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Performance Evaluation of Francis Turbine using thermodynamics analysis: A Case Study of Kali Gandaki A Hydropower Plant-144 MW

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Abstract

In this study, efficiency evaluation for Kali Gandaki Hydro Power Plant (KGAHPP), located in Syangja-Nepal, was performed experimentally by using thermodynamic method. Turbine efficiency was measured with direct method by measuring temperature of turbine inlet and outlet. Based on the measured data, the turbine efficiency increases with increasing turbine power upto the rated capacity and then start decreasing. The best efficiency point for the unit 1, unit 2 and unit 3 is 91.98%, 91.50% and 89.77% respectively, obtained at the rated power output of around 48 MW. Unit 1 is a newly installed refurbished turbine, unit 2 is operated for 1 year and unit 3 is operated for 2 years after last overhauling.

The performance curves, wicket gate opening and discharge of each unit shows that the efficiency degradation in first year is quiet less and after that it amplifies rapidly. Initially the fine finish coated surface provides better resistance to the erosion. When it begins, then the erosion intensifies so rapidly which ultimately lower the whole performance of the turbine. This study shows that using thermodynamic method for determination of turbine efficiency is an effective and easy method for knowing turbine performance. The same instrumentation and methods can be used in the other hydro power plants to find and analyze the efficiency of the turbine. .

Keywords

Turbine – Efficiency – Thermodynamic method – Refurbishment

1. Introduction

Performance evaluation of the turbine is done to know the actual condition of the turbine after long years of operation and also for comparison purpose. Generally, thermodynamic efficiency tests are conducted for newly installed turbine runner to test the efficiency guaranteed by the manufacturer or supplier to its customer. In the case of old turbines runner, efficiency tests are carried out in order to know the status of turbine runners in term of efficiency at the present situation. By knowing the turbine efficiency (efficiency of turbine runners in terms of hydraulic efficiency) quantitatively, it helps to optimize the power generation of the plant as well as cost effective planning for the maintenance.

Himalayan Rivers are recognized as sediment loaded rivers due to its steep gradients, young mountains and fragile geology. The power plants build and operated in such sediment loaded rivers have to suffer substantial wear in turbines. It is the fact of South Asia region including Nepal. Turbine wear causes considerable loss in power generation due to rapid reduction on turbine efficiency over time [1]. Some kinds of degradations of a turbine or the waterways will result in a decrease in efficiency. Examples of damages that can give a significant drop in efficiency are among others; increased leakage over labyrinth seals and guide vanes, guide vanes out of position, damaged runner blades, sediment erosion, cavitation, vortex formation etc. Efficiency measurements are also a good way to control the condition of a turbine [2].

The performance evaluation of the hydraulic turbine is generally done by three ways:

- Model tests
- Numerical Simulation
- Field acceptance Tests

Model tests and numerical simulations are only valid when geometric similitude is adhered to, i.e., there is no guarantee that the prototype machine is an accurate reproduction of the design. In addition, approach flow conditions, intake head losses, the effect of operating other adjacent units, etc., are not simulated in model tests. For these reasons, field performance tests are often performed. There are several different types of field tests, which serve different purposes. The absolute efficiency is measured for acceptance or performance tests. Relative efficiency is often measured when operating information or fine-tuning of turbine performance is desired [3].

Thermodynamic method is a direct and absolute method to measure the efficiency of the hydraulic turbine. The method results from the application of the principle of conservation of energy (first law of thermodynamics) to a transfer of energy between water and the runner/impeller through which it is flowing [4]. Flow measurement is not required. Under these conditions, that portion of the available energy not utilized in the machine to produce useful work results in increased internal energy of the fluid, which is sensed as an increase in temperature [5].

1.1 Basic Principle for Thermodynamic method of Efficiency Testing

The turbine efficiency is the power output/input ratio of the machine. The input can be expressed as the hydraulic energy available to the turbine, specific hydraulic energy E. The turbine output is the mechanical power delivered to the turbine shaft, which according to the law of conservation of energy, can be found as the difference in specific mechanical energy Em between the inlet and the outlet of the turbine [6].

The hydraulic efficiency of turbine is defined as the ratio of mechanical output power of runner to the hydraulic input power [4]. i.e.

$$\eta_h = \frac{p_m}{p_h} = \frac{E_m}{E + \frac{\Delta P_h}{P_m} E_m} \tag{1}$$

The unit efficiency, or the overall efficiency of hydroelectric generating unit, is defined as the ratio of the electrical power output to the hydraulic power input to the turbine, and is given by

$$\eta = \frac{p}{p_h} = \frac{P_m}{P_h} \times \frac{P}{P_m} = \eta_h \times \eta_m \tag{2}$$

Where $P_m[W]$ is mechanical power of runner which is located, $\eta_m[-](= P/P_m)$ is mechanical efficiency which is a result of losses in the turbine bearing, and $\eta_h[-](= P_m/P_h)$ is hydraulic efficiency which is a result of losses in the turbine runner transferred to the water resulting in a temperature increase that detectable by "Sea-Bird" thermometer and ΔP_h is hydraulic power loss due to leakage in Watt.

As mentioned, the Thermodynamic method interests in hydraulic efficiency that tells how efficient the turbine transforms hydraulic power to rotating mechanical power. And we know the general relation between power (P) and energy (E) is $P = \rho QE$ where $\rho[kg/m^3]$ is water density, and $Q[m^3/s]$ is turbine discharge. So the hydraulic efficiency becomes

$$\eta_h = \frac{E_m}{E} \tag{3}$$

Where $E_m[J/kg]$ $(= P_m/\rho Q)$ is specific mechanical energy which is specific energy of mechanical power transmitted through the coupling of the runner and shaft. Generally, in practical cases, E_m is determined by measuring the temperature inside two vessels connected to the upstream (11) and downstream (21) sections, where the kinetic heating of the probes can be neglected [7] and $E[J/kg]$ $(= P_h/\rho Q)$ is specific hydraulic energy which is specific energy of water available between the high and low pressure reference sections of the machine.

The specific hydraulic energy can be determined by measurement of entering and leaving the turbine performance variables such as pressure, velocity and level of water. So the hydraulic efficiency Equation (4) can be expressed as:

$$\eta_h = \frac{a(P_{abs1} - P_{abs2}) + C_p(\theta_1 - \theta_1) + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)}{\frac{P_{abs1} - P_{abs2}}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)} \tag{4}$$

Where the performance variables: $P_{abs}[Pa]$ is absolute pressure, $\theta[^\circ\mathrm{C}]$ is temperature, v $[m/s]$ is velocity, and z [m] is level; the Thermodynamic properties: a $[m^3/kg]$ is isothermal factor, $C_p[J/kg - ^\circ\mathrm{C}]$ is specific heat capacity, and $\rho[kg/m^3]$ is density; and the subscripts: "1" and "2" are high pressure and low pressure section which are referring to the centerlines of inlet and outlet respectively [4]. The test boundary is as shown in the figure 1.

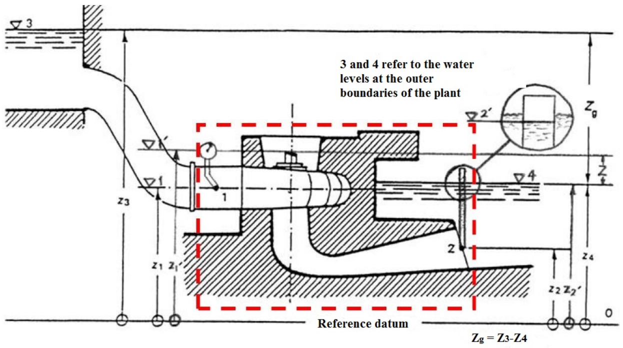

Figure 1: Test Boundary (Source: adapted from IEC60041-1991)

In practice the quantities are measured at the places 11 and 21 in measuring vessels. If the thermometers are placed directly in the main flow, the kinetic energy will normally not be measured, so the dynamic pressure will not be known. The measured kinetic energy is very near to the calculated one and has a negligible effect on the calculated efficiency. For that reason, it is also possible to calculated the pressure inside the probe using the static pressure plus the calculated kinetic energy ($P_{11} = P_1 + v_1^2/2$). Hence the pressure at the pressure port is the static head plus the velocity head [8].

Certain corrective terms (imperfect measurement conditions, secondary phenomena, etc.) must be taken into consideration. They are indicated by δE_m [4].Thus, δE_m is added to the above expression of E_m to get the practical expression.

Measurement of specific hydraulic energy $E = g \cdot H_n$ is simply a determination of the turbine net head H_n; However, the thermodynamic measurement of the specific mechanical energy is more challenging. The mechanical energy E_m is sometimes also called "total enthalpy", which is enthalpy i.e. $(= a \cdot \Delta p + C_p \cdot \Delta\Theta)$ plus velocity and elevation terms [6]. The thermodynamic test was carried out in accordance with the IEC 60041:1991 standard.

2. Objectives

The main objective of this paper is to test, analyze and compare the efficiency of Francis turbines at Kali Gandaki 'A' Hydropower Plant after years of operation and to find out the current status of turbine runners by field acceptance test. while the specific objectives are:

1. To measure the efficiency of turbine after refurbishment, after one and two year of continuous operation with thermodynamic method of efficiency testing.
2. To compare the current efficiency of the turbine, wicket gate opening and discharge with the guaranteed parameters provided by manufacturer.

3. Methodology

Temperature measurement

Temperature is the most sensitive and important parameter in the thermodynamic method of turbine efficiency measurement. It is very important to measure the temperatures accurately, as the difference in temperatures between upstream and downstream of the turbine has an impact on its efficiency. The temperature difference may be in the order of 0.1° C only. Hence, temperatures upstream and downstream of the turbine have to be measured simultaneously during the test. The sensors used was Seabird SBE38 with resolution of 0.001° C.

Figure 2: Installation of Sampling Probe at the Penstock

Figure 3: Installation of temperature probe with necessary cabling

The instruments were set up according to figure 4 .

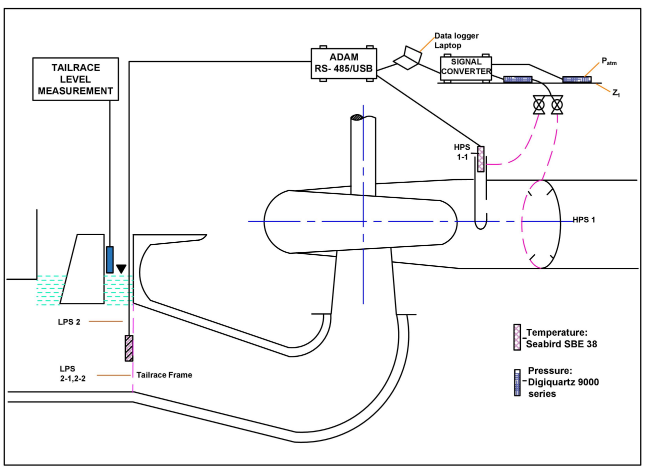

Figure 4: Experimental Setup

Pressure measurement

For the absolute pressure measurement Digiquartz Intelligent 9000 series pressure transmitters are used which has an uncertainty of $\pm 0.01\%$. There were two pressure measurement transducers; one for measuring the ambient pressure or atmospheric pressure inside the power house.

Measurement of other parameters

Besides the temperature and pressure,other parameter such as elevations are measured from the as-built drawings together with tape measurement at the site. Velocity is estimated on the basis of established engineering principles. Values of acceleration due to gravity (g), density of water (ρ), specific heat capacity of water (C_p) and isothermal factor (a) are abstracted from IEC 41 for given values of temperature and pressure.

Data processing

After completing the data processing and computation a report containing measured data and the status of the measured turbine in terms of hydraulic efficiency at the time of measurement will be prepared. Modern technology provides real time recording of measured data, immediate control and evaluation of the measurement, high accuracy and reduced error frequency of the measurements.

Data compilation and analysis

The data of the manufacturer's guaranteed efficiency, discharge and WG gate opening at the time of commissioning was collected and converted into spreadsheet data. The data of unit wise generation, outage and overhauling time were collected. These collected data were compared, analysed and evaluated with the current measured data and necessary tables,charts and available tools had been presented.

4. Results and Discussion

Evaluation and analysis of performance using thermodynamics analysis was carried out to obtain the efficiency and discharge of a turbine. Based on the measurements and the historical data, the findings are summarized and elaborated below with appropriate analysis.

4.1 Energy Generation Profile

The energy generation profile of each month for the previous eight fiscal years 2009/10 to 2016/17 were interpreted unit wise. The energy generation is divided into segment for each unit between the two consecutive overhauling. The average monthly generation of each unit is calculated using the generation data of previous eight years and the calculated data is used for comparison purpose to each unit generation.

From the figure 5, Unit 1 has more fluctuation on the generation after 1 year of overhauling. But the Unit 2 has smoother curve of generation and which is above the average generation, even after two year of operation.

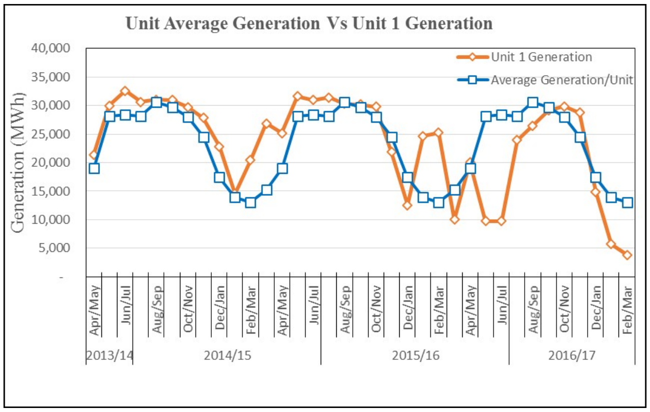

Figure 5: Generation curve between unit average generation and unit 1 generation

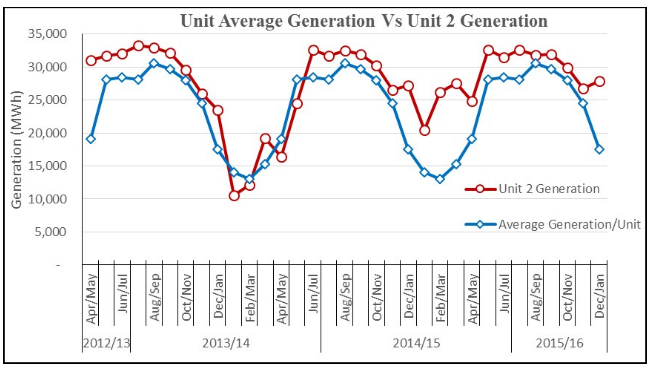

Figure 6: Generation curve between unit average generation and unit 2 generation

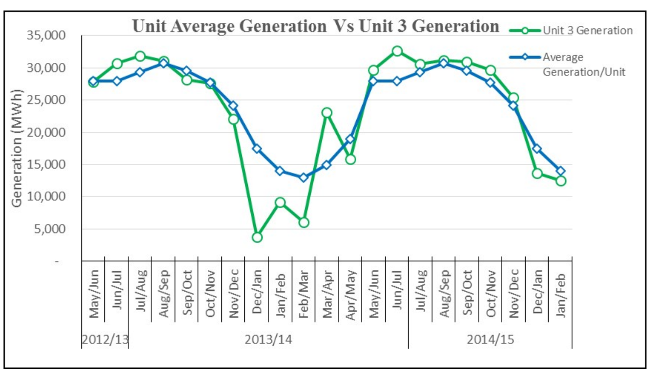

Figure 7: Generation curve between unit average generation and unit 3 generation

Likewise, Unit 3 has more fluctuation on generation pattern as compared to the average generation. The curve also shows that the power plant need priority to operate the recent overhauled turbine with less idle time, in order to get more generation with more efficiency. Proper decisions while operating the turbine according to the recent overhauled turbine enhanced the greater performance and condition of the power plant.

4.2 Result of the efficiency measurement

Six sets of measurements (about 20 %, 40 %, 60 %, 80 %, 100 % of design power output and maximum capacity) were carried out. Seventh set of measurement was carried out to check consistency of data at repeated generator output for about 80 % design output. These different levels of generated power output were chosen for test to cover the whole range of power output from the turbine.

Table 1: Results of thermodynamic efficiency measurements

Unit 1		Unit 2		Unit 3	
P (MW)	η (%)	P (MW)	η (%)	P (MW)	η (%)
9.42	63.72	10.56	66.64	9.26	57.17
19.19	75.78	19.07	76.51	18.52	71.35
28.28	85.01	28.68	86.44	28.35	83.59
37.77	91.78	38.33	90.25	38.56	89.10
48.14	91.96	48.32	91.50	48.30	89.77
50.32	91.98	57.21	91.70	54.34	88.75
47.76	92.13			48.14	89.64

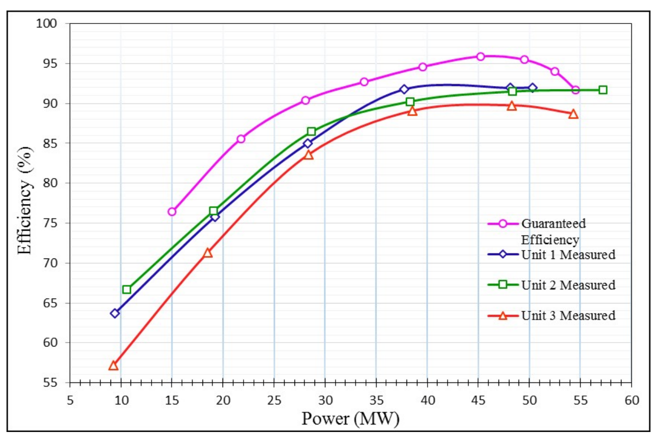

Figure 8: Curves of hydraulic efficiency Vs power output

As seen from the table 1 and figure 8, the turbine efficiency increases with increasing turbine power upto the rated capacity and then further increases of power start decreasing the efficiency. For the Unit 1, which is newly installed refurbished turbine has maximum efficiency 92.13%, obtained at power 47.76 MW. The turbine power cannot be increased further due to temperature problems of generator cooling and system frequency. Further increase in turbine power causes the decrease of turbine efficiency. The obtained efficiency is around 4% below than the guaranteed efficiency at the same point. This is due to the repeated continuous erosion and the refurbishment of the turbine in 15 years period. The runner blade and guide vane profiles change during the time of repairing is the main reason for lowering the efficiency of turbine.

Likewise, efficiency of the turbine runner of Unit 2, which operated nearly one year form last overhauling was calculated to be 91.70%, at the maximum power generation of 57.21 MW, whereas the best derived efficiency was 91.70% at the same generated output. However, the maximum efficiency for the unit 2 at the rated load (around 48MW) is 91.50%, which is 0.48% lower than the newly refurbished turbine.

Similarly, based on the measured data of Unit 3, which operated two years from last overhauling has best derived efficiency of 89.77% at 48.30 MW of generator output. This value is 6.23% lower than the manufactured guaranteed, 2.21% lower than the newly refurbished turbine and 1.73% lower than the one year operated turbine.

The above performance curves shows that the efficiency degradation in first year is quiet less and after that it amplifies rapidly. This verifies that it is difficult to start the erosion on the HVOF coated good finish surfaces of newly installed refurbished turbine. When it begins, then the erosion intensifies so rapidly which ultimately lower the performance of the turbine.

The scatter diagram of water temperature difference between the outlet of the draft tube and volute inlet are plotted in Fig.9. and shows that the maximum temperature difference of 0.1066 °C is obtained at power output of 9.26MW for Unit 3, also at that point minimum efficiency of 57.17% is obtained.Similarly, the minimum temperature difference of 0.0038 °C is obtained at power output of 48.30 MW for Unit 3, also at that point maximum efficiency for unit 3 is obtained, which is 89.77%.

Table 2: Temperature Difference measured during efficiency measurements

Unit 1		Unit 2		Unit 3	
P (MW)	Temp. diff.(°C)	P (MW)	Temp. diff.(°C)	P (MW)	Temp. diff.(°C)
9.42	0.0945	10.56	0.0889	9.26	0.1066
19.19	0.0591	19.07	0.0636	18.52	0.0611
28.28	0.0320	28.68	0.0302	28.35	0.0211
37.77	0.0131	38.33	0.0179	38.56	0.0054
48.14	0.0127	48.32	0.0164	48.30	0.0038
50.32	0.0136	57.21	0.0180	54.34	0.0088
47.76	0.0129			48.14	0.0051

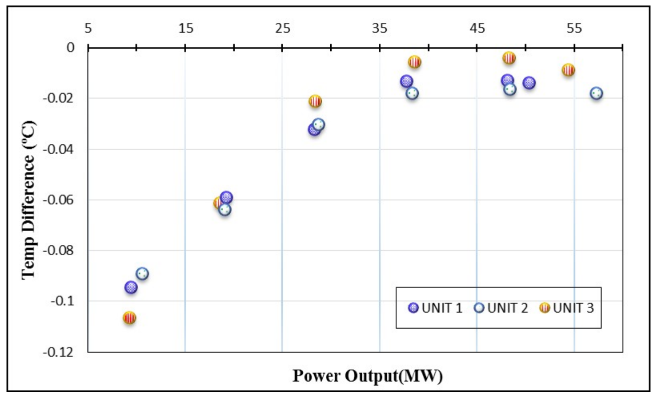

Figure 9: Scatter diagram of temperature difference Vs. power out

As seen from the figure, that the turbine efficiency decreases with increase of heating water through turbine blades. As well known from the literature, the temperature increase in water causes the loss of power. This shows that the turbine efficiency is directly influenced by water temperature. The turbine efficiency decreases with the increase of temperature difference.This shows that the turbine efficiency is directly influenced by water temperature and increasing of water temperature is a proper scale to determine losses.

4.3 Wicket Gate Opening and Discharge at different Load

As seen from the figure 10, the turbine efficiency increases with increasing turbine discharge upto the rated discharge of 44.86 m^3/s and then further increasing of discharge start decreasing the efficiency.

For the Unit 1 maximum efficiency of turbine is 92.13% obtained at turbine flow rate of 43.87 m^3/s. Likewise, for unit 2 maximum efficiency of 91.70% is obtained at discharge of 52.09m^3/s, whereas the efficiency of 91.50 % is obtained at the rated power output and discharge of 43.52 m^3/s.

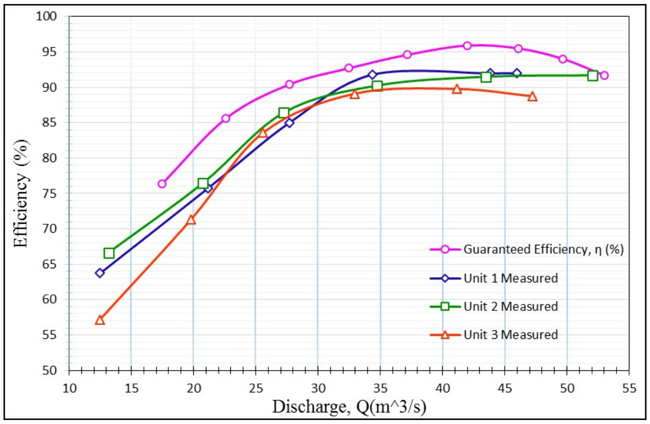

Figure 10: Curves of Efficiency Vs. Discharge

Similarly, based on the measured data of Unit 3, efficiency was calculated to be 88.75 % at maximum power generation of 54.34 MW and discharge of 47.21 m^3/s whereas the best derived efficiency was 89.77 % at 41.15 m^3/s of turbine flow rate.

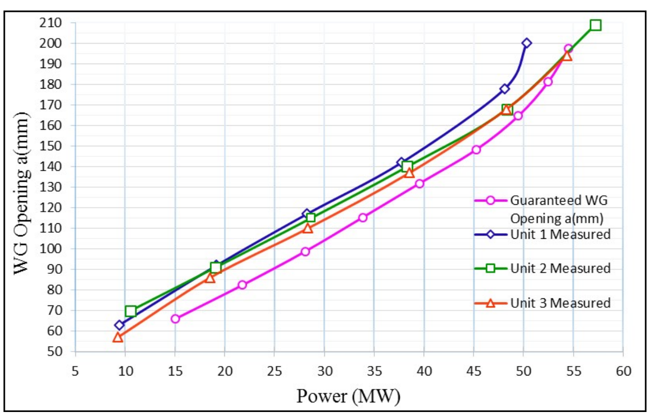

Figure 11: Curves of WG Opening Vs. power output

Figure 11 shows that the recently overhauled unit 1, which operates only 255.05 hours after last overhauling, opened more widely than the manufacturer assured opening. This shows that the turbine need more discharge for generating given power than the manufacturer claimed after 15 years of operation. The runner, wicket gates and stay vanes deviated from actual design with the repeated erosion and refurbished.

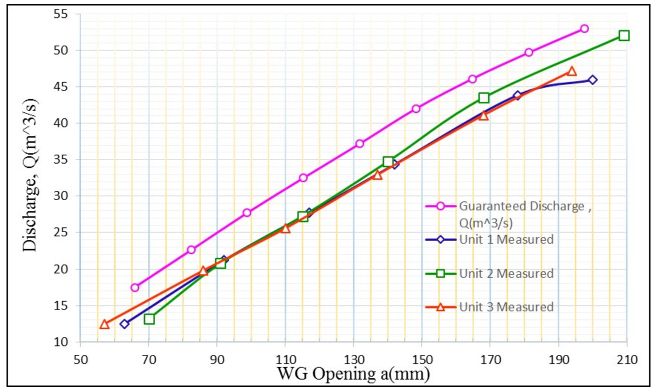

Figure 12: Curves of Discharge Vs. WG Opening

As seen from the Figure 12 that almost all units have almost equal discharge at the given wicket gate opening. However with the span of time due to repeated operation and refurbishment there is certain deviation of wicket gates profile from the guaranteed discharge at the given opening, which means more wicket gate opening is needed for delivering given discharge than at the time of commissioning.

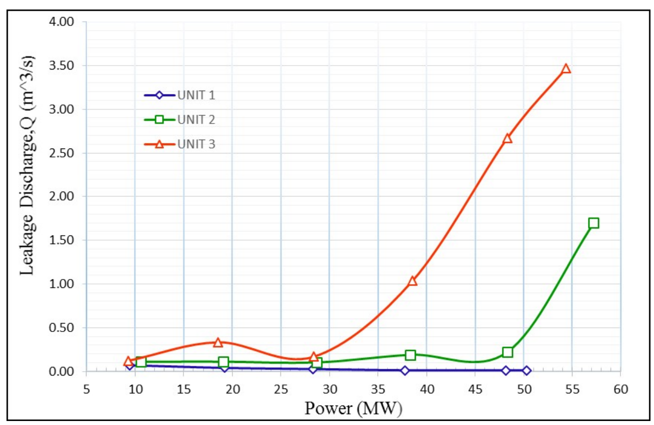

Figure 13: Curves of Leakage Discharge Vs. Power Output

Whereas from figure 13 due to the erosion on the turbine components and from above measured efficiency diagram that the efficiency of turbine decreases with the time of operation, which mean more discharge is needed to output given power. So, it is shown that with the span of operation time the leakage is more to the runner and more water is needed to produce given power than the refurbished or prototype turbine. This is due to the erosion of the guide vanes, shaft seal and labyrinth ring which result the leakage of water and more discharge is needed for generating given power.

5. Conclusion

Based on the measured data, the turbine efficiency increases with increasing turbine power upto the rated capacity and then start decreasing. Six sets of measurements (about 20%, 40%, 60%, 80%, 100% of design power output and maximum capacity) were carried out and the best efficiency for the newly installed refurbished turbine is 91.98% obtained at power output of 48.18MW and which is around 4% below than the guaranteed efficiency at the same output. Likewise for unit 2, which operated one year after last overhauling has the efficiency of 91.50% at the load of 48.32MW which is 0.48% lower than the newly refurbished turbine. Similarly, based on the measured data of unit 3, which operated two years from after last overhauling has the efficiency of 89.77% at the load of 48.30MW which is 6.23% lower than the manufactured guaranteed, 2.2% lower than the newly refurbished turbine and 1.73% lower than the one year operated turbine.

The performance curves shows that the efficiency degradation in first year is quiet less and after that it amplifies rapidly. Initially the fine finish coated surface provides better resistance to the erosion. When it begins, then the erosion intensifies so rapidly which ultimately lower the whole performance of the turbine. The efficiency measurements also shows that with the increase of operating time the erosion causes more leakage of water from the wicket gates , labyrinth ring and shaft seal decrease the efficiency of turbine, which means more discharge is required for eroded turbine than the new turbine at the given power output. Hence, the performance measurement and analysis of data helps to optimize the power generation of the plant as well as cost effective planning for the maintenance in this time of energy crisis.

Recommendations

The efficiency of not only KGAHPP but also other Nepalese Hydro Power Plants should be measured regularly so that the damage of turbine components due to sediment will be monitored, measured and maintained in right time to generate more energy both in wet and dry season. The life of the turbine and it components will be more if it is overhauled and repaired at the right time regularly. The performance of the newly installed turbine should be rechecked and assured either the manufacturer guaranteed efficiency is actually meeting with the field acceptance test

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