*to* use this arbitrary starting-point in reckoning what may be called the *internal energy* of the substance, which is the excess of the heat taken in over the external work done by the substance during its reception of heat. Thus the internal energy E of I lb of saturated steam at pressure *p* is equal to the total heat I, less that part of the total heat which is spent in doing external work, or

E=I*pw*/J.

The notion of internal energy is useful in calculating the heat taken in or rejected by steam during any stage of its expansion or com­pression in an engine. When a working substance passes from one condition to another its gain or loss of heat is determined by the equation

Heat taken in = increase of internal energy + external work. Any of the terms of this equation may be negative; the last term is negative when work is done, not by but upon the substance.

33. *Wet Steam.—*In calculations which relate to the action of steam in engines we have often to deal, not with *dry* saturated steam, but with *wet* steam, or steam which either carries in suspension, or is otherwise mixed with, a greater or less proportion of water. In any such mixture, assuming it to be in equilibrium, the steam and water have the same temperature, and the steam is saturated. The dryness of wet steam is measured by the proportion *q* of dry steam in each pound of the mixed substance. When that is known it is easy to determine the other physical constants: thus—

Latent heat of 1 lb of wet steam = *q*L;

Total heat of 1 ïb of wet steam = Iw+*q*L ;

Volume of 1 lb of wet steam = *qv*+(1*-q)w*

*= qy* very nearly, unless the steam is so wet as to consist mainly of water.

34. *Superheated Steam.—*Steam is superheated when its tempera­ture is raised, in any manner, above the temperature corresponding to saturation at the actual pressure. When considerably super­heated, steam approximates in behaviour to a perfect gas.

The specific heat during superheating is nearly constant at low pressures, its value being approximately 0·48; at high pressures it is higher, especially when the amount of superheating is slight. Callendar’s equations enable it to be calculated for any assigned conditions of temperature and pressure. They also allow a direct determination to be made of the total heat of superheated steam of given temperature and pressure, and from this by comparison with the total heat of saturated steam at the same pressure, the mean specific heat over any stated range of superheating may be found. Calling 1, the total heat of steam in the saturated condition, when the temperature is *t, κ* the mean specific heat in superheating at constant pressure to a higher temperature *t'* and I' the total heat in the superheated state, we have

I' =1, +κ(*t*'-*t*).

The following are values of κ:—

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Temperature of Superheat *t'* in °C. | Temperature of Saturation *t* in °C. | | | | |
| 80° | 120° | 160° | 180° | 200° |
| 100°  150°  200° | 0∙49  0∙49  0·49 | 0∙51  0∙51 | 0∙54 | 0∙57 |  |
| 250° | 0∙48 | 0∙50 | 0∙53 | 0∙56 | 0∙59 |
| 300° | 0∙48 | 0∙50 | 0∙52 | 0∙54 | 0∙57 |
| 350° | 0∙48 | 0∙49 | 0∙51 | 0∙53 | 0∙56 |
| 400 | 0∙48 | 0∙49 | 0∙51 | 0∙52 | 0∙55 |
| 450° | 0∙48 | 0∙49 | 0∙51 | 0∙52 | 0∙54 |

35. *Isothermal Expansion of Steam.—*The expansion of volume which occurs during the conversion of water into steam under constant pressure 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.

36. *Adiabatic Expansion of Steam.—*If steam initially dry be allowed to expand adiabatically (namely, without taking in or giving out any heat) it becomes wet. 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. Before expansion let the initial dryness of the steam be *q1* and its absolute temperature *τ.* Then, if it expand adiabatically until its temperature falls to τ, its dryness after expansion may be shown to be

τ /(7iLi . 1 τ1∖

9=l(-+loge7Λ

L1 and L are the latent heats (in thermal units) of I ïb of steam before and after expansion respectively. When the steam is dry to begin with, *q1* = 1.

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.

37. *Ideal Action of Heat Engine.—*According to the principles of thermodynamics (*q*.*v*.), the action of a heat engine depends on its receiving heat at a temperature higher than that at which it is capable of rejecting heat to surrounding objects. The working substance in the engine must necessarily pass from an upper tem­perature, at which it takes in heat, to a lower temperature, at which it rejects heat, the difference between the heat taken in and the heat rejected being the thermal equivalent of the work done. It may readily be shown that when the conditions are such as to make this difference as great as possible—in other words, to make the efficiency reach its ideal limit—the ratio of the heat taken in to the heat rejected depends only on the temperature at which reception and rejection of heat occur. Calling *τ*1 and *τ*2 the absolute temperatures at which heat is taken in and rejected respectively, and Q1 and Q2 the quantities of heat taken in and rejected, the limit of efficiency is reached when Q1/Q2 = τ1/τ2. The efficiency then has the value (Q1-Q2)/Q1 = (τ1-τ2)/τ1 and W, the work done, is Q1(τ1-τ2)/τ1.

In the ideal engine imagined by Carnot the action is of this simple character. the working substance is brought by adiabatic com­pression from the lower to the upper extreme of temperature. It then takes in heat, without changing in temperature. Next, it expands adiabatically until its temperature falls to the lower extreme and finally at that temperature it rejects enough heat to restore it to its initial state, thereby completing a cycle of operations.

38.. *Carnot's Cycle with Steam for Working Substance.—*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 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. Then we can perform as follows the ideal reversible cycle of operations first described by Carnot, which gives the highest possible efficiency attainable in any heat engine. 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. 9.

2. Remove A and apply

B. Allow the expansion to continue adiabatically *(bc)* with falling pressure, until the temperature falls to τ2. The pressure will then be *p2*, namely, the pressure given in the table corresponding 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" or diagram exhibiting the relation of pressure to volume for such a cycle is given in fig. 9. Since the process is reversible, and since heat is taken in only at *τ1* and rejected only at τ2, the ideal conditions for perfect efficiency are satisfied, and accordingly the efficiency is (τ1-τ2)/τ1. The heat taken in per lb of the fluid is Li, and the work done is Lι(τ1-τ2)/τ1, a result which may be used to check the calculation of the diagram.

39. *Efficiency of a Perfect Steam Engine: Limits of Temperature.—* 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 a practical limit is set by the mechanical difficulties, with regard to strength and. to lubrication, which attend the use of high-pressure steam. In engines of ordinary construction the pressure is rarely so much as 250 lb per sq. in.