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A review of microscopic interactions between cavitation bubbles and particles in silt-laden flow

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ABSTRACT

Erosion through synergetic effects between cavitation erosion and particle abrasion in silt-laden flow seriously affects the safe operations of hydroturbines. In this review, recent advances of cavitation inception on particles and microscopic interactions between bubbles and particles are reviewed and discussed. For cavitation inception, influences of several paramount parameters (e.g. types, sizes, shape and surface structure of particles, pressurization and memory effects) have been revealed and discussed. The interaction mechanisms between cavitation bubbles and particles are demonstrated using experimental data obtained with a single particle. Through the microscopic interactions, the particles can be accelerated by the collapsing bubbles up to 40 m/s and also be possibly split up by the cavitation, leading to deagglomeration of particle clusters.

Contents

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1. Introduction

As a well-known kind of renewable energy, hydropower plays an important role in the current energy supplying system [1,2]. Both large-scale hydroturbines (e.g. Francis turbines with the capacity of a single unit over 1000 MW [3]) and small-scale hydropower technologies [4–7] (e.g. pump as turbine technology [4]) are being vastly developed worldwidely together with the upgrading of the existing power plants [8]. Some special types of hydroturbines (e.g. reversible pump turbine [9–12]) has also attracted much attention due to the rapid increase of the wind and solar energies. With the fast development of the renewable energies (e.g. wind and solar energy), great instability problems of electrical grid are raised by the fluctuation of the output of those renewable energy (e.g. wind turbines in still days or solar power stations in cloudy days). If such kind of fluctuation exceeds certain amount, electricity generated by the above wind or solar power stations will be rejected by the electrical grid, leading to great economic losses. One of solutions to relieve the grid instabilities is the hydropower plant. Except the well-known reversible-pump turbine of pumped storage hydropower plant, the large-scale Francis turbine (with capacity of a single unit over 1000 MW) could be turned on or off easily on short notice (within several hours), serving as a source to follow the demand of the grid. Hence, currently, large-scale Francis turbine is also quite essential for the development of renewable energy. For example, the Francis turbines in many countries (e.g. Norway) are being required to be operated in a more wider range of parameter zone to meet the rapid change of power demand in the grid. Such kind of coordination or integration between hydropower and renewable energy is crucial for the raise of the penetration level of the renewable energy.

About the current researches on the hydroturbines, there are many paramount topics (e.g. efficiency enhancement [13], on-site monitoring [14,15], cavitation [16–18], vibration control strategies [19], and hydraulic transients [20]). Speaking of the cavitation research, it is well-known that the cavitation accelerated silt erosion is one of current challenges of hydroturbines (e.g. large-scale Francis turbine). Hence, the understanding of the underlying synergetic mechanisms between cavitation and particles is of significant importance for the development of both hydroturbine technology and renewable energy. According to the survey [21], over one third of the hydro turbines in China suffers from the abrasive erosion due to synergetic mechanism of cavitation erosion and particle abrasion.

Abrasive erosion can cause serious damage to the hydro turbines in many ways [22]. Firstly, abrasive erosion can affect safe operations of hydro power plant. The abrasive erosion can lead to the decrease of the efficiency of the hydroturbines, generation of noise and vibrations and possibly unplanned stop of the power plant. Secondly, abrasive erosion can reduce the repair duration of hydroturbines, increase the loss of materials and the number of components of hydroturbines for backup.

The particles in silt-laden flow can promote the occurrence of the cavitation through increasing the nuclei in the water. For example, Toshima et al. [23] reported that the incipient cavitation site numbers in silt-laden water can increase by 10–15% comparing with those in the tap water. One of the characteristics of abrasive erosion is that under certain conditions, the effects of cavitation erosion and particle abrasion can promote each other, leading to a fast and serious damage to the components of hydroturbines. For example, Brekke et al. [24] found that the needle tip of a Pelton turbine was seriously eroded by the coexistence of cavitation and silt erosion (as shown in Fig.1). After 300-hour operation, minor silt erosion was shown at the needle tip of the turbine. Owing to the initial damage to the surface, cavitation happens, acting effectively with erosion process and leading to a significant damage rate. After only another 300-hour operation, the needle tip has been damaged so seriously (referring to Fig.1b) that it should be replaced. For some cases, the extensive damage caused by erosion happens again even after repairment, leading to a great challenge to the safe operation of hydroturbines. For example, serious damage was observed at Tiloth hydropower station on the river Bhagirathi after 2600-hour operation however damage was observed again within 3000–5000 hours operation after repairment [25].

In the literature, many reviews and monographs [22,25–29] exist to reveal the mechanisms of the serious damage caused by synergies of cavitation and particles. Duan and Karelin [22] reviewed the abrasive erosion and corrosion in hydraulic

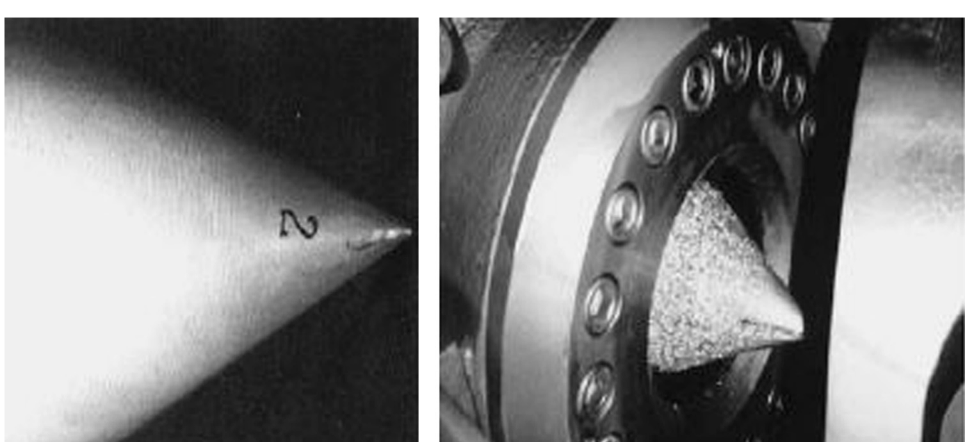

Fig. 1. A sample of synergetic erosion inside a Pelton turbine. (a) Initial stage with 300-hour operations with silt erosion on the needle tip; (b) subsequent synergetic erosion with 600-hour operations on the needle tip. The figure was adapted from Brekke et al. [24].