105. *Steam Turbines.—*Steam turbines are distinguished from all other types of steam engine by the fact that their action involves a double transformation of energy. The heat energy present in the steam is first employed to set the steam itself in motion, giving it kinetic energy, and this in turn is employed to do work on the turbine blades. A brief account of the main principles involved will make the action of the various types of steam turbine more intelligible.

106. *Theory of the Steam-jet.—*Consider an element of steam, of unit mass, acquiring kinetic energy in the expansion of the steam through a nozzle or other channel, from a region of pressure *p1* to a region of lower pressure *p2*. Its volume changes from *v1* to *v1* in the process. The work done upon it by steam from behind is *p1v1*. The work which it does on the steam in front is *p2v2*. The net amount of work done upon it is therefore *p1v1*-*p2v2*. Its velocity changes from V1 to V2; the kinetic energy which it gains is therefore (V22—V12)/2g. The internal energy changes from E1 to E2. Hence by the conservation of energy

(V22 - V12)/2*g*=J(E1 -E2) *+p1v1-p2v2*

which may be written

(V22-V12)/2*g*=J(I1-I2),

where I is the total heat (§ 31), which is equal to E+*pv*/J. It is assumed here that the action is adiabatic in the sense that no heat is received by the steam or given up by it to other bodies as the process goes on.

It is usual to speak of the change of I as the “ heat drop ” which the steam undergoes in acquiring velocity. When the heat drop is known the gain in velocity is readily found, as above. In determin­ing the best drop account must, of course, be taken of the wetness of the steam, or of its superheat if it has any. Thus, for superheated steam I = I2+κ(*t'-t*) where I2 is the total heat of saturated steam at the same pressure and κ(*t'*-*t*) represents the heat taken up in the process of superheating to the actual temperature *t'* from the temperature of saturation *t.* And for wet steam I = Iw+*q*L where Iw is the total heat of water, L the latent heat, and *q* is the dryness fraction.

During this process of expansion, which we assume to be adiabatic, the steam becomes wet, and the value of *q* accordingly falls. As has been shown in § 36, the dryness may be found at any stage in adiabatic expansion from the formula— s=r (⅛ι+log τ) '

*or* it may be determined by measurement from the entropy-temperature diagram. A still more convenient diagram in which the heat drop can be directly measured is one introduced by Mollier, in which the co-ordinates are the entropy and the total heat (see Mollier, *loc. cit.,* or Ewing’s *Steam Engine).*

The pressure-volume diagram gives a very useful alternative means of finding the heat drop or energy available for trans­formation. Consider steam or any other gas supplied at pressure *p1* and expanding to pressure *p*2, at which pressure it is discharged. The work which it does is measured by the area ABCD of the pressure­volume diagram (fig. 52), namely,

fydp∙

If this work is wholly done upon this steam in giving it velocity, the kinetic energy acquired is equal to it, that is w-vΛ/2g=y^.

We have already seen (§ 41) that in adiabatic expansion this integral measures the heat drop, being equal to I1-I2.

If the mode of expansion is such as to make *pvn* = constant, *n* being any index, then *ffydP = ~*

=7⅛[(i-dVi)m1,

where D is the ratio in which the pressure falls, namely *p2/p1:*

Now the adiabatic expansion of steam, starting from an initially dry saturated state, is very approximately represented by the formula *pv1·135* = constant. Hence the area of the pressure-volume diagram, which under these conditions measures the work theoretically obtainable, is equal to 8∙41 (1 — D0·119)*p1v1*, a quantity which will be found on evaluation to agree closely with the value of I1-I2.

107. *Form of the Jet in Adiabatic Expansion.—*As expansion pro­ceeds the volume of the steam, per pound, at any stage is found by multiplying the volume of 1 lb of saturated steam, at the pressure then reached, by the dryness fraction *q.* On comparing the velocity acquired at any intermediate stage of expansion—as calculated from the heat drop down to that stage—with the increase in volume, it will be found that in the earliest stages the gain in velocity is relatively great, but as expansion proceeds the increase in volume outstrips the increase in velocity. Hence the proper form for a nozzle to give adiabatic expansion is one in which the area of section at first contracts and afterwards becomes enlarged. The area of section to be provided for the discharge is found by dividing the volume *v* at each stage of the velocity V acquired up to that stage, and the ratio *v/*V at first diminishes and afterwards increases as the expansion proceeds. Take, for instance, as a numerical example, a case in which dry saturated steam is admitted to a nozzle at an absolute pressure of 213 lb per sq. in., and expands adiabatically, giving itself velocity, until the pressure falls to 1∙7 per sq. in. It will be found on working out numerical values that until the pressure falls to about 123 lb per sq. in. the steam is gaining velocity so rapidly that though its volume is expanding the stream-lines are convergent. Below that pressure, however, the augmentation of volume is rela­tively so great that a larger and larger area of section has to be provided for the flow. Thus, when the pressure is 123 lb per sq. in. the dryness *q* is 0∙96, the volume per pound is 3∙51 cub. ft., the heat drop is 251/4 thermal units, giving a velocity of 1510 ft. per second. Consequently, the area of the stream is 0∙00233 sq. ft. per pound of flow, and this is. the minimum value. When the pressure falls to 1∙7 lb per sq. in. the dryness *q* is 0∙784, the volume per pound is 157∙8 cub. ft., the heat drop is 175∙7 thermal units, giving a velocity of 3980 ft. per second, and consequently the area of the stream is 0∙0396 sq. ft. per pound of flow.

108. *De Laval's Divergent Nozzle.—*It is on this basis that De Laval’s divergent nozzle is designed. The "throat ” or smallest section is approached by a more or less rounded entrance, allowing the stream-lines to converge, and from the throat outwards the nozzle expands in any gradual manner, generally in fact as a simple cone (fig. 53). In the example just given the final area of section would be seventeen times that of the throat to provide for adiabatic expansion down to a pressure of 1∙7 lb per sq. in. With any final area less than this the pressure at exit would be higher than 1∙7 lb; it would in fact adjust itself to give a value of *v*/V corresponding to the area, and the remainder of the pressure drop would be wasted. For expansion to atmospheric pressure (14∙7 per sq. in.) the area at exit would be 3·14 times that of the throat.

The equation of velocity

V2 *n /.* tλw~i∖ X \_

2g n-ι∖1 » / 1

may be applied to calculate generally the discharge per square foot of stream section, and hence to find at what point in the fall of pressure this discharge becomes a maximum—in other words, to determine the pressure at the throat. Since *pυn = p1v1n*

1\_

τ = vχ/D" where *D = p/pι.*

The discharge per square foot when the volume is *v* is Q÷≠-√is-S(^7θ4i)!∙

Q will be a maximum when *d*Q/*d*D is zero, which occurs when d- (⅛)\*'

This result is general for any gas. With saturated steam, *n* being 1∙135, Q is a maximum when D = 0∙577, that is to say, the pressure at the throat is 577% of the initial pressure, a result which agrees with the figures quoted above for a particular case.

The maximum value of Q, namely the discharge in pounds per square foot at the throat, is

3∙6√ (*p*1/*v*1),

and the velocity there is 5∙85√ (*p*1/*v*1)*.* In these expressions *p1* is the initial pressure in pounds per square foot.

109. From these considerations it follows that, provided the final pressure is less than 0∙577 times the initial pressure, the total dis­charge depends simply on the least area of section of the nozzle and on the initial pressure, and is independent of the final pressure. By continuing the expansion in a divergent nozzle, after the throat is passed, the amount of discharge is not increased, but the steam is caused to acquire a greater velocity of exit, namely the velocity corresponding to the augmented pressure range.

110. When the pressure drop is small *(p2* greater than 0∙577 *p1)* the full velocity due to the drop is obtained without the use of a