II. *On the resistance of fluids to bodies passing through them. By* Jas. Walker,
Esq. F.R.S.E. Communicated by Davies Gilbert, *Esq. M.P. V.P.R.S.*

Read May 31, 1827.

THE principal object of this Paper is to explain a mode which I have taken
to measure the resistance of fluids to bodies passing through them. It is, I
believe, new; and being more simple and less subject to error than any yet
adopted, I have thought it my duty to offer it to the Royal Society, together
with the results of the experiments I have made up to the present time. I
intend to continue the experiments in a boat which is building for the purpose,
with some improvement in the machine, during the ensuing summer, the only
season in which it can well be done, nearly a perfect calm being necessary
for making them with accuracy. The machinery is of very easy construction,
and the description of it may, I hope, lead others to follow the example, and
to prosecute the inquiry in the same manner with surfaces of various forms
and sizes.

The resistance of fluids has long formed an interesting subject, and has
lately acquired a new importance from the introduction of steam in naviga-
tion, rendering the ratio between power and velocity essentially necessary to
be known. The comparison of canals with rail-roads, to which public atten-
tion has of late been much directed, depends also chiefly upon the ratio
between the resistance and velocity by each of those modes of conveyance. A
question connected with this latter subject, to which my attention has been
professionally called, led me to make the experiments I am about to detail.

It has been demonstrated and proved in the most satisfactory manner, by
various experiments, that the resistance from friction to a carriage upon a
road or rail-road is the same at all velocities. I know, therefore, that the
same strain upon a waggon which has the effect of moving it upon a rail-road
at the rate of one mile per hour, will (after the inertia is overcome) be indi-
cated at any other velocity at which the power is made to move; but I have

not found any theory or experiment by which, after knowing the strain upon a boat moving at the rate of two miles per hour, I have been able to fix satisfactorily the strain that is exerted upon it when moving at the rate of four miles per hour.
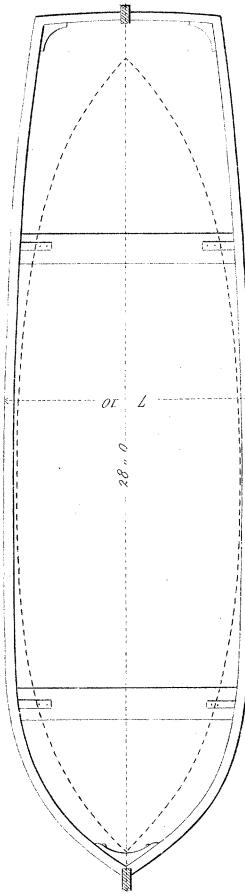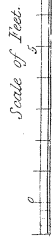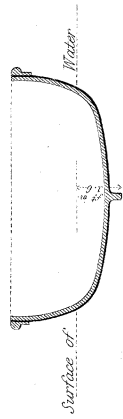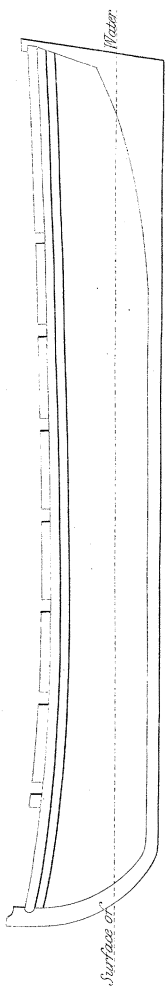
The resistance of the fluid *per se* increases in the duplicate ratio of the velocity.—Experiment has amply confirmed this theory in the abstract; but there are other elements of resistance caused by viscidity, by friction, by the accumulation of the water in front and the depression towards the stern of the boat, for which our ignorance of the laws which govern the internal motion of the fluid has prevented any correct theory from being suggested; and the experiments, from their disagreement, and from the way in which they have been made, have not done much to supply the defect.

The most important experiments upon this subject are those of the French Academy in 1776 and 1778, conducted by Bossut and others, and those that were made by the London Society for the Improvement of Naval Architecture between 1793 and 1798.
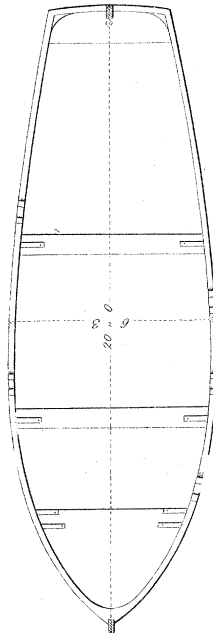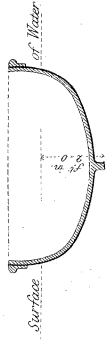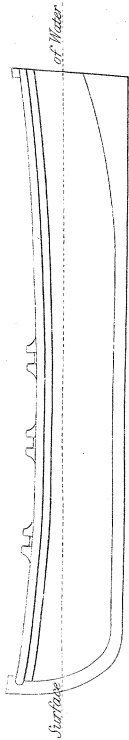
The French experiments of 1776 were made by means of boxes six feet in length (French measure), one foot wide, and two feet deep, or by the models of ships, of the same length, and nineteen inches wide; the depth of immersion varied from seven to sixteen inches; the velocity and resistance were calculated by the time of passing over fifty feet with uniform velocity. The motion was communicated by means of a silken cord two lines and a half in diameter, one end of which was attached to the float, while the other end was passed under a pulley or sheave, and then over another sheave at the height of seventy-six feet, when the weights were fastened to it.

The moving power does not appear in any case to have exceeded twenty-four pounds, nor the velocity two miles and a half per hour; and with those velocities the friction was considered so small as scarcely to be sensible. The general result was, that the resistance is in the duplicate ratio of the velocity; but the small velocities, the short distance, the friction of the sheaves, and the varying friction of the line dragged through the water, as well as the small sizes of the bodies themselves, have appeared to me objections to the application of the results of these experiments, especially to larger bodies and to higher velocities.
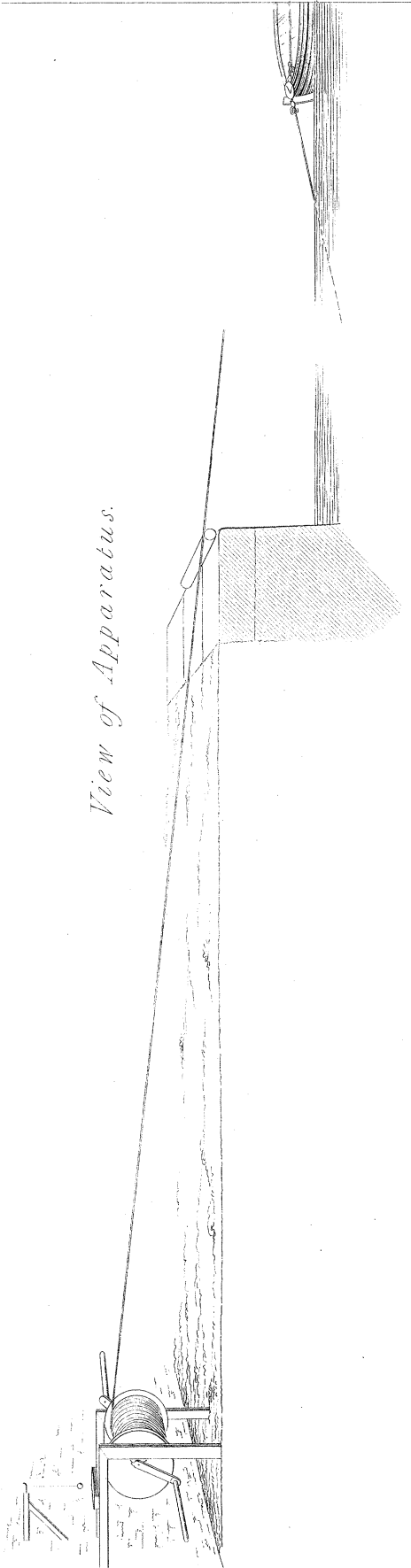
Smaller Boat.

of Water

Surface

Water Surface

Surface of Water

Surface

Large Boat.

Water Surface

Water

Surface of.

Surface of

Scale of Feet.

20 . 0

6 . 3

28 . 0

7 . 10

View of Apparatus.

The principal object of the experiments which were made by Bossut and Condorcet in 1778, was to ascertain the difference of resistance to bodies of different forms: they appear to have been made with great care, but with machinery of nearly the same description as those of 1776, and subject, as far as respects what I had in view, to the same objections as the former ones; only that the bodies were somewhat different in size, some of them being two feet and others four feet wide, with two feet depth of immersion.

The models which the London Society used for their experiments, so far as they have been published, were of various lengths, but all one foot broad and one foot deep; and either sunk considerably under the surface, and held there by bars attached to a floating body, or sunk until their upper surfaces were just level with the water. These were dragged across the water in the Green-land (now the Commercial) Dock, by means of a line passed under a sheave to the top of a triangle of poles, or shear legs, sixty feet high, thence through a system of pulleys, from which the box that contained the weight was suspended.

The friction and rigidity of this machinery and line were important, when the small size of the body to be moved is considered;—it appears that it amounted in most cases to thrice the calculated resistance of the body. A very small error in deducting for this must have been fatal to the accuracy of the experiment; and although every pains appear to have been taken to ascertain the deduction to be made, it is extremely difficult to get at it in all cases with the necessary correctness. It does not appear that the friction between the water and the rope was taken into account: this alone, in so great a length, must have been considerable; and not only so, but varying in extent in the same experiment, as the line became shorter, and different also in each experiment, according to the velocity.

My object has been to get rid of the liability to error from the above causes, and to show at one view the amount of all the resistances opposed to the body under different velocities: but to show those resistances without mixing them with the friction of the line through the water, or of the machinery.

The accompanying drawing will give a correct idea of the plan I took. The experiments were made in the middle of the East India Import Dock, which is 1410 feet in length, 560 feet wide, and 24 feet deep; so that there was no resistance from the sides or bottom of the dock. A spring weighing-machine

was fixed near the bow of the boat, the dial laid horizontally, so as to be easily seen by a person on board; one end of a line three-eighths of an inch in diameter was attached to the hook of the spring, the other end was carried ashore and attached to a reel or barrel three feet in diameter, the frame of which was firmly fixed in the ground, and the handles of sufficient length for the necessary number of men to turn the barrel. The velocities were calculated from the time of passing through 176 yards, or one-tenth of a mile; but to obtain uniform velocity, the boat was at each experiment drawn over twice the length, and the 176 yards taken in the middle of the distance by two marks upon the line. The time between the two marks coming to the edge of the dock was carefully noted by a person stationed there for the purpose. Three persons at least were on board the boat;—one to read off the strain shown upon the dial every two seconds, one to write them down, and a third to steady the boat. An exact uniformity of motion by the men at the handles was obtained, after a little practice, by means of a pendulum varying in length (as a quick or slow motion was required) hung up in sight of the men, by the oscillations of which they regulated the revolution of the handles.

It will easily be seen, that although the men who worked the barrel had to overcome the resistance arising from friction of the line through the water, and of the bearings of the barrel, the weights or strain marked by the hand or index of the dial on board the boat measured the resistances to the boat only.

The experiments in the Table A were made in a full built boat loaded with two tons two cwt., exclusive of the men. The length of the boat upon the surface of the water was eighteen feet six inches; the breadth, six feet; the depth of immersion, two feet; the whole depth of the boat being three feet, leaving one foot above water, and the greatest immersed cross section nine feet.

The experiments in Table B were made in the same boat as those of Table A, with about two tons of ballast.

Column 1. is the number of seconds employed in passing 176 yards, or one-tenth of a mile.—Column 2. the velocity per hour expressed in miles and decimals of a mile.—Column 3. the actual measure of resistance or strain shown upon the dial of the machine.—And Column 4. the resistance calculated upon the ratio of the square, taking one of the experiments as a standard.

TABLE A.

Number of Experiments.	1.	2.	3.	4.
	Seconds in passing 176 yards.	Miles and decimals per hour.	Actual resistance in pounds.	Calculated resistance in pounds, taking No. 5. as standard.
1	124	2,903	15,75	15,04
2	85	4,235	39,50	32,01
3	146	2,465	10,00	10,85
4	140	2,571	11,00	11,80
5	145	2,483	11,00	11,00 standard
6	140	2,571	12,00	11,80
7	120	3,000	14,00	16,06
8	120	3,000	14,00	16,06

TABLE B.

Number of Experiments.	1.	2.	3.	4.
	Seconds in passing 176 yards.	Miles and decimals per hour.	Actual resistance in pounds.	Calculated resistance in pounds, taking No. 4. as standard.
1	79	4,557	44,85	38,59
2	80	4,500	40,32	37,64
3	93	3,871	28,07	27,85
4	94	3,830	27,26	27,26 standard
5	78	4,165	49,34	39,59
6	141	2,553	10,03	12,12
7	142	2,535	9,47	11,94
8	142	2,535	9,52	11,94
9	142	2,535	10,10	11,94
10	143	2,517	9,23	11,78

As a number of the above velocities are nearly the same, I have averaged the results. The average resistance of Nos. 7, 8 and 10 (low velocities), is 9,41 pounds : the corresponding velocity, 2,529 miles. The average resistance of Nos. 1 and 2 (high velocities), is 42,59 pounds : the velocity, 4,529 miles per hour. The resistance calculated in the duplicate ratio of the velocities would be 38,11 pounds in place of 42,59.—Again, the same low velocities, Nos. 7, 8 and 10, compared with No. 3 (velocity 3,871), would give, by calculation, a resistance 22,04, while the actual resistance was 28,07.

The experiments in Table C were made in a boat twenty-eight feet in length (See the drawing); but being light, and more exposed to the action of the wind, the smaller boat already described was afterwards substituted.

TABLE C.

Number of Experiments.	1.	2.	3.	4.
	Seconds in passing 176 yards.	Miles and Decimals per hour.	Actual resistance in pounds.	Calculated resistance in pounds, taking No. 1. as standard.
1	162	2,222	13,08	13,08 standard
2	187	1,925	11,00	9,82
3	89	4,045	47,26	43,34
4	87	4,138	49,50	45,35
5	137	2,609	18,10	18,02

A few experiments were also made in a small Thames wherry, the distance 80 yards. The average velocity of four of these experiments was 106 yards per minute, or 3,60 miles per hour; resistance 10,4 pounds: and of four others, the velocity was 160 yards per minute, or 5,5 miles per hour; and the resistance 29 pounds; while the ratio of the square of the preceding four experiments would have given 24,27 pounds.

The smaller excess beyond the calculated resistance in the larger boat and the wherry, as compared with the other boat, I consider to have been owing to the form of the bow of those boats causing less heaping of the water in front of them.

In almost every experiment, therefore, the resistance shows an increase amounting to the square of the velocity; but where the velocity is considerable, the resistance follows a still higher ratio, and this in open water. In narrow canals the increase must be considerably greater.

The excess beyond the square is to be attributed in a great degree to the raising of the water at the bow in high velocities, and to the depression at the stern. This does not take place until the velocity is considerable; and in the low velocities of the French experiments it could not be so important.

The boats which I used were taken without any previous preparation; my object being to collect all the resistances to a boat in the ordinary state when in use; and the results have satisfied me, that, as respects the comparison of canal navigation with rail-roads, the rapid increase of resistance upon water brings the rail-road to a par with it at a lower velocity, than if the resistance upon canals were as the squares of the velocities, as hitherto calculated.

If, with a speed of two miles and a half per hour, thirty tons upon a canal be equal to seven tons and a half upon a level rail-road, a speed of five miles per hour would, upon the principle of the square, bring the rail-road and canal to an equality; while the result of the experiments makes the two modes of conveyance equal, considerably under four miles per hour, and gives the rail-road the decided preference at all higher velocities.

It will be observed, from the manner in which former experiments have been made, that the weights employed have been in proportion to the resistance; that is at least to the square of the velocity. The way in which I made the

experiments, required a weight or power at least in the ratio of the cube. Thus if the weight put into the scale in the former experiments produced a velocity 1, a weight 4 produced a velocity 2; while in my experiments, if one man at the wheel produced a velocity 1, eight men (even without regarding the excess beyond the commonly received theory) were required to produce a velocity 2. The cause is evident; and would scarcely deserve mentioning, but that it affords a simple way of removing the confusion I have heard and seen expressed on the subject of the ratio of the square and the cube. As the weight 4 descended in the scale with twice the velocity, the expense of power per second was as 8, or as the cube; but the distance (50 or 96 feet) being performed in half the number of seconds, brought the quantity of power exerted to pass through the given distance back to 4. And in my case, as one man overcame the resistance 1, four men would be required to overcome the resistance 4 with the same velocity: but the velocity being twice the former velocity, it required twice the power, or eight men; the distance was, however, gone over in half the time, so that the expense of power, by doubling the velocity, was only as 4 to 1, as in former experiments. So in overcoming the friction upon a road or rail-road, if a fixed engine of one-horse power move a waggon upon a level road one mile per hour, a two-horse power, acting through a wheel and pinion, or otherwise, will be required to double the speed, although the friction at all velocities is uniform : and *cæteris paribus*, the quantity of power required for moving a given weight a fixed distance upon land, is the same at all velocities; while upon water the quantity increases considerably beyond the square of the velocity.

The following statements with velocities at two and four miles per hour upon a road and upon water, show at one view the whole of the points.

Land Experiments.	*Water Experiments.*
Velocity per hour ....2 miles	Velocity per hour ....2 miles
Distance passed over ....2 miles	Distance passed over......2 miles
Power of engine required 1-horse	Power of engine required ..1-horse
Time occupied.....................1 hour	Time occupied ....1 hour
Quantity of mechanic ⎱ ....1 power expended ⎰	Quantity of mechanic ⎱ ...1 power expended ⎰

Land Experiments.	*Water Experiments.*
Velocity per hour ....4 miles	Velocity per hour ....4 miles
Distance passed over ....2 miles	Distance passed over......2 miles
Power of engine required..........2-horse	Power of engine required $\left\{\begin{array}{l}\text{8-horse by theory,}\\\text{more by experiment}\end{array}\right.$
Time occupied....................½ hour	Time occupied ....½ hour
Quantity of mechanic power expended $\left.\right\}$ 1	Quantity of mechanic power expended $\left.\right\}$ .. $\left\{\begin{array}{l}\text{4 by theory, more}\\\text{by experiment}\end{array}\right.$

But the most remarkable difference between the experiments I have made, and the others to which I have referred, is the absolute measure of resistance. By the French experiments, a square foot with a velocity 1,854 mile per hour, had a resistance of 7,25 pounds. My experiments with a midship section of nine feet superficial, and the same velocity, make the resistance eleven pounds, or only 1,22 per foot superficial. The difference between a flat opposing surface and the form of the boats I used, will account in part for this great variation: but on comparing another experiment of Bossut's, in which the front or prow is an angle of 96°, I found the resistance nine pounds per foot, with a velocity under two miles and one-third per hour; which exceeds my experiments in fully as great a proportion as the former: I am therefore disposed to think that much of the difference is to be ascribed to the way in which the experiments have heretofore been made, although it is certainly difficult to suppose so very great a disagreement from that cause alone. I have proved the accuracy of the weighing-machine I used; and the mode of making the experiments is so simple, that I think there is little room for error. I can only promise to take advantage of the approaching season, and to communicate without prejudice the results of any experiments I may make in confirmation or correction of what I have already done.