CEE:3371 Principles of Hydraulics and Hydrology

Project #1

Pelton Turbine Evaluation

Problem Statement

The *Englewood City Children's Museum* in Colorado has purchased a small Pelton turbine for its new display on renewable energy. The museum will divert water from South Platte River to a nearby elevated storage pond; a pipe system connects the pond to the turbine in the museum display. For educational purposes, the museum wishes to operate the turbine and sell the power on the open market. You have been hired as a consultant to the museum.

Because when the museum sells power to the market it only guarantees the frequency of the electrical power, and not the exact voltage or current; the frequency (60 Hz at the generator) is the constant of the experimental scenario. Although the voltage will remain relatively constant, approximately 110V AC (the same as residential power), the exact value will change somewhat with the load in the consumer grid. This variation is normal and is due to power lost in the wires, transformers, and other distribution equipment, which changes with the amount of electrical load. The 10 light bulbs on the ceiling simulate the electrical load, or the consumers in our scenario with all of their various electrical devices, lighting, heating, and air conditioning, along with commercial and industrial power needs.

Project Objectives

1. First, determine the operating characteristics of a hydropower plant under various loads in the power grid and measure the relevant variables needed to quantify the hydrodynamic input and electrical output.

2. Using the measurements for various loads in the system, determine the hydraulic, electric and total efficiency in the energy conversion.

3. Determine the energy (kWh) that can be generated from the laboratory-scale Pelton turbine, and the revenue it can generate ($/year) for the museum.

4. Recognize that for any input of hydraulic energy, the turbine has to provide constant current frequency (60 Hz), so that the turbine might have to operate in less than optimum conditions. Determine the maximum efficiency of the turbine for specified hydraulic input.

Site Information

The pipe system to be used for the Pelton turbine is shown schematically below:

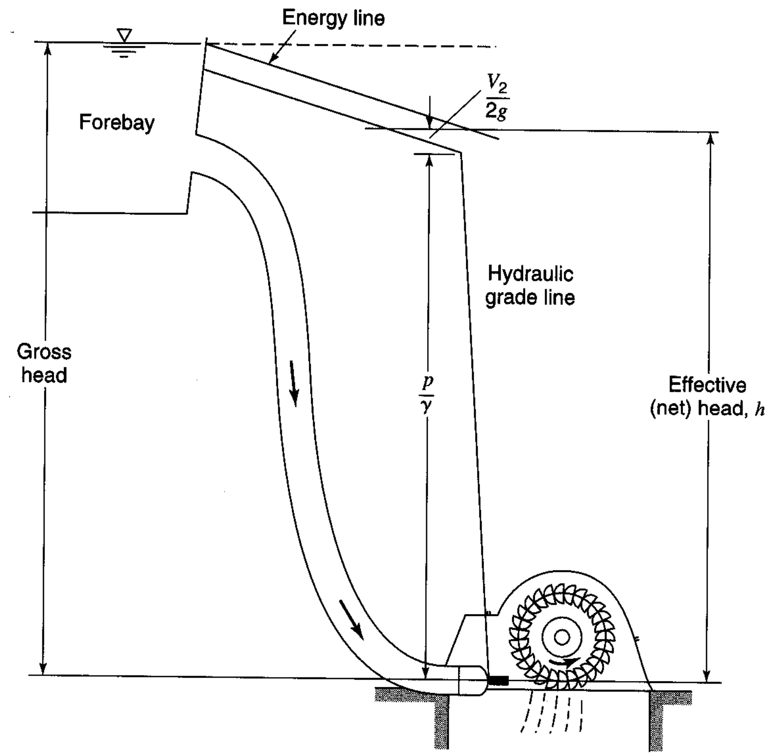


Figure 13.2.4 Definition sketch for impulse-turbine installation (from Linsley et al. (1992)).

Based on a preliminary analysis of the pipe system, the effective head available for the turbine is ~46.5 psi ($H_{available}$). Variations in the forebay water level may occur due to changes in pond storage; however, such variations are assumed to be minor for this evaluation.

Operational Information

The *Englewood City Children's Museum* is open 7 days a week and intends to operate the turbine from 9 am to 4 pm each day.

The museum has secured water rights to divert flows from the South Platte River at Englewood (USGS stream-gage 06711565). The allotted diversion is related to the *average monthly flow rate* in the river. The diversion allowed is:

South Platte Avg. Monthly Flow Conditions	Allotted Diversion (Q)
Less than 200 cfs	0.11 cfs
Greater than 200 cfs	0.35 cfs

Monthly statistics for USGS stream-gages are available from the class web site (icon.uiowa.edu). The unit price of the electricity (cents/kWh) in Colorado can be obtained from Energy Information Administration's webpage (http://www.eia.doe.gov/).

Turbine Equipment

The Pelton turbine has been delivered to the College laboratory facilities for testing. Your project team will run tests to determine the energy conversion efficiency (hydraulic and/or electrical and total) of the Pelton turbine for the proposed operating conditions ($H_{available}$, Q) under different loads (constant rotational speed) or for different rotational speeds.

Details of the experimental methods to be used to test the turbine are attached as Appendix A.

Project Report

Your project team must submit a draft and final project report to the museum's Board of Directors. The report should be concise and focused on answering the project objectives. The minimum required components are:

1. Calculate the hydraulic, electric and total efficiency for the four loads in the system under recommended operating conditions.

2. Determination of the optimum turbine operating condition (e.g., rotational speed) for the two flow diversion rates (based on the hydraulic efficiency curve only).

3. The energy generation (kWh/yr) for the recommended operating condition

4. The revenue generated through sales of the energy ($/yr) for the recommended condition.

The report should also contain sufficient technical information necessary to support your recommendations and conclusion; however, this information needs to be written at a level appropriate to the audience (i.e., the Board of Directors).

Consultation with College of Engineering Hanson Center for Technical Communication (CTC) is mandatory for this project. You should attach a copy of the Contact Report you obtain from CTC (which indicates the date you were seen and the help you received) to your project report

5. References

AIAA (1995). AIAA- 071 *Standard*, American Institute of Aeronautics and Astronautics, Washington, DC.

Granger, R.A. (1988). *Experiments in Fluid Mechanics*, Holt, Rinehart and Winston, Inc. New York, N.Y.

Marchman III, J.F. and Werme, T.D. (1984). Clark-Y Performance at Low Reynolds Numbers, *Proceedings* AIAA 22nd Aerospace Science Meeting, Reno, NE.

Robertson, J.A. and Crowe, C.T. (1993). *Engineering Fluid Mechanics,* 5th edition, Houghton Mifflin, Boston, MA.

Stern, F., Muste, M., Beninati, L-M., Eichinger, B. (1999). Summary of Experimental Uncertainty Assessment Methodology with Example, IIHR Report, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA.

White, F.M. (1994). *Fluid Mechanics,* 3rd edition, McGraw-Hill, Inc., New York, N.Y.

APPENDIX A

HYDROPOWER GENERATION SYSTEM

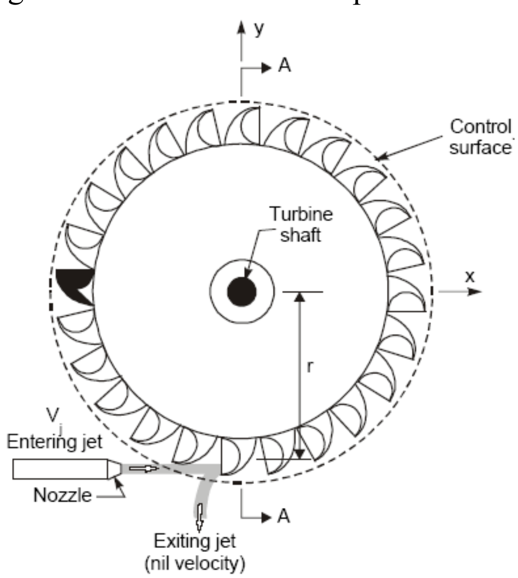
Principle

Turbines convert fluid energy into rotational mechanical energy, which is subsequently converted in electric energy. The Pelton turbine system is an example of a complete hydroelectric power system, from generator to consumer usage. The system is instrumented to allow documentation of the efficiency of the energy conversion in the hydropower plant.

Introduction

There are two types of turbines, reaction and the impulse, the difference being the manner of head conversion. In the reaction turbine, the fluid fills the blade passages, and the head change or pressure drop occurs within the runner. An impulse turbine first converts the water head through a nozzle into a high-velocity jet, which then strikes the buckets at one position as they pass by. The runner passages are not fully filled, and the jet flow past the buckets is essentially at constant pressure. Impulse turbines are ideally suited for high head and relatively low power. The Pelton turbine bought by the museum is an impulse turbine. The Pelton turbine consists of three basic components as shown in Figure 1: a stationary inlet nozzle, a runner, and a casing. The runner consists of multiple buckets mounted on a rotating wheel. The jet strikes the buckets and imparts momentum. The buckets are shaped in a manner to divide the flow in half and turn its relative velocity vector nearly 180°.

Figure 1. Schematic of an impulse turbine and photograph of the model Pelton turbine.



The primary feature of the impulse turbine is the power production as the jet is deflected by the moving buckets. Assuming that the speed of the exiting jet is zero (all of the kinetic energy of the jet is expended in driving the buckets), negligible head loss at the nozzle and at the impact with the buckets (assuming that the entire available head is converted into jet velocity), the energy equation applied to the control volume shown in Figure 1 provides the power extracted from the available head by the turbine

$$P_{available} = Q\ H_{available} \quad (1)$$

where Q is the discharge of the incoming jet, and $H_{available}$ is the available pressure head on the nozzle. By applying the principle of conservation of angular momentum (assuming negligible angular momentum for the exiting jet) to the same control volume about the axis of the turbine shaft the absolute value of the hydraulic power developed by the turbine can be written as

$$P_{hydraulic} = \omega T = 2\pi NT \quad (2)$$

where ω is the angular velocity of the runner, T is the torque acting on the turbine shaft, and N is the rotational speed of the runner. The hydraulic efficiency of the turbine is defined as the ratio between the mechanical power developed by the turbine to the available water power

$$\eta_{hydraulic} = P_{hydraulic} / P_{available} \quad (3)$$

In general, the efficiency of the turbine is provided with isoefficiency curves. They show the interrelationship among Q, ω and h. A typical isoefficiency plot is provided in Figure 2.

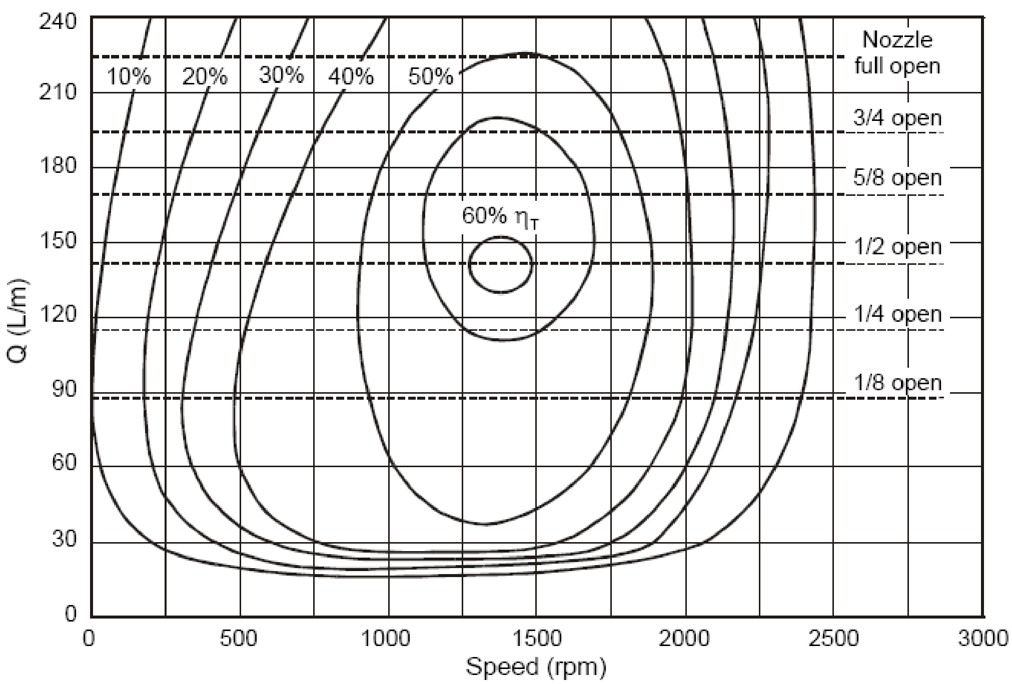


Figure 2. Isoefficiency curve for a laboratory-scale Pelton turbine.

Under ideal conditions, the maximum hydraulic power generated is about 85%, but experimental data shows that Pelton turbines are somewhat less efficient (approximately 80%) due to windage, mechanical friction, backsplashing, and nonuniform bucket flow.

The electrical power output of the turbine can be written as

$$P_{electrical} = V * I \qquad (4)$$

where V is the voltage and the I is the current. The electrical efficiency of the turbine is defined as the ratio between the electrical power developed by the turbine to the mechanical power

$$\eta_{electrical} = P_{electrical} / P_{hydraulic} \qquad (5)$$

Finally, the overall efficiency of the turbine is

$$\eta_{total} = \eta_{electrical} * \eta_{hydraulic} \qquad (6)$$

The purpose of the engineering evaluation is to determine the overall efficiency of a laboratory-scale Pelton turbine.

Experimental Design

The experimental setup accurately replicates all of the power production steps: conversion of hydraulic energy into mechanical energy, and subsequently into electric energy. To accomplish these energy transformation steps, the prototype hydropower plant comprises a turbine (which converts hydraulic energy to mechanical energy through the use of the rotation of the turbine shaft) that is coupled on the same shaft to an electric generator (which converts the mechanical energy to electric energy). The current created by the electric generator is then distributed to the public distribution network. The electric generator has to run continuously at the 60Hz standard frequency regardless of the number of users drawing from the system. An increase in the energy demand in the network requires more mechanical energy to be delivered to the electric generator (which causes the rotational speed of the generator to slow), which in turn requires an increase in hydraulic energy supplied by the turbine to maintain a constant speed. The increase in hydraulic energy can be obtained either by increasing the head on the turbine or the discharge passing through it.

The hydropower plant model has been set up in the Fluids Laboratory (Room 1246) in the Seaman Center. A schematic diagram and a photo of the experimental setup are shown in Figures 3 and 4, respectively. Similar to a prototype generation and distribution system, the setup contains a Pelton turbine, an electric generator, and simulated consumers. In real cases, the turbine and electric generator are placed on the same shaft, which is not the case in our system (because of lack of appropriate space and to dampen oscillations in the system). A transmission belt connects the turbine shaft with the electric generator instead. Consumers in the distributed network are simulated in the experiment by bulbs. The setup is instrumented to provide the generator rotational speed (in Hz), the voltage, and the current provided to the bulbs. Note that, similar to the prototype, the electric generator will be maintained at a rotational speed of 60 Hz, which provides 110 V as output (even when all the bulbs are off).

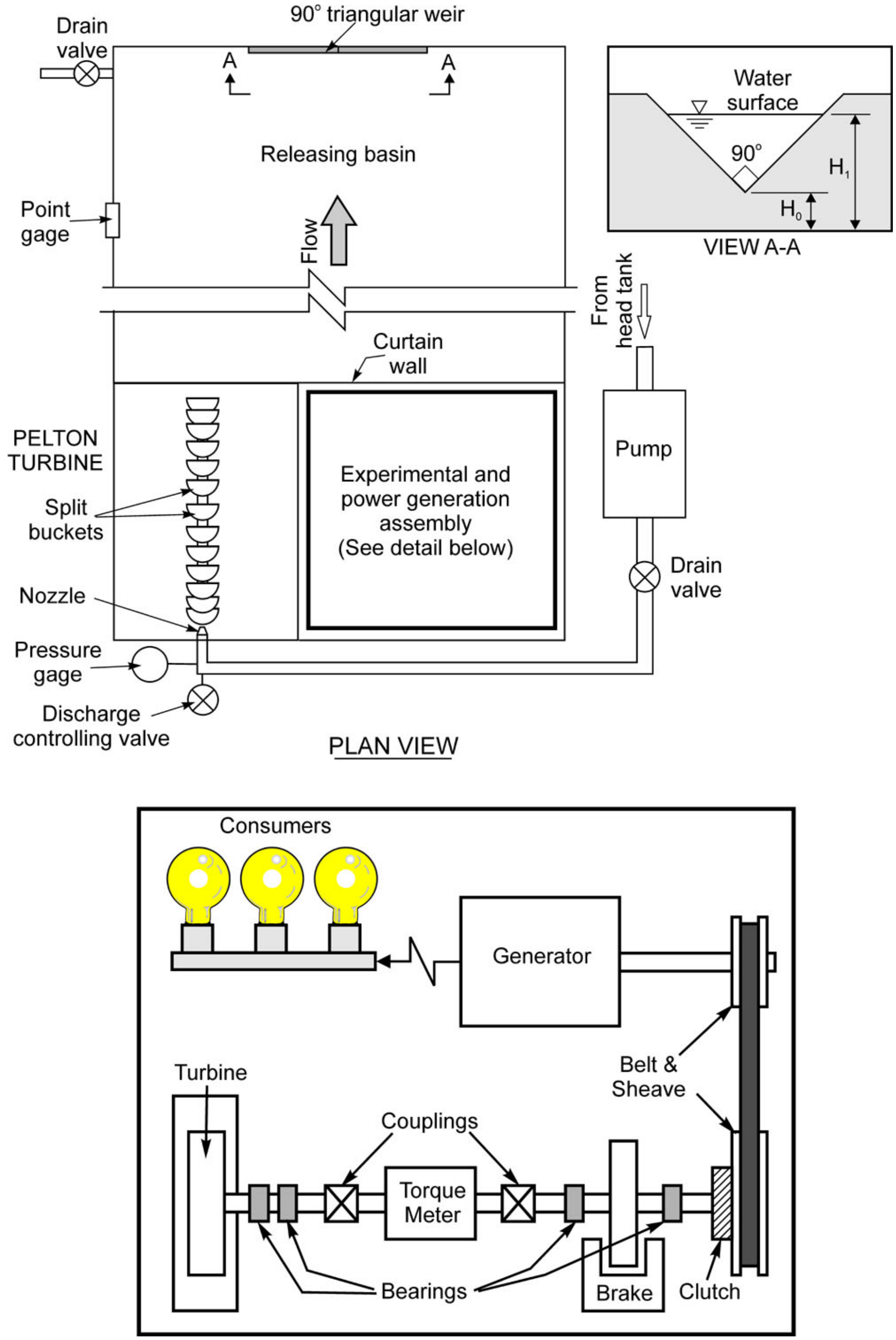
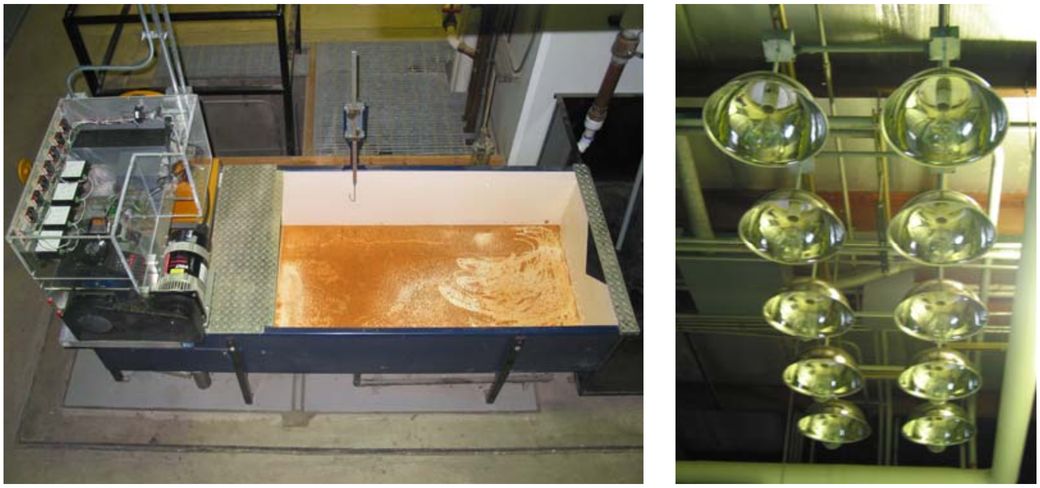


Figure 3. Schematic of the experimental setup.

a) b)



c)

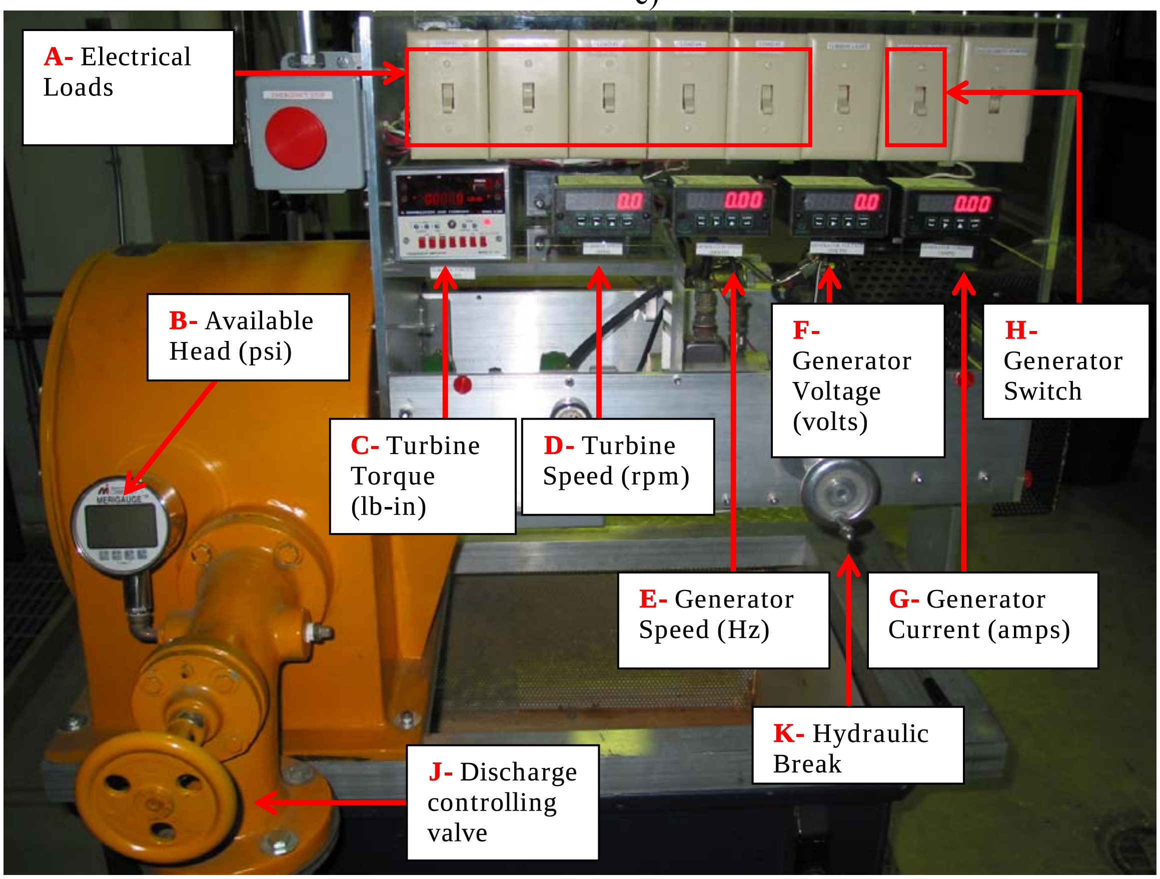


Figure 4. Photograph of the experimental setup; a) general view of the experiment; b) set of bulbs simulating consumer in the power grid; c) details of the experiment control panel

In addition to the components commonly found in hydropower plants, the experimental apparatus contains a mechanical brake consisting of a circular plate positioned on the turbine shaft with friction pads that can be applied to the plate. A hand wheel is used to control the hydraulic system pressure that applies friction to the disk to slow it (similar to an automobile break). The role of the mechanical torque is to simulate the electrical load applied by consumers on the distribution network. Specifically, the greater the consumer demand the greater the required torque on the system. A torque meter with a digital display is placed on the turbine shaft to measure the torque applied on the shaft. A digital display provides the shaft rotational speed (rotation per min). The two measurements are needed to compute the mechanical energy extracted from the shaft for various levels of friction applied by the friction plate.

The 10 light bulbs on the ceiling simulate the electrical load from the consumers in our scenario with all of their various electrical devices, lighting, heating, and air conditioning, along with commercial and industrial power needs. Two measurements are needed to compute the electrical energy extracted from the generator for various loads in the power grid. They are voltage and current of the generator.

The hydraulic head on the turbine is provided by a pump located in a nearby sump. A pressure gage is attached to the water pipe entering the turbine to read the available water head. The discharge to the setup is supplied by the pump and regulated by a discharge controlling valve. The water exiting the nozzle is collected in a releasing basin equipped with a triangular weir at the downstream end to allow measurement of the flow discharge. The turbine and the torque assembly are fully instrumented to determine the efficiency of the turbine for various loads applied on the shaft.

Procedures

Measurements will be taken to determine hydraulic, electric and total efficiency of the turbine under different loads and the correlation between efficiency and rotational speed for two discharges.

Each group of students will proceed with the sequence described below.

<u>Part-1: Estimation of the hydraulic, electrical and total efficiency of the turbine/electrical generator system:</u>

1. Close the drain valve positioned on the releasing basin (Figure 3).
2. Ensure that the brake (K in Figure 4) is not applied so there is no friction applied on the turbine shaft.
3. Open the discharge controlling valve (J in Figure 4) completely on the inlet pipe and record the pressure (psi) on the pressure gage (B in Figure 4).
4. Turn on the generator switch (H in Figure 4) and bring generator to 60Hz (E in Figure 4) using the input flow valve (J in Figure 4).
5. Apply the first electrical load to generator (A in Figure 4). As power line frequency drops, in order to maintain 60 Hz (E in Figure 4) open input valve (J in Figure 4) slowly.
6. Measure the rotational speed (rpm) of the shaft (D in Figure 4), residual torque (lb-in) (C in Figure 4), voltage (volts) (F in Figure 4) and the current (amps) (G in Figure 4).
7. Measure the head on the weir (H_1 in Figure 3) using the point gage.
8. Repeat steps 5-7 as second, third and fourth loads are added to the system.

Part-2: Estimation of the turbine hydraulic efficiency curve for two discharges (see Figure 2):

9. Ensure that the brake (K in Figure 4) is not applied so there is no friction applied to the turbine shaft. Turn off all of the load lights, but leave the generator engaged.
10. Open the discharge controlling valve (J in Figure 4) completely on the inlet pipe and record the pressure (psi) ($H_{available}$) on the pressure gage (B in Figure 4).
11. Measure the rotational speed (rpm) of the shaft (D in Figure 4), residual torque (lb-in) (C in Figure 4).
12. Slowly tighten the friction hand-wheel (K in Figure 4) and record the torque (C in Figure 4) as well as the rotational speed of the shaft (D in Figure 4) for 8-10 different speeds. The lowest rotational speed must be at least 500 rpm to keep the break from getting too hot. After three measurements, back off the break (K in Figure 4) and give it time to cool before proceeding.
13. Back off the brake completely (K in Figure 4) and measure the head on the weir (H_1, ft in Figure 3) using the point gage.
14. Decrease the discharge by partially closing the pipe inlet valve (J in Figure 4) until the meter reads the specified turbine speed (D in Figure 4). Repeat steps 11 through 13 with another discharge.
15. Open the drain valve (Figure 3) and allow the basin to drain until only a trickle of water flows over the weir. Measure the water depth indicated by the point gage (H_0 in Figure 3).

Measurements

Record the measured quantities in Table 1 and Table 2.

Table 1. Data acquisition and processing forms for Part-1.

	Data Acquisition					Data Reduction			
Operation	H_0 [ft]	H_1 [ft]	$H_{avail.}$ [psi]	T [lb-in]	N turbine [rpm]	Q [cfs]	$P_{available}$ [lbf*ft/sec]	P_{hydr} [lbf*ft/sec]	Hyd. Effic. [%]
5 Bulbs	0.988								
4 Bulbs	0.988								
3 Bulbs	0.988								
2 Bulbs	0.988								
1 Bulb	0.988								

Data Acquisition			Data Reduction		
Operation	Voltage [volts]	Current [amps]	P_{elec} [lbf*ft/sec]	Elec. Efficiency [%]	Overall Efficiency [%]
5 Bulbs					
4 Bulbs					
3 Bulbs					
2 Bulbs					
1 Bulb					

Data Analysis - Part-1

1. Determine the discharge through the system using the weir calibration equation
   $Q = 2.49(H_1 - H_0)^{2.48}$ (cfs)
2. Determine P_{avail}, P_{hydr}, P_{elec} (lbf-ft/sec) for four different loads in the system using the data reduction equations (1), (2) and (4).
3. Determine η_{hydr}, η_{elec}, η_{total} (efficiencies) using the data reduction equations (3), (5) and (6).

Table 2. Data acquisition and processing forms for Part-2

	Data Acquisition					Data Reduction			
	H0 [ft]	H1 [ft]	Havail. [psi]	T [lb-in]	N turbine [rpm]	Q [cfs]	Pavailable [lb*ft/sec]	Phydr [lb*ft/sec]	Hyd. Effic [%]
Run 1	0.988								
Run 2	0.988								

Data Analysis - Part-2

1. Determine the discharge through the system using the weir calibration equation
   $Q = 2.49(H_1 - H_0)^{2.48}$ (cfs)
2. Determine the hydraulic efficiency of the turbine using the data reduction equation (3).
3. Plot the rotational speed, N vs. the hydraulic efficiency, η_{hydr} of the turbine for each of the applied torque. Show the results for both runs (two discharges).

References

Robertson, J.A. and Crowe, C.T. (1993). *Engineering Fluid Mechanics,* 5th edition, Houghton Mifflin, Boston, MA.

White, F.M. (1994). *Fluid Mechanics,* 3rd edition, McGraw-Hill, Inc., New York, NY.