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Effect of temperature, suction head and flow velocity on cavitation in a Francis turbine of small hydro power plant

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ABSTRACT

Erosion due to cavitation in hydro turbines is one of the reasons for component failure that costs a lot to the hydro power plants. Inception and development of cavitation depend upon different parameters such as atmospheric pressure, suction head, velocity of flow, temperature, gas content in the liquid and operating hours of the turbine. Parameters generally considered for design of a turbine and are used to predict cavitation could be different at actual site. The cavitation in hydro turbine is predicted during model testing and correlated with specific speed. However the erosion and efficiency decay due to cavitation phenomena of turbines are too complex to stimulate which depends on other operating conditions at site.

Under the present study, an attempt has been made to carry out a numerical analysis to investigate the effect of temperature, suction head and flow velocity on cavitation in a Francis turbine by using CFX code. The experimental investigation has been carried out to validate the numerical method by visualization technique. Using numerical data obtained during analysis for different considered parameters, correlations are developed for efficiency loss and cavitation rate in Francis turbine as a function of these parameters i.e., temperature, suction head and flow velocity.

1. Introduction

Francis and Kaplan turbines basically reaction turbines are suitable for medium and low head hydro power sites. Application of Francis turbine has the higher percentile in all continents [1,2]. Small hydro power projects have potential to meet power requirements of remote and isolated areas and these plants do not associate the problems of deforestation and resettlement. These factors make small hydro projects attractive renewable source of power generation [3]. In India, a hydro power plant having capacity up to 25 MW is classified as SHP (small hydro power). The management of the large and small hydro power plants for achieving maximum efficiency with time is an important factor, but the plant components like turbine show the declining performance after a few years of operation as they get several damages due to many reasons like as erosion due to silt, cavitation, corrosion and fatigue.

One of the significant reasons is cavitation. According to Bernoulli's principles, an increase in velocity in a fluid is accompanied by a decrease in pressure. If at any point liquid flows into a region where the pressure is reduced to vapor pressure, the liquid boils and bubble formation takes place locally and when these bubbles reach to areas of higher pressure, they suddenly a collapse. This process is called cavitation. It produces high pressure pulses, when such collapse takes place adjacent to solid walls continually and at high frequency. The material in that area gets damaged due to pitting of solid surfaces. It causes the problem of noise, vibration in draft tubes and trailing edge of turbine blades and drop in efficiency [4]. Leading edge cavitation, traveling bubble cavitation, von Karman vortex cavitation and draft tube swirl are the main forms of cavitation that can arise in Francis turbines. The cavitation number used for determining the region where cavitation takes place in reaction turbines is called the Thoma cavitation coefficient (σ) or Thoma plant factor (σ_p) and expressed as;

$$\sigma = (H_a - H_v - H_s)/H \tag{1}$$

where Ha is the atmospheric pressure head, Hv is the vapor pressure in corresponding to the water temperature, Hs is the suction pressure at the outlet of reaction turbine or height of the turbine runner above the tail water surface, H is the working head of the

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Nomenclature

A	erosion factor [−]
b	number of blade [−]
B	value of atmospheric pressure less vapor pressure at tail water [N/m^2]
C_f	Plant use factor [−]
D	turbine throat diameter [m]
E	specific energy [m^2/s^2]
g	acceleration due to gravity [m/s^2]
H	working head [m]
Ha	atmospheric head [m]
Hs	suction head [m]
Hv	vapor pressure head [m]
I	erosion depth [mm]
I_c	cavitation intensity [−]
l_c	cavity length [m]
P	erosive power [W]
p	pressure [Pa]
p_a	atmospheric pressure [Pa]
p_v	vapor pressure [Pa]
R	turbine revised runner factor [−]
S	submergence height [m]
SE	material strain energy [−]
γ	specific weight of fluid [N/m^3]
S_t	Strouhal number relating to vortex shedding [−]
t	operation time [s]
U_∞	upstream flow velocity [m/s]
U_m	peripheral speed of model turbine [m/s]
U_r	peripheral speed of prototype turbine [m/s]
V	velocity [m/s]
α	guide vane opening position [degree]
δ_{ij}	Kronecker number [−]
μ	dynamic viscosity [m^2/s]
μ_t	turbulent viscosity [m^2/s]
ρ	density of fluid [kg/m^3]
ρ_m	mixture density [kg/m^3]

turbine. In order to have cavitation free operation of turbine, the parameter σ should be greater than critical cavitation coefficient (σ_c) which is generally determined by the designer/manufacturing of the turbine. Cavitation is not possible to eliminate completely, however it should be minimized and reduced within acceptable limits. The following empirical relationship is used for obtaining the value of σ_c, for Francis turbine [5].

$$\sigma_c = 0.625 \times (N_s/380.78)^2 \quad (2)$$

where Ns is the specific speed of the turbine. The runner design has a clear influence on the cavitation phenomena but there are two other important parameters which influence its inception and development; the machine setting level and the operation at off-design conditions [6]. The cavitation is a complex flow phenomenon and it could not be avoided under off design condition. Traditionally, the studies for cavitation completely rely on experimental model testing, which usually is very difficult, time consuming and costly. The rapid development in the CFD (Computational Fluid Dynamics) with computing power along full graphics plays an important role in conducting inner flow filed analyses in the early design process. CFD provides a cost effective and accurate alternative to model testing with variations on the simulation being performed quickly, offering obvious advantages. Furthermore, it allows engineers to test systems in a virtual environment.

In advancement of CFD technology, CFX code employed Rayleigh–Plesset (R–P) equation for cavitation analysis. It is widely used for the numerical modeling of complex real cavitating flows. Researchers have validated the CFX code in hydro machinery and different hydrofoils under cavitation and they presented a good agreement of results compared with experimental data. The methods of cavitation simulation based on Navier–Stroke equation have received increasing attention due to their superiority in physical modeling and computational capabilities for cavitation problem [7].

A number of studies were carried out on various aspects of cavitation phenomena viz; cavitation erosion, efficiency prediction, vapor volume fraction, frequency in unstable hydraulic behavior, pressure pulsation, cavitation vibration, noise, rotating cavitation and cavitation bubble collapse [8–17,20–22]. Different types of cavitation phenomena and their causes in hydro machines were discussed under some studies [6,8]. Furthermore, visualization of cavitation is becoming an important aspect of cavitation research in model testing [23–25].

A few studies were carried out on the development of erosion models [9,18,19] for hydraulic turbines and hydrofoils based on certain assumptions and field study.

Maekawa et al. [9] developed the relationship between the intensity of cavitation and the progress of erosion. They conducted the cavitation erosion acceleration test using special test equipment. The cavitation intensity was measured using impulse pressure sensors at three different points and found that relates to cavitation intensity is 6th power of peripheral speed, as expressed as;

$$I/t = A \times (Ic/SE) \times (Ur/Um)^6 \quad (3)$$

The empirical equation of the erosive power produced by a leading edge cavity based on 2D hydrofoil proposed by Avellan et al. [18], is given below;

$$P = 0.5\ \rho \times F(C_{pmax} + \sigma) \times S_t \times U_\infty^3 \times lc \quad (4)$$

where $F(C_{pmax} + \sigma)$ is a characteristic function of hydrofoil with influence of σ (cavitation number) and C_{pmax} is the maximum pressure coefficient. Gorden [19] suggested the correlation which is based on analysis of turbine cavitation data obtained from 729 numbers of hydro turbines. The cavitation erosion rate or weight loss in kg is an expressed as;

$$W = 2.178^m \times d^2 \quad (5)$$

where $m = 0.45V^2b - 0.56 + 2.3C_f - S - B - R$; V is velocity in m/s, b is the number of blades, C_f is plant use factor, S is submergence height in m, B is barometric pressure in m, R is turbine revise runner factor. Further, Xavier et al. [26] developed a correlation for cavitation intensity, having an exponent value of velocity as 6.7. Meulen and J. H. J [27] found that the intensity of the emitted cavitation luminescence with the exponent value of velocity between 3.9 and 7.2. Stinebring et al. [28] reported that the pitting rate scales with 6th power of velocity in the case of hydrofoil. Based on some study [29] it is reported that cavitation erosion inspections on a turbine may cost US $5000 in manpower and up to US $50 per