EP145 Introduction to Engineering

Topic 8

Temperature Related Parameters

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Introduction

In this chapter we will consider some concepts related to **Temperature and Heat** in Engineering.

Details can be found in [1] and [2].

Temperature

- **What is Temperature?**
  It is a physical property of matter that expresses the sense of hot, warm or cold.

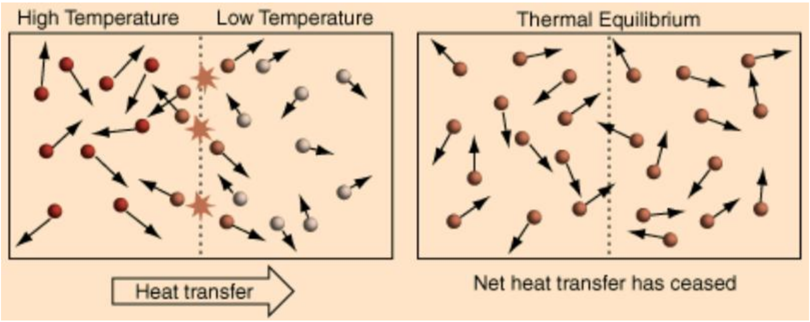
A convenient operational definition:

***temperature is that it is a measure of the average translational kinetic energy associated with the disordered microscopic motion of atoms and molecules*.**

- So, the temperature represents the level of molecular activity of a substance.

Air molecules are more active at 50 ^oC than they are at 25 ^oC.

When a high temperature object is placed in contact with a low temperature object, then energy will flow from the high temperature object to the lower temperature object, and they will approach an equilibrium temperature.



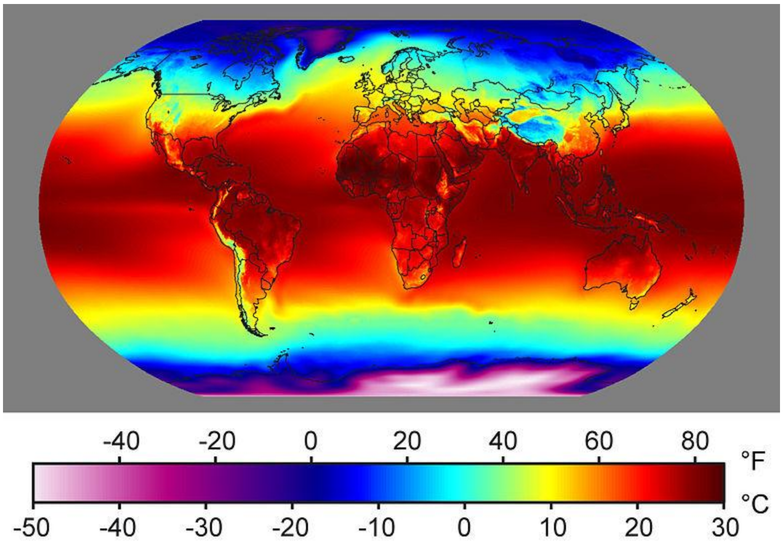
Temperature Measurement

- Temperature measurement using modern scientific **thermometers** and temperature scales goes back at least as far as the early 18th century.

- The basic unit of temperature in SI is the kelvin (K).
- Many methods have been developed for measuring temperature.
  - Glass thermometer filled with mercury
  - Thermocouples
  - Thermistors
  - Resistance Temperature Detector (RTD)
  - Pyrometer
  - Langmuir probes (for electron temperature of a plasma)
  - Infrared thermometers

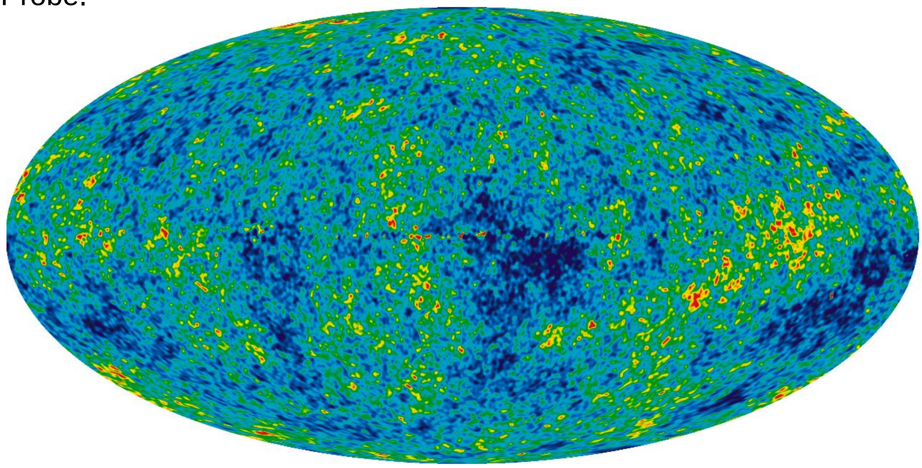
An image of two people in mid-infrared ("thermal") light (false-color)

Much of a person's energy is radiated away in the form of infrared light.
Some materials are transparent in the infrared, while opaque to visible light.



Annual Mean Temperature

The distribution of the cosmic microwave background radiation across the **universe** as measured by the Wilkinson Microwave Anisotropy Probe.



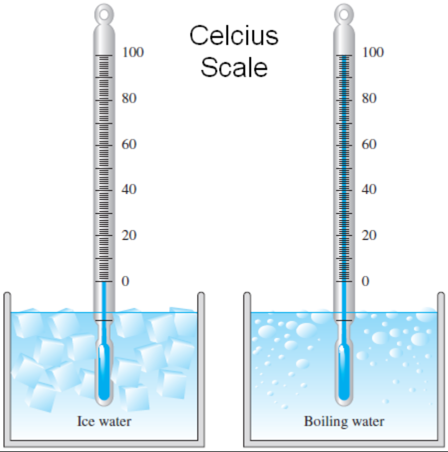
Temperature Scales

- Much of the world uses the Celsius scale (°C).
- The United States uses the Fahrenheit (°F) scale.
- Celcius has the same incremental scaling as the Kelvin scale (K) used by scientists.

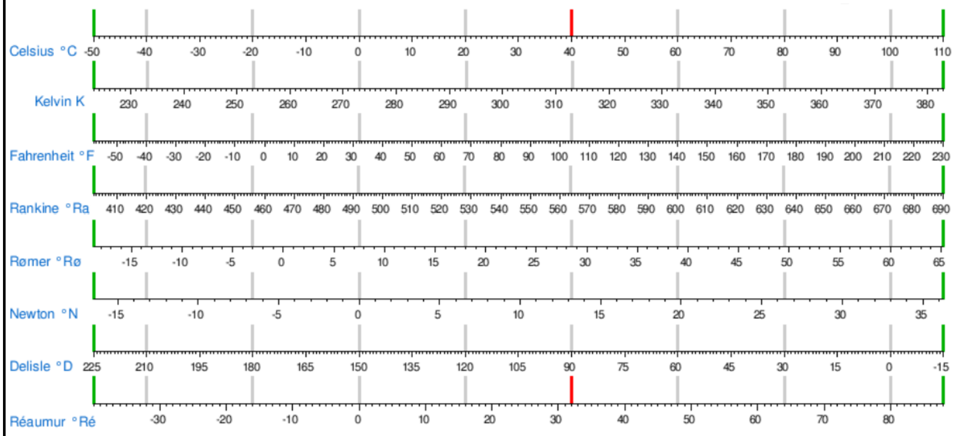
$$T(^{\circ}\mathrm{C}) = T(K) - 273.15$$

$$T(^{\circ}\mathrm{F}) = \frac{9}{5}T(^{\circ}\mathrm{C}) + 32$$

- There are other scales.

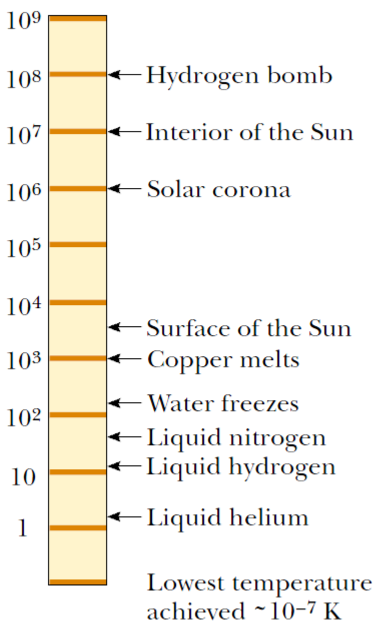


Conversion table between the different temperature units



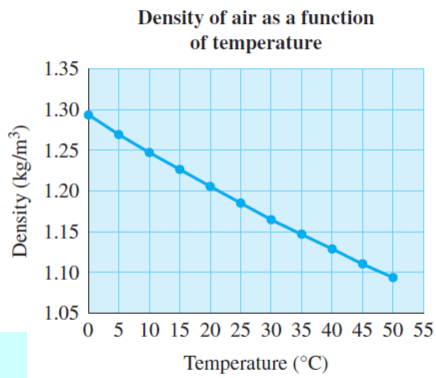
40 °C = 313.15 K = 104 °F = 563.67 °Ra = 28.5 °Rø = 13.2 °N = 90 °D = 32 °Ré

Temperature (K)



- Many physical properties of materials depend on temperature. Such as:

  - Matter phase solid, liquid, gaseous or plasma
  - density
  - viscosity
  - solubility
  - vapor pressure
  - electrical conductivity



Engineers must have a good understanding of temperature and its role in design.

Example 1

The air resistance to your car's motion is greater in winter than it is in summer, if the car is moving at the same speed.

Consider a car moving at 72 km/h and having the cross-section area 2 m^2 and drag coefficient 0.3.

Compute the drag force acting on the car

(a) when T_{air} = 5 ^oC

(b) when T_{air} = 40 ^oC

Local Weather Report

Turkish State Meteorological Service (Meteoroloji Genel Müdürlüğü)

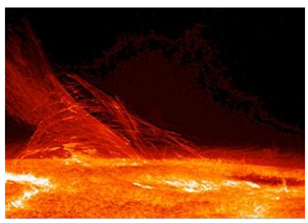
http://www.mgm.gov.tr

Extreme Maximum, Minimum and Average Temperatures Measured in Long Period (°C)

GAZİANTEP	January	February	March	April	May	June	July	August	September	October	November	December
Maximum Temp.	19.0	21.0	27.4	34.0	37.8	39.6	44.0	42.0	40.8	34.4	27.3	25.2
Minimum Temp.	-16.8	-15.6	-11.0	-2.5	3.2	7.1	11.8	12.7	6.4	-1.3	-7.0	-13.4
Average Temp.	3.1	4.4	8.4	13.3	18.7	24.1	27.9	27.5	22.9	16.4	9.3	4.8

Heat

Heat is energy transferred from one body to another by thermal interactions.



Heat transfer occurs whenever there is a temperature difference (ΔT)

- within an object
- between two bodies
- between a body and its surroundings

Heat always flows from a high-temperature region to a low-temperature region.

Heat transfer can occur in three ways: conduction, radiation and convection.

- **SI unit of Energy is Joule (J)**
  1 J = 1 N.m

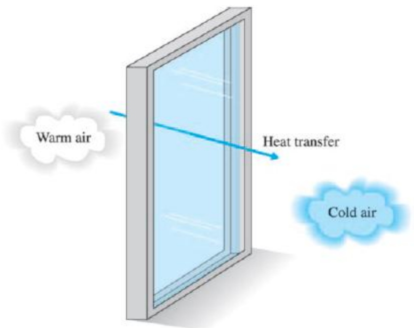
- **British Thermal Unit (Btu):**
  1 Btu = 1055 J

- **Calorie (cal):**
  1 cal = 4.186 J

- **SI unit of Power (Energy transfer rate) is Watt (W)**
  1 W = 1 J/s
  1 W = 3.4123 Btu/h
  1 cal/s = 4.186 W

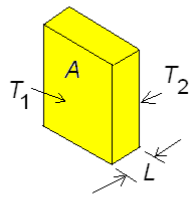
Conduction

Heat conduction is the transfer of heat energy by microscopic diffusion and collisions of particles within a body due to a temperature difference.



The rate of heat transfer by conduction is given by Fourier's law:

$$q = kA\frac{T_1 - T_2}{L}$$



where

q = heat transfer rate (W)

k = thermal conductivity (W/m.^{o}C, W/m.K)

A = area (m^2)

L = thickness of the material (m)

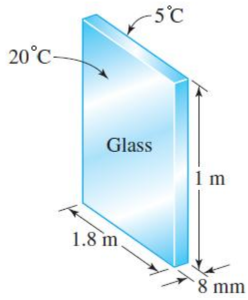
$T_1 - T_2$= temperature difference or temperature gradient (^{o}C)

Thermal Conductivity of Some Materials at 300 K

Material	Thermal Conductivity (W/m · k)
Air (at atmospheric pressure)	0.0263
Aluminum (pure)	237
Aluminum alloy-2024-T6 (4.5% copper, 1.5% magnesium, 0.6% manganese)	177
Asphalt	0.062
Bronze (90% copper, 10% aluminum)	52
Brass (70% copper, 30% zinc)	110
Brick (fire clay)	1.0
Concrete	1.4
Copper (pure)	401
Glass	1.4
Gold	317
Human fat layer	0.2
Human muscle	0.41
Human skin	0.37
Iron (pure)	80.2
Stainless steels (AISI 302, 304, 316, 347)	15.1, 14.9, 13.4, 14.2
Lead	35.3
Paper	0.18
Platinum (pure)	71.6
Sand	0.27
Silicon	148
Silver	429
Zinc	116
Water (liquid)	0.61

Example 2

Calculate the heat transfer rate from a single-pane glass window as shown in Fig with an inside surface temperature of 20 ºC and an outside surface temperature of 5 ºC. Thermal conductivity of the The glass is k = 1.4 W/m.K.



Example 3

For a solid food thermal conductivity in W/m.ºC is given by:

$$k = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_w$$

where X are the food mass fractions ($X_c + X_p + X_f + X_a + X_w = 1$) (c = "carbohydrate", p = "protein", f = "fat", a = "ash", and w= "water").

Calculate heat transfer rate for a food whose mass fractions are X_c=15%, X_p=8%, X_f=23%, X_a=2%, X_w=52% and physical parameters are A = 0.2 m^2, ΔT = 25 ºC and L = 0.05 m.

Solution:

$k = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_w$

= 0.25(0.15) + 0.155(0.08) + 0.16(0.23) + 0.135(0.02) + 0.58(0.52) = 0.391 W/m.ºC

$q = k\,A\,\Delta T / L$

= (0.391 W/m.ºC)(0.2 m^2)(25 ºC) / (0.05 m) = 39.1 W

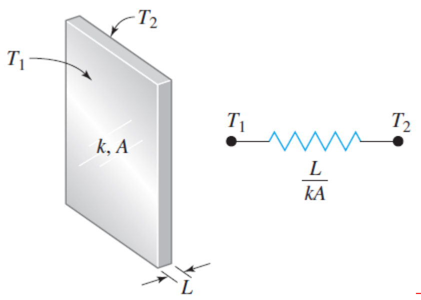
Thermal Resistance

It is important to have a well-insulated house. Because
the better insulated a house is,
the less the heating or cooling cost of the house.

$$q = kA\frac{T_1 - T_2}{L} \longrightarrow q = \frac{T_1 - T_2}{L / kA} = \frac{\text{temperatur e difference}}{\text{thermal resistance}}$$

Here thermal resistance:

$$R = \frac{L}{kA}$$



In engineering practice, the term L/k for a particular substance is referred to as the *R*-value of the material.

$$R\text{-value} = \frac{L}{k}$$

***R* Values for Some Common Building Materials**

Material	*R* value (ft^2·°F·h/Btu)
Hardwood siding (1 in. thick)	0.91
Wood shingles (lapped)	0.87
Brick (4 in. thick)	4.00
Concrete block (filled cores)	1.93
Fiberglass insulation (3.5 in. thick)	10.90
Fiberglass insulation (6 in. thick)	18.80
Fiberglass board (1 in. thick)	4.35
Cellulose fiber (1 in. thick)	3.70
Flat glass (0.125 in. thick)	0.89
Insulating glass (0.25-in. space)	1.54
Air space (3.5 in. thick)	1.01
Stagnant air layer	0.17
Drywall (0.5 in. thick)	0.45
Sheathing (0.5 in. thick)	1.32

Example 4

Determine the thermal resistance and *R*-value of the glass window of Example 2.

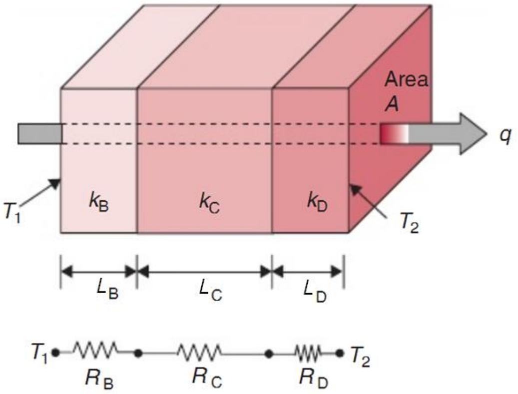
Solution:

$$R = \frac{L}{kA} = \frac{0.008\ \text{m}}{(1.4\ \text{W/m.K})(1.8\ \text{m}^2)} = 0.00317\ \text{K/W}$$

$$R\text{-value} = \frac{L}{k} = \frac{0.008\ \text{m}}{(1.4\ \text{W/m.K})} = 0.0057\ \text{m}^2.\text{K/W}$$

Multi-Layered Systems

Consider heat transfer through a composite wall made of several materials of different thermal conductivities and thicknesses.

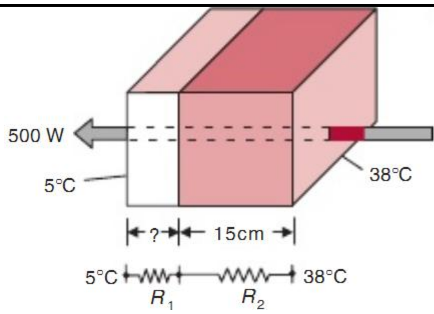


Using thermal resistance values for each layer, we can write:

$$q = \frac{T_1 - T_2}{\left(\frac{L_B}{k_B A} + \frac{L_C}{k_C A} + \frac{L_D}{k_D A}\right)}$$

$$q = \frac{T_1 - T_2}{R_B + R_C + R_D}$$

Example 5



A cold storage wall (3 m x 6 m) is constructed of 15 cm thick concrete (k_2 = 1.37 W/[m. ºC]). Insulation must be provided to maintain a heat transfer rate through the wall at or below 500 W. The thermal conductivity of the insulation is k_1 = 0.04 W/(m.ºC). The outside surface temperature of the wall is 38 ºC, and the inside wall temperature is 5 ºC.

(a) Compute the required thickness of the insulation. (**Ans: 4.3 cm**)

(b) Calculate reduction in heat loss. (**Ans: 91%**)

(a) *An insulation with a thickness of 4.3 cm will ensure that heat loss from the wall will remain below 500 W.*

(b) If there is no insulation, *for q = 500 W, at the end of concrete, temperature is 35 ºC.*

Temperature difference for concrete: ΔT = 38 - 35 = 3 ºC

New temperature difference: ΔT = 38 - 5 = 33 ºC

Hence the reduction in heat loss 1 - 3/33 = 0.91.

Heat Capacity

The energy Q transferred between a sample of mass *m* of a material and its surroundings to a temperature change ΔT is given by:

$$Q = mc\Delta T$$

Where

Q = energy transferred (J)

m = mass of the sample (kg)

c = specific heat capacity (J/kg.ºC)

Δ*T* = temperature difference (ºC or K)

Specific Heats of Some Substances at 25°C and Atmospheric Pressure

Substance	Specific heat c J/kg·°C	Specific heat c cal/g·°C
Elemental solids		
Aluminum	900	0.215
Beryllium	1 830	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Germanium	322	0.077
Gold	129	0.030 8
Iron	448	0.107
Lead	128	0.030 5
Silicon	703	0.168
Silver	234	0.056
Other solids		
Brass	380	0.092
Glass	837	0.200
Ice (−5°C)	2 090	0.50
Marble	860	0.21
Wood	1 700	0.41
Liquids		
Alcohol (ethyl)	2 400	0.58
Mercury	140	0.033
Water (15°C)	4 186	1.00
Gas		
Steam (100°C)	2 010	0.48

Example 6

An aluminum circular disk with a diameter, *d* = 15 cm and a thickness *t* = 4 mm is exposed to a heat source that puts out 200 J every second. The density of the aluminum is 2700 kg/m^3. Assuming no heat loss to the surrounding, estimate the temperature rise of the disk after 20 s.

(**Ans: ΔT = 24 oC**)

Change in Heat

Change in heat energy in a fluid stream, if its temperature changes from T_1 to T_2, is expressed as [3]:

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta m}{\Delta t} c(T_1 - T_2)$$

$$\dot{Q} = \dot{m}c(T_1 - T_2)$$

$$\boxed{q = \dot{m}c(T_1 - T_2)}$$

where

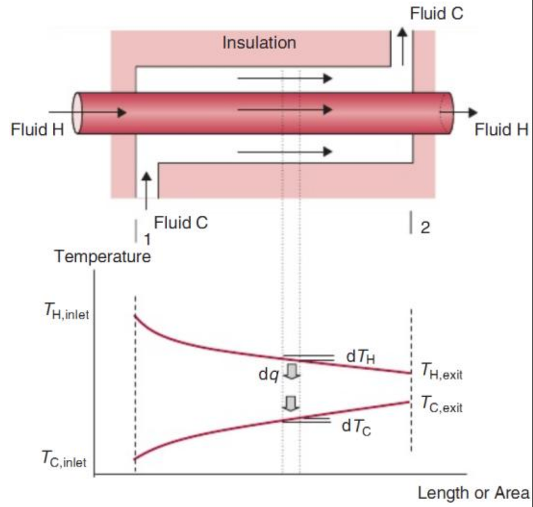
m-dot = mass flow rate of a fluid (kg/s)

c = the specific heat of the fluid.

The temperature change of a fluid is from some inlet temperature T_1 to an exit temperature T_2.

Heat Exchanger

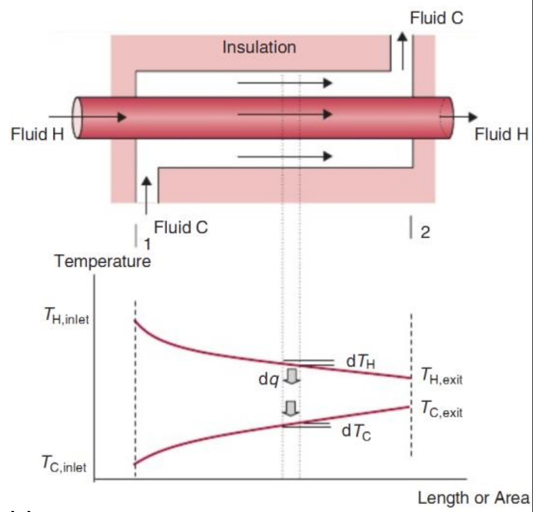
Consider a tubular heat exchanger as shown in Fig [3].



A hot fluid, H, enters the heat exchanger at location (1) and it flows through the inner pipe, exiting at location (2).

A cold fluid, C, enters the annular space between the outer and inner pipes of the tubular heat exchanger at location (1) and exits at location (2).

Assume that the heat transfer occurs only between fluids H and C.



For H,
temperature decreases from $T_{H,inlet}$ to $T_{H,exit}$.

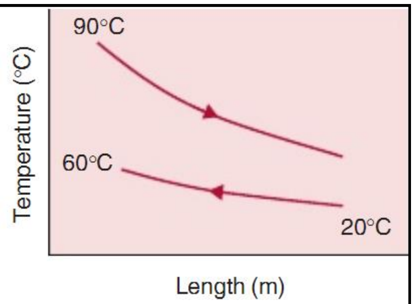
For C,
temperature increases from $T_{C,inlet}$ to $T_{C,exit}$.

The energy balance between fluids:

$$q = \dot{m}_H c_H (T_{\mathrm{H,inlet}} - T_{\mathrm{H,exit}}) = \dot{m}_C c_C (T_{C,\mathrm{exit}} - T_{C,\mathrm{inlet}})$$

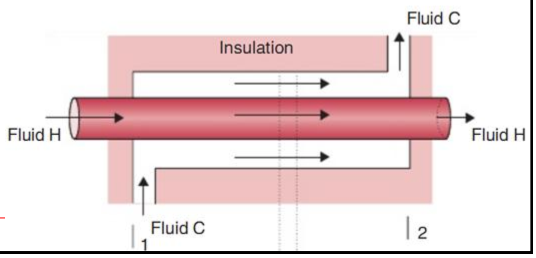
Example 7 [see Ref 3]

A liquid food (specific heat 4.0 kJ/kg. ºC) flows in the inner pipe of a double-pipe heat exchanger. The liquid food enters the heat exchanger at 20 ºC and exits at 60 ºC (see Fig). The flow rate of the liquid food is 0.5 kg/s. In the annular section, hot water at 90 ºC enters the heat exchanger and flows counter currently at a flow rate of 1 kg/s. The average specific heat of water is 4.18 kJ/(kg. ºC). Assume steady-state conditions.



(a) Calculate the exit temperature of water.

(b) Calculate the energy transferred per unit time to the fluid by water.

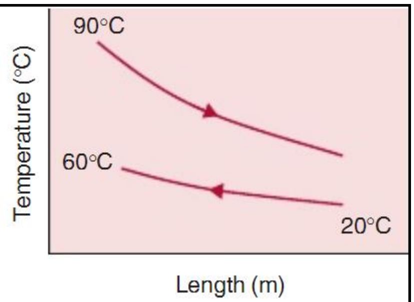


Solution

Given

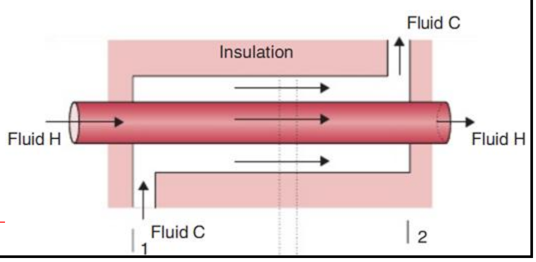
Liquid food:

- Inlet temperature = 20 ºC
- Exit temperature = 60 ºC
- Specific heat = 4.0 kJ/(kg. ºC)
- Flow rate = 0.5 kg/s



Water:

- Inlet temperature = 90 ºC
- Specific heat = 4.18 kJ/(kg. ºC)
- Flow rate = 1.0 kg/s



(a) Using simple heat balance equation:

$$q = \dot{m}_C c_C \Delta T_C = \dot{m}_H c_H \Delta T_H$$

$$\left(0.5\,\frac{\text{kg}}{\text{s}}\right)\left(4\,\frac{\text{kJ}}{\text{kg }^{\circ}\text{C}}\right)(60\ ^{\circ}\text{C} - 20\ ^{\circ}\text{C}) = \left(1\,\frac{\text{kg}}{\text{s}}\right)\left(4.18\,\frac{\text{kJ}}{\text{kg }^{\circ}\text{C}}\right)(90\ ^{\circ}\text{C} - T_E)$$

Solving $\boldsymbol{T_E = 70.9\ ^{o}C}$.

(b) The rate of energy transfer is:

$$q = \left(0.5\,\frac{\text{kg}}{\text{s}}\right)\left(4\,\frac{\text{kJ}}{\text{kg }^{\circ}\text{C}}\right)(60\ ^{\circ}\text{C} - 20\ ^{\circ}\text{C}) = 80\ \text{kJ/s} = 8 \times 10^4\ \text{W}$$

Questions

1. What is the equivalent value of T = 40 oC in degrees Fahrenheit, Rankine, and Kelvin?
2. On a summer day, in Gaziantep, the inside room temperature is maintained at 68 ^{o}F while the outdoor air temperature is a sizzling 110 ^{o}F. What is the outdoor-indoor temperature difference in
   (a) degree Fahrenheit, (b) degree Celsius, and (c) Kelvin?
3. Calculate the heat transfer rate from a 1000 ft^2, 6-in-thick concrete wall with inside and outside surface temperatures of 20 ^{o}C and 0 ^{o}C.
4. Calculate the amount of thermal energy required to raise the temperature of 20 gallon of water from 60 ^{o}F to 120 ^{o}F.
   Express your answer in Btu, J, and cal.
5. For Example 4, convert the thermal resistance and *R*-value results from SI units to British Units.

6. We have exposed 1 kg of water, 1 kg of brick, and 1 kg of concrete, each to a heat source that puts out 100 J every second. Assuming that all of the supplied energy goes to each material and they were all initially at the same temperature, which one of these materials will have a greater temperature rise after 10 s?

7. A copper plate, with dimensions of 3 cm x 3 cm x 5 cm (length, width, and thickness, respectively), is exposed to a thermal energy source that puts out 150 J every second. The density of copper is 8900 kg/m3. Assuming no heat loss to the surrounding block, determine the temperature rise in the plate after 10 seconds.

8. Repeat Example 5 for q = 1000 W.

9. Repeat Example 7 for liquid food with c = 8.0 kJ/kg. ^{o}C.

References

1. P. Kosky et al., *Exploring Engineering*, 2nd Ed. Elsevier Inc. (2010)

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6. http://en.wikipedia.org/wiki/Scale_of_temperature

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