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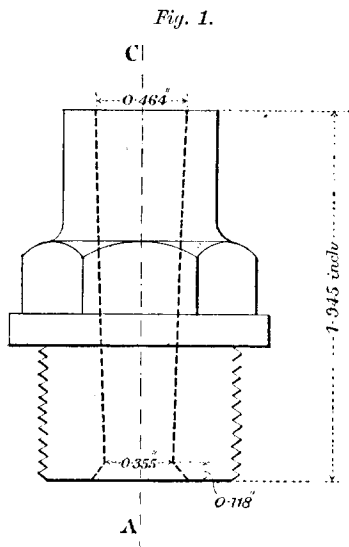
(Abridged.)

“The Temperature Gradient in De Laval Steam-Nozzles.”

By CYRIL BATHO, M.Sc., B.Eng.

THE present Paper describes some researches carried out by the Author during the year 1906 to determine the temperature gradient along a steam-turbine nozzle. The experiments, under the direction of Professor W. H. Watkinson, M. Inst. C.E., were commenced at the Walker Engineering Laboratories of the University of Liverpool, but some delay was caused during the summer by the failure of the steam supply at the University; through the courtesy of Mr. J. A. Brodie, M. Inst. C.E., City Engineer, however, work was resumed at one of the Liverpool Corporation refuse-destructors.

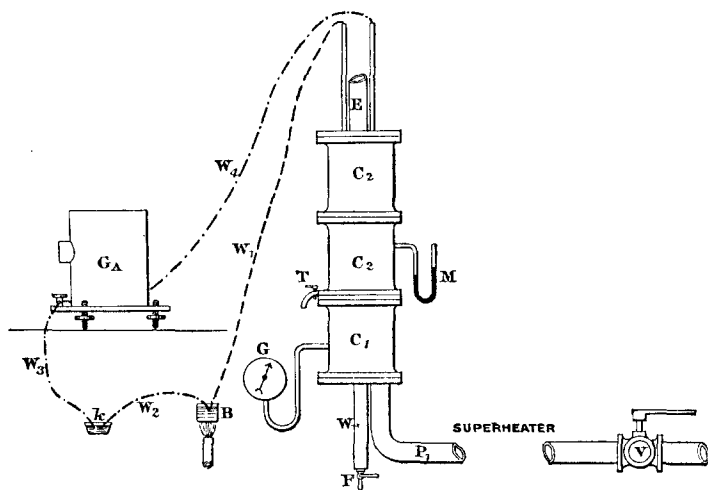
The De Laval nozzle is of the form shown in *Fig. 1*. Steam at a high pressure but low velocity enters the nozzle at A, and emerges from it at a high velocity but low pressure at C, a portion of its potential energy being converted into kinetic energy. In order to determine the action experimentally it is necessary to obtain the temperature, pressure and dryness of the steam at various points within the nozzle. Previous experimenters, for instance Dr. Stodola¹



¹ A. Stodola, “Steam-Turbines.” London, 1906.

of Zürich, have determined the pressure-distribution along the axis of the nozzle, by means of a small central tube having holes bored in its sides. This method is not very reliable, and the results obtained depend on the slope of the holes and the character of their edges; moreover the tube much increases the resistance to flow. It was suggested to the writer by Dr. J. H. Grindley, Assoc. Inst. C.E., then lecturer in Applied Mechanics at the University of Liverpool, that in the case of saturated steam the temperature, and hence the pressure, along the axis might be determined by means of a thermojunction. Precautions had to be taken to prevent the stream of vapour from impinging against the junction, which would cause too high a temperature to be registered, and it appeared that the only

Fig. 2.



way was to form the junction in a wire stretched along the axis of the nozzle. The wire had to be of small diameter to minimize the resistance to the steam, and the junction had to be practically a point so as to obtain the temperature at one section only; the wires used in the experiments had a diameter of 0.008 inch, and a point-junction was obtained by a method which will be described later.

Fig. 2 shows the general arrangement of the apparatus, and Fig. 3 the details of the cylinders, etc. Steam entered through the pipe P_1 to the cylinder C_1 , its pressure being regulated by means of the valve V ; from there it was discharged through the nozzle N into the exhaust-chamber C_2 , and finally passed into the atmosphere by means of the exhaust-pipe E , which was $1\frac{1}{2}$ inch in diameter. The

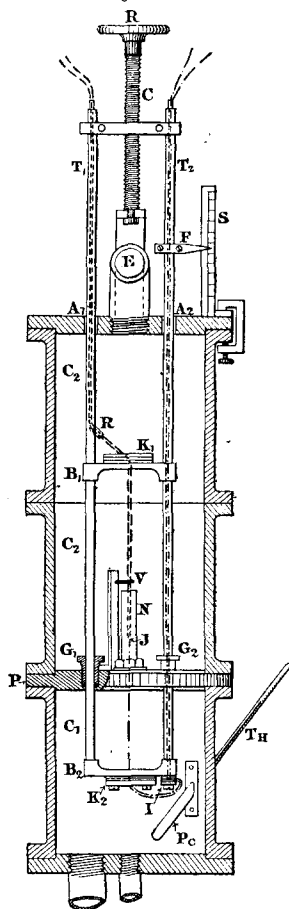
pressure in the supply-chamber C_1 was measured by means of a Bourdon pressure-gauge G , whilst a U-tube M , containing mercury, was used to measure the pressure in the exhaust-chamber C_2 .

The cylinder C_1 was of cast-iron $\frac{3}{8}$ inch thick, and was $7\frac{1}{4}$ inches high and of $6\frac{1}{4}$ inches internal diameter. Any condensed water collected in a well W , and was allowed to escape through a cock F ; this cock also served as an additional means of regulating the pressure in C_1 . The exhaust-chamber consisted of two cast-iron cylinders, each $\frac{1}{4}$ inch thick and $7\frac{1}{4}$ inches high. The cast-iron plate P , spigoted into C_1 and C_2 , carried the nozzle N under test, this being screwed into a central hole.

The measurement of the temperatures along the nozzle was made by means of a thermo-junction J (*Fig. 3*), the wires leading from this junction being stretched axially along the nozzle. Another junction was placed in a bath of cylinder-oil B (*Fig. 2*), and connected to the first by the wires W_1, W_2, W_3 and W_4 . The circuit also included an Ayrton-Mather aperiodic galvanometer G and a mercury key k .

In the earlier experiments platinum and platinum-iridium wires were used (0.01 inch in diameter) welded together in an oxy-hydrogen flame, but no satisfactory point-junction, without increased size at the weld, could be so obtained. The form finally adopted was a loop-junction formed of iron and german-silver wires, 0.008 inch in diameter, as shown in *Fig. 4*; the loop was made as narrow as possible, and the wires were quite close together. A point-junction was thus obtained, offering very little resistance to the flow of steam. Considerable difficulty was experienced at first in obtaining a thermo-junction which would not break after a few minutes' exposure to steam, and the best seldom stood more than 5 or 6 hours' exposure. Much depended upon the manner of insertion, the wires had to be stretched fairly tightly, and precautions taken to ensure that an equal tension

Fig. 3.



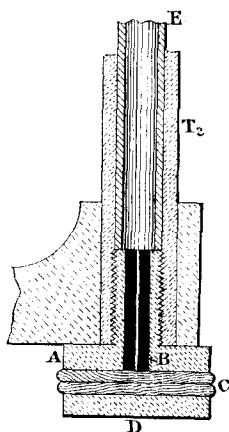
was given to the two limbs of each loop. It was noticed that breakage of the wires generally occurred at nearly the same point relatively to the nozzle, wherever the junction might be at the time. This point was in the nozzle and about $\frac{1}{8}$ inch below the outlet, which was singular, as it did not appear that the greatest amplitude of vibration would occur here. It was thought that a single steel wire might be used in place of the two loops, the thermo-junction being formed by annealing the steel up to a known point; it was not, however, found possible to anneal the steel uniformly, though by using a specially prepared material the method may yet be successful.

Fig. 4.



Several methods were tried for supporting the wire in the nozzle; that finally adopted was as follows: Two brass tubes, T_1 and T_2 (Fig. 3), $\frac{3}{8}$ inch in diameter and $\frac{1}{16}$ inch thick, passed through glands G_1 and G_2 in the nozzle-plate, and through easy-fitting holes in the top cover. They carried two bridge-pieces, B_1 and B_2 , placed 14 inches apart, and carefully set in a direct line with the axis of the nozzle. The wires passed through $\frac{1}{8}$ -inch diameter holes drilled in the centre of these pieces, and were held by the insulating clamps K_1 and K_2 . The upper wire entered the tube T_1 through the rubber plug R , and the lower wire passed through an insulating gland I into the tube T_2 .

Fig. 5.



A separate view of the insulating gland I is shown in Fig. 5. It consisted of a brass plug A screwed into the tube T_2 , into the centre of which a hole was bored, and fitted with a piece of insulating fibre B . The wire passed through this hole, so as to prevent all contact with the metal, and was caught between two pieces of asbestos C , which were held by a brass plate D fastened to A by two screws—not shown in the figure. Both T_1 and T_2 were lined with glass tubing as shown at E . To reduce the vibration in the unsupported wire between B_1 and B_2 a guide V was used, carried by a brass standard S insulated at the foot. Very slight but quick vibrations still occurred, but they had the effect of keeping the junction clean.

To alter the position of the junction in the nozzle, the tubes T_1 and

T_2 were slid up and down, being operated by the screw R working in a collar C. The position of the junction in the nozzle was found as follows: two holes were bored in the exhaust-cylinder, one level with the top of the nozzle and the other a little higher. The junction was adjusted to be exactly on a level with the top of the nozzle, by sighting through the lower hole, and sliding the tubes T_1 and T_2 up or down until the right position was attained; the interior of the cylinder being illuminated by a light applied to the upper hole. A finger F, screwed to T_2 and sliding against a scale S, was then adjusted to the zero of the scale; the junction could be thus set to any required position in the nozzle. During a test the two holes in the cylinder were plugged up.

To ascertain whether unequal expansion of the wires and of the brass tubes affected the position of the junction relatively to the scale, steam was admitted to the bottom cylinder until the apparatus was thoroughly heated. It was then shut off, and the position of the junction was examined, but no alteration relative to the scale was found. This operation was repeated after each experiment.

The wires leaving the tubes T_1 and T_2 were connected with other wires of the same material to prevent exterior thermo-electric effects. Thus, the wires W_2 , W_3 and W_4 (*Fig. 2*) were all of iron, whilst W_1 was of german-silver. All these wires were renewed each time a new junction was put in, and in the later experiments the wires leading from the tubes T_1 and T_2 were in one piece with the wires in the tubes. The second junction, i.e., the one between W_1 and W_2 , was immersed in an iron cup B, filled with cylinder-oil, and heated by means of a blow-lamp.

The key k consisted of a porcelain crucible filled with mercury, into which the wires W_2 and W_3 dipped.

Method of Experimenting.—The thermo-junction having been adjusted, and the cocks T and F (*Fig. 2*) opened, steam was turned on and allowed to flow through the apparatus for some time, until a steady condition was attained, and water ceased to collect in the well W. The cock F was then shut, and the pressure in C_1 was adjusted by means of the valve V. The readings were then taken in the following manner:—The oil-bath B was heated until the temperature of the thermo-junction placed in it was higher than that of the junction J, which was observed by repeatedly closing the circuit at K. The bath was then allowed to cool, K remaining closed, until the galvanometer recorded zero deflection; at this moment the temperature of the junction in the bath B was equal to that of the junction J, and

therefore to that of the steam in the nozzle at the point J. The thermometer in B was then read, as well as the back-pressure recorded by the mercury-gauge. The pressure and temperature in C_1 were of course kept constant during each experiment, and the pressure in C_1 had to be regulated very carefully, as even a slight change caused inaccuracy in the observed temperatures. It really would have been more satisfactory if a mercury-manometer instead of the Bourdon gauge had been used.

The first reading was taken when the junction J was in its lowest position, and subsequent readings as the junction was moved upwards towards the mouth. In this way it was possible, under favourable conditions, to obtain all the readings for one set of conditions with one heating of the bath B; usually however it was necessary to heat it several times. Readings could only be taken whilst the temperature of B was falling, because when rising the currents in the oil caused deceptive temperatures to be recorded by the bath thermometer, even though the junction was coiled round its bulb. Each pair of junctions was calibrated before being placed in the apparatus.

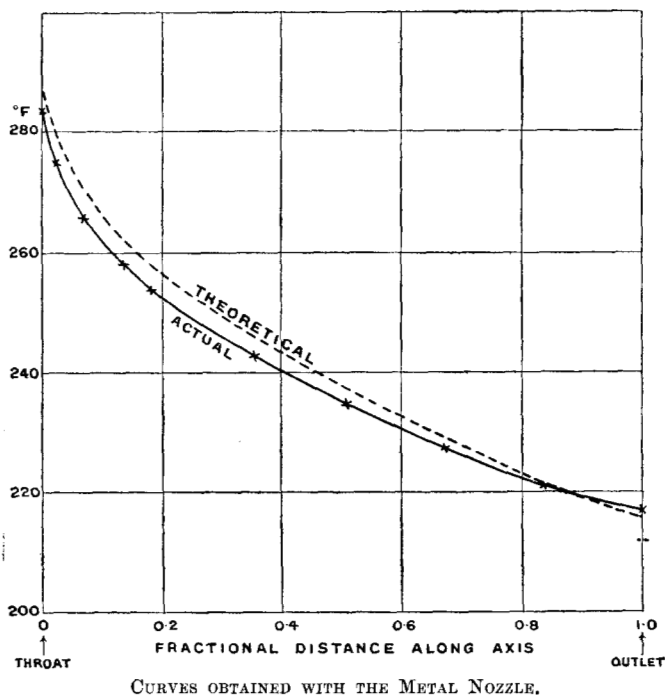
The first experiments were made with a brass nozzle of the ordinary De Laval type; it was an actual turbine-nozzle made by Messrs. Greenwood and Batley. The diameter at the throat was 0.356 inch, and it was designed for an admission pressure of 94.7 lbs. per square inch absolute with a final pressure of 16 lbs. per square inch absolute. As it appeared that the back-pressure in the cylinder C_2 was practically 16 lbs. per square inch absolute, and as a condenser was not available, it was necessary with the low admission pressures used to have a nozzle designed for this back-pressure. Such a one was accordingly designed (*Fig. 1*) with a length of 1.945 inch, the throat 0.118 inch from the end was 0.355 inch in diameter, and the bore was a straight taper; the outlet diameter was 0.464 inch, and the nozzle was highly polished inside.

A large number of experiments were carried out with this nozzle under the conditions for which it was designed. The readings agreed in a striking manner, and occasional discrepancies (never amounting to more than about 2° F.) were explainable by slight changes in the back-pressure. The mean result of these readings is shown in *Fig. 6*.

For reasons which will appear later, it was thought desirable also to make experiments with a non-conducting nozzle, but considerable difficulty was experienced in obtaining the correct profile. A porcelain nozzle with a glazed bore was first used, but it was found that the glazing rendered the walls uneven, and conflicting results were

obtained. It was, however, found possible to grind the inside of the nozzle by means of a steel lap, turned to the correct profile and rotated in a lathe; wet sand was used as a grinding material and the nozzle was pressed on by hand, several laps being used to obtain the proper taper. The entrance of the nozzle was ground by means of lead fed with wet sand, lead being used because it adapted itself to the profile and gave a rounded throat. The nozzle thus obtained gave fairly satisfactory results, but the friction

Fig. 6.

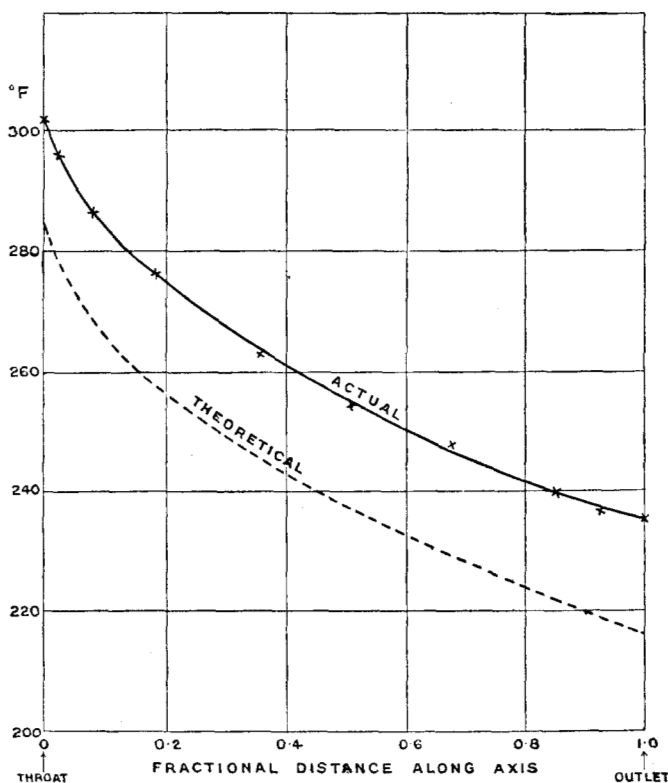


loss was high, although the walls were to all appearances quite smooth. The nozzle was 2.04 inches long, the throat being 0.187 inch from the entrance; it was 0.425 inch in diameter at the throat and 0.556 inch at the end, so that it was of the correct proportions for the same initial and final pressures as the metal nozzle, although the weight flow was greater (0.1918 lb. per second against 0.138 lb. per second with the metal nozzle). Several complete sets of experiments were made with this nozzle under the

correct pressure conditions, and the results are shown in *Fig. 7*. The readings agreed in a satisfactory manner, the greatest discrepancy from the mean being only 1° F.

It was found that, with the wires and galvanometer used, temperatures could be read to about $\frac{1}{3}$ of a degree Fahrenheit, which was a

Fig. 7.



CURVES OBTAINED WITH THE PORCELAIN NOZZLE.

sufficient degree of accuracy for the method of pressure-regulation adopted.

Theoretical Considerations.—The temperature curves for frictionless adiabatic flow in the nozzles used were obtained as follows:—

Let p_1 be the initial pressure in lbs. per square inch absolute.

„ p_2 „ final „ „ „ „

„ p „ pressure at any intermediate section having an area S.

Then the velocity, u , for frictionless adiabatic flow at the cross section of area S is given by the equation¹

$$\frac{u^2}{2g} = J \{ \lambda_1 - (h + x l) \} \quad . \quad . \quad . \quad (1)$$

λ_1 being the total heat of 1 lb. of dry saturated steam at the pressure p_1 ;

h the total heat of 1 lb. of water at temperature corresponding with p ;

l the latent heat of evaporation of 1 lb. of steam at the pressure p ;

and x the dryness fraction after adiabatic expansion from the pressure p_1 to the pressure p , the steam being initially dry.

But the weight-flow W is given by

$$W = \frac{S u}{x V}$$

V being the volume of 1 lb. of dry saturated steam at the pressure p .

Hence
$$W = \frac{S u}{x V} = \frac{S_o u_o}{x_o V_o}$$

the suffix o denoting the conditions at the throat,

therefore
$$S = S_o \frac{x V u_o}{x_o V_o u} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The area of the section at which the pressure p exists is known in terms of the area of the throat, and x and x_o can be found from the energy chart. Thus a curve may be drawn showing the pressure or temperature distribution along the axis of the nozzle.

If the actual pressure at the section S is p' instead of p , and if it is assumed that the only losses in the nozzle are those due to friction,

then
$$\frac{u'^2}{2g} = J \{ \lambda_1 - (h' + x' l') \}$$

and
$$W = \frac{A u'}{x' V'}$$

Therefore
$$\frac{u'^2}{2g} = J \left\{ \lambda_1 - \left(h' + \frac{A u'}{W V'} l' \right) \right\} \quad . \quad . \quad . \quad (3)$$

and W for the nozzle may be found from the theoretical equations,

¹ A. Stodola, "Steam-Turbines," p. 47.

which Professor Rateau,¹ Mr. W. Rosenhain,² and others have proved to be practically correct. Equation (3) gives the actual velocity at the section S, and the efficiency of the flow up to this section is thus equal to

$$\frac{\frac{W}{2g} \frac{u'^2}{u^2}}{\frac{W}{2g}} = \frac{u'^2}{u^2}.$$

There will be another loss at the end of the nozzle due to the sudden expansion of the steam to the back-pressure existing in the exhaust-chamber.

All these calculations assume that no heat-exchanges take place. If R units of heat are lost through the walls the velocity (u'') will be given by

$$\frac{u''^2}{2g} = J \left\{ \lambda_1 - R - \left(h' + \frac{A u''}{W V'} l' \right) \right\} \quad . \quad . \quad (4)$$

whilst if R units are added to the stream,

$$\frac{u''^2}{2g} = J \left\{ \lambda_1 + R - \left(h' + \frac{A u''}{W V'} l' \right) \right\} \quad . \quad . \quad (5)$$

equation (4) will give a lower and equation (5) a higher value than equation (1).

Discussion of the Results.—The results obtained with the metal nozzle are plotted as a temperature curve in *Fig. 6*, together with the theoretical frictionless adiabatic curve. The curves are only plotted from the throat to the end of the nozzle, since the entrance was too short to allow of temperature measurements being taken along it with any accuracy.

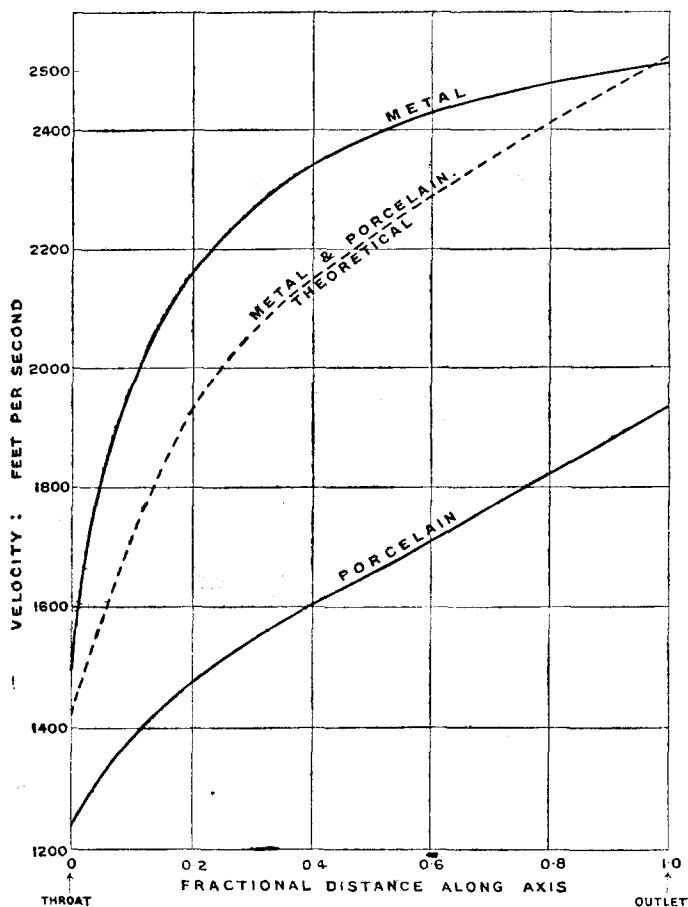
It will be noticed that the experimental temperature at the throat was only 284.1°F. instead of the theoretical 285.7°F. The actual temperature-curve drops more quickly than the adiabatic for about a third of the total length of the nozzle; it then begins to fall less quickly until, at 0.85 of the length of the nozzle from the throat, it cuts and rises above it; the actual temperature at the end of the nozzle being 217.5°F. instead of the theoretical 216°F. Now the velocity at the end of the nozzle calculated for adiabatic (not necessarily frictionless) flow from this final temperature of 217.5°F. was $2,520$ feet per second, while the velocity for frictionless adiabatic flow in the nozzle was $2,532$ feet per second. From this it would appear that the efficiency of the nozzle was about 99 per cent.—

¹ A. Rateau, "The Flow of Steam through Nozzles and Orifices." London, 1905.

² "Experiments on Steam-Jets." Minutes of Proceedings Inst. C.E., vol. cxl, p. 199.

a very high value. The matter requires closer consideration, however, and *Fig. 8* shows the velocity-curve obtained from the experimental temperatures by assuming no heat loss, together with the velocity-curve for frictionless adiabatic flow; it will be seen that the first curve rises above the second at the throat and remains

Fig. 8.



above it for some distance along the nozzle. But the actual velocity could not be greater than the velocity for frictionless adiabatic flow, and must therefore have been obtained from a wrong assumption; in short, the actual flow cannot have been adiabatic. Now if heat were lost from the steam, the velocity would be too

high when calculated for adiabatic flow from the temperature at any section; therefore it would appear that the steam lost heat along the nozzle. Unfortunately, in this case, the efficiency could not be arrived at from the experimental results, as there was no means of calculating the rate of heat-loss. Part of this loss at the throat might be due to eddies at the entrance of the nozzle, but the main part must be due to conduction of heat through the walls.¹

It was to obtain further evidence on this point that the experiments with the porcelain nozzle were carried out. Since porcelain is practically a non-conductor of heat, no heat exchange through the walls could take place. The experimental temperature curve for this nozzle is plotted together with the frictionless adiabatic temperature-curve in *Fig. 7*, and in *Fig. 8* the actual and theoretical velocity-curves are plotted. In the former figure it will be seen that the actual temperature-curve lies above the frictionless adiabatic curve throughout. At the throat, the actual temperature was 301.5° F. against 286.7° F. for frictionless flow, while at the mouth it was 234° F. as against 216° F.

If the efficiency at the end is calculated for adiabatic flow it will be found to be only 60 per cent., while at the throat it is about 67 per cent. It is to be feared that the frictional loss in this nozzle is higher than in the metal one, and that these efficiencies are unduly low; but although this would lessen the value of the comparison between the two, the experimental curve for the porcelain does not show any of the effects that have been attributed to heat-loss in the metal nozzle, as it is entirely above the adiabatic, and has nowhere a greater slope. Even supposing the friction in the porcelain nozzle to be three times that of the metal nozzle, the loss in the latter would be much greater than is apparently shown by the experimental curves.

Conduction of heat along the wires of the junction itself must be very small, because of the small diameter of the wires; besides, the friction of the steam against the junction would aid in equalising the temperature of the two if any difference existed. Again, if the conduction were appreciable, the experimental temperatures would be too high, and the real curve for the metal nozzle would be still further below the adiabatic.

The temperature registered by the junction might be rather higher than the mean temperature, owing to the friction of the

¹ Dr. Grindley has proved that there is such a heat-loss during flow through an orifice in a thin metal plate. See Proceedings Royal Society, vol. 66.

steam causing it to be superheated along the wire, but again this would also cause the real curve of temperature to be below the actual curve obtained.

Although the transmission of heat between a vapour and a surface probably varies directly as the velocity, the loss of heat will become less and less as the steam travels towards the end of the nozzle, because the temperature gradient between the outer wall and the core decreases. Some heat will travel along the walls of the nozzle, since the temperature of the walls must be higher at the throat than at the outlet, and possibly this may be given back to the steam at the end of the nozzle. But the friction of a vapour against a surface varies as some power (greater than 1) of the velocity, therefore the friction increases along the nozzle. It was thus probable that the friction-effect overcame the conduction-effect as the end of the nozzle was reached, causing the temperature curve to rise above the frictionless adiabatic curve, as shown in *Fig. 6*. It might be thought that the conduction of heat from the core of the stream to the walls of the nozzle would be inappreciable because of the very low conductivity of gases. But it must be remembered that the velocity of the steam in the nozzle was much above the critical velocity for steady motion of a gas, and that the rate of transmission was thereby greatly increased.

The experiments made by Dr. Stodola and others did not show this dip of the actual temperature curve below the adiabatic, but their method of experimenting was to measure the pressure gradient in the nozzle by means of a tube having a hole bored in the side, and communicating with a pressure-gauge. Besides greatly increasing the friction loss, this method could not be considered so reliable as the thermo-electric measurement of the temperature.

Fig. 9 shows the results of experiments made with the metal nozzle with an initial pressure of 64.7 lbs. per square inch absolute, i.e. less than the 94.7 lbs. per square inch absolute for which it was designed; the frictionless adiabatic curve is also given. It will be seen that the actual curve is entirely above the latter, and that it falls continuously along the axis, reaching a temperature lower than that corresponding with the back-pressure at the end of the nozzle.

Many experiments made with various initial pressures gave the same result, which is contrary to that obtained by Dr. Stodola.

Summary.—The chief conclusions to which these experiments lead are :—

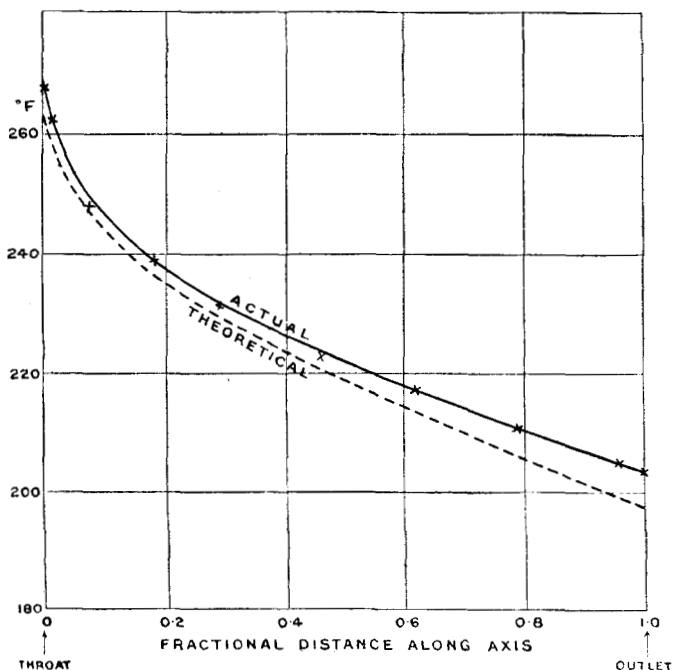
1. It is possible to measure accurately the temperature at various points in a nozzle by means of a thermo-junction.

2. It is shown by this method that there is a definite transfer of heat from the steam in the nozzle to the walls, part of which travels along the walls and may be given back to the steam at the end.

3. It is, therefore, incorrect to calculate the efficiency of the nozzle from the outlet-temperature without considering this heat loss.

4. With a nozzle of non-conducting material this heat transfer

Fig. 9.



CURVES OBTAINED WITH THE METAL NOZZLE
AT REDUCED PRESSURE.

does not occur, and if the bore can be made smooth enough, such nozzles would probably prove more efficient in actual practice than those made of metal.

5. When the initial pressure is less than that for which a nozzle is designed, the temperature falls continuously along the nozzle and reaches a temperature lower than that corresponding with the back-pressure at the outlet.

In conclusion, the Author desires to express his indebtedness to Professor Watkinson and Dr. Grindley for their valuable suggestions during the progress of the experiments, and to Mr. Okill (Research Assistant at the Walker Engineering Laboratories), who was associated with him throughout the experimental part of the work.

The Paper is accompanied by nine drawings from which the Figures in the text have been prepared.
