No. 1517

UNIQUE HYDRAULIC POWER PLANT AT THE HENRY FORD FARMS

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The hydraulic power plant at the Henry Ford Farms, Dearborn, Mich., contains two turbines designed to develop 85 h.p. each at 110 r.p.m. under 8-ft. head, together with electric generators. The plant supplies current for light, heat and power for Mr. Ford's residence, for the village pumping station, and for the miscellaneous requirements of the farms. It was built, to operate under somewhat unusual conditions of head and contains features which the author believes to be novel and unique.

2 The plant is located on the river Rouge, near its junction with the Detroit River, which latter varies considerably with the levels of the Great Lakes. The Rouge River is subject to the widest extremes in flow. At the point of location of the plant is a dam over which the normal run-off is 100 sec-ft. There are short intervals, however, when the run-off is so great that it fills the valley with water so that no sign of the dam is apparent; at these times the head over the dam is completely destroyed, but the condition lasts only a few hours until the high water wave has passed. There are longer periods when the level is affected by the Great Lake conditions causing back water in the tail race and consequent lowering of the head for days at a time. Also, there may be weeks of surplus flow at semi-high head. In fact, the conditions may be summarized as

a Low water with normal head

b Low water with head lowered by Great Lake conditions

c Normal flow under variable heads

d High water with approximately half normal head, which is also variable and dependent upon Great Lake conditions

e Very high water, but with head almost destroyed

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3 High water, with head varying from 2 to 5 ft., may persist for weeks at a time, so that provision to meet this condition was necessary. The condition of very high water but practically no head only obtains for a few hours at a time, and no adequate provision can be made for it, except the steam reserve.

4 To secure the maximum power effects and constant generator speeds through such a wide range of heads, and without employing a multiplicity of units with variable speeds, was quite a problem, and a description of its manner of solution should be of interest to engineers concerned with hydraulic power plant design.

THE POWER HOUSE

5 The power house, an adjunct to Mr. Ford's private laboratory, is a concrete structure. The foundation consists of a monolith of reinforced concrete. Conditions made it necessary to floor the head race, power house site and tail race with concrete for several feet in thickness. The head race, 31 ft. wide and 10 ft. deep, was completely arched over for approximately 150 ft., and the tail race was similarly arched, both for architectural reasons.

6 The power house is shown in cross section in Fig. 1. It is a 3-story building, the lower floor containing the two turbines, the middle containing the auxiliary apparatus for controlling the turbines, and the upper the two dynamos, the governors, the switchboard and one steam reserve unit. The turbine floor is divided into three separate penstocks, connected by an overhead gallery.

THE POWER PLANT

7 Ordinary precaution led to the provision of two units, each having the capacity of the normal flow of the stream under 8-ft. head. The speed of 110 r.p.m. was established for full head conditions and this speed was maintained at all heads, varying from 1 ft. up to the full head of 8 ft. Herein lies the unique feature of this plant—the maintenance of full speeds and good power through a wide range of low heads and in the face of the condition that, under ordinary settings, the turbines employed require slightly over 4 ft. head to bring them to maximum speed at full gate and no load conditions.

8 The turbines are of the vertical type, designed, as stated, to develop 85 h.p. each on the turbine shaft when operating under 8 ft. head at 110 r.p.m. They have wicket gates, operated by draw rods from a gate shaft reaching directly to the governor arm. The

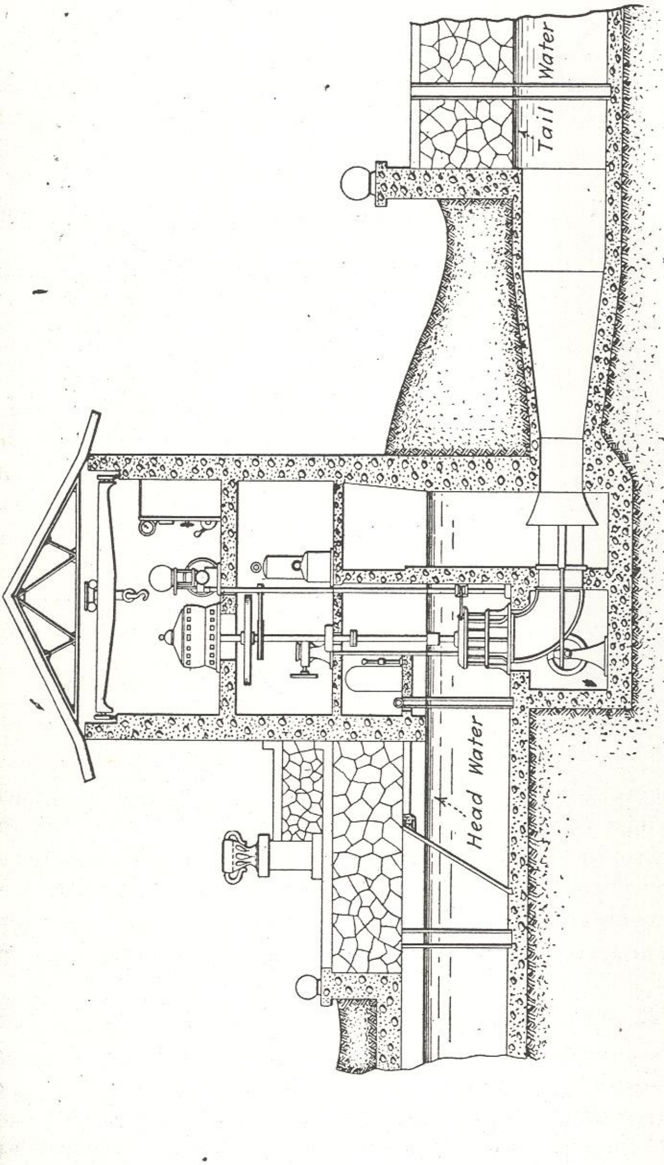

FIG. 1 CROSS SECTION OF POWER HOUSE AT THE HENRY FORD FARMS

turbine chambers are scroll-shaped, arranged for their respective right and left hand turbines. The weight ot the runners is sustained by roller bearings on top of the generators. All under water bearings are of bronze.

9 The two turbo-generators are of the vertical type, 55 kw. each, at 250 volts. They are direct current machines and have ample overload capacity. Each is self-contained, having a roller bearing on top which supports all the rotating parts, including the balance wheels and turbines.

10 A third steam engine generator is provided. This is horizontal, and is of 35-kw. capacity at 250 volts.

11 The governors are vertically driven, and direct connected. They are of the open system, oil-pressure type.

12 Full apparatus is provided in the top floor of the power house for recording test conditions.

13 The three penstocks on the lowest floor can be closed by folding head gates, manipulated by the overhead crane. Of these penstocks, the middle one is a common feeder for the others, each of which contains what has been termed a "turbine discharge accelerator." These accelerators are a form of draft tube, into which each turbine discharges and into which, also, water from the head race is discharged through a feeder. The head race water accentuates the turbine flow through the draft tube, having the same effect as an added head of head water. An illustration of one of the turbines with accelerator is shown in Fig. 2.

DISCHARGE ACCELERATORS

14 The purpose of the discharge accelerators is to transfer energy from surplus water (otherwise running over the dam or wasting) to the turbines, augmenting their power under subnormal heads after they have reached their otherwise full power at those heads. In other words, their effect is to boost the power of the turbines, working under low head conditions, beyond that which the conditions would seem to warrant.

15 The principle of the accelerator may be followed by reference to Fig. 3. In this figure is also shown a common siphon for purposes of comparison.

16 In the case of the siphon, the induced or suction head cannot be greater than the inducer, or pressure head. With the accelerator, the induced head may be greater than the inducer head. The accelerator is not an ejector.

17 The effect of the accelerator on the turbine is to partially remove the pressure at the discharge end without changing the pressure at the intake end. Under ordinary conditions, the pressure on both the head and tail water is 14.7 lb. per sq. in. alike. If the turbine were to discharge into tail water the pressure on which was, say, only 10 lb. per sq. in., the result would be the equivalent of adding slightly over 10 ft. head to the turbine, and as far as practical results were concerned, the turbine would now develop energy cor-

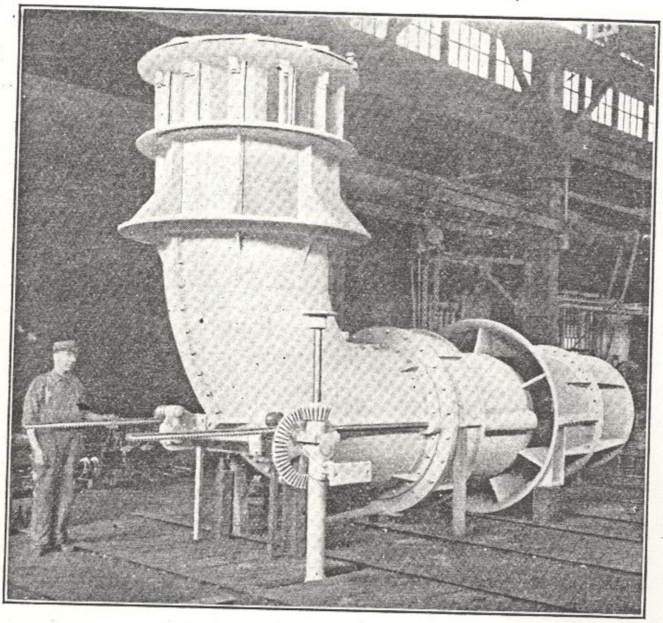

FIG. 2 85-H.P. TURBINE WITH DISCHARGE ACCELERATOR

responding to the increased head. This is the effect of the discharge accelerator, which may therefore be likened in principle to a condenser of a steam engine.

18 Each accelerator consists of a super draft tube, a concentrator, and an infuser as shown in Fig. 4. The infuser is provided with a gate, by means of which the amount of accelerator water may be varied at will, or shut off entirely, in the latter case leaving only the turbine discharging into the super draft tube.

19 The area of cross section of the concentrator is less than that of the turbine draft tube. The effect of this narrowed section

on the turbine discharge during its ordinary operation was in doubt during the construction period, but when the installation was completed tests showed that the effect was negligible.

ACCELERATOR TESTS

20 A series of tests was made on the accelerator of one unit on March 18, 1915, and the results are plotted in Fig. 5. In this figure, the scale of turbine horsepower is given on the left, kilowatts on the right and turbine gate opening in tenths below. A normal speed of

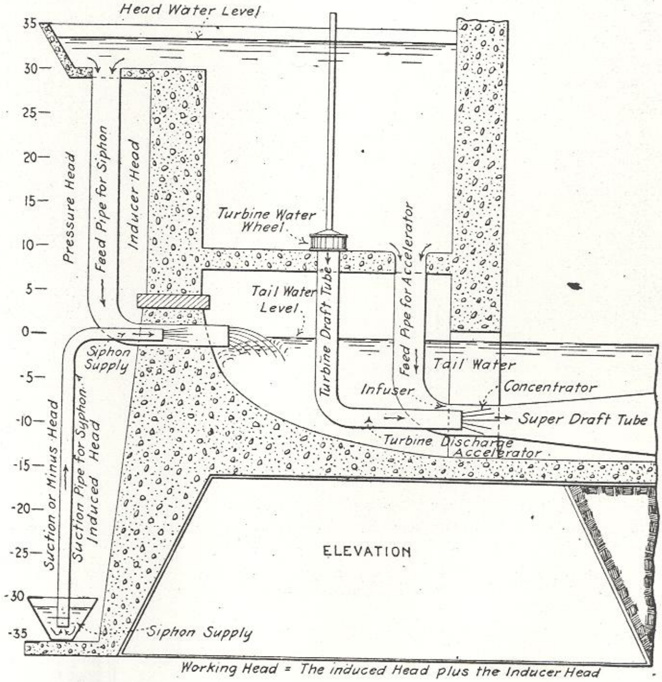

FIG. 3 COMPARISON OF SIPHON AND ACCELERATOR

110 r.p.m. was maintained throughout the tests. The energy was absorbed by a water rheostat, and the power was measured by the switchboard instruments, which are new, therefore substantially correct.

21 The purpose of Series I was to show the maximum power of the turbine when the accelerator gates were closed. The curve shows approximately 90 turbine h.p. at between 9/10 and full gate, but the head was slightly over 8 ft.

22 Series II shows readings made at the same turbine gate openings, but the accelerator gate was open 20 per cent of its range throughout the series. Although the actual head is lowered, there is an actual increase in power.

23 Series III was made with the accelerator gate open about 40 per cent of its travel. This resulted in a still further increase of power.

24 Series IV was made with the accelerator gate open about 60 per cent of its travel. Throughout this series, the accelerator was sucking some air, but the power increased.

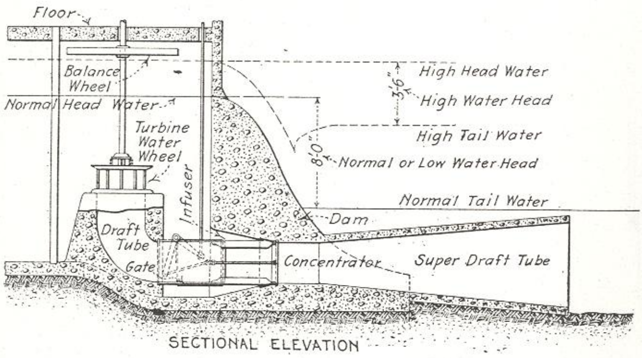

FIG. 4 85-H.P. TURBINE AND DISCHARGE ACCELERATOR

25 Series V was made with the accelerator gate open about 80 per cent of its travel. The accelerator sucked air violently during these last readings, but the power increased even though the head was less than 7 ft.

26 The excessive taking in of air prevented the further opening of the accelerator. Therefore its limit of action is unknown.

27 The curve in Series V shows 116 turbine h.p. at 6.94 ft. head. This curve, reduced by the well known formula, to an 8-ft. head shows that 143.5 h.p. can be obtained by the use of the accelerator from an 8-ft. head in connection with the identical turbine that had been guaranteed to develop 85 h.p. under 8-ft. head.

28 No attempt was made to measure the accelerator water used, as this test was made solely to demonstrate that a turbine can use waste water that would be detrimental to the power effects of the turbine if the accelerator were not used. The matter of measuring the water is a part of proposed further development, which will be continued until all the limitations are discovered.

29 The turbine discharge accelerator is the outcome of careful observation of draft tube phenomena for a term of years. During this observation, some of the apparently unexplainable characteristics of draft tubes have been fathomed.

30 Although other engineers have been working along the lines of this development, it is believed that the present instance is the

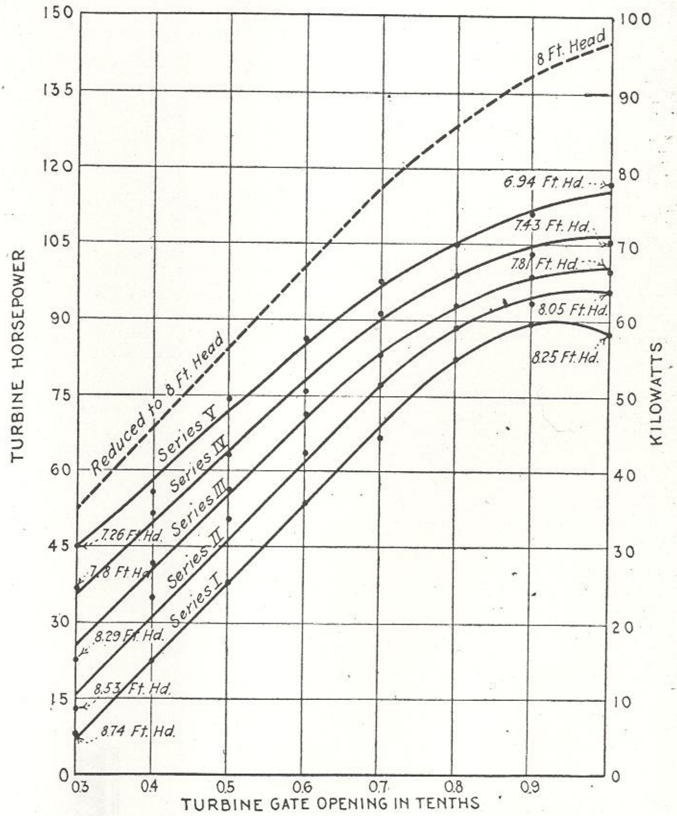

Fig. 5 Results of Tests on Accelerator

first practical demonstration of the decided advantage to be secured by the application of the turbine discharge accelerator, and the design of the device is believed to be original.

31 The possibilities and limitations of the accelerator have not yet been fully determined, although several years of experimentation have been spent in its development. In its operation, there seems to be some new and definite law, which has not yet been formulated.

32 So far, indications are that low heads may be boosted as much as from 100 to 500 per cent, depending on the conditions. The extreme limit appears to be the atmospheric head.

33 There seems to be every reason to believe that full turbine power from a water turbine can be obtained from all the water used (when based on the actual or working head) even though only a portion of the water passes through the turbine proper. A water power equipped with an accelerator can be speeded for full head at low water condition, and the same turbine can have its capacity practically doubled under the same head, if sufficient water is available. The power unit can develop its normal rated power at one-half head when sufficient water is available, and the turbine can furnish considerable power when the working head is less than 25 per cent of the normal head, and all this may be done at good efficiency.

34 A like reflection will show that with this system many water powers may become independent of steam or gas reserves, with the saving of the large expense these auxiliary power units now entail. With the accelerator, too, it is not necessary to provide so many power units in a given development, as the elasticity permits of good efficiency with fewer turbines.

35 There are very many cases in which low heads only are available and the water cannot be utilized practically and profitably. The accelerator can be used to boost the head in such cases to an amount at which development of the water power is possible. The accelerator can convert an actual head of 3 to 10 ft. into a working or effective head of 8 to 20 ft.

DISCUSSION

Clemens Herschel[1] (written). The idea of utilizing that portion of the freshet river flow that wastes over the dam, for the purpose of increasing the head acting on the turbines, at those times suffering from a diminution of the normal fall (or from "back-water"), is not new. Experiments on an apparatus of this kind were made by M. Saugey, superintendent of the Chevres power plant, owned by the city of Geneva, Switzerland, as early as June, 1905, and perhaps earlier; and Saugey's system was described in the Zeitschrift d. V. D. Ingenieure, about 1907, and in other

[1] 2 Wall Street, New York, N. Y.

journals. A pamphlet, without date, issued by the Société Hydro-Motrice, of Geneva, describes these and later experiments.

The efficiency of the Saugey apparatus, in terms of water lifted a certain height by means of other water falling a certain height, was about 3 per cent. This is pretty poor, even for an apparatus that operates by induced currents of fluids, but it gave the writer the impetus to accomplish something better, and led to his development of a hydraulic apparatus[1] for the purpose named above, which was called the "fall increaser," with a maximum efficiency found, as described above, of 30.4 per cent. To turbine builders and others, this does not sound like a very high efficiency, but it is believed to be very good for an induction current hydraulic apparatus.

It is quite fitting that the results of the experiments made with the fall increaser at the Holyoke Public Testing Flume in 1907 and 1908 should be recorded at this time. A brief mention of the fall increaser, with an up-to-date design of a power house fitted with fall increasers, may be found in Trans. A. S. C. E., November, 1915, in a discussion of a paper on Induced Currents of Fluids, by F. zur Nedden, Mem. Am. Soc. M. E.

In the field of the apparatus the paper describes, other things, principally cost, being equal, the most mechanically efficient apparatus alone will survive. From this viewpoint, it is to be regretted that there is no word or figure in the paper to permit a guess at the mechanical efficiency of the "discharge accelerator." Having conducted experiments with both the fall increaser, and also, to some extent at least, with a "discharge accelerator," the writer has not much faith in the efficiency of the latter. In the article mentioned above, he wrote: "The fall increaser is not an ejector, and experiments made with an ejector form of throat piece, and a 5½-in. nozzle endeavoring to operate it, gave so poor results (efficiency) that there was no encouragement to continue along those lines." As the author states in Par. 16 that "the accelerator is not an ejector," it will be necessary to add that what has been called above "an ejector form of throat piece," was similar to the discharge accelerator now shown. The difference consists in this: The turbine discharge entered the throat piece or mixing chamber through the annular area around the nozzle, instead of the operating water entering through the annular area, as in the discharge accelerator, with the turbine discharge blowing in through the nozzle. There cannot,

[1]See Harvard Engineering Journal, June, 1908, for description.

in the opinion of the writer, be any material difference in efficiency between these two arrangements. The discharge accelerator arrangement is, however, the better one for regulating or varying the discharge of the operating water.

Another quotation from the 1908 article is: "Nor does it seem to me that the forms of formulae found in the books and learned transactions for computing the work of ejectors, based on the assumption of an impact of the nozzle stream upon the water within the throat piece, are based upon a proper assumption to produce a correct formula for representing ejector action. To my mind an ejector is only another form of negative pressure apparatus, in which suction causes the water to enter the throat piece through a ring-shaped orifice situated all around the nozzle (in the accelerator through the nozzle), rather than through holes fashioned in the throat piece itself, and distributed over its whole outside surface, as in the fall increaser."

It might be thought that inasmuch as all these low fall turbine aids use freshet runs of the river to furnish the operating water, their efficiency is of no consequence, but as will be shown in detail, this is not so, except at exceptional times (at the Henry Ford Farms the times called *e*, which according to Par. 3, last only, as one may judge, certain set periods of hours during the year). From an experience of seven years in designing these plants for river situations of all kinds, the writer can state positively that the mechanical efficiency of the apparatus is of great importance, and so is the regime or character of the river on which the fall increaser is to be used.

It is all a question of kw-hr. produced by the fall increaser in the course of an average year's run of the river, set off against the construction cost; and fall increasers may or may not be of economic value, according to their efficiency. They have this in their favor, that their product is of annual recurrence, forever, while their construction cost (operation and maintenance are negligible quantities) is incurred but once. As a numerical example and to fix ideas, in a case examined some years ago, when the fall increaser was as yet new, the annual product of the fall increasers would have been 158 million kw. in an average year, delivered at times of high water and low fall, lasting in all some 180 days of the year; and the writer's estimated construction cost was one million dollars. From this case—a very favorable one—the net advantages range towards nothing, until in other cases, with rivers of a different régime, those advantages wholly disappear.

Fig. 6 shows the test apparatus of the fall increaser, as used in 1907 and 1908. *C* is the cast iron throat piece, the "soul" of the whole apparatus; situated as it is, suction, or negative pressure, is produced within it when water from the "operating water" penstock *B* flows through it. In the experiments, *B* was a 16-in. pipe, whose discharge was continuously measured by a venturi meter. The throat piece *C*, serving also as a mixing chamber for the operating water with the water that represented the turbine discharge, of "water lifted," (which was discharged into the "vacuum box"

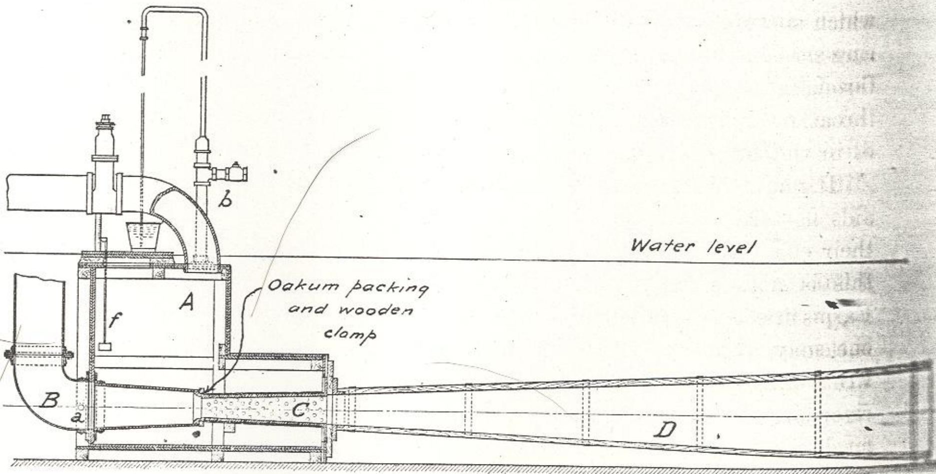

Fig. 6 Test Apparatus of Fall Increaser

A, through a 12-in. pipe), had for the best summit cone angle tested, 3½ degrees. "Water lifted" was continuously metered by a venturi meter. In the experiments, *C* was of various exact diameters at the upstream and downstream ends, approximating to 12 in. at the downstream end in all of them, and the two diameters varying as the throat piece was bored out to increase the diameter at one end or the other, so as to change the summit cone angle.

A was made of wood, was well braced inside, and of the peculiar L-shape shown, to fit into the space available in the testing flume. In practice, the vacuum chamber would be a concrete vault, with manhole entrance, and open for inspection when the turbine is shut off and the operating water is on.

The pipe *b*, tapped into the vacuum box, and sucking colored water out of the pail shown, served to measure the vacuum produced. Working with the turbine penstock shut off, the vacuum produced would easily hold suspended a water column 26 ft. high.

f is a float that indicated the water level within the vacuum box. To see *b* indicate a vacuum, while *f* showed the box *full* of water, was startling at first, but one soon learned to consider a body of contained water as readily subject to negative, as to positive pressure.

D is the draft tube proper, whose summit cone angle was 5 degrees. The working of the whole apparatus is not very sensitive as regards the length of this draft tube. A practical rule would be to make the discharge velocity not much over 8 ft. per sec.

The holes in the throat piece in actual use are recommended to be made either bevelling so as to facilitate flow downstream, or with rounded edges, of a uniform diameter, say 6 in., and sufficient in number to cause the velocity through them to be less than 4 ft. per sec. This obviates the need of any special outlet construction for the turbine discharge at times when the operating water is shut off, that is, on days ranging from normal to extreme low water in the river, which usually comprise about 180 days in the year.

Although a little turbine was mounted in the line of the 12-in. cast iron pipe, it was not used during the experiments, being clamped "still," and was only used as a supply orifice. We all know the effect of draft-tube suction on turbines, and this suction having been constantly measured, we know the effect it would have had on the turbine and its power had the turbine been allowed to revolve and generate power.

Dr. Ernst Duebi, at one time of Zürich, Switzerland, repeated the writer's tests in 1911, at Zürich, and added much information to that previously known concerning the fall increaser. His results were published in book form by Rascher & Cie., of Zürich and Leipzig, 1912.

Dr. Duebi saw fit in his experiments designedly to let the turbine revolve during the tests, and thus proved once again that added suction within the draft tube of a turbine, adds fall to the fall otherwise "acting on the wheel." The experiments were conducted with great care; they were made wholly independently of those at Holyoke, and it has been very gratifying to have their added testimony to the efficiency of the fall increaser.

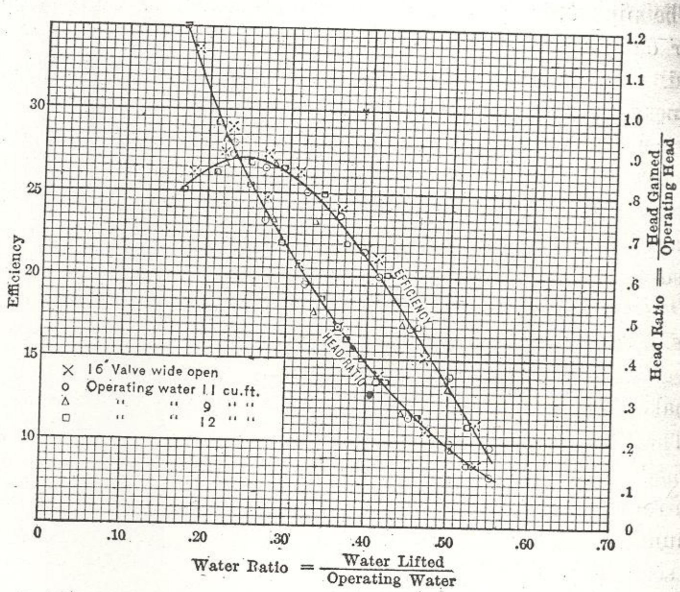

FIG. 7 EXPERIMENTS ON "FALL INCREASER." THROAT PIECE "F," ALL HOLES OPEN

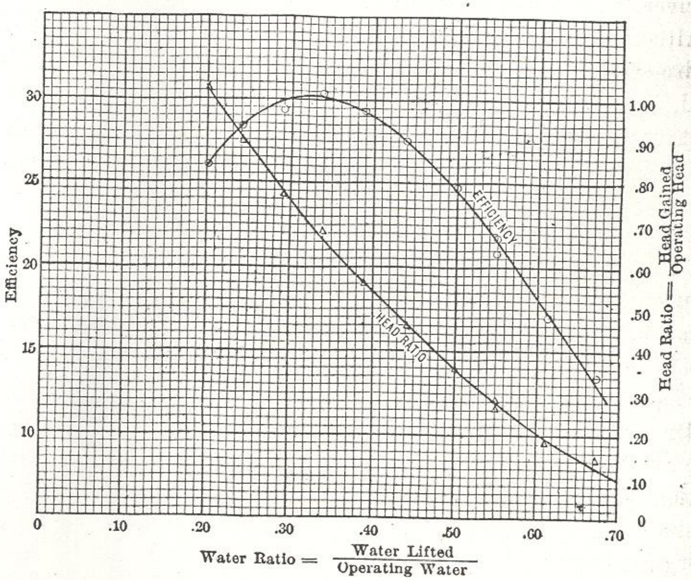

FIG. 8 EXPERIMENTS ON "FALL INCREASER" THROAT PIECE "B," ALL HOLES OPEN

TABLE 1 EXPERIMENTS ON "FALL-INCREASER" THROAT PIECE "F," ALL HOLES OPEN.

February 24, 1908

Number of experiment	Time	Height of water in: Forebay	Height of water in: 16 in. pipe next the vacuum-box	Height of water in: Tail-race	Operating Head Col. 4 — Col. 5	Operating Water.	Water Lifted	Head gained by use of Fall-Increaser	Ht. of Water in vacuum-box by float	Air-valve	Gauge on 12 in. valve	Water-ratio = Col. 8 / Col. 7	Head-ratio = Col. 9 / Col. 6	Quantity (a)	Efficiency = Col. 15 / (Col. 6 x Col. 7)
		Feet				Cubic Feet per second		Feet							%
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	9.05	99.23	94.89	81.96	12.93	11.39	6.00	1.93	Full	Shut	56.1	0.53	0.15	16.62	11.3
2	9.10	99.25	94.70	81.95	12 75	11.63	5.50	2.88	—	"	52.8	.47	.23	22.58	15.2
3	9.13	99.29	94.37	81.95	12.42	12.06	5.00	4.52	—	"	47.2	.41	.36	31.64	21.1
4	9.16	99.35	94.11	81.95	12.16	12.39	4.50	5.87	—	"	43.0	.36	.48	36.20	24.0
5	9.20	99.41	93.82	81.95	11.87	12.84	4.00	7.50	—	"	39.0	.31	.63	40.25	26.4
6	9.23	99.55	93.53	81.94	11.59	13.20	3.50	9.10	—	"	35.0	.27	.79	42.10	27.5
7	9.27	99.67	93.26	81.94	11.32	13.60	3.00	10.83	—	"	31.5	.22	.96	42.22	27.4
8	9.30	99.72	92.97	81.93	11.04	13.97	2.50	12.58	—	"	28.2	.18	1.14	40.20	26.1
9	9.34	99.72	88.96	81.81	7.15	11.01	2.50	6.58	—	"	29.1	.23	.92	21.42	27.2
10	9.37	99.64	89.73	81.81	7.92	11.01	3.00	5.80	—	"	33.1	.27	.73	23.11	26.5
11	9.41	99.62	90.43	81.85	8.58	11.00	3.50	5.00	—	"	36.7	.32	.58	23.62	25 0
12	9.44	99.60	91.36	81.86	9.50	11.05	4.00	4.53	—	"	40.4	.36	.48	24.91	23.7
13	9.48	99.59	91.74	81.88	9.86	10.95	4.50	3.45	—	"	44.3	.41	.35	21.72	20.1
14	9.53	99.57	92.81	81.90	10.91	11.00	5.00	2.86	—	"	48 9	.45	.26	20.33	16.9
15	9.56	99.52	93.55	81.93	11.62	11.03	5.50	2.39	—	"	52.6	.50	.20	18.13	14.1
16	9.59	99.47	94.19	81.94	12.25	10.98	6.00	1.50	—	"	57.1	.55	.12	13.16	9.8
17	10.05	99.50	89.31	81.80	7 51	9 01	4.50	1.40	—	"	46.0	.50	.19	9.02	13.3
18	10.08	99.49	88.68	81.79	6 89	8.99	4.00	1.85	—	"	42.3	.44	.27	10.57	17.1
19	10.11	99 47	88.08	81 77	6.31	8.97	3.50	2.52	—	"	38.2	.39	.40	12.24	21.6
20	10.14	99.48	87.65	81.75	5.90	9.00	3.00	3.02	—	"	35.0	.33	.51	12.38	23.3
21	10.18	99.50	86.85	81.72	5.13	8.99	2.50	3.72	—	"	30.3	.28	.73	12.36	26.8
22	10.22	99.52	86.26	81.71	4.55	8.98	2.00	4.22	—	"	26.6	.22	.93	10.99	26.8
23	10.27	99.52	89.33	81.83	7.50	12.05	2.00	8.97	—	"	25.5	.17	1.20	22.82	25.2
24	10.30	99.54	90.25	81.85	8 40	12.00	2.50	8.17	—	"	29.3	.21	.97	26.46	26.3
25	10.33	99.56	90 94	81.86	9.08	11.99	3.00	7.43	—	"	32 4	.25	.82	29.34	26.9
26	10.36	99.57	91.80	81.88	9.92	11.99	3.50	6.75	—	"	36.0	.29	.68	31.53	26.5
27	10.40	99.60	92.55	81.90	10.65	11.91	4.00	5.83	—	"	39.6	.34	.55	31 71	25.0
28	10.44	99.59	93.85	81.94	11.91	12.11	4.50	5.30	—	"	43.8	.37	.45	32.89	22.1
29	10.48	99.58	94.32	81.95	12.37	11.98	5.00	4.28	—	"	47.5	.42	.35	29 89	20.2
30	10.51	99.57	94.83	81.96	12.87	11.92	5.50	3.37	—	"	51.4	.46	.26	26.26	17.1
31	10.55	99.57	95.22	81.96	13.26	11 48	6.02	1.93	—	"	56.8	.52	.15	16.94	11.1
32	10.59	99.56	95.27	81.95	13.32	11.32	6.00	2.30	79.65	open	59.4				
33	11.03	99.57	95.08	81.94	13.14	11.61	5.50	3.36	78.58	"	55.6				
34	11.06	99.58	94.92	81.93	12.99	11.81	5.00	4.13	77.80	"	52.0				
35	11.09	99.60	94.82	81.91	12.91	11.89	4.50	4.33	77.58	"	48.1				
36	11.13	99.62	94.86	81.88	12.98	11.92	4.00	4.38	77.50	"	43.9				

TABLE 2 THROAT PIECE "B," ALL HOLES OPEN.

February 18, 1908

1	9.07	99.66	95.88	81.92	13.96	10.83	6.00	3.70	Full	Shut	Not Taken	.55	.27	31.57	20.9
2	9.10	99.65	96.10	81.93	14.17	10.58	6.50	2.73	"	"		.61	.19	25.59	17.1
3	9.14	99.67	96.29	81.94	14.35	10.40	6.99	2.00	"	"		.67	.14	20.20	13.5
4	9.18	99.68	95.88	81.93	13.95	10.84	6.00	3.88	"	"		.55	.28	33.00	21.8
5	9.22	99.68	95.67	81.92	13.75	11.08	5.49	4.95	"	"		.50	.36	37.84	24.8
6	9.26	99 67	95 37	81.92	13.45	11.38	5.00	6.13	"	"		.44	.46	42 06	27.5
7	9.30	99.68	95.13	81.91	13.22	11.64	4.50	7.37	"	"		.39	.56	45.08	29.3
8	9.33	99.67	94.86	81.89	12.97	11.91	4.00	8.78	"	"		.34	.68	46.92	30 4
9	9.36	99.66	94.66	81.89	12.77	12.12	3.50	9.85	"	"		.29	.77	45.58	29.4
10	9.39	99.64	94.39	81.88	12.51	12.38	3.00	11.25	"	"		.24	.90	44.00	28.4
11	9.42	99.61	94.16	81 87	12.29	12.60	2.50	12.52	"	"		.20	1.02	40.37	26.1

The essential results found in the experiments at Holyoke are shown in Figs. 7 and 8, and are tabulated in Tables 1 and 2.

Table 1 gives the results of experiments on throat piece F, while Table 2 gives the full-gate operating-water experiments on throat piece B. As will be seen from Table 1, and from its representation in Fig. 7, the efficiency of the fall increaser is the same for equal ratios of (water lifted) $\div$ (operating water) and of (head gained) $\div$ (operating head), called respectively, the "water ratio" and the "head ratio." This having proved true in all the complete series of experiments, it authorizes the plotting of the diagram for throat piece B, from the results alone of the full-gate operating-water experiments made with that throat piece.

In an apparatus of this sort it does not palpably appear what is the true efficiency of the apparatus.

The fall increaser comprises the vacuum box, no less than the throat piece and its feed, and exhaust; and as such, causes an increased discharge of the turbine to which it is applied, as well as an increase of fall acting on the turbine, as has already been noted.

Let $h =$ operating head, on 16-in. pipe

$h' =$ head gained; or vacuum

$Q' =$ water lifted $=$ discharge of turbine under head $(h+h')$

$Q =$ discharge of turbine under head h.

The work done by the turbine without the increaser is equal to Qh; and the work done by the turbine with the increaser $= Q'(h+h')$.

Also $Q : Q' = \sqrt{h} : \sqrt{h+h'}$, or $Q = \dfrac{Q'\sqrt{h}}{\sqrt{h+h'}}$

Work gained by the use of the increaser

$$= Q'\,(h+h') - Q\,h.$$

$$= Q'\,(h+h') - \frac{Q'\,h\,\sqrt{h}}{\sqrt{h+h'}} = (a)$$

And the efficiency of the increaser is this quantity, divided by the work employed to gain it; or

$$\text{Efficiency} = \frac{(a)}{\text{operating water} \times h.}$$

The fact that the efficiency of the fall increaser is the same for equal water-ratios and head-ratios is a valuable one, enabling the normal efficiency to be maintained for all the varying discharges of the turbine.

Fig. 9 shows a design of power house, with fall increaser, made for the City of Geneva, Switzerland, site not yet built upon. That the design had novelty in 1907 may be gathered from the fact that patents were issued for it by the United States, Canada, France, Switzerland, Italy, Sweden and Germany.

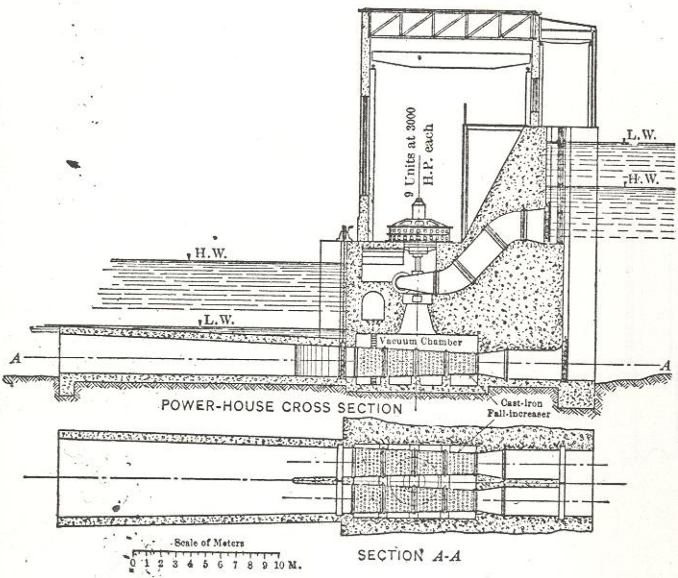

FIG. 9 POWER HOUSE WITH FALL INCREASERS

At the site named, the water upstream from the power house is lowest (must be *held* lowest) in times of freshet in the river, there being lift gates designed to create the mill pond, instead of a dam. At the same time there is "back-water;" or in other words, the fall is reduced doubly (shutting up like an accordion), which accounts for the elevation of H.W., Fig. 9, being at a *lower* elevation than that of L.W.

Note the ready means supplied by fall increasers for getting rid of rack-trash. It needs but to be pushed *down,* into the suction area of the fall increasers, to pass through them and out through the tail-race, instead of being laboriously raked *up* and carried ashore and away.

It is evident that to enable the use of freshet water to operate the fall increasers, a head race of any material length is inadmissible. The power house must be at or very near the dam. This requirement eliminates the majority of hydroelectric plants from a consideration of fitting them with fall increasers.

The next elimination takes place when the character or regime of the river is taken into consideration. Rivers differ in this respect far more than one would suspect; and a careful analysis of their modes of flow during all the days of several years,—the more the better—are required, before their regimes may be adequately portrayed.

This is done by setting up for them what have been called "duration curves." Every engineer knows what hopeless looking messes a plotted series of daily discharge curves (or pictured saw teeth) make, the ordinates representing *consecutive* days of the year, and the abscissae gage heights, or sec-ft. of river flow. But let each year

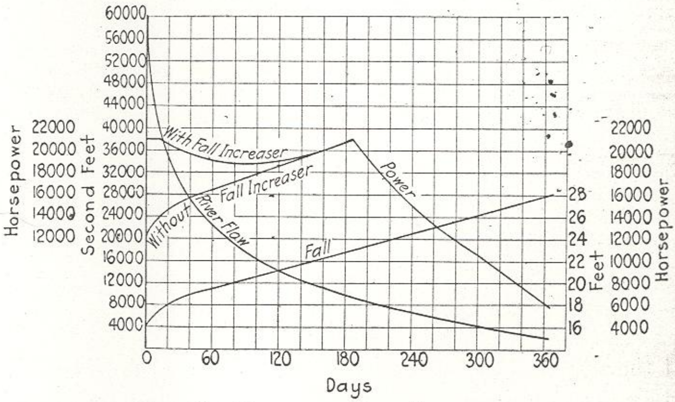

FIG. 10 EFFECT OF FALL INCREASERS

be represented by these same daily quantities, plotted in the order of their size, and we get at once a smooth curve[1] of quantities flowing in the river for the 365 days of the year, useful in more ways than one. Fig. 10 shows such a curve of river flow.

Besides showing a curve of river flow, Fig. 10 indicates the corresponding falls that obtain synchronously at the mill site under consideration; and from these two the power curve at this site, *without* the use of fall increasers, may readily be computed and plotted. From the power curve we may, with the aid of Fig. 8,

[1]See also Trans. A. S. C. E., 1907, A tabular analysis of 20 years' flow of the Connecticut River; and Doc. 1400, H.R., 62nd Congress, 3d Session, 15 years' flow of the Potomac River at Great Falls near Washington.

compute and plot the power curve for the back-water days of the year *with* the use of the fall increaser. The area included between the last two curves named gives the total horsepower-days or kw-hr. which fall increasers would produce annually forever on that mill site. Note that at first there is not water enough in the river to operate *all* the fall increasers, causing a sagging down of the curve and only a gradual bringing of the curve up and back to normal full power. Here is where the efficiency of fall increasers becomes of great moment.

There only remains to compare the productive value of fall increasers with the interest on the construction cost. The result depends mainly on the regime of the river. Fall increasers are useless where the river flow is effectively regulated by great lakes or reservoirs causing a uniform discharge of the river. They are uneconomical on rivers that have only a few days of the year of back-water. On the other hand at times a single year's output of kw-hr. will nearly pay for their construction cost; and heat engines put in to supplement the low water run of the river cannot afford to burn fuel in competition with the cost of a kilowatt-hour when produced by the fall increasers in the days of freshet water during the year.

It would also seem that, tide mills, which may have an inexhaustible water supply, but which all have a greatly varying fall during the 24 hours, could materially benefit by the use of fall increasers; and if the "discharge accelerator" will show the proper cost and efficiencies, it can presumably compete in this and other cases.

A prime mover, or apparatus to increase the power of a prime mover, is palpably without index by which to judge of its value, so long as its *mechanical efficiency* has not been determined. In the present case this would call for a statement of the amount of water the discharge accelerator consumer per horsepower developed.

A series of constructions, all aiming to utilize waste water, and known by such names as "compensators," "ejector flow increasers," etc., have been built and may be found at Warren, Ohio; at Eldora, Iowa; at the U. S. dam between St. Paul and Minneapolis, and on the Huron River near Ann Arbor, Michigan. None of these have been tested for efficiency.

R. L. DAUGHERTY.[1] The writer has been much interested in this paper by Mr. Replogle. It is hard for some people to realize that a water power plant may have to shut down because of a superabundance of water as well as because of lack of water. Such a situation is only met with in the case of a low head plant where the fall available may be almost destroyed in time of flood. The writer has found it necessary to explain a number of times why it is that such a fall decreases in time of high water. This point is illustrated in Fig. 11. This photograph, while of a relatively small stream, shows the effect just as well as one of a much larger stream and fall. In this particular case the depth of water flowing over

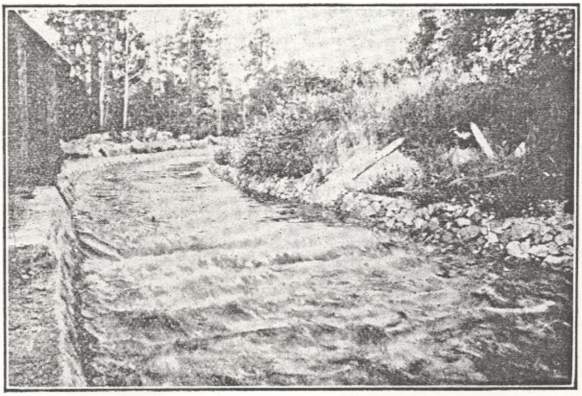

FIG. 11 LOW HEAD IN TIME OF HIGH WATER

the crest of the submerged dam was practically equal to the height of the dam above the bed of the canal. It may be seen that the dam does little more than create a disturbance in the flow of the water, and the fall is very slight. In fact a portion of this very small fall is due to the fact that some of the water is diverted at this point.

Under such circumstances the amount of water consumed by a turbine will be much less than the normal amount, and the head being less also the power will be seriously reduced. The device which Mr. Replogle has employed makes it possible to consume more water and thus to compensate for the reduction of head.

It would be of considerable interest if we knew the amount of water actually discharged by the turbines during the tests made by

[1]Asst. Prof. Hydraulics, Sibley College, Cornell University, Ithaca, N. Y.

the author, and also the additional water used to produce this effect. It is to be hoped that the author will be able to secure these data at some future time.

It is well known that it costs more per horsepower to develop a given amount of power under a low head than under a high head. As the author states, many low head powers are not utilized, though there is an abundance of water, due to the high cost. Such a device as this, used constantly, converts a low head plant into one of somewhat higher head. The actual amount of water consumed by the plant including that wasted through the accelerators may not be much more than the amount required to develop the same power under the lower head without the accelerators. It would be interesting if the author could give comparative efficiencies in such a case. Of course for the discharge of flood waters only, the efficiency is of no consequence, but for constant use it would be.

While this accelerator is different in detail, it seems to be similar in principle to the fall increaser described by Clemens Herschel in *Engineering News,* Vol. 73, p. 84.

THE AUTHOR. In reply to Mr. Daugherty, data regarding the amount of water actually discharged during the tests could not be procured at the time the tests were made. Some data have been secured in preliminary tests of a very small turbine, and these compare favorably with the results secured by Mr. Herschel.

It was preferred to make no reference to efficiency tests until such tests could be made in a logical and comprehensive manner. These will be made in the course of further development.

Of constructions suggested by other engineers the author obtained his first knowledge through the U. S. Patent Office. He believes the construction described is original.

Any construction designed for the purpose of mechanically mixing the two streams of water is erroneous from an efficiency point of view. Mixing implies eddies, and eddy currents transform the kinetic energy in the inducer water into heat. In the preliminary tests the very poorest results out of several hundreds were from a carefully designed mixer.

In reply to Mr. Herschel, there can be no doubt of the real values to be obtained from the use of the atmospheric head with surplus water. The means applied are of no special importance. The doubt in Mr. Herschel's mind is in regard to efficiency, but as he says best overall efficiency is in returns from investment.

The efficiencies quoted by Mr. Herschel seem to be low. From the author's point of view the apparatus he shows has been provided with the best possible means to produce eddy currents and friction. The grating or perforated throat certainly impedes the inducer stream. The turbine water entering at right angles to the inducer stream causes endless eddy currents. The abrupt orifices are causes of much friction. It is possible that if the whole throat section were removed the efficiency would be as high as that stated.

In conclusion, it was thought that the facts gathered to date regarding the accelerator described in the paper might be of interest, but the author has substantial reasons to believe that much higher efficiencies than those given can be obtained from this class of apparatus.