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Flow measurements around guide vanes of Francis turbine: A PIV approach

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ABSTRACT

A guide vane cascade is developed for the study of flow in the distributor of a low specific speed Francis turbine. Velocity and pressure measurements are done with Reynold's number 1.15 E+07, at 80% of BEP flow as in a reference prototype turbine. This work illustrates the development of test setup and focuses on investigation of PIV methods applied for the velocity measurements. Techniques developed for *'in-situ'* calibration of PIV setup and methods applied for image processing are discussed in details. Approach to estimate total uncertainty in PIV measurements and minimum no of image pairs required for statistical convergence of velocity field is presented. Reference measurements are done along the plane of chord, from guide vane wall to its mid-span. Flow velocity exceeding 35 m/s, at the runner inlet of Francis turbine, is reported for the first time from such experimental studies. Flow phenomenon inside Francis turbine distributor are characterized and comparison are done with the cases for prototype turbines. The cascade setup is found to reproduce the flow conditions inside a Francis turbine distributor, except the rotor-stator-interaction. PIV methods are generalized for the cases of similar measurements and the results will be applicable to validate numerical studies.

1. Introduction

Since the first installation of hydroelectric power plant in 1827, this green energy technology has undergone several innovations and capacity enhancements. At present hydropower sector produces more than 1211 GW electricity worldwide, which is about 20% of total electricity supply [2]. As thermal energy is not associated with hydropower system, the efficiency of this technology may reach 100% in theory [3]. In practice, up to 93% efficiency is possible, which makes hydropower one of the most efficient and economic energy resources. Two third of technically feasible hydropower resources are still undeveloped. More than 80% of the undeveloped hydropower resources lie in Asia, South America and Africa [4]. Hence, future of hydropower developments will be more localized in these regions.

Energy conversion process in a hydropower system occurs in several intermittent stages. Major stages include conversion of potential energy stored in reservoir to kinetic and pressure energy in the penstock, then to mechanical energy in the turbine, and finally to electrical energy in the generators. The most complicated energy conversion occurs inside the turbines, where water transfers its hydraulic energy and exits out from the system. The turbines are mechanical components, which include runners that are driven by hydraulic energy of water. Depending upon nature of flow parameters and mechanism of energy conversion, the hydro turbines are classified into several types. Francis type of turbines, which harness both kinetic and potential energy in water, are most commonly used in hydropower systems due to its high efficiency and flexibility [5].

Fig. 1 shows cross section of a Francis turbine with flow velocities at respective components. Spiral casing (SC), stay vanes (SV) and guide vanes (GV), together, are often called as the distributor part of turbine. Flow accelerates inside the distributor and normally 50% potential energy is converted to kinetic energy before water enters into runner. GV regulates the flow into runner and gives it correct tangential velocity required for the energy conversion process. Water leaves runner with a high relative velocity and exits through draft tube.

Francis turbines are normally designed with the aim to maximize hydraulic efficiency, minimize size and avoid cavitation [6]. These conditions demands high flow velocity and high blade

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Nomenclature

C	total flow velocity, m/s
C_m	meridional component of C, m/s
C_u	tangential component of C, m/s
E	specific hydraulic energy, jkg^{-1}
g	acceleration due to gravity, m/s^2
H	height of runner, m
H_n	net/effective head to turbine, m
n	rotational speed of runner, s^{-1}
N_{QE}	specific speed,
P	pressure, Pa
Q	discharge through turbine, m^3/s
S	span, m
U	runner peripheral velocity, m/s
W	relative velocity, m/s
β	runner inlet angle, deg
ε	uncertainty, %
η_h	hydraulic efficiency,
ω	runner angular speed, rad/s

Subscripts

in, o	inlet and outlet of respective parts
int	instantaneous
red	reduced
rep	repetition
sys	systematic
t	total

Abbreviations

BEP	best efficiency point
GV	guide vane
GVds	guide vane downstream
IA	interrogation area
IEC	international electrotechnical commission
R	runner
RSI	rotor-stator-interaction
PIV	particle image velocimetry
SC	spiral casing
SV	stay vane; *TGV* test guide vane

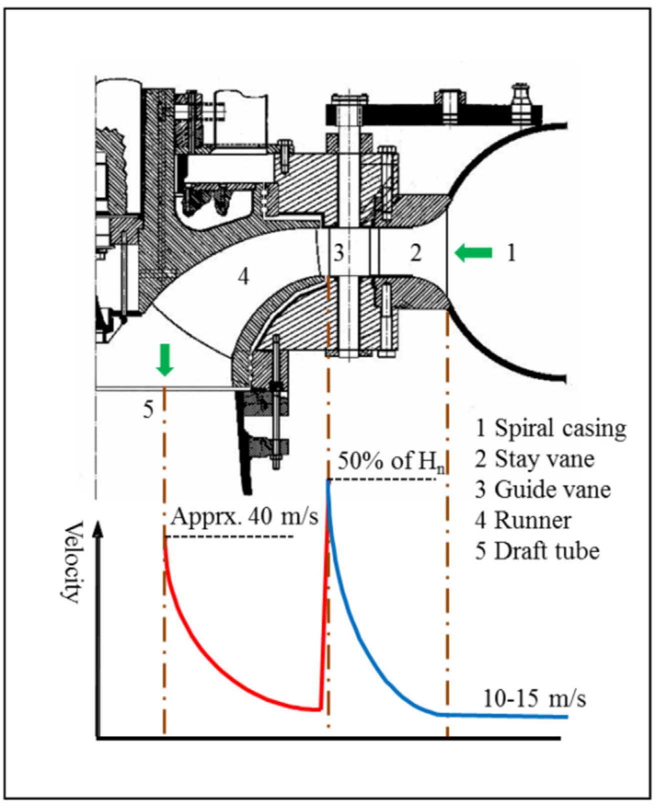

Fig. 1. Velocity distribution inside Francis turbine [1].

loading inside runner. Such conditions induce several undesirable effects, particularly at off design operating points. Secondary flows originating from distributor, and pressure pulsations originating from draft tube, are identified as the most undesirable phenomenon inside Francis turbines [7]. Furthermore, the rotating runner interacts with static distributor and produces periodic disturbance in flow, called as rotor-stator-interaction (RSI). High velocity in distributor produces wake, which further interacts with RSI and downstream flow. These phenomenon cause non-uniform pressure and velocity distribution inside turbine and induce dynamic load on runner [8]. Performance and effective life of a Francis turbine is highly dependent on minimization of such undesirable phenomenon. Operating condition with sediment laden flow and cavitating flows add additional challenges. Problems induced by the eroded surfaces due material removal are often associated with such operating conditions [9].

Different approaches to design and optimize Francis turbine for specific design requirements have been proposed by several researchers [10–12]. Traditional designs methods are specifically developed for the clean water operation and hence such turbines are not operating satisfactorily in sediment laden projects [13]. There has been some attempts for design improvements of Francis turbines for operation in high sediment load, but necessity of further research has been identified for technological advancement [14]. In the future, development of hydropower will occur in across the region, where problem of sediment erosion of mechanical components has been a major challenge [4]. Hence, the optimization of design procedures, to include sediment erosion as one of the design parameters appears as a research gap at present.

The presented work is a part of a study to understand the phenomenon and the effects of sediment erosion in guide vanes on the flow conditions in Francis turbine distributor. A guide vane cascade has been developed to reproduce the flow inside Francis turbine at the prototype operating conditions, with the flexibility of PIV measurements. Pressure and velocity measurements have been conducted to study flow characteristics inside the distributor system. This paper discusses the procedures used to develop the cascade, methods used for PIV measurement technique, and the results for the reference case. The presented results will be used to compare with the cases of eroded guide vanes and optimized designs of guide vanes. The experimental data will also be made available to validate numerical modelling for similar studies.

2. Development of test setup

2.1. Reference turbine

Jhimruk Hydroelectric Centre in Nepal is considered as the reference case for this study. The power plant has three units of