IV. *On the Pressure produced on a flat Plate when opposed to a Stream of Air issuing from an Orifice in a plane Surface.*

BY ROBERT WILLIS, B.A.

FELLOW OF CAIUS COLLEGE, AND OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY.

[Read *April* 21, 1828.]

THE singular and apparently paradoxical result obtained by opposing a flat plate to a current of elastic fluid issuing from an orifice in a plane surface, has lately excited considerable interest, especially on the Continent, where it was first brought into notice. In its simplest form the experiment consists in this. If we blow through a tube, the aperture of which terminates in a flat plate, and apply a circular disc of card or any other convenient material to the aperture, we find that as long as the blast is continued, the disc is attracted to the plate instead of being repelled, as might naturally have been expected. Some pins must be fixed into the plate, to prevent the disc from slipping off sideways.

This appears to have been first discovered, apparently by accident, at the iron-works of Fourchambault, where one of their forge-bellows opened in a flat wall, and it was found that a board presented to the blast was sucked up against the wall. It was there exhibited to Messrs. Thenard and Clement Desormes, in October 1826, and shortly afterwards a paper appeared in the *Bulletin Universel*, in which the latter gentleman considered a similar phenomenon with respect to the escape of steam under high pressure, and the danger of failure to which the common safety-valves of steam-boilers were exposed, by this singular fact. M. Hachette then succeeded in simplifying the form of the experiment, so that it might be performed by a pair of common bellows, or a stream of air from the mouth. He also produced the same effects by using a stream of water instead of air. (The particulars may be found, *Bull. Univ.* E. VII. pp. 41. 104. *Ann. de Chimie,* 1827, T. XXXV. p. 34, and T. XXXVI. p. 69. *Quarterly Journal,* 1827, Vol. I. p. 472, and Vol. II. p. 193. Some similar phenomena may, however, be seen in *Young's Nat. Phil.* Vol. I. pp. 298, 778.)

My object in the present Memoir is to detail some experiments which were undertaken for the purpose of examining some of the laws of this phenomenon more minutely than has hitherto been done.

In order to put it into a shape more convenient for investigation, some tubes of different diameters, terminating in flat plates, were connected to the wind-chest of an organ capable of furnishing a regular blast of any pressure not exceeding six inches of water, and a balance of light wood about six feet long, together with a number of discs of tin of various diameters, which could be attached by means of a screw to one of its extremities, being provided; then, by adding weights to the other extremity, and counterbalancing these by placing known weights on the centers of the discs, the effects of varying the orifice, pressure, &c. could be measured. The balance was made of considerable length, that the parallelism of the discs might not be sensibly affected by its motion.

Let *CBD*, Fig. 1, be a section of the lower plate provided with its tube *AB*, through which a constant blast is maintained. Bring the upper disc *GH* gradually down to *CD*, preserving its parallelism with the lower plate, and keeping its center perpendicularly over the center of the orifice. It will be at first violently repelled by a force which will be found to increase till the disc reaches a point *k*, thence the force diminishes to a point *l*, where the disc appears in a state of unstable equilibrium. Bringing it still lower it will be attracted by a force which increases, reaches a maximum at *m*, and diminishes till the disc is placed in stable equilibrium at *n*, and will be repelled if pressed still further down.

TABLE I.

Diameter of disc.................	.8	1	1.5	2	2.5	3	4
Distance of stable equilibrium...	.015	.015	.02	.025	.025	.025	.025
Distance of unstable equilibrium.	.07	.12	.23	.3	.36	.43	.6

This table shews the distance of these points of stable and unstable equilibrium from the lower plate, in the case of an orifice .25 in diameter, and a pressure of 6 inches. *The measures throughout this paper must be understood of inches, unless otherwise expressed.* The next table shews the weight in grains required to pull discs of various diameters off the lower plate. It must be observed, however, that it is extremely difficult to ascertain the exact weight required to do this, and this difficulty is increased by a certain tremulous motion which the disc is apt to acquire. The general results are, that when the diameter of the disc is something less than twice that of the orifice, it is blown off*, that upon increasing the diameter of the disc larger

* This fact has been also observed by R. Younge, esq. in the *Phil. Mag.* April 1828, p. 282.

weights are required to pull it off, till we reach a certain point beyond which the same or a rather less weight is required, however the diameter of the disc be increased. Also that the weights increase with the increase of the orifice, or of the pressure.

TABLE II.

		Diameter of Disc.													
		.25	.35	.4	.45	.5	.6	.7	.75	.8	1	1.5	2	2.5	3
Diameter of Orifice.	.375							0	13	46	129	247	294	327	348
	.25			0	7	30	55	62		86	119	157	175	188	172
	.125	0	11	15		24	27	28		30	31	31	29	26	25

TABLE III.

Pressure in Inches.	1	2	3	4	5	6
Grains.	45	94	145	203	263	327

To understand these phenomena more perfectly, it is necessary to have some means of estimating the pressure on the lower surface of the disc at any required distance from its center. I shall proceed, therefore, to describe an instrument which is adapted to this purpose.

Fig. 2, a section.

Fig. 3. Plan of the lower surface of *FG* seen from below.

ABCD is the lower plate having a tube *B* opening at its center, and communicating with the wind-chest.

FG a circular piece which performs the office of the disc, and is furnished with three legs of slender wire *rs*, *rs*, *rs*, passing through holes in the lower plate, and by which it is kept in its place with its center coinciding with the axis of the tube, while its distance from the lower plate is determined either by the three screws *t*, *t*, *t*, which rest on the lower plate, or by placing washers of known thickness on the wires *rs*. The diameter of its lower surface is 2.4 inches.

This disc is perforated with a circular aperture *vwx* (Fig. 3.), into which is accurately fitted a plug *H* furnished with a shoulder *pp*, which rests on the upper surface of the disc, and serves to keep the lower surfaces of *FG* and *H* in the same plane, and these lower surfaces being turned flat in a lathe, both from the center of the plug *H*, it is evident that they will accurately coincide in whatever position *H* is turned. On the top of *H* is fixed a water-gage *KLM* which communicates with a small hole *i* (diameter .05) drilled in the lower surface of *H*. The relative positions of *FG*, *H* and *i*, will be better understood by referring to Fig. 3, which is a view of the lower surface of the disc. It will be evident that this hole *i* may be placed at any required distance from the center *FG*, while the gage will measure the difference between the atmospheric pressure and the pressure at that point of the lower surface arising from the blast. An index *z*, traversing a graduated scale, serves to shew the distance of *i* from the center of *FG*.

It appears from this instrument that in general the pressure on the disc will be such as is represented in Fig. 4, where the dark parts represent condensation, the mean tint the pressure of the atmosphere, and the light parts rarefaction.

Proceeding from the center of the disc we come to a circle *Aa*, on every point of whose circumference the pressure equals that of the atmosphere, then to a circle *Bb*, where rarefaction is at a maximum, then to a second neutral circle *Cc*, and then again to one *Dd*, where the condensation attains a second maximum. Taking these circles as the most characteristic points of the phenomenon, I have, in Tables V. and VI. given their radii together with the amount of the maximum rarefaction and condensation at different distances of the disc from the plate, and with various orifices and pressures. Table IV. shews the pressure indicated by the gage at different distances from the center of the disc, and at different distances of the disc from the plate.

TABLE IV.

Pressure 6 Inches.														
Diameter of Orifice .375														
Distance of Disc from Plate.	Distance of the Gage from the center of the Orifice.													
	.1	.15	.2	.25	.3	.35	.4	.45	.5	.6	.7	.8	.9	1
.5	4.	3.8	3.6	3	2.1	1.2	.55	.25	.13	.1				$\overline{.1}$
.25	4.	3.8	3.35	2.6	1.7	.7	.14		$\overline{.1}$	$\overline{.13}$	$\overline{.2}$	$\overline{.28}$	$\overline{.29}$	$\overline{.3}$
.125	4.1	3.8	3.1	2.06	.7	$\overline{.4}$	$\overline{.8}$	$\overline{1.}$	$\overline{1.08}$	$\overline{1.08}$	$\overline{.9}$	$\overline{.6}$	$\overline{.25}$	$\overline{.15}$
.062	4.6	4.3	3.15	.67	$\overline{2.8}$	$\overline{3.57}$	$\overline{2.95}$	$\overline{2.1}$	$\overline{1.34}$	$\overline{.52}$	$\overline{.2}$	$\overline{.09}$	$\overline{.04}$	$\overline{.02}$
.031	5.	4.75	3.75	$\overline{.7}$	$\overline{5.65}$	$\overline{3.25}$	$\overline{1.53}$	$\overline{.95}$	$\overline{.65}$	$\overline{.3}$	$\overline{.15}$	$\overline{.1}$	$\overline{.06}$	$\overline{.03}$
.024	5.	4.75	4.5	$\overline{.95}$	$\overline{5.2}$	$\overline{2.4}$	$\overline{1.2}$	$\overline{.8}$	$\overline{.53}$	$\overline{.25}$	$\overline{.13}$	$\overline{.05}$	$\overline{.03}$	.03
.018	5.25	5.15	4.55	0	$\overline{4.8}$	$\overline{1.35}$	$\overline{.7}$	$\overline{.5}$	$\overline{.25}$	$\overline{.09}$	.05	.1	.1	.05
.015	5.3	5.25	4.8	.65	$\overline{3.5}$	$\overline{.75}$	$\overline{.33}$	$\overline{.13}$	.01	.15	.2	.19	.18	.17
.012	5.45	5.45	5.05	1.75	$\overline{1.8}$	$\overline{.3}$	.2	.3	.43	.45	.47	.5	.4	.35
.009	5.5	5.5	5.3	2.9	.35	.7	.95	1.05	1.2	1.2	1.1	1.05	.9	.8
.006	5.5	5.5	5.5	4.3	2.65	2.75	2.73	2.65	2.57	2.3	2.2	1.85	1.55	1.25

Note. The pressures less than the atmospheric are marked —.

TABLE V.

Pressure at Orifice 6 Inches.																				
	Diameter of Orifice .375						Diameter of Orifice .25							Diameter of Orifice .125						
Dist. of Disc from Plate.	Radius of Neut. Circle.	Minimum Pressure.		Radius of 2d Neut. Circle.	2d Maximum Pressure.		Pressure over Orifice.	Radius of Neut. Circle.	Minimum Pressure.		Radius of 2d Neut. Circle.	2d Maximum Pressure.		Pressure over Orifice.	Radius of Neut. Circle.	Minimum Pressure.		Radius of 2d Neut. Circle.	2d Maximum Pressure.	
		Rad^s.	Am^t.		Rad^s.	Am^t.			Rad^s.	Am^t.		Rad^s.	Am^t.			Rad^s.	Am^t.		Rad^s.	Am^t.
.5	.77						3.2	.72						3.6	.53					
.25	.485						3.3	.45	.9	− .16				4.3	.34	.6	− .01			
.125	.33	.57	− 1.08				3.5	.26	.6	− .5				4.5	.22	.45	− .15			
.062	.26	.34	− 3.6				3.85	.183	.295	− 1.63				4.6	.13	.27	− .52			
.031	.245	.29	− 5.7				4.6	.148	.21	− 4.1	.77		+ .02	4.7	.09	.145	− 1.85	.6		
.024	.248	.28	− 5.6	.95			5	.145	.195	− 4.6	.52		+ .05	4.9	.07	.13	− 2.8	.42		+ .05
.018	.25	.279	− 4.85	.65		+ .1	5.2	.149	.185	− 4.6	.45	.7	+ .15	5.1	.08	.115	− 2.75	.35	.6	+ .12
.015	.253	.278	− 3.8	.485	.8	+ .2	5.3	.15	.18	− 4.	.323	.65	+ .45	5.2	.09	.11	− 2.6	.24	.45	+ .22
.012	.257	.276	− 2.55	.366	.75	+ .5	5.4	.155	.18	− 3.	.26	.6	+ .8	5.3	.09	.1	− 1.35	.15	.28	+ .56
.009	.27	.275	− .2	.28	.52	+ 1.3	5.5	.168	.18	− 1.5	.235	.4	+ 1.55	5.4	.1			.1	.23	+ 1.26
.006		.3	+ 2.65				5.6		.18	+ 1.8				5.5						

Note. The pressures greater than the atmospheric are marked + and those less −.

TABLE VI.

Diameter of Orifice .375																		
	Distance of Discs.																	
	.5	.25	.125			.062			.031				.01					
Pressure at Orifice in inches.	Radius of Neut. Circle.	Neutral Circle.	Neutral Circle.	Minimum Pressure. Rad^s.	Minimum Pressure. Am^t.	Neutral Circle.	Minimum Pressure. Rad^s.	Minimum Pressure. Am^t.	Neutral Circle.	Minimum Pressure. Rad^s.	Minimum Pressure. Am^t.	2d Neutral Circle.	Neutral Circle.	Minimum Pressure. Rad^s.	Minimum Pressure. Am^t.	2d Neutral Circle.	2d Maximum Pressure. Rad^s.	2d Maximum Pressure. Am^t.
1	.765	.43	.325	.53	$\overline{.18}$	.26	.34	$\overline{.56}$	.253	.3	$\overline{.65}$	.5					.46	.33
2	.77	.435	.327	.55	$\overline{.35}$	.26	.34	$\overline{1.15}$	.249	.3	$\overline{1.57}$	.7	.27	.28	$\overline{.05}$	.295	.46	.43
3	.775	.44	.329	.55	$\overline{.55}$	.33	.34	$\overline{1.7}$	.248	.295	$\overline{2.5}$	.82	.265	.28	$\overline{.4}$	.32	.52	.5
4	.783	.44	.33	.565	$\overline{.7}$	.33	.34	$\overline{2.3}$	.247	.29	$\overline{3.5}$	.84	.262	.276	$\overline{.8}$	.33	.52	.59
5	.79	.437	.33	.567	$\overline{.87}$	.33	.34	$\overline{2.65}$	.246	.29	$\overline{4.6}$	.88	.26	.276	$\overline{1.25}$	.339	.52	.6
6	.77	.435	.33	.57	$\overline{1.08}$	.26	.34	$\overline{3.6}$	.245	.29	$\overline{5.7}$	.89	.26	.276	$\overline{1.8}$	.34	.52	.6

It appears from this Table that upon varying the pressure the radii of the principal circles remain very nearly constant, while the amount of the minimum pressure varies nearly as the pressure applied at the orifice, except when the plates are very near indeed.

The pressure on any circle of the disc is plainly proportional to the pressure indicated by the gage on that circle and to its radius, jointly. The curves in Fig. 6. are constructed on this principle, their abscissæ representing the distance of the gage from the center, and their ordinates being taken proportional to (pressure) × (distance), the ordinates becoming of course negative when the pressure is less than that of the atmosphere. Hence the area will represent the whole difference between the pressure on the lower surface of the disc and the atmospheric pressure, the upward pressure being proportional to the areas above the axis, and the downward pressure to those below. These diagrams, therefore, shew, by inspection, the variations of pressure at different distances of the disc from the plate.

Thus at .5 it is plainly repelled, at about .25 in equilibrium, from .24 to .024 attracted, between .024 and .018 in equilibrium, and from .018 to contact repelled.

The center of the orifice is in all these figures at the left hand, and the decimals are the distances of the disc from the plate.

To ascertain the effect produced by varying the diameter of the disc, a gage *ABCD*, Fig. 5, was provided, which terminated in a flat horizontal tube, made so thin that it could be introduced between two plates at a distance of .08 from each other, the upper plate being, for the convenience of seeing the point of the gage, of glass; and sustained by three little knobs or feet, which served to maintain its distance and parallelism with the lower plate, and yet allowed it to be moved about into any position with respect to the orifice.

Inferring then that the pressure of the current, estimated at right angles to its direction, would be the same whether measured in a direction parallel or perpendicular to the disc, the end of the gage was placed, as in the figure, at right angles to the radius, and upon moving it to different distances from the center of the orifice, its indications were found actually to agree with those already obtained by means of the gage before described.

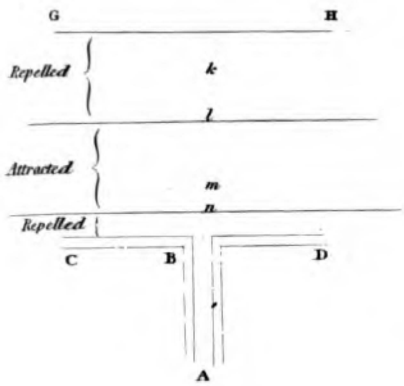
Now upon keeping this gage fixed at any distance whatever from the center of the orifice, and observing its indications while the upper plate was moved about, it was found that the pressure was not at all affected by such motion, unless the edge of the upper plate was brought very near the point of the gage, when the pressure became slightly diminished. It may be concluded from this that *cæt. par.* the pressure at any point of the disc at a given distance from the orifice, is not affected by increasing or diminishing the diameter of the disc, or otherwise altering its figure, and this may serve to show why the small discs are blown off: for if in Fig. 4, the disc be reduced to the diameter of *Aa*, there will be no rarefaction, and it must necessarily be repelled. Again, if it be made at all greater than *Cc*, the rarefaction will not be increased, but the condensation will slightly, and therefore it will sustain a rather less weight upon further increasing it.

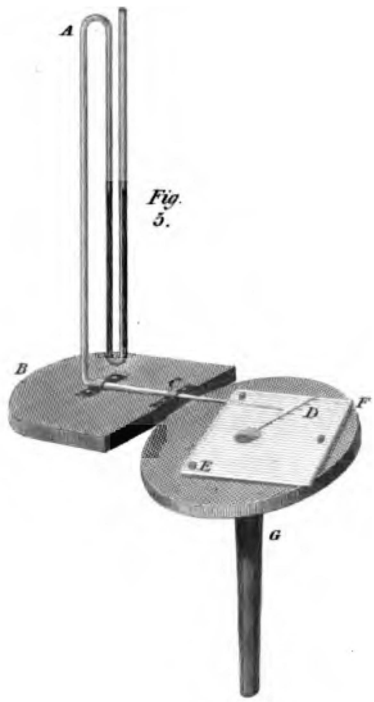
A good experiment in illustration of all this is one that was devised by Hauksbee, as long ago as 1719. He shewed that when a current of air was made to pass through a small box, the air contained in the box became considerably rarefied. From this and similar experiments it appears that a current of air communicates its motion to the particles in its immediate neighbourhood, and carries them along with it. In our experiment, then, the first portion of air when it issues from the orifice instead of dispersing itself in distinct streams, communicates its motion to the air contained previously between the plates, and carries it away so that the succeeding portions are compelled to fill the whole space. The air may then be considered as issuing in successive concentric annuli from a cylindrical aperture, whose length is the circumference of the orifice, and height the distance between the plates. Now as the particles in each annulus issue with a certain velocity, and in lines radiating from the center, they must necessarily increase their distance from each other, and hence the air in the annulus becomes suddenly rarefied, by which means its progressive velocity and the pressure on the preceding and succeeding portions is variously modified. Some of these modifications I have attempted to develope experimentally, and have ventured to submit these results to the Society in the hope that they may be found useful hereafter in confirming any theoretical views of the subject which may appear, and in the mean time may serve to throw some light on a phenomenon which is doubtless possessed of very great interest.

R. WILLIS.

CAIUS COLLEGE,
April 21, 1828.

Fig. 1.





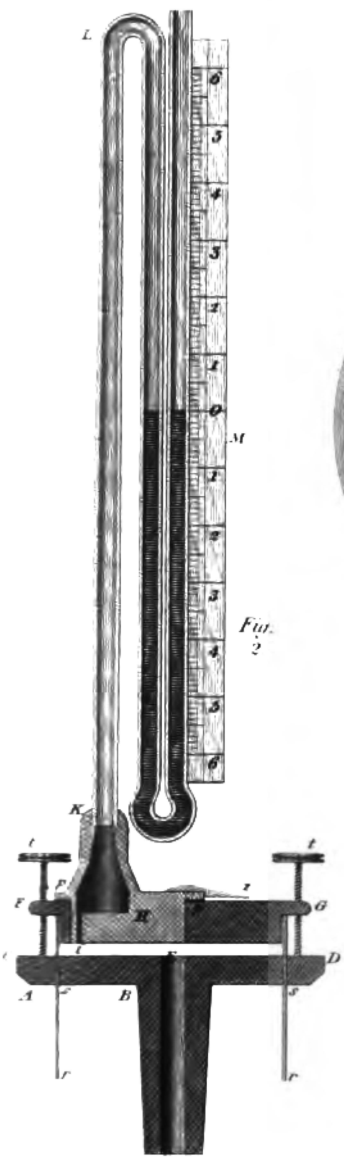


Fig. 4.

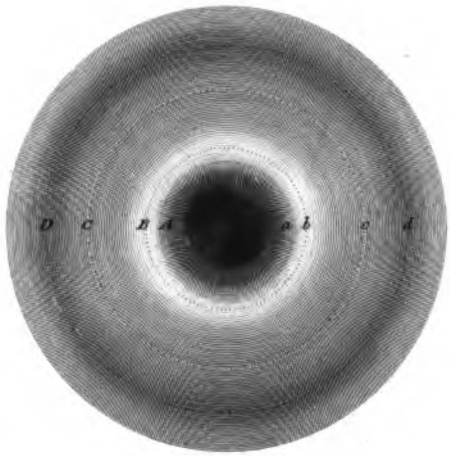


Fig. 3.

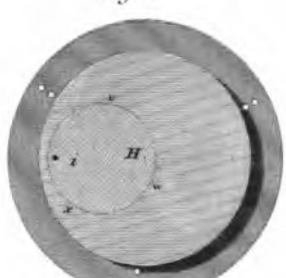


Fig. 6.