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Experimental investigations on a common centrifugal pump operating under gas entrainment conditions

Thomas Schäfer [a,*], Martin Neumann [b], André Bieberle [a], Uwe Hampel [a,b]

[a] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Fluid Dynamics, Germany*
[b] *Technische Universität Dresden, AREVA Endowed Chair of Imaging Techniques in Energy and Process Engineering, Germany*

HIGHLIGHTS

- The pump performance has been evaluated for several gas entrainment conditions.
- The gas entraining flow regime has a large impact on the pump performance.
- High-resolution gamma-ray computed tomography (HireCT) has been applied.
- Gas holdup inside the operating impeller has been visualized and quantified.
- Gas holdup profiles along selected streamlines have been calculated.

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ABSTRACT

This paper presents an experimental study on the effects of additional gas entrainment in centrifugal pumps designed for conveying liquid phases only. The pump performance has been evaluated for several gas entrainment conditions, and for various operational settings of the pump, such as its alignment and the rotational speed of the impeller. As a main performance indicator the impact of entrained gas on the hydraulic power of the pump has been analyzed using experimental data. Additionally, high-resolution gamma-ray computed tomography (HireCT) operated in time-averaged rotation-synchronized scanning mode has been applied to quantify local phase fraction distributions inside the rapidly rotating pump impeller. Based on these quantitative tomographic measurements, gas holdup profiles along selected streamlines have been calculated and gas accumulation areas inside the impeller chambers have been visualized. Thus, various internally accumulated gas holdup patterns have been identified and, eventually, associated with characteristic pump performance behaviors. Moreover, the tomographic measuring method allowed an enhanced gas holdup analysis in specified pump compartments. As a result, the related specific gas and liquid phase holdup profiles have been evaluated.

1. Introduction

The reliable operation of pumps in power stations is essential for highly available, efficient and safe generation of electricity. For example, in nuclear power stations with light water reactors, emergency core cooling systems are operated with centrifugal pumps. During a loss-of-coolant accident (LOCA) they continuously convey the coolant to steadily discharge all decay heat produced inside the core. Therefore, coolant is taken from reservoirs, which are, for example, the condensation chambers or the reactor sump. Since the coolant in these reservoirs has free surfaces, gas entrainment due to hollow vortex formation may occur. The vortex formation is initiated by small surface vortices, which are always present in such reservoirs, and can lead to large developed gas entraining hollow vortices (Hecker, 1981). This process depends on various conditions, such as the suction rate of the coolant, the critical submergence of the intake and its geometry, as well as the fluid properties of the coolant (Caruso et al., 2014; Kimura et al., 2008). Gas entrainment into the coolant results in a gas/liquid two-phase flow, which passes the subsequently connected system components of the cooling circuit, like pumps and valves. Preferably, gas entrainment should be avoided, since these system components are usually designed for single-phase liquid flow and the entrained gas may lead to undesired operational states, attended by vibrations and increased mechanical load, which can even damage these components.

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[*] Corresponding author.
E-mail address: thomas.schaefer@hzdr.de (T. Schäfer).

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In the past, several experimental and numerical studies have been performed, to investigate the operation behavior of centrifugal pumps under various operation conditions. Operation of centrifugal pumps under single-phase flow conditions has been investigated, for example, regarding effects like flow induced pressure pulsations and resulting vibrations and noise (Suhane, 2012) or during start up (Zhang et al., 2013). Furthermore, effects of unsteady flow patterns, resulting from pressure fluctuations, on the pump operation have been analyzed, using numerical models (Gonzalez and Santolaria, 2006). Also the influence of the impeller geometries on the hydrodynamics of centrifugal pumps have been numerically investigated and improved designs have been verified (Grapsas et al., 2007; Zhou et al., 2013).

Moreover, observations on centrifugal pumps operating under two-phase flow conditions have been reported. Amongst others, scale model pumps were analyzed in the event of a LOCA by conducting blow down test (Narabayashi et al., 1985) or a full-size nuclear reactor pump was experimentally investigated under high pressure steam/water two-phase flow conditions (Chan et al., 1999). Furthermore, in comparison to experimental results, the gas fraction, pressure and velocity in the impeller of a centrifugal pump were numerically calculated, applying Reynolds-averaged Navier-Stokes equations (Pak and Lee, 1998), or consequences of two-phase flow due to cavitation were identified (Duplaa et al., 2013; Tan et al., 2013; Coutier-Delgosha et al., 2003). Another numerical study was focused on the influence of bubble diameter and void fraction of entrained gas on the pump operation (Caridad et al., 2008). Recently, the gas accumulation inside a closed impeller of an industrial centrifugal pump under various gas entrainment conditions has been quantified, and corresponding gas holdup areas have been visualized, using high-resolution gamma-ray computed tomography (Schäfer et al., 2015; Neumann et al., 2016).

This study contributes to a better understanding of the impacts of gas entrainment on the performance of centrifugal pumps and provides additional knowledge to operate centrifugal pumps under such conditions or even to improve the pump design correspondingly. Besides, additional datasets are provided for a better modelling of two-phase flows in centrifugal pumps, which may improve future CFD calculations.

2. Materials and methods

In this experimental study a common industrial centrifugal pump (Etachrom BC 032-160/074 C11, KSB) has been investigated, equipped with a closed radial multi vane impeller. The centrifugal pump can be installed either horizontally or vertically, regarding to the impeller orientation, and it is connected to a flow loop, where a defined gas-liquid two-phase flow is circulated by the investigated pump itself. For the experiments, tap water is used as liquid phase and de-oiled pressurized air as gas phase. The liquid is stored in a 600 l reservoir. The liquid flow rate is measured by a magnetic inductive liquid flow meter (MAG 1100 and MAG 6000, Siemens, ±0.25% FS for liquid velocity >0.5 m/s). The liquid flow meter and a liquid temperature sensor (PT100, ±0.5 K) are installed upstream of the pump, between the liquid reservoir and an in-house developed gas injection module. Here, gas is injected via four hole-type nozzles, which are uniformly arranged around the circumference of the pipe. The gas injection module is installed at the suction side of the pump and provides an adjustable gas-liquid two-phase flow. The injected gas volume fraction ε_{in} ($0 \leqslant \varepsilon_{in} < 1$) can be adjusted and the required gas flow rate Q_G is controlled by an air mass flow controller (FMA2600, Omega Newport, ±0.2% FS), which is triggered by a programmable logic controller (SPS-ILC350ETH, Phoenix Contact) considering the current liquid flow rate Q_L according to

$$Q_G = \frac{\varepsilon_{in}}{1 - \varepsilon_{in}} \cdot Q_L. \tag{1}$$

Optionally, a sophisticated swirl element can be installed inside the gas injection module behind the gas inlet nozzles to adjust the flow regime of the two-phase flow (Fig. 1a). Thus, for the experiments, both typical flow regimes, occurring at gas entrainment due to hollow vortex formation, can be provided at the suction side of the pump. These are either a gas-liquid flow with disperse gas phase ("bubbly two-phase flow") (Fig. 1b) or a swirling gas-liquid flow with central formed gas core ("swirling two-phase flow") (Fig. 1c).

Furthermore, a heat exchanger (C200 301-1, Funke) in combination with a controlled thermostat (Unistat Tango) is installed in the flow loop at the pressure side of the centrifugal pump to provide a constant liquid temperature of $T = 30\,^{\circ}\mathrm{C}$ for the experiments. The two-phase flow is conveyed from the gas injection module through the centrifugal pump and the heat exchanger back to the liquid reservoir which acts also as a two-staged separator. Here, the injected gas phase is separated from the liquid phase. Furthermore, the flow loop is instrumented with two pressure sensors to measure the relative pressure at the suction side (PXM419-001BCGI, Omega Newport, ±0.08% FS) and the differential pressure across the pump (PD23, Omega Newport, ±0.5% FS).

Additionally, high-resolution gamma-ray computed tomography (HireCT) (Hampel et al., 2007; Bieberle et al., 2012, 2013; Schubert et al., 2011) has been applied to discover the phase distribution inside the operating pump impeller by contactless measurement. The HireCT-system is able to scan objects, which have a maximal diameter of 700 mm. It consists of a temperature stabilized detector arc including 320 scintillation detector elements with a sensitive area of 2 mm × 4 mm and is operated with a collimated isotopic source (^{137}Cs, energy: 662 keV, activity: 180 GBq). The investigated centrifugal pump was placed between the source and the detector arc, which are both fixed on a movable desk.

To resolve the phase fraction distribution inside the fast rotating impeller of the operating pump sharply, tomographic scans are synchronized with the rotational speed of the impeller (Fig. 2). Therefore, the rotational speed is measured, using a Hall-effect sensor (GS105502, ZF Electronics). The Hall-effect sensor is placed close to the driving shaft and is connected directly to the HireCT-scanner. This advanced CT measuring method, which is known as time-averaged rotation-synchronized computed tomog-

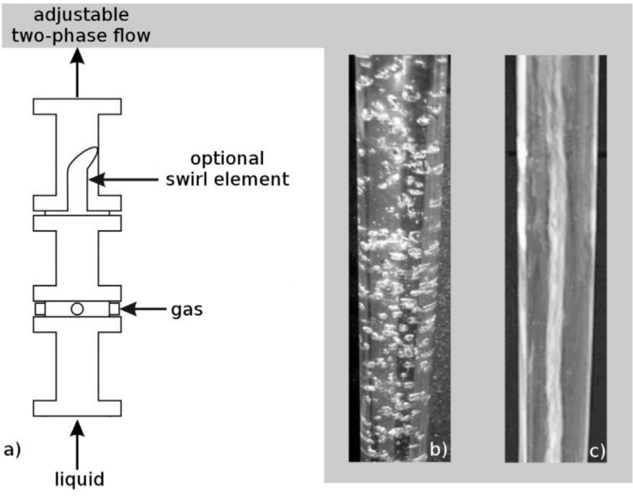

Fig. 1. a) Sketch of the multi-mode gas injection module and adjustable flow regimes: b) gas-liquid flow with disperse gas phase ("bubbly two-phase flow") and c) swirling gas-liquid flow with central formed gas core ("swirling two-phase flow").