SUPERHEATED STEAM

Superheated steam, as already stated, is steam the temperature of which exceeds that of saturated steam at the same pressure. It is produced by the addition of heat to saturated steam which has been removed from contact with the water from which it was generated. The properties of superheated steam approximate those of a perfect gas rather than of a vapor. Saturated steam cannot be superheated when it is in contact with water which is also heated, neither can superheated steam condense without first being reduced to the temperature of saturated steam. Just so long as its temperature is above that of saturated steam at a corresponding pressure it is superheated, and before condensation can take place that superheat must first be lost through radiation or some other means. Table 24[20] gives such properties of superheated steam for varying pressures as are necessary for use in ordinary engineering practice.

Specific Heat of Superheated Steam—The specific heat of superheated steam at atmospheric pressure and near saturation point was determined by Regnault, in 1862, who gives it the value of 0.48. Regnault's value was based on four series of experiments, all at atmospheric pressure and with about the same temperature range, the maximum of which was 231.1 degrees centigrade. For fifty years after Regnault's determination, this value was accepted and applied to higher pressures and temperatures as well as to the range of his experiments. More recent investigations have shown that the specific heat is not a constant and varies with both pressure and the temperature. A number of experiments have been made by various investigators and, up to the present, the most reliable appear to be those of Knoblauch and Jacob. Messrs. Marks and Davis have used the values as determined by Knoblauch and Jacob with slight modifications. The first consists in a varying of the curves at low pressures close to saturation because of thermodynamic evidence and in view of Regnault's determination at atmospheric pressure. The second modification is at high degrees of superheat to follow Holborn's and Henning's curve, which is accepted as authentic.

For the sake of convenience, the mean specific heat of superheated steam at various pressures and temperatures is given in tabulated form in Table 25. These values have been calculated from Marks and Davis Steam Tables by deducting from the total heat of one pound of steam at any pressure for any degree of superheat the total heat of one pound of saturated steam at the same pressure and dividing the difference by the number of degrees of superheat and, therefore, represent the average specific heat starting from that at saturation to the value at the particular pressure and temperature.[21] Expressed as a formula this calculation is represented by

$$\text{Sp. Ht.} = \frac{H_{sup} - H_{sat}}{S_{sup} - S_{sat}} \qquad (8)$$

Where H_{sup} = total heat of one pound of superheated steam at any pressure and temperature,

H_{sat} = total heat of one pound of saturated steam at same pressure, [Pg 138]

S_{sup} = temperature of superheated steam taken,

S_{sat} = temperature of saturated steam corresponding to the pressure taken.

TABLE 25

MEAN SPECIFIC HEAT OF SUPERHEATED STEAM
CALCULATED FROM MARKS AND DAVIS TABLES

Gauge Pressure	**Degree of Superheat**																	
	50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**225**	**250**
50	.518	.517	.514	.513	.511	.510	.508	.507	.505	.504	.503	.502	.501	.500	.500	.499	.497	.496

60	.528	.525	.523	.521	.519	.517	.515	.513	.512	.511	.509	.508	.507	.506	.504	.504	.502	.500
70	.536	.534	.531	.529	.527	.524	.522	.520	.518	.516	.515	.513	.512	.511	.510	.509	.506	.504
80	.544	.542	.539	.535	.532	.530	.528	.526	.524	.522	.520	.518	.516	.515	.514	.513	.511	.508
90	.553	.550	.546	.543	.539	.536	.534	.532	.529	.527	.525	.523	.521	.519	.518	.517	.514	.510
100	.562	.557	.553	.549	.544	.542	.539	.536	.533	.531	.529	.527	.525	.523	.522	.521	.517	.513
110	.570	.565	.560	.556	.552	.548	.545	.542	.539	.536	.534	.532	.529	.528	.526	.525	.520	.517
120	.578	.573	.567	.561	.557	.554	.550	.546	.543	.540	.537	.535	.533	.531	.529	.528	.523	.519
130	.586	.580	.574	.569	.564	.560	.555	.552	.548	.545	.542	.539	.537	.535	.533	.531	.527	.523
140	.594	.588	.581	.575	.570	.565	.561	.557	.553	.550	.547	.544	.541	.539	.536	.534	.530	.526
150	.604	.595	.587	.581	.576	.570	.566	.561	.557	.554	.550	.547	.544	.542	.539	.537	.533	.529
160	.612	.603	.596	.589	.582	.576	.571	.566	.562	.558	.554	.551	.548	.545	.543	.541	.536	.531
170	.620	.612	.603	.595	.588	.582	.576	.571	.566	.562	.558	.555	.552	.549	.546	.544	.538	.533
180	.628	.618	.610	.601	.593	.587	.581	.575	.570	.566	.561	.558	.555	.552	.549	.546	.540	.536
190	.638	.627	.617	.608	.599	.592	.585	.579	.574	.569	.565	.562	.558	.555	.552	.549	.543	.538
200	.648	.635	.624	.614	.605	.597	.590	.584	.578	.574	.569	.566	.562	.558	.555	.552	.546	.541
210	.656	.643	.631	.620	.611	.602	.595	.588	.583	.578	.573	.569	.565	.561	.558	.555	.549	.543
220	.664	.650	.637	.626	.616	.607	.600	.592	.586	.581	.577	.572	.568	.564	.561	.558	.551	.545
230	.672	.658	.644	.633	.622	.613	.605	.597	.591	.585	.580	.575	.572	.567	.564	.561	.554	.548
240	.684	.668	.653	.640	.629	.619	.610	.602	.595	.589	.584	.579	.575	.571	.567	.564	.556	.550
250	.692	.675	.659	.645	.633	.623	.614	.606	.599	.593	.587	.582	.577	.574	.570	.567	.559	.553

Factor of Evaporation with Superheated Steam—When superheat is present in the steam during a boiler trial, where superheated steam tables are available, the formula for determining the factor of evaporation is that already given, (*2*),[22] namely,

$$\text{Factor of evaporation} = \frac{H - h}{L}$$

Here H = total heat in one pound of superheated steam from the table, *h* and L having the same values as in (*2*).

Where no such tables are available but the specific heat of superheat is known, the formula becomes:

$$\text{Factor of evaporation} = \frac{H - h + \text{Sp. Ht.}(T - t)}{L}$$

Where H = total heat in one pound of saturated steam at pressure existing in trial,
h = sensible heat above 32 degrees in one pound of water at the temperature entering the boiler,
t_{sat} = temperature of saturated steam, corresponding to pressure existing,
T = temperature of superheated steam as determined in the trial, [Pg 139]

t = temperature of saturated steam corresponding to the boiler pressure,
Sp. Ht. = mean specific heat of superheated steam at the pressure and temperature as found in the trial,
L = latent heat of one pound of saturated steam at atmospheric pressure.

Advantages of the Use of Superheated Steam—In considering the saving possible by the use of superheated steam, it is too often assumed that there is only a saving in the prime movers, a saving which is at least partially offset by an increase in the fuel consumption of the boilers generating steam. This misconception is due to the fact that the fuel consumption of the boiler is only considered in connection with a definite weight of steam. It is true that where such a definite weight is to be superheated, an added amount of fuel must be burned. With a properly designed superheater where the combined efficiency of the boiler and superheater will be at least as high as of a boiler alone, the approximate increase in coal consumption for producing a given weight of steam will be as follows:

Superheat Degrees	***Added Fuel Per Cent***	***Superheat Degrees***	***Added Fuel Per Cent***
25	1.59	100	5.69
50	3.07	150	8.19
75	4.38	200	0.58

These figures represent the added fuel necessary for superheating a definite weight of steam to the number of degrees as given. The standard basis, however, of boiler evaporation is one of heat units and, considered from such a standpoint, again providing the efficiency of the boiler and superheater is as high, as of a boiler alone, there is no additional fuel required to generate steam containing a definite number of heat units whether such units be due to superheat or saturation. That is, if 6 per cent more fuel is required to generate and superheat to 100 degrees, a definite weight of steam, over what would be required to produce the same weight of saturated steam, that steam when superheated, will contain 6 per cent more heat units above the fuel water temperature than if saturated. This holds true if the efficiency of the boiler and superheater combined is the same as of the boiler alone. As a matter of fact, the efficiency of a boiler and superheater, where the latter is properly designed and located, will be slightly higher for the same set of furnace conditions than would the efficiency of a boiler in which no superheater were installed. A superheater, properly placed within the boiler setting in such way that products of combustion for generating saturated steam are utilized as well for superheating that steam, will not in any way alter furnace conditions. With a given set of such furnace conditions for a given amount of coal burned, the fact that additional surface, whether as boiler heating or superheating surface, is placed in such a manner that the gases must sweep over it, will tend to lower the temperature of the exit gases. It is such a lowering of exit gas temperatures that is the ultimate indication of added efficiency. Though the amount of this added efficiency is difficult to determine by test, that there is an increase is unquestionable.

Where a properly designed superheater is installed in a boiler the heating surface of the boiler proper, in the generation of a definite number of heat units, is relieved of a portion of the work which would be required were these heat units delivered in saturated steam. Such a superheater needs practically no attention, is not subject to a large upkeep cost or depreciation, and performs its function without in any way [Pg 140] interfering with the operation of the boiler. Its use, therefore from the standpoint of the boiler room, results in a saving in wear and tear due to the lower ratings at which the boiler may be run, or its use will lead to the possibility of obtaining the same number of boiler horse power from a smaller number of boilers, with the boiler heating surface doing exactly the same amount of work as if the superheaters were not installed. The saving due to the added boiler efficiency that will be obtained is obvious.

Following the course of the steam in a plant, the next advantage of the use of superheated steam is the absence of water in the steam pipes. The thermal conductivity of superheated steam, that is, its power to give up its heat to surrounding bodies, is much lower than that of saturated steam and its heat, therefore, will not be transmitted so rapidly to the walls of the pipes as when saturated steam is flowing through the pipes. The loss of heat radiated from a steam pipe, assuming no loss in pressure, represents the equivalent condensation when the pipe is carrying saturated steam. In well-covered steam mains, the heat lost by radiation when carrying superheated steam is accompanied only by a reduction of the superheat which, if it be sufficiently high at the boiler, will enable a considerable amount of heat to be radiated and still deliver dry or superheated steam to the prime movers.

It is in the prime movers that the advantages of the use of superheated steam are most clearly seen.

In an engine, steam is admitted into a space that has been cooled by the steam exhausted during the previous stroke. The heat necessary to warm the cylinder walls from the temperature of the exhaust to that of the entering steam can be supplied only by the entering steam. If this steam be saturated, such an adding of heat to the walls at the expense of the heat of the entering steam results in the condensation of a portion. This initial condensation is seldom less than from 20 to 30 per cent of the total weight of steam entering the cylinder. It is obvious that if the steam entering be superheated, it must be reduced to the temperature of saturated steam at the corresponding pressure before any condensation can take place. If the steam be superheated sufficiently to allow a reduction in temperature equivalent to the quantity of heat that must be imparted to the cylinder walls and still remain superheated, it is clear that initial condensation is avoided. For example: assume one pound of saturated steam at 200 pounds gauge pressure to enter a cylinder which has been cooled by the exhaust. Assume the initial condensation to be 20 per cent. The latent heat of the steam is given up in condensation; hence, .20 × 838 = 167.6 B. t. u. are given up by the steam. If one pound of superheated steam enters the same cylinder, it would have to be superheated to a point where its total heat is 1199 + 168 = 1367 B. t. u. or, at 200 pounds gauge pressure, superheated approximately 325 degrees if the heat given up to the cylinder walls were the same as for the saturated steam. As superheated steam conducts heat less rapidly than saturated steam, the amount of heat imparted will be less than for the saturated steam and consequently the amount of superheat required to prevent condensation will be less than the above figure. This, of course, is the extreme case of a simple engine with the range of temperature change a maximum. As cylinders are added, the range in each is decreased and the condensation is proportionate.

The true economy of the use of superheated steam is best shown in a comparison of the “heat consumption” of an engine. This is the number of heat units required [Pg 141] in developing one indicated horse power and the measure of the relative performance of two engines is based on a comparison of their heat consumption as the measure of a boiler is based on its evaporation from and at 212 degrees. The water consumption of an engine in pounds per indicated horse power is in no sense a true indication of its efficiency. The initial pressures and corresponding temperatures may differ widely and thus make a difference in the temperature of the exhaust and hence in the temperature of the condensed steam returned to the boiler. For example: suppose a certain weight of steam at 150 pounds absolute pressure and 358 degrees be expanded to atmospheric pressure, the temperature then being 212 degrees. If the same weight of steam be expanded from an initial pressure of 125 pounds absolute and 344 degrees, to enable it to do the same amount of work, that is, to give up the same amount of heat, expansion then must be carried to a point below atmospheric pressure to, say, 13 pounds absolute, the final temperature of the steam then being 206 degrees. In actual practice, it has been observed that the water consumption of a compound piston engine running on 26-inch vacuum and returning the condensed steam at 140 degrees was approximately the same as when running on 28-inch vacuum and returning water at 90 degrees. With an equal water consumption for the two sets of conditions, the economy in the former case would be greater than in the latter, since it would be necessary to add less heat to the water returned to the boiler to raise it to the steam temperature.

The lower the heat consumption of an engine per indicated horse power, the higher its economy and the less the number of heat units must be imparted to the steam generated. This in turn leads to the lowering of the amount of fuel that must be burned per indicated horse power.

With the saving in fuel by the reduction of heat consumption of an engine indicated, it remains to be shown the effect of the use of superheated steam on such heat consumption. As already explained, the use of superheated steam reduces condensation not only in the mains but especially in the steam cylinder, leaving a greater quantity of steam available to do the work. Furthermore, a portion of the saturated steam introduced into a cylinder will condense during adiabatic expansion, this condensation increasing as expansion progresses. Since superheated steam cannot condense until it becomes saturated, not only is initial condensation prevented by its use but also such condensation as would occur during expansion. When superheated sufficiently, steam delivered by the exhaust will still be dry. In the avoidance of such condensation, there is a direct saving in the heat consumption of an engine, the heat given up being utilized in the developing of power and not in changing the condition of the working fluid. That is, while the number of heat units lost in overcoming condensation effects would be the same in either case, when saturated steam is condensed the water of condensation has no power to do work while the superheated steam, even after it has lost a like number of heat units, still has the power of expansion. The saving through the use of superheated steam in the heat consumption of an engine decreases demands on the boiler and hence the fuel consumption per unit of power.

Superheated Steam for Steam Turbines—Experience in using superheated steam in connection with steam turbines has shown that it leads to economy and that it undoubtedly pays to use superheated steam in place of saturated steam. This is so well established that it is standard practice to use superheated steam in connection [Pg 142] with steam turbines. Aside from the economy secured through using superheated steam, there is an important advantage arising through the fact that it materially reduces the erosion of the turbine blades by the action of water that would be carried by saturated steam. In using saturated steam in a steam turbine or piston engine, the work done on expanding the steam causes condensation of a portion of the steam, so that even were the steam dry on entering the turbine, it would contain water on leaving the turbine. By superheating the steam the water that exists in the low pressure stages of the turbine may be reduced to an amount that will not cause trouble.

Again, if saturated steam contains moisture, the effect of this moisture on the economy of a steam turbine is to reduce the economy to a greater extent than the proportion by weight of water, one per cent of water causing approximately a falling off of 2 per cent in the economy.

The water rate of a large economical steam turbine with superheated steam is reduced about one per cent, for every 12 degrees of superheat up to 200 degrees Fahrenheit of superheat. To superheat one pound of steam 12 degrees requires about 7 B. t. u. and if 1050 B. t. u. are required at the boiler to evaporate one pound of the saturated steam from the temperature of the feed water, the heat required for the superheated steam would be 1057 degrees. One per cent of saving, therefore, in the water consumption would correspond to a net saving of about one-third of one per cent in the coal consumption. On this basis 100 degrees of superheat with an economical steam turbine would result in somewhat over 3 per cent of saving in the coal for equal boiler efficiencies. As a boiler with a properly designed superheater placed within the setting is more economical for a given capacity than a boiler without a superheater, the minimum gain in the coal consumption would be, say, 4 or 5 per cent as compared to a plant with the same boilers without superheaters.

The above estimates are on the basis of a thoroughly dry saturated steam or steam just at the point of being superheated or containing a few degrees of superheat. If the saturated steam is moist, the saving due to superheat is more and ordinarily the gain in economy due to superheated steam, for equal boiler efficiencies, as compared with commercially dry steam is, say, 5 per cent for each 100 degrees of superheat. Aside from this gain, as already stated, superheated steam prevents erosion of the turbine buckets that would be caused by water in the steam, and for the reasons enumerated it is standard practice to use superheated steam for turbine work. The less economical the steam motor, the more the gain due to superheated steam, and where there are a number of auxiliaries that are run with superheated steam, the percentage of gain will be greater than the figures given above, which are the minimum and are for the most economical type of large steam turbines.

An example from actual practice will perhaps best illustrate and emphasize the foregoing facts. In October 1909, a series of comparable tests were conducted by The Babcock & Wilcox Co. on the steam yacht “Idalia” to determine the steam consumption both with saturated and superheated steam of the main engine on that yacht, including as well the feed pump, circulating pump and air pump. These tests are more representative than are most tests of like character in that the saving in the steam consumption of the auxiliaries, which were much more wasteful than the main engine, formed an important factor. A résumé of these tests was published in the Journal of the Society of Naval Engineers, November 1909.

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The main engines of the “Idalia” are four cylinder, triple expansion, $11\frac{1}{2}$ × 19 inches by $22\frac{11}{16}$ × 18 inches stroke. Steam is supplied by a Babcock & Wilcox marine boiler having 2500 square feet of boiler heating surface, 340 square feet of superheating surface and 65 square feet of grate surface.

The auxiliaries consist of a feed pump 6 × 4 × 6 inches, an independent air pump 6 × 12 × 8 inches, and a centrifugal pump driven by a reciprocating engine $5\frac{7}{16}$ × 5 inches. Under ordinary operating conditions the superheat existing is about 100 degrees Fahrenheit.

Tests were made with various degrees of superheat, the amount being varied by by-passing the gases and in the tests with the lower amounts of superheat by passing a portion of the steam from the boiler to the steam main without passing it through the superheater. Steam temperature readings were taken at the engine throttle. In the tests with saturated steam, the superheater was completely cut out of the system. Careful calorimeter measurements were taken, showing that the saturated steam delivered to the superheater was dry.

The weight of steam used was determined from the weight of the condensed steam discharge from the surface condenser, the water being pumped from the hot well into a tank mounted on platform scales. The same indicators, thermometers and gauges were used in all the tests, so that the results are directly comparable. The indicators used were of the outside spring type so that there was no effect of the temperature of the steam. All tests were of sufficient duration to show a uniformity of results by hours. A summary of the results secured is given in Table 26, which shows the water rate per indicated horse power and the heat consumption. The latter figures are computed on the basis of the heat imparted to the steam above the actual temperature of the feed water and, as stated, these are the results that are directly comparable.

TABLE 26

RESULTS OF “IDALIA” TESTS

Date	**1909**	**Oct. 11**	**Oct. 14**	**Oct. 14**	**Oct. 12**	**Oct. 13**
Degrees of superheat Fahrenheit		0	7	88	96	105
Pressures, pounds per square inch above Atmospheric Pressure	**Throttle**	190	196	201	198	203
	First Receiver	68.4	66.0	64.3	61.9	63.0
	Second Receiver	9.7	9.2	8.7	7.8	8.4
Vacuum, inches		25.5	25.9	25.9	25.4	25.2
Temperature, Degrees Fahrenheit	**Feed**	201	206	205	202	200
	Hot Well	116	109.5	115	111.5	111
Revolutions per minute	**Air Pump**	57	56	53	54	45
	Circulating Pump	196	198	196	198	197

Main Engine	194.3	191.5	195.1	191.5	193.1
Indicated Horse Power, Main Engine	512.3	495.2	521.1	498.3	502.2
Water per hour, total pounds	9397	8430	8234	7902	7790
Water per indicated Horse Power, pounds	18.3	17.0	15.8	15.8	15.5
B. t. u. per minute per indicated Horse Power	314	300	284	286	283
Per cent Saving of Steam	…	7.1	13.7	13.7	15.3
Percent Saving of Fuel (computed)	…	4.4	9.5	8.9	9.9

The table shows that the saving in steam consumption with 105 degrees of superheat was 15.3 per cent and in heat consumption about 10 per cent. This may be [Pg 144] safely stated to be a conservative representation of the saving that may be accomplished by the use of superheated steam in a plant as a whole, where superheated steam is furnished not only to the main engine but also to the auxiliaries. The figures may be taken as conservative for the reason that in addition to the saving as shown in the table, there would be in an ordinary plant a saving much greater than is generally realized in the drips, where the loss with saturated steam is greatly in excess of that with superheated steam.

The most conclusive and most practical evidence that a saving is possible through the use of superheated steam is in the fact that in the largest and most economical plants it is used almost without exception. Regardless of any such evidence, however, there is a deep rooted conviction in the minds of certain engineers that the use of superheated steam will involve operating difficulties which, with additional first cost, will more than offset any fuel saving. There are, of course, conditions under which the installation of superheaters would in no way be advisable. With a poorly designed superheater, no gain would result. In general, it may be stated that in a new plant, properly designed, with a boiler and superheater which will have an efficiency at least as high as a boiler without a superheater, a gain is certain.

Such a gain is dependent upon the class of engine and the power plant equipment in general. In determining the advisability of making a superheater installation, all of the factors entering into each individual case should be considered and balanced, with a view to determining the saving in relation to cost, maintenance, depreciation etc.

In highly economical plants, where the water consumption for an indicated horse power is low, the gain will be less than would result from the use of superheated steam in less economical plants where the water consumption is higher. It is impossible to make an accurate statement as to the saving possible but, broadly, it may vary from 3 to 5 per cent for 100 degrees of superheat in the large and economical plants using turbines or steam engines, in which there is a large ratio of expansion, to from 10 to 25 per cent for 100 degrees of superheat for the less economical steam motors.

Though a properly designed superheater will tend to raise rather than to decrease the boiler efficiency, it does not follow that all superheaters are efficient, for if the gases in passing over the superheater do not follow the path they would ordinarily take in passing over the boiler heating surface, a loss may result. This is noticeably true where part of the gases are passed over the superheater and are allowed to pass over only a part or in some cases none of the boiler heating surface.

With moderate degrees of superheat, from 100 to 200 degrees, where the piping is properly installed, there will be no greater operating difficulties than with saturated steam. Engine and turbine builders guarantee satisfactory operation with superheated steam. With high degrees of superheat, say, over 250 degrees, apparatus of a special nature must be used and it is questionable whether the additional care and liability to operating difficulties will offset any fuel saving accomplished. It is well established, however, that the operating difficulties, with the degrees of superheat to which this article is limited, have been entirely overcome.

The use of cast-iron fittings with superheated steam has been widely discussed. It is an undoubted fact that while in some instances superheated steam has caused deterioration of such fittings, in others cast-iron fittings have been used with 150 degrees of superheat without the least difficulty. The quality of the cast iron used in [Pg 145] such fittings has doubtless a large bearing on the life of such fittings for this service. The difficulties that have been encountered are an increase in the size of the fittings and eventually a deterioration great enough to lead to serious breakage, the development of cracks, and when flanges are drawn up too tightly, the breaking of a flange from the body of the fitting. The latter difficulty is undoubtedly due, in certain instances, to the form of flange in which the strain of the connecting bolts tended to distort the metal.

The Babcock & Wilcox Co. have used steel castings in superheated steam work over a long period and experience has shown that this metal is suitable for the service. There seems to be a general tendency toward the use of steel fittings. In European practice, until recently, cast iron was used with apparently satisfactory results. The claim of European engineers was to the effect that their cast iron was of better quality than that found in this country and thus explained the results secured. Recently, however, certain difficulties have been encountered with such fittings and European engineers are leaning toward the use of steel for this work.

The degree of superheat produced by a superheater placed within the boiler setting will vary according to the class of fuel used, the form of furnace, the condition of the fire and the rate at which the boiler is being operated. This is necessarily true of any superheater swept by the main body of the products of combustion and is a fact that should be appreciated by the prospective user of superheated steam. With a properly designed superheater, however, such fluctuations would not be excessive, provided the boilers are properly operated. As a matter of fact the point to be guarded against in the use of superheated steam is that a maximum should not be exceeded. While, as stated, there may be a considerable fluctuation in the temperature of the steam as delivered from individual superheaters, where there are a number of boilers on a line the temperature of the combined flow of steam in the main will be found to be practically a constant, resulting from the offsetting of various furnace conditions of one boiler by another.