II. Theory of Heat-Engines.

23. A heat-engine acts by taking in heat, converting a part of the heat received into mechanical energy, which appears as the work done by the engine, and rejecting the remainder, still in the form of heat. The theory of heat-engines comprises the study of the amount of work done, in its relation to the heat supplied and to the heat rejected. The theory is based on the two laws of thermodynamics, which may be stated here as follows :—

Law 1. *When mechanical energy is produced from heat, 1 thermal unit of heat goes out of existence for every 772 foot-pounds of work done; and, conversely, when heat is produced by the expenditure of mechanical energy, 1 thermal unit of heat comes into existence for every 772 foot-pounds of work spent.*

The “thermal unit” is the heat required to raise the tempera­ture of 1 lb of water 1 degree Fahr. when at its temperature of maximum density. The equivalent quantity of work, 772 foot­pounds, was determined by the experiments of Joule, and is called Joule’s equivalent. Later researches by Joule and others have indicated that this number is probably too small; it should perhaps be as much as 774 foot-pounds. Joule’s original value is still generally used by engineers; and as it enters into many published tables it may conveniently be adhered to until its accuracy is more definitely disproved. Since a definite number of foot-pounds are equivalent to 1 thermal unit, we may, if we please, express quantities of work in thermal units, or quantities of heat in foot-pounds ; the latter practice will frequently be found useful.

Law 2. *It is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature.*

This is the form in which the second law has been stated by Clausius. Another statement of it, different in form but similar in effect, has been given by Thomson. Its force may not be immediately obvious, but it will be shown below that it introduces a most important limitation of the power which any engine has of converting heat into work. So far as the first law shows, there is nothing to prevent the whole heat taken in by the engine from changing into mechanical energy. In consequence of the second law, however, no heat-engine converts, or can convert, more than a small fraction of the heat supplied to it into work ; a large part is necessarily rejected as heat. The ratio

Heat converted into work Heat taken in by the engine

is a fraction always much less than unity. This ratio is called the *efficiency* of the engine considered as a heat-engine.

24. In every heat-engine there is a *working substance* which takes in and rejects heat, thereby suffering changes of form, or more commonly of volume, and does work by overcoming resistance to these changes of form or volume. The working substance may be gaseous, liquid, or solid. We can, for example, imagine a heat- engine in which the working substance is a long metallic rod, arranged to act as the pawl of a ratchet-wheel with fine teeth. Let the rod be heated so that it elongates sufficiently to drive the wheel forward through the space of one tooth. Then let the rod be cooled (say by applying cold water), the wheel being meanwhile held from returning by a separate click or detent. The rod, on cooling, will retract so as to engage itself with the next succeeding tooth, which may then be driven forward by heating the rod again, and so on. To make it evident that such an engine would do work, we have only to suppose that the ratchet-wheel carries round with it a drum by which a weight is wound up. We have, then, a complete heat-engine, in which the working substance is a solid rod, which receives heat by being brought into contact with some source of heat at a comparatively high temperature, transforms a small part of this heat into work, and rejects the remainder to what we may call a receiver of heat, at a comparatively low temperature. The greater part of the heat may be said simply to pass through the engine, from the source to the receiver, *becoming degraded as regards temperature* as it goes. We shall see presently that this is typical of the action of all heat-engines ; when they are doing work, the heat which they reject is rejected at a tempera­ture lower than that at which it is taken in. They convert some heat into work only by letting down a much larger quantity of heat from a high to a relatively low temperature. The action is analogous to that of a water-wheel, which does work by letting down water from a high to a lower level, but with this important difference that in the transfer which occurs in heat-engines an amount of heat disappears which is equivalent to the work done.

25. In almost all actual heat-engines the working substance is a fluid. In some it is air, in some a mixture of several gases. In the steam-engine the working fluid is a mixture (in varying proportions) of water and steam. With a fluid for working substance, work is done by changes of volume only ; its amount depends solely on the relation of pressure to volume during the change, and not at all on the form of the vessels in which the change takes place. Leta diagram be drawn (fig. 9) in which the relation of the intensity of pressure

to the volume of any supposed working substance is graphically exhibited by the line ABC, where AM, CN are pressures and AP, CQ are volumes, then the work done by the substance in expand­ing from A to C is the area of the figure MABCN, And similarly, if the substance be compressed from

C back to its original volume in such a manner that the line CDA repre­sents the relation of pressure and volume during compression, the work done *upon* the substance is the figure NCDAM. Taking the two operations together, we find that the substance has done a net amount of work equal to the area of the shaded figure ABCDA, or ∫P*d*V. This is an ex­ample and a generalization of the method of representing work which Watt introduced by his inven­tion of the indicator ; the figure ABCDA may be called the indicator diagram of the supposed action.

26. Generally in heat-engines the working substance returns periodically to the same state of temperature, pressure, volume, and physical condition. When this has occurred the substance is said to have passed through a complete cycle of operations. For example, in a condensing steam-engine, water taken from the hot- well is pumped into the boiler ; it then passes into the cylinder as steam, passes thence into the condenser, and thence again into the hot-well ; it completes the cycle by returning to the same con­dition as at first. In other less obvious cases, as in that of the non-condensing steam-engine, a little consideration will show that the cycle is completed, not indeed by the same portion of working substance being returned to the boiler, but by an equal quantity of water being fed to it, while the steam which has been discharged into the atmosphere cools to the temperature of the feed. In the theory of heat-engines it is of the first importance to consider (as was first done by Carnot in 1824) the cycle of operations per­formed by the working substance as a complete whole. If we stop short of the completion of a cycle matters are complicated by the fact that the substance is in a state different from its initial state, and may therefore have changed its stock of internal energy. After a complete cycle, on the other hand, we know at once that, since the condition is the same, the internal energy of the substance is the same as at first, and therefore—

Heat taken in = work done + heat rejected.

27. It will serve our purpose best to approach the theory of heat-engines by considering, in the first instance, the action of an engine in which the working substance is any one of the so-called permanent gases, or a mixture of them, such as air. The word permanent, as applied to a gas, can now@@1 be understood only as meaning that the gas is liquefied with difficulty—either by the use of extremely low temperature or extremely high pressure or both. So long as gases are under conditions of pressure and tem­perature widely different from those which produce liquefaction, they conform very approximately to certain simple laws—laws which may be regarded as *rigorously* applicable to ideal substances called *perfect* gases. After stating these laws briefly we shall examine the efficiency of a heat-engine using a gas in a certain manner as working substance, and then show that the conclusion so derived has a general application to all heat-engines whatsoever. In this procedure there is no sacrifice of generality, and a part of the process is of independent service in the discussion of actual air-engines.

28. The laws of the permanent gases are the following :—

Law 1 (Boyle). *The volume of a given mass of gas varies*

*inversely as the pressure, the temperature being kept constant.*

Thus, if V be the volume of 1 lb of a gas in cubic feet, and P the pressure in pounds per square foot, so long as the temperature is unchanged—

P∞ V-1, or PV=constant.

For air the value of the constant is 26220 when the temperature is 32° F.

29. Law 2 (Charles). *Under constant pressure equal volumes of different gases increase equally for the same increment of tempera­ture. Also, if a gas be heated under constant pressure, equal incre­ments of its volume correspond very nearly to equal intervals of tem­perature as determined by the scale of a mercury thermometer.*

Thus, let us take, say, 493 cubic inches of hydrogen, also of oxygen, of air, &c., all at 32° F., and, keeping each at a constant pressure (not necessarily the same for all), heat all so that their temperature rises 1° F. We shall find that each has expanded by sensibly the same amount and now occupies 494 cubic inches. And further, if we heat any one through another 1 F. to 34 F., we shall find that its volume is now 495 cubic inches, and so on. Thus for any gas, kept at constant pressure, if the volume was

@@@1 Since the liquefaction of hydrogen and other gases by MM. Cailletet and Pictet.