HEAT AND MASS TRANSFER (ADVANCED COURSE)

Associate Professor of Heat and Power
Engineering Department, KNRTU-KAI, PhD
Konstantin V. Altunin

Lesson 1.

Main objectives:

1. Find out basics of convection, conduction and radiation
2. Understand main principles of heat travel
3. Learn main units of energy
4. Find out temperature scales
5. Learn about specific heats of liquids, gases and solids

Basics of Heat Transfer

- Heat is the form of energy that can be transferred from one system to another as a result of temperature difference.
- The science that deals with the determination of the rates of such energy transfers is the heat transfer.
- Heat transfer is the exchange of thermal energy between physical systems, depending on temperature and pressure by dissipating heat.
- There are three main heat transfer mechanisms including conduction, convection and radiation

Heat Transfer

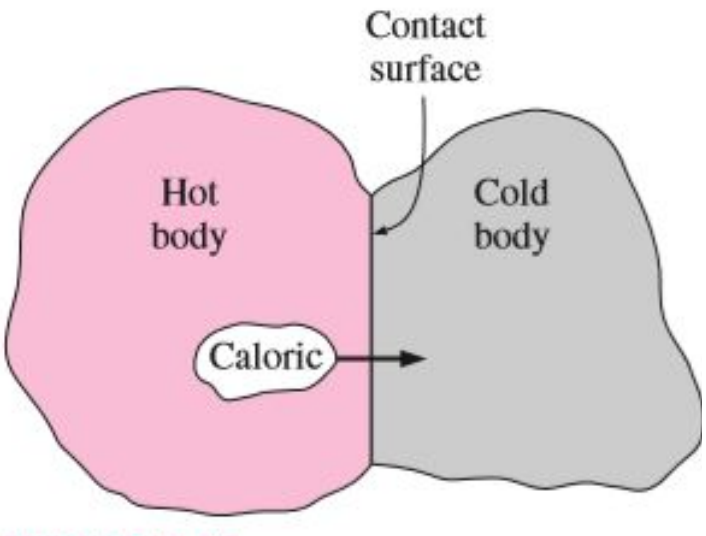


Fig. 1. In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

Heat Transfer

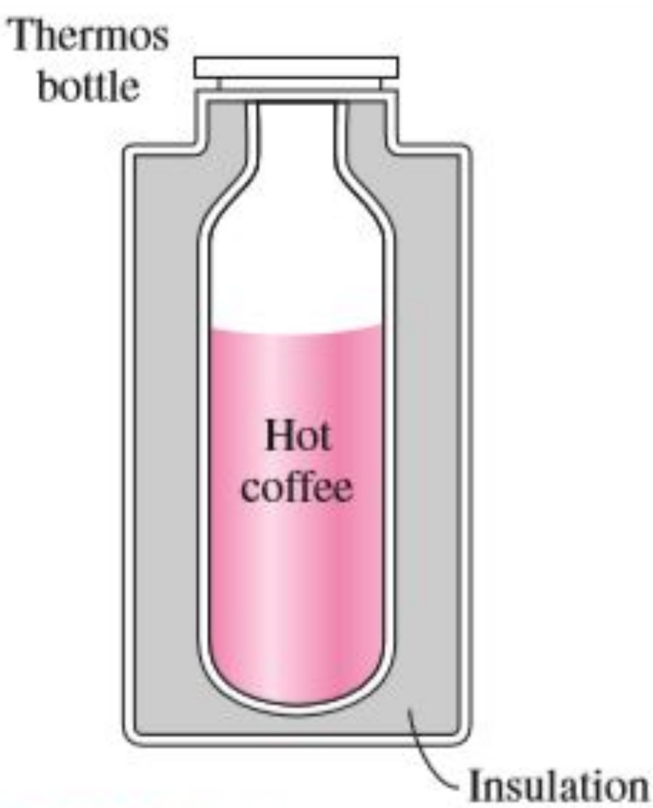
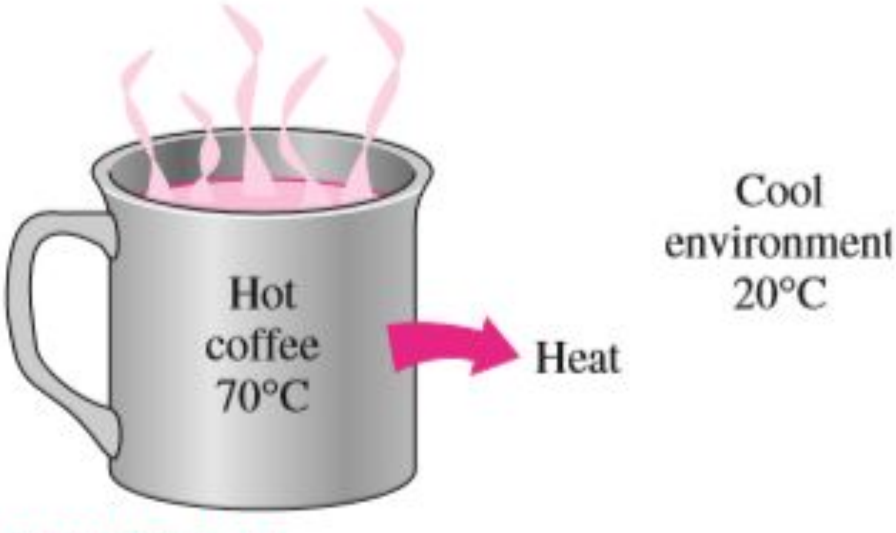


Fig. 2. We are normally interested in how long it takes for the hot coffee in a thermos to cool to a certain temperature, which cannot be determined from a thermodynamic analysis alone.

Heat Transfer

Fig. 3. Heat flows in the direction of decreasing temperature



Heat Transfer

Keeping in line with current practice, we will refer to the thermal energy as *heat* and the transfer of thermal energy as *heat transfer*. The amount of heat transferred during the process is denoted by Q. The amount of heat transferred per unit time is called **heat transfer rate,** and is denoted by $\dot{Q}$. The overdot stands for the time derivative, or "per unit time." The heat transfer rate $\dot{Q}$ has the unit J/s, which is equivalent to W.

When the *rate* of heat transfer $\dot{Q}$ is available, then the total amount of heat transfer Q during a time interval Δt can be determined from

$$Q = \int_0^{\Delta t} \dot{Q}\,dt \qquad \text{(J)}$$

provided that the variation of $\dot{Q}$ with time is known. For the special case of $\dot{Q}$ = constant, the equation above reduces to

$$Q = \dot{Q}\,\Delta t \qquad \text{(J)}$$

Heat Transfer

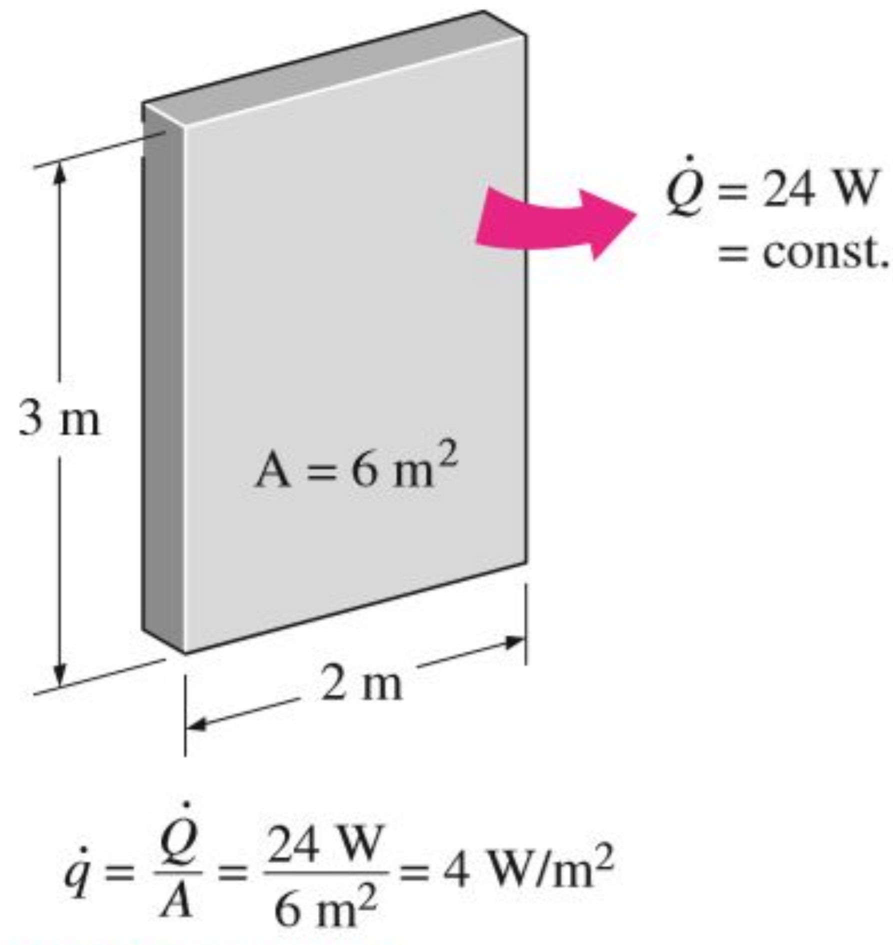
The rate of heat transfer per unit area normal to the direction of heat transfer is called **heat flux,**

$$\dot{q} = \frac{\dot{Q}}{A} \qquad (\mathrm{W/m^2})$$

where A is the heat transfer area. The unit of heat flux in English units is $\mathrm{Btu/h \cdot ft^2}$. Note that heat flux may vary with time as well as position on a surface.

Heat Flux

Fig. 4. An example of heat flux (heat transfer per unit time and per unit area)



Application areas of Heat Transfer

- Heat transfer is commonly encountered in engineering systems and other aspects of life, and one does not need to go very far to see some application areas of heat transfer. In fact, one does not need to go anywhere. The human body is constantly rejecting heat to its surroundings, and human comfort is closely tied to the rate of this heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions.

Application areas of Heat Transfer

- Many ordinary household appliances are designed, in whole or in part, by using the principles of heat transfer. Some examples include the electric or gas range, the heating and air-conditioning system, the refrigerator and freezer, the water heater, the iron, and even the computer, the TV, etc. Of course, energy-efficient homes are designed on the basis of minimizing heat loss in winter and heat gain in summer.
- Heat transfer plays a major role in the design of many other devices, such as car radiators, solar collectors, various components of power plants, and even spacecraft.
- The optimal insulation thickness in the walls and roofs of the houses, on hot water or steam pipes, or on water heaters is again determined on the basis of a heat transfer analysis with economic consideration

Application areas of Heat Transfer

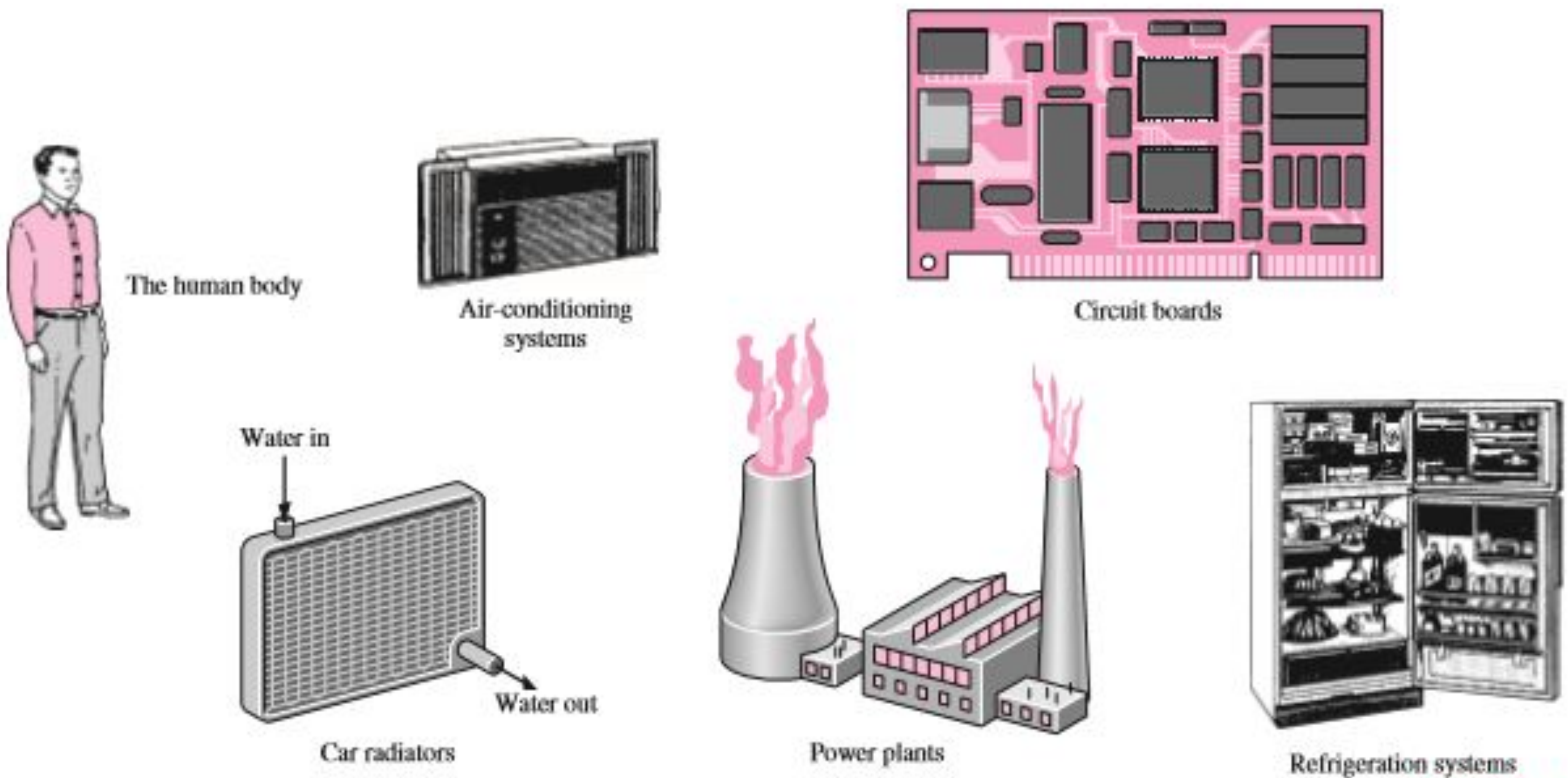


Fig. 5. Heat Transfer around us

Conduction

- Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion. In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

Conduction

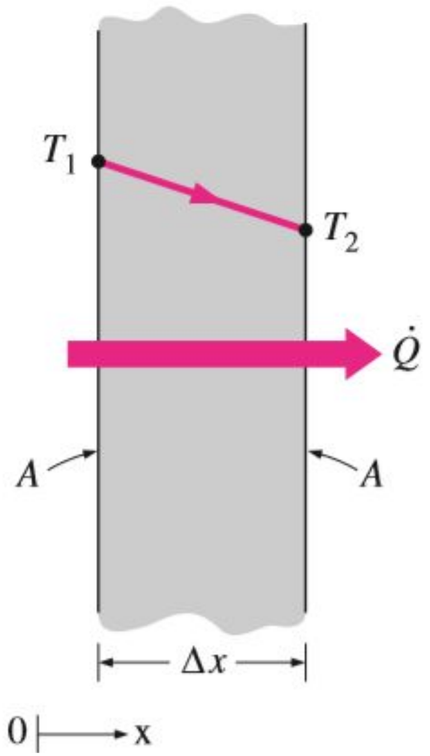


Fig. 6. Heat conduction through a large plane wall of thickness Δx and area A

Convection

- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.
- The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction

Convection

- Convection is called forced convection if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called natural (or free) convection if the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.

Convection

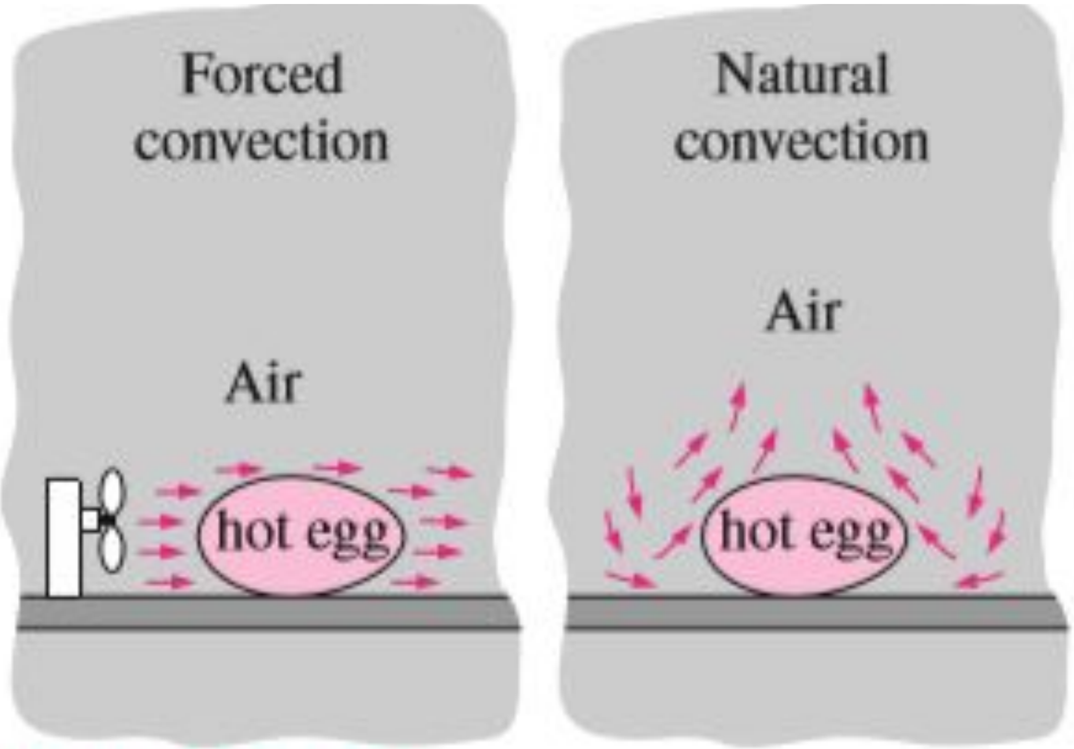


Fig. 7. The cooling of a boiled egg by forced and natural convection

Radiation

- Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.
- Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium.
- In fact, energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
- All bodies at a temperature above absolute zero emit thermal radiation

Radiation

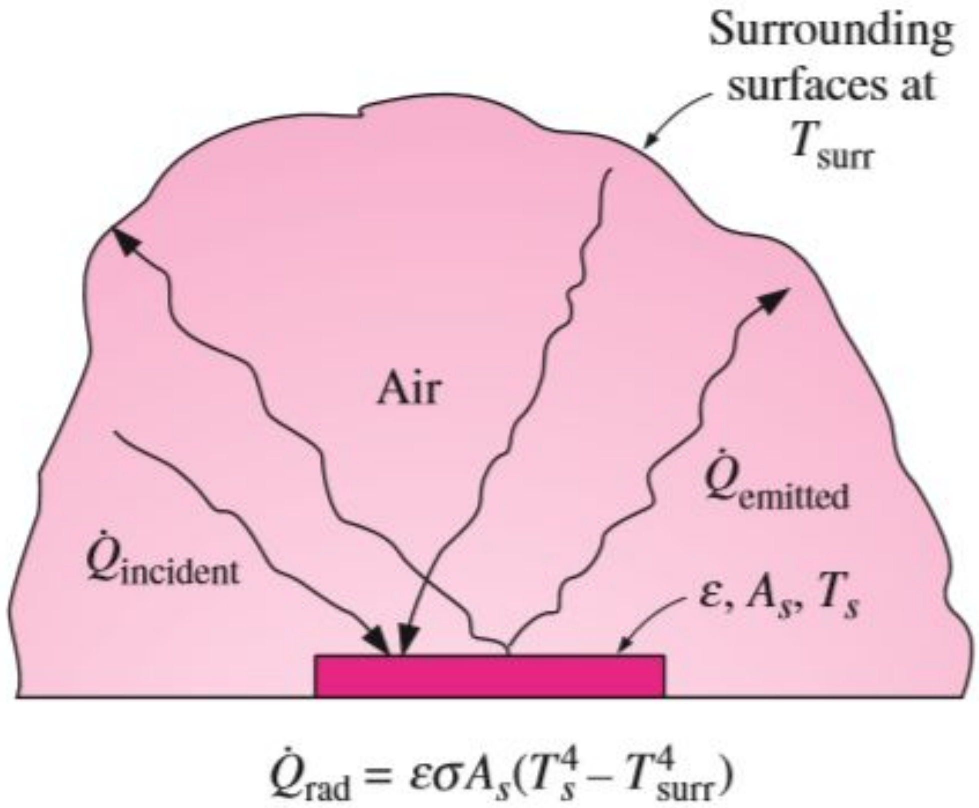


Fig. 8. Radiation heat transfer between a surface and the surfaces surrounding it.

Radiation

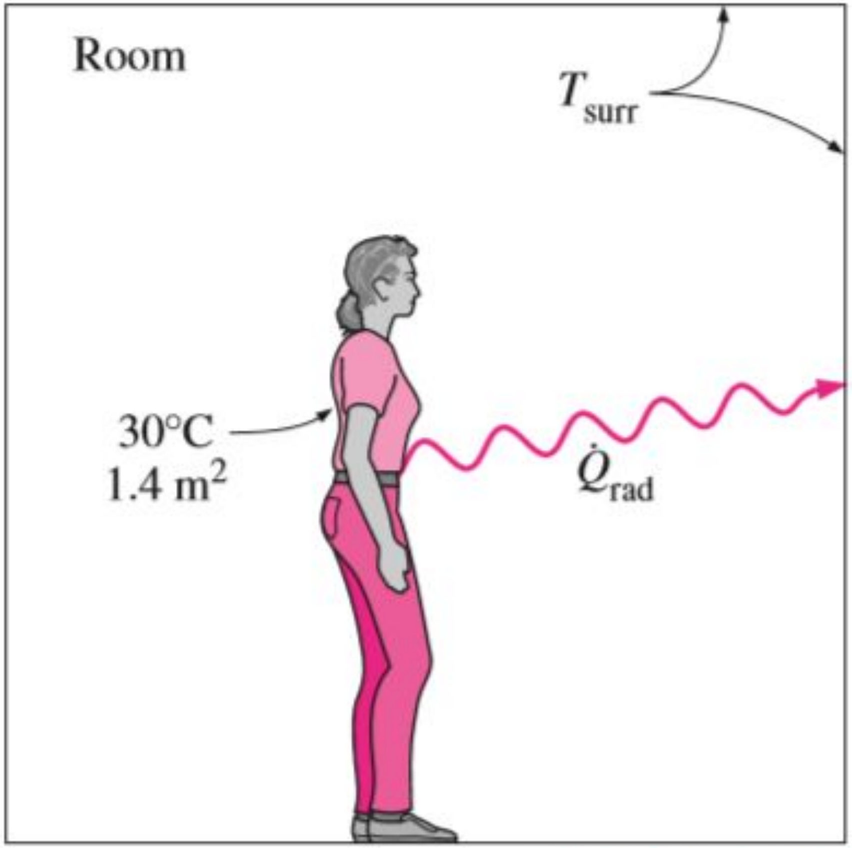


Fig. 9. A human body can also radiate heat outside if there is a temperature difference (as an example here the surrounding temperature is lower than the temperature of a person, say, lower than 30^0C).

Main Units of Energy

The international unit of energy is *joule* (J) or *kilojoule* (1 kJ = 1000 J). In the English system, the unit of energy is the *British thermal unit* (Btu), which is defined as the energy needed to raise the temperature of 1 lbm of water at 60°F by 1°F. The magnitudes of kJ and Btu are almost identical (1 Btu = 1.055056 kJ). Another well-known unit of energy is the *calorie* (1 cal = 4.1868 J), which is defined as the energy needed to raise the temperature of 1 gram of water at 14.5°C by 1°C.

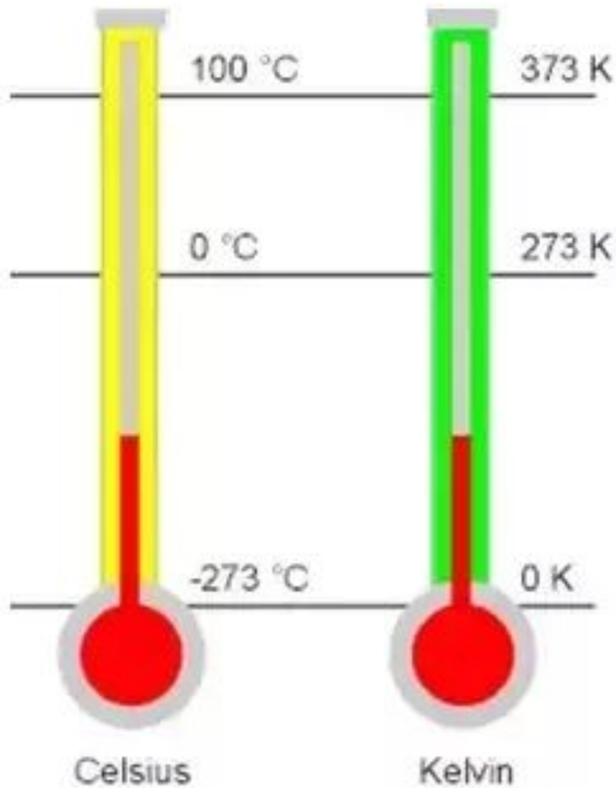
British Thermal Unit

- The **British thermal unit** (**BTU** or **Btu**) is a traditional unit of work equal to about 1055 joules. It is the amount of work needed to raise the temperature of one pound of water by one degree Fahrenheit (Physical analogue: one four-inch wooden kitchen match consumed completely generates approximately 1 BTU). The **British thermal unit** (**BTU** or **Btu**) is a traditional unit of work equal to about 1055 joules.

Temperature scales

Celsius vs. Kelvin Temperature

- The Celsius and Kelvin scale are related **unit for unit**. One degree unit on the Celsius scale is equivalent to one degree unit on the Kelvin scale. The only difference between these two scales is the zero point.



Celsius vs. Fahrenheit degrees

Celsius to Fahrenheit: $(°C \times {}^{9}/_{5}) + 32 = °F$
Fahrenheit to Celsius: $(°F - 32) \times {}^{5}/_{9} = °C$

Example: Convert 26° Celsius *(a nice warm day)* to Fahrenheit

First: 26° × 9/5 = 234/5 = 46,8
Then: 46,8 + 32 = **78,8°** F

Example: Convert 98,6° Fahrenheit *(normal body temperature)* to Celsius

First: 98,6° – 32 = 66,6
Then: 66,6 × 5/9 = 333/9 = **37°** C

Typical Temperatures

°C	°F	Description
100	**212**	Water boils
40	**104**	Hot Bath
37	**98,6**	Body temperature
30	**86**	Beach weather
21	70	Room temperature
10	**50**	Cool Day
0	**32**	Freezing point of water
−18	0	Very Cold Day
−40	**−40**	Extremely Cold Day (and the same number!)
(**bold** are exact)		

16 is about 61
28 is about 82

Specific heats of Gases, Liquids and Solids

- Specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree
- The specific heat at constant volume *Cv* can be viewed as the energy required to raise the temperature of a unit mass of a substance by one degree as the volume is held constant. The energy required to do the same as the pressure is held constant is the specific heat at constant pressure *Cp*.

Specific Heat

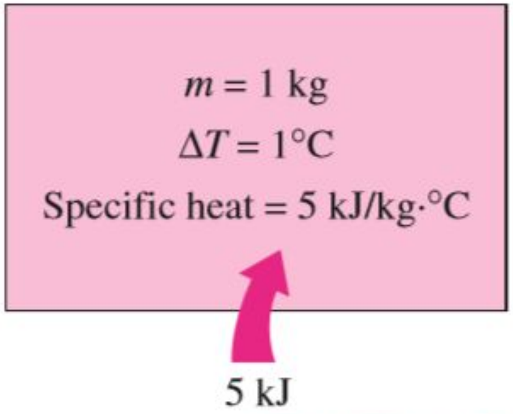


Fig. 10. Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

Specific Heat

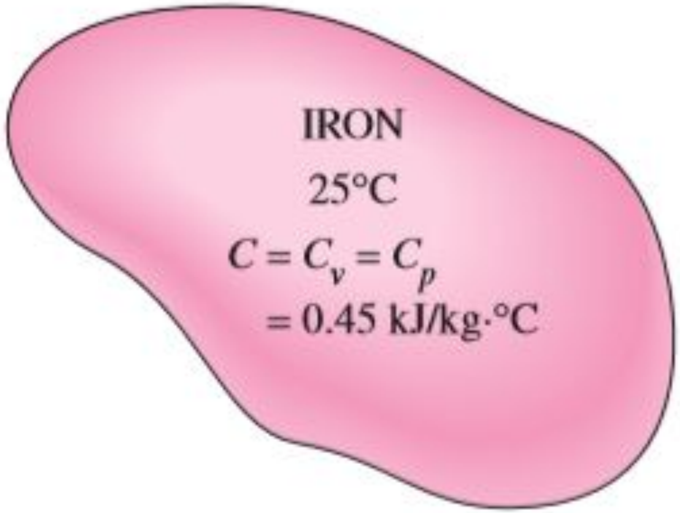


Fig. 11. The *Cv* and *Cp* values of incompressible substances are identical and are denoted by *C*.

Specific Heat

The differential changes in the internal energy u and enthalpy h of an ideal gas can be expressed in terms of the specific heats as

$$du = C_v\,dT \qquad \text{and} \qquad dh = C_p\,dT$$

The finite changes in the internal energy and enthalpy of an ideal gas during a process can be expressed approximately by using specific heat values at the average temperature as

$$\Delta u = C_{v,\,\text{ave}}\Delta T \qquad \text{and} \qquad \Delta h = C_{p,\,\text{ave}}\Delta T \qquad \text{(J/g)}$$

or

$$\Delta U = mC_{v,\,\text{ave}}\Delta T \qquad \text{and} \qquad \Delta H = mC_{p,\,\text{ave}}\Delta T \qquad \text{(J)}$$

where m is the mass of the system.

Specific Heat

The amount of heat required to raise the temperature of one gram of substance by one degree Celsius.

Substance	Specific Heat (J/g·K)
Water (liquid)	4.18
Ethanol (liquid)	2.44
Water (solid)	2.06
Water (vapor)	1.87
Aluminum (solid)	0.897
Carbon (graphite,solid)	0.709
Iron (solid)	0.449
Copper (solid)	0.385
Mercury (liquid)	0.140
Lead (solid)	0.129
Gold (solid)	0.129

Specific Heat of Water

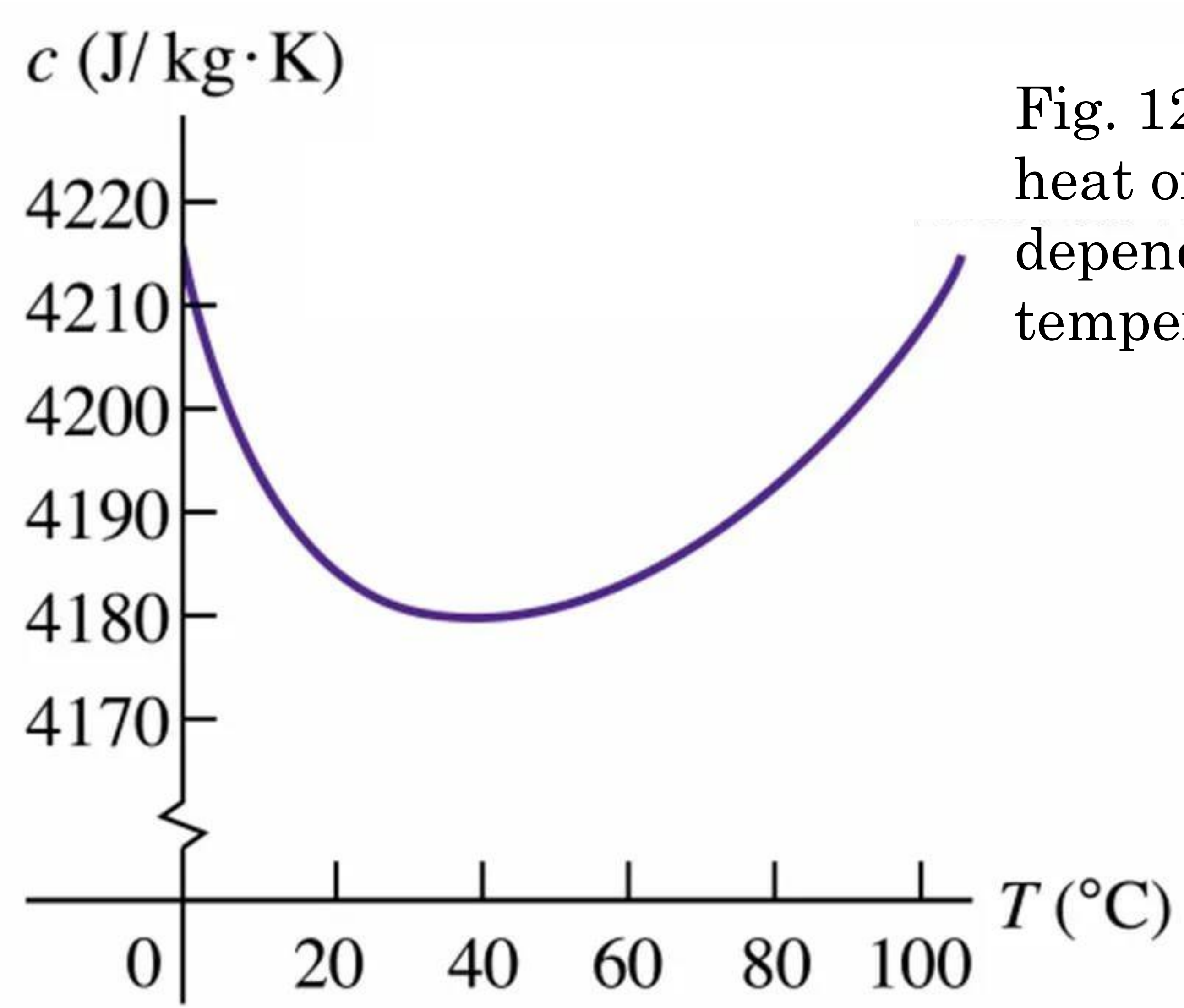


Fig. 12. Specific heat of water depending on temperature

Thank you for attention!