It must not be supposed that the efficiency (τ1-τ2)/τ1 is actually attained, or is even attainable. Many causes conspire to prevent steam engines from being thermodynamically perfect, and some of the causes of imperfection cannot be removed.

40. *Engine with Separate Organs.—*In the ideal engine represented in fig. 10 the functions of boiler, cylinder and condenser are com­bined in a single vessel; but, provided the working substance passes through the same cycle of operations, it is indifferent whether these are performed in several vessels or in one. To approach a little more closely the conditions that hold in practice, we may think of

the engine as consisting of a boiler A (fig. 10) kept at τ1, a non-conducting cylinder and piston B, a surface con­denser C kept at τ2, and a feed-pump D which restores the condensed water to the boiler. When the several organs of the engine are separated in this way we can still carry out the first three stages of the cyclic process described in § 38. The first stage of that cycle corresponds to the *admission* of steam from the boiler into the cylinder. Then the point known as the point of *cut-off* is reached, at which admission ceases, and the steam already in the cylinder is allowed to expand, exerting a diminishing pres­sure on the piston. This is the second stage, or the stage of *expansion.* The process of expansion may be carried on until the pressure falls to that of the condenser, in which case the expansion is said to be complete. At the end of the expansion *release* takes place, that is to say, communication is opened with the con­denser. Then the return stroke begins, and a period termed the *■exhaust* occurs, that is to say, steam passes out of the cylinder, into the condenser, where it is condensed at the pressure in the condenser, which is felt as a *back pressure* opposing the return of the piston. So far, all has been essentially reversible and identical with the corresponding parts of Carnot’s cycle.

But we cannot complete the cycle as Carnot’s cycle was completed. The existence of a separate condenser makes the fourth stage, that of adiabatic compression, impracticable, and the best we can do is to continue the exhaust until condensation is complete, and then return the condensed water to the boiler.

41. *Rankine Cycle.—*It follows that the ideal cycle of Carnot is not an appropriate standard with which to compare the action of a real steam engine. Instead of it we have, in the engine with separated organs, a cycle which is commonly called the Rankine cycle, which differs from the Carnot cycle only in this, that the stage of adiabatic compression, is wanting and its place is taken by a direct return of the condensed water to the boiler, a process which makes the water receive heat at various temperatures, ranging from the temperature of the condenser up to that of the boiler. The chief part of the heat which the working substance receives is still taken in at the upper limit of temperature, during the process of changing from water to steam. But a small part is taken in at lower tempera­tures, namely, in the heating of the feed water in its transfer to the boiler. Any heat so taken in has less availability for conversion into work than if it were taken in at the top of the range, and conse­quently the ideal efficiency of the cycle falls somewhat short of this ideal reached in the cycle of Carnot.

But the principle still applies that with respect to each portion of the heat that is taken jn, the fraction convertible into work under ideally favourable conditions is measured by (τ-τ2)/τ, where τ is the absolute temperature at which that portion of heat is received, and τ2 is the temperature at which heat is rejected. Accordingly, we may investigate as follows the ideal performance of an engine following the Rankine cycle. Let δQ represent that portion of the whole heat which is taken in at any temperature τ. Then the greatest amount of work obtainable from that portion of heat is δQ(τ-τ2)/τ, and the whole amount of work ideally obtainable in the complete process is found by calculating ∑δQ(τ-τ2)/τ where the summation includes all the heat that is taken in. In a steam engine using saturated steam the principal item in this sum is the latent heat L1, which is taken in at constant temperature τ1, during the change of state from water to steam. But there is, in addition, the heat taken in’by the feed-water before it reaches the temperature at which steam is formed, and this may be represented as the sum of a scries of elements σδτ taken in at varying temperatures τ, where σ is the specific heat of water. Thus if W represents the thermal equivalent of the work theoretically obtainable per lb of steam, under ideally favourable conditions,

w sgfr(τ~τ⅞) + L1(ti-t2)

T T1

The experiments of Regnault show that σ, within the limits of temperature that obtain in boilers, is a nearly constant quantity, and no serious error will be introduced in this integration by treating it as a constant, with a value equal to the mean value, as determined by Regnault, between the limits of τ1 and τ2. On this basis

λV=σ(τι-*τ^)-στ2* loge—÷-i^1 "~τ2)∙

τ2 T1

It is usual to take σ as practically equal to 1, which makes W=(τ1-τ2) ÷”) —τ2logJ-∙

This expresses the greatest amount of work which each pound of steam can yield when the temperature τ1 at which it reaches the engine and the temperature τ2 at which it leaves the engine are assigned. It consequently serves as a standard with which the actual per­formance may usefully be compared. The actual yield per lb of steam is always considerably less, chiefly because the ideal condition of adiabatic expansion from the higher to the lower extreme of temperature is never satisfied.

A more simple expression for the work theoretically obtainable per lb of steam when expanded adiabatically under the conditions of the Rankine. cycle, is

I1-I2,

where I1 is the total heat of the working substance in the initial state, before the adiabatic expansion, and I2 is its total heat after that expansion. For it may readily be proved that, in an adiabatic process,

I>-ls=j∫Jt⅜,

and this integral is the area of the indicator diagram when the substance is taken in at *p1* expanded to *p2* and discharged at *p2.*

This expression applies whether the steam is initially superheated or not. I2 will in general be the total heat of a wet mixture, and to calculate it we must know the condition as to wetness which results from the expansion. This is most easily found, especially when there has been initial superheat, by making use of the entropy-temperature diagram to be presently described, or by other graphic methods, for an account of which the reader should refer to the paper by Mollier already cited, or to J. A. Ewing’s *The Steam Engine and other Heat Engines* (3rd ed.).

*42. Entropy.—*The study of steam-engine problems is greatly assisted by introducing the idea of entropy and making use of dia­grams in which the two co-ordinates arc entropy and temperature. Entropy is a condition of the working substance defined by the statement that when any quantity of heat δQ is received by, or generated in, or rejected by the substance, when its absolute tem­perature is τ, the substance gains or loses entropy by the amount δQ/τ. Thus ΣδQ/τ measures the whole change of entropy in a process which involves the taking in or rejection of heat at more than one temperature. We shall denote entropy by *φ,* and consider it as reckoned per unit of mass of the substance. Since by definition of entropy δ*φ*=δQ/τ, τδ*φ*=δQ, and hence if a curve be drawn with τ and *φ* for ordinates to exhibit the action of a working substance, the area under the curve, or *∫τdφ* being equal to ΣδQ, measures the heat which the substance has received or rejected during the operation which the curve represents.

In a reversible cycle of operations Carnot’s principle shows that ΣδQ/τ=0, and it is obvious in such a case that the entropy returns at the end of the cycle to its primitive value. The same result may be extended to a cycle which includes any non-reversible step, by taking account of the heat generated within the substance by such a step, as if it were heat communicated from outside, in the reckoning of entropy. Thus, for example, if at one stage in the cycle the sub­stance passes through a throttle-valve, which lowers its pressure without letting it do work, the action is equivalent in effect to an adiabatic expansion, together with the communication to the sub­stance, as heat, of the work which is lost in consequence of the irreversible expansion through the throttle-valve taking the place of adiabatic expansion against a piston. If this heat be included in the reckoning ΣδQ/τ = o for the complete cycle.

The entropy-temperature diagram for any complete cyclic process is a closed curve, and the area it encloses, being the excess of the heat received over the heat rejected, measures the work done. the entropy-temperature diagram shares this useful characteristic with the pressure-volume diagram, and in addition it shows directly the heat received and the heat rejected by the areas under the forward and backward limbs of the curve. To draw the entropy-tempera­ture diagram for the ideal steam engine (namely, the engine following the Rankine cycle), we have to reckon first the entropy which water acquires in being heated, and next the entropy L1/τ1 which is acquired when the conversion into steam has taken place. Reckoning from any standard temperature τ0, in the heating of the feed-water up to any temperature τ, the entropy acquired is

*Γτ cdτ*

*^tc J* τ0 τ

and taking σ as sensibly constant,

*φw= φ* (logετ — logετ0).

During evaporation at τ1 a quantity of heat L1 is taken in at temperature τ1, and hence the entropy of the steam

*φ2 - φw* + L1/τ1 = σ logετ1-logετ0) +L1/τ1.