European Journal of Mechanics B/Fluids 28 (2009) 444–464

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

www.elsevier.com/locate/ejmflu

Experiments and modeling of cavitating flows in venturi: attached sheet cavitation

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ARTICLE INFO

Article history:
Received 5 July 2007
Received in revised form 28 April 2008
Accepted 4 September 2008
Available online 13 September 2008

Keywords:
Cavitation
Modeling
Optical probe
Two-phase flow

ABSTRACT

Correlated experimental and numerical studies were carried out to analyze cavitating flows and to describe the two-phase flow structures of attached sheet cavitation in Venturi geometries. New double optical probe measurements were performed and special data processing methods were developed to estimate void ratio and velocity fields for cold water flows.

By applying a computational method previously developed in LEGI (*Laboratoire des Ecoulements Géophysiques et Industriels, Grenoble, France*) based on the code Fine$^{\text{TM}}$/Turbo and on a barotropic approach, several steady calculations were performed in cold water cavitating flows. Local and global analyzes based on comparisons between experimental and numerical results were proposed.

0. Introduction

The present work follows previous experimental and numerical studies carried out by the Turbomachinery and Cavitation team of LEGI (*Laboratoire des Ecoulements Géophysiques et Industriels, Grenoble, France*) (Stutz and Reboud [1–4]; Pouffary et al. [5,6]; Coutier-Delgosha et al. [7]).

The main purpose of this paper is to describe the two-phase flow structure of a "quasi-stable" attached cavitation sheet both by experiments and computational fluid dynamics (CFD) means. An accurate description of the two-phase structure is essential to describe the cavitation process occurring in this kind of flow. Furthermore, confrontation between experimental and CFD results are essential to validate and to improve physical and numerical cavitating flow models.

Because of cavitating flow complexity, the main challenges are to obtain experimentally void ratio and velocity fields inside the sheet, and to perform reliable numerical simulations.

Experimental studies in cavitation sheets were often limited to the measurements of global flow characteristics or eventually to some local data in the surrounding liquid flow area. Previous work mainly focused on pressure and temperature fields at the wall, external flow velocity and geometrical description of the cavity shapes. See for example Laberteaux et al. [8], Le et al. [9] and Callenaere et al. [10] among others. On the opposite, the two-phase flow structure of attached cavities has been the subject of very few measurements. Let us recall the work of Kamono et al. [11] who performed velocity measurements in natural and ventilated cavities using a double hot-wire anemometer on a foil section. Bubble detection was also performed by Ceccio and Brennen [12] who used silver epoxy electrodes flush-mounted on a hydrofoil surface for individual bubble velocity detection.

More recently some other techniques have been applied to the investigation of such diphasic flows. Iyer and Ceccio [13] used Fluorescent Particle Image Velocimetry (PIV-LIF) to obtain both the mean velocity field and the Reynolds stress tensor in a cavitating turbulent free shear layer. Dular et al. [14] also used PIV-LIF technique to obtain the velocity field inside and outside of the cavitation sheet existing on a hydrofoil model. It is clear that PIV-LIF is a particularly performing tool to obtain mean and turbulent velocity fields. However it is a very expensive and sophisticated technique and it is almost impossible to perform precise local void ratio measurements with such technology. It must then be coupled to another measurement system to obtain this information in the studied flow.

This can be done by using X-ray absorption technique which is a very performing tool to measure void ratio in two-phase cavitating flows. Using this system we can obtain a very reliable estimation of the void ratio field. This technique may be used with two kinds of data processing methods:

- Firstly, acquisition of spatially integrated void ratio temporal variations. This process was used by Stutz et al. [15] to qualify the dynamic behavior of a cavitation sheet over a Venturi with strong adverse pressure gradient leading to a periodic pulsation of the rear part of the sheet.
- Secondly, acquisition of the spatial distribution of temporally averaged void ratio by a tomographic reconstruction algorithm of the void ratio field. Results on a very complex 3D geometry (Rocket turbopump inducer) were obtained in our team by Hassan et al. [16,17]. They described the spatial and temporal

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doi:10.1016/j.euromechflu.2008.09.001

repartition of the void ratio over the entire flow field in a real rocket engine turbopump inducer.

However the X-Ray absorption technique is not able to measure exactly the mean and turbulent velocity fields at a sufficiently fine spatial resolution to obtain mean and fluctuating values compatibles with Reynolds averaging hypothesis.

It is clear that both the PIV-LIF and X-ray absorption techniques are presumably one of the best possible choices available today to obtain velocity and/or void-ratio fields in cavitating two-phase flows. The main counterpart is that they are very expensive and that they must be used in a synergy process to obtain data both on velocity and void ratio fields. On the opposite, the use of double optical probe is a very cheap method to obtain, from only one measurement, rather accurate data about both velocity and void ratio fields. We then decide, in the present work, to use a double optical probe (as in Stutz and Reboud [2] and Stutz [4]) to perform both void ratio and longitudinal velocity measurements. This technique has been chosen among other possibilities (see Stutz and Reboud [1] for a review) because it has proven to be well adapted to the particular flow configuration under study.

The present work is an extension of Stutz's one [4]. The experimental technique has been improved and particularly, a new algorithm has been introduced to perform velocity-field statistic computations. Furthermore, comparisons with CFD results have been done to assess and calibrate numerical tools developed in our team and applied to simulate 2D and 3D cavitating flows (Pouffary et al. [5,6,18], Coutier-Delgosha et al. [7]).

The studies fit into a research logic carried out for many years by our team in collaboration with the French Space Agency (*Centre National d'Etudes Spatiales, CNES*) and the Rocket Engine Division of Snecma. The aims are to develop, to calibrate, to validate modeling tools in order to simulate the cavitating operation of rocket engine turbopump inducers, and to progress in the understanding and prediction of the mechanisms associated with cavitation in the case of cryogenic fluids, like LH2 and LOx.

In this context, in a parallel with experimental studies, two simulation tools using different numerical schemes have been developed, based mainly on the barotropic cavitation model proposed by Delannoy and Kueny [19], which links the fluid density to the pressure variations. The first numerical code, named "IZ", allows 2D simulations and has been widely applied in our team to analyze unsteady cavitating flows (Reboud et al. [20]; Lohrberg et al. [21]; Coutier-Delgosha et al. [22,23], Fortes et al. [24]). More recently, through collaborations between the LEGI laboratory and Numeca International, the cavitation physical model was implemented in the commercial code Fine/Turbo$^{\mathrm{TM}}$, which allows 3D simulations in turbomachinery geometries (Pouffary et al. [5], Coutier-Delgosha et al. [7]). Previous versions of this numerical tool have been applied and tested also on various 2D flow configurations (Pouffary et al. [6,18]).

On steady configurations, the calibration and validation of the code have been performed considering global flow parameters, such as, for example, cavity length, total vapor volume and global machinery performances (Pouffary et al. [5], Coutier-Delgosha et al. [7,25]). Unsteady calculations performed with this code have provided very good qualitative results and analyzes (Pouffary et al. [6,18]), but no quantitative validation has been carried out in these cases.

In spite of the progress of CFD, unsteady calculations, mainly in turbomachinery geometries, are very time consuming and a steady approach is still interesting (even if it cannot represent the physical mechanisms observed completely). In this context, in complement to previous works and in order to carry on with calibration/validation of Fine/Turbo$^{\mathrm{TM}}$, calculations performed in the present study aim to evaluate the capability of the numerical tool to predict local parameters of cavitating flows (void ratio, pressure and velocity fields) from a steady approach.

As a step to develop and test numerical and experimental tools, in this paper we present studies performed in the case of cold water. In order to facilitate and to carry out local measurements and analyzes, cavitating flows inside space turbopump inducers are simulated by Venturi geometries.

Section 1 presents the experimental device used for recent tests in cold water. Section 2 describes the new data processing methods developed to evaluate, from measurements by double optical probes, the void ratio and velocity fields in cavitating flows. The experimental approach has been applied for a Venturi geometry (named "Venturi 4°"), where the cavitating flow is characterized by a quasi-steady attached sheet cavitation. Comparisons with previous experimental results obtained by Stutz [4] are presented in Section 3.

The numerical model applied to simulate water cavitating flow in "Venturi 4°" geometry is presented in Section 4. Global and local analyzes based on the comparison between experimental and numerical results are presented in Section 5.

1. Experimental device

The experimental device includes mainly a test loop and a sensor (a double optical probe) associated with an acquisition module.

1.1. The test loop

The Venturi type test section of the CREMHYG (INPG Grenoble) cavitation small tunnel was dimensioned and designed to simulate cavitating flows developing on the blades of space turbopump inducers. The hydraulic system (Fig. 1) is composed of a circulation pump and of a free surface tank, used to impose the reference pressure in the circuit and to resorb dissolved gases. The flow rate, controlled by a computer, is measured by means of an electromagnetic flow meter. The pressure within the flow is measured by two sensors located in the free surface tank and in the entry section of the Venturi (S_i). The adjustment of the pressure in the circuit is obtained by managing the air pressure over the free surface of the tank by means of a vacuum pump. The measurement accuracies are evaluated to be:

$\Delta Q/Q = \pm 0{,}25\%$ for flow rate,

$\Delta P = \pm 0{,}05$ bar for the pressure.

The Venturi test section consists in parallel sidewalls generating rectangular cross sections. The bottom wall can be equipped with several interchangeable Venturi profiles allowing the study of cavitation on various geometries. These profiles are equipped to receive pressure sensors, temperature sensors, or double optical probes.

In the present study, we use a profile with a convergence angle of 4.3° and a divergence angle of 4°, illustrated in Fig. 2. The edge forming the throat of the Venturi is used to fix the separation point of the cavitation cavity. This profile is characterized by the following geometrical data:

Inlet section: $S_i = 50 \times 44\ \mathrm{mm}^2$ (where the reference pressure is measured);
Throat section: $S_{\mathrm{throat}} = 43.7 \times 44\ \mathrm{mm}^2$;
Length of the test section (chord): $L_{\mathrm{ref}} = 252$ mm.

This profile is equipped with five probing holes to take various measurements such as the local void ratio, instantaneous local speed and pressure. Their horizontal positions X_I from the throat of the Venturi are: