SUPERSATURATED STEAM

A Thesis

Submitted for the Degree of

MASTER OF SCIENCE

in

Mechanical Engineering

by

Samuel C. Stovall, Jr.

B. S. in M. E. 1922

Georgie School of Technology

Approved by ______________________________

Professor of Mechanical Engineering.

June

1928

25364

TABLE OF CONTENTS

THE CLASSICAL OR THEORETICAL CONSIDERATION

The phenomena of supersaturation occurs, or is likely to occur, when there is a change in the state of matter from a liquid to a vapor or vice versa. For this reason, the author will take up first the theory regarding the change of state.

In Figure 1. the ordinate represents pressure, the abscissa the volume. It is known that when we take a substance in a gaseous state and at constant temperature change either the volume or the pressure, we will obtain a curve such as Number I in Figure 1. At higher temperatures this curve approaches a rectangular hyperbola, according to the perfect gas law, P. V. = R. T. At lower temperatures we will get a curve similar to Number II which follows the equation as determined by Joule-Thomson ($PV = RT - \frac{np_2}{3t}$). Now if we take the same substance and plot the isothermal curves at lower temperatures, we find that we will have a series of curves corresponding to curves III, IV, V and VI. At the point C on curve IV, we find that we have a condition where two phases are capable of existing at once and this point is called the critical point.

Let us now take a substance at a temperature lower than the critical point and plot a P-V diagram, as shown in Figure 2. The curve L-D represents the substance in the liquid state and the curve or straight line D-F, the substance as it is in the process of changing from a liquid to a gas, and the curve F-B the substance as it is in a gaseous state. During the process involved from D to F, where the substance is changing from a liquid to a gas, or a gas to a liquid, there exists at ordinary temperatures, a state of ebullition in which there is a surface dividing the gas from the liquid and in which the particles of gas and liquid are in equilibrium at this surface. At a point between D and F there is capable of existing a mixture of gas and liquid. Until the time of Andrews, it was thought to be impossible to change from one state to another without this condition existing. However, Andrews showed that it was possible to change from one state to another by keeping the substance perfectly homogeneous. This to say, he showed that it was possible to go from point F to the point P without having any unhomogeneous mixture. He did this by taking the substance in a gaseous state at the point F and compressed and simultaneously heated it along a curve F-K to a temperature above the critical temperature. At the point K it is quite evident that the substance is in the form of a superheated vapor. He then cooled the substance along the line H-L to its original temperature and then expanded it along the line L-D, and thereby was able to go from the point F to the point D having the substance remain perfectly homogeneous throughout the process.

Amagat also showed that it was possible to extend the curve L-D to the point G, if the liquid was carefully freed from any foreign matter. At the same time he showed by experiment that it was possible to extend the vapor curve from the point F to the point H, if the same precaution were taken.

These two facts, as brought out by Andrews and Amagat, led James Thomson in 1871 to argue that there must be some regular curve connecting the liquid curve and the vapor curve, such as D-G-E-H-F. It is quite evident that the equation for such a curve must be of an odd degree in V, because V increases with diminishing P at both ends of the curve. And furthermore, the equation must be a third degree in V, since more than one volume can correspond to a given pressure. At lower temperatures three roots of the equation are real and at the critical point the three coincide and at higher temperatures two of the roots must become imaginary.

The simplest equation for representing such a curve was proposed by Van der Waals in his essay on continuity of the liquid and gaseous states in 1873.
$((P - a1/V^2)\ (V - b) = RT)$.

Figure 3. shows a series of isothermals on a P-V diagram, as determined from Van der Waals' equation

The area enclosed by the curve A,Cw,b represents a mixture of liquid and vapors; that area to the right of the curve represents the vapor state and that to the left the liquid state; the highest point "Cw" on this curve being the critical temperature and the region above this point represents the superheated condition of the vapor.

The area below isothermals and constant pressure lines represents the condition of "supersaturation" and the region above isothermals and constant pressure lines represents that which is super-cooled liquid. According to theory there is no reason why the isothermal curves cannot be followed and, as has been said before, parts of them have already been obtained.

As this paper is to deal with the supersaturated vapor, the next topic taken up will be the experimental work.

THE EXPERIMENTAL WORK

The most concise experimental work that has been done on supersaturated vapor is contained in the Philosophical Transactions of the Royal Society of London, "On the Condensation of Water Vapor in the Presence of Dust Free Air and Other Gases." This work was done in 1857 by C. R. T. Wilson, in order to check some of the results previously obtained by Coulier, Aitken, Kiessling and R. V. Helmholtz.

His experiments were performed in the apparatus as shown in Figure 5, in which the air, saturated with water, was placed in the vessel A, which was immersed in the Bell jar B. The air in the space A could be compressed or expanded at will, by connecting the space E to the vacuum in jar F. This was done by pulling up the stopper D. When the air had been exhausted out of the space E, the water in the Bell jar B would occupy this volume, which had previously been occupied by the air, thereby expanding the air in A. Compression of the gas in A was accomplished by opening the pinch cock T and admitting air in the top of the jar, thereby restoring the water in chamber A to its original position. The change in pressure and likewise volume of the saturated air in A, was determined by observing with a telescope the height to which the water would raise in A and after the experiment this volume was calibrated.

In view of the fact that Wilson did not make any effort to measure any change in temperature, he wished to make his experiment in the shortest time possible, so as to make any flow of heat into the vessel A negligible, and this was done by proportioning the jar F to the space E, so as to make the change in volume of the air in A occur quickly.

As Wilson wished to observe the fog in the air, the experiment was carried on in a dark room, with the light from a luminous gas flame focused in the center of the space A.

It was observed that when ordinary saturated air was placed in the space A, a small change in volume would cause the fog to form. However, after the air had been alternately expanded and contracted a number of times, it was noted that unless the change in volume exceeded 0.81 of the original volume, that there was no fog or condensation whatsoever in the air. He accounted for this phenomena by assuming that when the air was taken into the jar from the room, there existed dust particles which caused the condensation and fog to take place and when these dust particles had been collected on the fog and had settled to the bottom of the jar, that there were no dust particles existing in the air, and, therefore, that there were no nuclei upon which water in liquid form could collect and for which reason a condition of supersaturation of the vapor which was present in the air, was set up.

He observed that if the change in volume was greater than $V_2/V_1 = 1.26$ that condensation would occur and a fog would be formed, regardless of how many times the air had previously been contracted and expanded. From this he came to the conclusion that there were nuclei formed in the air other than dust particles, from which condensation could occur.

As has been said, he made no effort to control or maintain the temperature of the room, other than depending upon the quickness of the expansion. He therefore assumed that the condition of supersaturation was an unstable condition which might or might not be true, in view of the fact that the stability of necessity depends upon the temperature. The following table gives the results of the volume changes at which condensation would take place in what he calls "Dust free saturated air". Of course, it must be evident that his method of arriving at this ratio was by trial and error and the details of the experiment would take too much space for this paper, but can be found from the reference named above.

Somewhat later he performed similar experiments by using another form of apparatus, as shown in Figure 6. The purpose of building this second apparatus was that he might be able to obtain more accurate results by having a smaller volume of air and making the expansion or contraction occur in a shorter time interval.

Referring to Figure 6, the air was placed in the space A, which was fitted at the bottom with a piston P, made of ground glass and lubricated with water. The space C was connected through the tube S to the chamber M, the volume of which was varied by means of the mercurial reservoir R, connected with the chamber M by a rubber hose. The pressure in the chamber L was observed by means of the mercurial manometer N. The chamber C was connected to the atmosphere by means of the plug G. In case of there being a vacuum in the chamber M and C, the piston P would be in a lower position, giving the maximum volume to the gas in A and vice versa when the pressure in the chamber M would take place. The quickness of the expansion was obtained by compressing the air in A and opening the chamber C to the atmosphere by means of the plug G. By calculation he showed that it was theoretically possible to move the piston P, thereby expanding the air in A through a distance of two centimeters in 1/150th of a second. That part of the apparatus above the cock T was for maintaining the gas in A saturated and also for introducing the gas into chamber A.

As in the other apparatus, the change in volume and pressure was noted by a telescope. In this case the pressure was observed by means of the manometer N and the volume was calculated from Boyle's law. Again the apparatus was illuminated by means of a gas flame in a dark room and no temperature changes were reported.

In this second form of apparatus the same results were observed as in the first apparatus. The same ratio V_2/V_1 of 1.252 was obtained for causing condensation after the air had been freed of the so-called dust particles.

Some of the more interesting things which he determined with this apparatus were by using gases which were saturated, whereas in the other apparatus only air was used. The table shows the V_1/V_2 causing condensation with the different gases.

Wilson also devoted a great deal of time to observing the phenomena which occurred with greater expansions than the ratio of V_2/V_1 of 1.252. He found a very distinct color phenomena occurring for different ratios and also the number of drops of rain or fog which would occur. He noted, for instance, that if V_2/V_1 was increased from 1.37 to 1.38, the increase in the number of drops was so great that it no longer resembled rain but was a distinct fog, which took several minutes to settle.

With expansions greater than this, the density of the fog would increase with great rapidity as the expansion was increased. Color diffraction rains made their appearance when V_2/V_1 was about 1.38 and they increased rapidly in brilliancy and in size as the expansion was made greater.

Before V_2/V_1 reached 1.4, the region within the first range which was whitish, with smaller expansions became brilliantly colored. He noted that the color phenomena beyond the range of V_2/V_1 of 1.4 became very definite, as for example, if V_2/V_1 was between 1.41 and 1.42, brilliant greens and blue greens were observed. About 1.42 there was a change from blue to red through violet. The violet appeared only for a very small range of pressures and then changed completely to blue and red.

These observations, together with the number of drops, enabled him to calculate the size of the nuclei which would cause condensation to take place. His observation of bombarding the gases with X Rays was also recorded. He found that after the gases had been freed of dust particles, X Rays caused no change in the ratio at which condensation would take place, nor would X Rays cause condensation to take place when the vapor was existent in a supersaturated state. This was equally true with all the gases that he tried. It was, however, noted that the X Rays caused a great deal of change in the color phenomena when the expansion was carried to a greater ratio than V_2/V_1 was 1.252.

It might be of interest to note the fact that Wilson and also Aitken carried on their experiments primarily from a weather standpoint and were endeavoring to account for the London fogs. Aitken in particular, suggested means by which some of the fog in London could be prevented, by freeing the air of dust particles.

EXPERIMENTAL WORK DONE BY AITKEN

Aitken's work on supersaturation covered a period from 1880 to 1892 and is covered by his report to the Royal Society of Edinburgh, Volume 11, and his report to the Royal Society of London, Volume 51.

In 1880 his experiment consisted of having two large glass receivers, one of which was filled with steam and the other with air, and observing the effects produced when the steam was admitted to the glass receiver filled with air. The air in the glass receiver being the atmospheric air under one set of experiments and under another set of experiments, the air which was filtered through a cotton wool filter to remove the dust particles.

He states that the difference in the behavior of the steam in the two cases was explained by the corresponding phenomena of supersaturation as occurred in freezing, melting and boiling, for he observed that when steam was admitted to air which had the dust particles in it, the vapor immediately condensed to form a cloud or rain, whereas when the vapor was admitted to the air which had been filtered, that there was no condensation and he states that this was due to the fact that there were no nuclei present upon which the vapor could condense.

He also tried another set of experiments by taking the air which had been filtered and passing steam into it, thereby having a supersaturation of the water vapor, and then he tried to determine what would cause condensation to take place. He found that the particles driven off by heating any such substance as glass, iron or brass, would immediately cause a condensation which produced a dense fog of the supersaturated water vapor. He also determined the fact that a particle of the weight of 100th of a grain of an iron wire would produce supersaturation (later he determined that one hundred thousanth of a grain would cause the same effect).

As has been stated before, the main purpose of Aitken's experiments is given by the title of his paper "Dust, Fogs and Clouds", and he devotes a great deal of space to connecting the phenomena with atmospheric conditions.

In 1892 Aitken seemed to have become interested again in the phenomena connected with cloudy condensations and in a report before the Royal Society of London, he gives a very lengthy report on experiments that he had conducted between 1880 and this time.

In this work he uses a steam jet exhausting into the atmosphere and divides the results into two parts, "Dense condensation" and "Ordinary condensation".

His apparatus consisted of a copper boiler which he states "could be pressed fully to one atmosphere", with a nozzle located at some distance from the boiler to prevent the hot gasses from influencing the jet; the steam being conveyed by means of a metal pipe to the nozzle, with a water trap placed near the end of the pipe to prevent irregularities produced by the water condensing in the pipe line leading to the nozzle. His nozzle was made of brass and bored to a diameter of one millimeter, widening inwards, while the outside of the nozzle was turned to a fine edge in front. He does not state, however, as to whether or not the nozzle was designed to give maximum velocity conditions and from reading his report, it is to be doubted whether or not it was known at this time how he designed such a nozzle, but nevertheless, this is the first experiment of any kind to be found on supersaturation when water vapor is discharged through a nozzle.

He observed that the conditions which caused a fog in his earlier experiments where the air had been filtered, would produce a denser fog when brought into contact with the steam jet and it is for this reason that he divides his observations into the two parts, i.e., "dense condensation" and "ordinary condensation". That is to say, when a copper wire was heated in the presence of the supersaturated vapor contained in the filtered air, condensation would be brought about, whereas, if the copper wire were placed in the jet of steam, which was already fog, a very much denser fog would take place. In these latter experiments he determines several other methods for causing such a condition to be brought about and illustrates that as "Five ways of changing the ordinary into the dense form of condensation".

1. Electrification of the jet.
2. An increase in the number of dust nuclei.
3. Cold or low temperature of the air.
4. High pressure of the steam.
5. Obstructions in front of the jet and rough or irregular nozzles.

His observations upon the electrification of the jet would in some ways tend to be contradictory to the results obtained by Wilson, for he determined that if an electrical discharge was passed through the jet a very decided change in the kind of condensation would occur. It is the opinion of the author of this paper, however, that this was due to a breaking up or explosion of the particles in the jet, which would be quite different results than that produced by bombarding the jet with X-Rays.

Aitken's entire work on the electrification of the jet seems to be limited to having a static electrical discharge take place through the jet and it is rather interesting to note the reason that he thought of using the electrical charge. It seems to be due to the fact that he observed his tea every morning and for this reason the following quotation will be given from his paper.

> "Take a small open vessel full of hot water. It is better to color the water nearly black for convenience of observation, a cup of tea without cream does very well for the purpose. Place the cup on a table between the window and the observer. Now look at the cup from such a position that no bright light is reflected from the surface of the liquid

and there will be seen what looks like a scum on the surface of the tea. That scum is, however, only a multitude of small mist drops which have condensed out of the rising steam and have fallen on the surface of the liquid where they are seen floating.

"If now we take a piece of brown paper or any convenient material, and rub it slightly to charge it and hold it over the cup, the 'scum' will disappear at once and be replaced by other drops when the electrified body is removed. As in Lord Rayleigh's experiment, a very feeble electrification is sufficient to cause the absorption of the drops into the body of the liquid".

It seems to have been for this reason that Aitken thought of passing an electrical discharge through the jet to see what would happen. As to whether or not he used any other electrical phenomena, it is not known except the fact that he makes the statement - "the necessary condition for electrically producing any effect on the jet, is that the particles of the jet be electrified either by direct discharge or by an induction discharge. The mere presence of an electrified body near the jet has no influence whatever."

His observation on the second of the five ways, namely "An increase in the number of dust nuclei", consisted in knowing that the condensation became very much denser when the surrounding air contained products of combustion, as driven off from the flame of a Bunsen burner.

His observation on the cold or low temperature of the air would seem at the present time to be very obvious, but for the sake of interest, a paragraph from his paper will be quoted, in order to show that it was a very puzzling thing in 1892.

"When I first encountered this new influence, it directly *puzzled me*. I had opened the window of the room where the experiments were being made and when the fresh air came in, the jet began to behave itself in the most uncertain way; at one moment it was quite steady, ordinary condensation, and the next it would conduct itself as if electrically excited. Even after the window was closed it continued to change from the ordinary to the dense form of condensation in a puzzling way. It was first thought that the outer air might be electrified and tests were accordingly made to see if this were the case. These tests showed that if it were electrified it could be so but slightly, as it did not effect a gold leaf electroscope which it would be required to have done to have produced the increased density observed in the steam abundant. The only other influence I could think of as likely to cause the effect was some unknown effect of cold. I therefore took a metal tube which had been used in the previous experiment for conveying the products of combustion from the flame to the jet and cooled it. Now presenting one end of this cooled tube to the jet, it at once responded and the condensation became as dense as if the flame had been on the other end of the tube, or as if the jet had been electrified."

It would appeal that his denser condensation was to be quite expected when the temperature was lowered for this phenomena, can quite easily be shown on the temperature entropy diagram in Figure A-B. It is evident that as the steam was issuing from the jet, it was in condition very close to the saturated line E-M and any drop in temperature would immediately cause the expansion line G-B of the steam to enter immediately further into the wet region, as indicated on the left side of the curve E-M. He also observed that the change in the type of condensation was dependent upon the temperature of the cold air:

for instance, he observed that up to a temperature of 46° the condensation was dense and neither electricity nor the products of combustion had any effect on the density, but when the temperature raised to about 48°, the electrical discharge began to produce a slight effect on increasing the density. At 48° the electrical discharge produced a very decided effect, as well as the products of combustion. This phenomena might be explained by what Wilson called the volume ratio at which rain-like condensation took place; for in Wilson's experiments his volume ratio was obtained at a given temperature and in view of the fact that a mixture of steam and water can hold to one degree of freedom. That is to say, the pressure and the temperature must be dependent upon each other and for that reason it is very evident that at 48° in Aitken's experiments he had passed the critical point in temperature, just as Wilson had passed the critical point in pressure for the temperature that he was experimenting at when he determined the volume ratio V_2/V_1 of 1.252.

Aitken's fourth method was by having a higher pressure of the steam and his observation was quite similar to that with the low pressure steam and here again he noted the effects of temperature, whereas, with low pressure steam at certain temperatures, he would observe condensation to be changed. In the case of the high pressure quite different temperatures for the same condensation would be observed. It would appear that this observation proves again that the critical point where supersaturation breaks down is just as much dependent upon the temperature as it is upon the volume, though this statement is an opinion of the author and has not been borne out in any experimental work to his knowledge.

The effects produced by his fifth way; in which condensation can be changed, i.e., "Rough nozzles and obstructions in front of jets"; were very similar to the "High pressure steam" and caused the results to take place quicker, which he very nicely accounts for by saying that there were eddy currents produced.

About 75 per cent. of Mr. Aitken's report is devoted to "Color phenomena connected with cloudy condensation", which would appear to be beyond the scope of this paper, since it deals with regions beyond the supersaturated conditions and also Aitken's observations were very similar to those already given by Wilson.

Aitken, a few years later, developed an instrument which he called "A simple pocket dust collector", i.e., an instrument which could be carried in the pocket for counting the dust particles in the air. A drawing of this pocket dust collector is shown in Figure 7, which was nothing more than a small glass tube of a known dimension into which he could bring a sample of the air of which he wished to know the number of dust particles, and then saturate it by means of water which was kept in a container and compressing and expanding the air, which would cause the dust particles to collect on the drops of water and settle to the bottom, thereby being counted.

Although the works of Wilson and Aitken are not the only experiments which have been performed on supersaturated water vapor, they appear to give the most concise and detailed accounts at their time and also at the present time, for so far as the author has been able to determine, there have been no other experiments performed, or no other information determined about the phenomena of supersaturation. There have been, however, a great many experiments to determine the effect of supersaturation, which will be taken up next, but it is thought that before any knowledge can be found on supersaturation, more time must be spent on observing the phenomena rather than the effect and in order to do so it might be of advantage to repeat the experiments of both Wilson and Aitken and observing more accurately than they were capable of doing at their time, and also to determine if there is not some temperature relation as well as volume relation, to what Wilson calls the critical volume ratio for rain-like condensation. The experimental and theoretical work which has been done to determine the effect of supersaturation in nozzle and steam turbines will next be taken up.

EFFECTS OF SUPERSATURATION

When there exists a mixture of steam and water, such as water being evaporated from a vessel, we have a condition existing where the vapor pressure and the pressure of the vapor between the two surfaces are equal, and therefore, the temperature of the water and the steam is the same. The condition is quite different now, where we have drops of water in the presence of steam, for it is impossible to have the drops at the same temperature as the steam, due to the difference in pressure between the steam and the water in the drop.

Referring to Figure 8, we have a capillary tube which cannot be wetted, immersed in water. It is a well known fact that the water in the capillary tube would be compressed by the amount h. P will represent the vapor pressure along the surface E, and likewise the pressure of the liquid on the surface E. Pressure P_2 represents the pressure normal to the surface of the semispherical drop. If we let r. represent the radius of the drop in centimeters, σ represents the surface tension of the liquid in dynes per centimeter, then, the total normal pressure will be $\pi r^2 P$ and the resisting pressure will be $2\pi r\sigma$, from which it is evident that P_2 is equal to $2\sigma/r$.

By this method Wilson and Marsden derived the following relation between the pressures $\ln P/P_2 = \frac{1}{RT} \cdot \frac{2\sigma}{r}$. Where R is the gas constant, T, the absolute temperature, and from the fact that Wilson determined that the ratio of the P's was equal to 8 and by means of Wolf's formula for the surface tension of water, it is possible to calculate the radius of the drop in order that the pressure will be equal to that of the vapor. It was found that this radius was 5×10^{-8} cm, which is approaching molecular dimensions.

Of course, it is impossible to in any way determine experimentally this condition, and it is based entirely upon theoretical consideration, which if true, would indicate that the temperature of the drops was quite different from the temperature of the water vapor in order that equilibrium might exist. It is also easily seen that the converse of evaporation is equally true. That is to say, that when a mass of steam starts to condense it is necessary that the condensation start from some appreciable size drop, and if such is the case, the simple thermo equilibrium cannot exist as would exist in case of water vapor over a surface of water.

It would appear as tho the condensation of steam was very erratic, such as having its temperature lowered beyond the point where it could start to condense and then the condensation taking place very similar to explosion.

As Mr. Mellanby says - "At the present time the subject suffers from over-development in a theoretical sense, and the almost complete lack of well defined data renders even in our range of experimental results but little value."

It is somewhat difficult to give any definite information on the effects of supersaturation, for there exist more opinions on the subject than experimental facts and for this reason the author wishes to divide this section into two parts, namely, the the theoretical, and experimental. Of course, there is no definite line dividing the two, for a great many of the theoretical ideas have been developed by trying to interpret experimental data.

In Callendar's treatise on the Properties of Steam will be found many pages, devoted to the pure theory of supersaturation, and for that reason the author will limit the discussion to the theory as developed by other authors.

Experiments have shown that the flow through nozzles is very much greater than would be expected by theory. This is a very disconcerting fact because it would be expected that the flow would be less, due to the friction of the steam passing through the nozzle. Since so many experiments have shown the same results, it would be fair to assume that the experimental error has been eliminated. Thus, by accepting the results of the experiments as a fact, the whole theory of the effects of supersaturation has been developed.

The first application of supersaturation to heat engines, however, was given by Callendar and Nicholson in a paper read before the Institute of Civil Engineers, in London on November 30, 1897. In this paper the authors note the fact that in a reciprocating engine there appear to be what they call a missing quantity of heat and suggested that this might be due to a supersaturation of the steam as it expanded.

The first observations of a nozzle were noted by Lorenz and Stodola, who noted that excess discharge and that the temperature would be well below saturation, though Stodola was unable to detect the low temperature. Though Stodola did not know why, or at least, he did not state why he could not find the temperature lower than that of saturation, it would be quite evident that it is impossible to measure the temperature of a drop, due to the fact that any thermometer immersed in the fluid would produce a condensing surface and would not read the correct temperature.

From this fact, namely, the excess discharge of a nozzle, Martin in 1913 attempted to account for this fact by means of the supersaturation theory.

Martin says that there exist on the temperature entropy diagram, similar sets of hypothetical constant pressure lines, as determined on the P-V diagram of Van der Waals equation. Referring to Figure A-B, if we take dry saturated steam, whose condition is represented by the point E and let it expand adiabatically along the line E-C, it is quite evident that the dryness fraction at the end of expansion is equal to $\frac{CL}{LM}$

If, however, the steam after expanding to the point

C, reached the temperature C, with another dryness fraction, which was less than $\frac{CL}{LM}$, it is evident that it must lie on another pressure curve or the extension of a pressure curve G-B, and for this reason Martin says that there are existing the curve A-C-B on the temperature entropy diagram.

Assuming that the point C is the supersaturation limit, as determined by Wilson, and by determining a set of such conditions we would get another curve, such as W-N, which Martin names the Wilson line.

Later, Martin working upon this assumption, works out what he calls a "new theory of the steam turbine". His purpose for doing this was due to the fact that it was found from test of steam turbines that a greater advantage was obtained by using superheated steam than would theoretically be produced. The manufacturers of turbines have thought this was due to the mechanical or hydraulic efficiency. Martin in his new theory of the steam turbine, showed that this discrepancy could easily be accounted for by assuming that a condition of supersaturation existed when the steam passed through the turbine, because the speed of the steam, or its "life" was a fraction of a second, and therefore, it was highly probable that the nuclei for the steam to condense upon did not exist.

Working on this theory from the radius of the drop and its pressure for equilibrium, the properties at Wilson line can be calculated and table I gives these results.

It will be noticed that corresponding to 40° centigrade, no condensation can take place until the pressure is approximately seven times that of saturated vapor. The effect of such a condition existing in a heat engine is quite obvious, due to the fact that the efficiency of an engine depends upon the ability of that engine to rob the working substance of its heat and a great part of the heat of the working substance of a turbine is obtained due to condensation, and when this condensation does not occur or occurs late, it must of necessity cut down the efficiency, especially if the condition of the fluid is not the same as the turbine blades were designed for.

The theoretical values for the supersaturation limit have been worked up by Callendar and plate 10 shows the total heat on the H log P diagram. The curve A-B represents the adiabatic for saturated steam. The curve A-D, that for dry steam, corresponding from 165 points to one point without condensation. This shows heat drops amounting to 20 per cent. of one point. The curve S-S shows the supersaturation limit, assuming that condensation begins very rapidly when the pressure is eight times the normal saturation, corresponding to the temperature.

If the temperature of the steam cannot fall below this limit, the adiabatic or supersaturated steam A-C will begin to diverge from the drier adiabatic A-D at the point where it crosses the curve S-S, and the latter part of the supersaturation period will approximate more closely to A-B than to A-D.

WORK DONE BY PROFESSOR GOODENOUGH

UNIVERSITY OF ILLINOIS

Since 1920 Professor Goodenough has been working in conjunction with the General Electric Company at Schenectady, New York, in order to determine some of the properties and effects of supersaturated steam on the steam turbine. The properties were determined by taking the results of velocities and discharges on the General Electric Company's nozzles and determining the conditions or properties of the steam, in order to meet the experimental results as obtained. Professor Goodenough worked upon the theory that there were drops of water in the steam as it passed through the nozzle and assuming these drops to be of the diameter as determined by Wilson, he determined the properties of the steam for the critical ratio of p. to ps. = 8, according to Wilson. These results are purely theoretical, which give the coefficient of discharge, as determined by the General Electric Company.

SUMMARY

The work done on supersaturation to this time leads to the fact that it is quite evident that a condition of supersaturation can and does exist up to a certain point. This point has been determined experimentally by Wilson and Stodola, though they differ widely, Wilson determining that the ratio of the pressure of dry saturated steam to that at which condensation would begin under supersaturated conditions, or 8; whereas, Stodola finds it to be 3. As has been said, all evidence points to the fact that a condition other than dry saturated does exist, but what is the cause of this existence is yet not determined. There have been two ideas advanced, one being that the time is an important factor, namely, the steam does not have time to change into water as it passes through a nozzle; the other idea being that the condition of supersaturation is a stable one when nuclei are not present for condensation to take place. All evidence, however, shows that under certain conditions, namely, the pressure ratio being below certain value, that condensation will take place regardless of the ratio of flow through the nozzle, whether or not nuclei are present for condensation. The cause and the properties of this existing condition of the steam has, so far, been hypothetical and theoretical, principally due to the

difficulty of either observing what happens, or of determining the pressure and temperature conditions. The difficulty of determining the temperature has already been mentioned in the first part of this paper, namely, that it is practically impossible to determine with any degree of accuracy, the temperature of a fluid in motion.

CONCLUSION AND SUGGESTIONS

The author can easily conclude by saying that something should be found out, but it would be incomplete without giving some suggestion for the method of procedure. There seems to be no reason to believe that a condition of supersaturation does not exist in all substances as well as in water. As a matter of fact, it has definitely been found to exist in carbon dioxide, for which reason it would seem logical that some substance, or at least not a complex substance should be experimented with at first, and in carrying on this experimental work it would seem that a repetition of Calendar's experiments might lead to more conclusive results, working towards the idea of performing his experiments with more accuracy than could be obtained at that time, and also with the idea of finding whether or not the condition of supersaturation was a stable condition; that is to say, to find whether once the substance was placed in a supersaturated condition, it would remain in such a condition indefinitely, with the pressure and temperature being held constant. Of course, observations on the ratio of pressure must necessarily be made and it must necessarily be determined whether or not the varying of these pressure ratios has anything to do with the existence of the supersaturated state. It may be well also to determine definitely the particular ratio of pressures at which it is impossible to obtain the supersaturated condition. Also, it might be well to find what external changes could be made so as to produce condensation when supersaturation did exist, such as determining definitely whether or not X-Rays would cause any effect.

Although it would seem very probable that such work as this might lead towards giving information on a supersaturated condition, it might be found advisable at the same time to make experiments on the steam as it is in motion, as through a nozzle. Of course, some method must be developed for determining the correct temperature and pressure, and some method must be devised whereby the condition of the steam can be decided upon without depending upon the visibility, as already has been tried by means of glass nozzles. As a suggestion, very accurate resistance thermometers might be imbedded in the side of the nozzle to determine the temperature. Of course, it would be necessary to make the flow of heat through the walls of the nozzles 0, and such a nozzle must be proportioned so as the temperature on the periphery of the jet of steam must correspond very closely to its average temperature. As to determining the condition of the steam, it might be possible to observe what effect on the temperature heat would have by being added to the steam as it passes through the nozzle.

The author would suggest as his preferred method of procedure, that of repeating Wilson's experiments, either upon water or some less complex substance, such as mercury.

Of course, it is realized that, as in all scientific investigations, it would take perhaps the lifetime of an investigator to do this work, and perhaps it would not lead to any definite results.

BIBLIOGRAPHY OF SUPER-SATURATION

Callendar's Book on the Properties of Steam

C. T. R. Wilson
Phil. Trans. 1897 Vol. 189, pp 307

H. M. Martin
New Theory of the Steam Turbine
London Engineering July 5, 1918, Et Seq

The Proportioning of Steam Turbine Blading
London Engineer Jan. 6, 1922, Et Seq

K. Bauman

Recent Developments in Large Steam Turbine Practice
London Engineering April 8, 1921 Et Seq

A. L. Mellanby
The Supersaturated Condition as Shown by Nozzle Flow
London Engineering June 30, 1922 Et Seq

Aitken
Trans. Royal Soc. Edinburgh 1861

Callendar and Nicholson
On the Law of the Condensation of Steam
Proc. I. C. E. Nov. 30, 1897

Callendar
Vapors, Encyclopaedia Britannica, 11th Edition.

Lorenz
Z.V.D.I. October 31, 1903

Stodola
Z.V.D.I. December 5, 1903

Martin
London Eng. Jan. 10, 1913

Callendar
On the Steady Flow of Steam Through a Nozzle or Throttle
Proc. I.M.E. February 1915

Steam Action in Simple Nozzle Forms
British Association Section G - Aug. 1920, or London Engineering, September 3, 1920

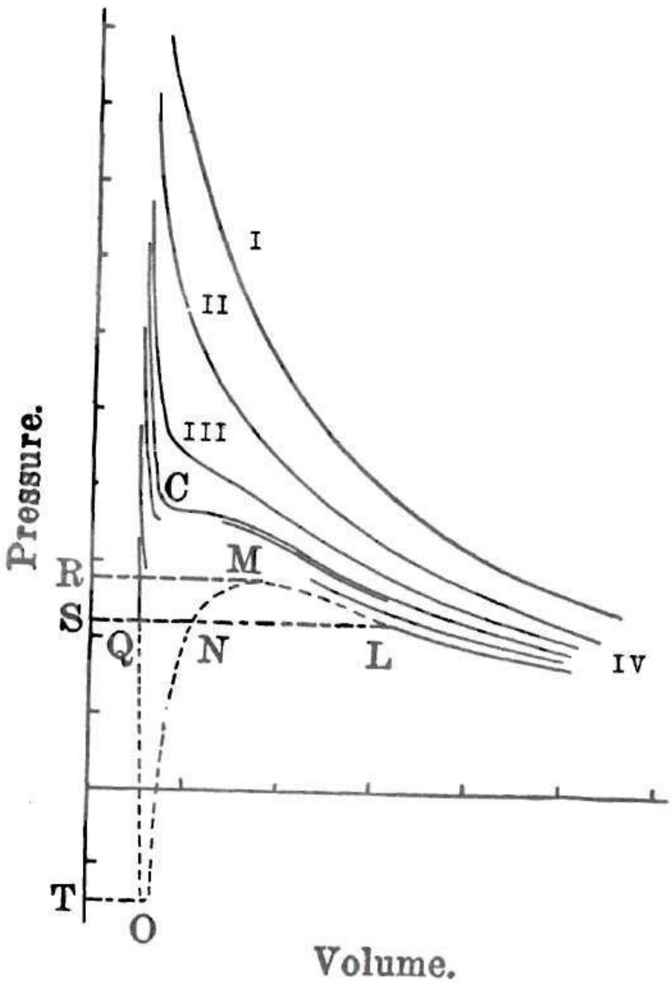
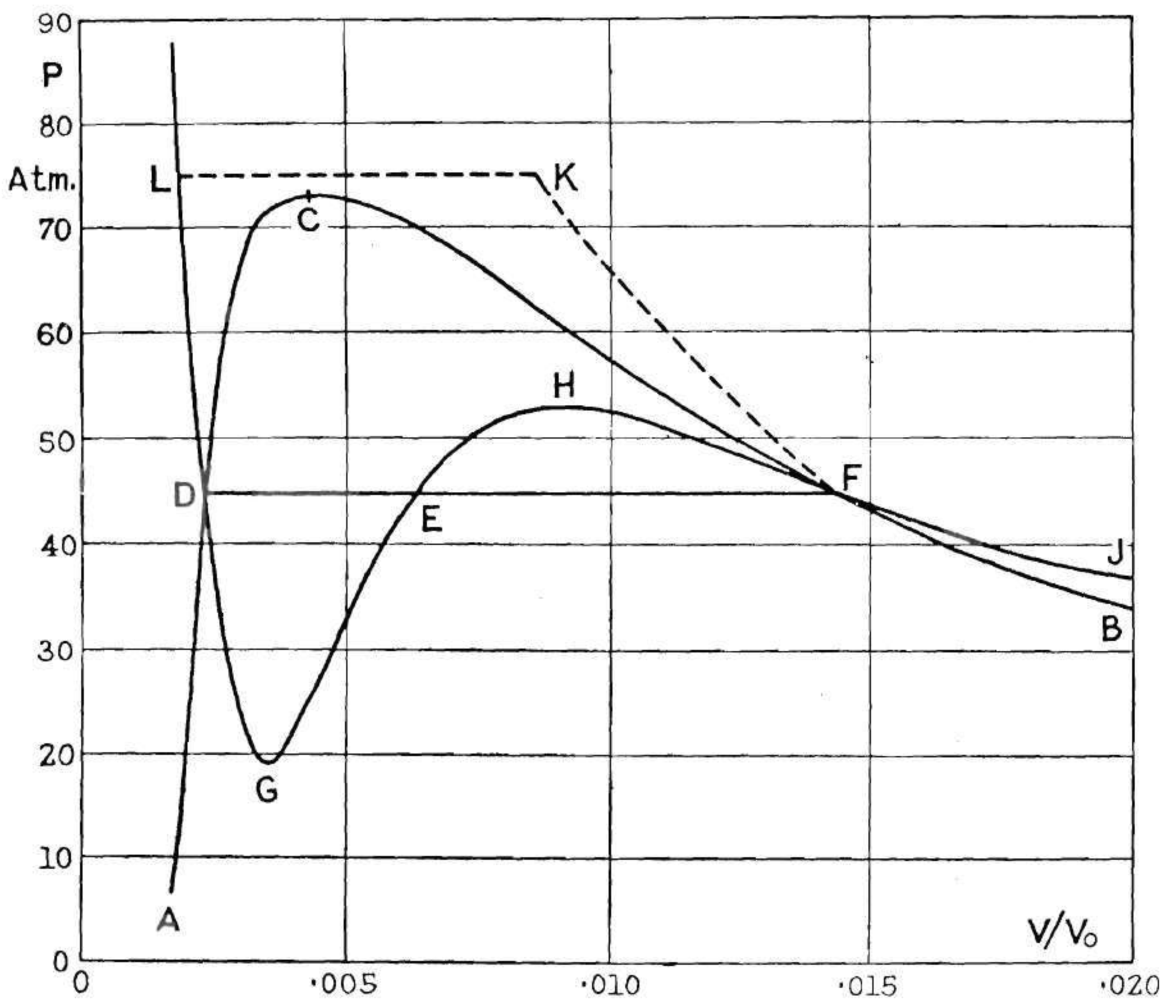


FIG. 1



90
P
80
Atm.
70
60
50
40
30
20
10
0
L
K
C
H
D
F
E
J
B
G
A
V/V₀
0
·005
·010
·015
·020

FIG. 2

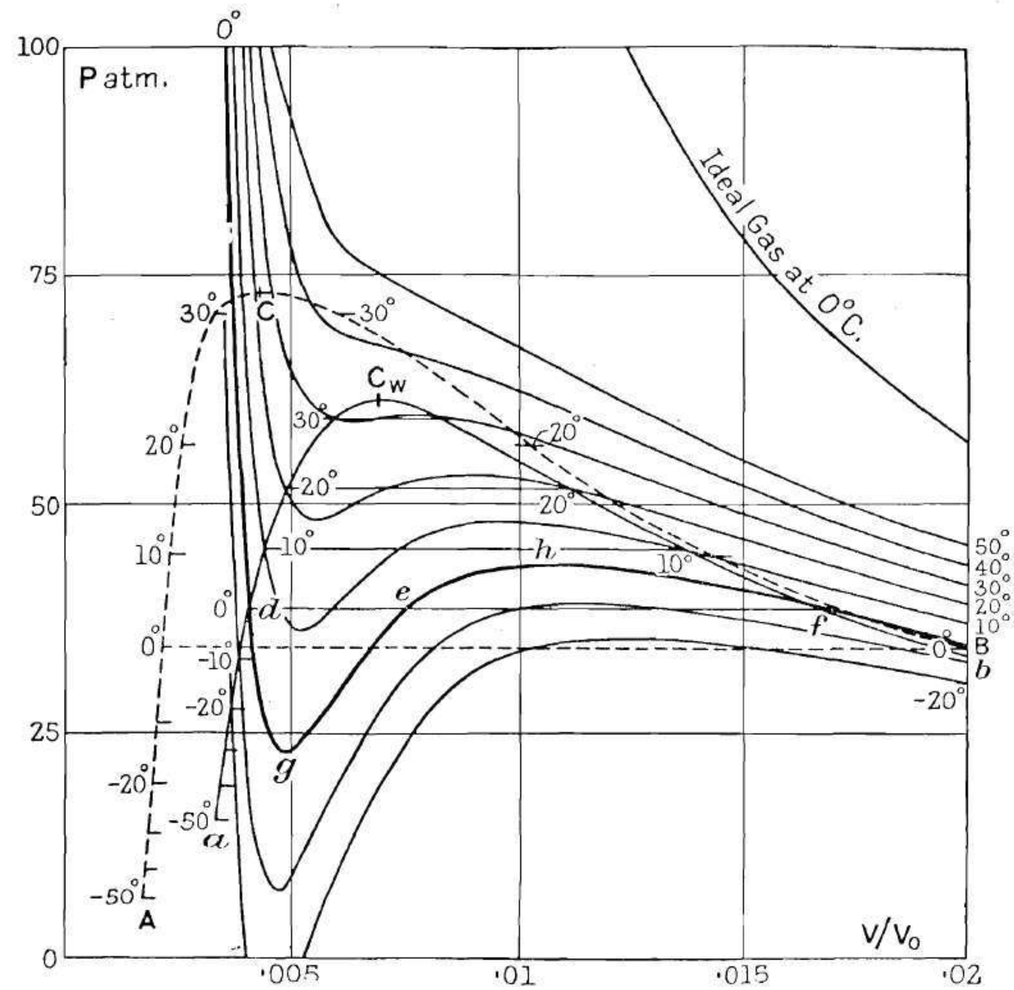

P atm.
Ideal Gas at 0°C.
V/V₀
C
C_W
A
B
a
b
d
e
f
g
h
50°
40°
30°
20°
10°
0°
-20°
-50°
100
75
50
25
0
·005
·01
·015
·02

FIG. 3

Page missing from thesis

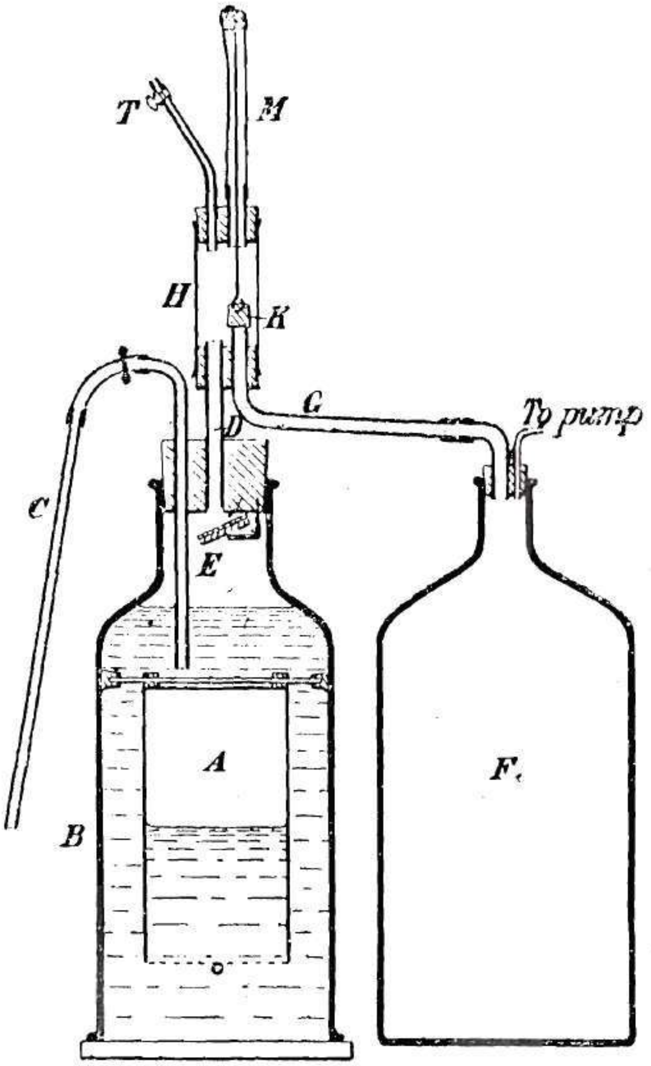


FIG. 5

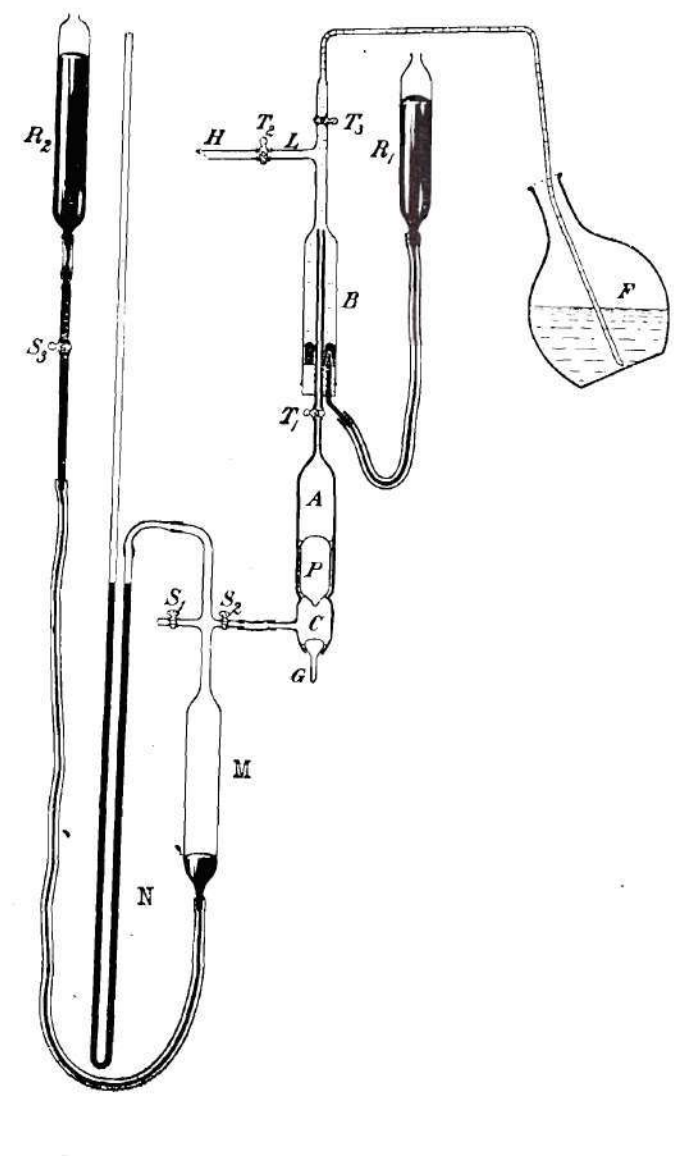


FIG. 6

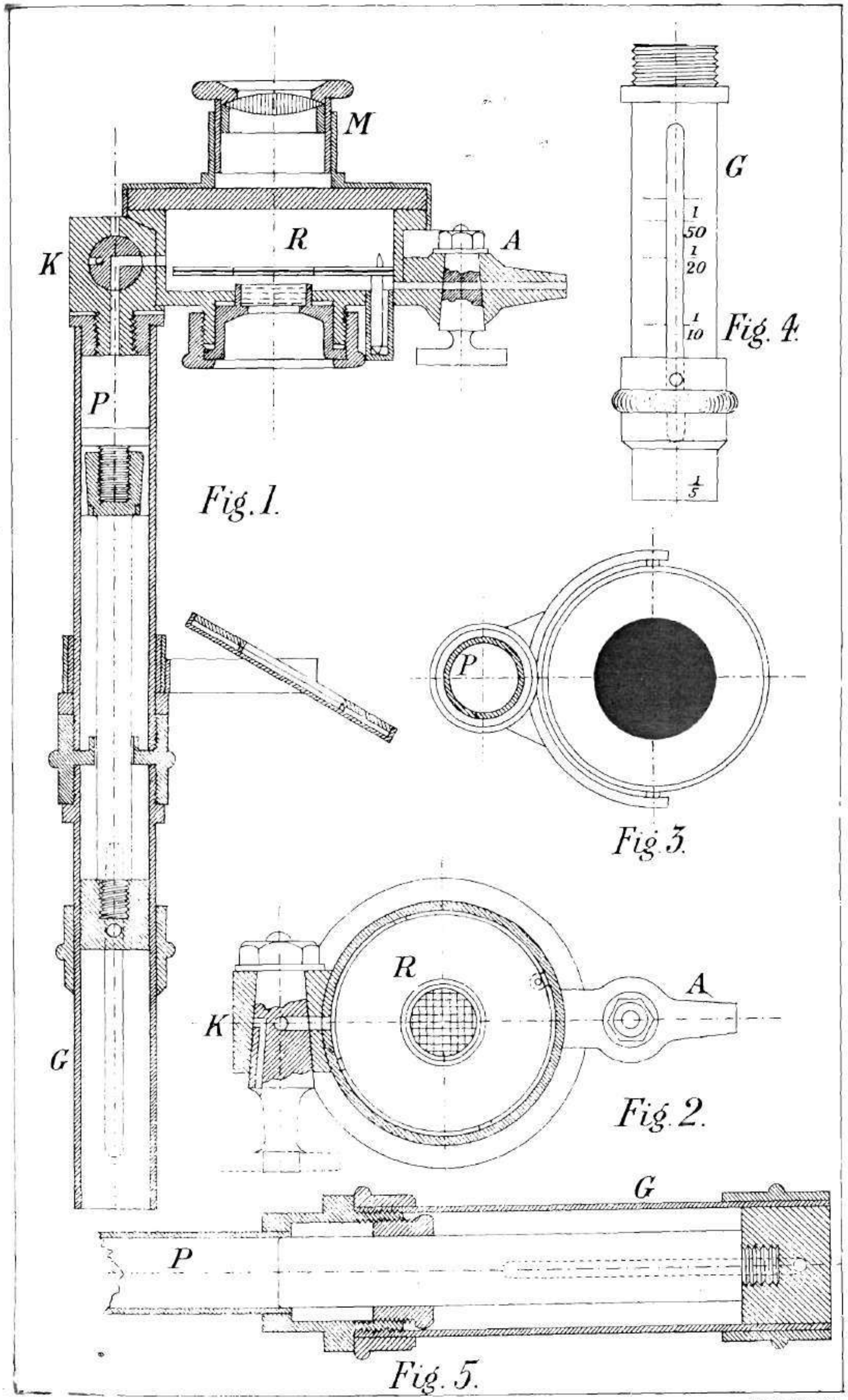

M
R
K
A
P
G
1
50
1
20
1
10
1
5
Fig. 4.
Fig. 1.
Fig. 3.
Fig. 2.
Fig. 5.
A. Ritchie & Son, Edin.

FIG. 7

Fig. 6.

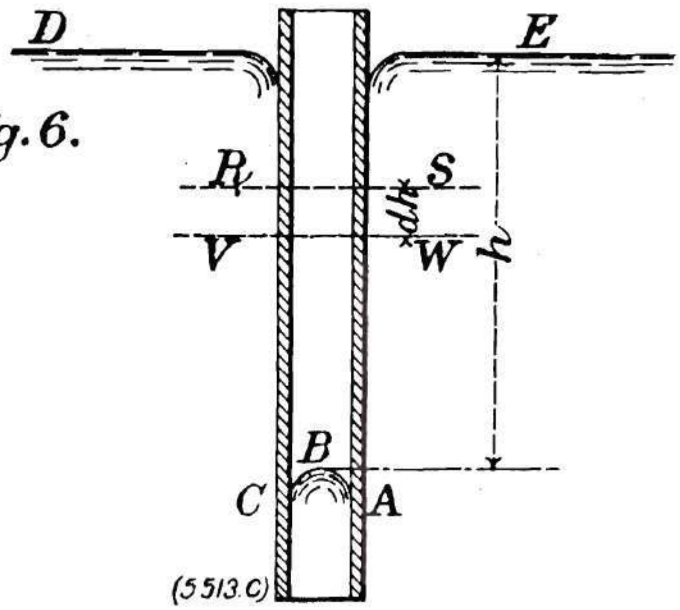


FIG. 8

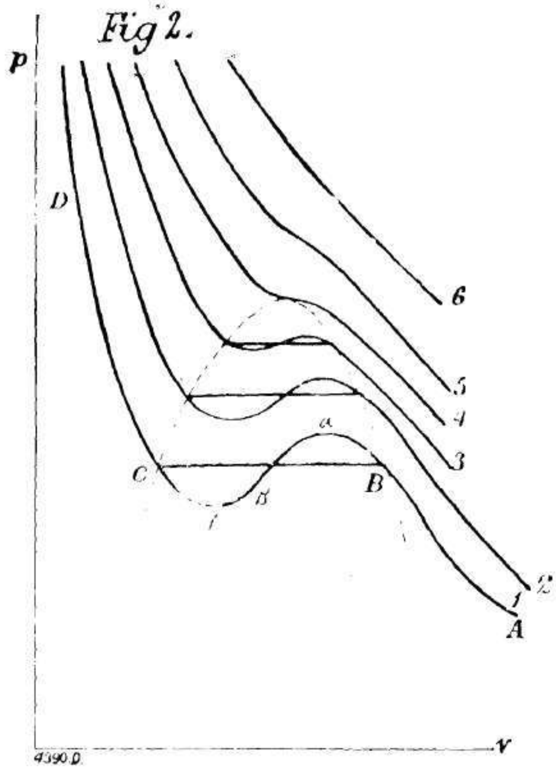


Fig 2.
p
D
6
5
4
3
C
B
a
2
1
A
v
4390.D.

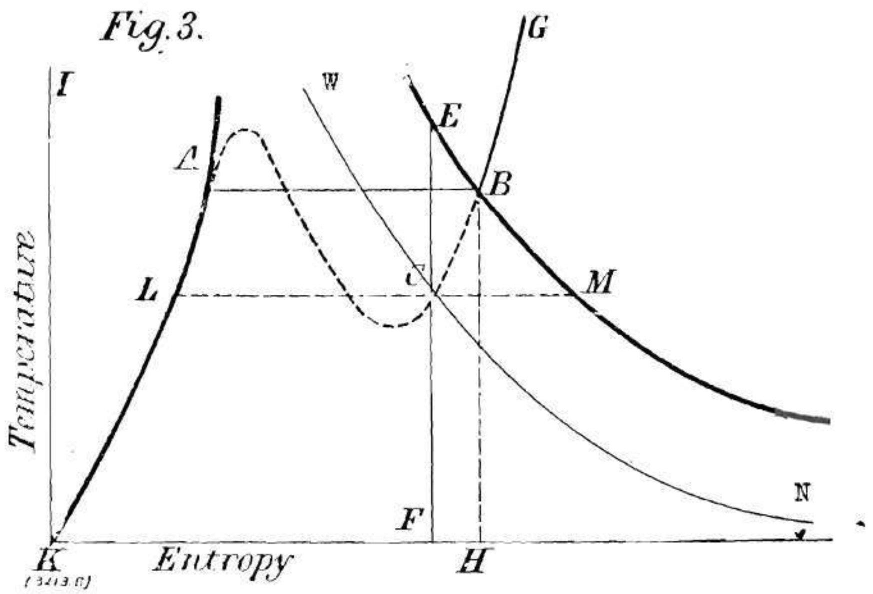


Fig. 3.
I
W
G
E
B
L
C
M
Temperature
N
F
K
H
Entropy

FIG. 9

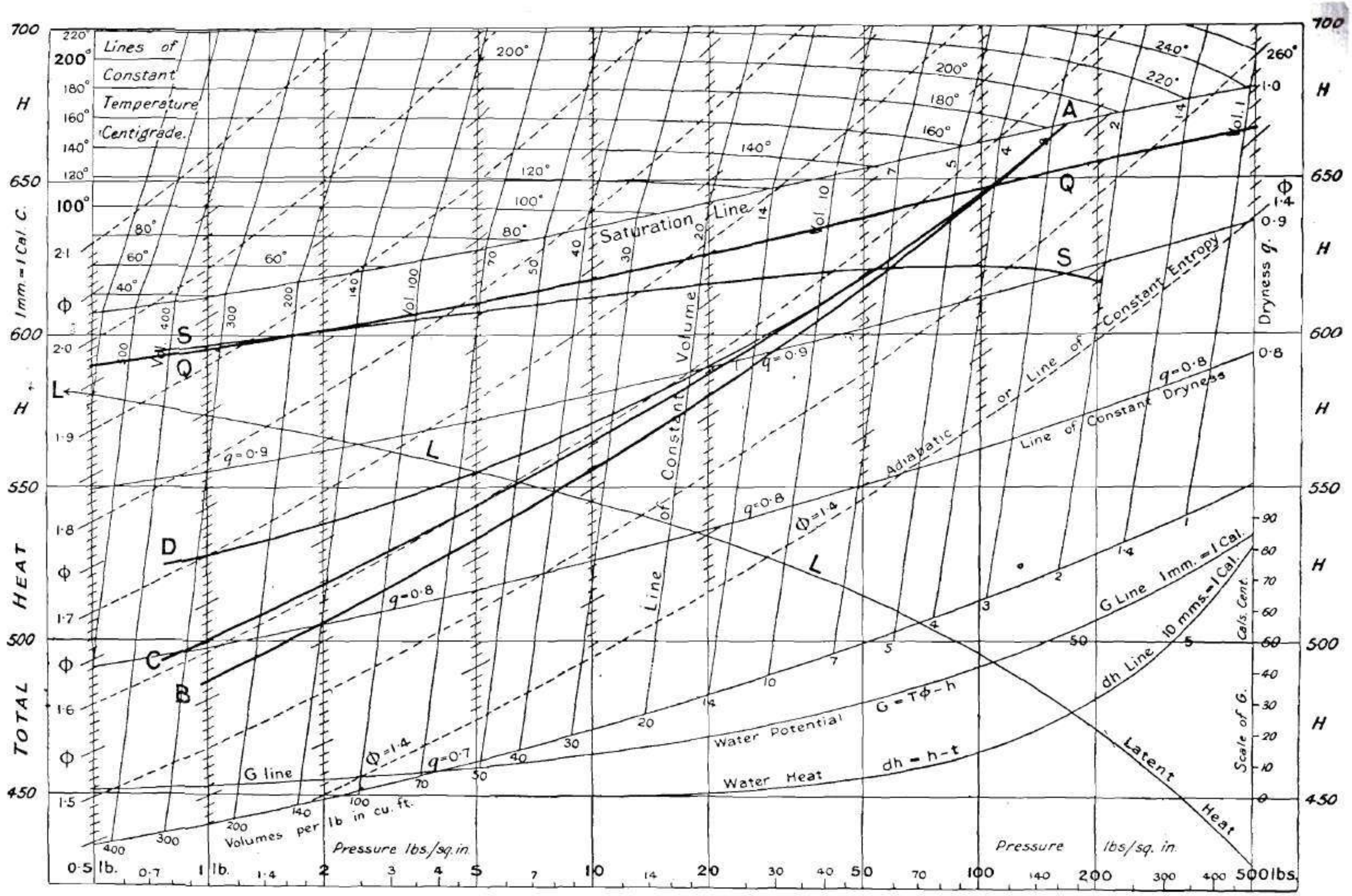

Lines of Constant Temperature Centigrade.
Saturation Line
Line of Constant Volume
Adiabatic or Line of Constant Entropy
Line of Constant Dryness
q=0·9
q=0·8
q=0·7
Φ=1·4
G line
G Line 1mm.=1 Cal.
dh Line 10 mms.=1 Cal.
Water Potential G=TΦ−h
Water Heat dh=h−t
Latent Heat
Volumes per lb in cu. ft.
Pressure lbs/sq. in.
TOTAL HEAT
1mm.=1 Cal. C.
Dryness q.
Scale of G. Cals. Cent.
700
650
600
550
500
450
0·5 lb.
1 lb.
500 lbs.

FIG 10

PROPERTIES OF STEAM AT WILSON L.

Temp. oC	Press. /sq.in.	Vol. ft/cu.ft.	Equit. Temp. oC	Equit. Vol. cu.ft/lb.	Total Heat F.P.C.	Entropy
0	.988	295.3	38.52	325.85	593.79	1.9098
10	1.739	173.3	49.41	191.50	598.28	1.8641
20	2.935	106.1	60.33	116.91	602.64	1.8220
30	4.764	67.44	71.19	74.218	606.85	1.7825
40	7.478	44.091	82.13	48.474	610.90	1.7476
50	11.39	29.732	93.00	32.666	614.75	1.7141
60	16.81	20.566	103.89	22.576	618.36	1.6830
70	24.36	14.531	114.80	15.951	621.70	1.6537
80	34.41	10.506	125.66	11.537	624.56	1.6261
90	47.60	7.720	136.57	8.638	627.47	1.5998
100	64.64	5.778	147.48	6.353	630.01	1.5748
110	86.28	4.389	158.40	4.832	632.10	1.5508
120	113.37	3.376	169.48	3.713	633.89	1.5278