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THE PROCESSES OF STEAM IN ITS DEVELOPMENT OF POWER BY MEANS OF A STEAM ENGINE.

BY CHIEF ENGINEER ISHERWOOD, U.S.N.

[*A Lecture delivered before the Sibley College of the Cornell University, Ithaca, N. Y., December 13, 1889.*]

[*Concluded from vol. c, p. 317.*]

The steam jacket is a contrivance for maintaining the metal of the cylinder at the temperature of the entering steam, and thus preventing the liquefaction due to the heat interaction of the metal; the liquefactions due to the other specified causes are not however affected by the jacket; it does not touch them. As the result of the prevention of the liquefaction due to the heat interaction of the metal, there is no water of liquefaction to be revaporized during the expansion portion of the stroke of the piston, therefore the pressure shown on the indicator diagram by the expanding steam would be less than in the case of non-jacketed cylinders, were it not for the increase of pressure caused by the higher temperature of the jacket. As a practical fact, the pressure of the expanding steam in both jacketed and non-jacketed cylinders closely follows the Mariotte law, the increased pressure due to the jacket temperature when the jacket is used, being about equalled by the increased

pressure due to the vaporization of water of liquefaction when the jacket is not used. The heat imparted to the metal of the cylinder by the steam jacket is entirely utilized in the production of power by increasing the pressure of the expanding steam—superheating it—the temperature of that steam being maintained constant throughout its expansion and equal to that of the jacket steam, so that the pressures of the expanding steam are in exact accordance with the Mariotte law. The water of liquefaction drawn from the steam jacket represents the heat that has been imparted to the expanding steam and wholly used by the latter in the production of increased pressure upon the piston. The net result of employing the steam jacket is the prevention of all the liquefaction caused by the heat interaction of the metal and the expanding steam, without expenditure of heat therefor. The steam jacket places the cylinder in nearly the economic position it would have, were it made of some adiabatic material, some material impervious to heat. If the cylinder metal were absolutely impervious to heat, the pressure of the expanding steam in a steam jacketed cylinder would be as much less than the pressure, according to the Mariotte law, as was due to the loss of heat transmuted into the power developed by that steam. James Watt considered the steam jacket to be his greatest invention, and there can be no doubt, from the point of view of intellectuality and complete originality, of the accuracy of that opinion, although he did not know either the rationale or the limits of its efficiency. It was a real inspiration of genius. The efficiency of the steam jacket is mainly connected with the expansive use of steam, and is in proportion to the measure of expansion with which the steam is used. When the steam is used without any, or with but little expansion, the advantage of the jacket is nothing or next to nothing, and how Watt, whose practice was restricted to low-pressure steam used with very little expansion, could have formed so high an opinion of its economic value under such limitations, is inconceivable. His estimate of its efficiency was strangely exaggerated, and the reasons he assigned for its

beneficial action were both erroneous and inadequate. After Watt, low pressures and small expansions remaining still the rule, the steam jacket fell into disuse, as its economic results in such cases proved too small to justify the construction expense and supervision trouble connected with its employment. However, since high pressures and large expansions have become the general practice, the steam jacket has been reintroduced, and the economic gain obtained by it under these conditions fully sustains the exalted opinion which its inventor always had of it.

Beside the steam jacket as a furnisher of heat externally to the metal of the cylinder, there are three other sources, namely, the heat carried by conduction from the valve chest of the cylinder, the heat generated by the friction of the piston, piston rod, and slide valve, and the sensible heat produced by the cushioning of the steam in the cylinder. The first two of these sources of heat are obvious, the last requires explanation.

The cushioning of the back pressure steam is effected by the closing of the exhaust port of the cylinder before the piston reaches the end of its stroke, thus imprisoning whatever back-pressure steam then remains in the cylinder. The piston, continuing to advance, compresses or "cushions" this steam, increasing not only its pressure by the compression, but its sensible heat by the thermal equivalent of the work done by the compression. Now the back-pressure steam thus heated by the work of compression, is in contact at the commencement of the compression with the metal of the cylinder at the temperature of the back pressure just previous to the commencement of the compression. From the moment, therefore, that the cushioning commences, the cooler metal takes up heat from the cushioned steam and liquefies an equivalent portion of it. This continuous compression, generation of sensible heat and abstraction of the same by the metal, continues until the end of the stroke of the piston is reached. The metal thus abstracting a large portion of the heat of compression, has its own temperature correspondingly increased, with the economic result that less of the steam entering from the

boiler on the opening of the steam port is liquefied by that metal. The compressed back-pressure steam having its temperature at the commencement of the compression the same as that of the metal with which it is in contact, increases very slowly in pressure owing to this abstraction of heat, and a great deal of compression is required to produce much of a "cushion" curve on the indicator diagram. The experimental curve varies enormously from the theoretical one. In fact, considerable reduction of space takes place before the curve sensibly commences; the liquefaction by the cool metal being equal to the compression. When the compression has reached a certain degree, and consequent high temperature, the liquefaction of the compressed steam has become so great that there is no further increase of pressure, and the curve rather abruptly changes to nearly a horizontal line, showing that the abstraction of heat from the steam by the metal has become equal to the heat put into the steam by the compression. This appearance can always be observed on the diagram if the steam eccentric be set "late" so as not to give "lead" to the entering steam, but, on the contrary, opening the steam port a little after the piston has commenced its return stroke. When there is steam "lead" this appearance is masked, but it is always there, and the cause of it renders any cushioning up to the pressure of the entering steam very difficult to obtain; hence, notwithstanding the greatest practicable amount of cushioning, some steam lead is always found necessary to fill the waste spaces at the end of the cylinder with steam of boiler pressure at the commencement of the stroke of the piston. Were it not for the air mingled with the back-pressure steam, the "cushion" curve would be much less than it appears on the indicator diagram.

Evidently, all the heat of compression put into the back pressure by the cushioning, that was abstracted by the cooler metal of the cylinder upon which the cushioning was effected, went to increase the temperature of that metal, and to thereby reduce its liquefying power upon the steam entering from the boiler on the opening of the steam valve.

The temperature thus imparted was a clear thermal gain; the bulk of pressure cushioned reproducing the power expended in the cushioning. The entire indicator diagram, measured down to the zero line of pressure, represents the entire dynamic effect of the steam per stroke of piston; the weight of steam expended to produce this diagram is also evidently the weight entering the cylinder per stroke of piston from the boiler plus the weight of the cushioned steam; and, just as evidently, the weight of steam entering the cylinder from the boiler per stroke of piston produces the whole of the diagram, excepting the cushioned portion, that is, the portion between the zero line and the back pressure line during the cushioning portion of the stroke of the piston, so that, consequently, this portion must be produced by exactly the weight of steam cushioned. Hence, there is neither loss nor gain dynamically by cushioning; but there is in all cases the thermal gain described.

As an illustration of the effect exerted upon the cushioning by the temperature of the metal of the cylinder, may be stated that the cushion curves formed with the same mechanism, the same back pressure, and the same point of closing the exhaust port, are very different, according as the steam entering the cylinder is of higher or lower pressure. As the pressure of the entering steam is lowered—its temperature lowering with its pressure—the temperature of the metal of the entire cylinder is lowered, the same measure of expansion being used, so that when the cushioning commences, the back-pressure steam is compressed upon metal of lower temperature than would have been the case had the entering steam been of higher pressure and temperature. The result appears on the indicator diagram in the smaller curves of the cushioning, these curves becoming less and less marked as the pressure of the entering steam is more and more lowered. The curves, as the entering steam is lowered in pressure, seem to commence later and later and to rise to a less and less height, the liquefaction during the compression becoming greater and greater in proportion to the less and less temperature of the metal of the cylinder.

There is an absolute practical necessity in order to

avoid shock from concussion, to bring the piston and its attached parts to rest slowly as the end of the stroke is approached, and to have the waste spaces at the end of the cylinder filled with steam of the boiler pressure ready for the return stroke, and to have such an opening of the steam port as will maintain this pressure with the moving piston up to the point of cutting off the steam. All this is accomplished by giving the steam valve "lead;" but the method entails a serious economic loss. The steam admitted during the lead simply adds to the back pressure against the piston, and nothing is recovered from it; the additional back pressure is a total dynamical loss. Hence, these waste spaces should be filled as much as possible by cushioned back pressure, and the "lead" reduced to the minimum possible. In this way, if the setting of the valve has been judiciously done, a further gain can be indirectly made by cushioning.

There has been shown in the case of a non-steam-jacketed cylinder, that during the portion of the stroke of its piston between the commencement of the stroke and the point of cutting off the steam, the cylinder acts as a surface condenser, liquefying sufficient of the entering steam to furnish the heat needed to raise the temperature of the metal of the cylinder from the back pressure temperature to the temperature of the entering steam. But from the point of cutting off to the end of the stroke of the piston, and during the whole of the exhaust stroke, the cylinder acts as a boiler, boiling off and revaporizing the water of liquefaction deposited on the metallic surfaces during the portion of the stroke between its commencement and the closing of the cut-off valve. Now, there can be known by calculation whether all of this water of liquefaction is revaporized during the expansion portion of the stroke of the piston, or whether some of it is revaporized during the exhaust stroke while the exhaust port is open. If it is wholly vaporized during the expansion portion of the stroke, leaving nothing to be boiled off during the exhaust stroke, a very valuable and interesting result follows, namely, the determination experimentally by weight of nearly all the steam liquefied by molecular action

as distinct from the weight of steam liquefied by metallic interaction, both being experimentally determinable.

There has been shown that the liquefaction of steam in a cylinder doing work is of two entirely different kinds, due to distinctly different causes: one kind is the result of the heat interaction of the metal of the cylinder with the steam, whereby the varying temperature of the metal with which the steam is in contact, alternately liquefies and re-evaporates the steam. This is a surface liquefaction and reevaporation, the action being on the boundaries of the steam as a mass, and not molecularly within the steam. The whole of the water of liquefaction of this kind is present as water in the cylinder at the point of cutting off, and the difference between the weight of steam present as such at this point, calculated from the pressure there, as shown on the indicator diagram, and the weight of feed water pumped into the boiler gives the weight of steam liquefied by this cause.

Now, suppose the entire weight of water of liquefaction present in the cylinder at the point of cutting off, to be vaporized during the expansion portion of the stroke of the piston, then, if there were no liquefaction due purely to the molecular actions of the steam, the weight of steam present as such in the cylinder at the end of the stroke of the piston, calculated from the pressure there, as shown on the indicator diagram, should be the same as the weight of feed water pumped into the boiler. It cannot be more, and, if less, the difference is wholly due to the molecular liquefactions of the expanding steam hereinbefore described from leaving the boiler to arriving at the end of the stroke of the piston. Now, if the aggregate weight of these calculated molecular liquefactions, added to the weight of the steam determined at the end of the stroke of the piston by the indicator, equals the weight of feed water pumped into the boiler during the same time, all the water of liquefaction due to the interaction of the metal of the cylinder, has been vaporized during the expansion portion of the stroke of the piston; but, if the weight thus obtained be less than the weight of water pumped into the boiler, then the difference is the weight of water of liquefaction due to the interaction

of the metal of the cylinder vaporized during the exhaust stroke of the piston.

Up to the present moment, there is universally held in the case of a condensing engine using the steam expansively and having the boiler fed with water from the hot well that when the exhaust steam is liquefied in the condenser by the application of cold condensing or injection water the entire heat present in the steam in the boiler will be recovered in the injection water and in the heat (ascertained by calculation) transmuted into the external work done by the expanding steam. This belief, however, is entirely erroneous; the heat ascertained as above being always greatly less than the heat present in the steam in the boiler. This fact is easily ascertainable experimentally, and is shown by every experiment that has ever been made in which the weight of the injection water, and its initial and final temperatures have been given. In fact, the difference between the quantity of heat present in the steam in the boiler, and the quantity of heat present in the injection water after its liquefaction of the exhaust steam, is exactly the quantity of heat lost as such by being transmuted into the various molecular actions of the steam while passing through the engine from the boiler to the condenser, including the heat transmuted into the external work of the expanding steam. If, now, from this difference there be subtracted the heat transmuted into the external work done by the expanding steam, a quantity easily calculable, the remainder will be the heat transmuted into the other molecular actions of the steam while passing through the engine from the boiler to the condenser. Thus, not only the fact, but the amount of these molecular actions can be shown experimentally, proving beyond the possibility of doubt the accuracy of the provisions herein shown both qualitatively and quantitatively. The quantitative result will not be affected by the loss of heat from the external radiations of the boiler, or the steam pipe, and of the cylinder; but it will be affected and to the amount of the heat thus radiated, by the external radiations from the exhaust pipe, from the condenser, from the air pump, and from the hot well. If these latter, how

ever, are well protected by non-heat conducting material, and they should be during an experiment, the loss of heat from this cause will be insignificant.

The loss of heat by radiation from the external surfaces of the boiler, steam pipe and cylinder, increases the consumption of fuel in the furnace, because the resulting water of liquefaction has to be revaporized, but does not affect either the weight of steam used, as measured by weight of feed water pumped into the boiler, nor the quantity of heat present in it.

The final generalizations are as follows :

The entire liquefactions of steam in the cylinder of a working steam engine are due to the transmutation of part of the *vis viva* of the steam molecules into either internal or external work—into either mass *vis viva* or into increased molecular *vis viva* of a smaller number of molecules.

This transmutation is only possible when the steam is used expansively; consequently, when it is used without expansion, there is no liquefaction, or "cylinder condensation" properly so-called. The heat above the heat in the feed water, found in the water of liquefaction deposited on the interior surfaces of a non-steam-jacketed cylinder is exactly equal to the heat absorbed from the metal of the cylinder by the expanding steam from the point of cutting off to the delivering of the steam into the condenser. All other liquefactions from the boiler to the condenser are due to the molecular work of the steam undergoing expansion from the various causes in action, and are not affected by the metal of the cylinder.

The water of liquefaction deposited on the interior surfaces of the cylinder is only made possible by the variations in temperature of the metal of the cylinder, caused by the similar variations in the temperature of the expanding steam, consequently when the variation of the temperature of the metal of the cylinder is rendered impossible by the employment of a steam jacket capable of maintaining the metal of the cylinder at the constant temperature of the boiler steam, there is no deposition of water of liquefaction on the surfaces of the cylinder, and the losses of heat are

confined to what belong to the molecular actions of the steam alone.

The losses by the interaction, of the metal of the cylinder with the heat of the steam, are preventable by the employment of a steam jacket, but not the losses by the molecular action of the steam.

The entire losses of heat, to which the so-called "cylinder condensation" is due, are caused by the use of the steam expansively, and are greater with greater measures of expansion.

As regards the measure of expansion with which steam can be most economically used, a limit is, therefore, soon reached in practice, depending on the boiler pressure, the back pressure against the piston, the pressure required to work the engine *per se*, and on the use or non-use of the steam jacket, when the losses caused by the expansion neutralize the gain due to the expansion, the practical limit of expansion is attained, and, if it be carried further, loss will be experienced.

Thus far, no reference has been made to the obvious loss of heat from a cylinder by external radiation, in order not to complicate the essentials of the problem by mingling non-essentials with them. The loss by radiation can be reduced by suitable coverings of non-heat conducting materials until it becomes nearly insensible, and such should always be the case with practical steam engines.

Whatever liquefaction of steam due to external radiation there may be in a cylinder, will take place during the entire stroke of its piston, but, of course, will be greater at those parts of the stroke where the pressure is greater. This water of liquefaction will be revaporized in whole or in part under the lessening pressures in the cylinder due to the expansion of the steam, and the resulting steam will be utilized as pressure on the piston, but any part of this water that may be vaporized during the exhaust stroke will pass to the condenser as steam without doing work on the piston. The heat of vaporization of this latter part will be wholly lost.

The cooling of the metal of the cylinder by this abstrac-

tion of heat, caused by the revaporization of the water of liquefaction due to the external radiation, has to be restored by heat taken from the steam entering from the boiler, consequently there will be a liquefaction additional to those already described, in the cylinder between the commencement of the stroke of the piston and the point of cutting off the steam, equivalent to the heat lost by radiation.

The greater the loss of heat by steam liquefaction in the cylinder, the greater, proportionally to power developed by the engine, will be the work done by the air pump in discharging the greater quantity of mingled injection water and water of steam liquefaction, and of air and vapor, because the greater will be the weight of steam used per unit of time per unit of power. Also the greater will be the work done by the feed pump.

In order that steam may flow from one vessel to another, as from a boiler to a cylinder, or from a cylinder to a condenser, the pressure in the receiving vessel must be less than the pressure in the delivering vessel, and, as a consequence, the steam is expanded during the operation by the difference due to the two pressures. Now this expansion commences at the orifice by which the steam leaves the delivering vessel, and it continues to the receiving vessel. The steam is thus really transported by its own expansion, and is not pushed forward by the pressure in the delivering vessel as a piston is pushed forward by water pressure in a hydraulic cylinder. The delivering vessel maintains a supply of steam of the pressure in it at the orifice and that pressure acts as a fulcrum or surface of resistance for the expansion. There thus results that the work of transportation of the steam from the boiler to the cylinder, and from the cylinder to the condenser is done at the expense of the heat in the expanding steam which suffers, consequently, a proportional molecular liquefaction due, first, to the work of expansion and, second, to the increased latent heat of the steam after its expansion. The pressures of the steam thus expanding form a curve similar to the curve of the expanding steam on an indicator diagram. For these reasons the economy of a steam engine is considerably affected by the

length of the steam pipe—supposing it to have no external radiation—and by the length of the exhaust pipe. The longer the steam pipe, the greater will be the difference between the pressure in the boiler and in the cylinder before the point of cutting off, and the greater this difference the greater will be the liquefaction in the cylinder. The longer the exhaust pipe the greater will be the difference between the pressure in the condenser and the back pressure against the piston, and the greater will be the liquefaction in the cylinder. Also the higher the steam pressure used in the boiler, the greater will be the difference between that pressure and the pressure in the cylinder previous to the point of cutting off the steam. And the greater the pressure of the steam in the cylinder at the end of the stroke of its piston, the greater will be the difference between the back pressure against the piston and the pressure in the condenser.

The throttled use of steam does not affect its economic result in any sensible degree. Throttling is an imperfect method of using the steam expansively. It is attended by some gain due to the expansion, and some gain due to the difference between the temperatures before and after the throttling. It is attended by the liquefaction losses due to the expansion *per se*, and *due to the transportation of the steam from the boiler to the cylinder under the lessened pressure of the throttling*, and due to the external work of the expansion. The gains are so nearly equivalent to the losses that the net result is sensibly nothing.

There now remains to make an application of the principles hereinbefore enumerated and demonstrated, to the case of a non-jacketed steam cylinder of a simple engine using saturated steam expansively :

(A) As regards the transportation of the steam from the boiler to the cylinder; let P be the steam pressure in the boiler in pounds per square inch above zero, and P' the steam pressure in the cylinder at the point of cutting off, in pounds per square inch above zero. Let V be the number of cubic feet of steam of the pressure P drawn from the boiler per hour, and V' the number of cubic feet of steam of the same

aggregate weight in the cylinder at the pressure P' ; then $V' - V$ will be the difference of the two bulks of steam in cubic feet. This difference has been forced into the cylinder against the pressure P' , and there has consequently been done per hour the number of foot-pounds of work represented by $V' - V \times P' \times 144$, the 144 being the number of square inches in a square foot. The heat or *vis viva* transmuted into this work has been furnished by the expanding steam itself, which has undergone a corresponding liquefaction. The quantity of heat so transmuted is given in Fahrenheit units, by dividing the number of foot-pounds of work by the mechanical equivalent ($789\frac{1}{4}$ foot-pounds) of one Fahrenheit unit of heat: hence,

$$\frac{V' - V \times P' \times 144}{789\frac{1}{4}}$$

equals the number of Fahrenheit units of heat transmuted into the work of transporting the steam from the boiler to the cylinder. Dividing this latter quantity by the latent heat of the mean pressure due to the pressures P and P' , there will be obtained the number of pounds weight of steam liquefied to furnish the above number of Fahrenheit units of heat.

(B) Now there was a further liquefaction of this steam due to its increased latent heat after expansion. Let L be the latent heat at the pressure P , and L' the latent heat at the pressure P' . Then

$$\frac{L' - L}{L}$$

will give the fraction which the difference of the latent heats is of the latent heat at the pressure P . Multiplying the weight of steam in pounds per hour drawn from the boiler by

$$\frac{L' - L}{L},$$

there will be obtained the weight in pounds per hour of steam liquefied in consequence of the increase of its latent heat when expanded from the pressure P to the pressure P' . Multiplying this latter weight by $L' - L$ gives the number

of Fahrenheit units of heat transmuted into the work of expanding the steam *per se*.

(A) + (B) gives the total quantity of heat stricken out of existence as such, by being transmuted into the mass and molecular work of transporting the given weight of steam per hour from the boiler to the cylinder.

(C) After the closing of the cut-off valve, the steam commences to expand, doing external work, and continues the expansion until the piston has reached the end of its stroke. The mean pressure of this expansion must be obtained from the indicator diagram, as it cannot be calculated. Now this mean pressure in pounds per square inch above zero, multiplied by the number of cubic feet of space displaced per hour by the piston corresponding to the expansion portion of its stroke, and by 144, will give the number of foot-pounds of work done per hour by the expansion of the steam. The heat or *vis viva* transmuted into this work has been furnished by the expanding steam itself, which has undergone a corresponding liquefaction. The quantity of heat so transmuted is given in Fahrenheit units by dividing the number of foot-pounds of work by the mechanical equivalent ($789\frac{1}{4}$ foot-pounds) of one Fahrenheit unit of heat. Dividing the number of Fahrenheit units of heat so obtained per hour by the latent heat of the mean pressure of the expanding steam, gives the number of pounds weight of steam liquefied per hour to furnish the above number of Fahrenheit units of heat.

With the immediately above calculation the weight of steam liquefied in the cylinder previous to the commencement of the expansion has no connection. The indicator diagram shows that a certain number of foot-pounds of work has actually been done by the steam during the expansion, and from that amount of work the number of Fahrenheit units of heat transmuted are calculated.

(D) Now there was a further liquefaction of the expanding steam, additional to that due to the work of expansion performed (C), caused by its increasing latent heat as its expansion proceeded. To calculate this quantity, there must be known the weight as well as the pressure of the expand-

ing steam, and this weight cannot be precisely known. At the commencement of the expansion, the weight of steam per hour, as such, in the cylinder is the difference between the weight drawn from the boiler per hour, and the weight liquefied in the cylinder between the commencement of the stroke of the piston and the point of cutting off the steam, but during the expansion a considerable portion of this water is revaporized, the revaporization being gradually effected from the beginning to the end of the expansion, and, as a result, the weight of steam is different at every point in the expansion curve. To approximately calculate the liquefaction of the expanding steam due to the increase in its latent heat, the expansion curve on the indicator diagram must be divided into a number of equal parts—the greater the number the more accurate the result—and the weight of steam, as such, in the cylinder must be calculated from the pressure on the curve at each end of each of these parts, and the mean taken for each part as the weight of steam present for that part. The latent heats must also be obtained for the pressures at each end of each part. Then, the calculation can be made for each part as previously described in (B). Calling W the weight in pounds of steam present per hour for any one part, and L and L' the latent heats due to the pressures at the beginning and end of this part, then

$$\frac{L' - L}{L} \times W$$

will equal the number of pounds weight of steam liquefied per hour by the expansion *per se*. And this product multiplied by $L' - L$ gives the number of Fahrenheit units of heat transmuted per hour into the work of expanding the steam *per se*. The sum of the quantities obtained in this manner for all of the parts, will approximately equal the heat transmuted per hour into the work of expansion *per se* for the entire expansion.

(C) + (D) gives the total quantity of heat stricken out of existence as such, by being transmuted into the mass and molecular work done by the expanding steam between the

point of cutting off the steam in the cylinder and the end of the stroke of the piston.

(E) When the piston reaches the end of its stroke, the exhaust valve opens and the steam contained in the cylinder is expelled therefrom by its own expansion into the condenser, where it is instantly annihilated, so that no mass work is done by the steam on entering the condenser, the only work done being the molecular work due to the expansion *per se*.

(F) The number of Fahrenheit units of heat transmuted per hour into the molecular work of the expansion *per se* of the exhausting steam will be given by multiplying the weight W in pounds of steam in the cylinder per hour at the end of the stroke of the piston, by

$$\frac{L' - L}{L} \times L' - L$$

(L being the latent heat due to the pressure in pounds per square inch above zero in the cylinder at the end of the stroke of the piston, and L' being the latent heat due to the virtual steam pressure in pounds per square inch above zero in the condenser). The weight of steam liquefied per hour by the expansion *per se*, will be

$$W \times \frac{L' - L}{L}.$$

(G) If the weight of steam in the cylinder per hour at the end of the stroke of the piston, plus the weights liquefied molecularly as calculated in (A), (B), (C), (D), and (F), is the same as the weight of steam drawn from the boiler per hour, the cycle of operations is complete; but should it be less, then there will remain a weight of water of liquefaction in the cylinder at the end of the stroke of the piston equal to the difference between the weights of steam referred to. This water of liquefaction will be revaporized during the exhaust stroke of the piston and the steam thus evaporated will, during its expulsion from the cylinder into the condenser, by its own expansion, do molecular work at the expense of an equivalent quantity of heat.

(H) Calling L the latent heat of steam of the back pressure against the piston, and L' the latent heat of steam of the condenser pressure, and W the weight in pounds of the water of liquefaction revaporized in the cylinder during the exhaust stroke of the piston, the number of Fahrenheit units of heat transmuted into the work of the expansion of the steam *per se*, will be

$$W \times L' - L \times L' - L.$$

(I) There will additionally be abstracted from the metal of the cylinder the number of Fahrenheit units of heat required for the vaporization of the weight W of water of liquefaction under the back pressure against the piston. This will be given by multiplying W in pounds by the latent heat normal to the back pressure against the piston.

The back pressure against the piston is always greater than the pressure in the condenser, in order that there may be a flow from the former into the latter. The piston does not push out the back pressure; it increases that pressure in the cylinder so that the outflow can be produced by the expansion of the back pressure steam. The difference between the cylinder back pressure and the condenser pressure, supposing the latter constant, is regulated by the relative area of the exhaust port, reciprocating speed of piston, length and sinuosity of conduit from the exhaust port to the condenser, and pressure of the steam in the cylinder at the end of the stroke of the piston. The greater the last three and the smaller the first, the greater will be the difference between the mean back pressure against the piston, exclusive of the "cushion" pressure, and the pressure in the condenser.

The greater the pressure of the steam at the end of the stroke of the piston, the greater will be the back pressure against the piston. Now, inasmuch as with a given initial pressure, the steam will have lower and lower pressures at the end of the stroke of the piston as the measure of expansion, with which it is used, is more and more increased, and as the less pressure at the end of the stroke of the piston is

attended by a less back pressure against the piston, there can thus be realized from expansion a greater economic gain in the performance of external work than is strictly due to it. The true method of ascertaining the economy belonging to different measures of expansion, is to use the powers calculated for the mean cylinder pressures measured down to the zero line, and not the powers calculated for the indicator or net pressures.

The number of units of heat in the water of liquefaction in the cylinder at the point of cutting off the steam will be the weight in pounds of that water multiplied by the latent heat of the steam of the pressure at that point.

The number of units of heat in the injection water above the initial heat in that water, will be, after it has condensed the exhaust steam to the temperature of the feed water, the heat in the boiler steam above the heat in the feed water, minus the sum of the units of heat determined in (A), (B), (C), (D), (F), and (H); these units of heat having been absolutely stricken out of existence, as such, during the processes of the steam from the boiler to the condenser.

The effect of increased reciprocating speed of piston, all other things remaining constant, is to both increase the power developed by the engine and to decrease the liquefaction of steam per stroke of piston, due to the interaction of the metal of the cylinder; the liquefactions due to all other causes remain per stroke of piston exactly the same. The liquefaction due to the interaction of the metal of the cylinder is related to *time*—the heat has to be received and delivered by the metal—the less the time the less in some ratio is this liquefaction, consequently increasing the number of strokes made by the piston per minute decreases proportionally the time of contact and correspondingly lessens this liquefaction per stroke. The liquefactions due to other causes are not affected by time.

If the steam pressure be increased, all other things remaining constant, the power developed by the engine will be increased, and the liquefaction due to the interaction of the metal of the cylinder will be decreased proportionally to power developed, because the steam temperatures in-

crease in a far less ratio than the steam pressures, and the liquefaction due to the interaction of the metal of the cylinder is wholly caused by difference of steam temperature on that metal. The liquefactions due to other causes increase in proportion to the increased pressure and, therefore, remain unaffected proportionally to power developed. The foregoing is one of the causes—and not the least—of the increased economy resulting from the use of increased pressures of steam.

When higher pressures are employed in the same engine in conjunction with the higher speeds corresponding to them, the economic gain is in the compound ratio of the two gains just described, and becomes very strongly marked.

NOTE BY THE AUTHOR.—A number of experiments with steam-jacketed cylinders have shown but little or no economic gain from the addition of the jackets, but in these cases there is great doubt whether the *nominally* steam-jacketed cylinder was *really* steam jacketed. When the jacket is in one casting with the cylinder, the cores are very difficult of removal; in fact, in such cases, they are rarely completely removed, so that what steam there may be in the jackets does not come properly in contact with the cylinder. Indeed, the cylinder is only very partially steam jacketed. As regards the cylinder heads, they, too, are very incompletely jacketed; their cores are difficult of removal also. Many steam-jacketed cylinders have very imperfect provision for promptly drawing off the water of liquefaction from the jackets, and still more imperfect are the arrangements for filling them with steam. Very rarely are the small pipes leading from the main steam pipe to the jackets sufficiently large of area to supply the jackets with steam of boiler pressure, in which case the jackets operate a loss by abstracting heat from the cylinder instead of imparting it. In all cases when experiment shows but little or no gain from the jackets, the latter should be carefully examined to ascertain whether the cores have been completely removed. Gauges should be placed on the jackets to ascertain if the full boiler pressure is in them; and, above all, the water of

liquefaction drawn from the jackets should be measured. Where the quantity of this water is less than from six to twelve per centum of the feed water, either the cores have not been completely removed from the jackets, or the latter have not been supplied with steam of the boiler pressure, or have not been promptly drained of the water of liquefaction. Unless these important points are attended to, the experiments are worthless, as showing the inutility of steam jackets. Experiments made by competent experimenters, who take nothing for granted, but experimentally determine and verify every fact, are of the highest value; but those made by incompetent ones are worse than useless—they are misleading. The writer knows of no properly made experiments with steam jackets that did not show a considerable economy resulting from their use, and greater as the steam was used with greater measures of expansion.

STEAM HEATING OF PASSENGER TRAINS ON THE PENNSYLVANIA RAILROAD.*

Several requests have been made for a description of the passenger car steam-heating system with which the Pennsylvania Railroad has been experimenting.

Much attention has been given to the broad question of car heating by water and steam for several years, and the process of elimination has confirmed the belief on our part that the return system is the one which must finally prevail if the best results are desired; whether the arrangement which is now being applied to the cars of the Pennsylvania Railroad is the best that can be devised, can only be determined by a longer service than has yet been possible.

Briefly, a return system is one which, by the aid of a pump or other vacuum producing device, brings back to the tender of the locomotive the water of condensation derived from the steam which has given up its heat in warming the cars.

In the Pennsylvania Railroad system (see diagram), an

* From the Proceedings of the Stated Meeting of the Inst., Sept. 17, 1890.