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Numerical and experimental study of the leakage flow in guide vanes with different hydrofoils

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ABSTRACT

Clearance gaps between guide vanes and cover plates of Francis turbines tend to increase in size due to simultaneous effect of secondary flow and erosion in sediment affected hydropower plants. The pressure difference between the two sides of the guide vane induces leakage flow through the gap. This flow enters into the suction side with high acceleration, disturbing the primary flow and causing more erosion and losses in downstream turbine components. A cascade rig containing a single guide vane passage has been built to study the effect of the clearance gap using pressure sensors and PIV (Particle Image Velocimetry) technique. This study focuses on developing a numerical model of the test rig, validating the results with experiments and investigating the behavior of leakage flow numerically. It was observed from both CFD and experiment that the leakage flow forms a passage vortex, which shifts away from the wall while travelling downstream. The streamlines contributing to the formation of this vortex have been discussed. Furthermore, the reference guide vane with symmetrical hydrofoil has been compared with four cambered profiles, in terms of the guide vane loading and the consequent effect on the leakage flow. A dimensionless term called Leakage Flow Factor (L_{ff}) has been introduced to compare the performances of hydrofoils. It is shown that the leakage flow and its effect on increasing losses and erosion can be minimized by changing the pressure distribution over the guide vane.

1. Introduction

The relation between the guide vane wear, leakage flow through clearance gaps and efficiency drop in high head Francis turbines was studied by Brekke (1988) in 1980s. It was seen that the erosion of the facing plates underneath the edges of guide vanes increased the size of the clearance gaps, adding to the losses in the turbine. Although this study was focused on power plants of Norway, the consequences was found to be more apparent and vulnerable in the power plants of Himalaya and Andes, which are exposed to hard sand particles in higher concentration (Bajracharya, Joshi, Saini, & Dahlhaug, 2008; Neopane, Dahlhaug, & Cervantes, 2012; Padhy & Saini, 2008). Fig. 1 shows the guide vanes in Nepalese power plants, which are eroded at the span ends. These ends are connected to the facing plates leaving a small clearance, which provides possibility to change the opening angle based on operating conditions. When the sand particles pass through these gaps with high acceleration, eroded grooves are formed, which eventually increase the gap size. The pressure difference between the pressure and the suction side of the guide vane profile drives the flow into the clearance gap and mixes with the main flow in the suction side. This flow contains circulations, which travels downstream into the runner, causing more damages and losses. The simultaneous nature of the erosion and flow phenomena in Francis turbines and the role of guide vane in this process have been explained by Thapa, Dahlhaug, and Thapa (2014) and Chitrakar, Neopane, and Dahlhaug (2016). In Kaligandaki-A hydropower plant running with the net head and flow of 115 m and 47 m/s^3 respectively. Koirala, Thapa, Neopane, Zhu, and Chhetry (2016) reported that the size of the clearance gap increased from the designed value of 0.6 mm to 2.5 mm in the leading edge and 4.2 mm in the trailing edge in average after 16,500 operational hours due to erosion.

The practices of using numerical techniques (CFD) for predicting the flow fields and erosion in turbines can be found in literatures (Neopane et al., 2012; Thapa, Gjosater, Eltvik, Dahlhaug, & Thapa, 2012). These techniques are also used to optimize the design of the turbine components and investigate the performances of several designs with minimum cost (Chitrakar,

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Nomenclature

L_{ff}	leakage flow factor
PIV	Particle Image Velocimetry
CFD	Computational Fluid Dynamics
LDA	Laser Doppler Anemometry
C_m	meridional velocity component
C_u	tangential velocity component
V_o	reference velocity
SVout	stay vane outlet
GVout	guide vane outlet
GVin	guide vane inlet
Rin	runner inlet
NACA	National Advisory Committee for Aeronautics
C_p	normalized pressure
LE	Leading Edge
TE	Trailing Edge
PS	Pressure Side
SS	Suction Side
C_{TP}	normalized total pressure

Cervantes, & Thapa, 2014; Thapa, Thapa, Eltvik, Gjosater, & Dahlhaug, 2012). However, fidelity of the numerical results depend on the validation with the results from experiments. In general, the prototype turbine is usually scaled down and/or simplified to minimize the cost and effort involved in experiments. In recent studies, the prediction of flow phenomena in Francis turbines using Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) are becoming popular. An LDA measurement was conducted in a guide vane case rig to study the formation of wakes for different guide vane profiles (Antonsen, 2007). The wake flow and Rotor-Stator-Interaction (RSI) phenomena were studied through experimental TRPIV (Transient Particle Image Velocimetry) from a hydrofoil in a stream of 9 m/s, using different angles of attack (Finstad, 2012). A PIV experiment was performed in a complete Francis hydro-turbine model of diameter 0.15 m by using transparent vanes and covers and drilling a hole on the casing at the measurement location for capturing the flow (Su et al., 2014).

The leakage flow through clearance gaps and consequent vortices are studied in many turbomachinery applications. The effect of reduced tip clearance was studied using 3D Navier-Stokes CFD code in a linear turbine cascade (Tallman & Lakshminarayana, 2001). The study focused on types of streamlines at different planes and vortices formed from the gap region for each line. A Stereo Particle Image Velocimetry (SPIV) was used to study the tip leakage vortex (TLV) in a NACA0009 hydrofoil in a simplified case study (Dreyer, Decaix, Munch-Alligne, & Farhat, 2014). This study also used high-speed flow visualization and showed a strong influence of the wall proximity on the vortex path. The authors explained that the shifting of TLV away from the hydrofoil as the result of potential flow effect. Eide (Eide, 2004) explained by building a 2-D numerical model of guide vanes including clearance gap, that out of 5–6% of the total losses developed in a high head Francis runner, around 1.5% is due to the leakage flow in guide vanes. Some qualitative experimental approaches for studying tip leakage vortex through hydrofoils and their effects on cavitation can also be found in a literature (Murayama, Yoshida, & Tsujimoto, 2006).

A single guide vane cascade rig was recently developed in the Waterpower Laboratory at the Norwegian University of Science and Technology (Thapa, Dahlhaug, & Thapa, 2016; Thapa, Trivedi, & Dahlhaug, 2016), which contains a 1:1 scale guide vane of Jhimruk Hydropower Plant, located in Nepal. The power plant (3 × 4.2 MW) runs with a net head of 201.5 m, and 2.35 m^3/s flow in each of the three units. By using PIV, the velocity field around the guide vane can be measured. The rig also allows the measurement of the effect of the clearance gap on the main flow by milling one end of the blade. The pressure measurements can be carried out along the mid-span surface and another end of the blade. The objective of this study is to perform numerical study of the flow inside the same test rig and validate with PIV results. The numerical model is used to compare the leakage flow between different hydrofoil shaped guide vanes. Following sections contain definition of the quantities, which are used to compare the results between CFD and PIV, and between the hydrofoils studied numerically.

1.1. Measured quantities

Fig. 2 shows the boundary of the measurement, which contains two guide vane passages (one on each side). The guide vane is oriented in the opening angle corresponding to the design condition. The figure also shows the circumferential locations corresponding to stay vane outlet (SVout), guide vane inlet (GVin), guide vane outlet (GVout) and runner inlet (Rin) of the real turbine. Although the rig does not include the runner, Rin position is required to investigate how the flow enters the runner. The space between guide vane outlet and runner inlet represents vaneless region of the real turbine. The secondary flow in the form of wakes and leakages through clearance gaps undergo dissipation in this space before reaching the runner inlet. The dissipation of these flows can be visualized in between these two curves. The velocities in Cartesian co-ordinate system is converted into the cylindrical co-ordinate system with the equations:

$$C_m = -(u\cos\theta + v\sin\theta) \tag{1}$$

$$C_u = (u\sin\theta - v\cos\theta) \tag{2}$$

The Cartesian velocity components u, v and the angle θ are explained in Fig. 3. The terms C_u and C_m are the tangential and meridional components of the velocity, which are analogous to

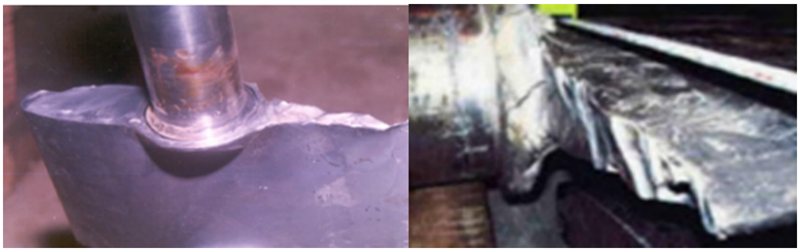

Fig. 1. Erosion of the guide vane ends in Jhimruk (Neopane et al., 2012) and KG-A (Koirala et al., 2016).