Laws of Thermodynamics

Some of the most fundamental principles of physics are the first and second laws of thermodynamics which we list briefly here:

First Law of Thermodynamics

The first law of thermodynamics states that heat and work are equivalent energy forms and that the total energy stored in a thermodynamic system (per unit mass) can increase or decreased either by work done on that system or by heat addition to the system. Denoting the total stored energy per unit mass by e^* and a change in that quantity by de^* the first law states that

$$de^* \;=\; dq + dw \tag{Acc1}$$

In other words both heat and work done can contribute to or remove the fund of energy embodied in the total internal energy There are several important postscripts to this equation:

- the total stored energy (per unit mass) should include not only the internal energy, e, but also the common, global translational energy (per unit mass), $|u|^2/2$, the gravitational potential energy, gz, and any other form of stored energy such as chemical or electrical energy. In the context of the fluid mechanical system under consideration in these pages, the first two will be included though the other forms will be omitted for simplicity.

- the heat added, dq, should include all forms of heat addition whether by conduction or radiation. In many of the circumstances considered herein the heat added will be zero.

- the work done, dw, should include not only the work done on the fluid by the pressures acting on the surface of the control volume, $-d(p/\rho)$, but also any work done internally by a moving device within the control volume which will be referred to as *shaft work*. An example of the latter might be the shaft work done by a propeller inside the control volume.

One form of the first law that will often occur in the context of compressible fluid mechanics is that for flows in which $dq = 0$ and the shaft work is zero so the first law becomes

$$d\left(e + \frac{|u|^2}{2} + gz\right) \;=\; -d\left(\frac{p}{\rho}\right) \tag{Acc2}$$

so that

$$d\left(e + \frac{p}{\rho} + \frac{|u|^2}{2} + gz\right) \;=\; dh^* \;=\; 0 \tag{Acc3}$$

In other words the total enthalpy is constant in such flows and this result is very useful and important in analyzing those flows. More precise detail on this will be given in the section on the energy equation in compressible flows.

In a reversible process, dq can be equated to Tds. Moreover, for any process the work done, dw, is given by $-pd(1/\rho)$ and, therefore, in a reversible thermodynamic process the first law can be written as

$$de^* \;=\; Tds \;-\; pd\left(\frac{1}{\rho}\right) \tag{Acc4}$$

This is one of a set of relations called Maxwell's equations. For a static system this is more familiarly written as

$$de = Tds - pd\left(\frac{1}{\rho}\right) \tag{Acc5}$$

Another of Maxwell's equations for a reversible process is derived from the definition of the enthalpy, $h = e + p/\rho$. Taking the derivative of this and substituting the expression (Acc5) for e leads to another of Maxwell's equations for reversible thermodynamic processes, namely

$$dh = Tds + \frac{dp}{\rho} \tag{Acc6}$$

Second Law of Thermodynamics

The second law of thermodynamics states that the change in entropy as a consequence of any process will always be given by the inequality:

$$Tds > dq \tag{Acc4}$$

though in any reversible process $dq = Tds$. It follows that in any adiabatic process for which $dq = 0$ the change in the entropy will either be positive, if the change is irreversible or it will be zero in a reversible process. Consequently a reversible adiabatic process is isentropic but an irreversible process will lead to an increase in entropy. In many analyses of fluid flows in which irreversible effects such friction are neglected for simplicity it will therefore follow that the flow is isentropic. Thus a number of the sections in the chapter on compressible flows deal with isentropic flows. But in the same chapter we will also deal with some irreversible adiabatic flows such as those that occur in shock waves and there we will make use of the second law of thermodynamics and the fact that $ds > 0$.

Processes at Constant Volume and Constant Pressure

Finally we take note of two properties that are relevant to thermodynamic processes that occur at constant volume and at constant pressure.

During a constant volume process, $d(1/\rho) = 0$, and therefore $dw = 0$ so that $de = dq$. Consequently denoting the derivative de/dT at constant volume by c_v this implies that $dq = c_v dT$ and

$$de = c_v \, dT \tag{Acc5}$$

and c_v is known as the *specific heat at constant volume.*

During a constant pressure process, $dp = 0$, and it follows from the definition of enthalpy that $dh = dq$. Consequently denoting the derivative dh/dT at constant pressure by c_p this implies that

$$dh = c_p \, dT \tag{Acc6}$$

and c_p is known as the *specific heat at constant pressure.*

The ratio of specific heats, c_p/c_v is denoted by γ and is a simple constant for most gases. It takes a value of 1.4 for air. Moreover kinetic theory leads to the result that $\mathcal{R} = c_p - c_v$.