CENTER OF EXCELLENCE AT KATHMANDU UNIVERSITY FOR R&D AND TEST CERTIFICATION OF HYDRAULIC TURBINES

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ABSTRACT

Growth in global demand of clean energy has also increased hydropower development activities. This has also increased the necessity of overall efficiency improvements in hydropower plants for producing larger power with same site conditions. Efficiency improvement by design optimization of turbines is primary task in elevating performance of any hydropower projects. Institutional laboratory test facilities, which are expensive and demand high level of proficiency, are needed to certify performance of turbines. Due to the lack of well equipped and standard test facilities at South Asia region, efficiency measurement of turbines is mostly done at project sites.

Kathmandu University (KU) is an autonomous, not-for-profit, non - government institution dedicated to maintain high standards of academic excellence. With technical support from Norwegian Institute of Science and Technology (NTNU), KU has been upgrading its competency to support the ambitious plan of Government of Nepal (2010) to develop 38,000 MW of Hydropower in 25 years. KU is collaborating with national and international experts and institutions for this venture.

Turbine Testing Laboratory (TTL), under construction at KU with financial assistance from NORAD, Norway, aims to deliver its facilities to local and international developers and consultants by the mid of 2011. With 30 meter open head and 150 meter closed head, TTL is capable of testing different range prototypes up to 300kW and conduct model tests for larger sizes. Internationally recognized certification endorsed by International Electrotechnical Commission (IEC-60193) will be maintained at TTL for model tests. The technical support for the laboratory will be provided by Waterpower Laboratory, NTNU which has experience of turbine testing for almost 100 years. In coming years, TTL intends to include state of the art technologies such as Computational Fluid Dynamics (CFD), Finite Element Method (FEM) analysis for new design or upgrading existing turbines, innovative design of hydro-mechanical components for power plants, and specialized trainings to engineers and technicians.

This paper elaborates the utility of TTL in South Asia region with its objectives and specifications. Scope and partnerships for developing a center of excellence at TTL for R&D of hydraulic turbines are also presented. Need and possibilities of creating a new turbine manufacturer in Nepal, by the combined effort of academic institutions and manufacturing industries has been analyzed. Beside these, the progress of design optimization of Francis turbine at Jhimruk power plant for reduction of adverse impact of sediment erosion has been discussed.

KEYWORDS: “Kathmandu University”, “performance test”, “hydraulic turbines”, “design optimization”, “sediment erosion”

1. INTRODUCTION

Even after more than a century of progressive experiences, hydraulic machinery design is a challenging domain for engineers. The design process ranges from geometry manipulation to predicting performance analysis [1]. Hydro turbines are generally tailor made machines designed to suit a particular site condition. The designs need verification as they are based on empirical assumptions. The verification processes also can be carried out in a controlled environment such as by conducting experiments in a well-equipped and standardized laboratory.

Over the last few decades, the use of computer aided tools such as CAD, CFD, FEM, etc. for design of turbine has greatly improved turbine performance due to iterative and optimized design process [1,2]. However, use of computing software in design process includes many assumptions. To overcome some of these theoretical designed flaws model tests may be performed. The model test methodology for hydraulic turbines has been prescribed by International Electrotechnical Commission (IEC-60193) standards. Following the same standard of model tests for turbines designed by differing assumptions will still bring uniformity for comparisons and performance guarantee of each design.

The center of excellence for R&D of hydraulic turbines at TTL, as conceived by KU, provide state of the art engineering solutions to design problems of hydraulic turbines along with model test certification of IEC standard.

2. TURBINE DESIGN AND MODEL TESTS

Practice of design optimization and verification

Equations of classical theories were used as primary means to shape the blade of turbine runner up to early sixties. Optimizations of such design were based on hit and trial modification with model experiments. The current trend for turbine design is to shape blade geometry based on classical approach and optimize the design by using the CFD techniques [2,3].

The new approach is to see the design process of a turbine as an optimization problem. Final design of turbine is optimum solution enhanced from existing designs to suit a special set of conditions. CFD techniques are used for optimization and validity of the optimum design is assured by the model test at standard test laboratory.

Fig.1 & Fig. 2 show the optimization methodology and model test verification process that would be applied for R&D at TTL. The design problem is formulated mathematically to interpret solution as combination of geometric parameters. Due to variation in design criteria for each hydro power plant, design problem of turbine is unique in itself. Hence many factors ranging from the geometric shape definition, evaluation and optimizing computing algorithms need to be carefully considered for every individual case. The following points provide some insight to be considered when formulating the design optimization (Fig. 1).

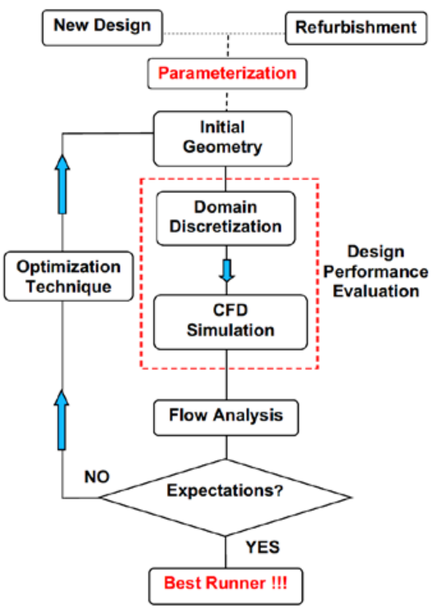

Fig. 1 Optimization for runner design [1]

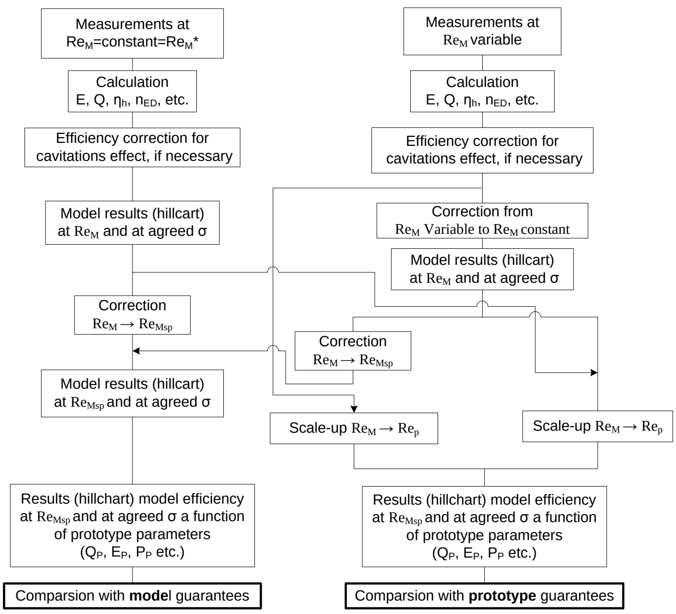

Fig 2. Procedures for calculating comparative test results [4]

- *Parameterization*: It is to establish a fixed number of parameters, which are able to represent the geometric entity that is expected to be improved. The most important factor is their number. A high parameter number may increase the shape manipulation complexity, where a low number may provide a poor and a limited range of feasible solutions.
- *Performance Evaluation*: The performance of new design is estimated by running (CFD, FEM, etc.) simulations. Depending on the model the time consumed at this stage can be significant. Thus simplified models are used to accelerate the process. However, it leads to accurate results to support decisions.
- *Objective Function: It is the relation between design solutions with input variables. Moreover, the best solution changes from case to case.*
- *Optimization Technique*: It is improvement in design resulting from fine tuning each variable in relation to desired solution.

The main hydraulic performance parameters, which can be verified by model tests, are: power, discharge and /or specific hydraulic energy, efficiency, pressure oscillations, cavitation performance, and runaway speed. A basic requirement for determining prototype performance from model tests is to have geometric similarity between model and prototype. Model tests are seldom carried out at the same Reynolds number as the prototype. Hence, the hydraulic efficiency calculated for each point with different Reynolds (Re_M) number is scaled to prototype Reynolds number (Re_p). Results of model tests are presented in form of “Hill Diagrams” of prototype as a function of prototype performance parameters, which are derived from the model Hill Diagram with appropriate scaling methods (Fig. 2).

Turbine Test verification practices and facilities

Large turbines neither can be tested at site nor in real condition for which it is designed. The tests are done on scaled models on scaled hydraulic conditions **[5]**. Such model tests process is a time consuming job and it demands well calibrated equipment, which are costly and often tailor made. Larger turbine companies such as Andritz, Voith and Rainpower (Formerly Kvaerner) have their own test facilities. However, smaller developers and consultants concerned with hydro power cannot afford such a big investment. Consequently several projects have faced surprises during their operation.
There are some renowned independent or university owned laboratories in Europe and Asia for R&D, education and training in hydraulic turbines. They include:

- Waterpower Laboratory, NTNU, Norway
- Laboratory for Hydraulic Machinery (LHM), EPFL, Switzerland
- Global Scale Model Test Laboratory, ALSTOM Hydro, France
- Toshiba Hydraulic Research Laboratory, Japan
- The Hydraulic Machinery Laboratory of IWHR, China

The facilities available in such laboratories are used not only for research but also as means to generate revenue for universities. Turbo institute in Croatia is has tested more than 100 turbines**.** LHM-EPFL has carried out model test of more than 42 projects ranging from 18 MW to 770 MW for North American hydropower industries **[5]**. With its model test facility of 1000 kW, Toshiba is able to conduct model tests for hydro power plant with net head of 2000 m **[6]**. With the rise in necessity of design verification and performance guarantee, model tests of turbines have become an international business.

Nepal does not have much experience of turbine model testing. Until now, model tests of turbines purchased by Nepal Electric Authority and other Independent Power Producers in Nepal are carried out by laboratories abroad. Model tests of major hydropower projects in Nepal, Kaligandaki (144 MW, Toshiba), Marsyangdi (69 MW, Voith) and Middle Marsyangdi (70 MW, Voith) were conducted by the respective manufacturers at their own test facilities. Nepal Hydro Electric Pvt. Ltd. (NHE) had tested smaller turbines for certification of their product manufactured for Indian market. BalajuYantraShala, a private limited company in Nepal developed its design competence for cross flow turbine due to testing of its turbines. However, both these company turbines were for micro-hydro projects, both tests were done on prototypes and both tests were done at smaller laboratories **[5,7]**. There is an institution in Nepal, Hydro Lab Pvt. Ltd. for physical and civil engineering modeling of hydraulic systems, but there is no institution to carry out research and development of hydro-mechanical components.

A survey is being conducted by Roorkee University to assimilate the need of a modern test facility for hydraulic turbines in India [8]. An advertisement was published by Bharat Heavy Electricals Limited (BHEL) in India, for consultation to modernize its existing hydro turbine testing lab to meet the international standards [9]. These scenario show that a well equipped test facility to conduct model test of turbines for larger projects is necessary but lacking in South Asia.

Prospects of modern turbine test facility in South Asia region

There is an additional challenge in operation of hydropower plants in Nepal and South Asia region due to special problems like excessive sedimentation and sand erosion of turbine components. The test facility in the region can assist for design modification and performance analysis for sediment resistant hydro turbines. In the absence of test facilities in the region, there is no significant contribution in R&D of hydro turbines to tackle the local problems. In summary, justification for the need of a turbine testing laboratory in the region is presented in Table 1.

Table 1: Objectives and activities of new turbine test facility in the region

S.N.	Objectives	Activities
1	Build competence and knowledge in Nepal and for South Asia region	• Teaching/learning facility
		• Industrial courses
		• Staff training for the industry
		• R&D back-up for industrial development
2	Build a laboratory for hydro turbines	• Certification of mini- and micro-turbines sold on the Nepali and the regional market
		• Model testing of turbines for larger power plants
3	Center for research	• Sand erosion research in turbines
		• Turbine and pump development
		• Maintenance of turbines
4	Meeting place for the industry and university	• Student projects for the industry
		• Share information and experience at regional level

With the establishment of turbine laboratory in the country, the investment in hydropower projects will be saved by reducing uncertainties of turbine performance and competence in turbine design and manufacturing will be established.

3. HYDRAULIC TURBINE R&D EXPERIENCES AT KU

From different miniature laboratory setups up to TTL

Since its establishment, KU has been putting its effort into development of hydro turbines for Nepalese context. At present KU have two miniature turbine laboratories Pico Turbine Laboratory and Waterpower Laboratory. The Pico Turbine Laboratory is dedicated for research and development of axial flow Pico propeller turbines. It has produced one low-cost 800 W Pico set having 90% overall efficiency (Fig. 3a). Now it is developing a similar 1.5 kW set, amenable to mass-production at low cost [10].

The Waterpower Laboratory is dedicated for design and performance analysis of Pelton and Francis turbines and also provides professional trainings. This laboratory is also used for research on issues related to sand erosion of turbine components. Five different Pelton bucket profiles designed at KU are being tested for impact and flow visualization (Fig. 3b) **[11]**. Francis turbine for 130 kW micro hydro projects (Fig. 3c) is under development by Center of excellence for production and transportation of electrical energy at KU. The turbine will be tested at TTL facilities.

(a) (b) (c) (d)

Fig. 3 Research at the miniature turbine laboratory at Kathmandu University: (a) 800 W Propeller Turbine designed and tested at Pico turbine test laboratory **[10]**, (b) Flow visualization in Pelton bucket at water power laboratory **[11]** (c) 130 kW Francis turbine waiting for model test at new TTL, (d) Sand erosion test of stainless steel and HVOF coating **[5]**.

Sand erosion tests have been carried out with "Rotating Disc Apparatus" developed by a post graduate student research studies. Erosion tests have been done for the stainless steel and HVOF-coated WC-Co-Cr coating used in Kaligandaki hydropower project in Nepal **[12]**. Test objective was to compare performance of HVOF coatings with stainless steel (Fig. 3d). This provided an opportunity for accelerated sand erosion testing for a comparison of different materials. The same setup is used for studying combined effect of sand erosion and cavitation **[13]**.

The TTL is in final stage of civil construction. It will have a system connected with lower and upper reservoirs to circulate water necessary to run turbines (Fig. 4). The topography of the laboratory location (at the main campus) provides 30 meter natural static head. This is a unique feature of such a test laboratory, as it provides natural flow conditions to the tests. The water from the lower reservoir will be re-circulated to the upper reservoir by two pumps of 160 kW, head 75 m, flow rate 0.25 m^3/ sec.

The laboratory will be equipped with a state of the art control system with electromagnetic flow meters, pressure transducers and sensors. The two pumps can be operated in series as well as parallel circuits in a close loop to obtain different operational regimes with maximum head of 150m. With this system, the largest turbine that can be tested will be 300 kW. The system will be able to test both reaction and impulse turbines (Figure 5). There is a provision to calibrate appropriate instruments against weight of water.

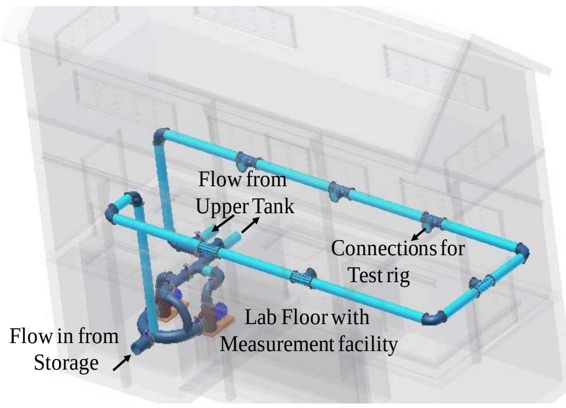

Fig. 4 Piping and Pump Arrangement of Turbine Testing Laboratory

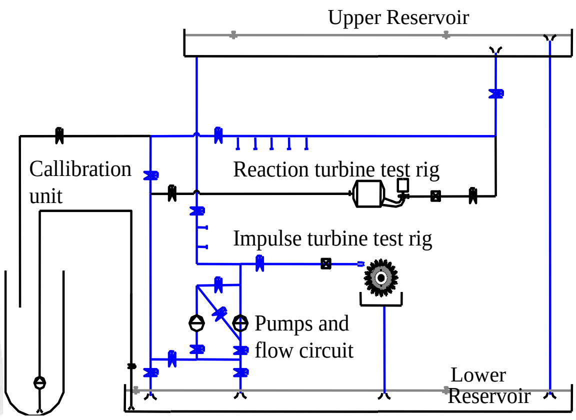

Fig. 5 Schematic layout for turbine testing and calibration arrangement

The estimated cost of development of the laboratory is NRs. 97 million (about US$1.31 million). NORAD has contributed 60% of the cost. KU and Nepalese industries have shared equally to the remaining expenses. The lab will be operated on business principles under the direction of a board representing KU and other stake holders by the mid of year 2011.

4. CURRENT UTILIZATION OF TTL

Strategic planning for long term use of TTL is underway. However, TTL is already active in several areas of Hydropower development some of them are as follows:

a) Combined R&D activities with RenewableNepal support

RenewableNepal is research program leading to business development funded by NORAD and managed by KU in cooperation with SINTEF Energy Research, Norway. This support is making Nepal more independent and self-reliant in utilizing its own huge hydropower resources as well as other renewable energy resources. Under the RenewableNepal Program, TTL has been granted sum of 5.7 million NRs. to initiate combined R&D works for design of hydro turbines to resist sediment erosion. KU and NTNU as Nepalese and Norwegian research institutes, and NHE and DynaVec as Nepalese and Norwegian manufacturing industries, have formed a project consortium with the following objectives:

1. Develop a new design philosophy for Francis turbine to minimize losses due to sediment erosion by technology transfer and innovation.
2. Create a Center of Excellence at TTL for research and development of hydraulic turbines as a foundation for a new turbine manufacturer in Nepal.
3. Prepare technical background and understanding between local and international institutions and industries for establishing a new turbine manufacturer in Nepal.

The project has duration of three years, with start date of August 2010.

This project is aimed to transfer the Norwegian turbines R&D competency of to Nepalese research institute and Norwegian expertise in manufacturing of turbines to Nepalese manufacturer. The ultimate goal is the holistic and long-term sustainable development of hydropower business in Nepal.

NTNU will support KU to develop the Center of Excellence at TTL, which will provide professional consultancy to the manufacturing industries and other developers in the region for design and tests of turbines. By combined R&D activities a new design philosophy of erosion resistant Francis turbines will be developed and verified at TTL. DynaVec and NHE will cooperate together for creating a turbine manufacturer in Nepal for commercialization of the new design in local and international market (Fig. 6a & Table 2).

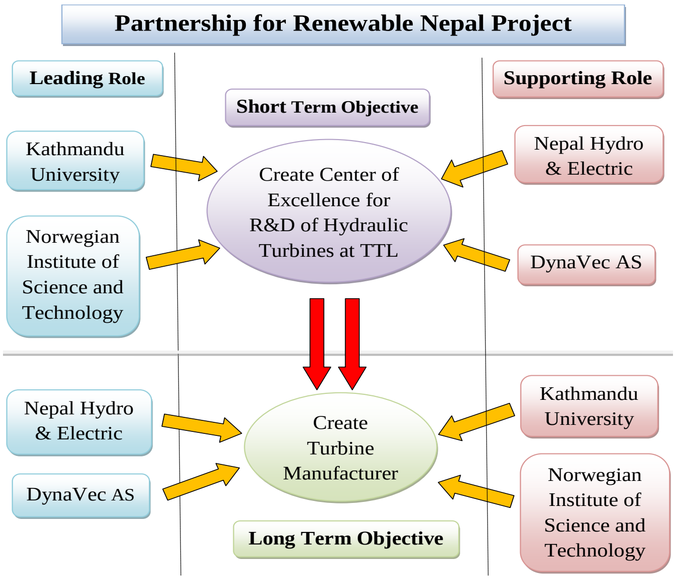

Fig. 6 Renewable Nepal Project objective at TTL

Table 2 Renewable Nepal Project Stage and Goals

S.N.	Project Stage	Goal
1	Development of Theoretical Foundation	New Design Philosophy of Francis Runner
2	Develop Research Competency at TTL, KU	Hardware, software and expertise for CFD tools in R&D of Turbines.
3	Design Verification	New Design ready to be implemented Commercially.
4	Background for Commercialization	Motivate investors for a new turbine manufacturer in Nepal.

b) Design improvements of turbines for micro/ mini hydropower projects:

KU waterpower laboratory will be incorporated under TTL with following activities:

Further improvements of Pelton buckets: Improvements of Pelton buckets are on the R&D stage. It is expected to reach to manufacturer after second stage of optimization as a result from past research. Target has been set for runners up to 500 kW with efficiency of 85%.

Test verification and improvements of Francis runner: The modified 130 kW Francis runner is under development process. The test would be done at new TTL facility. The results will be evaluated and optimization will be done for its commercial use. The design of the runner for the projects up to 1 MW by local manufacturing has been expected to match subsidy policy of government of Nepal up to 1 MW.
Pump-as-turbine for micro hydro projects: Nepalese Micro-Hydropower plants are suffering from low plant efficiency particularly due to poorly designed and manufactured turbines. Possibilities of use of pumps as turbines have been attempted at several sites in other developing countries. New thread of research has been initiated at TTL to optimize impeller of centrifugal pump to be used as generating unit in micro-hydro projects.

c) Data bank and Technical support:

Apart from the R&D works, TTL has also been commencing other relevant activities, which will directly or indirectly support hydropower development in the country and in region. This includes:

i. Data bank of design and performance of Hydro-Mechanical and Electro-Mechanical equipments of major Hydropower projects in Nepal.
ii. Data bank of feasibility study and design requirements for upcoming projects.
iii. Provide professional consultancy services for design and test certification of turbine and associated parts.
iv. Provide relevant short term courses and training programs to industrial staffs and professionals

5. R&D FOR JHIMRUK HYDROELECTRIC CENTER

The power plant: JHC is a run of the river hydro power plant, located at the western part of Nepal and own by Butwal Power Company (BPC). It consists of three similar Francis turbines each operating under a net head of 201.5 m and discharge of 2.35 m^3/s through each unit. The plant is in service since 1994 with a design output of 12.6 MW, and the turbine efficiency is measured as 89.75 % for a new refurbished turbine. A river flow distribution shows that JHC can be operated at design output for approximately 60 % of the time in a year **[14]**.

Jhimruk Hydroelectric Center (JHC) is special case for turbine R&D activities in the region. JHC uses high head Francis turbine operating at high speed of 1000 rpm and concentration of sediment through runner reaches 2500 PPM with more than 75% of hard particles in it **[15]**. New design of Francis turbine for such adverse condition is under R&D stage with RenewableNepal support. JHC will be used as the test case to compare empirical design with the model tests results at TTL.

Sediment and effect on efficiency: The sediment yield is 5,500 tones/km^2, the sediment concentration varies between 0 and 57,000 PPM, the annual sediment load through the turbines is calculated as 35,314 kg/m^3 for a 40 % plant load factor **[14]**. 90 % of the particles entering the turbines is below 0.1 mm in diameter and consists of 62 % quartz, and the sediment particles are relatively rounded in comparison to those in other rivers in Nepal.

JHC has not operated satisfactorily for the owners since the start of operation in 1994. The excessive amount of suspended sediments in Jhimruk River causes severe erosive wear on all the components that are in contact with the water. In the 11 weeks of turbine efficiency measurements in 2003, the suspended sediment load 6,900 tons passed through turbine unit number three. At this condition the drop in turbine efficiency was measured by 4 % **[14]**.

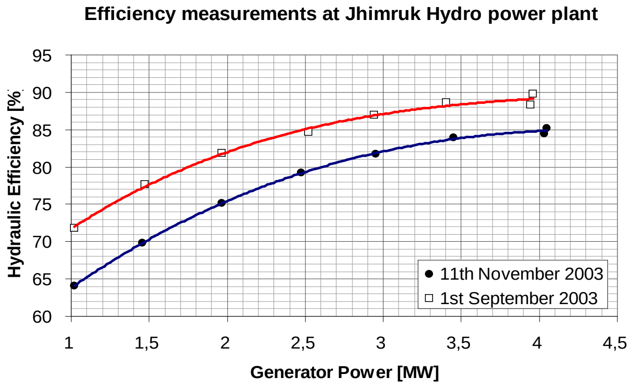

Fig. 7 Turbine efficiency measurements at JHC **[14]**

Fig. 8 Erosion of runner at the out let during the operation period of 1year at JHC *(Courtesy, BPC)*

Fig.7 shows that the turbine efficiency loss the period of 11 weeks was 4% at best efficiency load and 8% at 25% load. Maximum efficiency for a new refurbished turbine is 89.75 %. It is assumed that 25% of the losses come from the guide vanes, 25% originates from the turbine runner and 50% comes from the labyrinth sealing rings **[14]**. Fig. 8 shows erosion of runner at the out let during the operation period of 1 year. The heavy loss of turbine material and propagation of crack between the runner vane and crown can be seen.

Proposed Modifications in Turbine

Francis turbines suffer from sediment erosion in three different parts. These are the stay vanes, guide vanes and runner vanes. There have been several studies conducted to minimize the sediment erosion in these turbine parts at JHC. These studies mainly point out the following finding.

A solution to the erosion problem in the stay vanes is to design them at the outside of the spiral casing instead of at the inside. By doing so both the erosion and friction of the stay vanes drop to zero. Two different possibilities exist to reduce the erosion in the guide vane cascade. One is to increase the reaction degree with an increase in pole pair number. The other idea is to modify turbine design to without guide vanes. By doing so entire problem of erosion at guide vanes will be eliminated. However, these possibilities are inapplicable due to various hydraulic reasons **[14].**

In order to reduce the erosion in the runner cascade, different changes in the design have been identified **[16]**. To reduce erosion at the inlet, the reaction degree should be equal to the half of hydraulic efficiency. To decrease erosion in the runner blade, the runner should be designed with a low relative velocity giving minimum. The erosion at the outlet of runner can be reduced by increasing the number of pole pairs in the generator. Erosion at outlet can also be controlled by cutting off the runner-end, as outlet erosion is proportional to cube of the outlet radius.

Numerical analysis followed by CFD evaluation of above modifications in turbine for Jhimruk power plant has been carried out. The simulation of erosion indicated that at outlet erosion has reduced by around 70% and the overall erosion rate by around 50% **[16]**. However, the study also found that these improvements at JHC are uneconomical due to higher replacement cost of a bigger turbines and generators**.**

New design Philosophy for Francis Turbine

Past research to reduce sediment erosion in turbines with conventional design have not yielded positive results. This has laid out a need to design and manufacture of turbine with newer concepts. DynaVec has developed a Francis runner that is coated and then bolted together instead of conventional welding. The idea is patented and tested on several turbines **[17]**. The recent runner has been installed and evaluated at Cahaua Power plant in Peru. The plant has rated power output of 42 MW, gross head of 220 meter with 2 Francis turbines. Sediment the passing turbine has above 65% of quartz and feldspar content and a maximum sediment load of 36 kg/s **[17]**.

Study **[17]** conducted at the Cahua Power plant with new runner has measured the following findings. The power plant has generated 13.1 GWh extra energy in the period from 13th March until 9th

June 2009. The sediment load in this period was 131.000 tons and the maximum sediment concentration during operation was 20000 ppm. The efficiency has dropped less than 1% at full load and the large surfaces of the runner, guide vanes and covers has no visible erosion. The coated areas have lost maximum 30% of its initial thickness.

With the success at Cahua, DynaVec along with, NTNU, KU and NHE has been working for further modifications in runner profile with new design concepts to develop better sediment resistant turbines for South Asia market. JHC would be the test site of the new design as the operating conditions at JHC is a typical bench mark of sediment erosion problems in South Asia region.

6. CONCLUSION

Turbomachinery design remains a complex task, combining multi-disciplinary engineering fields. Recently, the use of modern techniques like CFD for predicting the flow in these machines has brought substantial improvements in their design. However, physical test of turbine is always necessary to validate such design improvements. A standardized test facility for model tests of hydraulic turbines is still lacking in Nepal and the region.

KU has been playing a leading role for developments of better turbines for the Nepalese context. With its R&D experiences at miniature laboratories for micro hydro projects, KU is building a modern hi-tech turbine testing laboratory at its campus premises in Dhulikhel. The lab is equipped with the state of the art facilities and the lab services would be open from mid of 2011.

A consortium has been formed at the TTL with the Nepalese and Norwegian research and industrial professionals to develop new design philosophy of Francis turbine to resist erosion problems. Jhimruk power plant in Nepal has been chosen as the test case for this R&D works due to its unique operating features.

The resources and facilities at TTL are open and will be shared at the regional level for the holistic development of hydropower business.

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