22 Solar Thermal Energy

Solar thermal energy is an application of solar energy that is very different from photovoltaics. In contrast to photovoltaics, where we used electrodynamics and solid state physics for explaining the underlying principles, solar thermal energy is mainly based on the laws of thermodynamics. In this chapter we give a brief introduction to that field. After introducing some basics in Section 22.1, we will discuss Solar Thermal Heating in Section 22.2 and Concentrated Solar (electric) Power (CSP) in Section 22.3.

22.1 Solar thermal basics

We start this section with the definition of *heat*, which sometimes also is called *thermal energy*. The molecules of a body with a temperature different from 0 K exhibit a disordered movement. The kinetic energy of this movement is called *heat*. The average of this kinetic energy is related linearly to the temperature of the body.[1] Usually, we denote heat with the symbol Q. As it is a form of energy, its unit is Joule (J).

If two bodies with different temperatures are brought together, heat will flow from the hotter to the cooler body and as a result the cooler body will be heated. Dependent on its physical properties and temperature, this heat can be absorbed in the cooler body in two forms, sensible heat and latent heat.

Sensible heat is that form of heat that results in changes in temperature. It is given as

$$Q = mC_p(T_2 - T_1), \tag{22.1}$$

where Q is the amount of heat that is absorbed by the body, m is its mass, C_p is its *heat capacity* and $(T_2 - T_1)$ is the temperature difference. On the other hand, if a body absorbs or

[1] The interested reader will find more details in standard textbooks on physics or thermodynamics. This definition is taken from Ref. [182].

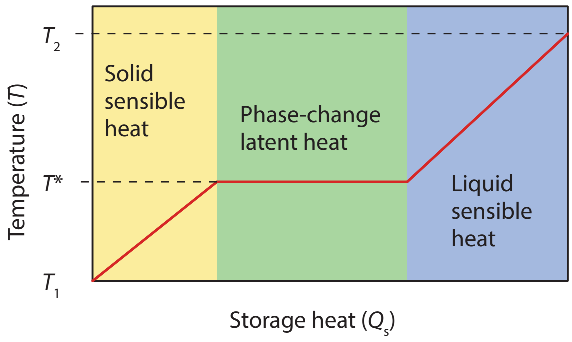

Figure 22.1: Illustrating the difference of sensible and latent heat.

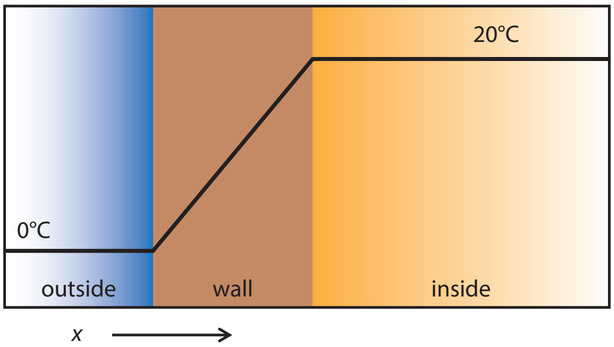

Figure 22.2: Illustrating conductive heat transfer through a wall.

releases *latent heat*, the temperature stays constant but the phase changes. This happens for example when ice is melting: When its temperature is equivalent to its melting point, heat that is absorbed by the ice will not result in increasing temperature but in transformation into from the solid to the liquid phase, which is water. Mathematically, this is expressed as

$$Q = mL, \tag{22.2}$$

where L is the *specific latent heat*.

The two forms of heat are illustrated in Fig. 22.1, which shows what happens when a body absorbs heat. In the beginning, the body is solid and has temperature T_1. It then heats up and the heat is stored as solid sensible heat. When its melting point T^* is achieved, its temperature will not increase any more but the phase will change from solid to liquid. After everything is molten, the liquid will heat up further, the heat now is stored as liquid sensible heat.

Now we will take a look at the three basic mechanisms of heat transfer: conduction, convection and radiation.

Conduction is the transfer of heat in a medium due to a temperature gradient. For a better understanding we look at the heating of a house during winter, as illustrated in Fig. 22.2. The inside of the house is warm at 20°C, but the outside is cold with a temperature

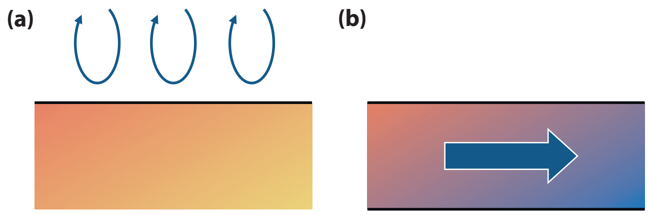

Figure 22.3: Illustrating (a) natural and (b) forced conductive heat between a solid and a surrounding fluid.

of 0°C. Because of this heat gradient, heat will be transferred from the inside through the wall to the outside. Mathematically, heat conduction can be described by the *Fourier law*,

$$\frac{\mathrm{d}Q_{\mathrm{cond}}}{\mathrm{d}t} = -kA\frac{\mathrm{d}T}{\mathrm{d}x}, \tag{22.3}$$

where $\mathrm{d}Q/\mathrm{d}t$ is the heat flow in W, k is the thermal conductivity of the wall [given in W/(Km)], A is the contact area given in m^2 and $\mathrm{d}T/\mathrm{d}x$ is the temperature gradient in the x direction given in K/m. If we assume the wall to be made from a uniform material, we can assume that $\mathrm{d}T/\mathrm{d}x$ is constant throughout the wall and we can replace it by $\Delta T/\Delta x$, where Δx is the thickness of the wall.

Convection is the second possible mechanism for heat transfer. It is the transfer of heat by the movement of a fluid. We distinguish between two forms of convection, as sketched in Fig. 22.3: In *forced convection* the movement of the fluid is caused by external variables, while in *natural convection* the movement of the fluid is caused by density differences due to temperature gradients. In both cases, the heat transfer from a medium of temperature T_1 into a fluid of temperature T_2 can be described by *Newton's law*

$$\frac{\mathrm{d}Q_{\mathrm{conv}}}{\mathrm{d}t} = -hA(T_1 - T_2), \tag{22.4}$$

where h is the *heat transfer coefficient* which is given in $\mathrm{W}/(\mathrm{m}^2\mathrm{K})$. We will not discuss the calculation of h in detail but we want to mention that it depends on various factors such as the velocity of the fluid, the shape of the surface or the kind of flow that is present, *i.e.* whether it is laminar or turbulent flow.

The third heat transfer mechanism is *radiative heat transfer*, which is the most important mechanism of heat transfer for solar thermal systems. As we already discussed in Chapter 5, thermal radiation is electromagnetic radiation propagated through space at the speed of light. Thermal radiation is emitted by bodies depending on their temperature. This is caused when excited electrons fall back on their ground level and emit a photon and hence electromagnetic radiation.

As discussed in Chapter 5, a *blackbody* is an idealised concept of a body, which is a perfect absorber of radiation, independent on the wavelength or direction of the incident light. Further, it is a perfect emitter of thermal radiation. The Stefan-Boltzmann law [Eq. (5.19)] describes the total radiant emittance of a black body of temperature T,

$$M_e^{BB}(T) = \sigma T^4, \tag{22.5}$$

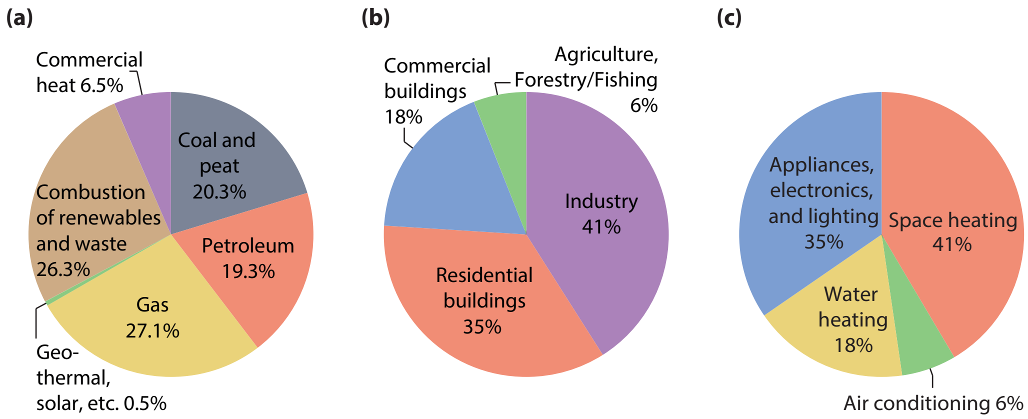

Figure 22.4: (a) The used primary energy suppliers for the generation of heat and (b) the demand of heat by sector [13]. (c) Energy consumption of U.S. homes [183]. All data is for 2009. Percentage of gas in (a) might be significantly higher nowadays due to the strong growth in shale gas usage (©OECD/IEA 2012, Insights Series 2012: Policies for renewable heat, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions).

where M is given in W/m^2 and $\sigma \approx 5.670 \cdot 10^{-8}\,\text{W}/(\text{m}^2\text{K}^4)$ is the Stefan-Boltzmann constant. In nature, no black bodies exist. However we can describe them as so-called *grey bodies*. The energy emitted by a grey body still can be described by Plank's law [Eq. (5.18a)] when it is multiplied with a wavelength dependent emission coefficient $\epsilon(\lambda)$. For a blackbody we would have $\epsilon(\lambda) \equiv 1$.

22.2 Solar thermal heating

About half of the world's energy consumption is in the form of *heat*. About two thirds of the heat demand is covered by coal, oil, and natural gas, as we can see in Fig. 22.4 (a). As shown in Fig. 22.4 (b), heat is mainly used in the industrial sector for facilitating for example chemical processes and in the residential sector for heating and warm water supply.

Figure 22.4 (c) shows the total energy demand of a typical household in the United States. We see that space heating and water heating represent 59% of the total energy consumption. If also the demand for cooling is taken into account, about two third of the energy consumption are related to the use of heat.

The residential demand for heat can at least partially covered with a *solar water heater*, which is a combination of a solar collector array, an energy transfer system and a storage tank, as sketched in Fig. 22.5. The main part of a solar water heater is the *collector array*, which absorbs solar radiation and converts it into heat. This heat is absorbed by a heat transfer fluid that passes through the collector. The heat can be stored or used directly. The amount of the hot water produced by a solar water heater throughout a year depends on the type and size of the solar collector array, the size of the water storage, the amount of sunshine available at the site and the seasonal hot water demand pattern.