perfect gas, and may be called “steam gas.” It then follows the equation PV=85∙5τ,

and the specific heat at constant pressure, K*p*, is 871 foot-pounds or 0·48 thermal unit. At very low temperatures steam approximates closely to the condition of a perfect gas when very slightly super­heated, and even when saturated ; at high temperatures a much greater amount of superheating is necessary to bring about an approach to the perfectly gaseous state. The total heat required for the production of superheated steam under any constant pressure, when the superheating is sufficient to bring the steam to the state of steam gas, may therefore be reckoned by taking the total heat of saturated steam at a low temperature and adding to it the product of K*p*, into the excess of temperature above that. Thus Rankine, treating saturated steam at 32° F. as a gas, gives the formula

H'=1092 + 0∙48(*t*'-32)

to express the heat of formation (under any constant pressure) of superheated steam, at any temperature *t'* which is so much above the temperature of saturation corresponding to the actual pressure that the steam may be treated as a perfect gas. Calculated from its chemical composition, the density of steam gas should be 0·622 times that of air at the same pressure and temperature. The value of γ or K*p*∕K*v* for steam gas is 1·3. These formulas, dealing as they do with steam which is so highly superheated as to be perfectly gaseous, fail to apply to high-pressure steam that is heated but little above its temperature of saturation. The relation of pressure to volume and temperature in the region which lies between the saturated and the perfectly gaseous states has been experimented on by Hirn.@@1 Formulas which are applicable with more or less accuracy to steam in either the saturated or superheated condition have been devised by Hirn, Zeuner,@@2 Ritter,@@3 and others.

66. The expansion of volume which occurs during the conversion of water into steam under constant pressure—the second stage of the process described in § 55—is isothermal. From what has been already said it is obvious that steam, or any other saturated vapour, can be expanded or compressed isothermally only when wet, and that evaporation (in the one case) or condensation (in the other) must accompany the process. Isothermal lines for a working sub­stance which consists of a liquid and its vapour are straight lines of uniform pressure.

67. The form of adiabatic lines for substances of the same class depends not only on the particular fluid, but also· on the propor­tion of liquid to vapour in the mixture. In the case of steam, it has been shown by Rankine and Clausius that if steam initially dry be allowed to expand adiabatically it becomes wet, and if initially wet (unless very wet@@4) it becomes wetter. A part of the steam is condensed by the process of adiabatic expansion, at first in the form of minute particles suspended throughout the mass. The temperature and pressure fall ; and, as that part of the sub­stance which remains uncondensed is saturated, the relation of pressure to temperature throughout the expansion is that which holds for saturated steam. The following formula, proved by Rankine@@5 and Clausius@@6 (see § 75), serves to calculate the extent to which condensation takes place during adiabatic expansion, and so allows the relation of pressure to volume to be determined.

Before expansion, let the initial dryness of the steam be *q*1 and its absolute temperature τ1. Then, if it expand adiabatically until its temperature falls to τ, its dryness after expansion is

5-χ(⅛+1°i∙v)∙

L1 and L are the latent heats (in thermal units) of 1 lb of steam before and after expansion respectively. When the steam is dry to begin with, *q*1 = l.

This formula is easily applied to the construction of the adiabatic curve when the initial pressure and the pressure after expansion are given, the corresponding values τ and L being found from the table. It is less convenient if the data are the initial pressure and the initial and final volumes, or the initial pressure and the ratio of expansion *r.* An approximate formula more appropriate in that case is

P*vn*=constant, or P∕P1 = (*v*∕*v*1)*n* = *rn*.

Here *v* and *v*1 denote the volume of 1 lb of the mixture of steam and water before and after expansion respectively, and are to be distinguished from V and V1, which we have already used to denote the volume of 1 lb of dry saturated steam at pressures P and P1. The index *n* has a value which depends on the degree of initial dryness *q*1*.*

According to Zeuner,@@7 *n*=1·035 + 0·1*q*1, so that for *q*1 = l 0∙95 0∙9 0∙85 0·8 075 07

*n*=1·135 1·130 1·125 1·120 1·115 1·110 1·105.

Rankine gave for this index the value 10/9, which is too small if the steam be initially dry. He determined it by examining the expansion curves of indicator diagrams taken from working steam- engines ; but, as we shall see later, the expansion of steam in an actual engine is by no means adiabatic, on account of the transfer of heat which goes on between the working fluid and the metal of the cylinder and piston. When it is desired to draw an adiabatic curve for steam, that value of *n* must be chosen which refers to the degree of dryness at the beginning of the expansion.

68. We are now in a position to study the action of a heat-engine employing steam as the working substance. To simplify the first consideration as far as possible, let it be supposed that we have, as before, a long cylinder composed of non-conducting material except at the base, and fitted with a non-conducting piston ; also a source of heat A at some temperature τ1 ; a receiver of heat, or, as we may now call it, a condenser C, at a lower temperature τ2 ; and a non-con­ducting cover B (as in § 40). Then we can perform Carnot’s cycle of operations as follows. To fix the ideas, suppose that there is 1 lb of water in the cylinder to begin with, at the temperature τ1 :—

(1) Apply A, and allow the piston to rise. The water will take in heat and be converted into steam, expanding isothermally at constant pressure P1. This part of the operation

is shown by the line *ab* in fig. 14.

(2) Remove A and apply B. Allow the expan­

sion to continue adiabatically (*bc*)*,* with falling pressure, until the temperature falls to τ2. The pressure will then be P2. corresponding (in Table II.) to τ2.

(3) Remove B, apply C, and compress. Steam is condensed by rejecting heat to C. The action is iso­thermal, and the pressure remains P2. Let this be continued until a certain point *d* is reached, after which adiabatic compression will complete the cycle.

(4) Remove C and apply B. Continue the compression, which is now adiabatic. If the point *d* has been rightly chosen, this will complete the cycle by restoring the working fluid to the state of water at temperature τ1.

The indicator diagram for the cycle is given in fig. 14, as cal­culated by the help of the equations in § 67 and of Table II. for a particular example, in which *p*1 = 90 lb per square inch (τ1 = 781), and the expansion is continued down to the pressure of the atmo­sphere, 147 lb per square inch (τ2=673). Since the process is reversible, and since heat is taken in only at τ1 and rejected only at τ2, the efficiency is (τ1- τ2)∕τ2, The heat taken in per lb of the fluid is L1, and the work done is L1 (τ1-τ2)∕τ1, a result which may be used to check the calculation of the diagram.

69. If the action here described could be realized in practice, we should have a thermodynamically perfect steam-engine using saturated steam. The fraction of the heat supplied to it which such an engine would convert into work would depend simply on the temperature, and therefore on the pressure, at which the steam was produced and condensed. The temperature of con­densation is limited by the consideration that there must be an abundant supply of some substance to absorb the rejected heat ; water is actually used for this purpose, so that τ2 has for its lower limit the temperature of the available water-supply.

To the higher temperature τ1 and pressure P1 no limit can be set except such as is brought about in practice by the mechanical diffi­culties, with regard to strength and to lubrication, which attend the use of high-pressure steam. By a very special construction of engine and boiler Mr Perkins has been able to use steam with a pressure as high as 500 lb per square inch ; with engines of the usual construction the value ranges from 190 lb downwards.

If the temperature of condensation be taken as 60° F., as a lower limit, the efficiency of a perfect steam-engine, using saturated steam, would depend on the value of P1, the absolute pressure of production of the steam, as follows :—

For perfect steam-engine, with condensation at 60° F.,

P1 in lb per square inch being 40 80 120 160 200

Highest ideal efficiency = ·284 ·326 ·350 ·368 ·381

But it must not be supposed that these values of the efficiency are actually attained, or are even attainable. Many causes conspire to prevent steam-engines from being thermodynamically perfect, and some of the causes of imperfection cannot be removed. These num­bers will serve, however, as a standard of comparison in judging of

@@@1 *Théorie Mécanique de la Chaleur.*

@@@2 *Ztschr. d. Vereins deutscher Ingenieure,* vol. xi.

@@@3 *Wied. Ann.,* 1878. For a discussion of several of these formulas, see a paper by H. Dyer, *Trans. Inst. of Engineers and Shipbuilders in Scotland,* 1885.

@@@4 Prof. Cotterill, in his *Treatise on the Steam-Engine,* § 79, has calculated (using the equation which follows in the text) that, when a mixture of steam and water expands adiabatically, steam condenses if the proportion of steam be, roughly, over 50 per cent., but water is evaporated if the proportion of steam be less than about 50 per cent. The exact proportion depends on the initial pressure.

@@@5 *Steam-Engine,* § 281.

@@@6 *Mechanical Theory of Heat* (tr. by W. R. Browne), chap. vi. J 12.

@@@7 *Grundzüge der Mech. Wärmetheorie,* p 342. See also Grashof, *Resultate aus der Mech. Wärmetheorie,* § 37. In the adiabatic compression of wet steam n=1 034+0 11*q*1, where *q*1 is the dryness at the beginning of compression.