

EFFICIENCY MEASUREMENT OF HYDRO MACHINE BY THERMODYNAMIC METHOD

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ABSTRACT

The thermodynamic method is an absolute method of measuring hydraulic efficiency of hydraulic machines based on the principle of conservation of energy, i.e. first law of thermodynamics. The efficiency is calculated directly from the specific hydraulic energy and specific mechanical energy equations. The temperature difference between the inlet and outlet of the machine is very small, typically of the order of a few milli-Kelvins. Hence it is a very difficult and critical task to measure the temperature rise accurately. High-resolution high-accuracy data acquisition system alongwith precision type temperature sensors are essential for temperature measurements.

Efficiency measurement using thermodynamic method has been carried out by the authors in laboratory, both on a turbine and a pump, using stable temperature sensors, electronic pressure transmitters and high-precision high-resolution data acquisition system. Thermo-wells are formed at inlet and outlet of the machine under test for simultaneous temperature measurement at both the points. High-precision RTDs of Pt-100 type (class 1/10 DIN, 0.03 °C accuracy) are used for the measurement of temperatures.

The results of efficiency measurement of turbine and pump in laboratory using thermodynamic method have been found to be very satisfactory. The same instrumentation with suitable adaptation can be used for the efficiency measurement on site.

KEYWORDS: Hydraulic machine, Hydraulic efficiency, Thermodynamic method

1. INTRODUCTION

It is invariably in the best interest of a hydroelectric power plant to have efficiency of its hydraulic turbines measured at the start of operation and subsequently at regular intervals. Usually the performance of large turbines is determined first in model tests. However prototype turbine installations always have some differences from their model, which alter their performance. Hence prototype testing at the site is always considered desirable. In general efficiency testing of prototype is used (a) to check that contract guarantees have been met, (b) to adjust blade-gate mechanism of Kaplan turbine for optimum efficiency, (c) to check the proper adjustment and operation of governor (d) to obtain information that can be used to evaluate machine wear and cavitation degradation, and (e) to obtain accurate information of water use [Sheldon (1982)].

On the other hand, determination of efficiency of a generating unit, comprising turbine and electric generator on a common machine shaft or coupled through a speed-changing gear box, requires measurement of hydraulic power input to the turbine and electric power output from the generator, and calculation of the ratio of the two powers. The hydraulic input power is calculated from the discharge and head measurements on the turbine and its hydraulic circuit as per IEC 60041. The electric power output is measured using preferably an integrating-type high-accuracy digital wattmeter connected to the generator terminals through high-accuracy-class current and voltage transformers [Verma and Kumar, (2007)].

Thermodynamic method is the primary or absolute method of hydraulic efficiency measurement. Measurements of specific energies are carried out for the efficiency evaluation. Basic working principle of the thermodynamic method is the principle of conservation of energy, i.e. first law of thermodynamics. In this method, law of conservation of energy is applied to a transfer of energy between water and the runner through which it is flowing. Hydraulic losses cause an increase in the temperature of the water passing through the turbine. This temperature increase is a measure of hydraulic losses, which can be calculated using specific heat of water. The same principle applies to the measurements on hydraulic pump. Very small temperatures differences have to be measured in either case.

2. EFFICIENCY DEFINITIONS AND CALCULATIONS

2.1 Efficiencies of Turbine and Turbine-Generator Unit

The hydraulic efficiency of turbine is defined as the ratio of mechanical output power of runner and hydraulic input power, and is given in "Eq (1)" [IEC-60041]:

$$\eta_h = \frac{P_m}{P_h} = \frac{E_m}{E + E_m \left(\frac{\Delta P_h}{P_m} \right)} \quad (1)$$

The unit efficiency, or the efficiency of hydro electric generating unit, is defined as the ratio of the electrical power output, and is given by "Eq (2)" [IEC-60041]:

$$\eta = \frac{\text{Electrical power output}}{\text{Hydraulic power input to turbine}} = \frac{P_e}{P_h} \quad (2)$$

Where,

- η = Overall efficiency of turbine-generator unit
- η_h = Hydraulic efficiency
- P_m = Mechanical power of runner in W
- P_h = Hydraulic power available in W
- P_e = Electrical power output of generator in W
- E_m = Specific mechanical energy in J/kg.
- E = Specific hydraulic energy of machine J/kg
- ΔP_h = Hydraulic power loss due to leakage in W

Hydraulic power input to the turbine is given by

$$P_h = \rho g H Q \quad (3)$$

Where,

- ρ = actual density of water (at actual temperature and pressure) in kg/m³
- g = actual acceleration due to gravity (function of latitude and altitude above mean sea level) in m/s²
- Q = discharge rate of water through the turbine in m³/s
- H = net head of water in m

2.2 Efficiencies of Pump and Pump-Motor Unit

The hydraulic efficiency of pump is defined as the ratio of hydraulic power output of pump and mechanical power input to the impeller, and is given by

$$\eta_h = \frac{P_h}{P_m} = \frac{E + E_m \left(\frac{\Delta P_h}{P_m} \right)}{E_m} \quad (4)$$

The overall efficiency of pump-motor unit is defined as the ratio of the actually produced hydraulic power and the electrical input power, and is given by

$$\eta = \frac{\text{Hydraulic power output}}{\text{Electrical power input to motor}} \quad (5)$$

$$\eta = \frac{P_h}{P_e}$$

Where,

η = Overall efficiency of pump-motor unit
 η_h = Hydraulic efficiency of pump
 P_m = Mechanical power input to the impeller in W
 P_h = Hydraulic power output of pump in W
 P_e = Electrical power input to motor in W
 E_m = Specific mechanical energy in J/kg
 E = Specific hydraulic energy of machine J/kg
 ΔP_h = Hydraulic power loss due to leakage in W

2.3 Specific Hydraulic Energy (E)

Specific hydraulic energy is the hydraulic energy per unit mass. Specific energy of water available between the high and low pressure reference sections of a machine taking into account the effect of compressibility is given by

$$E = \frac{P_1 - P_2}{\rho} + \frac{(V_1^2 - V_2^2)}{2} + g(Z_1 - Z_2) \quad (6)$$

Where,

ρ = average value of density of water (P, T) in kg/m^3
 P_1, P_2 = absolute pressure in Pa
 V_1, V_2 = velocity in m/s
 g = average value of acceleration due to gravity is m/s^2
 Z_1, Z_2 = geodetic head in m
 Indices 1 & 2 are for high-pressure and low-pressure measuring sections, respectively.

2.4 Specific Mechanical Energy (E_m)

It is the mechanical energy per unit mass. It can be also defined as mechanical power transmitted through the coupling of runner and shaft per unit mass flow rate. If no auxiliary discharge is added or subtracted between the reference section, E_m is calculated by

$$E_m = a(P_1 - P_2) + C_p(\theta_1 - \theta_2) + \frac{(V_1^2 - V_2^2)}{2} + g(Z_1 - Z_2) \quad (7)$$

Where,

a = isothermal factor of water f (P, θ) in kg/m^3
 C_p = specific heat of water f (P, θ) in J/kg/K
 P_1, P_2 = absolute pressure in Pa
 θ_1, θ_2 = temperature in K
 V_1, V_2 = velocity in m/s
 g = average value of acceleration due to gravity in m/s^2
 Z_1, Z_2 = geodetic head in m
 Indices 1 & 2 are for high-pressure and low-pressure measuring sections, respectively.

3. EXPERIMENTATION ON TURBINE

Main objective of this experiment was to find out the hydraulic efficiency of pump as turbine using the thermodynamic method and the overall efficiency of hydro-electric generating unit by the head-discharge method. The experiment was carried out in Hydro Mechanical Laboratory of Alternate Hydro Energy Centre at Indian Institute of Technology Roorkee. The experimental setup is described below:

3.1 Description of Experimental Set Up

The experimental setup consists of two pumps which are connected in closed loop with the help of MS piping and tank as shown in Fig.1.

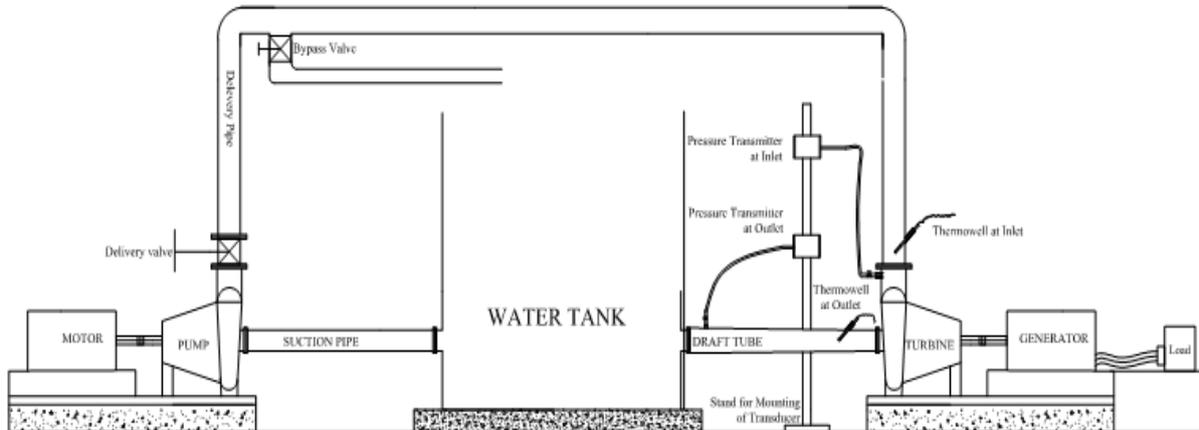


Fig.1. Experimental set up for Turbine Testing

Input pump was used to create head and discharge and another pump works in turbine mode (know as pump as turbine). Suction pipe of input pump draws water from MS tank. Delivery pipe of pump is taken to the turbine side through closed piping and connected to the turbine inlet. The water flow to the turbine can be adjusted by means of a manually controlled throttle valve, fixed at the delivery of the input pump. A bypass valve is provided at the delivery side of the input pump to bypass the flow to the tank, if required. Turbine outlet is released in storage tank through a conical draft tube. Tank is open to atmosphere and suction pipe of input pump is connected to the tank at the bottom. Turbine is coupled to a generator through rigid coupling. The generator terminals are in turn connected to load (incandescent lamps) through a load control circuit.

3.2 Measurement and Measuring Instruments

Measurements of the various parameters required for the efficiency evaluation of the turbine were done in following manner using different instruments.

3.2.1 Temperature Measurement

Simultaneous measurement of temperature at inlet and outlet of the hydro turbine was critical task in this experiment, as efficiency of the machine is proportional to the temperature rise of the water when it passes from the inlet to the outlet of machine. Temperature rise due the friction losses in the machine is very small, of the order of a few milli-Kelvins. Hence very precise and accurate instrumentation is required for the measurement of temperatures. Resistance temperature detectors (RTDs) of Pt-100 type and high-precision multi-channel data acquisition system with 0.0001 °C resolution were used for the measurement. Thermowells were formed at the inlet and outlet of the turbine at an angle of 45° with vertical as shown in Fig 1.



Fig.2. Thermowells and thermometers at the inlet and outlet of the turbine

3.2.2 Pressure Measurement

For the pressure measurement in pipe, 1/2 inch pressure taps were made at an angle of 45° with horizontal and vertical planes. As pipe diameter is small, only a single tap is provided at the inlet as well as at outlet of turbine. Simultaneous pressure measurement at inlet and outlet sections was carried out by using electronic pressure transmitters of 0-800 kPa and 0-200 kPa ranges. They are high-precision high-resolution gauge pressure transmitters having 0.075% basic accuracy.

3.2.3 Discharge Measurement

Pipe size being small (75 mm internal diameter), ultrasonic transient time flow meter (UTTf) with clamp on transducers (R.R. Make) was used for the discharge measurement. A pair of ultrasonic transducer was mounted in reflection mode on the pipe. Readings of the UTTf averaged over 60 second periods by the instrument was taken every minute during the efficiency test at each load.

3.2.4 Electrical Power Measurement

Electrical power output measurement is required for the evaluation of the overall efficiency of the turbine-generator unit. The electrical power output of generator was measured by connecting a precision-class 3- phase digital wattmeter (Hioki 3165) at the output terminals of the generator. It was used in integrating mode so that average value is available accurately at the end of a test run.

3.3 Experimental Procedure

To determine hydraulic efficiency of turbine using thermodynamic method, the parameters required to be measured are temperatures, pressures and flow. Simultaneous measurements of the all parameters were carried out at high pressure (inlet) and low pressure (outlet) section of the turbine as follows:

Before starting the experiment it was ensured that main control valve is in closed position, RTD were placed in thermowells and all the instruments are appropriately connected. The inlet pump was then started and the main control valve opened slowly. Generator loading was done after opening main control valve for full position. Frequency of the generator was checked and a 10-min run was given to stabilize the system. After stabilization, temperature data logging was started. For initial 2 minutes, Pt-100 (Sr. No.1021) was kept at the inlet thermowell and Pt-100 (Sr. No. 1017) at outlet of turbine. Subsequently, 2 minute reading was taken for interchanged positions of RTDs. Averaged values of the temperature difference for both the positions of RTDs were calculated. Mean of the two averaged values was taken in order to eliminate the calibration error of RTDs. During this period, measurement of all other parameters (pressure, discharge and power output) was also carried out simultaneously. The procedure was then repeated for different openings of the main control valve, that is for different values of loads on the unit

3.4 Average Temperature Calculation for Turbine

Average temperature difference is calculated using the averaged values of the temperatures at inlet and outlet of turbine for initial and interchanged positions of the RTDs.

$$\begin{aligned}
 &\text{Average temperature at inlet for initial position of RTDs} &&= T_{11} \\
 &\text{Average temperature at outlet for initial position of RTDs} &&= T_{21} \\
 &\text{Average temperature difference for initial position of RTDs} \quad (T_{d1}) &&= (T_{11} - T_{21}) \\
 &\text{Average temperature at inlet after interchanging RTDs} &&= T_{12} \\
 &\text{Average temperature at outlet after interchanging RTDs} &&= T_{22} \\
 &\text{Average temperature difference after interchanging RTD} \quad (T_{d2}) &&= (T_{12} - T_{22}) \\
 &\text{Average temperature difference for efficiency calculation} \quad (T_d) &&= (T_{d1} + T_{d2}) / 2
 \end{aligned}$$

A summary of observations for different valve openings is presented in table 1.

Table1: Summary of observations for different opening and different reading of Turbine

Parameter	Unit	First Valve Position (Fully Open)	Second Valve Position	Third Valve Position	Fourth Valve Position (No Load)
Average Temperature at Inlet for Initial position of RTDs (T_{1i})	°C	34.819066	36.12936	39.42196	36.44228
Average Temperature at Outlet for Initial position of RTDs (T_{2i})	°C	34.853175	36.14999	39.46274	36.49302
Average Temperature Difference for Initial position of RTDs (T_{di})	°C	- 0.03411	- 0.02064	- 0.04078	- 0.05074
Average Temperature at Inlet after Interchanging RTDs (T_{12})	°C	35.276207	36.52970	40.07831	36.89479
Average Temperature at Outlet after Interchanging RTDs (T_{22})	°C	35.297137	36.56699	40.09371	36.92495
Average Temperature Difference after Interchanging RTD (T_{d2})	°C	- 0.0209305	- 0.03729	- 0.01540	- 0.03016
Average Temperature Difference (Initial & interchanged positions) (T_d)	°C	- 0.0275228	- 0.0289616	- 0.02809	- 0.040452
Pressure at Inlet (P_1)	kg/cm ²	3.47	3.28	3.18	3.1
Pressure at Outlet (P_2)	kg/cm ²	0.02	0.02	0.02	0.01
Pressure Difference (P_1-P_2)	kg/cm ²	3.45	3.26	3.16	3.09
Average Discharge (Q)	lps	23.57	20.8	20.43	20
Electrical Power Output (P_e)	kW	1.580	0.445	0.204	No Load

4. EXPERIMENTATION ON PUMP

The main objective of this experiment was to find out the hydraulic efficiency of pump using the thermodynamic method and the overall efficiency of pump-motor unit by head-discharge method. Similar procedure was followed for the experimentation as explained in section 3.3. Readings of different parameters, viz. temperatures, pressure, power input and discharge were taken at different valve openings. A summary of observations for different positions of the valve is presented in table 2.

Table 2 summary of observations for pump

Parameter	Unit	First Valve Position (Fully Open)	Second Valve Position	Third Valve Position	Fourth Valve Position
Average Temperature at Inlet for Initial position of RTDs (T_{21})	°C	33.06034	34.84361	37.661853	38.730219
Average Temperature at Outlet for Initial position of RTDs (T_{11})	°C	33.17022	34.93641	37.77516	38.87345
Average Temperature Difference for Initial position of RTDs (T_{d1})	°C	0.10988	0.09280	0.11331	0.14323
Average Temperature at Inlet after Interchanging RTDs (T_{22})	°C	33.50716	35.18486	38.04304	39.20754
Average Temperature at Outlet after Interchanging RTDs (T_{12})	°C	33.59267	35.28620	38.16170	39.32551

Parameter	Unit	First Valve Position (Fully Open)	Second Valve Position	Third Valve Position	Fourth Valve Position
Average Temperature Difference after Interchanging RTD (T_{d2})	$^{\circ}\text{C}$	0.08550	0.10135	0.11866	0.11797
Average Temperature Difference (Initial & interchanged positions) (T_d)	$^{\circ}\text{C}$	0.0976901	0.0970749	0.1159839	0.1305989
Pressure at Outlet (P_1)	kg/cm^2	5.23	5.33	5.5	5.6
Pressure at Inlet (P_2)	kg/cm^2	-0.21	-0.18	-0.15	-0.12
Pressure Difference ($P_1 - P_2$)	kg/cm^2	5.44	5.51	5.65	5.72
Average Discharge (Q)	lps	27.3	26.18	23.5	21.9
Electrical Power input (P_e)	kW	27.120	26.010	25.210	24.050

5. RESULTS OF EXPERIMENTATION

5.1 Results for Turbine & T-G Unit

Calculations for the hydraulic efficiency of the turbine and overall efficiency of the turbine-generator unit are summarily given in table 3. Efficiency versus discharge and efficiency versus load curves are plotted in figures 3 and 4, respectively.

Table 3: Efficiency calculations for turbine and T-G unit

Valve Position	Temp. Difference (mK)	Discharge (lps)	Head (m)	Electrical Power Output (kW)	Hydraulic Efficiency of Turbine (Thermodynamic method)	Overall Efficiency of T-G Unit (Discharge-head method)
1 (Fully open)	27.5228	23.57	35.71	1.58	56.8 %	19.77 %
2	28.9616	20.8	33.72	0.445	53.92 %	6.5 %
3	28.090	20.43	32.71	0.204	51.84 %	3.0 %
4	40.452	20.0	31.99	0.0	35.33 %	0.0 %

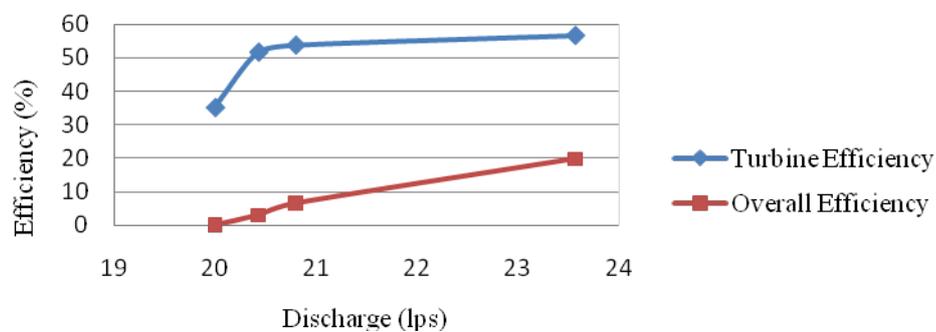


Fig. 3 Efficiency versus discharge curves for turbine

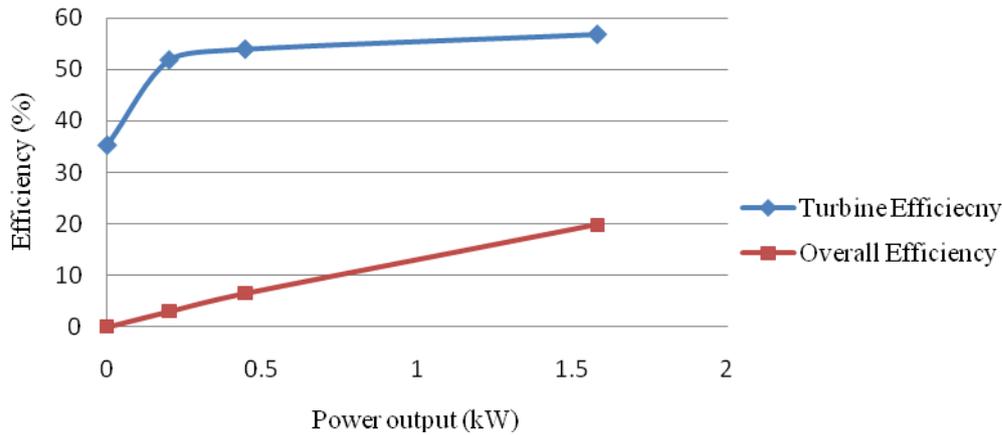


Fig. 4 Efficiency versus power output of generator

The maximum turbine efficiency and overall efficiency are seen at the full opening of the valve. There is very large difference in the turbine efficiency and overall efficiency of hydro-electric generating unit. This is due to a very low efficiency of the generator. The generator rating is 10 kW and it was operated in range of 15 % to 0 % of the rated load. The maximum turbine efficiency is found to be 56.8 % and maximum overall efficiency as 19.77 %.

Uncertainty analysis was carried out for turbine efficiency measurement by thermodynamic method and overall efficiency of hydroelectric generating unit by head-discharge method. The values of uncertainties assessed are 2.1 % and 1.5 %, respectively.

5.2 Results for Pump and P-M Unit

The results are shown in table 4 and figures 5 and 6. The maximum pump efficiency and overall efficiency were found at the second opening of the valve. The difference between the pump efficiency and overall efficiency of pump-motor unit is reasonable. The uncertainty of measurement of pump efficiency and overall efficiency has been assessed as 1.1 % and 1.5 %, respectively.

Uncertainty analysis was carried out for turbine efficiency measurement by thermodynamic method and overall efficiency of hydroelectric generating unit by head-discharge method. The values of uncertainties assessed are 2.1 % and 1.5 % respectively.

Table 4: Efficiency calculations for pump and P-M unit

Valve Position	Temp. Difference (mK)	Discharge (lps)	Head (m)	Electrical Power Input (kW)	Hydraulic Efficiency of Pump (Thermodynamic method)	Overall Efficiency of P-M Unit (Discharge head method)
1 (Fully open)	97.6901	27.3	55.58	27.12	60.6 %	54.5 %
2	97.0749	26.18	56.32	26.01	61.38 %	55.19 %
3	115.9839	23.5	57.767	24.88	57.32 %	53.08 %
4	130.5989	21.9	58.51	24.05	54.46 %	51.8 %

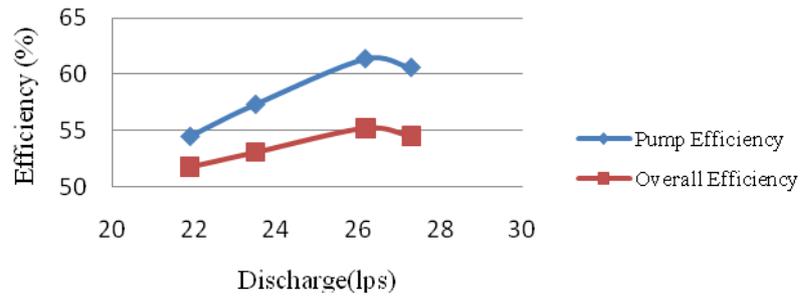


Fig. 5 Efficiency versus discharge curves for pump

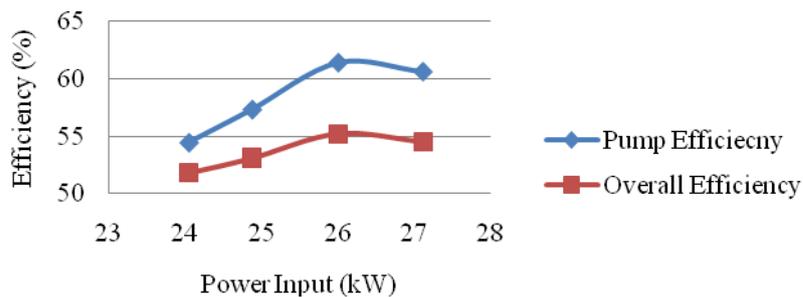


Fig. 6 Efficiency versus power input curves for pump

6. CONCLUSION

The results of hydraulic efficiency measurement carried out on turbine and pump in laboratory using thermodynamic method are satisfactory. Temperature measurement at inlet and outlet was the most critical task in whole experimentation. It is observed that temperature rise of water is head dependent. During the testing of the turbine, the operating head was low hence temperature difference was small. During the experimentation on the pump, the operating head was much larger and so was the temperature rise.

Experimental setup was in closed loop and due to that there was continuous rise in water temperature. No cooling arrangement was feasible, and therefore the duration of the observations had to be restricted.

Uncertainty analysis was carried out for measurements on both turbine and pump. It is noted that for thermodynamic method uncertainty in efficiency measurement of the turbine is more than uncertainty in efficiency measurement of the pump. This is explained by the fact that the temperature rise in case of turbine with lower head is much lower than in case of pump with higher head, although their hydraulic efficiencies are of the same order. This conclusion is in agreement with the rule of thumb that higher the head, more suitable is the thermodynamic method for measuring hydraulic efficiency.

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