such as that of the gas in Joule’s experiment, § 33, and it excludes also what may be called imperfectly-resisted expansion, such as would occur if the fluid were allowed to expand into a closed chamber in which the pressure was less than that of the fluid, or if the piston in a cylinder rose so fast as to cause, through the inertia of the ex­panding fluid, local variations of pressure throughout the cylinder.

To make a heat-engine, working within given limits of tempera­ture, as efficient as possible we must therefore strive—(1) to take in no heat except at the highest temperature, and to reject no heat except at the lowest temperature ; (2) to secure that the working substance shall, when receiving heat, be at the temperature of the body from which the heat comes, and that it shall, when giving up heat, be at the temperature of the body to which heat is given up ; (3) to avoid free or imperfectly-resisted expansion. If these conditions are fulfilled the engine is a perfect heat-engine.

The first and second of these conditions are satisfied if in the action of the engine the working substance changes its tempera­ture from τ1 to τ2 by adiabatic expansion, and from τ2 to τ1 by adiabatic compression, thereby being enabled to take in and reject heat at the ends of the range without taking in or rejecting any by the way. This is the action in Carnot's engine (§ 40).

52. But if we can cause the working substance to deposit heat in some body within the engine while passing from τ1 to τ2, in such a manner that the transfer of heat from the substance to this body is reversible (satisfying the second condition above), then when we wish the working substance to pass from τ2 to τ1 we may reverse this transfer and so recover the heat that was deposited in this body. This alternate storing and restoring of heat may then take the place of adiabatic expansion and compression, in causing the tem­perature of the working substance to pass from τ1 to τ2 and from τ2 to τ1 respectively. The alternate storing and restoring is an action occurring wholly within the engine, and is therefore distinct from the taking in and rejecting of heat by the engine.

53. In 1827 Robert Stirling designed an apparatus, called a *re­generator,* by which this process of alternate storing and restoring of heat could be actually performed. For the present purpose it will suffice to describe the regenerator as a passage through which the working fluid can travel in either direction, whose walls have a very large capacity for heat, so that the amount alternately given to or taken from them by the working fluid causes no more than an insensible rise or fall in their temperature. The temperature of the walls at one end of the passage is τ1, and this tapers continuously down to τ2 at the other end. When the working fluid at tempera­ture τ1 enters the hot end and passes through, it comes out at the cold end at temperature τ2, having stored in tho walls of the regenerator an amount of heat which it will pick up again when passed through in the opposite direction. During the return journey its temperature rises from τ2 to τ1. The process is strictly reversible, or rather would be so if the regenerator had an unlimited capacity for heat, if no conduction of heat took place along its walls from the hot to the cold end, and if no loss took place by conduction or radiation from its external surface.

54. Using air as the working substance, and employing his regenerator, Stirling made an engine (to be described later) which, allowing for practical imperfections, is the earliest example of a truly reversible engine. The cycle of operations in Stirling’s engine is substantially this :—

(1) Air (which has been heated to τ1 by passing through the regenerator) is allowed to expand isothermally through a ratio *r,* taking in heat from a furnace and raising a piston. Heat taken in (per lb of air) = *c*τ1 logε*r*.

(2) The air is caused to pass through the regenerator from the hot to the cold end, depositing heat and having its temperature lowered to τ2, without change of volume. Heat stored in regenerator = K*p*(τ1 - τ2). The pressure of course falls.

(3) The air is then compressed isothermally to its original volume at τ2 in contact with a refrigerator (or receiver of heat). Heat rejected = *c*τ2logε*r*.

(4) The air is again passed through the regenerator from the cold to the hot end, taking up heat and having its temperature raised to τ1. Heat restored by the regenerator=K*p*(τ1 - τ2).

τιa, . cτ1loger-cτ2loger τ1-τ2

Efficiency = i = .

j cτ1loger τ1

The indicator diagram of the action is shown in fig. 13, and a diagram of the engine is given in chap. XIV. Stirling’s engine is important, not as a present-day heat-engine (though it has recently been revived in small forms after a long interval of disuse), but because it is typical of the only mode, other than Carnot’s plan of adiabatic expansion and compression, by which the action of a heat-engine can be made reversible. Valuable as the regenerator has proved in metallurgy and other industrial processes, its actual application to heat-engines has hitherto been very limited. An­

other way of using it in air-engines was designed by Ericsson, and attempts have been made by C. W. Siemens and F. Jenkin to apply it to steam-engines and to gas-engines. But almost all actual engines, in so far as they can be said to approach the condition of reversibility, do so, not by the use of the regenerative principle, but by more or less nearly adiabatic expansion and compression after the manner of Carnot’s ideal engine.

III. Properties of Steam and Theory of the Steam-Engine.

55. We have now to consider the action of heat-engines in which the working substance is water and water-vapour or steam. The properties of steam are most conveniently stated by referring in the first instance to what happens when steam is formed *under constant pressure.* This is substantially the process which occurs in the boiler of a steam-engine when the engine is at work. To fix the ideas we may suppose that the vessel in which steam is to be formed is a long upright cylinder fitted with a piston which may be loaded so that it exerts a constant pressure on the fluid below. Let there be, to begin with, at the foot of the cylinder a quantity of water (which for convenience of numerical statement we shall take as 1 lb), at any temperature *t*0 ; and let the piston press on the surface of the water with a force of P lb per square foot. Let heat now be applied to the bottom of the cylinder. As it enters the water it will produce the follow­ing effects in three stages :—

(1) The temperature of the water rises until a certain tempera­ture *t* is reached, at which steam begins to be formed. The value of *t* depends on the particular pressure P which the piston exerts. Until the temperature *t* is reached there is nothing but water below the piston.

(2) Steam is formed, more heat being taken in. The piston (which is supposed to exert a constant pressure) rises. No further increase of temperature occurs during this stage, which continues until all the water is converted into steam. During this stage the steam which is formed is said to be *saturated.* The volume which the piston encloses at the end of this stage,— the volume, namely, of 1 lb of saturated steam at pressure P (and temperature *t),—*will be denoted by V in cubic feet.

(3) If after all the water is converted into steam more heat be allowed to enter, the volume will increase and the temperature will rise. The steam is then said to be *superheated.*

56. The difference between saturated and superheated steam may be expressed by saying that if water (at the temperature of the steam) be mixed with steam some of the water will be evaporated if the steam is superheated, but none if the steam is saturated. Any vapour in contact with its liquid and in thermal equilibrium is necessarily saturated. When saturated its properties differ con­siderably, as a rule, from those of a perfect gas, but when super­heated they approach those of a perfect gas more and more closely the farther the process of superheating is carried, that is to say, the more the temperature is raised above *t,* the temperature of saturation corresponding to the given pressure P.

57. The temperature *t* at which steam is formed depends on the value of P. Their relation was determined with great care by Regnault, in a series of classical experiments on which our knowledge of the properties of steam chiefly depends.@@1 The pressure of saturated steam rises with the temperature at a rate which increases rapidly in the upper regions of the scale. This will be apparent from the first and second columns of Table II., given on next page, which is compiled from Rankine’s reduction of Regnault’s results. The first column gives the temperature on the Fahr. scale; the second gives the corresponding pressure in pounds per square inch. Rankine has also expressed the relation of temperature and pressure in saturated steam by the following formula (which is applicable with other constants to other va­pours@@2):—

1 β,,vv, 2732 396945 logp = 6∙1007 2- ,

τ τ^,

where *p* is the pressure in pounds per square inch, and τ is the absolute temperature in Fahr. degrees. For most purposes, how­ever, it is more convenient to find the pressure corresponding to a given temperature, or the temperature corresponding to a given pressure, from the table by interpolation.

58. The same table shows the volume V, in cubic feet, occupied by 1 lb of saturated steam at each pressure. This is a quantity the direct experimental measurement of which is of very great difficulty. It may, however, be calculated, from a knowledge of other properties of steam, by a process which will be described later (§ 75). The values of V given in the table were determined by Rankine by means of this process; they agree fairly well with such direct observations of the density of steam as have been hitherto

@@@1 *Hem. Inst. France,* 1847, vol. xxi. An account of Regnault’s methods of experiment and a statement of his results expressed in British measures will be found in Dixon’s *Treatise on Heat. .*

@@@2 *Phil. Mag.,* Dec. 1854, or *Manual of the Steam-Engine,* p. 237.