EXPERIMENTS ON THE ESCAPE OF STEAM THROUGH CIRCULAR ORIFICES.

BY M. A. RATEAU, OF PARIS.

(Translated from the French.)

The design of steam turbines depends upon the knowledge of the laws which determine the escape of steam through converging or converging-diverging orifices. In order to verify exactly the formulæ for the escape of steam, the author undertook, in 1895-1896, at St. Etienne, a series of experiments on this subject, according to a method which gives the greatest possible precision. A short indication of these experiments has been given in the report on steam turbines which the author had the honour to present last year at the International Congress of Applied Mechanics in Paris. But at that time he had not yet completed all the calculations of the results of his experiments, whereas now he is able to give an account of the results. They differ a little from those the author provisionally announced at the Congress of 1900.

Those investigators who experimented before and since the author, namely, Minary and Résal in 1861, Peabody and Kunhard in 1890, Parenty in 1891, Miller and Read in 1895, and Rosenheim in 1900, have all used the same method, which consists of condensing in a surface condenser the steam, which escapes by the orifice for a sufficiently long period, and then weighing the condensed water. But this method, beyond being very laborious, cannot give great

precision, because in the first place it is very difficult to keep the initial steam-pressure (*pression d'amont*), P , constant during the whole of the experiments, and the steam, being never absolutely dry, the water which it carries with it is weighed with the condensed water, so that the results found must be generally over-estimated.

The author therefore proposed to remove these causes of error so as to obtain exact results within two-thousandths, and to use, besides, sufficiently large orifices to deliver up to more than 900 kg. of steam per hour.

He has reached the desired result by condensing the steam in a stream of water with the use of an ejector-condenser, and by measuring the total yield of water per second and the initial and final temperatures of this stream. Thus he was able to make all the readings at the same moment, as soon as constant conditions were obtained; and each experiment did not last more than one or two minutes. It has been possible thus without much trouble to make more than a hundred and forty observations under the most varied conditions.

Fig. 1 represents diagrammatically the apparatus employed. A is the ejector-condenser which receives steam through the pipe B, and cold water by the pipe C. The hot water containing condensed steam escapes by the pipe D into the sheet-iron chamber E, where the air separates out; then it goes out through the converging orifice F at a pressure measured by the water gauge hh .

The rise in temperature of the water is measured by the thermometers e and f graduated to twentieths of a degree, and previously calibrated in comparison with a Baudin thermometer.

The nozzle to be tested is placed within the pipe at I. It receives the vapour through the pipe H, 50 mm. diameter, and throws it into the large pipe B of 120 mm. diameter. The initial pressure P (*à l'amont*) was measured by one or other of the gauges a or b . The resultant pressure p (*à l'aval*) was measured by either the metallic pressure-gauge m , or the mercury gauge cd .

The steam, arriving from the boiler by the pipe N, rushes with centrifugal force into the separator J, on account of the partial vacuum therein; nearly the whole water carried over falls down

FIG. 1.

Diagrammatic Sketch of Apparatus.

there, and the small quantity remaining can be measured by the specially arranged apparatus L.

The author was thus assured from the beginning of his experiments that the quantity of water passing the separator never exceeded two to three-thousandths, and as the error due to this method could not exceed half of this amount, or an insignificant figure, he has neglected it.

The pressure before passing the nozzle could be regulated at will by means of the cock K; a special valve, actuated by the crank *g*, enabled the pressure *p* (*aval*) to be fixed at any desired amount above the lowest pressure caused by the ejector-condenser. The author has thus been able to operate through a long range of pressures, from 0.10 to 12 kg. per cm.² (1.4 to 170.6 lbs. per square inch). The rate of flow through the water-orifice F had been previously measured with great care by means of the barrel G graduated along the tube KK.

The author has experimented successfully upon a thin-walled orifice, and upon three converging nozzles having respectively a diameter at the narrowest part of 10.49, 15.19 and 24.20 mm. (0.41, 0.59 and 0.95 inch).

Without entering into detail of the figures involved in these calculations, Fig. 2 gives in graphic form the results obtained with converging orifices, in all cases where the subsequent pressure *p* (*aval*) was less than 0.58 of the initial pressure *P*. The points indicate the ratio $\frac{I}{P}$ rate of consumption in grammes per second and per cm.² of orifice, at the absolute pressure *P* (*d'amont*) in kg. per cm.² for different values of *P*.

There are fifty-nine results which approximate to the theoretical straight line AB, calculated from Regnault's tables by the thermodynamical formula, assuming that the mechanical equivalent of heat is equal to 425 kilogrammètres per calorie. The differences do not usually exceed 2 per cent. The mean of the results gives a figure seven thousandths in excess, when compared with the theoretical calculation. This difference may be due to the displacement of the thermometer zeros (of 1 to 2 tenths of a degree) during the course of the trials. It will be observed that this would not exceed 3.5

FIG. 2.

Comparison of Experiments on Converging Orifices and Theoretical Calculations.

Ratio $\frac{1}{P}$ gr per sec per cm^2 of orifice

thousandths, if one assumed for the theoretical calculation a value 428 for the mechanical equivalent E , which is now admitted; for the formula of the speed of escape includes $\sqrt{2gE}$ as a factor.

The scale of ordinates in the figure is contorted on account of the method of recording small differences. To show clearly the value of the differences, straight lines ab and $a'b'$ have been drawn on Fig. 2. These differ from the theoretical line by one per cent. more and less respectively. The line CD corresponds to Grashof's formula

$$I = 15.26 P^{0.9696}.$$

The correspondence between the theory and the practice is satisfactory. It is the same when the subsequent pressure p (*aval*) exceeds $0.58 P$, in which case the consumption of steam depends on the two pressures p and P simultaneously, whilst the consumption depends on P only if p is less than $0.58 P$.

In the latter case the consumption may be very exactly represented by the formula

$$I = P(15.20 - 0.96 \log. P),$$

I being the consumption in grammes per second and per cm.^2 of orifice, and P the initial pressure in kg. per cm.^2

The Paper is illustrated by 2 Figs. in the letterpress.

Discussion.

The CHAIRMAN said that M. Rateau's second Paper was one which did not lend itself to reading. It was entitled "Experiments on the Escape of Steam through Orifices." He might say that the discharge of steam in connection with the design of steam turbines was a matter to which M. Rateau had devoted very great attention, and one in which he had carried out a large amount of experimental work. Any deductions at which he might have arrived were therefore worthy of every possible attention at their hands. He would now ask any

gentlemen who were interested in these Papers to give them their views upon them. The first Paper dealt with a very ingenious means of utilizing the exhaust steam in such circumstances as M. Rateau had described.

Professor A. STODOLA, of Zurich, said he would like to make a few remarks in regard to the statements which were expressed in the Paper. He thought that they had still much to do in the way of increasing the economy of the steam-engine, and especially of the steam-motor which needed to be increased very much in its efficiency. As to whether all the predictions would be corroborated by practice was still a question. Like Professor Schröter and his colleagues, he now took the opportunity, as representing Switzerland, of tendering his very hearty thanks for the kind reception which they had given them, and also congratulated them on the brilliant success of the great Congress which had been arranged.

Mr. BRYAN DONKIN, Vice-Chairman, said that they might call this apparatus a sort of heat or thermal unit fly-wheel, taking in heat and giving it out when required. With regard to the second Paper, it ought to be entitled "Experiments on the Measurement of the Quantity of Steam through Circular Orifices." The subject was brought before the Congress in Paris last year, the Paper being originally published in French, and he would strongly recommend engineers to study the original. Steam could be very accurately measured in bulk through orifices, if correct co-efficients were used. In his first Paper M. Rateau said the application of 250 H.P. was in course of erection at the Bruay Mines in the north of France, and would be working in a few months' time. It would be very interesting if he would kindly give them the results of these practical experiments.

M. RATEAU, who replied in French, returned thanks for the reception of his Paper. He thanked the Chairman particularly for his kind words, and also thought that Professor Stodola's opinion on his (M. Rateau's) proposed system was valuable, because of the

(M. Rateau.)

authority which it acquired from his remarkable lectures on Applied Mechanics at the Polytechnic in Zurich. He was glad to see as Vice-Chairman of the Mechanical Section his friend Mr. Donkin, who was well known in France, as in all industrial countries, by his numerous Works, notably on the passage of heat through cylinder walls. He thanked Mr. Donkin for his remarks upon the two short Papers, and agreed with him that the steam accumulator was in fact a heat fly-wheel. He wished to take this opportunity of expressing his regret that he had not sufficient command of the English language, and had thus been deprived, on the previous day, of having the pleasure of taking part in the discussion on Steam Turbines. He would have then expressed his opinion that steam turbines existed for the utilisation of low-pressure steam. He himself had carried out in France for some years researches on steam turbines, and he followed with interest the progress of the Parsons Turbine. It would have given him pleasure to signify his respect for the persevering energy shown for nearly twenty years by the Hon. C. A. Parsons in bringing this question of steam turbines to a successful issue. The numerous and considerable difficulties raised in the problem of the industrial application of steam turbines were well known ; and one must admire the ingenuity with which they have been conquered in the Parsons turbine. Referring to the accumulator, he explained that the diagram (page 947) showed accurately the apparatus which had been fitted to the winding engines at the Bruay Mines, and said that he would like to communicate the results of its working at a future date.

The CHAIRMAN hoped that after some experience had been gained with the winding engines at Bruay, M. Rateau would contribute a Paper giving the results. The device described was particularly interesting in its application to engines such as winding and reversing rolling-mill engines. He asked them to accord a hearty vote of thanks to M. Rateau for his Papers, and for the explanations he had given.

Communication.

Mr. MICHAEL LONGRIDGE expressed regret that there had been no time for a discussion on this Paper, as he would have liked to hear the name of Halpin as well as that of Parsons mentioned in connection with M. Rateau's ingenious combination; for if the Parsons' turbine was necessary to utilise the low-pressure steam from the reciprocating engine, the thermal storage system, associated in this country at least with the name of Mr. Halpin, was equally necessary to provide the steam while the reciprocating engine was at rest. The combination was a very happy one and calculated to effect some saving in colliery working, provided the thermal storage vessels were properly designed. It was a question whether an independent condensing plant applied to the winding engine would not in many cases yield nearly as good a commercial result.

M. RATEAU wrote in French that he had read with interest the reports of Mr. Halpin's system of Thermal Storage, and he thanked Mr. Longridge for having drawn his attention to these. Mr. Halpin had proposed to remedy the deficiency found in central electric stations, by installing steam generators capable of completing the maximum power required at the station during a very short period of the day; for this purpose he added to the boilers vessels full of cold water (which simply formed annexes to the boilers), and he worked them at a pressure well above that necessary for the engines, so that these vessels constituted a heat fly-wheel capable of furnishing steam to the engines during a considerable time. In short, this was the development to the full extent of what had been already done in many places, by increasing the capacity of the boilers, particularly on locomotives and in ships, and thus producing steam in a boiler at a pressure 3 to 6 kg. per cm.² higher than that which the cylinders required, and interposing a reducing valve between them and the boiler. The author's object

was quite different. He proposed to utilise the low-pressure steam coming from the exhaust pipe of an engine working irregularly; and for this purpose he interposed an accumulator between this engine and the low-pressure steam turbine. He saw nothing in Mr. Halpin's system which corresponded to the utilisation of low-pressure steam by an engine fed by steam from another.