International Journal of Heat and Fluid Flow 71 (2018) 460–469

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Experimental investigation of flow patterns and external performance of a centrifugal pump that transports gas-liquid two-phase mixtures

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ARTICLE INFO

Keywords:
Centrifugal pump
Gas-liquid two-phase flow
Flow pattern
Inlet gas volume fraction
External performance
High-speed photography

ABSTRACT

In order to reveal the mechanism of two-phase flow inside a centrifugal pump, visualization experiments were performed to investigate the gas-liquid two-phase flow patterns by using high-speed photography. Meanwhile, the external performance of the pump was measured under different conditions. The flow patterns in the suction pipe can be classified into plug flow and stratified flow distinguished by the critical inlet gas volume fraction (*IGVF*) of 6.2%. The critical *IGVF* of the pump is not obviously influenced by the rotational speed and initial liquid volume flow rate. The flow patterns in the impeller and volute can be classified into four categories with the increasing *IGVF*. The liquid volume flow rate has a small change in the condition of isolated bubbles flow, an obvious decrease in the condition of bubbly flow, a sharp decrease in the condition of gas pocket flow, and a gentle reduction in the condition of gas-liquid separation flow. Once the *IGVF* reaches the critical value, some bubbles in the volute begin to flow back into the impeller near the volute tongue. When the flow pattern transfers from gas pocket flow to gas-liquid separation flow, some bubbles in the discharge pipe flow back into the impeller. When the height of gas in the suction pipe reaches a critical value about 70 mm, bubbles sometimes flow into the volute and sometimes flow back into impeller, and the liquid volume flow rate is nearly to be zero. The differential pressure of the pump decreases with the increase of *IGVF*, and it decreases with the increase of initial liquid volume flow rate at the same *IGVF*.

1. Introduction

Centrifugal pumps are wildly used in petroleum, chemical and nuclear industries. They run most efficiently when transporting single-phase fluid. In fact, the presence of gas causes head and liquid flow rate degradation (Li, 2016; Huang et al., 2014). Undoubtedly, the separation of gas and liquid has some influence on the normal transportation of fluids (Neumann et al., 2016; Tremante et al., 2002; Fu et al., 2015). Moreover, if the inlet gas volume fraction (*IGVF*) exceeds a certain value, the centrifugal pump will be blocked by the gas, and the performance of the centrifugal pump decreases dramatically. However, the physical mechanism that governs the two-phase flow is not well understood. Hence, it is very important and necessary to study the flow pattern within the centrifugal pump and its effect on the hydraulic performance.

Many investigations on the flow of the gas-liquid two-phase in the pumps have been carried out in recent years (Caridad and Kenyery, 2005; Lissett Barrios and Prado, 2011a,b; Sun and Prado, 2005; Gruselle et al., 2011). Zhu et al. (2008) studied the performance of a centrifugal-vortex pump for gas-liquid two-phase mixtures compared with pure-water experimental results. They analyzed the effect of gas phase on pump performance and presented a design method of small-flow high-head centrifugal-vortex pump. Zhang et al. (2015, 2016) carried out visualization experiments to investigate the gas-liquid two-phase flow patterns at the entry section and the impellers inside a multiphase pump under different operating conditions. They found that the average diameter of the bubbles increased with the increase of the *IGVF* but decreased with the increase of the rotational speed. According to the captured flow phenomena, they classified the flow patterns in the impellers into four categories. Wang et al. (2016) proposed a new developed gas-liquid flow computational model, named two-phase three-component computational model, to improve the numerical simulation accuracy for predicting the cavitating flow in centrifugal pumps. Caridad et al. (2008) investigated the characterization of a centrifugal pump impeller under two-phase flow conditions by numerical simulation. They discussed the relationship among the impeller head, the relative flow angle at the outlet and the liquid flow rate, and performed a sensibility analysis with regard to

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https://doi.org/10.1016/j.ijheatfluidflow.2018.05.011
Received 2 September 2017; Received in revised form 12 May 2018; Accepted 12 May 2018
Available online 18 May 2018
0142-727X/

the gas-void fraction and the bubble diameter. Caridad and Kenyery (2004) used a two fluid model in three-dimensional CFD simulations to obtain the pressure, liquid and gas velocity fields as well as the gas volume fraction distribution inside a submersible pump impeller in the hypothesis of an incompressible fluid. They pointed out that the weakness of the turbulence models for two-phase flow needed to be overcome in order to carry out more rigorous analysis. Of course, this should be based on a deep and comprehensive understanding of the two-phase flow in the pump.

However, the flow through centrifugal pumps is quite complex, and there are many factors affecting the flow, such as pump geometry, rotational speed, suction pressure, initial liquid flow rate, *IGVF*, etc. (Matsushita et al., 2009; Paternost et al., 2015; Zhang et al., 2014). Moreover, it is difficult to visualize the flow field experimentally as well as to obtain the velocity profile for each of the phases exactly. Due to the lack of understanding of two-phase flow in the pump, most of the existing models and correlations which estimate the performance deterioration in such kind of centrifugal pumps are merely empirical. So far, it is still a difficult task to predict the performance of centrifugal pumps carrying gas-liquid two-phase mixtures accurately.

In this paper, water and air are selected as the liquid phase and gas phase, respectively. In order to reveal the evolution law of flow in the centrifugal pump with the increase of the *IGVF*, an ordinary camera is adopted to record the whole test process. And the flow in the pump is captured by a high-speed camera under different working conditions to further investigate the movement law of bubbles and gas-liquid two-phase flow patterns. In the previous study, researchers mainly paid attention to the flow in the impeller (Murakami and Minemura, 1974a,b, Minemura et al., 1985). In this paper, the flow in the suction pipe and the volute is also studied. Usually, predecessors mainly studied the flow when the *IGVF* was less than the critical value. Based on this, the research of the flow after reaching the critical value is carried out in this paper, and the relationship among flow patterns, *IGVF*, liquid flow rate Q_g and height of the gas in the suction pipe h_g is revealed. The results of the experiment can provide a reference for the operation and optimization of the centrifugal pump.

2. Experimental apparatus and principle

2.1. Test bench

The test bench, which is shown in Fig. 1, is primarily composed of a liquid circulation line, a gas line, a centrifugal pump, a motor, a frequency converter, a water tank, a data acquisition system and a high-speed camera. The main instruments used in test bench are listed in Table 1. Under the design condition, the standard deviations of head, flow rate, shaft-power and total efficiency are 0.097 m, 0.045 m^3/h, 3.480 W and 0.298%, respectively.

First, air driven by an air pump enters the liquid circulation line and mixes with water before the centrifugal pump. Then, the mixture of air and water enters the centrifugal pump for pressurization. Furthermore, the mixture is discharged from the centrifugal pump to the water tank. Subsequently, the water is recirculated in the liquid circulation line and the air is released from the top of the water tank.

Table 1
Main instruments used in the experiment.

Instrument	Type	Parameters	Measuring range	Accuracy
Rotary flow meter	LZB-6WB	Gas flow rate	1–40 L/min	2.5%
Turbine flow meter	LWGY-50A0A3T	Liquid flow rate	2–40 m^3/h	0.5%
Pressure transmitter	WT2000	Pressure at the inlet	−100–100 kPa	0.1%
		Pressure at the outlet	0–1.2 MPa	0.1%
Rotational speed detector	SZGB-6	Rotational speed of the pump	1–30,000 rpm	0.1%

The objective of this test is to study the influence of the *IGVF* and rotational speed on the flow patterns and external performance. Thus, the test is carried out under the following conditions: *IGVF* over the range from 0% to critical *IGVF* and rotational speeds of 950 rpm, 1200 rpm and 1450 rpm. The *IGVF* can be calculated by:

$$IGVF = Q_g/(Q_g + Q_l) \tag{1}$$

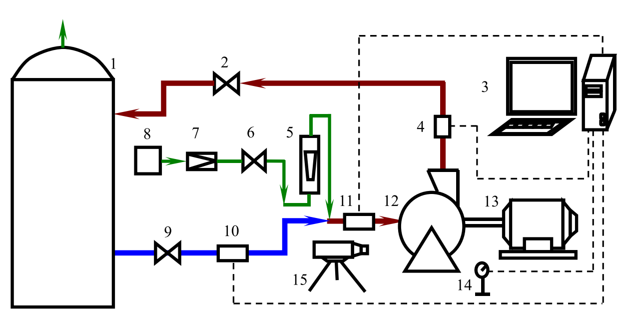
2.2. Centrifugal pump

In order to perform the visualization measurement of the gas-liquid two-phase flow in the centrifugal pump, both the volute and impeller are made of acrylic, which provides good transparency. The structure of the pump is based on the IS80-50-250 type centrifugal pump. The primary structure and design parameters of the centrifugal pump are listed in Table 2. The impeller is shown in Fig. 2. The overall shape of the pump can be seen in Section 3.1.

2.3. Visualization measurement method

The key to the success of two-phase flow measurement in the centrifugal pump is to take clear bubble images. In this paper, an i-SPEED 3 type high-speed camera is used to capture the flow in the pump. Meanwhile, a common camera is used to record the whole process of the test.

Due to the limitation of the test space, the centrifugal pump is divided into four regions A, B, C and D. The four regions and the layout of the high-speed camera are shown in Fig. 3. The flow around the volute tongue in region A can disturb the flow at the impeller outlet and can be



1-water tank, 2-regulating valve, 3-computer, 4-pressure transmitter at pump outlet, 5- rotary flow meter, 6-gas control valve, 7-pressure reducing valve, 8-air pump, 9-ball valve, 10-turbine flow meter, 11-pressure transmitter at pump inlet, 12-centrifugal pump, 13-motor, 14- rotational speed detector, 15-high-speed camera

Fig. 1. Schematic diagram of the centrifugal pump test bench.