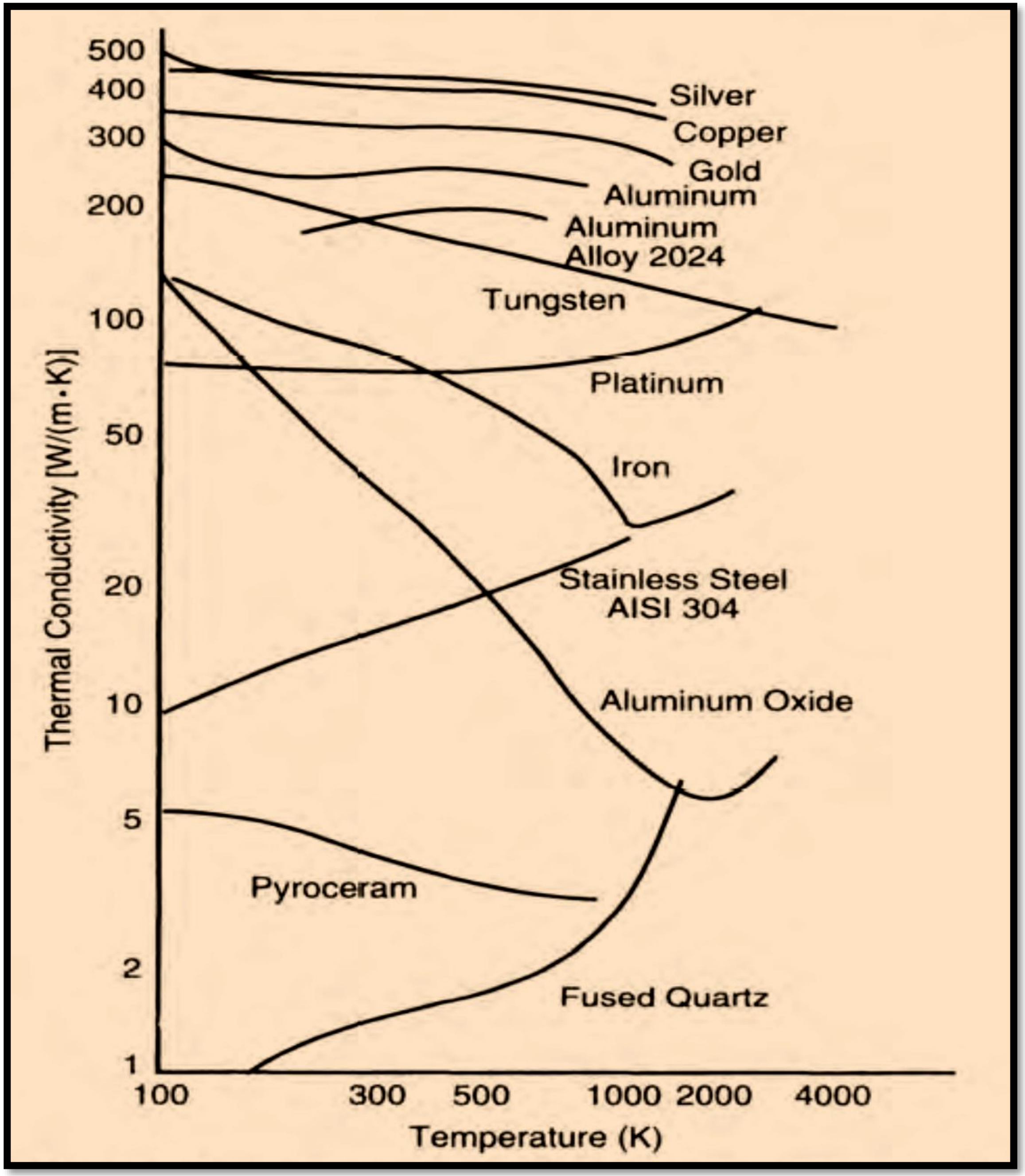
Comparison between different heat transfer modes

Conduction	Convection	Radiation
Material continuity	Material continuity	Possible in the absence of material continuity (i.e. vacuum)
Motion not necessary	Depends on fluid motion (fluid dynamics)	Motion not necessary
Occurs in solids, liquids, and gases	Occurs in liquids, gases, and multiphase mixtures	Occurs in trans-parent media, mainly gases

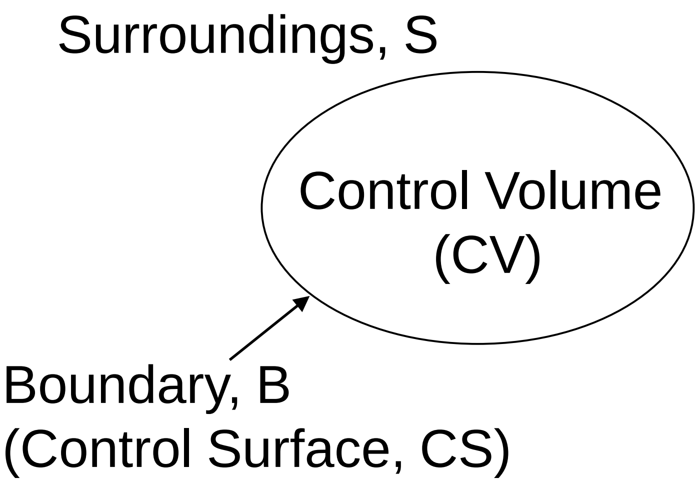
Thermal conductivity

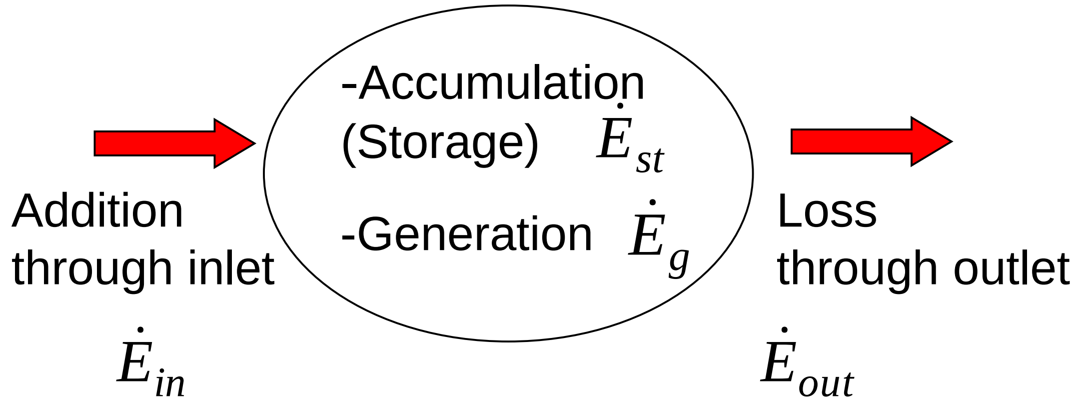


Solid thermal conductivity



Conservation of Energy





- Energy conservation on a rate basis:

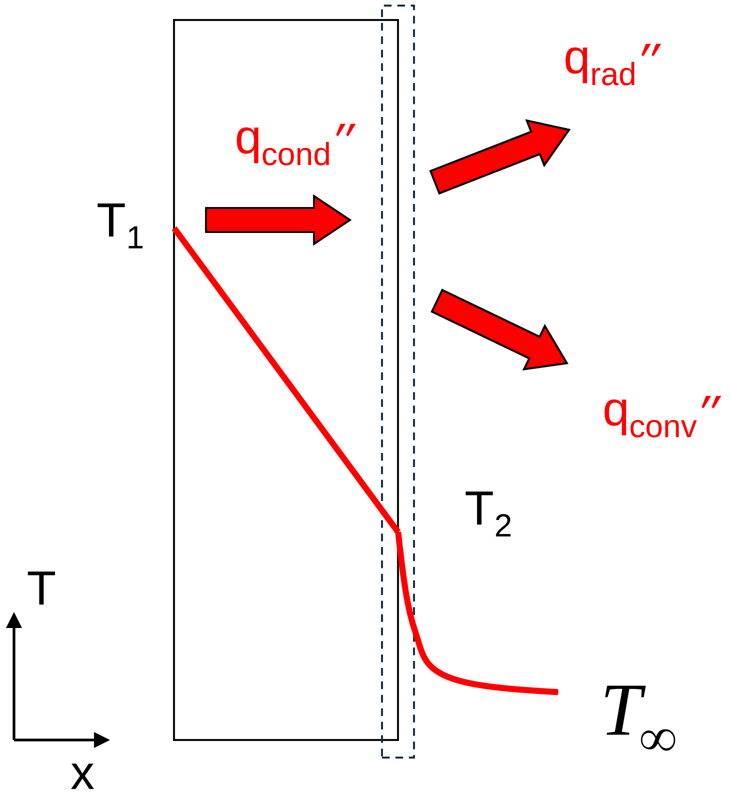
$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \frac{dE_{st}}{dt} = \dot{E}_{st}$$

Units W=J/s

- Inflow and outflow are surface phenomena
- Generation and accumulation are volumetric phenomena

Surface Energy Balance

For a control surface:



$$\dot{E}_{in} - \dot{E}_{out} = 0$$

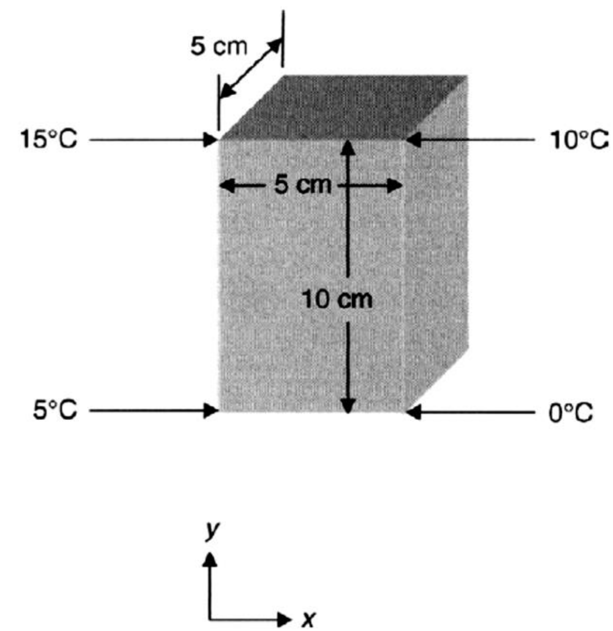
or

$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$

Example 1

The block of 304 stainless steel shown below is well insulated on the front and back surfaces, and the temperature in the block varies linearly in both the *x*- and *y*-directions, find:

(a) The heat fluxes and heat flows in the *x*- and *y*-directions.
(b) The magnitude and direction of the heat flux vector.



Solution

(a) From Table A.1, the thermal conductivity of 304 stainless steel is 14.4 W/m · K. The cross-sectional areas are:

$$A_x = 10 \times 5 = 50\,\text{cm}^2 = 0.0050\,\text{m}^2$$

$$A_y = 5 \times 5 = 25\,\text{cm}^2 = 0.0025\,\text{m}^2$$

Using Equation (1.7) and replacing the partial derivatives with finite differences (since the temperature variation is linear), the heat fluxes are:

$$\hat{q}_x = -k\frac{\partial T}{\partial x} = -k\frac{\Delta T}{\Delta x} = -14.4\left(\frac{-5}{0.05}\right) = 1440\,\text{W/m}^2$$

$$\hat{q}_y = -k\frac{\partial T}{\partial y} = -k\frac{\Delta T}{\Delta y} = -14.4\left(\frac{10}{0.1}\right) = -1440\,\text{W/m}^2$$

The heat flows are obtained by multiplying the fluxes by the corresponding cross-sectional areas:

$$q_x = \hat{q}_x A_x = 1440 \times 0.005 = 7.2\,\text{W}$$

$$q_y = \hat{q}_y A_y = -1440 \times 0.0025 = -3.6\,\text{W}$$

(b) From Equation (1.6):

$$\vec{\hat{q}} = \hat{q}_x \vec{i} + \hat{q}_y \vec{j}$$

$$\vec{\hat{q}} = 1440\,\vec{i} - 1440\,\vec{j}$$

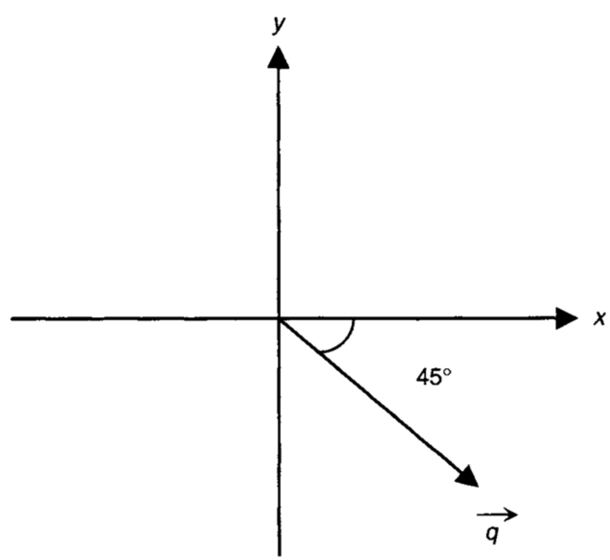
$$\left|\vec{\hat{q}}\right| = [(1440)^2 + (-1440)^2]^{0.5} = 2036.5\,\text{W/m}^2$$

The angle, θ, between the heat flux vector and the x-axis is calculated as follows:

$$\tan\theta = \hat{q}_y/\hat{q}_x = -1440/1440 = -1.0$$

$$\theta = -45^\circ$$

The direction of the heat flux vector, which is the direction in which heat flows, is indicated in the sketch below.



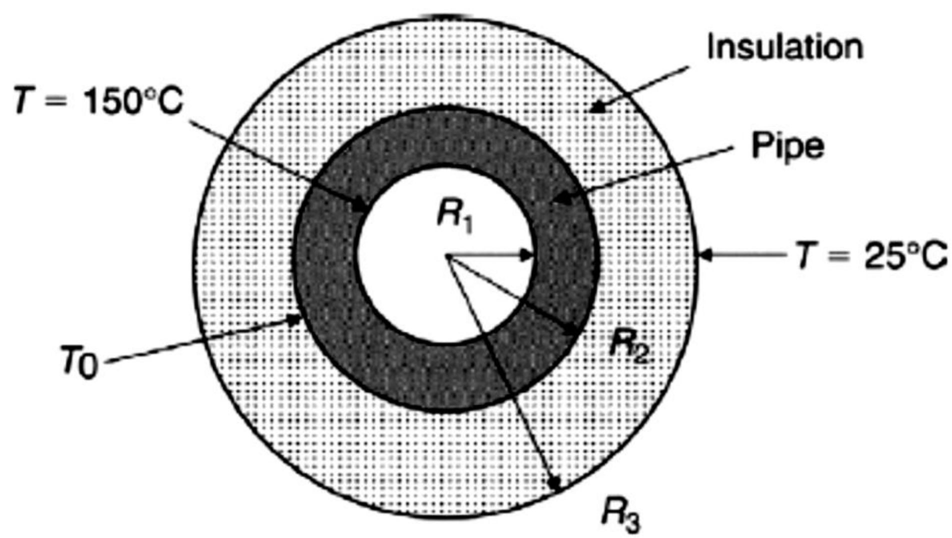
Example 2

A 5-cm (2-in.) schedule 40 steel pipe carries a heat-transfer fluid and is covered with a 2-cm layer of calcium silicate insulation ($k = 0.06\ \mathrm{W/m \cdot K}$) to reduce the heat loss. The inside and outside pipe diameters are 5.25 cm and 6.03 cm, respectively. If the inner pipe surface is at 150°C and the exterior surface of the insulation is at 25°C, calculate:

(a) The rate of heat loss per unit length of pipe.
(b) The temperature of the outer pipe surface.

Solution

- Firstly, sketch the problem.



$$q_r = \frac{\Delta T}{R_{th}} = \frac{150 - 25}{R_{th}}$$

$$R_{th} = R_{pipe} + R_{insulation}$$

$$R_{th} = \frac{\ln(R_2/R_1)}{2\pi k_{steel} L} + \frac{\ln(R_3/R_2)}{2\pi k_{ins} L}$$

$$R_1 = 5.25/2 = 2.625\,\text{cm}$$

$$R_2 = 6.03/2 = 3.015\,\text{cm}$$

$$R_3 = 3.015 + 2 = 5.015\,\text{cm}$$

$$k_{steel} = 43\,\text{W/m}\cdot\text{K (Table A.1)}$$

$$k_{ins} = 0.06\,\text{W/m}\cdot\text{K (given)}$$

$$L = 1\,\text{m}$$

$$R_{th} = \frac{\ln\left(\frac{3.015}{2.625}\right)}{2\pi \times 43} + \frac{\ln\left(\frac{5.015}{3.015}\right)}{2\pi \times 0.06} = 0.000513 + 1.349723$$

$$= 1.350236\,\text{K/W}$$

$$q_r = \frac{125}{1.350236} \cong 92.6\,\text{W/m of pipe}$$

(b) Writing the heat Equation for the pipe wall only:

$$q_r = \frac{150 - T_0}{R_{pipe}}$$

$$92.6 = \frac{150 - T_0}{0.000513}$$

$$T_0 = 150 - 0.0475 \cong 149.95°C$$

Clearly, the resistance of the pipe wall is negligible compared with that of the insulation, and the temperature difference across the pipe wall is a correspondingly small fraction of the total temperature difference in the system.

comments

- It should be pointed out that the calculation in the previous Example tends to overestimate the rate of heat transfer because it assumes that the insulation is in perfect thermal contact with the pipe wall.
- Since solid surfaces are not perfectly smooth, there will generally be air gaps between two adjacent solid materials. Since air is a very poor conductor of heat, even a thin layer of air can result in a substantial thermal resistance.
- This additional resistance at the interface between two materials is called the contact resistance. Therefore, the total thermal resistance becomes as follows:

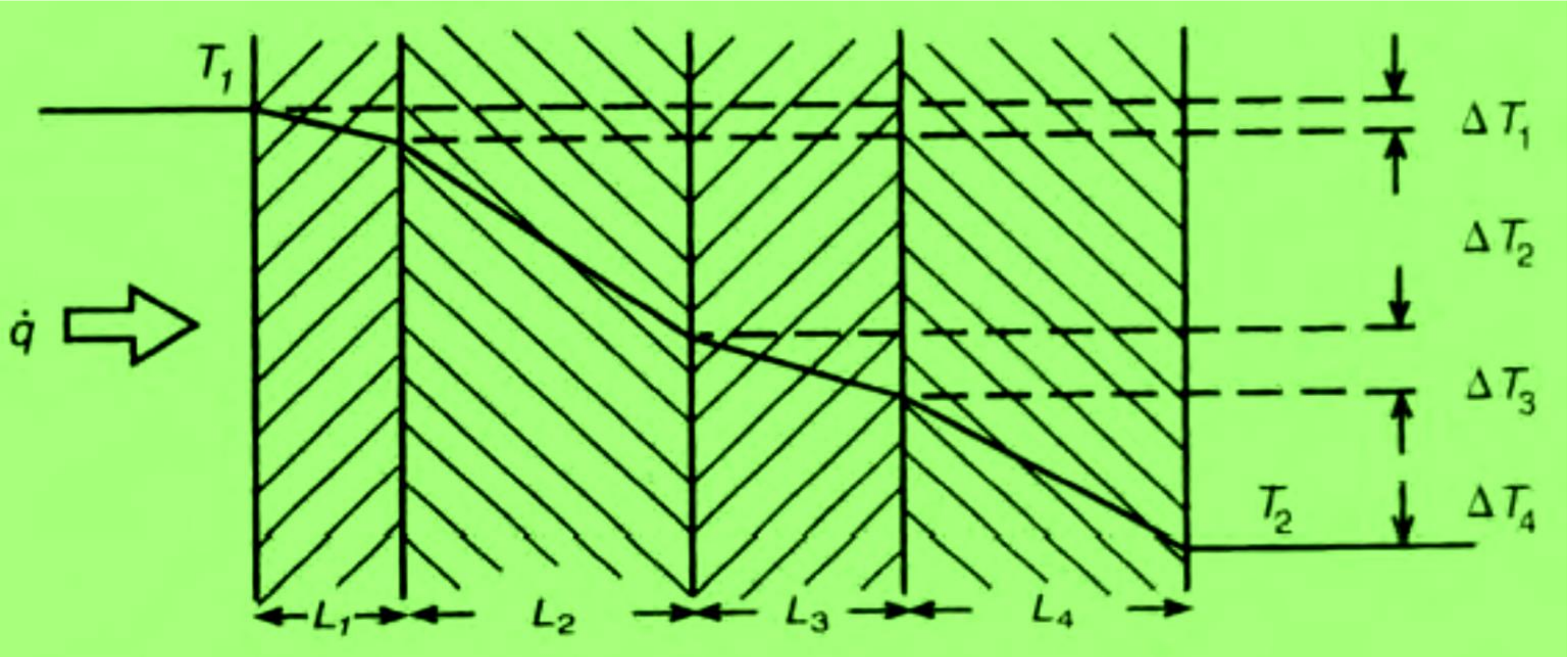
$$R_{th} = R_{pipe} + R_{insulation} + R_{contact}$$

Example: 3 furnace walls

A one square meter, 6-mm-thick steel furnace door [conductivity 30 W/(m · K)] is insulated on the inside by a 2-cm-thick layer of ceramic fiber matting [conductivity 0.05 W/(m · K)] and a 10-cm-thick layer of refractory brick [conductivity 1.0 W/(m · K)]. If the temperature of the brick surface in the furnace is 700°C and the outside steel surface of the door is at 50°C, what is the heat loss by conduction through the door? If the maximum temperature of the ceramic fiber were limited to 500°C, what would its thickness have to be and what effect would this have on heat loss?

Ceramic fiber mat

General Schematic diagram



Conduction through multiple layers

Solution. First calculate the thermal resistance of the three components. Note that in this example $A = 1\ \text{m}^2$ so that $R_t = L/\lambda \quad \text{K/W}$.
Steel door:

$$L = 6 \times 10^{-3}\ \text{m}, \quad \lambda = 30\ \text{W/(m} \cdot \text{K)}, \quad R_{t_1} = 2 \times 10^{-4}\ \text{K/W}$$

Ceramic fiber:

$$L = 2 \times 10^{-2}\ \text{m}, \quad \lambda = 5 \times 10^{-2}\ \text{W/(m} \cdot \text{K)}, \quad R_{t_2} = 0.4\ \text{K/W}$$

Refractory brick:

$$L = 1 \times 10^{-1}\ \text{m}, \quad \lambda = 1\ \text{W/(m} \cdot \text{K)}, \quad R_{t_3} = 0.1\ \text{K/W}$$

Clearly the thermal resistance of the steel door can be neglected and the total resistance of the insulation is 0.5 K/W. The total heat loss by conduction is therefore

$$\dot{Q} = (T_1 - T_2)/\sum R_t = (700 - 50)/0.5 = 1300\ \text{W}$$

The resistance of the ceramic fiber is 4/5 of the total and the temperature drop through it is therefore $4/5 \times 650 = 520°C$, i.e. its maximum temperature is 570°C. To bring this figure down to 500°C the temperature drop would have to be reduced to 450°C, and the new resistance of the fiber, $R_{t'_2}$, would then be a fraction 450/650 of the total, i.e.,

$$\frac{R_{t'_2}}{R_{t'_2} + 0.1} = \frac{450}{650}$$

Note: Assume steel layer temp. is constant =50°C

Temp diff overall

i.e., $R_{t'_2} = 0.225$ K/W, which represents a thickness of 1.125 cm

Note that with this reduced thickness of ceramic fiber the total thermal resistance is 0.325 K/W and the heat loss through the door is increased to 2.0 kW.

This example illustrates how temperature constraints on materials limit the degree of insulation that can be achieved within a given volume.

Look!!! Ceramic layer: Max temp. ↓ $R_{t2''}$ ↓ thick↓ Q↑

Schematic for example