In an experiment described by Professor J. J. Thomson, a beam of cathode rays was bent to a radius of curvature of 9 cm. in a field of 35 units. Thus a field of 315 would have been required to bend it to a radius of 1 cm.

Let us now collect the results obtained, and compare them with this. The field which would be required to produce a curvature of 1 cm. radius would be

For cathode rays	3×10^2
,, Becquerel rays	5×10^3
,, Röntgen rays not less than	6×10^7.

If the Röntgen rays are magnetically deflected at all, it is by an amount less than a ten-thousandth part of that observed in the case of the Becquerel rays.

The magnetic deflectibility of the Becquerel rays cannot but be considered to be a most characteristic property. And the above result appears to make it tolerably certain that the Röntgen rays do not possess this property. It is to be concluded, therefore, that the Becquerel rays are, after all, essentially different in character from the Röntgen rays.

"An Experimental Investigation of the Thermo-dynamical Properties of Superheated Steam." By JOHN H. GRINDLEY, B.Sc., Wh. Sch., Exhibition (1851) Scholar, late Fellow of the Victoria University. Communicated by Professor OSBORNE REYNOLDS, F.R.S. Received April 21, 1899,—Read January 18, 1900.

(Abstract.)

PART I.—*On the Law of Flow of Saturated Steam through Small Orifices.*

In making experiments on the thermal properties of superheated steam obtained by wiredrawing saturated steam, it is essential that certain laws assumed in theory to govern the flow through the orifice should obtain in practice.

Among these laws the only one on which a difference would be expected to exist between experiment and theory, is the law of adiabatic expansion assumed to hold during the flow.

Since such adiabatical flow is not only assumed, but is indispensable in obtaining temperature results in the wiredrawn steam which will enable deductions to be made by theory of the initial dryness of the steam or its thermal condition after wiredrawing, it was found im-

portant to know the circumstances under which adiabatic flow could be experimentally obtained.

Many experimental results have already been given by various experimenters which indicate the laws governing the flow through various types of orifices, and to some extent bear out the theoretical conclusions on the subject, but so far as the author is aware, no experiments have yet been made with saturated steam, showing results which entirely agree with those deduced from theory by assuming adiabatic flow, and hence arose the necessity of making experiments with this object in view.

It appears from the theory, that when the ratio (the lower to the higher) of the two pressures causing the flow through the orifice is diminished below a certain value, the upper pressure being kept constant, the rate of discharge of the steam should be constant. This value of the pressure ratio depends entirely on the law of expansion assumed to hold during the flow. By assuming this law to be represented by an equation of the form

$$pv^n = \text{constant},$$

p being the pressure, v the specific volume of the gas, and n a constant for any particular gas, we can deduce this value of the pressure ratio giving maximum flow in the form

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}.$$

Putting $n = 10/9$ we get for saturated steam expanding adiabatically during its flow through the orifice.

$$\frac{p_2}{p_1} = 0{\cdot}5824.$$

If now the flow of steam be truly adiabatic in an experiment, this particular value of the pressure ratio giving the maximum flow should be actually found by the experiment, and if some other value than this be obtained the law of flow will not then be the true adiabatic one for saturated steam.

Hence the attainment of this particular value of the pressure ratio giving the maximum discharge was made the object of the experimental inquiry here described, since it would follow that the law of expansion through the orifice was then truly the adiabatic law for saturated steam.

To begin with, an orifice was drilled in a piece of thin sheet brass the nature of which should create, if possible, a large deviation from the adiabatic in the actual law of flow through the orifice. Experiments were then made with this orifice placed between a steam chest and a condenser, the weight of steam passing per minute being taken

at various pressures over a wide range of pressure ratio, the upper pressure being kept constant. It was found that the maximum rate of discharge did not occur until the ratio of pressures had fallen to 0·33, a value far below that given by the theory, and indicating a far different law of flow through the orifice than the adiabatic.

As a contrast to this, since the main element in the question appeared to be the conductivity of the substance in which the orifice is made, the later experiments were made with an orifice drilled in a glass plate, the orifice being neither sharp lipped nor smoothly rounded, the lip in the best circumstances presenting a rough chipped edge. Now with such material for an orifice plate, it is evident that any passage of heat between the glass and the steam will be very small, and also that if adiabatic flow is not now obtained, then either there must be a passage of heat between various portions of the glass and the steam in contact with them, or heat must be conducted along the stream of vapour itself, the latter being considered negligible from considerations of gaseous conductivity.

The experiments made with this orifice show a complete agreement between the results of experiment and theory, and that the law of flow through an orifice drilled in a plate of glass, no conditions being attached as to the roundness or otherwise of the lip of the orifice, is precisely the adiabatic law assumed in the theory.

PART II.—*On the Cooling of Saturated Steam by Free Expansion.*

In Regnault's experiments on the total heats of saturated steam under various pressures, the steam was withdrawn upwards from a boiler, allowing any entrained moisture in the steam to be separated by gravity. Saturated steam obtained in any other manner would not necessarily have the same total heat as that obtained by Regnault at the same pressure, and it is therefore of great importance to note that the dryness of the steam in Regnault's experiments was obtained by the simple method of draining suspended moisture from it.

Hence, since the foundation of most of the researches on het thermal properties of steam rests upon Regnault's results, it would be well to accept as a definition of dry saturated steam that condition of steam which is obtained by draining from wet steam any entangled moisture.

In making experiments on the thermal condition of superheated steam obtained by wiredrawing saturated steam, a knowledge of the total heat of evaporation of the steam before wiredrawing is necessary, and as Regnault's tables of the total heats of saturated steam only apply to steam obtained in the above manner, it must also be obtained in the same manner for these tables to apply.

The precise object of this paper is to describe a research on the thermal properties of superheated steam, these properties being deduced

from a knowledge of those of saturated steam already obtained by Regnault.

The temperature and pressure of saturated steam in a steam chest in which a constant supply of steam is kept is taken, the steam is then drawn upwards to an orifice, and, after wiredrawing, its pressure and temperature are again taken, using for the determination of the latter a thermo-electric junction immersed in the steam.

Special precautions were found necessary, and special apparatus designed to prevent losses of heat by radiation from the channel containing the wiredrawn steam, a steam jacket of peculiar construction enveloping this channel completely, and by adjusting the temperature of the jacket to equality with that in the wiredrawn steam, all radiation was effectively prevented from this portion of the apparatus.

Again, communication of heat from one side to the other of the orifice through the substance in which the orifice is made was prevented, and true adiabatic flow obtained through the orifice by drilling it in a piece of plate glass, such as that described in the research on the law of flow through orifices.

During an experiment, the pressure in the steam chest being kept constant, a series of temperature readings at various values of the lower pressure were observed in the wiredrawn steam. By this means a curve showing the cooling of the steam for any degree of wiredrawing from an initial constant pressure could be drawn on a pressure-temperature diagram.

Provided now that the total heat of steam before passing the orifice was known, it would be possible to deduce from these temperature and pressure results the values of the mean specific heat at constant pressure of superheated steam between the saturated condition and the temperature of the wiredrawn steam at any given pressure, and further, the total heat of steam at any pressure and temperature obtained by such wiredrawing, would be known.

Whether the steam was in the same condition before wiredrawing as that obtained in Regnault's experiments was certainly not an easy point to decide. In both cases, however, the steam was obtained by draining any suspended moisture from steam initially wet, but whether this process of drainage always brought the steam into the same condition as to dryness, whatever the degree of wetness originally in the steam, was as yet an open question, which could only be decided by experiment. Accordingly experiments were conducted with saturated steam at a known pressure and temperature in the steam chest, but at different degrees of wetness in different experiments. The results obtained are very important, as the maximum difference of temperature at any particular pressure in the wiredrawn steam which could be found to exist between experiments with different degrees of wetness in the steam in the steam chest was 0·35° F., and generally the differ-

ence could not be distinguished, it being remarked that if the dryness of the steam before passing the orifice had been altered by so little as 0·06 per cent., a difference of 1° F. should have been observed in the temperature of the wiredrawn steam.

It would, therefore, appear that saturated steam at any particular pressure obtained by relieving it of suspended moisture by gravitation has only one condition as to its dryness, and also that steam in this particular condition was obtained both in these experiments and in those of Regnault, and it is therefore taken that the steam before wire-drawing has a total heat given by Regnault's tables of the total heats of saturated steam.

Further experiments were also made to observe the effect of altering the position of the thermo-electric junction in the wiredrawn steam, of the effect of the steam jacket on the temperature of the wiredrawn steam, and of the effect of the velocity of the steam through the apparatus on these temperature readings. The amount of the corrections required for the conduction of heat between various portions of the apparatus and the steam was also calculated, but on account of the precautions taken these were generally found to be negligible. The method of fixing the absolute temperature of the wiredrawn steam should be here mentioned, as it is a point of great importance, on account of the difficulties attending the accurate measurement of the temperature. In the experiments the thermometer was used merely as a scale to compare the temperature of the wiredrawn steam with that of saturated steam under a known pressure flowing through the same portions of the apparatus with about the same velocity, the fixing of the temperature being again dependent on Regnault's tables of the pressure-temperature relation of saturated steam.

The final results obtained show clearly that within the limits of temperature obtained by wiredrawing saturated steam at temperatures varying from 240° to 380° F., the condition of the steam known as a perfect gas was not obtained, even when the wiredrawing was continued to 3 lbs. or 4 lbs. per square inch absolute pressure; and further, that between the same temperatures and between pressures of 2·5 lbs. and 195 lbs. per square inch, there was not found any indication of a constant value of the specific heat at constant pressure in the superheated steam. The specific heat at constant pressure was found to increase with temperature, the mean specific heat at atmospheric pressure between the temperatures 230·7° and 246·5° being 0·4317, and between temperatures 295° and 311·5° the mean specific heat was 0·6482.

As regards the variation in the value of the specific heat at constant pressure of superheated steam with the pressure, it appears from an examination of the results obtained at about the same temperature but under different pressures, that if any such variation in the

specific heat exists it will be very small compared with the variation with temperature, such examination indicating that the value of the specific heat is sensibly independent of the pressure.

The law of cooling followed by the wiredrawn steam is slightly different from that obtaining in many other gases, viz., that the fall of temperature varies directly as the difference of pressure. The rate of cooling was found to diminish with increase of initial temperature.

The curves showing the pressure-temperature relations of the superheated steam wiredrawn from definite initial pressures, seem to follow for a short distance the law of boiling points, and the experiments show that this coincidence always exists in saturated steam, and may well be mistaken for evidence of wetness in the steam.

Tables showing the fall of temperature with pressure in the wiredrawn steam, of the total heat of the steam under certain pressures and temperatures, and of the mean value of the specific heat at constant pressure of superheated steam at definite pressures and between definite temperatures, accompany the paper.

Part III.

In this portion of the paper the two properties of steam deduced directly from the experimental figures, viz., the specific heat K_p and the cooling effect $\delta\theta/\delta p$ or c, are more directly considered. In the first place, the cooling effect c is found to be inversely proportional to $\tau^{3\cdot8}$, where τ is the absolute temperature.

It is then shown that the following formula

$$\frac{\partial}{\partial p}(K_p) = -\frac{\partial}{\partial \tau}(cK_p)$$

is capable of strict proof from thermodynamical principles, the interpretation of the formula being that the variation of K_p with the pressure at constant temperature is equal to the variation of the product cK_p with the absolute temperature at constant pressure, but of opposite sign.

Applying this to steam when superheated, it has been shown in Part II of the paper that the variation $\frac{\partial}{\partial p}(K_p)$ is zero to the degree of accuracy to which the experiments have been taken. It follows, therefore, from the above formula, that the variation $\frac{\partial}{\partial \tau}(cK_p)$ should equal zero; hence, the values of the product cK_p have been tabulated for different pressures and temperatures, and so far as the results go, it is clearly shown that the product cK_p is an absolute constant, which means that the variations $\frac{\partial}{\partial \tau}(cK_p)$ and $\frac{\partial}{\partial p}(cK_p)$ are both zero.

Since the variation $\frac{\partial}{\partial \tau}(c\mathrm{K}_p) = 0$, it is possible to integrate at once for the case of superheated steam Thomson's formula for the cooling effect c, which may be written

$$\frac{d\tau}{\tau} = \frac{dv}{v + c\mathrm{K}_p},$$

the resulting equation being

$$\frac{v + c\mathrm{K}_p}{\tau} = \mathrm{A},$$

when A may be a function of the pressure. This equation has been used to find the specific volumes of superheated steam under various conditions of pressure and temperature, the value of A being deduced from known data in the saturated condition of the steam.

The calculated specific volumes, the accuracy of which depends solely on the experimental results obtained in the research, are compared with those obtained experimentally by Hirn, the results in general agreeing very well.

It is also of interest to notice that in any gas in which K_p does not vary with the pressure, the product $c\mathrm{K}_p$ must also be independent of the temperature in that particular gas, since the equation

$$\frac{\partial}{\partial p}(\mathrm{K}_p) = -\frac{\partial}{\partial \tau}(c\mathrm{K}_p)$$

must be satisfied identically, and hence the equation

$$\frac{v + c\mathrm{K}_p}{\tau} = \frac{dv}{d\tau}$$

must be immediately integrable for the gas in the form

$$\frac{v + c\mathrm{K}_p}{\tau} = f(p).$$