1.5: Heat Transfer in Practical Devices

The amount of heat transferred to or from a system undergoing change is an important thermodynamic variable. In practical devices, the rate at which heat can be transferred to or from a system plays a very important role also. Consider again the work produced by heating a gas that is confined in a cylinder that is closed by a piston. Clearly, the rate at which heat can be transferred from the outside to the gas determines the rate at which the piston moves outward and thus the rate at which work is done on the environment.

Does it matter whether the heat-transfer process is fast or slow? If the heat cost nothing, would we care if our engine produced work only very slowly? After all, if we want more work and the heat is free, we need only build more engines; eventually we will have enough of them to produce any required amount of work. Of course, heat is not free; more significantly for our present considerations, the engines are not free either. Engineers and accountants call the cost of heat an operating costcost:operating. There are many other operating costs, like labor, supplies, insurance, and taxes. The cost of the engine is called a capital costcost:capital. To find the total cost of a unit of work, we need to add up the various operating costs and a part of the cost of the engine.

$$\text{cost of a unit of work } = \text{fuel cost } + \text{ other operating costs } + \text{ capital cost}$$

The difference between an operating cost and a capital cost is that an operating cost is incurred at (about) the same time that the product, in this case a unit of work, is created. In contrast, a capital cost is incurred well before the product is created. The purchase of a machine is a typical capital expense. The cost of the machine is incurred long before the machine makes its last product. This occurs because the machine must be paid for when it is acquired, but it continues to function over a useful lifetime that is typically many years. For example, if an engine that costs $1,000,000 can produce a maximum of 1,000,000 units of work before it wears out, the minimum contribution that the cost of the engine makes to the cost of the work it produces is $1 per unit. The life of the engine also enters into the estimation of capital cost. If some of the work done by the engine will be produced ten years in the future, we will be foregoing the interest that we could otherwise have earned on the money that we invested in the engine while we wait around to get the future work. Operating costs are well defined because they are incurred here and now. Capital costs are more problematic, because they depend upon assumptions about things like the life of the machine and the variation in interest rates during that life.

Suppose that we are developing a new engine. All else being equal, we can decrease the capital-cost component of the work our engine produces by decreasing the time it needs to produce a unit of work. The savings occurs because we can get the same amount of work from a smaller and hence less-costly engine. Since each unit of work requires that the same amount of heat be moved, we can make the engine smaller only if we can move heat around more quickly. In internal combustion engines, we get heat into the engine:internal combustion with a combustion reaction (an explosion) and take most of it out again by venting the combustion products (the exhaust gas). So internal combustion engines have the great advantage that both of these steps can be fast. Steam engines are successful because we can get heat into the engine quickly by allowing steam to flow from a boiler into the engine. We can remove heat from the steam engine quickly by venting the spent steam, which is feasible because the working fluid is water. The Stirling engine is a type of external combustion engine that works by alternately heating (expanding) and cooling (compressing) an enclosed working fluid. Stirling engines have theoretical advantages, but they are not economically competitive, essentially because heat transfer to and from the working fluid cannot be made fast enough.

Why does anyone care about capital cost? Well, we can be sure that the owner of an engine will be keenly interested in minimizing the dollars that come out of his pocket. But capital cost is also a measure of the consumption of resources—resources that may have more valuable alternative uses. So if any segment of an economy uses resources inefficiently, other segments of that economy must give up other goals that could have been achieved using the wasted resources. Economic activity benefits many people besides the owners of capital. If capital is used inefficiently, society as a whole is poorer as a result.

Heat transfer has a profound effect also on the design of the machines that manufacture chemicals. This occurs most conspicuously in processes that involve very exothermic reactions. If heat cannot be removed from the reacting material fast enough, the temperature of the material rises. The higher temperature may cause side reactions that decrease the yield of the product. If the temperature rises enough, there may be an explosion. For such reactions, the equipment needed to achieve rapid heat transfer, and to manage the rate of heat production and dissipation, may account for a large fraction of the cost of the whole plant. In some cases, chemical reactions used for the production of chemicals produce enough heat that it is practical to use this “waste heat” for the production of electricity.