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ENERGY TRANSFERS IN CYCLIC HEAT ENGINES

Heat engines are made to provide mechanical energy from thermal energy. Efficiency is a convenient measure of how well this is done. The overall efficiency of an engine is usually thought of as the product of two more basic efficiencies: the thermal efficiency of the engine cycle and the cyclic mechanical efficiency of the complete device. The first is well treated in classical thermodynamics. The second, mechanical efficiency, is the subject of this work.

Analysis of the mechanical efficiency of heat engines can be only as general as the conceptual basis on which it is built. The model used here has a level of generality matching that used in classical thermodynamics to analyze the thermal efficiency of heat engines.

HEAT ENGINE DIAGRAMS

Figure 1.1 is a representation of a cyclic heat engine typically found in thermodynamics textbooks. G represents the body of the working substance, and T_H and T_C are the temperatures of the heat source and sink, respectively. The net or *indicated cyclic work* done by the engine working substance is the difference $Q_i - Q_o = W$ between the heat absorbed from the high temperature source and the heat rejected to the lower temperature reservoir during a complete cycle.

Although the diagram is adequate for discussing the *thermal efficiency* $\eta_t = W/Q_i$ of the cycle, it does not allow the analysis of all of

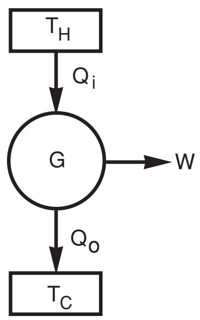

Figure 1.1 Cyclic heat engine diagram depicting heat transfers Q_i and Q_o to and from the working substance and indicated work output W.

the mechanical energy transfers that determine the mechanical efficiency of a complete engine. In fact, work must be done on the engine fluid to carry out half the cycle.

This is quite clear in looking at any pressure–volume (p–V) diagram of an engine cycle. An example is given in Figure 1.2 with characteristics that are typical of the cycles encountered in elementary thermodynamics and normal practice. What is termed as a *regular cycle* is described by a pair of functions p_c and p_e defined and continuous on a closed bounded interval $I = [V_m, V_M]$ representing the volume

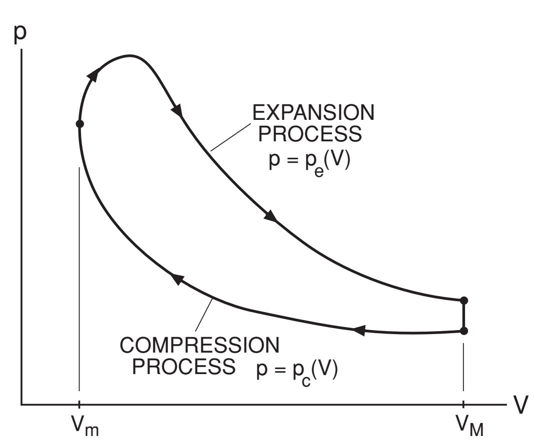

Figure 1.2 A regular cycle in the p–V plane.

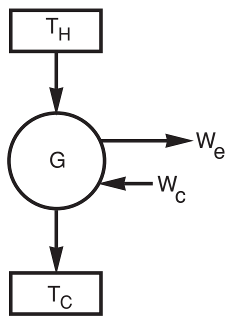

Figure 1.3 Heat engine diagram showing work transfers W_c and W_e with the working substance.

variation of the cycle. The functions represent the compression and expansion pressures of the cycle, with vertical segments supplied at volume extremes if necessary. For an engine, the cycle is oriented as shown in the figure, whereas compressors or heat pumps have the opposite orientation; the discussion will be limited to engines until a later chapter.

The area enclosed by the cycle in the p–V plane is the indicated work W of the engine. This net cyclic work is the difference between two distinct work processes. It is the difference between the work done by the engine fluid during expansion and the work done on it during compression. The *absolute expansion work* of the cycle is the area directly under the upper curve $p = p_e(V)$:

$$W_e = \int_{V_m}^{V_M} p_e(V)\,dV. \tag{1.1}$$

The *absolute compression work* of the cycle is the area directly below the cycle, which represents work that must be done on the engine substance to carry out the compression process described by the lower curve $p = p_c(V)$:

$$W_c = \int_{V_m}^{V_M} p_c(V)\,dV. \tag{1.2}$$

Both work quantities as defined here are positive, and $W = W_e - W_c$.

Figure 1.3 shows the individual expansion and compression work transfers. In a reciprocating or cyclic working engine, the expansion and compression processes do not take place simultaneously but rather sequentially. Thus to realize a self-acting reciprocating engine, means must be provided to divert and store some of the absolute expansion work and redirect it to the engine working fluid when it needs to carry out its absolute compression work.

THE BASIC CYCLIC HEAT ENGINE

Most practical engines have the features depicted conceptually in Figure 1.4. This is the type of engine to be dealt with here and will be referred to as a *reciprocating* or *cyclic kinematic* engine. The working substance, typically a gas, is contained in a capsule called the *work-space*, which is equipped with a means for varying the volume, usually a *piston*. Only a single body of working gas will be considered for the present. This does not represent a significant loss of applicability because most multi-cylinder engines can be considered as parallel connections of single-workspace engines. A later chapter will treat more complex arrangements of multi-piston engines.

The workspace is also equipped with means to interact thermally with heat reservoirs (not shown in Figure 1.4). The prime characteristic of the reciprocating engine is the *mechanism* linking the piston to the output *shaft*. This link is a kinematic one. The motion of the piston and

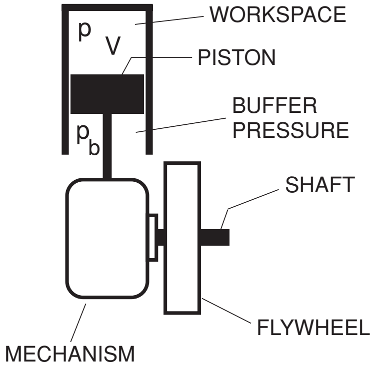

Figure 1.4 The elements of a reciprocating heat engine.

all other moving parts of the engine is completely constrained by the mechanism. The mechanism transmits force or torque as well as motion, so it is actually a *machine* in proper parlance, but the term *mechansim* will be used here to help avoid confusion with the engine as a whole.

The workspace usually contains other devices not shown in the figure such as valves or displacers or whatever may be necessary to carry the working fluid through the desired thermodynamic cycle. These devices, as well as auxiliary pumps, fans, etc., are kinematically linked to and are driven by the mechanism and are conceptually considered as part of the mechanism in the analysis here.

In the turbine type of heat engine, the expansion and compression processes take place simultaneously in different locations in the engine, and the processes are continuous. In cyclic kinematic engines, the processes are discrete and sequential. Because of this, a kinematic engine must be equipped with at least one work reservoir. For single-workspace engines with a rotating shaft output, this reservoir invariably takes the form of a *flywheel*, as Figure 1.4 depicts. Other devices can be used such as pendulums or springs at appropriate places. In multi-workspace engines, each workspace can use some of the others for this purpose as well.

Under steady state operation, the flywheel does not experience a net gain in energy over a cycle. During each cycle, it absorbs, stores, and returns energy to the engine that is necessary to sustain the cycle; the remainder is directed through the output shaft for use outside the engine.

BUFFER PRESSURE

The single-workspace engine needs nothing more in principle than the features described, but in practice it has a near constant external *buffer pressure* acting on the non-workspace side of the piston. The source of this pressure is usually due to the surrounding atmosphere, but sometimes a special enclosure or *buffer space* is constructed to permit the use of elevated pressure. As will be shown, buffer pressure

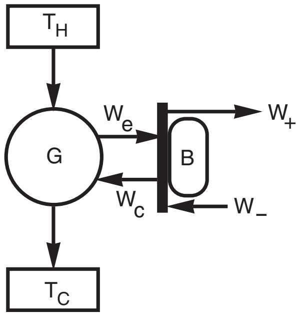

Figure 1.5 An engine diagram showing the effect of buffer pressure on piston work transfers.

has a significant influence on the mechanical efficiency of a kinematic engine.

All work transferred through the engine mechanism is subject to some loss due to friction. This applies to transfer in both directions: from flywheel to piston as well as from piston to flywheel and output shaft. The works transferred are not generally W_e and W_c because of the action of the buffer pressure. The buffer gas, like the flywheel, absorbs, stores, and returns energy to the working gas during the cycle. But it acts directly on the piston and thus diverts and recycles some work duty away from the mechanism. Figure 1.5 represents the buffer space with the element labeled B. The work quantities that must be mechanically transmitted to and from the engine piston are reduced from W_e and W_c by the influence of the buffer gas pressure to what will be denoted by W_+ and W_-. This reduces the friction losses in the mechanism section of the engine in a way to be precisely described shortly. W_+ and W_- will be referred to as the *efficacious* and *forced piston work*, respectively. Conceptually, W_+ is the non-negative work done on the mechanism by the piston in each cycle; W_- is the non-negative work done on the piston by the mechanism in each cycle. Note that both of these quantities are non-negative by definition. Also take note of the fact that the arrows in Figure 1.5 refer to positive work transfer only; they do not necessarily correspond to the direction of piston motion or to the direction of force or torque.

Since buffer presure acts directly on the piston, it is not subject to the frictional losses that energy storage in the flywheel entails. Any piston seal friction present is most appropriately included with the friction of the mechanism section and not associated with the buffer gas. The buffer gas, however, may suffer loss in another way when the buffer space volume is finite. This loss is often termed *hysteresis* or *transient heat transfer loss* (West, 1986). It occurs when the pressure of the buffer space fluctuates with the volume changes induced by the piston motion. In the interior of the buffer space, the gas experiences a corresponding temperature fluctuation. The walls of the buffer space are nearly isothermal. This produces a net flow of energy from the gas to the container walls over each cycle. To counter this in practice, one makes the buffer space volume as large as practical. This minimizes the pressure excursion and therefore minimizes the hysteresis loss. Usually the pressure variation can be kept relatively small, and therefore it is reasonable in most analyses to assume the ideal of constant buffer pressure. C*onstant buffer pressure will be our usual assumption* in all of the following work except where noted, as in Chapter 8. If the pressure is constant, the buffer gas acts as a lossless energy reservoir in direct communication with the piston. In this ideal case the difference between the efficacious and forced work is exactly the indicated work of the cycle:

$$W_+ - W_- = W = W_e - W_c \,.$$

Other devices can be arranged to act on the piston directly, such as springs or weights, but assuming a constant buffer pressure is adequate to cover most applications.

SHAFT WORK

The complete cyclic kinematic heat engine as just described can be conceptually represented by the diagram of Figure 1.6. Device M represents

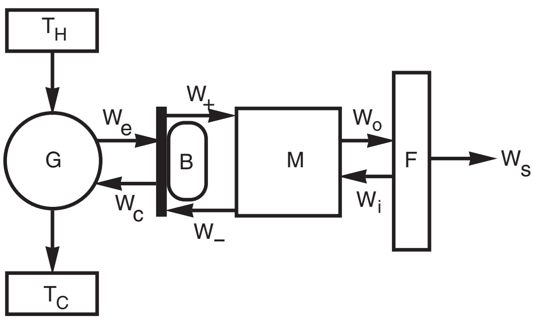

Figure 1.6 Diagram showing the work transfers between the basic components of a cyclic kinematic heat engine.

the mechanism and F the flywheel. The quantity W_s is the *cyclic shaft work*. In practical terms it is the useful work coming out of the engine in each cycle. In the diagram, it is the difference between the cyclic work W_o received by the flywheel/output shaft from the mechanism and the cyclic work W_i taken from the flywheel and directed into the mechanism to sustain operation: $W_s = W_o - W_i$.

W_o is the efficacious piston work W_+ reduced by friction losses in passing through the mechanism. W_i is the work that the flywheel must feed into the mechanism in order to deliver, after having been reduced by friction losses in passing through the mechanism, the work W_- that the piston is forced to do. The effectiveness of the mechanism in transmitting all this work determines the difference between the indicated work of the engine cycle and the shaft work that is ultimately delivered:

$$W_o \leq W_+ \quad \text{and} \quad W_i \geq W_- \quad \text{make} \quad W_s = W_o - W_i \leq W_+ - W_- = W\,.$$

A subtle point, however, is that the shaft work also depends on how much energy the mechanism must transmit. How much is determined by the positive and negative piston works. The magnitude of these quantities are dependent not only upon the compression and expansion works of the cycle, W_c and W_e, but also depend significantly upon cycle shape and buffer pressure.

BUFFER PRESSURE AND ENERGY TRANSFERS

Figure 1.7 illustrates how buffer pressure level determines where and when efficacious and forced piston work occurs. An elliptical *p–V* cycle is shown with an increasing sequence of constant buffer pressure levels. A plus sign along a segment of the cycle indicates efficacious piston work, i.e., where positive work is done on the mechanism by the piston. This occurs during those portions of the cycle where either the workspace pressure is above the buffer pressure and the piston is effecting a volume expansion, or where the workspace pressure is below the buffer pressure and a compression is taking place. A minus sign signifies the opposite situation, namely, a process in which work must be taken from the flywheel and transmitted to the piston by the mechanism. Note that the signs do not necessarily relate to the direction of piston motion but rather denote the direction of positive work transfer between the piston and the mechanism.

These energy exchanges and the corresponding mechanical losses will be quantified in the following chapters, but some important and useful points should be intuitively clear at this juncture. First, an engine buffered as in Figure 1.7(a) will require more flywheel effect than that in (b). Case (c) will require even less, and (d) will need minimal flywheel assistance. Accordingly, larger mechanical losses appear more likely in Case (a) than in (b) and so on to (d). This will in fact be shown to be the case under very general assumptions in the next chapter. Higher buffer pressures as in (e), (f), and (g) have effects similar to the lower pressures.

It should also be noted that no choice of constant buffer pressure will entirely eliminate the need for a flywheel for this particular cycle. At any buffer pressure level there will be some segment labeled with a minus sign, and therefore some stored flywheel energy will be needed. This is typical for most cycles but is not always the case. For example, in each cycle in Figure 1.8 there is at least one buffer pressure level that results in only work transfer from the piston to the output shaft and no forced piston work occurs.

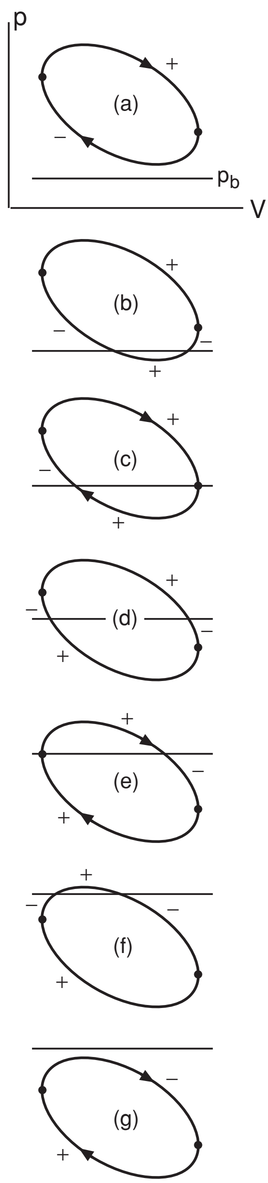

Figure 1.7 An elliptical engine cycle shown with various buffer pressure levels. The signs indicate the direction of energy transfer between the piston and the mechanism.