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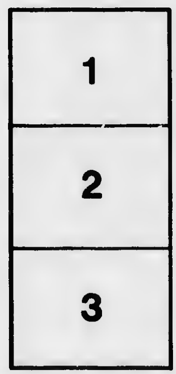
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DCII.*

THE SATURATION CURVE AS A REFERENCE LINE FOR INDICATOR DIAGRAMS.

BY R. C. CARPENTER, ITAHCA, NEW YORK.

(Member of the Society.)

THE following paper is intended to describe a graphical system which the writer has employed for giving more complete information regarding the heat interchanges which occur in the steam engine than obtained by the usual method of reducing the data of an engine test. During the past year, the students in laboratory practice of steam engineering at Sibley College, have all been required to make a graphical thermal analysis based on the use of the saturation curve as explained in the following article. The article is intended simply to give information showing the use of the method and some examples are given which show the character of the results which can readily be obtained. No attempt is made to show by these examples any results which have a general application and it is not expected that any conclusions except such as relate to the method itself will be drawn from the tests presented. In apology for the elementary way in which the very simple system is described, I may say that the article is intended principally for students in technical schools.

This system cannot be considered as new in its general fratures, as I find that it has been used in a somewhat similar way both by Professor Unwin and Professor Cotterell, but there it has been helpful in many ways as a rapid and graphical method of determining the quality and thermal condition of the steam during expansion, and in some respects the method presents novel features. It seems to have been used very little, possibly

* Presented at the Montreal meeting, June, 1894, of the American Society of Mechanical Engineers and forming part of volume XV. of the *Transactions*.

not at all by American engineers. Thinking that a method which we have found useful might prove of interest, especially to technical students, I have ventured to describe it.

The method is, itself, quite simple and can be readily explained by reference to the diagrams in Fig. 1. In those diagrams *aormn* is the actual diagram obtained from the engine, *KR* represents the atmospheric line, *bb* the clearance line, and *K'R'* represents the line of no pressure or vacuum line. *ob* represents the volume of clearance and *ON* represents the volume corresponding to piston displacement. From the end of the compression curve an hyperbola is produced backward an upward, a_5a, to the line, *bc*, which latter corresponds to the boiler pressure

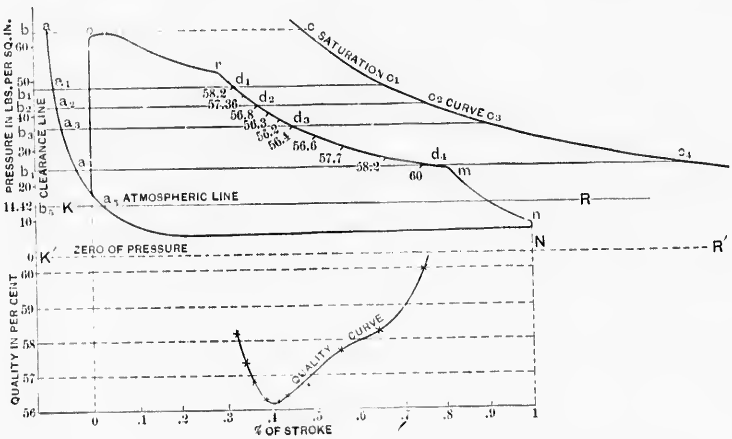

Fig. 1.

of steam. The volume of steam filling the clearance space corresponds with very little error to the distance *ab* on the same scale as the volume of piston displacement. To use this method, the weight of steam used per stroke is required. This is to be found by an ordinary efficiency test of the engine, either by condensing the steam, or from a boiler test. The data then which we are supposed to possess, gives us data from which we can compute the weight of steam per stroke of the engine. By consulting steam tables the volume corresponding to the weight delivered for the given pressure can be ascertained. This volume is then laid off to the same scale as the diagram in a horizontal direction from the point which corresponds to the volume of steam filling the clearance at boiler pressure. In the diagram under consideration, this volume corresponds to the distance ac, which is laid off from the point a for the reason stated. The values given in the steam table for different pressures multiplied by fractors for weight of steam and for the scale used, give abscissae of the other points in the saturation curve. In the test represented by the diagrams in Fig. 1, we have for the saturation curve the line $cc_1 c_2 c_3 c_4$. The abscissae of this curve for any given pressure ordinate shows the total volume that the same weight of dry and saturated steam would have had, to the same scale as the piston displacement. If now a horizontal line be drawn extending from the clearance line to the saturation curve, the ratio of the distance from the clearance line to the expansion curve, to the whole line is the quality of the steam.* Thus through the point Fig. 1, d_1, draw the horizontal line, $b_1 c_1$, then the ratio of $b_1 d_1$, to $b_1 c_1$, is the quality at the point d_1; in the same manner $b_2 d_2 \div b_2 c_2$ is the quality at d_2, etc. The variation in quality from point to point as obtained in that manner is shown for different positions in the stroke by the curve below the diagram, from which it is seen that the quality during the early periods of expansion rapidly diminished then gradually increased so that just before the period of exhaust opening, the quality increased considerable above that at the beginning. From a study of the conditions the same method could be applied during the period of compression, the only difficulty being this, that the quality of steam at any point in the cylinder during compression is not positively known, and an assumption must be made which is perhaps no better than to assume that during compression the curve is hyperbolic. The weight of steam imprisioned in the clearance spaces is always a very small percentage of the total, hence any error which is made in assuming hyperbolic compression cannot affect the results seriously, in fact it becomes of very little moment. There is very much in this graphic analysis which brings out thermal properties in a way better calculated to make an impression upon the mind than the analytic and more difficult methods of Hirn's analysis. I have employed this method in the Sibley College tests as supplementary to the analytical method devised by Hirn. So far as

* There is a slight error in this assumption, due to the volume of the entrained water. The error is in general less than can be measured. A table for correction is given at the end of the article.

the quality shown during expansion, the two methods have always given substantially the same results. The difference in in fact depending simply upon the accuracy with which either the computation or the drawing was made. In the test for Hirn's analysis, the total heat discharged from the engine is always measured or computed so that the quality of the exhaust steam can be determined. The same data could be used in conjunction with the graphical method described, in which case the heat interchanges could be very readily and quickly computed, using the diagrams to obtain the quality at any given point thus, if from an ordinary test the weight of steam at any point is given and the quality is shown by the graphical method which has been explained, the total heat is computed from a simple formula which is no doubt familiar to all.

Thus, let $x =$ the quality as determined from the diagram, ρ the internal latent heat, q the sensible heat, for the given pressures. The latter being obtained from a steam table. Then the total heat in one pound of steam will be $x\rho + q$, which can be computed from the data at hand. If r is the total latent heat, the total heat available after condensation would be $xr + q$.

While the graphical method will not replace the more tedious and exact analytical one for all purposes, yet it is believed that it will give all the practical results which can be obtained from the analytical method with much less work and in general, in a manner which is more readily understood by the student in technical schools and I think will on the whole prove of some value to practical engineers. This, I believe, has not been the case with the analytical method of determining the heat losses.

As another illustration of the method of using saturation curves, reference is made to Figs. 2 and 3 in which case we have the same engine working with the same brake load and practically the same I. H. P. The load was very light; and in the one case, the engine was worked with very little compression and in the other, (see Fig 3), with a great deal of compression. The discussion here is merely to show the method of obtaining the results by a graphical process and no reference is made to the relative economy in the two trials for the reason that it will probably form the subject of a paper before the society by one of my colleagues in Sibley College. In these figures "A" Fig 2 is an exact copy of the diagram as obtained from the indicator. In Fig. 2, diagram "B," the line AB represents the expansion curve drawn to an enlarged scale. The saturation curve represented by KL is drawn to the same scale of volumes. The

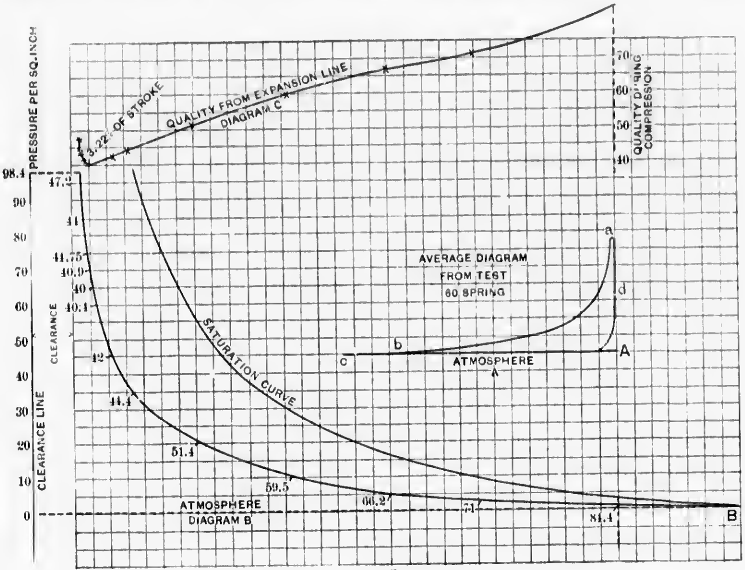

Fig. 2.

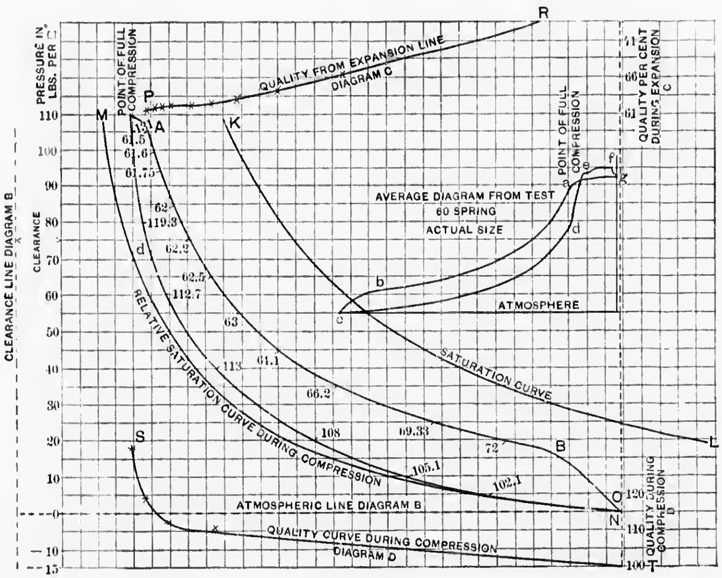

Fig. 3.

quality at vario points on the expansion line denoted by figures and also represented by the curve, diagram "C" at the top of the figure. In Fig. 3 is shown the diagram, actual and enlarged in diagrams "A" and "B" respectively, the saturation curve corresponding to the weight of steam imprisoned in the clearance spaces, is drawn on the supposition that this steam is dry at the beginning of compression. The quality at different points in the compression curve and at different points in the expansion line, is denoted by figures on the enlarged diagram. The quality is also shown graphically by curves at the upper and lower portions of the figure. While no discussion of the results will be made here, it is interesting to note the improved character of the quality of steam produced by the late compression. It should not, however, be concluded that the one case is for this reason much superior in economy to the other, as I believe that certain compensating disadvantages were experienced which made the economical results practically the same in both cases.

The application of this method to a compound or triple expansion engine, is quite similar to that described for the simple engine. In general, it will be found very much better to have the scale of pressures to as large a scale as possible, since in this case both the expansion curve and the saturation curve become more nearly vertical, and the intersection of the horizontal line becomes better defined, and is much more accurate. It has been our custom to treat each diagram from a compound or triple expansion engine, as already explained for the simple engine, and to obtain the positions of the saturation curve before the combined diagram showing all the cards to the same scale were constructed.

In making the combined diagram, we have tried various plans in order to have a continuous curve of reference to which they might be referred. To do this it is necessary to represent the diagrams as drawn from different clearance lines. Even then, because of the different weights of steam caught in the clearance spaces, the saturation curve would not be continuous, or, if adjusted, so as to be continuous it would have a different curvature for the part corresponding to each cylinder in each case. This later objection will not hold when the hyperbola is used as a reference line, however. The result of various experiments in combining diagrams has been to satisfy me that the method of drawing the diagrams to the same pressure and volume scale is on the whole as good as any that has been devised. This method, however, gives us a broken saturation curve, as will be seen by referring to Fig. 4 which gives the combined diagrams from the Sibley College experimental engine, yet, on the whole, it seems to be the only method of

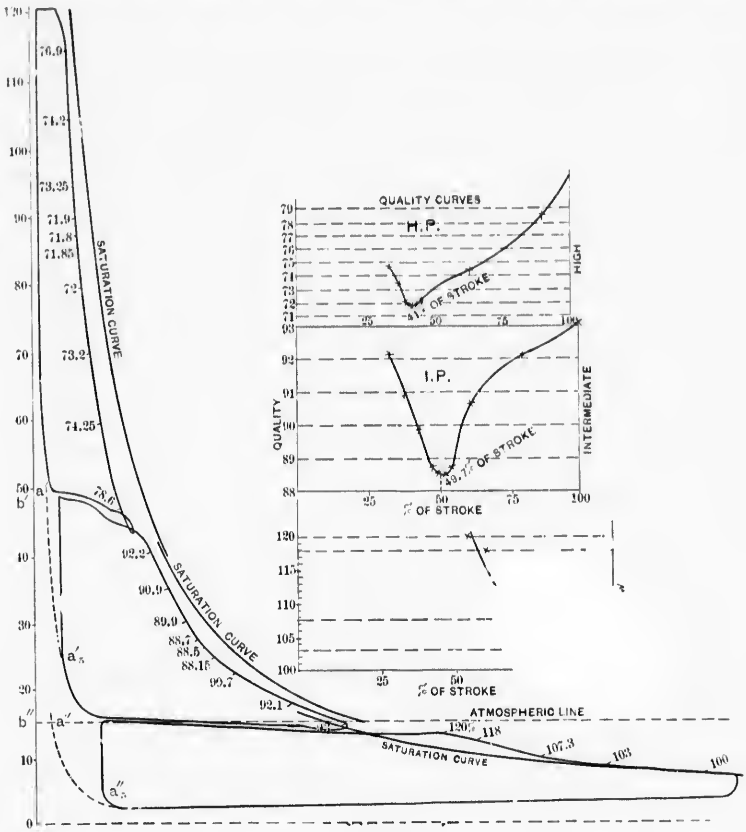

Fig. 4.

representing the diagrams which is general in its nature. It is true that very much smoother expansion curves are obtained for the combined diagrams which, for some cases, may more fairly represent the condition of the engine by combining the diagrams in such a manner that continuous reference curves are obtained either hyperbolic or in the form of the saturation line. But, it is believed, that on the whole no injustice is done by the distortions which sometime occur in the application of the method of applying unifrom scale of pressure and volume.

In Fig. 4 are shown the combined diagrams from the high, intermediate, and low pressure cylinders of the triple expansion engine at Sibley College. The saturation curve drawn as already explained for each diagram separately is given, and the corresponding quality is marked on the expansion curves for various points in each cylinder. The curves of quality are shown graphically to the right of the diagram. The engine, in this case, was steam jacketed with high pressure steam on all the cylinders and in both receivers. The effect of the jacket steam on the quality is very marked as is shown by reference to the expansion curve of the low pressure cylinder. It will be noted in this case that the figures indicate in some stages a quality exceeding one hundred. This number should be considered in its true significance as representing the ratio of heat to that in the same weight of dry and saturated steam rather than as representing the per cent of dry steam. This can be taken merely as representing a superheated condition without a specific statement of the degree of superheat. I am well aware that there may be some objections to the use of the word "quality," as cover this case, but its convenience is certainly very great as it saves a laborious calculation, which is of no value when completed.

The peculiar form of the quality curves shown in the figures as pertaining to the high and intermediate cylinders seems very generally true for the usual conditious of the steam engine. In a great many trials that we have considered, the curves have the form shown in each case.

The point of contraflexure in these curves usually occurs some little distance after the cut-off and indicates, of course, the position in the cylinder where the quality has become constant and condensation has ceased and re-evaporation has begun. The peculiar curvature occuring after re-evaporation begins is no doubt largely due to the rapid motion of the piston when near the centre of the stroke and to its very slow motion near the end.

These few remarks serve to show in a general way the character of the analysis and the results which may be obtained by using a saturated curve as explained. I think it will be conceded that as a method, it is certainly worth careful consideration. The information regarding the interchanges of heat can not be obtained so readily by any other method that is known to the writer, while I believe it will be found to compare well with any for completeness and accuracy of information.

Applications of the methods which have been here described have already been presented to the society in the discussion of the tests of the Milwaukee engine by Dr. Thurston, read at the fall meeting, and, also, a paper at the present meeting on the subject of *The Steam Jacket*, also by Dr. Thurston.

In presenting the drawings for this paper the writer is under obligation to Mr. Thomas Hall, a graduate student in Sibley College.

ERRATA.

THE proofs of the writer's article were not seen by him, and correction for several errors which are quite apparent could not be made. In one place, however, the construction is such as to give a meaning quite contrary to that which the writer intended. It is believed that the privilege of correction under these circumstances will be freely accorded.

Aside from simple errors of construction, of which no correction need be made at this place, the principal misinterpretation is likely to occur with reference to the remarks on page 8 made respecting the combined diagram shown in Fig. 4. Without

DIAGRAM SHOWING RELATION OF PRESSURE, VOLUME AND ABSOLUTE TEMPERATURE OF SATURATED AND SUPERHEATED STEAM.

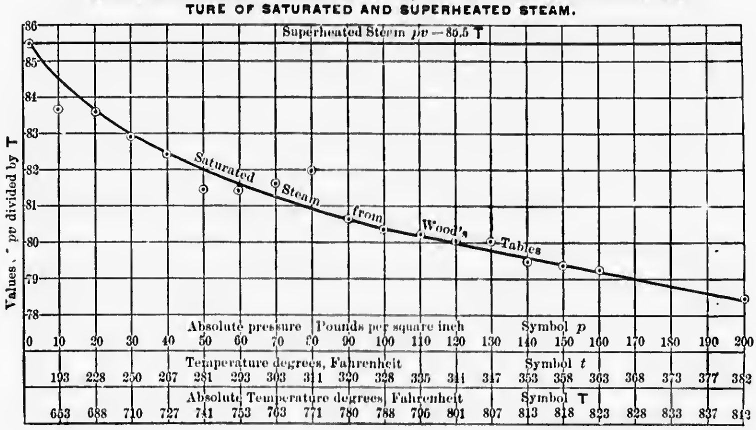

Fig. 4.

attempting to point out specifically the change of construction which is required, I will merely say that the substitution of the word "heat" for "volume" is responsible for a great portion of the difficulty. The writer wishes to state as a substitution for these remarks that the term "quality" was not intended to be used with reference to the low-pressure cylinder. For this case the numbers on the expansion curve represent ratio of volumes of equal weights of steam in saturated and superheated conditions; it is somewhat doubtful if the degree of superheat can be computed. See following note.

NOTE.—*Error of determining quality of the steam.* The quality of the steam can be defined as the percentage by weight of steam in a mixture of steam and water. Denote the quality by x, the percentage of moisture by weight, $100 - x$, the volume in cubic feet of one pound of dry and saturated steam by v, volume of one pound of water by c, the volume of one pound of the mixture by w.

Then will we have

$$xv + (100 - x)\,c = w,$$

from which

$$x = \frac{w - c}{v - c} = \frac{w}{v} - \left(100 - \frac{w}{v}\right) c.$$

In the above expression w corresponds to the actual volume shown by the diagram for any given pressure, v that of the corresponding volume measured to the saturation curve; the quotient $w \div v$ being the quantity which has been taken as the quality in the preceding discussion. From the above formula it is evident that the true quality will be less than the quantity so obtained by an amount the value of which is expressed in the second term of the second member. This last quantity is always very small. The value of c is nearly constant, and may be taken without sensible error as 0.016. The value of this correction does not equal 1% until the quality has become less than 40%, or until the amount of moisture exceeds 60%. The following table gives the percentage of correction for different conditions with respect to volumes of the steam.

TABLE FOR CORRECTING VALUES OF QUALITY AS OBTAINED FROM RATIO OF VOLUMES AS EXPLAINED IN PAPER.

A Percentage obtained by ratio of volumes $v' \div v$.	B Correction to be subtracted. Percentage.	C True value of the *quality* × per cent.	A Percentage obtained by ratio of volumes $v' \div v$.	B Correction to be subtracted. Percentage.	C True value of the *quality* × per cent.
100	0.000	100.00	70	0.48	69.52
98	0.032	97.968	65	0.56	64.44
96	0.064	95.936	60	0.64	59.36
95	0.080	94.92	55	0.72	54.28
94	0.096	93.904	50	0.80	49.20
92	0.128	91.872	45	0.88	44.12
90	0.16	89.84	40	0.96	39.04
85	0.24	84.76	35	1.04	33.96
80	0.32	79.68	30	1.12	28.88
75	0.40	74.60	25	1.20	23.80

Application to Superheated Steam.

If the volume of steam for a given pressure is greater than that obtained by measuring to the saturation curve, the steam is superheated. It is somewhat doubtful if the degree of superheat can be determined by the increase in volume. If we could consider steam when superheated as a perfect gas, the product of pressure and volume divided by absolute temperature would be constant; farther, for any given pressure the volume would vary directly as the temperature.

I have been unable to find much information relating to the properties of superheated steam. It seems, however, generally admitted that until the degree of superheat becomes considerable the temperature does not increase at the same rate as the volume. After the steam is superheated considerably, it behaves like a perfect gas, of which the equation is $pv = 85.5$ ft.-lbs., in which p is the pressure in pounds per square foot, v the volume in cubic feet, and T the absolute temperature. The range of temperature required for the steam to pass from the saturated to the gaseous condition for any given pressure is given by Hirn* as 16° Fahr., and by Siemens as 18° Fahr.

The following diagram was constructed by computing ratio of $\frac{pv}{T}$ from the values given in the steam table in Wood's *Thermodynamics* and shows the relation between p, v, and T for different pressures with saturated steam. The straight line represents the equation as given above for superheated steam. It is to be noticed that the constant for saturated steam varies from 85.5 at 1 lb. pressure to 78.5 at 200 lbs. pressure.

An application of these equations to the diagram of the low-pressure cylinder in Fig. 4 would indicate that the steam entering the low-pressure cylinder was 240° in temperature. As the jacket steam was only 350°, this amount seems unreasonably high.

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* See Thurston's *Steam Engine*, vol. i p. 771; *Theory Mecanique de la Chaleur*, Ency. Britannica, vol.