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## EXPERIMENTS ON THE COMPRESSION OF AIR BY THE DIRECT ACTION OF WATER.

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Some ten years ago, the writer's attention was called to the compressing of air for mechanical purposes by causing it, in the form of minute bubbles, to be carried downward in a current of water and lodged in a receiver by changing the direction of the current from vertical to horizontal.

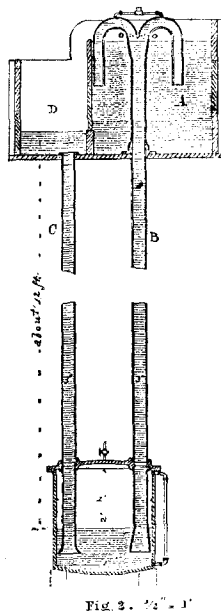
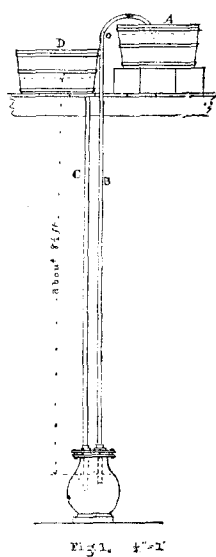
Such a method appeared to promise important advantages over existing methods of utilizing water power, putting it in a form to be transmitted to distant points and allowing the location of mills and factories to be chosen without reference to the requirements of water wheels.

The application of this method on a scale corresponding to a high degree of efficiency would involve a large expense and its entirely novel and experimental character seemed to render hopeless any attempt to bring it to the notice of capitalists. Nothing was therefore done in the way of its development beyond theoretical researches and some crude and simple experiments till within a couple of years.

Public attention was first called to the subject in a paper published in the JOURNAL OF THE FRANKLIN INSTITUTE for September, 1877, in which the theory of the method was set forth and its probable

advantages pointed out. This had the effect to excite the interest of a prominent New England manufacturer, Gen. J. C. Palfrey of Boston, at whose expense the experiments to be detailed have been mainly conducted.

It was well understood that a practically satisfactory efficiency could not be obtained from a model. With a low velocity, narrow passages and small head, the resistances bear a large proportion to the motive power, and may even absorb it altogether. Theoretical considerations indicate that the efficiency increases with these several elements, till it may in certain conditions reach as high as 80 per cent. or even higher.



The apparatus first tried is represented in Fig. 1. Two glass tubes, *B* and *C*, were passed through the cover of a strong glass vessel, the fittings being, as near as possible, air-tight. The tube *B* terminated at the upper end in a siphon, and dipped into a tub, *A*, kept nearly full of water. The tube *C* opened into another tub, *D*. The tube *B* had a small orifice at the summit, closed by a flap valve, for exhausting the air. There was another minute orifice at *o*. The two tubs being filled with water as indicated by the dotted lines, the water, of course, filling the receiver and rising in the tube *B* to the level of the

surface in the tub *D*, the siphon was set in action by placing the finger over the orifice *o*, and exhausting the air by applying the mouth to the summit orifice, then closing the latter. The flow was kept up by dipping the water from the lower to the higher tub. The pressure within the tube at the point *o* being a little less than that of the atmosphere, the air enters there and is carried downward by the current and lodged in the receiver.

This device worked very well as an illustration of the method.

The quantity of air collected in the receiver was very small. No attempt at an exact estimate of the useful effect was made. It was very slight, probably not over 5 per cent., certainly not over 10 per cent. of the power expended. The diameter of the tubes was  $1\frac{1}{4}$  inches. The air accumulated under a pressure of 8 or 9 feet of water. The head or difference of level between the two tubs was 8 to 12 inches.

No difficulties not previously foreseen being developed by this experiment, it was decided to try the method on a larger scale. For this purpose the apparatus represented in Fig. 2 was constructed. The receiver was of cast iron, circular, 2 feet diameter, 2 feet high. The pipes *B* and *C* were of iron 3 inches diameter inside. The water was supplied from a wooden tank in two compartments, *A*, *D*, the flow being maintained by pumping the water from the lower to the higher level, with a small centrifugal pump driven by steam, which does not appear in the cut. The pipe *B* terminated, as before, in a siphon, or rather this time, in two siphons, provided at their summits with connections for an air pump to set them in action. The air was admitted, as before, through minute orifices, *o*, *o*, just above the surface of the water in the chamber *A*. A glass gauge on the receiver showed the quantity of air contained in it. The pressure of the air is measured by a column of water equal to the height of the surface in the chamber *D* above that in the receiver.

This apparatus was exhibited at the fair of the charitable Mechanic Association in Boston, in 1878. It was afterwards set up in the laboratory of mechanical engineering at the Massachusetts Institute of Technology, and became the subject of critical experiments by Professor Whitaker and members of his class. The quantity of water was inferred from the velocity of the pump. The velocity could also be observed, but not very closely, in the descending shaft, which, near the bottom, was of glass. From the best data attainable, Mr. Whitaker computed the efficiency at  $26\frac{1}{2}$  per cent; that is, the power repre-

sented by the air after compression is but  $26\frac{1}{2}$  per cent. of that represented by the water employed in compressing it. The head in this experiment was about 25 inches. This result, though at once accepted by the unthinking as a failure of the method, was so entirely in accordance with the true theory of the subject that it strengthened our confidence and induced us to make a trial upon a larger scale. In the meantime I had been called by business to St. Paul, Minn.

The application of this method on any greater than the laboratory scale requires conditions very rarely met with, viz.: a deep pit, free from water, in the immediate vicinity of a small waterfall. These conditions happened to be presented at the Falls of St. Anthony, on the Mississippi river a few miles above St. Paul. A vertical shaft was sunk by the United States Engineer Department, several years since, in the work for the preservation of the falls, and had never been refilled. It was about 36 feet deep and was drained by a pipe opening into the river below the falls. Its clear dimensions, inside the timbering, were about  $6 \times 14$  feet. It occupied a narrow island between two mill ponds, one of which was maintained some 8 or 10 feet higher than the other.

Permission to occupy this shaft for the purpose in question was readily given by the officer in charge of works in this district, C. J. Allen, Captain of Engineers, and Dr. S. H. Chute, one of the managers of the St. Anthony Water Power Company, kindly gave permission to use the water and make the necessary excavation for races. The apparatus, except the raceways, is shown in Figs. 3, 4 and 5. Figure 3 is a vertical longitudinal section; Fig. 4 a cross section through the air chamber, and Fig. 5 a plan. The apparatus consists of a strong wooden tank at the bottom of the pit, with two vertical shafts or channels rising to the surface of the ground. The shaft for the descent of the water, in which a considerable velocity is required, is  $15 \times 30$  inches. The ascending shaft, whose function is to return the water to the surface with as little loss of head as possible, is  $24 \times 48$  inches. The upper part of the tank between the vertical passages is occupied by the air chamber which is lined with zinc and is furnished with a cock, *f*, operated from above, as shown, for the escape of air. The air chamber is separated from the passage below it by a partition of boards laid with openings which allow the air to pass freely into the chamber. It will be noticed that the descending shaft, at the bottom, is contracted strongly in the plane of the section, though it expands



to the air chamber, as in the arrangement already described. The drenching to which it would subject an observer, however, decided me to abandon this, and adopt an arrangement bringing all the essential facts of the process under the eye of a single observer above ground. An opening, *g*, was made in the side of the air chamber just 21 inches below the top, opening into the ascending shaft. The filling of the air chamber to the depth of 21 inches was announced by the appearance of large bubbles in the chamber *D*, followed in a few seconds by a violent commotion therein. By raising the lever, *h*, the air accumulated in the chamber was discharged, the cessation of the loud hissing indicating the complete emptying of the chamber.

The water was discharged from the chamber *D* over a weir 5.56 feet long. A gauge in this chamber indicated the depth on the weir, and, in connection with another in the chamber *A*, the fall. The fall, it is hardly necessary to observe, is the height of the surface in the chamber *A* above that in the chamber *D*. The pressure of the air is determined by the height in the latter above that in the air chamber. The leakage, which was considerable, was readily determined by observing the rate at which the water fell in the chamber *D* after shutting off its admission. The fall was varied by adjustable weir plank. At each change of weir plank, the reading of the gauge was taken when the water was exactly at the crest of the weir. This reading subtracted from that taken during the flow of the water gave the depth on the weir. No microscopic nicety, but only substantial accuracy was attempted in any of these observations. The tank and the lower part of the ascending shaft were of four inch pine plank. The rest of three and two inch plank, all confined by an immense number of screw and lag bolts with large cast iron washers. The timber was put in quite dry and joints paid with white lead and oil in the expectation that the swelling would make all tight. This expectation was not fully realized, the great pressure starting some of the joints and causing considerable leakage, amounting in some cases to nearly half a cubic foot per second. This was, of course, added to the quantity passing the weir.

As originally constructed, the upper part of the shaft was provided with a siphon, as in previous arrangements. Meeting with great difficulty in exhausting the air, I decided to take it out and rebuild it on a different plan, but in the meantime took occasion to make an experiment which I had contemplated from the first, viz., to ascertain whether the introduction of the air could not be equally well accomplished by

giving the water a slight fall at its entrance. The readiness with which water in violent agitation breaks into foam is familiar to all, as well as the fact that foam is nothing more than water impregnated with minute air bubbles.

The method adopted was the one indicated in the sketch, viz., allowing the water to fall into the descending shaft over a barrier of stop-plank. The complete success of the experiment made it apparent that the siphon might henceforth be dismissed from the method, although it would undoubtedly have some advantage as regards efficiency, especially with a low head.

In the theory of the subject formerly presented I assumed 12 inches per second as the velocity with which bubbles of air rise in still water. This was founded on experiments with bubbles formed by air escaping through orifices. In the process above described the air appears to be broken up into finer bubbles, which do not rise so fast. I found that a velocity of 0.75 ft. per sec. in the descending shaft brought an appreciable quantity of air into the chamber; 0.86 ft. brought it in freely.

The mode of conducting experiments on compression was as follows: The water being turned on and flowing in full volume over the weir, the air chamber being empty, the escape valve was closed by the lever, *h*, and at the same instant a stop watch was started. The gauges in *A* and *D* were observed and recorded; then the eye was fixed on the surface in *D*. On the appearance of large air bubbles here, the watch was stopped. It must be observed that when the velocity in the descending shaft much exceeded three feet per second large quantities of air were carried past the air chamber, and rose in the ascending shaft. There was no danger, however, of confounding these bubbles with those announcing the filling of the air chamber, the latter being larger and immediately followed by a great commotion in the basin *D*.

The passage of air past the air chamber disposes of one difficulty that has been predicted of this method, viz., that the air would tend to aggregate in large masses. No tendency of this kind was observable in the air coming up the ascending shaft, though it had traversed a distance of over 70 feet. It reached the surface in fine bubbles, very nearly uniform in size.

The capacity of the air chamber, filled to a depth of 21 inches, was 71.19 cubic feet. The following is an example of the computations:

Take experiment No. 1. Fall, 4.07 feet; depth on weir, 0.63 ft.;

quantity of water,  $1.665 \times (5.56 - 0.2 \times 0.63) + (\text{leakage}) 0.41 = 9.45$  cubic feet per second.

Pressure of air, . . . . . 27.58 ft. water.

Power of 1 cub. ft. air—Admission,  $27.58 \times 62.3 = 1780.5$  ft. lbs.

“ “ “ —Expansion  $= \frac{1780.5}{2} \times \frac{27.58}{34} = 747.8$  “ “

Total, . . . . . 2528.3 “ “

Time, from closing of escape valve to appearance of bubbles, 2 m. 48 s.

Velocity of water in ascending shaft,  $\frac{9.45}{8} = 1.18$  do. of air, 2.18 ft. per second.

Time of rising of air bubbles,  $\frac{27.58}{2.18} = 13$  seconds.

Time of filling of air chamber = 2 m. 48 s. — 13 s. = 2 m. 35 s. = 2.583 minutes.

Quantity of air per minute  $= \frac{71.19}{2.583} = 27.60$  cubic feet.

Power of air per minute  $= 2528.3 \times 27.60 = 69781$  ft. lbs.

“ “ water “  $= 4.07 \times 9.45 \times 60 \times 62.3 = 143780$  ft. lbs.

Percentage of useful effect  $= \frac{69781}{143780} = 48.5$  per cent.

No account was taken of the leakage of air, which was slight. The assumption that the mean pressure during expansion is half the initial pressure rather over-estimates the power of the air. On the other hand, taking an atmosphere at 34 feet water (its value at the sea level) leads to a greater error in the opposite direction. The bottom of the pit is about 750 feet above the sea level.

A large number of experiments were made before discovering the most advantageous conditions of working. Table I contains all the experiments covered by the dates therein given.

The best efficiency is 52 per cent., being about double the best result obtained with the apparatus, Fig. 2. This percentage would, of course, be entirely unsatisfactory in a practical motor; but an air-compressing system on a practical scale would exceed this model, in dimensions, in greater ratio than this exceeds the apparatus represented in Fig. 2. The object of these experiments is to ascertain what could be expected from such a system. Let us first see how these results accord with the theory of the subject.



TABLE I.

*Results of Experiments in Compressing Air by causing it to mix with a Descending Current of Water.*

No. of exp.	Date.—1880.	Head.—Feet.	Pressure on air in chamber, in feet of water.	Quantity of water.—Cub. feet per sec.	Quantity of air carried into chamber.—Cub. feet per minute.	Power due to one cub. foot of air.—Ft. lbs.	Total power of air for one minute.—Ft. lbs.	Total power of water for one minute.—Ft. lbs.	Percentage of useful effect.	Velocity in the descending shaft.—Feet per sec.
1	May 30	4.07	28.58	9.45	27.60	2528.3	69781	143780	48.5	3.02
2	" "	3.24	29.43	9.89	18.59	2627.4	48843	119780	40.8	3.16
3	" "	2.62	30.08	9.45	14.47	2703.2	39115	92549	42.3	3.02
4	" 31	2.54	29.91	5.92	8.53	2683.3	22877	56207	40.4	1.89
5	" "	0.98	.....	14.03	0.00	.....	.....	.....	.....	4.49
6	" "	4.82	27.68	10.34	31.49	2426.3	76193	186297	40.9	3.31
7	" "	4.70	27.75	11.89	38.07	2434.4	92668	208890	44.3	3.80
8	" "	4.77	27.75	11.89	35.95	2434.4	87522	212000	41.3	3.80
9	" "	4.81	27.72	11.22	42.12	2430.7	102391	201733	50.7	3.59
10	" "	4.87	27.68	10.34	36.89	2427.2	89529	188230	47.6	3.31
11	" "	4.94	27.58	8.23	27.31	2415.2	65951	151973	43.4	2.63
12	June 2	4.78	27.64	9.46	34.90	2422.4	84519	169040	50.0	3.03
13	" "	4.79	27.64	9.46	36.41	2422.4	88200	169381	52.1	3.03
14	" "	5.01	27.47	6.10	21.42	2402.7	51476	114237	45.0	1.95
15	" "	5.02	27.46	5.92	21.44	2401.9	51503	111090	46.4	1.89

The losses of power, or the losses of head, which are the same thing, the head being taken to represent the power in any given experiment, are of three kinds: First, the loss at the entrance, or the fall required to impregnate the air with bubbles. This did not admit of very close measurement, but, as near as could be estimated, did not differ materially from one foot in all the experiments. Second, the resistances to movement. In experiment No. 5, with no air passing, a velocity of 4.49 feet per second in the descending shaft corresponds to a head of 0.98 feet wholly absorbed in resistances to movement. This gives the means of finding the resistance to movement for any other velocity, such resistance being represented by a head which is proportional to the square of the velocity. Third, a certain loss is occasioned by the fact that the air does not move downward with the same velocity as the water. The air bubbles, as I find, would rise in still water at the rate of 0.75 foot per second. When the water, therefore, is moving downward at the rate of 3 feet per second the air goes only 2.25.

There is, then, a loss of power of  $\frac{0.75}{3.00} = 25$  per cent. of the head

employed in compressing the air. Let us now apply these principles to computing the head in experiment 1.

Head lost at entrance,				1.000 feet.
“ “ in resistance to movement	$= 0.98 \left( \frac{3.02}{4.49} \right)^2$			$= 0.443$ “
“ “ slip	$= (4.07 - 1.443) \times \frac{0.75}{3.02}$			$= 0.653$ “
“ expended usefully	$= 4.07 \times 48.5$			$= 1.974$ “
Total,				<u>4.070</u> “

TABLE II.

Expt.			Expt.		
Head.			Head.		
No.	Observed.	Computed.	No.	Observed.	Computed.
1	4.07	4.07	9	4.81	4.73
2	3.24	3.22	10	4.87	4.61
3	2.62	2.84	11	4.94	4.51
4	2.54	2.74	12	4.78	4.66
6	4.82	4.25	13	4.79	4.77
7	4.70	4.38	14	5.01	4.92
8	4.77	4.28	15	5.02	5.03

Table II contains the results of this calculation applied to all the experiments. The computed head falls short of the observed head in the experiments with velocities exceeding 3 feet per second, as was to be expected, since in these cases large quantities of air were carried past the chamber, involving resistances not taken account of in the computation. Moreover, in these cases, air counting as water, the tendency is to over-estimate the quantity passing the weir. One thing is especially to be noted. In the experiments giving the best results the agreement is quite satisfactory. We may, therefore, I apprehend, apply this method, with a good degree of confidence, to a system of practical size, understanding always that it is working to its best advantage.

For a system of practical size, we may fix the following dimensions: Descending shaft, 10 feet diameter, making the mean radius six times that of the model. Ascending shaft in same proportion. Depth, 120 feet, corresponding to a pressure of about 50 pounds per square inch, making the journey of the water about four times that in experiment 5. Fall, 15 feet. Velocity in descending shaft, 6 feet per second. It would not be advisable to make such a system an exact copy of the model which, owing to the limited space, could not have the form best calculated to avoid loss of head.

The loss of head in experiment 5 was 0.98 foot, with a velocity of 4.49 feet per second.

The loss in the straight passages, by the best formulas, could not have exceeded . . . . . 0.200 foot.

The loss due to bends, chiefly the bend at the bottom of the descending shaft, which the results show to be more abrupt than necessary, was . . . . . 0.250 "

A loss also occurs at the entrance,

$$\text{represented by } \left\{ \left( \frac{1}{0.68} \right)^2 - 1 \right\} \left( \frac{4.49}{2g} \right)^2 . . . = 0.365 "$$

0.68 being the coefficient of contraction of the water at its entrance to the descending shaft. The remainder, 0.165 "

0.980 "

is a part of the head due to the initial velocity which, it is evident, was not wholly suppressed, the enlargement of the channel under the air chamber being a little too abrupt. This is evident, also, from the readiness with which air was carried past the chamber, implying commotion in the water, which retarded the elimination of the air.

The item 0.365 might have been wholly suppressed by suitably rounding the entrance to the descending shaft. We will therefore reject it in applying the results to the proposed system.

The frictional head proper (0.200) is directly proportional to the square of the velocity, directly as the distance traversed by the water, and inversely as the mean radius of the channel. The other items of head (0.250 + 0.165 = 0.415) are directly as the square of the velocity. The losses in the proposed system of channels will therefore be as follows:

