Energy Conversion and Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Unsteady numerical simulation for gas–liquid two-phase flow in self-priming process of centrifugal pump

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Self-priming pump
Self-priming process
Gas–liquid two-phase flow
Void fraction
Unsteady numerical simulation

ABSTRACT

Self-priming pumps start up without pre-irrigation, and then work as common pumps when air in the pump is exhausted. The transient gas–liquid flow at the start-up stage inside a self-priming pump is an interesting process which greatly influences performance of the pump. In this paper, a conventional vertical self-priming centrifugal pump was selected as the object. Using unsteady numerical simulation, the authors investigated the transient gas–liquid two-phase flow in the self-priming centrifugal pump during the self-priming process. The main innovation in the simulation was that a section of the suction pipe filled with air was set as the initial condition, which conformed to the actual self-priming conditions. The gas–liquid two-phase distribution, the pressure and velocity in relation to time were computed and analyzed. Flow rates of both phases with time at the pump inlet and outlet were obtained based on the simulation, which could be used to estimate the self-priming time and other performance parameters. Finally, the numerical method and results for gas–liquid two-phase flow in the self-priming pump was partly validated by the pump performance test.

1. Introduction

Self-priming centrifugal pumps, with the advantages of convenient use, simple operation, reliable work and other characteristics, are widely applied to energy, agriculture, mining, chemical industry and other fields [1,2].

Based on the self-priming principle, the self-priming pumps can be classified into two types: the outside-mixing type and the inside-mixing type. The inside-mixing type is the one in which gas and liquid mix each other all the way from the impeller inlet to the pump outlet. The outside-mixing type is the one in which two phases mix only outside the impeller. Due to simplicity of structure, the outside-mixing self-priming pumps are more widely used all over the world. Self-priming pump first works as a vacuum pump after start-up. While the air in the suction pipe is exhausted, the machine turns into the common water pump. Thus, the performance of self-priming pump includes both pump and self-priming characteristics such as the self-priming time and the self-priming height, which are usually determined by measurement.

With the rapid development of computing technology, some numerical simulations were recently performed on gas–liquid two-phase flow in centrifugal pump, to understand flow field and hydraulic performance of centrifugal pumps. Researchers once carried out studies on the two-phase flow in which fluids and bubbles were researched by convergent multiphase flow numerical methods [3–9]. Kiyoshi and Tomomi predicted the behavior of gas–liquid two-phase flows in a centrifugal pump impeller using a homogeneous bubbly flow model. The calculation obtained the velocity and the void fraction that were conformed with experiment [4]. There were also papers introducing gas–liquid flow in self-priming pumps [10–14]. A study investigated the inner flow and distribution of gas and liquid phase in the self-priming pump assuming certain void fractions [11]. Another study combined with rotational speed curve of the impeller and pressure curve of the pump outlet from tests, and took them as boundary conditions in simulation. The results suggested that approach was good in simulating the two-phase flow in the pump during starting period [12,13]. Besides, studies were done under way to improve the self-priming ability [15,16]. An analysis used orthogonal design to discuss structural parameters of a self-priming pump volume to get optimization designs [15]. Furthermore, the very important self-priming process would take place on the moment pump started. Thus the research progress on the unsteady flow due to transient operation would promote the movement on self-priming mechanism. It is reported that transient operation would lead to great changes of the performance of a centrifugal pump [17–22]. However, modeling in these simulations was based on the

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http://dx.doi.org/10.1016/j.enconman.2014.03.023
0196-8904/

Please cite this article in press as: Huang S et al. Unsteady numerical simulation for gas–liquid two-phase flow in self-priming process of centrifugal pump. Energy Convers Manage (2014), http://dx.doi.org/10.1016/j.enconman.2014.03.023

boundary conditions that void fractions were fixed at the pump entrance. Actually, the inlet pipe is always filled with a long distance of air. Thus the boundary conditions are considerably different from practical situation that a part of suction line is filled with air before start-up. Furthermore, the void fraction at pump entrance varies with time greatly during the self-priming process. In this paper, therefore, a section of the suction pipe filled with air was set as the initial condition to simulate the transient gas–liquid two-phase flow in an outside-mixing self-priming centrifugal pump during the self-priming process.

2. Calculation method

2.1. Main configuration of the self-priming centrifugal pump

A common vertical outside-mixing self-priming centrifugal pump was selected as the research object. Its performance parameters at design point was mass flow $q_v = 80\ m^3/h$, head $H = 36$ m, rotation speed $n = 2900$ r/min. The main configuration parameters of the pump were listed in Table 1. Besides impeller and volute, the self-priming pump also consisted of a liquid-storage chamber and a gas–liquid separated chamber. There was a hole (opening) at the volute to enable air out of the volute, and there was a board in the gas–liquid separated chamber to make the air move upwards and be exhausted from the pump outlet.

2.2. Mathematic models for two-phase flow

There are Lagrangian and Eulerian two modeling techniques for multiphase flow analysis. The Eulerian approach is more complex but generally can simulate flows with wide range of volume fraction. In this approach, the different phases are treated as interpenetrating continua. Conservation equations for each phase are derived to obtain a set of equations with regard to momentum, continuity and energy. On the other hand, the investigated case is turbulently two-phase flow so a turbulence model should be properly chosen to close the Reynolds average Navier–Stokes (RANS) equations. Some researchers [23–24] compared different turbulence models along with the standard logarithmic wall functions with the experimental data for rotating pumps and concluded that the standard k–e model had a satisfactory agreement. Hence, Eulerian multiphase approach along with standard k–e turbulence model was used. Considering the general situation with total phase number N, the conservation equations for phase qth are [25] :

Table 1
Main configuration parameters of the vertical self-priming centrifugal pump.

Components	Parameter	Unit	Value
Pipeline	Diameter	mm	100
	Length	mm	495
Liquid-storage chamber	Diameter	mm	380
	Height	mm	250
Gas–liquid separated chamber	Diameter	mm	380
	Height	mm	180
	Board	mm	65 × 100 × 10
Volute	Outlet	mm	65 × 70
	Hole's Diameter	mm	22
Impeller	Revolution	rpm	2900
	Outlet width	mm	35
	Outlet diameter	mm	185
	Inlet diameter	mm	110
	Installation height	mm	200
	Blade Number		6

Continuity equation:

$$\frac{\partial \alpha_q}{\partial t} + \nabla \cdot (\alpha_q \vec{v}_q) = 0 \tag{1}$$

Momentum Equations:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{v}_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \vec{v}_q) = -\alpha_q \nabla_p + \nabla \cdot [\tau_q] + \alpha_q \rho_q \vec{g} + \alpha_q \rho_q (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{Vm,q}) + \sum_{p=1}^{n} K_{pq}(\vec{v}_p - \vec{v}_q) \tag{2}$$

Phase stress–strain tensor:

$$[\bar{\tau}_q] = \alpha_q \mu_q (\nabla \vec{v}_q + \nabla \vec{v}_q^{\,T}) + \alpha_q \left(\lambda_q - \frac{2}{3}\mu_g\right) \nabla \cdot \vec{v}_q [I] \tag{3}$$

Reynolds stress tensor:

$$[\tau'_q] = -\frac{2}{3}(\rho_q k_q + \rho_q \mu_{t,q} \nabla \cdot \vec{v}_q)[I] + \rho_q \mu_{t,q} (\nabla \vec{v}_q + \nabla \vec{v}_q^{\,T}) \tag{4}$$

Turbulent viscosity:

$$\mu_{t,q} = \rho_q C_\mu \frac{k_q^2}{\varepsilon_q} \tag{5}$$

Turbulent kinetic energy k_q:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q k_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q k_q) = \nabla \cdot \left(\alpha_q \frac{\mu_{t,q}}{\sigma_k} \nabla k_q\right) + (\alpha_q G_{k,q} - \alpha_q \rho_q \varepsilon_q) + \sum_{l=1}^{N} K_{lq}(C_{lq} k_l - C_{ql} k_q) - \sum_{l=1}^{N} K_{lq}(\vec{v}_l - \vec{v}_q) \cdot \frac{\mu_{t,l}}{\alpha_l \sigma_l} \nabla \alpha_l + \sum_{l=1}^{N} K_{lq}(\vec{v}_l - \vec{v}_q) \cdot \frac{\mu_{t,q}}{\alpha_q \sigma_q} \nabla \alpha_q \tag{6}$$

Turbulent dissipation ratio ε_q:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \varepsilon_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \varepsilon_q) = \nabla \cdot \left(\alpha_q \frac{\mu_{t,q}}{\sigma_\varepsilon} \nabla \varepsilon_q\right) + \frac{\varepsilon_q}{k_q}\left[C_{1\varepsilon} \alpha_q G_{k,q} - C_{2\varepsilon} \alpha_q \rho_q \varepsilon_q + C_{3\varepsilon}\left(\sum_{l=1}^{N} K_{lq}(C_{lq} k_l - C_{ql} k_q) - \sum_{l=1}^{N} K_{lq}(\vec{v}_l - \vec{v}_q) \cdot \frac{\mu_{t,l}}{\alpha_l \sigma_l} \nabla \alpha_l + \sum_{l=1}^{N} K_{lq}(\vec{v}_l - \vec{v}_q) \cdot \frac{\mu_{t,q}}{\alpha_q \sigma_q} \nabla \alpha_q\right)\right] \tag{7}$$

where α_q is volume fraction of phase qth. λ_q and μ_q are bulk viscosity and shear one. $\vec{g}$ is acceleration due to gravity. K_{pq} is coefficient of the momentum exchange term for turbulent flows. $\vec{F}_{lift,q}$, $\vec{F}_q$ and $\vec{F}_{Vm,q}$, are the lift force, external body force and virtual mass force, respectively. Eqs. (1)–(7) constitute the closure formulations for the current simulation. The detailed relevant coefficients in these equations can be referred to Ref. [25].

2.3. Computational domains and meshes

A 3-D computational domain in the self-priming pump was created by the Pro/E software, as shown in Fig. 1. Fig. 1(a) is the whole view of the self-priming pump. The liquid-storage chamber was connected with the suction pipe. The impeller and the volute were located in the gas–liquid separated chamber right above the liquid storage chamber. Fig. 1(b) is the local view of the gas–liquid separated chamber. The locations of the volute hole, of the volute outlet and of the board can be clearly seen in Fig. 1(b).

The 3-D computational domain was imported into the ANSYS–ICEM software to generate the structured and unstructured