CHAPTER 7

THE TRANSPORT OF HEAT

In this chapter, we shall take a closer look at the transport of entropy. Simple aspects will be introduced that go beyond what we already studied in Chapter 4 (Section 4.6). This extends the treatment of thermal processes into the realm of phenomena which are missing from the theory of the thermodynamics of ideal fluids (Chapter 5). Many texts on thermodynamics and on heat transfer sharply distinguish between the two subjects, which only emphasizes that a unified presentation of all thermal phenomena is called for. While we will not achieve the stated goal in this chapter, the ground will be prepared for a theory of continuum thermodynamics of which we will get a first glimpse in Part III.

The first section of this chapter provides a qualitative description of the three types of entropy transport: conduction, convection, and radiation. It introduces the formulation of the law of balance of entropy for a uniform body. Then, simple applications of all three forms of heat transfer will be discussed, giving an overview of some practical problems. Flow systems, i.e., open systems where fluids transport dissolved substances, entropy and momentum will be introduced in Chapter 8. There we extend the notion of chemical potential to fluids in flow systems.

Entropy production in heat transfer will be considered as we go along, preparing the ground for the concept of minimization of irreversibility in thermal design which will be applied in Chapter 9.

7.1 TRANSPORT PROCESSES AND THE BALANCE OF ENTROPY

In this section, I will describe qualitatively the basic phenomena underlying the transport of heat. Simple observations tell us that entropy can flow in three different ways: conduction, convection, and radiation. Consideration of these types of transport will lead to the formulation of the law of balance of entropy in a more general form than previously encountered, and will yield a better understanding of the role of hotness in thermal processes. In the end, the equation of balance of entropy will contain terms describing the different modes of transport.

These types of transfer processes are found not only in thermal physics, but in other fields of the natural sciences as well. Momentum transports have been classified in the same manner in Chapter 3. For this reason alone, it is important to have a clear understanding of the nature of entropy transfer.
7.1.1 Conductive Transport of Entropy

Heat one end of a metal rod over a flame; in a very short time the other end will feel hot as well. If you throw a hot stone in cold water, it will cool down while the water gets warmer. In a heat exchanger, a hot fluid flows through pipes, heating a cooler fluid which flows around the pipes. In all of these examples, entropy is removed from some bodies and added to others. Why else should some objects become colder while others heat up? The possibility of changing the temperature by compression, i.e., adiabatic processes, does not occur in these examples. Therefore we say that entropy has been transferred. Obviously, entropy flows from hotter to colder bodies.

How is entropy transported in these examples, and what are possible conditions for this process to occur? First, we observe that material transport cannot be involved. A piece of metal heated at one end retains its integrity. A hot stone does not dissolve in water, thereby spreading the entropy it contains. In the case of the heat exchanger, it is true that the fluids move; however, entropy must be transferred through the walls of the pipes. Heat therefore flows through bodies without the help of a body transporting it, and it flows from one body to another if the two are brought in direct contact. These are examples of heat conduction (conduction or diffusion of entropy).

An example that we studied in Chapter 4 tells us something about the role of temperature in the conductive transport of entropy. Two bodies having different temperatures are brought in thermal contact, and their hotnesses are monitored. It is found that the temperatures of the bodies change until they have become equal. As long as they are changing, entropy must be flowing: one of the bodies is cooled, the other is heated. In the end, however, the exchange stops. We conclude that entropy flows conductively as long as there is a difference of temperatures between the bodies exchanging heat, and that by itself, entropy flows only from hotter to colder objects.

Driving forces. This type of behavior is well known from a number of different physical phenomena. Connect two containers having different cross sections that are filled with water up to different levels; let the water flow between them. As a different example, connect two electrically charged spheres with a wire and monitor the electrical potential of each of the spheres. We know what will happen in both cases: the water levels in the containers will reach the same height, and the electric potentials of the two spheres will be the same after the process ends (Chapter 1). In each case, something flows as long as there is a difference of potentials, i.e., a driving force. In analogy to these well-known phenomena, we shall interpret the conductive transport of entropy as follows:

In conductive transport, entropy flows by itself through bodies from points of higher to points of lower temperature. In other words, entropy flows as long as there is a difference of temperatures, i.e., a thermal driving force.

The balance of entropy. Conductive transport of heat is a prime example of an irreversible process (Section 4.6.3). A body conducting entropy produces more entropy at the same time. This must be so because in a steady-state process, the same amount of energy which enters the body at high temperature leaves it at a lower thermal level. Therefore, the current of entropy leaving the body must be larger than the one entering. Clearly then, the equation of balance of entropy must include the production term for entropy in addition to the term describing conductive transfer of heat into and out of the body: