

EXPERIMENTAL AND PRACTICAL ENGINEERING
HYDRAULICS OF THE LATE 18TH CENTURY

by

J. J. Doland
Professor of Civil Engineering
University of Illinois
Urbana, Illinois

The State of Illinois has recently been engaged in a program to restore the old grist and saw mills which played important roles in its pioneer development. It is desired to make these restorations as nearly authentic as is possible. The department of Public Works and Buildings has done considerable research work which has included: the collection and study of original parts of buildings and equipment, the information which could be gained from the accounts of persons who had visited or patronized the mills while they were in operation, and the examination of letters and other writings which might uncover authentic information.

After the tentative plans had been developed they were sent to the University of Illinois for checking with respect to the hydraulics and the technical features of the mechanical equipment. It seemed illogical, impractical, and unfair to attempt to apply modern water power theories to prove or disprove the engineering soundness of a project which in effect was over 100 years old. It was decided, therefore, that the proper approach would be for the designer to become an engineer or millwright of 1800 and hence be guided only by the theories and practices then in vogue and by every scrap of evidence which remained to indicate the intent and execution of the original designer and builder.

The examination of a portion of the 18th century literature on hydraulics revealed facts and philosophical opinions which are no doubt commonplace to many, but were quite interesting, informative, and even startling to the author.

The book of earliest date examined is one entitled, "An Introduction to a General System of Hydrostaticks and Hydraulicks, Phil-

osophical and Practical” by Stephen Switzer and published at London in 1729. The title page announces that the book contains in general:

“A Physico-mechanical Enquiry into the Origin and Rise of Springs, and of all the Hypotheses relating thereto; as also the Principles of Waterworks and the Draughts and Descriptions of some of the best Engines for raising and distributing Water for the Supply of Country Seats, Cities, Towns corporate etc.

“Deduced from the Theory of Archimedes, Gallileo, Torricelli, Boyle, Wallis, Plot, Hooke, Marriotte, Desaguliers, Derham, Hauksbee and others.

“Reduced to practice by Vitruvius, Bockler, de Caus and other Architects and amongst the ancient Romans, Italians, French, Flemings and Dutch, and much improved by later Practice and Experience.”

Mr. Switzer was evidently quite a scholar and philosopher. He was also an advance proponent of conservation and flood control. The opening paragraphs of his preface, although expressed in quaint language, nevertheless have a familiar sound in these times of Tennessee Valleys and such. He says:

“Even as Paradise itself, tho’ of Divine Appointment, must have been deem’d an immodel’d and imperfect Plan, had it not been watered by the same all-powerful Hand which first made it; so never can our Gardens and Fields (the nearest Epitomy and Resemblance of that happy and blessed Place to be met with here below) be said to be any way perfect or capable of subsisting without it (water).

“The entire want of Water that is in some and the ill Use or little Management of it, which is to be found in other Places are I humbly hope, sufficient to excuse me from making any Apology for my Presuming to attempt at the undertaking of a System the Steps of which so few have trod before me, and which I have with much Care and Pains drawn together, for the Improvement of these and future Times.”

Switzer’s preface also includes an interesting review of the work of his predecessors from Archimedes to Hooke. After denying the need for an apology at the beginning he breaks down in the final paragraph and offers one. At the same time he attempts to spike the guns of such critics as may arise. Until a more able pen than his does a better job, he says:

“ the good natured Part of the World will ('tis humbly hoped) excuse my Presumption in aiming at so great a Work as this is, the Paths of which so few have trod before me (especially in the comprehensive Manner in which this is endeavor'd to be drawn) ; this added to the Diversion I have had in compiling it and in taking (tho' but a transient View) of some of the most wonderful Phaenomena's of Nature, will sufficiently recompense the Pains I have been at and set me above the little Cavils of mercenary and pretended Wits.”

The author is borrowing (with obvious modifications) the words of Mr. Switzer to offer his apology for this paper with the hope that the readers are of the “good natured Part of the World” and that as “Wits” they are neither mercenary nor pretended.

Switzer's discussion of the theories to explain the source of the water issuing from springs, pressure, momentum, elasticity, friction loss in pipes, effects of capillarity, viscosity, siphonic action and other phenomena sheds considerable light upon the state of the art of hydraulics and hydrology in 1729.

Briefly, it may be stated that fundamental, though perhaps somewhat unrefined, concepts of pressure head, velocity head, and spouting velocity were well established; losses due to friction, orifice contractions, and effects of impulse and momentum were under study and offered the most challenging problems.

John Smeaton enters the picture as an authority about 1750. At this point the philosophers and architects began to lose control of the field because he was the first man to call himself a civil engineer. A man of many other accomplishments, Smeaton was also a research hydraulician. He had some sound ideas in regard to the danger of drawing deductions too hastily from the results of tests and he was probably among the first to sound a warning concerning the correlation between the performance of models and their prototypes. He says in the introduction to a paper entitled, “An Experimental Enquiry concerning the Natural Power of Water and Wind” read before the Royal Society of London, May 3 and 10, 1759:

“What I have to communicate on this subject was originally deduced from experiments made on working models, which I look upon as the best means of obtaining the outlines in mechanical inquiries. But in this case it is necessary to distinguish the circumstances in which a model differs from a machine in large: *otherwise a model is more apt to lead us from the truth than towards it.* Hence the com-

mon observation, that a thing may do very well in a model that will not answer in large. And, indeed, though the utmost circumspection be used in this way, the best structure of machines cannot be fully ascertained, but by making trials with them of their proper size”

In the same paper Smeaton describes the apparatus he devised and the tests he made to determine the ratio between power and effect on undershot and overshot water wheels. An examination of Figs. 1 and 2 discloses that Smeaton was using a recirculating hy-

draulic laboratory. The apparatus consisted of a constant head tank fitted with a float gage and an adjustable orifice. The recirculating pump had a barrel five inches in diameter and a stroke of eleven inches. It was fitted with the necessary valves and stroke limiting devices.

GV, he says, “is a cylinder of wood fixed upon the pump rod and reaches above the surface of the water; this piece of wood being of such thickness that its section is half the diameter of the pump barrel, will cause the water to rise in the head as much while the piston is descending as while rising, and will thereby keep the gage rod *FG* more equally to its height.”

R is “the scale into which the weights are put for trying the power of the water” and *O* “is a cylinder on which the cord winds, and which being con-

ducted over the pulleys *P* and *Q* raises *R*.

“The pump made use of for replenishing the head with water was so carefully made, that, no water escaped back through the leathers, it delivered the same quantity at every stroke, whether it worked quick or slow, and by ascertaining the quantity of 12 strokes,

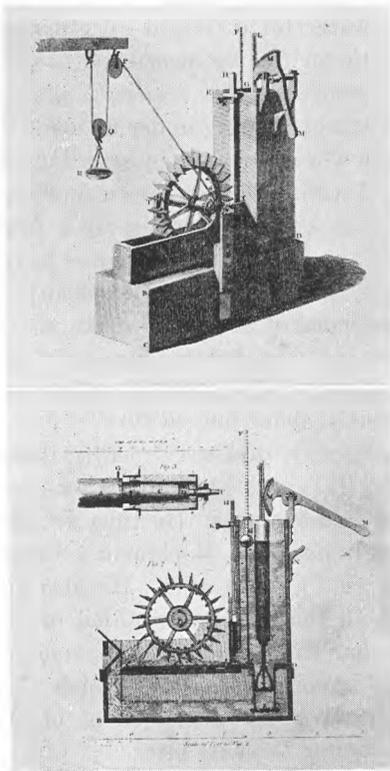


FIG. 1.

and counting the number of strokes in a minute that was sufficient to keep the surface of the water to the same height, the quantity expended was found."

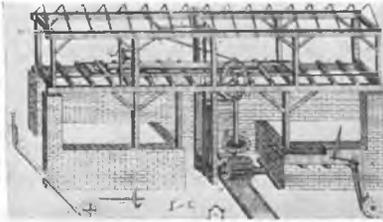


FIG. 2.

Smeaton was very much interested in the ratio of the peripheral velocity of the wheel to the velocity of water which would produce maximum power. He measured the velocity of the water for different apertures of the orifice by measuring the circumferential velocity of the wheel running under no load. He

accounted for the friction losses in the wheel bearings by winding the cord around the drum in the reverse direction to that shown in Fig. 2 and placing weights in the pan. He thus attempted to supply a force to assist the water in turning the wheel by an amount just equal to the retarding friction. He concluded that the ratio of wheel velocity to water velocity should be in the neighborhood of one to three. An analysis of Smeaton's experimental results indicate that his measured water velocities were too high by an amount which would reduce the ratio to that of modern practice, namely about one to two.

Smeaton used the same apparatus, with necessary modifications, for testing models of overshot wheels. He established to his own satisfaction their superiority over the undershot type. He thus verified the theories of Desaguliers and Parent and also Maclaurin's "fluxionary" (calculus) deductions based on Parent's work. He also disproved the theories of Belidor who held that "Water applied undershot will do six times more execution than the same applied overshot." These results were destined to become important findings which were to exert considerable influence upon the early development of the United States which was to come into being 25 years later.

Another Englishman, John Banks, published a "Treatise on Mills" in London in 1795. Banks, a strong advocate of the hydraulic laboratory, seems to have begun his researches about 1770. That he had considerable mathematical ability is demonstrated by his use of the calculus in his treatise. Nevertheless, he has this to say in regard to the experimental approach and its limitations:

"However satisfactory mathematical reasoning may be to some,

yet experimental proof is desirable, and, to many, much more so than the former; and without experiments, we often want data to reason from. But if we have certain principles, the conclusions drawn therefrom will often differ considerably from experiment, or rather the

No.	Height of water in the cistern.		Turns of the wheel unloaded.	Virtual head deduced therefrom.	Turns at the maximum.	Load at the equilibrium.		Load at the maximum.	Water expended in a minute.	Power.	Effect.	Ratio of the power and effect.	Ratio of the velocity of the water and wheel.	Ratio of the load at the equilibrium, to the load at the maximum.	Experiments.
	In.	oz.				lb.	oz.								
1	33	88	15,85	30,	13	10	10	9	275,	4358	1411	10:3,24	10:3,4	10:7,75	At the 1st hole.
2	30	86	15,0	30,	12	10	9	6	264,7	3970	1266	10:3,2	10:3,5	10:7,4	
3	27	82	13,7	28,	11	2	8	6	243,	3329	1044	10:3,15	10:3,4	10:7,5	
4	24	78	12,3	27,7	9	10	7	5	235,	2890	901,4	10:3,12	10:3,55	10:7,53	
5	21	75	11,4	25,9	8	10	6	5	214,	2439	735,7	10:3,02	10:3,43	10:7,32	
6	18	70	9,95	23,3	6	10	5	5	199,	1970	561,8	10:2,85	10:3,36	10:8,02	
7	15	65	8,54	23,4	5	2	4	4	178,5	1524	442,5	10:2,9	10:3,6	10:8,3	
8	12	60	7,29	22,	3	10	3	5	161,	1173	328,	10:2,8	10:3,77	10:9,1	
9	9	52	5,47	19,	2	12	2	8	134,	733	213,7	10:2,9	10:3,65	10:9,1	
10	6	42	3,55	16,	1	12	1	10	114,	404,7	117	10:2,82	10:3,8	10:9,3	
11	24	84	14,2	30,75	13	10	10	14	342,	4890	1505	10:3,075	10:3,66	10:7,9	At the 2d.
12	21	81	13,5	29,	11	10	9	6	297,	4009	1223	10:3,01	10:3,62	10:8,05	
13	18	72	10,5	26,	9	10	8	7	285,	2993	975	10:3,25	10:3,6	10:8,75	
14	15	69	9,6	25,	7	10	6	14	277,	2659	774	10:2,92	10:3,62	10:9,	
15	12	63	8,0	25,	5	10	4	14	234,	1872	549	10:2,94	10:3,97	10:8,7	
16	9	56	6,37	23,	4	0	3	13	201,	1280	390	10:3,05	10:4,1	10:9,5	
17	6	46	4,25	21,	2	8	2	4	167,5	712	212	10:2,98	10:4,55	10:9,	
18	15	72	10,5	29,	11	10	9	6	357,	3748	1210	10:3,23	10:4,02	10:8,05	The 3d.
19	12	66	8,75	26,75	8	10	7	6	330,	2887	878	10:3,05	10:4,05	10:8,1	
20	9	58	6,8	24,5	5	8	5	0	255,	1734	541	10:3,01	10:4,22	10:9,1	
21	6	48	4,7	23,5	3	2	3	0	228,	1064	317	10:2,99	10:4,9	10:9,6	
22	12	68	9,3	27,	9	2	8	6	359,	3338	1006	10:3,02	10:3,97	10:9,17	4th.
23	9	58	6,8	26,25	6	2	5	13	332,	2257	686	10:3,04	10:4,52	10:9,5	
24	6	48	4,7	24,5	3	12	3	8	262,	1231	385	10:3,13	10:5,1	10:9,35	
25	9	60	7,29	27,3	6	12	0	6	355,	2588	783	10:3,03	10:4,55	10:9,45	5th.
26	6	50	5,03	24,6	4	6	4	1	307,	1544	450	10:2,92	10:4,9	10:9,3	
27	6	50	5,03	26,	4	15	4	9	360,	1811	534	10:2,95	10:5,2	10:9,25	6th.
1.	2.	3.	4.	5.	6	7.	8.	9	10.	11	12.	13.			

TABLE I

experiment from the theory. For the theory supposes the bodies to move in free space, without friction, or any kind of resistance; but as these impediments cannot be entirely removed, the experiments cannot perfectly coincide with the theory, though in some cases they come exceedingly near."

Mr. Banks offers an interesting side light which seems to indi-

cate something of the attitude of the late 18th century toward female scientists. He says in his preface:

“And though I have had much practice in making experiments, I have not trusted entirely to my own observations, but have been assisted in the whole, by one or more gentlemen well acquainted with the subject. At Coventry, by the Rev. Mr. Banks, of Monks Kirkby, by my eldest son, and by my wife, who, though a woman, is perhaps as accurate in making experiments in philosophy, and some branches of chemistry, as most of men.”

Banks directed his activity toward the mathematical analysis and experimental determination of the laws of circular motion, the optimum ratio of circumferential velocity of mill wheels to the velocity of the propellant water, and the flow of water through orifices. It is interesting to note that the 18th century experimentors charged all of the contraction effect of orifices to a velocity reduction, although Banks noticed it.

Banks performed a number of experiments on the discharge through orifices. He was interested in determining the ratio between the actual velocity and the theoretical velocity based on the $2gh$ relation.

He reports that he began his experiments with orifices on plates $1/40$ inch thick and carried on with plates of greater thickness. He found that the discharge under corresponding heads was greater for the thicker plates than it was for the thin plates. Working apparently without an understanding of the effect of the contraction, he was seeking the conditions by which the maximum ratio of actual velocity to the theoretical could be obtained. The results of his orifice plate experiments were unsatisfactory to him so he devised a conical orifice. Concerning this he says:

“But as my view was to obtain the greatest velocity I shall take no notice of any but the cone, which I found to be best. This I made of brass about $1/10$ of a foot in length and the top diameter about twice as much as the bottom or aperture. The stream discharged through this is remarkably different from that discharged through the plate. This (the stream) appears like a piece of crystal glass to the distance of some feet, more or less, according to the head; neither has it that contraction just below the aperture as observed in one flowing through a thin plate; and the observed velocity at the depth of seven feet falls $1\frac{1}{4}$ foot short of the computed.”

As a result of his researches he found the value of the velocity coefficient to range from 0.91 to 0.96. Apparently he did not trust these values in the face of the results reported by his predecessors. He reduced his coefficient to 0.75 and finally appears to recommend 0.672, which he arrived at by averaging the results of others as shown in the following table.

Newton707
Boffuet615
Banks750
Michelotti625
Hellham705
Smeaton631

6)4.033

Mean = .672

In connection with the Illinois mill restorations, the failure of the early hydraulicians to account for the orifice contraction was the source of considerable confusion in the attempt to develop a design practice as of 1800.

This practice was based largely upon the work of Oliver Evans, an American. In 1787, Evans published a book entitled "The Young Mill-Wright and Miller Guide." It passed through several editions, the last of which was probably published in 1836.

The Evans book appeared at a very opportune time for America. The Revolutionary War was over and the newly born United States was faced with the problem of building up the industrial phase of its economic system in order to improve its position and assure the permanence of its independence. Steam engineering was then in its infancy so that water wheels formed the principal source of mechanical power during that early period of industrial advance. Thomas Jones writing in 1834 says that the great superiority of American mills over those of any other part of the world was due to the work of Evans. Like many other engineers and scientists some of his contemporaries did not appreciate him. Jones says:

"Mr. Evans experienced the fate of most other meritorious inventors; the combined powers of prejudice and of interest deprived him of all benefit from his labors and like Whitney he was compelled to depend upon other pursuits for the means of establishing himself

in the world. His regard, as an inventor, was a long continuous series of ruinous litigation and the eventual success of the powerful phalanx which was in league against him."

Evans was much impressed by the work of Smeaton but he did not agree with Smeaton's one-to-three ratio of wheel to water velocity for the undershot types. Evans reports that William Waring, a teacher in Friends College, Philadelphia, in 1790 read a paper, "wherein he had shown that the velocity of the undershot water wheel to produce maximum effect must be just one half the velocity of the water."

Evans quotes Waring's mathematical analysis which is practically the same as that used today. However, he did not agree with this conclusion and felt that Smeaton had been deceived by the imperfections of the model shown in Fig. 1. Through a deductive process he decided that the correct ratio of wheel to water velocity should be 0.577.

Evans wasn't very clear about the discharge through orifices and contrary to Smeaton and Banks he based his practice upon the theoretical spouting velocity and was therefore closer to the truth than his predecessors. Concerning orifices Evans says:

"Of The Friction Of The Apertures Of Spouting Fluids. The doctrine of this species of friction appears to be as follows:

- "1. The ratio of the friction of round apertures, is as their diameters, nearly; while the quantity expended, is as the squares of their diameters.
- "2. The friction of an aperture of any regular or irregular figure, is as the length of the sum of the circumscribing lines, nearly; the quantities being as the areas of the aperture, therefore
- "3. The less the head or pressure, and the larger the aperture, the less the ratio of the friction; therefore
- "4. This friction need not be much regarded, in the large openings or apertures of undershot mills, where the gates are from 2 to 15 inches in their shortest sides; but it very sensibly affects the small apertures of high overshot mills, with great heads, where their shortest sides are from five-tenths of an inch to two inches."

In addition to treatises on mechanics and hydraulics, Evans' book covers the entire range of the then extant water wheel types except the reaction wheel. He also includes in more or less detail practical discussions on the design of pumps, conveying apparatus, mill buildings and appurtenances, gears, gudgeons, and other pertinent subjects. As an interesting sidelight, it may be noted that he coined the word, CUBOCH, to define a unit of power. This word seems to have completely disappeared from modern literature. In explaining his terminology for the amount of power available in a given stream Mr. Evans says, "Multiply the cubic feet expended per second by its vertical perpendicular descent in feet and the product will be a true measure of the power per second. This measure must have a name which I call CUBOCH; this is one cubic foot of water, multiplied by one foot descent is one cuboch or the unit of power."

The performance of grist and saw mills was rated by the number of cubochs which had to be applied to the wheel in order to saw logs or grind grain at a given rate. It appears that 112 cubochs of power were required to drive five foot diameter mill stones 97 revolutions per minute. Under these conditions the stones would grind 5 bushels of wheat per hour.

The term "efficiency" as applied to water power does not appear in these writings. The term "ratio of power to effect" had the same connotation. Smeaton's experiments, using the recirculating device previously discussed on undershot wheels, showed ratios of from 10:7.6 to 10:5.2 or efficiencies of from 76 percent to 52 percent.

The research, in connection with the Illinois mill restorations, quite definitely establishes the fact that many of the American mills of 1790-1840 were planned and built in accordance with the theories and rules of practice laid down by Evans. With the aid of Evans' treatise, and model tests conducted by Professor William J. Putnam at the University of Illinois on an old fashioned tub wheel, it became possible to fit together the disjointed bits of available evidence into logical plans for reasonably authentic replicas.

An interesting feature, disclosed by the reading and study of old treatises on mechanics and hydraulics, is the philosophical approach which was almost invariably used. The increasing use of mathematical expressions and coined words to provide greater facility for scientific expression throughout the past fifty years seems to have tended to obscure the relationship of words and symbols to the na-

tural phenomenon which they represent. In the 18th century, explanations were in simple and related language.

It is true, however, that even then there was a strong tendency to formulize fundamentals and to develop the application of scientific principles to design and construction by means of a series of rules carefully expressed in logical numerical order. The growth of this tendency from 1729 to 1800 is marked by the difference between the language of Switzer and that of Evans. The introductory statement in the latter's book is as follows:

“Although there are many good, practical workmen who are entirely ignorant of the theory of mechanics as a science it will be universally acknowledged that an acquaintance with the general properties of matter and the laws of motion would not only be gratifying to every intelligent mind but would introduce a certainty into many mechanical operations which would insure their success.”

Part II is introduced thus: “What was said in the first part was meant to establish theories and to furnish easy rules—This part is particularly intended for the help of young and practical millwrights whose time will not admit of a full investigation of those principles and theories which have been laid down; I shall, therefore, endeavour to reduce the substance of all that has been said to a few tables, rules, and short directions, which, if found to agree with experience, will be sufficient for the practitioner.”

The latter statement might be used verbatim to describe some of the educational processes in hydraulics today. It is entirely possible therefore, that some of our bad habits are too steeped in tradition to be corrected. It may be comforting, however, to throw a portion of the blame on the teachers and scientists of the late 18th century.