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IR measurements of the thermodynamic effects in cavitating flow

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ABSTRACT

The understanding of the thermodynamic effects of cavitating flow is crucial for applications like turbopumps for liquid hydrogen LH2 and oxygen LOx in space launcher engines. Experimental studies of this phenomenon are rare as most of them were performed in the 1960s and 1970s. The present study presents time resolved IR (Infra-Red) measurements of thermodynamic effects of cavitating flow in a Venturi nozzle.

Developed cavitating flow of hot water (95 °C) was observed at different operating conditions – both conventional high speed visualization and high speed IR thermography were used to evaluate the flow parameters.

Both the mean features of the temperature distributions and the dynamics of the temperature field were investigated. As a result of evaporation and consequent latent heat flow in the vicinity of the throat a temperature depression of approximately 0.4 K was measured. In the region of pressure recuperation, where the cavitation structures collapse, the temperature rise of up to 1.4 K was recorded. It was found that the temperature dynamics closely follows the dynamics of cavitation structures.

Finally experimental results were compared against a simple model based on the Rayleigh–Plesset equation and the thermal delay theory and plausible agreement was achieved.

Experimental data is most valuable for further development of numerical models which are, due to poor ensemble of existing experimental results, still at a very rudimentary level.

1. Introduction

Cavitation is characterized by vapor generation and condensation due to pressure changes at approximately constant temperature of the fluid. Is it justified to use the isothermal approach when we are dealing with liquids such as cold water, where the influence of the temperature variations on the integral liquid properties is negligible (Hord et al., 1972).

A detailed look in the formation of a cavitation bubble shows that it is formed by the local pressure drop, which causes the gas inside the cavitation nucleus to expand what consequently triggers evaporation. The latent heat is then supplied from the surrounding liquid, creating a thermal boundary layer around the bubble. The heat transfer causes a local decrease of the liquid temperature, which results in a slight drop of the vapor pressure (Franc and Michel, 2004). This phenomenon delays the further development of the bubble, because now a greater pressure drop is needed to maintain the process. This phenomenon is known as thermal delay (Brennen, 1995).

When the local surrounding pressure rises, the bubble starts to collapse. During the collapse the condensation occurs and in the final stages the gases also violently compress, which leads to considerable rise of the temperature inside the bubble (Hauke et al., 2007).

As a rule of a thumb the thermodynamic effects can usually be neglected in fluids for which the critical point temperature is much higher than the working temperature. However, the effects become significant when the critical point temperature is close to the temperature of the fluid, like in case of cryogenic fluids (Stahl and Stepanoff, 1956). By formation of cavitation bubble in cryogenic liquids a significant temperature drop occurs, which causes a delay in development of the bubble. The understanding of this thermodynamic effect is therefore crucial for example in turbopumps for liquid hydrogen LH2 and oxygen LOx in space launcher engines – particularity well known is the failure of the Japanese H-II rocket due to rotating cavitation in the LH2 turbopump (Sekita et al., 2001). Consequently, nowadays much effort is put into development of CFD (Computational Fluid Dynamics) methods for the prediction of thermodynamic effects of cavitation of cryogenic fluids (Utturkar et al., 2005; Hosangadi and Ahuja, 2005; Goncalvès and Fortes Patella, 2010, 2011, Goncalvès et al., 2010).

The first study, where the thermodynamic effects on pump performance were considered, was conducted by Stahl and Stepanoff

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(1956). Sarosdy and Acosta (1961) reported significant difference in the appearance of cavitation in water and in refrigerant Freon. The thermodynamic effects were experimentally quantified by Ruggeri and Moore (1969) who investigated the variations of pump performance for various temperatures, fluids and operating conditions. The most extensive experiments on cryogenic cavitation were conducted by Hord et al. (1972) and Hord (1973a, b). His results, acquired in Venturi nozzle, and on hydrofoil and ogive models are still considered as a benchmark for validating numerical models for thermodynamic effects in cavitation. Recent investigations have focused on the influence of the thermodynamic effects on performance and cavitation instabilities in rotating machinery. Franc et al. (2004) analyzed the cavitation instabilities on an inducer in water and in refrigerant R114. A similar study was conducted by Cervone et al. (2005) with cold and hot water at 293 K and 343 K, respectively.

Due to complexity of the experimental investigation of the local temperature variations, the past studies mostly concentrated on the consequences of the thermodynamic effects, rather than on the investigation of the mechanism itself. Fruman et al. (1999) measured the local wall temperature under the cavity with five micro-thermocouples. More recently, measurements of the temperature depression within the sheet cavity at the leading edge of inducer blades were conducted by Franc et al. (2010). Rimbert et al. (2012) locally measured the temperature by two-color laser in a microcavitation channel, and investigated the relationship between the void fraction and the temperature variation. Meanwhile Dular and Coutier-Delgosha (2013) used a high-speed infrared (IR) camera to measure the temperature on a single cavitation bubble.

Until now the thermodynamic effects were usually estimated by rudimentary models, which most of them were proposed between 1960 and 1990. The most commonly used parameter is the B-factor, which is a dimensionless temperature depression proposed by Stepanoff (1961). Brennen (1973) defined the Σ parameter, which depends only on fluid temperature, a similar parameter α was proposed by Kato (1984) and Watanabe et al. (2007) proposed a non-dimensional Σ^* parameter.

The present study shows innovative, direct measurement of thermodynamic effects in cavitating flow by a non-invasive method. A high speed IR camera was used to measure the temperature field in the cavitating flow; simultaneously visualization by a conventional high-speed camera was made.

2. Measurements

Experiments were conducted at the University of Ljubljana in Laboratory for Water and Turbine Machines.

2.1. Experimental set-up and the Venturi geometry

The experimental set-up is shown in Fig. 1.

The cavitation tunnel consists of two 2 L reservoirs (1 and 2), a convergent–divergent Venturi nozzle (3) and a ball valve (4). The first reservoir (1) is filled with the working fluid (hot water) and pressurized to the desired level (through pressure pipe connection (5)). Similarly, in the second, empty, reservoir (2), the pressure level can also be adjusted by the second pressure pipe (6). At a rapid opening of the ball valve (4), the working fluid is pushed from the first reservoir through the Venturi nozzle (3), where the cavitation occurs, to the second reservoir (2). During the 3–5 second long experiment the pressures in both reservoirs were recorded by Hygrosens DRTR-AL-10-V-R16B pressure transmitters at a rate of 1000 Hz.

The geometry of the Venturi test section is shown in Fig. 2. The constriction with a converging angle of 18° and diverging angle of

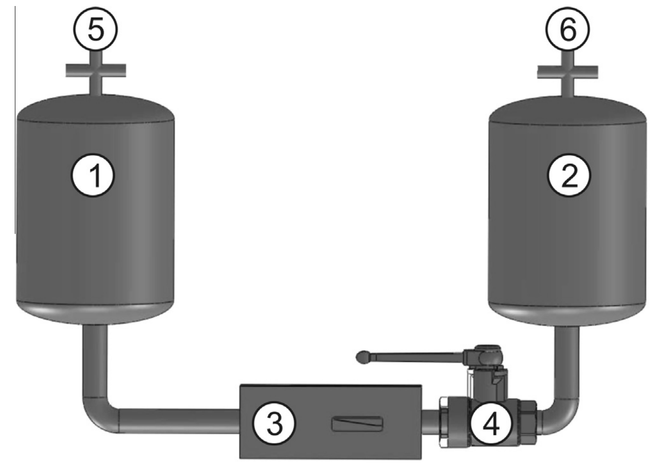

Fig. 1. Experimental set-up.

8° was used. The channel of the test section was machined (milled) out of three aluminum blocks and later polished by 1 μm emulsion. The section itself is made from two parts – lower, with the converging/diverging walls and upper, straight part. This enabled machining of a sharp transition between the converging and diverging part of the Venturi (the radius at the throat was made as small as possible – about 0.2 mm). The cross-section of the test section channel is reduced from $6 \times 5\ \text{mm}^2$ at the inlet, to the $1 \times 5\ \text{mm}^2$ at the throat.

Downstream of the throat of the Venturi nozzle an observation window, made out of sapphire glass, was installed – sapphire glass had to be used since it is transparent in both visible and infrared light spectrum.

The flow velocity changes during the experiment as a result of changing pressure difference between the two reservoirs. Nevertheless, during a short period of time (about 0.3 s) the pressure difference remained constant at a desired level so that measurement point could be easily determined.

Developed cavitating flow was observed at several pressure differences which give values of cavitation number (1.3, 1.8 and 2.3). These were defined as the difference between the pressure in the first reservoir p_1 and vapor pressure p_v (p_v(95 °C) = 84513 Pa) divided by the difference in pressure between the two reservoirs (p_1–p_2):

$$\sigma = \frac{p_1 - p_v}{p_1 - p_2} \tag{1}$$

Decreasing the cavitation number, results in higher probability in cavitation occurrence or in an increase of the magnitude of the already present cavitation. Considering the combination of

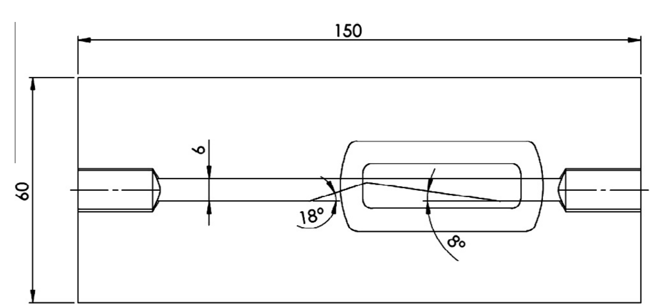

Fig. 2. Convergent–divergent Venturi nozzle (the flow direction is from the left to the right).