MECHANICS, PHYSICS, AND CHEMISTRY

On the Motion of Water through Pipes. By HENRY HENNESSY, M.R.I.A.*

A very elaborate series of experiments have been recently made at Paris, on the motion of water through pipes, by M. Darcy, director of the public water works of that city. A memoir detailing the methods of experiment, and the results obtained, having been submitted to the Academy of Sciences, a commission of inquiry was appointed, from which has emanated an extremely valuable report, drawn up by M. Morin, and published in the number of the *Comptes Rendus* which has been just received.

The utility of economizing and properly regulating the supply of water to towns and manufactories, is now so fully recognised—the industrial and social importance of any practical conclusions that may be drawn from well-conducted hydraulic experiments, so completely admitted—that it appears desirable to give the utmost publicity to these investigations.

The experimental and mathematical researches which have hitherto formed the basis for engineering calculations, have generally afforded but little information as to the influence of the condition of the interior surfaces of the pipes on the resistance to the flow of water. Partly resulting from this cause is the fact not unfrequently observed in connexion with great water works, that while the volume of water actually discharged through new cast iron pipes is generally greater than that deduced from scientific rules, as soon as the pipes have been some time in use, and that deposits have been formed in them, the state of things is entirely reversed.

One of the chief objects of M. Darcy's investigations being to clear up practical difficulties of this kind, he proceeded to make a series of experiments, in order to determine—

1. The influences of the state of the surfaces on the discharge.
2. The influence of the diameters of the pipes on the resistance.

He used pipes varying in diameter from the smallest ever used for practical purposes, to half a metre, or a little more than 1 ft. 7½ in. The pipes were also of different materials, some of drawn iron or lead, and some of iron coated with pitch, or of smooth glass, also cast iron pipes, some of them quite new, some old with deposits, and some old without deposits.

The experimental arrangements were such that the observer was able to measure the pressure or effectual head of water in the iron pipes at the origin of movement and at distances of 50 and 100 metres (164 and 328 feet) farther on. The differences would give the measure of the loss occasioned by the resistance of the surfaces.

The leaden pipes, which were 50 metres long, or more than twelve hundred times the diameter of the thickest employed, had the pressures measured at a distance of 25 metres. A similar arrangement was made in the glass tubes, which had nearly the same dimensions. The mean velocities obtained in these experiments varied from 0.03 metres to 5 or

* From the Lond. Civ. Eng. and Arch's. Jour. September, 1854.

6 metres per second; that is, from 1·18-inch to 16 feet 5 inches, or 19 feet 8½ inches nearly; thus going even beyond the limits used in practice. The inclinations and diameters of the several pipes were carefully measured by the most approved methods.

The most important general result deduced from these experiments is, that the nature and state of the interior of the pipes exercise a considerable influence on the discharge.

It appears, for example, that compared with the formulæ of M. Prony, iron pipes coated with pitch give discharges greater than the calculated results, in the proportion of nearly 4 to 3; that glass gives similar results; but that in cast iron pipes, whose diameter had been only very slightly diminished by deposits, the velocities, and therefore the effective discharges, were decidedly less than the theoretical indications, while after a thorough scouring a perfect agreement became manifest.

The diameters of the pipes seemed also to exercise a more decided influence on the discharge than what had hitherto been assigned to them; for with small diameters the results were less than by the formulæ, while they were greater for large diameters. This influence of the diameters was probably overlooked, as suggested by M. Darcy, from the fortuitous compensation established between the resistance in very thin but smooth pipes, and those of considerable thickness but encumbered by deposits.

From a discussion of his experimental results, it follows that the law of resistance is generally expressed by the usual formula:

$$v^2 B + v A = R I$$

R being the mean radius or hydraulic mean depth, I the inclination of the tube due to the resistance, v the velocity of efflux, and A and B constants. But an exception to this law holds in the case of very thin tubes and low velocities, in which case the term B disappears, and the resistance is proportioned to the velocity simply. As might be expected, therefore, the diameter and the substances composing the different pipes have been found to influence the values of A and B , for these have been found to differ in tubes of the same dimensions but of different degrees of internal smoothness, and also in those which were equally smooth but with unequal radii.

In pipes containing much deposited matter, which is usual in those that have been some time in service, it appears from M. Darcy's experiments that the resistance (as admitted by several engineers) could be safely considered as simply proportional to the square of the velocity, thus simplifying practical calculations. These experiments being made with pressures so varied and so considerable, an admirable opportunity was afforded for testing the long admitted principle, that the resistance presented by the sides of a tube to the liquid passing through, is independent of the pressure of that liquid. It was found, for example, that where the head of water varied in the ratio of from about 55 feet 9 inches to 85 feet 4 inches, and again from about 72 feet to 131 feet, between the two parts of the pipe submitted to observation, the differences or losses of head have remained the same for both parts. Such decisive results completely confirm the important hydraulic principle just mentioned.

In order to determine the numerical values of the constants A and B in the formula,

$$v^2 B + v A = R I,$$

M. Morin objects very properly to the use of the method of least squares, as not only requiring very troublesome calculations, but also introducing into the results the influence of mere accidental anomalies, which such experiments sometimes present. He prefers a graphical representation of the actual results of experiments, as being more expeditious, and capable of rendering more palpable such accidental circumstances as may deviate from the usual law. M. Darcy has employed this method simultaneously with that of least squares, and has thus, in a great measure, obviated the imperfections of the latter. Observers in every department of physical science might profit by the hint of M. Morin, as to the successive employment of the two methods; by which, we presume, he means the application, first of the graphical method, so as to detect the accidental anomalies, and then, on their elimination, the application of the method of least squares to the purified results.

After determining the values of the constant coefficients for tubes of different materials and dimensions, M. Darcy has estimated, by the aid of his formulæ, the velocities corresponding to the different inclinations, and has compared them with the observed velocities. This comparison shows, that for all kinds of pipes, and for every diameter, as soon as the velocities attain a few décimètres,* the formula of resistance may be changed to

$$v^2 B_1 = R I,$$

and this will be especially correct for pipes containing deposits; that is, for working pipes in their usual condition.

A comparison of the values obtained for the coefficient which determines the resistance in tubes differing but slightly in thickness, has shown that their different degrees of smoothness, and general condition of their internal surfaces, exercise very remarkable effects on the amount of that resistance. Thus, tubes of thin sheet iron coated with pitch, of clean cast iron, and of cast iron covered with deposits, each having in inches respectively the diameters, 7.717, 7.401, and 9.567, gave for B_1 values which varied proportionally from 1 to 1.5 and 3. This result shows, that in estimating the action of a series of pipes for water works, they should be always supposed to have arrived at the normal condition of being coated with more or less deposit, no matter how comparatively smooth they may be at the time of laying them down.

Having found by experiment that the resistance diminishes with an increase of diameter, M. Darcy sought the law of variation as some simple function of the diameter, and he has shown that B_1 , in the formula last given, may be represented by two terms, one constant, and the other varying inversely with the diameter of the tube. The law thus becomes

$$R I = v^2 \left(a + \frac{b}{R} \right)$$

* One decimetre = 3.93708 inches, not much less than 4 inches.

Or if L represent the length of the pipe and H the height due to the resistance,

$$H = v^2 \frac{L}{R} \left(a + \frac{b}{R} \right)$$

From a series of eight experiments with tubes of drawn and cast iron, sensibly of the same degree of smoothness, and with diameters varying from half a metre down to 0.122 metre, M. Darcy has obtained the following numerical values:—

$$a = .0000507, \quad b = .00000647.$$

When the values of R , L , and v are given in English feet—

$$a = .0000507, \quad b = .00002122.$$

The expression generally recognised among hydraulic engineers as equivalent to the foregoing, is given by Mr. Neville in the form,*

$$R I = v^2 \left(a + \frac{b}{v^{\frac{1}{2}}} \right)$$

Where

$$a = .00005585, \quad b = .00006659.$$

On making use of these results a very satisfactory agreement was found with observation, so that it was possible to safely calculate the values of B_1 in the formula of $v^2 B_1 = R I$, for all diameters, for every centimetre from the first up to 50, or half a metre, and also for every 5 centimetres up to a metre. By simple transformations of the preceding formulæ, which will readily occur to scientific readers, it is possible to obtain rules for calculating the inclination required for obtaining a given velocity with a certain diameter of pipe, or the converse problem of finding the velocity corresponding to a given inclination.

The variation of the coefficient of resistance, which must be taken into account for narrow pipes, is much less perceptible in those with diameters greater than from about 5 to 6 inches, and it may be considered, without inconvenience, as constant for all those of greater diameter.

M. Darcy has also turned his attention to another question connected with the motion of fluids in pipes, which, although comparatively unimportant for practical purposes, possesses much scientific interest. The point referred to, is the law of variation of velocity of the particles of fluid from the axis of a pipe where it is a maximum, to the surface where it is a minimum. With the aid of a small and very slender Pitot tube, of which one branch could be placed parallel to the axis of the pipe at different distances from that axis, and of a manometer giving the pressure exercised on the surface, he has determined the excess of pressure observed at the Pitot tube over that on the manometer, and by a special process, the velocity of the fluid acting on this tube, or some quantity proportional to the velocity. Comparing in this way, for different inclinations, the excess of velocities in the axis over the velocities at different distances therefrom with the square roots of the inclinations, it followed:—

1. That the ratio of this excess to the inclinations was constant.

* See 'Hydraulic Tables, Coefficients, and Formulæ,' by John Neville, C.E., M.R.I.A., County Surveyor of Louth.

2. That the ratio of this excess to the $\frac{3}{2}$ power of the distance of a moving particle from the axis was constant for the same inclination.

3. That the ratio K of the same excess to the product $r^{\frac{3}{2}}\sqrt{I}$, constant for the same pipe, varies from one pipe to another inversely as the radius, so that $\frac{K}{R}$ is constant.

It is hence easy to infer that the relation between the velocity V , of the particles situated in the axis of a pipe, with the velocity v , of those situated at a distance r , from the axis, is represented by

$$V - v = \frac{Kr^{\frac{3}{2}}\sqrt{I}}{R}$$

Whence, if w represent the velocity of a particle at the surface of the pipe,

$$w = V - K\sqrt{RI}; \text{ or, } K\sqrt{I} = \frac{V - w}{\sqrt{R}}$$

Whence substituting, we obtain,

$$v = V - (V - w) \frac{r}{R} \sqrt{\frac{r}{R}}$$

From which the velocity of any particle may be obtained if the velocities in the axis and at the surface are known.

It finally appears that for the mean velocity u , M. Darcy has deduced the expression,

$$u = \frac{3v + 4w}{7}.$$

By comparing the results of experiments made with different pipes, M. Darcy has been led to conclude, that although the degree of smoothness of the interior of a pipe must influence the resistance, and consequently the mean velocity of the fluid, it does not affect the law of variation of velocities from the axis to the surface, which appears to depend on the viscosity or molecular condition of the liquid.

It seems that the conclusions at which M. Darcy has arrived relative to the coefficient of contraction have not been considered quite satisfactory. It appears from the theory established by M. Poncelet, that the coefficient in question is a function of that at the opening of the tube, which varies with the head of water, the dimensions of the orifices, and the velocity. It follows, therefore, that the coefficient of contraction at the origin of the pipes ought itself to vary with these quantities; but M. Darcy has obtained a constant coefficient, such as is generally admitted, and this only by a compensation of differences. We have very little doubt that a more correct result would have been obtained if he had employed in the discussion of his experiments, the graphical method in the peculiar way to which attention has been already directed.

Here we must conclude our account of these important researches, which we are glad to learn will be published in detail by the Academy of Sciences, in the '*Mémoires des Savants Etrangers*.'—*Dublin Monthly Journ. of Industrial Progress*.

On the Progress of Naval Architecture and Steam Navigation.

By MR. SCOTT RUSSELL.*

It was mainly (the lecturer said) in respect to speed that the great improvements in the last twenty years had been made. Within that time, the principle and the means of gaining speed had become definitely known, and this Association had had a great deal to do with the establishment of that principle, which consisted mainly in the particular formation of the water-lines of the vessel. The old ships had a round, bluff, duck's-breast bow, with a sloping narrow stern. At length the idea was arrived at of making a boat with a bow, the water-lines of which should correspond with the wave of the sea itself, which should gently and gradually divide the particles of water, which would then give a quiet and easy passage to the vessel entering, whether propelled by steam or by sails, without resisting their progress, and heaping a mound of water before the bows, as in the case of the old bluff, round-built vessels. It seemed now to be universally admitted in Europe and in America, that if a ship-builder wanted to have a very easy and fast-going ship, he must give her bow, not the round convex line formerly adopted, but a fine, long, hollow line, such as the meeting might observe for themselves in all the recently built vessels. Practical men, when they desired to build a fast ship, saw that they must now no longer use the convex water-line, but they must build with a hollow water-line at the bow, and in this consisted the great revolution which had taken place during the last twenty years. Whereas, formerly, the broadest part of the vessel was only a third part from the bow, the broadest part was now nearer to the stern than to the bow in the proportion of two to three, so that the shape of the ship under the water was very nearly reversed. The ship out of the water might remain very nearly the same, but where she cut the water the lines were as he had described. It was on this principle that American clipper ships and English ships which happened to be very fast, were built, and upon which he would say, without fear of contradiction, every vessel, to gain anything like sixteen miles an hour, must be built. Now there was, in addition to this, another very important principle which had been discovered. That was the virtue of the length. It used to be a dogma, in the time of his pupilage, that no steamboat could ever, by any possibility, go faster than nine statute miles an hour. He was born and bred in that belief. Nine statute miles an hour was the creed of his instructor in ship-building. At that time they had very short vessels, and they endeavored, by putting enormous power in them, to compel them to go through the water whether they would or not. He remembered being present at the trial trip of a vessel, out of which had been taken 50-horse power engines, and engines of 70-horse power substituted. It was a most extraordinary fact, that she only gained something like a quarter of a knot an hour by that enormous addition to her power and fuel, because she had not sufficient length to go by any force at a high speed; and the more she was driven through the water, the greater was the resistance made by the water which she

* From the Lond. Prac. Mec. Jour., Dec., 1854.

raised before her. The principle was ascertained, that, if you wanted the particles of water to go out of the way of the vessel when going very fast, you must give the particles more time to do so. Now, this might appear a contradiction in terms, but the faster the vessel was to go through the water the more time must be allowed to the particles of water to give way. It was found that it was more easy to push a vessel with an elongated body through the water at a great speed, than the short vessels which had been in use. This was reduced to a regular principle, the result of which was, that it was now certain that twenty-four feet of length in the entrance lines of a vessel, would give eight miles an hour easily; to go at sixteen miles an hour, the entrance lines should be nearly 96 feet long. To give twenty-four miles an hour, the entrance should be 216 feet long, so that they could not expect to get twenty-four miles an hour until they had made up their minds to build ships something like 400 feet long. From all the experiments he had made, and had seen made, these facts were undoubted. The clipper ships and fast steamers had lengthened their bow-lines until they had got the necessary length for speed; and if those present looked at any vessel which had got the reputation of going sixteen miles an hour, he believed they would find that to be the fact. Indeed, he did not believe there was in existence a vessel shorter than 180 feet which could go sixteen miles an hour; and if there were any such vessel forced to go more than sixteen miles, it was at an expenditure of power which was perfectly preposterous. They would, therefore, perceive why such a large vessel as the *Himalaya* had such great speed. The *Himalaya* had a length of 350 feet, and should have the greatest speed for the smallest power of any merchant vessel hitherto. If, in a like manner, they looked at the large clipper ships of 2000 and 3000 tons burden now built, they would find that the principle was taken advantage of, and that their bows were elongated to a great length. But what else was being done? The owners of the clipper ships were finding out that, by the lengthening of the bow, and making the lines more hollow, they could reduce the sails and spars, and yet preserve their speed, finding that the ships could not do in the water what force of canvas could never alone accomplish. Like every truth, the shape of a vessel had been long since found out and lost again. The London wherry was built as perfectly upon the lines he had described; as if it had been mathematically constructed upon them. In India, the boats were made precisely upon that form, and they were the fastest boats in the world, as a class. The Turkish caiques had the same shape, and they were very fine vessels. In Spain, they had arrived by some means at a form not very different; and throughout the whole of the last war, the Spanish vessels were the best vessels, and the best England took. The smugglers, because they risked their necks upon the speed of their ships, quickly found out what shape was best; and some of the most beautiful ships that ever came into our possession in that way were built in that form. The Americans had made very early an experiment of the kind in steamboats. They lengthened their steamers at a very early period, and they now generally build upon this plan, and with the hollow lines. They had done wonders in this way, and he believed, in England, wonders were also being done. It was not easy to carry the elongating of

the vessels much further in wooden ships, because they could not get timber large enough, and it was impossible to make it strong enough by joining; but he believed Professor Fairbairn had discovered the means of joining iron, so as to make it equal in strength to solid metal. Having alluded to the building of the *Great Western*, and subsequently of the *Great Britain*, and the prophetic doubts expressed at first regarding the fate of each, the speaker proceeded to describe the great vessel now being built by him upon the Thames, for the Eastern Steam Navigation Company, to trade with India and Australia. He showed how the difficulty of carrying coals, and having to stop for them, and buy them at high rates at St. Vincent and the Cape of Good Hope, and sometimes the Mauritius, created such an expense that no freights could cover; he showed how it became necessary to construct a vessel large enough to carry her own coals all the way. When, therefore, he told them that the vessel being constructed was expected to make the voyage to Australia in 30 days, carrying a sufficient freight, with 600 first class and 1000 second class passengers, having three large tiers of decks, 8 feet each in height—that she was 675 feet long, 83 feet beam, 60 feet deep—when he told them, that he had just measured St. George's Hall, and found that it would not fairly represent this ship, being only 169 feet, instead of 675 feet long—that up to the top of the hall it was only 82 feet high, and up to the spring of the arch about the height of the ship—that the breadth of St. George's Hall was only 77 feet, being 6 feet narrower than the hold of the ship, it would give them the nearest approximation he could convey to the size of the vessel. In reply to a question, he stated that the huge vessel which he had described would draw 20 feet when light, and 30 feet loaded.—*Proc. Brit. Association*, Sept. 22, 1854.

*Purification of Coal Gas.**

Even those who insist on the comparative purity of our metropolitan gas have admitted, so far as regards one of the most obnoxious of its elements, namely, sulphuret of carbon, not only that it is contaminated with this impurity, but that all endeavors to withdraw it, short of destruction of the gas itself as an illuminator, have hitherto been fruitless. It ought to afford the gas companies high gratification, therefore, to learn that it is positively asserted that this grand desideratum has at length been attained, and that the alleged means of withdrawing, not only the sulphuret of carbon, but at the same time the ammonia with which admittedly their gas is also contaminated, are so simple, so available, and so easily applied, that no new or expensive apparatus whatever is requisite in order to accomplish an end which will not only remove more than one constant source of mischief, but greatly enhance the illuminative power, and hence the value of their gas, and that, too, at a cost to themselves almost nominal. All that is necessary, it is stated, is to use strata of hydrated clay along with the lime usually employed in the purification of coal gas. The efficacy of this mode of purification has already been tested, it appears, at the Wakefield gas-works, on upwards of 3,000,000

* From the London Builder, No. 585.