Art. 181. Special Devices

Many devices to increase the efficiency of reaction turbines, particularly at part gate, have been proposed. In the Fourneyron turbine a common plan is to divide the wheel into three parts by horizontal partitions between the vanes, so that these are completely filled with water when the gate is either one-third or two-thirds closed (see Fig. 182*d*). The surface exposed to friction is thus, however, materially increased at full gate.

The Boyden diffuser is another device used with outward-flow reaction turbines. This consists of a fixed wooden annular frame D placed around the wheel W, through which the water must pass after exit from the wheel. Its width is about four or five times that of the wheel, and at the outer end its depth becomes about double that of the wheel. The effect of this is like a draft tube, and although the absolute velocity of the water when issuing from the wheel is greater than before, the absolute velocity of the water coming out of the diffuser is less, and hence a greater amount of energy is imparted to the turbine. It has been shown above that the efficiency of a reaction turbine is increased by making the exit depth d_1 greater than the entrance depth d, and the fixed diffuser produces the same result. By the use of this diffuser Boyden increased the efficiency of the Fourneyron reaction turbine several percent.

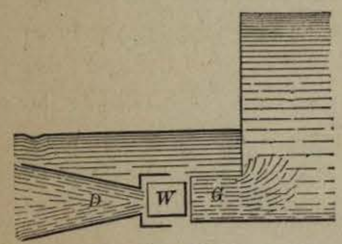

Fig. 181.

The pneumatic turbine of Girard was devised to overcome the loss in reaction turbines due to a partial closing of the gate. The turbine was inclosed in a kind of bell into which air could be pumped, thus lowering the tail-water level around the wheel. At part gate this pump is put into action, and as a consequence the air is admitted into the wheel, and the water flowing through it does not fill the spaces between the vanes. Hence the action becomes like that of an impulse turbine, and the full efficiency is maintained, although power is lost in compressing the air.

At a high stage of the stream, when water flows to waste over the dam, backwater usually lessens the available fall and power. To increase that fall and power, Herschel in 1908 devised and tested at the Holyoke Testing Flume the plan of connecting the lower end of the turbine draft tube to a chamber wherein a partial vacuum is produced by causing part of the waste to flow through a tube shaped like the Venturi meter, suitable connections being made between the specially designed throat of the tube and the vacuum chamber. This device, called "the fall increaser,"* gives greater available power at high water stages, since the vacuum head h_1 is added to the head h between the upper and lower water levels, and since the discharge through the turbine is also increased.

The screw turbine consists of one or two turns of a helicoidal surface around a vertical shaft, the screw being inclosed in a cylindrical case. At a point of entrance the downward pressure of the water can be resolved into two components, a relative velocity V parallel to the surface and a horizontal velocity u which corresponds to the velocity of the wheel. At the point of exit it can be resolved in like manner into V_1 and u_1. But, as in other cases, the condition for high efficiency is $u_1 = V_1$, and since the water moves parallel to the axis, $u_1 = u$. Applying the general formula of Art. 175, it is seen that this can only occur when the head h is zero or when the velocity u is infinite. The screw turbine is hence like a reaction wheel, and high efficiency can never practically be obtained.

Prob. 181. Consult Rühlmann's Maschinenlehre, vol. 1, pp. 360–425, and describe a scheme for "ventilating" a turbine in order to increase its efficiency.

Art. 182. The Niagara Turbines

A number of turbines have been installed at Niagara Falls, N.Y., for the utilization of a portion of the power of the great falls. Those to be here briefly described are the ten large wheels designed by Faesch and Picard, of Geneva, Switzerland, and erected from 1894 to 1900 for the Niagara Falls Power Company. The entire plant is to include twenty-one twin outward-flow reaction turbines, each of about 5000 horse-power. It is located

* Harvard Engineering Journal, June, 1908.

about $1\frac{1}{4}$ miles above the American fall, where a canal leads water from the river to the wheel pit. The water is carried down the pit through steel penstocks to the turbines, which are placed 136 feet below the water level in the canal. After passing through the wheels the waste water is conveyed to the river below the American fall by a tunnel 7000 feet long.*

Fig. 182*a* shows a cross-section of the wheel-pit, with an end view of a penstock, wheel case, and shaft. Fig. 182*b* exhibits part of a longitudinal section of the wheel pit and a side view of two of the penstocks, with the inclosing cases and shafts of the turbines. These figures show a rock-surface wheel pit, but this surface was later protected by a brick lining having a thickness of about 15 inches. The width of the wheel pit is 20 feet at the top and 16 feet at the bottom, and the cylindrical penstock is $7\frac{1}{2}$ feet in diameter. The shaft of the turbine is a steel tube

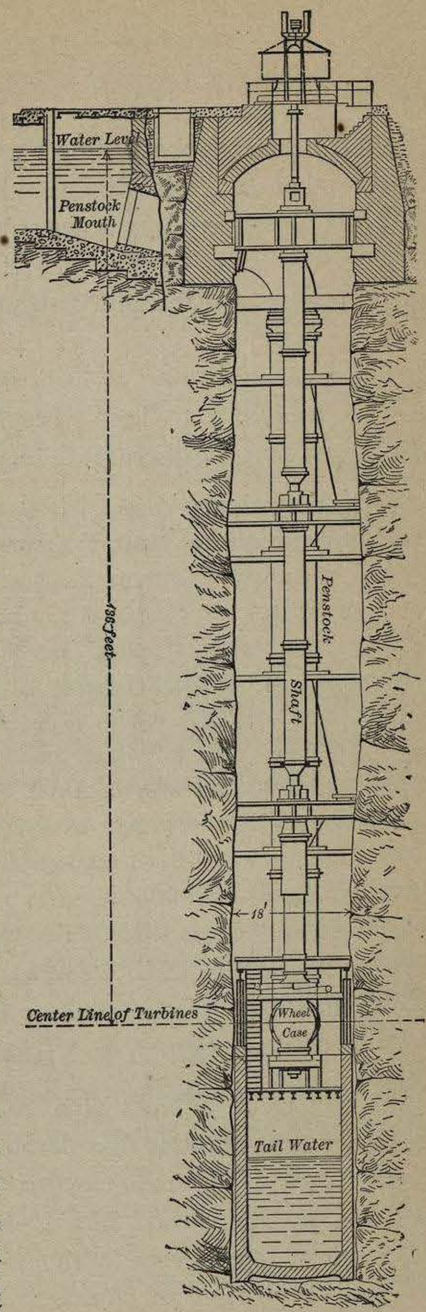

Fig. 182*a*.

* Engineering News, 1892, vol. 27, p. 74, and 1893, vol. 29, p. 294.

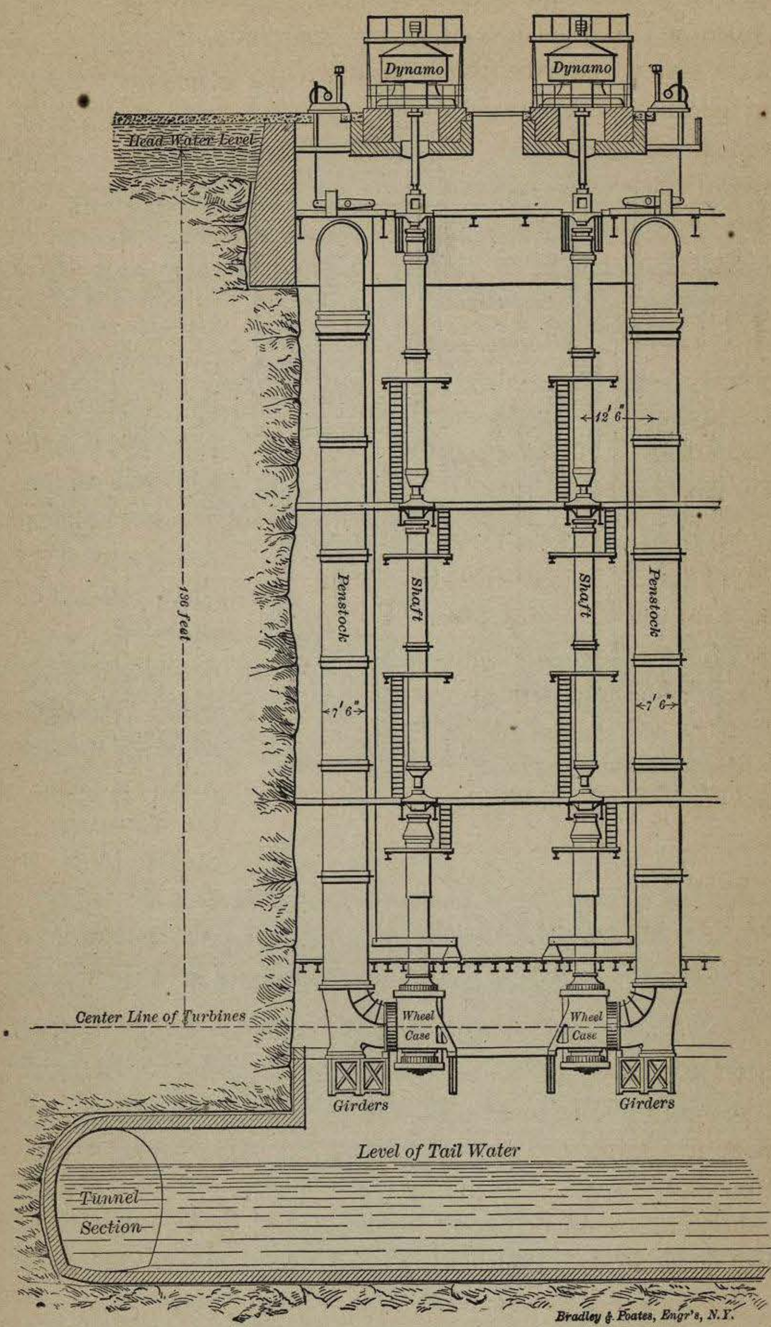

Fig. 182*b*.

38 inches in diameter, built in three sections, and connected by short solid steel shafts 11 inches in diameter which revolve in bearings. At the top of each shaft is a dynamo for generating the electric power.

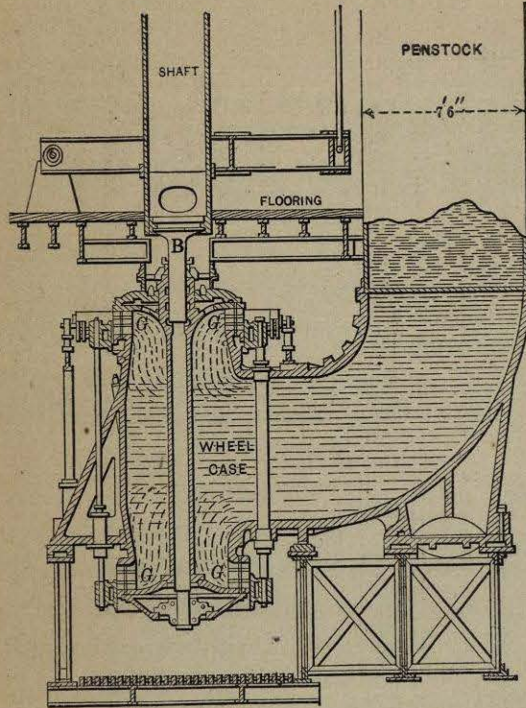

Fig. 182c.

In Fig. 182c is shown a vertical section of the lower part of the penstock, shaft, and twin wheels. The water fills the casing around the shaft, passes both upward and downward to the guide passages, marked G, through which it enters the two wheels, causes them to revolve, and then drops down to the tail race at the entrance to the tunnel, which carries it away to the river. The gate for regulating the discharge is seen upon the outside of the wheels.

Fig. 182d gives a larger vertical section of the lower wheel with the guides, shaft, and connecting members. The guide passages, marked G, and the wheel passages, marked W, are triple, so that the latter may be filled not only at full gate, but also when it is one-third or two-thirds opened, thus avoiding the loss of energy due to sudden enlargement of the flowing stream. The two horizontal partitions in the wheel are also advantageous in strengthening it. The inner radius of the wheel is $31\frac{1}{2}$ inches and the outer radius is $37\frac{1}{2}$ inches, while the depth is about 12 inches. In this figure the gates are represented as closed.

In Fig. 182e is shown a half-plan of one of the wheels, on a part of which are seen the guides and vanes, there being 36 of

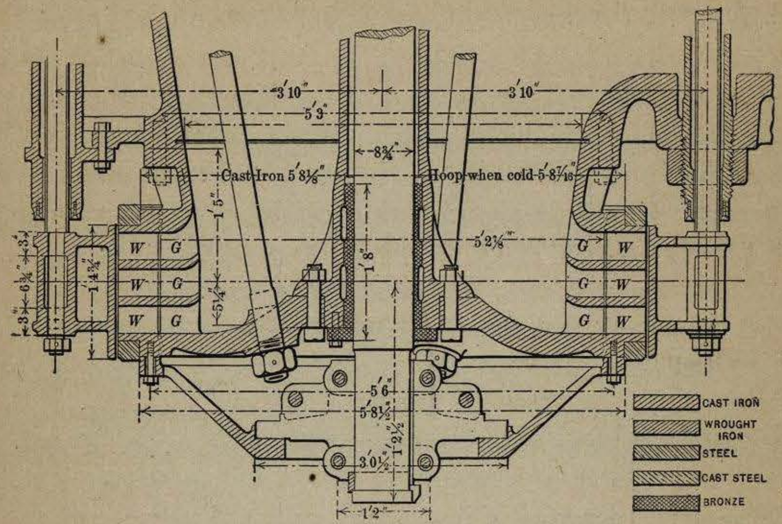

Fig. 182d.

the former and 32 of the latter. The value of the approach angle α is 19° 06′, the mean value of the entrance angle ϕ is 110° 40′, and the exit angle β is 13° $17\frac{1}{2}$′. Although the water on leaving

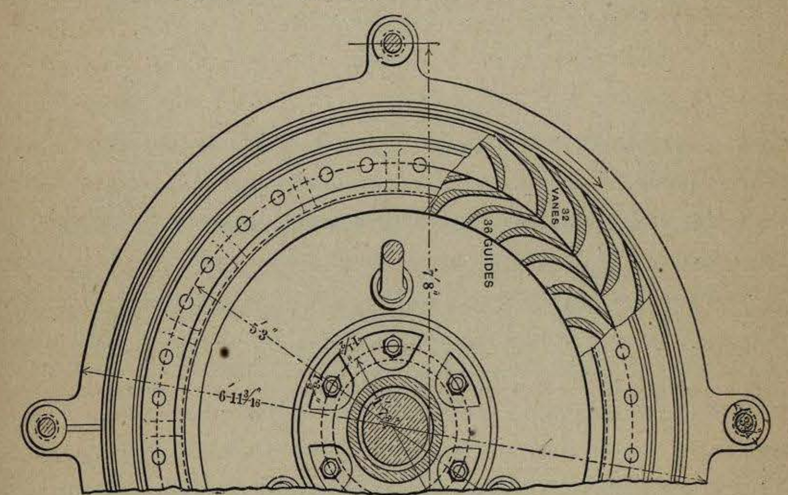

Fig. 182e.

the wheel is discharged into the air, the very small annular space between the guides and vanes, together with the decreasing area between the vanes from the entrance to the exit orifices, insures that the wheels act like reaction turbines for the three positions of the gates corresponding to the three horizontal stages.

The average discharge through one of these twin turbines is about 430 cubic feet per second, and the theoretic power due to this discharge is 6645 horse-powers. Hence if 5000 horse-powers be utilized, the efficiency is 75.2 percent. Under this discharge the mean velocity in the penstock is nearly 10 feet per second, but the loss of head due to friction in the penstock will be but a small fraction of a foot. The pressure-head in the wheel case is then practically that due to the actual static head, or closely $141\frac{1}{2}$ feet upon the lower and 130 feet upon the upper wheel. Although the penstock is smaller in section than generally thought necessary for such a large discharge, the loss of head that occurs in it is insignificant; and it will be seen in Fig. 182*a* to be connected with the head canal and with the wheel case by easy curves, and that its section is enlarged in making these approaches.

A test of one of these wheels, made in 1895, showed that 5498 electrical horse-powers were generated by an expenditure of 447.2 cubic feet of water per second under a head of 135.1. The efficiency of the dynamo being 97 percent, the efficiency of the wheel and approaches was $82\frac{1}{2}$ percent. The water was measured, when entering the penstock, by a current meter of the kind illustrated in Art. 40.

From formula $(176)_4$ the advantageous velocity of the inner circumference of the upper wheel, taking $h = 130\frac{1}{2}$ feet, is found to be 68.88 feet per second, and that for the lower wheel, taking $h = 141\frac{1}{2}$ feet, is found to be 71.73 feet per second. Perhaps the mean of these, or 70.31 feet per second, closely corresponds with the advantageous velocity for the two combined. The number of revolutions per minute for the condition of maximum efficiency is then closely 250. The absolute velocity of the water when entering the wheel is about 66 feet per second, so that the pressure-head in the guide passages of the upper wheel is nearly 66 feet. The mean absolute velocity of the water when leaving

the wheels is about 19 feet per second, so that the loss due to this is only about 4 percent of the total head.

The weight of the dynamo, shaft, and turbine is balanced, when the wheels are in motion, by the upward pressure of the water in the wheel case on a piston placed above the upper wheel. The upper disk containing the guides is, for this purpose, perforated, so that the water pressure can be transmitted through it. In Fig. 182*c* these perforations can be seen, and the balancing piston is marked *B*. The lower disk, on the other hand, is solid, and the weight of the water upon it is carried by inclined rods upward to the wheel case, which together with the penstock is supported upon several girders. At the upper end of the shaft is a thrust bearing to receive the excess of vertical pressure, which may be either upward or downward under different conditions of power and speed.

A governor is provided for the regulation of the speed, and this is located on the surface near the dynamo. It is of the centrifugal-ball type, and so connected with the main shaft and the turbine gates that the latter are partially closed whenever from any cause the speed increases. These gates are so set that the orifices of the upper and lower wheels are not simultaneously closed, one gate being in advance of the other by about the width of one division stage. The revolving field magnets of the dynamo also serve as a fly-wheel for equalizing the speed. With this method of regulation it is insured that the speed cannot increase more than 3 or 4 percent when 25 percent of the work is suddenly removed.

The above description refers to the ten turbines in wheel pit No. 1. The illustrations are those of the wheels called units 1, 2, and 3, which are installed in 1894 and 1895. Units 4 to 10 inclusive, installed in 1898–1900, are of the same type except that both the penstock and wheel case have cast-iron ribs on their sides which rest on massive castings built into the masonry of the side walls. This arrangement dispenses with the supporting girders shown in Figs. 182*a*–182*c*, and gives much greater rigidity to both penstocks and wheels.

The excavation of a new wheel pit, called No. 2, was begun in 1896, and the installation of units 11–21 was completed in 1903. These wheels have penstocks and shafting similar to those of units 1–10, but the wheels are of the Jonval type, the flow being inward and downward. The wheel case has the form of a flattened sphere, the water entering from one side and passing through the guides to a single turbine 64 inches in diameter and 23.5 inches deep. After leaving the wheel, the water passes to two draft tubes, each about 58 inches in diameter, and is discharged near the invert of the tail race at an angle of 45° to the horizontal axis of the wheel pit. The wheel case is supported on these two draft tubes as on two legs, while the penstock is supported on iron lugs in the same way as those of units 4–10. By these draft tubes the head on the wheel is increased to 144 feet, this being the difference from the water level in the head race to that in the tail race. The balancing pistons are below the wheels, and are supported from an independent pipe instead of from the penstock. Each shaft is also supplied with an oil step-bearing, which is designed to support, if necessary, the entire revolving weight at the normal speed of 250 revolutions per minute.

Prob. 182*a*. Compute the hydraulic efficiency of the turbines described above. Compute the velocity v_0 with which the water enters the lower wheel and the velocity v_1 with which it leaves the same when the speed is 250 revolutions per minute.

Prob. 182*b*. Compute the efficiency of a reaction wheel under a head of 3.5 meters when the radius of the exit orifices is 0.64 meters, the coefficient of velocity 0.95, and the number of revolutions per minute is 130.

Prob. 182*c*. Design an outward-flow reaction turbine which shall use 8 cubic meters of water per second under a head of 12.4 meters, taking the entrance angle ϕ as 90°.

Prob. 182*d*. A dynamo delivering 4100 kilowatts has an efficiency of 97.5 percent, while the efficiency of the turbine is 81.3 percent and that of the approaches to the turbine is 99.7 percent. The turbine is of the Jonval type, and the difference between the levels of head and tail race is 14.4 meters. How many cubic meters of water are used per second?

Prob. 182*e*. Consult engineering periodicals and describe other large power plants for the development of electrical energy which have been installed at Niagara Falls, especially that of the Canadian Niagara Power Company and that of the Ontario Power Company.

CHAPTER 15

NAVAL HYDROMECHANICS

Art. 183. General Principles

In this chapter is to be discussed in a brief and elementary manner the subject of the resistance of water to the motion of vessels, and the general hydrodynamic principles relating to their propulsion. The water may be at rest and the vessel in motion, or both may be in motion as in the case of a boat going up or down a river. In either event the velocity of the vessel relative to the water need only be considered, and this will be called v. The simplest method of propulsion is by the oar or paddle; then come the paddle wheel, and the jet and screw propellers. The action of the wind upon sails will not be here discussed, as it is outside of the scope of this book.

The unit of linear measure used on the ocean is generally the nautical mile, while one nautical mile per hour is called a knot. One nautical mile is about 6080 feet, so that knots may be transformed into feet per second by multiplying by 1.69, and feet per second may be transformed into knots by multiplying by 0.592. On rivers the speed is estimated in statute miles per hour, and the corresponding multipliers will be 1.47 and 0.682. One kilometer per hour equals 0.621 miles per hour or 0.91 feet per second. On the ocean the weight of a cubic foot of water is to be taken as about 64 pounds (it is often used as 64.32 pounds, so that the numerical value is the same as $2g$), and in rivers at 62.5 pounds.

The speed of a ship at sea was formerly roughly measured by observations with the log, which is a triangular piece of wood attached to a cord which is divided by tags into lengths of about $50\frac{2}{3}$ feet. The log being thrown into the water, it remains sta-