6.1.4
HYDRAULIC TURBINES

WARREN G. WHIPPEN
HOWARD A. MAYO, JR.
DONALD R. WEBB

PUMPING APPLICATIONS

In many pumping applications, the liquid remains at a high pressure after it has completed its cycle. It is often economically desirable to recover some of the energy, which will otherwise have to be dissipated when the liquid is brought back to a lower pressure. Instead of running the liquid through a pressure-reducing valve to destroy the energy, a hydraulic turbine may be installed. This turbine can therefore assist in driving the process pumps. There are many such applications in use. Among these are the use of turbine-driven pumps in gas-cleaning operations. Here the solutions from scrubber towers are passed through turbines that in turn drive pumps. Some of the solutions involved in such a process are water saturated with carbon dioxide at a temperature of 40 to 70°F (4 to 21°C) and potassium carbonate containing dissolved carbon dioxide at a specific gravity of 1.31. A liquid at the much lower specific gravity of 0.84 has been used in power-recovery turbines in a glycol-ethylene hydration process.

One of the oldest applications of turbine-driven pumps was for fire-fighting equipment in mills having a natural head of water. The large volume of low head water was routed through a hydraulic turbine that drove the pump to pressurize a sprinkler system or provide high-pressure water to the fire-hose connections. Today, hydraulic turbines are used to drive pumps that generate fire-fighting foam.

At thermal power plants, cooling water returning from the cooling towers has been used to drive a hydraulic turbine directly connected to a pump that provides part of the cooling water. Naturally, in such an application, the power from the turbine alone is not enough to maintain the pumping system. Therefore an auxiliary power source is also required.

Turbines using oil pressure have been employed at thermal power plants. Large steam turbines obtain bearing oil and control oil pressure from a main feed pump that is directly connected to the steam turbine shaft. A small amount of the oil at this high pressure is used for the relay control, with the majority of the oil going to the bearings at a lower pressure. To reduce the oil pressure from that required by the relays to that needed by the bearings, the oil is passed through a turbine driving a booster pump that pressurizes the oil at the intake of the main pump. At locations with high flood levels, it is preferable to locate pumps and electrical equipment above flood level. Some recent steam power plant installations have used the return from the condenser to the river (normally an appreciable drop in head) to drive a hydraulic turbine, which in turn may assist in driving the condensate pumps. Also, effluent from sewage treatment plants may have a significant discharge head.

It is often economical to use a small volume of water at a high head to move a large volume of water at a low head. Of course, the reverse application can also be accomplished. The former procedure is employed at hydroelectric projects where it is necessary to operate fishways to enable migrating fish to continue traveling upstream over the dam. The large volume of water is used both to attract the fish to the fish flume and to transport the fish to the fish ladders. An example of such an installation can be seen in Figure 1.

Turbines have also been used to start large pumping units when the hydraulic conditions are suitable. The impulse turbine, which develops maximum torque at zero speed, is especially useful for this application. The power required on such a starting turbine would be less than the power required on a starting motor to do the same job. Many electric controls can be eliminated when starting with a turbine. An illustration of this application is shown in Figure 2.

Desalinization plants have been built wherein salt is removed from seawater by pumping it through a membrane at high pressure. Only pure water goes through the membrane, with most of the sea water being used to carry away the salt. This excess high-pressure sea water is then put through a power-recovery turbine that helps to drive the high-pressure pumps.

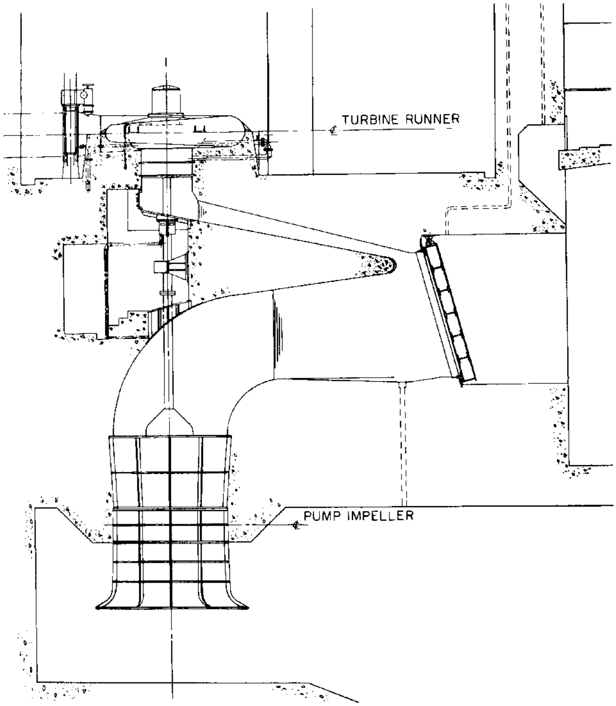

FIGURE 1 Turbine-driven fishway pumps. High head, low volume Francis-type turbine drives a low head, high-volume propeller pump at Rocky Reach, Washington.

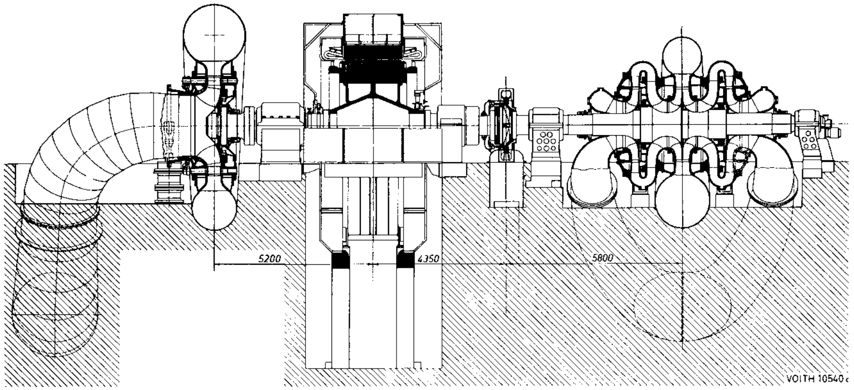

FIGURE 2 Impulse runner used to start a large pump. Left to right: Francis turbine, generator motor, starting impulse turbine, and two-stage double-suction storage pump (Adapted from Voith Publication 1429, J. M. Voith GmbH, Heidenheim, Germany).

It is often desirable to have the turbine and pump running at different speeds, and this has been accomplished by means of a variable-speed coupling between turbine and pump. Reliable low-speed gear increasers or reducers of up to 35,000 hp (26,000 kW) are being built by many manufacturers. In applications such as starting a pump by means of a turbine, a mechanism may be needed to disengage the turbine after the pump has been started, in order to minimize windage and friction. Disengaging couplings may be hydraulic or mechanical and may be actuated when the unit is stationary or rotating, depending on the application. However, it is possible to allow the turbine to spin in air with the pump after the pump has been started. Figure 3 is an illustration of a turbine-drive pump arrangement.

TYPES OF TURBINES

Three types of turbines will be discussed: propeller (fixed and adjustable blades), Francis, and impulse. Figures 4 to 7 are illustrations of these turbine runners. Figure 8 shows a complete Francis turbine unit. The fixed- and adjustable-blade propellers and runners are essentially the same, with the exception that the adjustable is suited to a much wider range of loading conditions. This versatility is reflected in a higher manufacturing cost for the adjustable blade. The Francis runner is much like a centrifugal pump impeller running backward. The impulse runner (or Pelton wheel) is for high-head applications. The water is first channeled through a nozzle that directs a jet of water into the bowl-shaped runner buckets. This jet then discharges into the atmosphere. When a high back pressure is present in the housing, the impulse wheel cannot discharge properly. The performance drops off rapidly as the back pressure is increased. However, it is sometimes possible to admit low air pressure into the impulse runner housing to lower the level of the liquid surface to below the level of the runner. When the high turbine back pressure cannot be eliminated, a Francis turbine will perform much better than an impulse turbine. Figure 9 illustrates the relative efficiencies of the different types of runners. The fixed-blade propeller and Francis runners operate most efficiently in a range near full load, and operating time should be limited at low loads. The impulse and adjustable-blade runners, however, are designed for high efficiencies over a large load range. The adjustable-blade propeller accomplishes this by changing the angle of its blades by means of linkage in the hub of the runner. With the impulse runner, the size of the jet is controlled by the nozzle needle, which enables the runner to maintain high efficiencies at low loads.

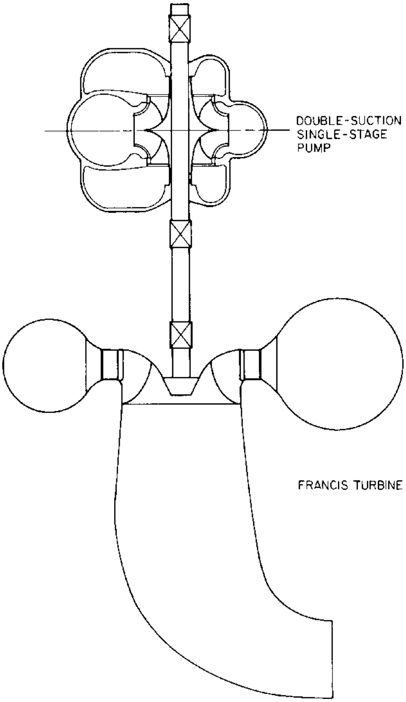

FIGURE 3 Double-suction single-stage pump driven by a Francis turbine (Voith Siemens Hydro)

FIGURE 4 Mixed flow propeller runner (Voith Siemens Hydro)

TURBINE ARRANGEMENTS

As is typical with pumps, hydraulic turbines are usually arranged with their power shafts either vertical or horizontal. In recent years, several low head installations have had inclined shafts to reduce excavation costs. The large (above 10,000 hp or 7,000 kW) vertical propeller turbines with concrete water passages have not been used with pumps. This is also true with very large, high head Francis turbines with steel-lined spiral shaped water passages. Mid-size and small hydraulic turbines of all three types may have vertical or horizontal shafts and usually steel water passages when used with pumps. Horizontal shaft arrangements have the advantage of better access to each piece of equipment. They usually require a greater floor area but lower power/pump house. For low heads (under 30’ or 10 meters), propeller turbine installations have used inclined shafts with Bulb and Pit generator housings. TUBE turbines with a nearly straight draft tube have also been arranged with inclined shafts. For very low heads (under 15’ or 5 meters), water wheels extending the width of a spillway are being considered where conventional hydraulic turbines are too costly.

Each project or site is likely to have special conditions, which will influence selection of the optimum turbine and pump arrangement.

Flow Units The size of hydraulic turbines has become so large that the earlier conventional flow quantity of cubic feet/minute (cfm) is today cubic feet/second (cfs) or cubic meters per second (cms). The following conversions are therefore useful:

FIGURE 5 Adjustable-blade propeller runner. “Kaplan” turbines have adjustable blades coordinated with adjustable wicket gates (Voith Siemens Hydro)

FIGURE 6 Francis runner has shorter buckets than a centrifugal pump impeller (Voith Siemens Hydro)

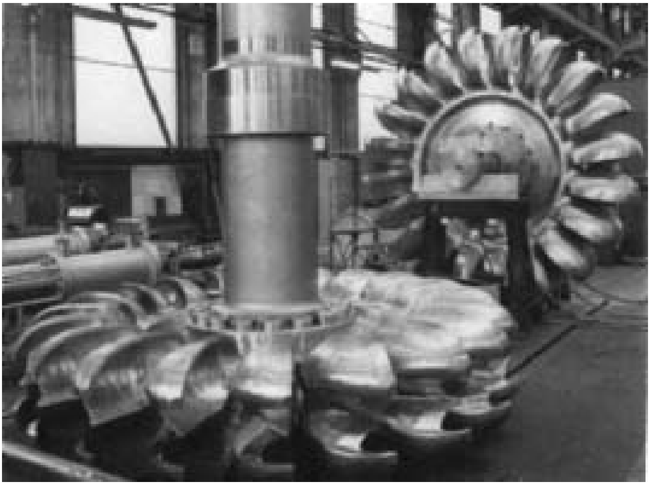

FIGURE 7 Impulse (or Pelton) runners (Voith Siemens Hydro)

1 cfs = 449 gpm or 1.077 mgd
1 cubic foot = 7.48 US gallons
British imperial gallon = 1.2009 US gallon
1 cms = 35.3 cfs

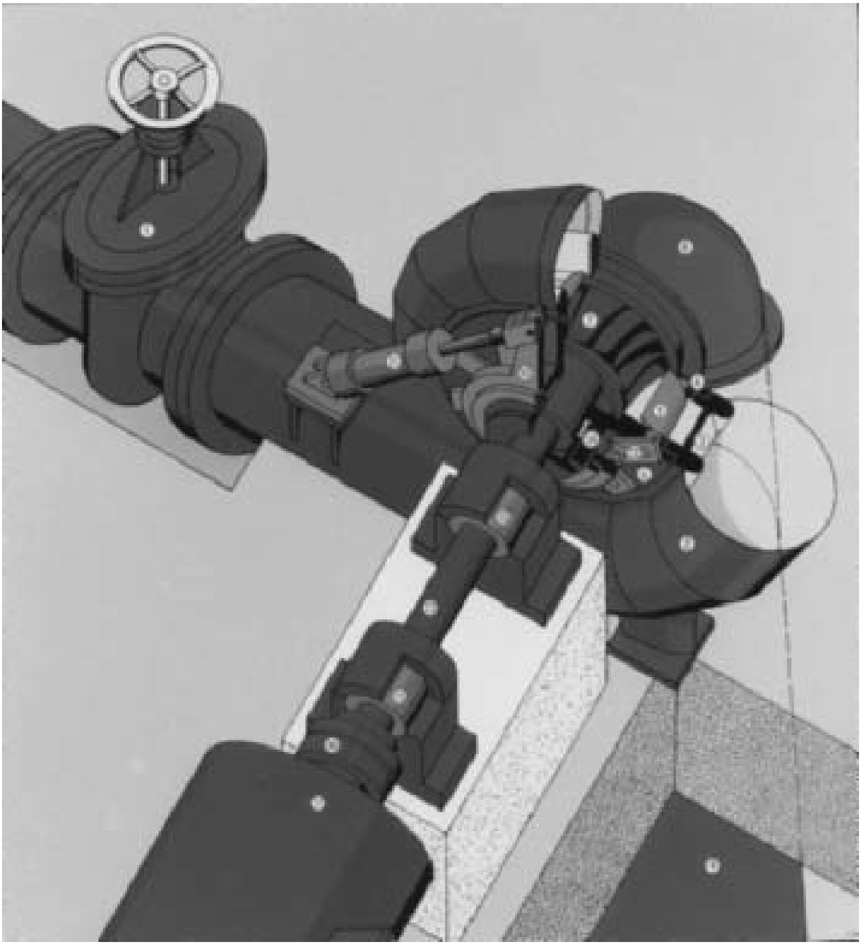

FIGURE 8 Complete standard Francis turbine unit with spiral case and elbow draft tube: 1) Shut-off valve, 2) Spiral case, 3) Stay ring, 4) Curb ring, 5) Guide vane, 6) Turbine cover, 7) Runner, 8) Draft tube elbow, 9) Draft tube, 10) Operating ring, 11) Servomotor, 12) Lever, 13) Turbine shaft, 14) Shaft seal, 15) Bearing, 16) Flexible coupling, 17) Generator (Voith Siemens Hydro)

Specific speed This is the speed at which a runner will rotate if the runner diameter is such that, under 1 ft (1 m) net head, it will develop 1 hp (1 kW):

In USCS units $$N_s = \frac{\text{rpm} \times \text{hp}^{1/2}}{\text{ft}^{5/4}}$$

In SI units $$N_s = \frac{\text{rpm} \times \text{kW}^{1/2}}{\text{m}^{5/4}}$$

The specific speed is an important factor governing the selection of the type of runner best suited for a given operating range. The impulse wheels have very low specific speeds

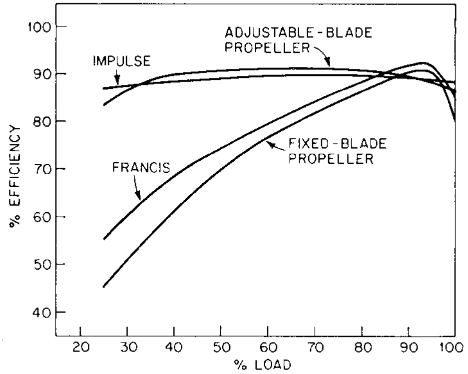

FIGURE 9 Efficiency versus load for different runner types

relative to propellers, and the specific speed of a Francis turbine lies between the impulse and propeller. Table 1 shows some statistics for existing units.*

SIZES AND RATINGS

Although power-recovery turbines are relatively small, there are much larger turbines in existence that could be used to drive pumps. Turbines of the following sizes do exist: propeller, 405.5-in (10.3-dm) diameter; Francis, 288-in (7.3-m) diameter; and impulse, 176-in (4.5-m) diameter. The extreme range of power, head, and speed is shown in Table 2.

GENERAL CHARACTERISTICS

Sigma As in pumps, the problem of cavitation also exists in turbines. Sigma is defined as follows:

$$\sigma = \frac{H_a - H_s}{H}$$

where H_a = feet (meters) of atmospheric pressure minus vapor pressure

H_s = distance in feet (meters) the centerline of the blades is above tailwater for vertical units or distance in feet (meters) the highest point of the blade is above tailwater for horizontal units

H = feet (meters) of elevation between inlet head water surface and tailwater surface elevation

Critical sigma is defined as that point at which cavitation begins to affect the performance of the turbine. Figure 10 shows the relationship between critical sigma and specific speed and also shows which type of runner is best for a given specific speed. The impulse

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*Universal specific speed Ω_s (defined in Chapter 1 and Section 2.1) is found from these turbine N_s-values as follows:

$$\Omega_s = \frac{N_s(USCS)}{4.344\sqrt{\eta_t \times \text{sp. gr.}}} = \frac{N_s(SI)}{16.564\sqrt{\eta_t \times \text{sp. gr.}}}$$

where η_t is the turbine efficiency in percent.

TABLE 1 Turbine statistics of existing units

Speed, rpm	Power, hp[a]	Head, ft[b]	N_s, USCS[c]	Type[d]	Use[e]	Supplier[f]
450	2,000	925	3.94	I	SUP	BLH
450	450	485	4.19	I	SUP	BLH
750	170	575	3.47	I	SUP	BLH
340	570	485	3.57	I	SUP	BLH
1,775	264	1,085	4.63	I	SUP	BLH
437.5	425	405	4.97	I	SUP	BLH
1,770	640	960	8.38	I	SUP	BLH
1,775	230	1,085	4.32	I	SUP	BLH
720	885	460	10.05	I	SUP	BLH
900	640	866	4.85	I	SUP	BLH
3,550	85	1,920	2.58	I	SUP	BLH
690	535	86.5	60.50	F	FW	BLH
126	670	80	13.63	F	FW	BLH
450	2,600	118	58.90	F	SUP	LEF
525	1,050	83.5	67.39	F	SUP	LEF
900	750	123	60.18	F	SUP	LEF
1,000	375	96	64.43	F	SUP	LEF
700	53	150	9.71	I	SUP	LEF
750	160	30	135.13	P	SUP	LEF
882	128	70	49.26	F	SUP	LEF
1,750	145	135	45.78	F	SUP	LEF
1,750	220	135	56.39	F	SUP	LEF
280	200	14	146.20	P	SUP	A-C
550	400	35	129.21	P	IR	A-C
3,450	7.5	196	12.89	I	PP	A-C
1,775	353	1,085	5.36	I	ST	A-C
1,185	280	231	22.01	I	ST	A-C
1,775	300	1,510	3.27	I	CH	A-C
1,300	1.6	150	3.13	I	PP	A-C
700	1,760	798	6.92	I	ST	A-C
600	392	460	5.58	I	SUP	A-C
122	973	65	20.61	F	FW	A-C
108	1,200	75	16.95	F	FW	A-C

[a] kW = 0.746 hp

[b] m = 0.3048 ft

[c] N_s (SI) = 3.814 N_s (USCS)

[d] I = impulse, P = propeller, F = Francis

[e] SUP = supplement electric motor to drive pump, FW = drives fishway pumps, ST = scrubber-tower application, PP = turbine drives petroleum pumps, CH = power recovery in chemical plant, IR = irrigation project.

[f] BLH = Baldwin-Lima-Hamilton Corp., LEF = The James Leffel Co., A-C = Allis-Chalmers Corporation, since 1986 Voith Hydro, Inc., also American Hydro Corp.

wheel is not affected by sigma because it is a free jet action and therefore not subject to low-pressure areas.

Affinity Laws The relationships between head, discharge, speed, power, and diameter can be seen in the following equations, where Q = rate of discharge, H = head, N = speed, P = power, D = diameter, and subscripts denote two geometrically similar units with the same specific speed:

TABLE 2 Range of power, head, discharge, and speed of existing units of one manufacturer

	Propeller		Francis		Impulse	
	Low	High	Low	High	Low	High
Power hp[a]	82.5	268,000	1.2	820,000	1.6	330,000
Head ft[b]	6.0	180	4.0	2,204	75.0	5,790
Speed, rpm	50	750	56.4	3,500	180	3,600

[a] kW = 0.746 hp

[b] m = 0.3048 ft

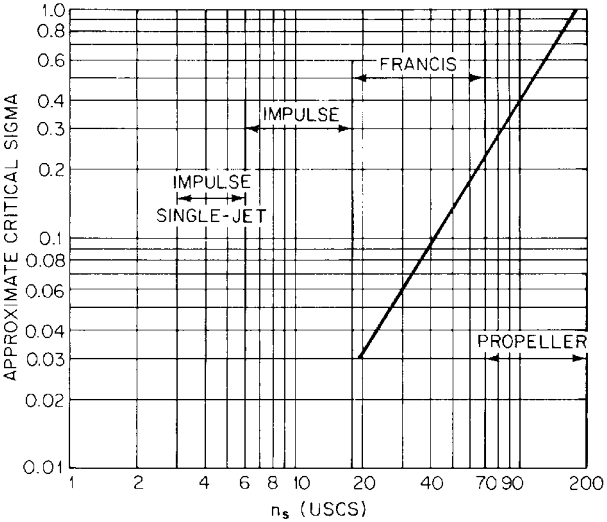

FIGURE 10 Critical sigma versus N_s. Specific speed N_s (SI) = 3.814 N_s (USCS)

$$\frac{Q_1}{N_1D_1^3} = \frac{Q_2}{N_2D_2^3}$$

$$\frac{Q_1^2}{H_1D_1^4} = \frac{Q_2^2}{H_2D_2^4}$$

$$\frac{N_1^2D_1^2}{H_1} = \frac{N_2^2D_2^2}{H_2}$$

$$\frac{P_1}{N_1^3D_1^5} = \frac{P_2}{N_2^3D_2^5}$$

Most designs used are tested as exact homologous models, and performance is stepped up from the model by the normal affinity laws given above. Because of difficulties in measuring large flows at the field installation, only approximate or relative flow metering is normally done.

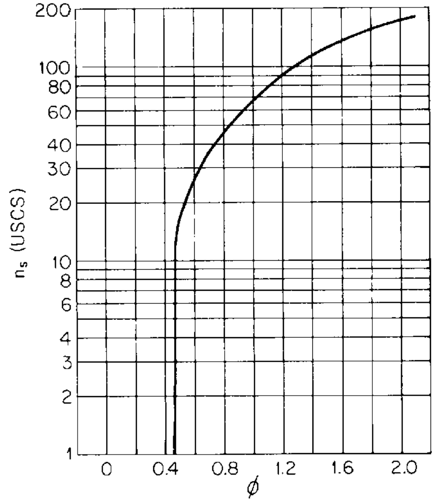

FIGURE 11 Specific speed versus ϕ. Specific speed N_s (SI) = 3.814N_s (USCS)

Speed Characteristic This is defined as the peripheral speed of the runner divided by the spouting or free discharge velocity of the water:

$$\phi = \frac{u}{(2gH)^{1/2}}$$

where ϕ = speed characteristic
u = peripheral speed of runner, ft/s (m/s)
H = head, ft (m)
g = 32.2 ft/s^2 (9.807 m/s^2)

A plot of ϕ versus speed can be seen in Figure 11, which shows that ϕ becomes constant at after the specific speed has dropped into the impulse-runner region. Theoretically, for maximum energy conversion, ϕ should equal 0.5 for impulse runners. However, because of small losses in the runner, this value is set at approximately 0.46. Control of the hydraulic turbine can be accomplished by means of a governor or a flow or load control system.

Torque All hydraulic turbines have maximum torque at zero speed; therefore, they have ideal starting characteristics. The pump can be accelerated to design speed by gradually opening the turbine gates or inlet valve while keeping within the limitations of hydraulic transients.

DATA REQUIRED FOR TURBINE SELECTION

The turbine supplier should have the following information in order to select the best combination of size and type runner:

1. Head available, head range, and head duration.
2. Power and speed required to drive pump.

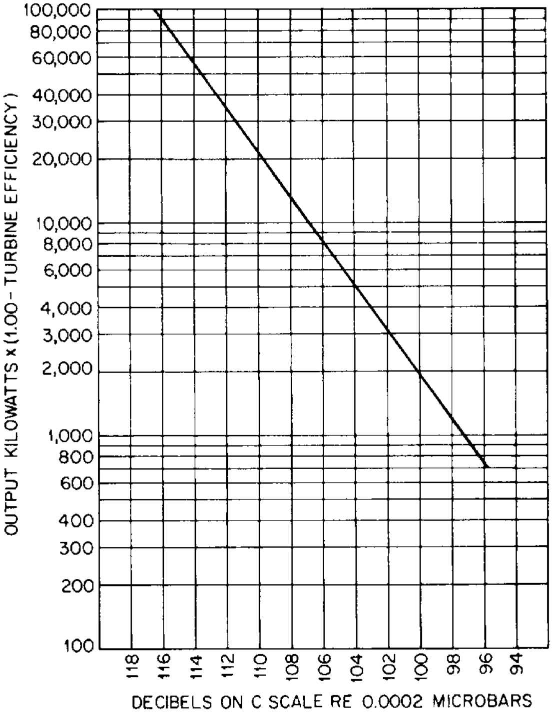

FIGURE 12 Sound level readings taken 3 ft (0.9 m) from main shaft. Hydraulic losses are approximated output in kilowatts × (1.00 − turbine efficiency). (From L. F. Henry: "Selection of Reversible Pump/Turbine Specific Speeds." Paper presented at meeting on pumped-storage development and its environmental effects, University of Wisconsin, September 1971.)

3. Description of fluid to be handled, including chemical composition and specific gravity.
4. Possibility of adding air to system. Turbine will operate satisfactorily without air, but air may be added to system to reduce pressure fluctuations (normally one-third of rpm in frequency) at part load and possibly to smooth unit operation at full load.
5. If corrosive fluid is to be handled, description of the materials required.
6. Controls from pumping process that will affect turbine operation. If speed is a controlling factor, the possibility of using a speed-varying device should be considered.
7. Back pressure on the turbine.
8. Noise-level trends for the turbine. Figure 12 illustrates noise levels recorded on some rather large turbine units. Ear protection is required for noise levels above 85 db.

FURTHER READING

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