Experimental investigation of turbulence within unsteady cavitation

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Abstract

An experimental study based on fast X-ray imaging was performed to investigate the turbulence within unsteady cavitating flows. Cloud cavitation in a small scale Venturi type section, characterized by periodical large-scale oscillations of the sheet cavity, was investigated. The flow was seeded with microscopic radio-opaque tracers, and acquisition was performed at the Advanced Photon Source facility of the Argonne National Laboratory. Simultaneous measurements of the liquid and the vapour velocities were obtained by PIV-like image cross-correlations applied to particle and bubble images, while the distribution of the vapour volume fraction was derived from local X-ray absorption. The data obtained from this process were used to determine the distributions of the turbulent kinetic energy k and the turbulent shear stress τ, for several conditions of cavitating flows. The results were then confronted to Reboud's modification of two-equation eddy viscosity models, which is commonly used to improve the turbulence modelling by reducing the mixture turbulent viscosity in the low void ratio areas of the flow. A nice agreement between the current results and this empirical modification was obtained, explaining *a posteriori* why Reboud's correction leads to major improvements in the simulation of cloud cavitation.

Keywords: turbulence, cavitation, X-ray imaging

1 Introduction

Cavitation is one of the most challenging phenomena hydraulic machines encounter, it poses considerable difficulties in both design and maintenance operations. Described as the formation of vapour structures within a liquid when subjected to a sufficiently low pressure, cavitation usually appears in rotating machinery as unsteady clouds which are associated with many undesired effects, such as efficiency loss due to the increase of the hydrodynamic drag, blade erosion, vibrations as well as noise. Overall, these phenomena are linked to the complex unsteady mechanisms governing the development and the behaviour of cavitating flows.

During the last decades, several numerical research studies were performed in order to simulate this complex two-phase flows, and a large number of these studies used simple geometry configurations such as two-dimensional foil sections or 2D Venturi-type sections. Although several physical and numerical models have been developed to investigate both stable and unstable cavities, the turbulence modelling remains one of the main challenges in the numerical simulations. The classical turbulence models, based on Bradshaw assumption, have shown their limitations when comes to predicting the unstable behaviour of unsteady cavitation. To overcome this problem, Reboud *et al* [1] and Coutier-Delgosha *et al* [2] have proposed an arbitrary modification of the turbulent viscosity to improve the modelling of unsteady self-oscillatory behaviour of sheet cavitation. In this case, the density ρ used in the standard models was replaced by a function $f(\rho)$ where $f(\rho) = \rho_v + (1 - \propto)^m(\rho_l - \rho_v)$ with $\propto$ the vapour volume fraction and $m > 1$. This function is thus equal to ρ_v or ρ_l in the regions containing, respectively, pure vapour or pure liquid, but it decreases rapidly toward ρ_v for intermediate void ratios. Authors have shown that this arbitrary modification reduces the effective viscosity in the mixture and takes into account the influence of the liquid/vapour mixture high compressibility on the turbulence structure. Although this correction has since shown its effectiveness and thus have been widely used in the numerical simulations of cavitation, it remains arbitrary and no experimental work has been able to demonstrate its validity, mainly due to the lack of experimental results.

In fact, velocity measurements were performed in several experimental studies using techniques such as PIV [3, 4] and optical probes [5]. Nonetheless, measurements within this type of flows face, in general, some quite strong impediments and hence insufficient results were heretofore obtained. In high void fraction regions such as the upstream part of sheet cavities, velocity measurements are hardly accessible due to the opacity of the flow as a consequence of high reflections of both laser and fluorescent lights emitted by seeding particles on the two-phase flow structures. Consequently, most of the studies using PIV have focused on low void fraction regions such as wakes or in some cases, next to the test section wall where the flow is less opaque [6]. X-rays have also been used in the study of cavitation, while their use has mostly focused on the study of cavity structures and their role in the behaviour of unsteady cavities. High-frequency measurements of the local volume fraction of vapour using X-ray

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densitometry demonstrates the effect of the flows composition in the break-down of unsteady sheet cavities [7] and the importance of bubble shock waves within the cavity in the formation of large-scale shedding [8].
All these techniques have enabled to obtain valuable information about the structures and the dynamics of unsteady sheet cavities, however, they didn't enable to have access to simultaneous measurements of the two-flow velocities as well as the vapour volume fractions, which is crucial in the study of the turbulence. For all the above reasons, a new experimental technique based on synchrotron X-ray imaging was developed, making measurements of vapour volume fraction and velocity fields of both gaseous and liquid phases accessible.

In this paper, measurements of the vapour volume fraction and both phases velocities within a cavity inside a Venturi-type test section are performed and used to determine the distributions of the turbulent kinetic energy k and the turbulent shear stress τ, for unsteady cavitating flow conditions. The results are then confronted to Reboud's modification of two-equation eddy viscosity models, which is commonly used to improve the turbulence modelling by reducing the mixture turbulent viscosity in the low void ratio areas of the flow. A nice agreement between the current results and this empirical modification are obtained.

2 Experimental setup

2 .1 Test rig and test section

The experiments were held at the APS synchrotron of the Argonne National Laboratory. A portable hydraulic loop was hence used. It is equipped with multiple sensors which allow to regulate and maintain all flow conditions (inlet pressure, mass flow rate and temperature) stable throughout the experiments.

Cavitation was produced in a 2D Venturi profile (figure.1) identical to the one of the water tunnel of the LEGI Laboratory (Grenoble, France), which is characterised by a convergent angle of 18° and a divergent angle of 8° and was used in numerous previous experimental and numerical studies [5, 9]. Due to the small size of the X-ray beam cross-section and to ensure a satisfactory signal/noise ratio when both the flow and the test section walls are crossed by the beam, the new test section was scaled down 10 times from the original tunnel. The design of the test section allows to modify easily the height of the Venturi entrance *he* and hence the flow configuration. To avoid the scale effect and ensure unsteady cavitation [10], a configuration with a height of 17mm (instead of 5mm) at the Venturi entrance was chosen.

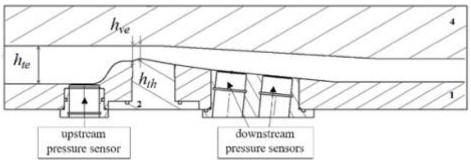

Figure 1: test section

2 .2 X-ray imaging

Thanks to the characteristics of the APS synchrotron X-ray beam, the imaging in this work is based upon two different mechanisms: absorption and phase-contrast enhancement. The imaging technique and both mechanisms are summarized in figures 2(a) and 2(b) and are explained in more detail in [11].

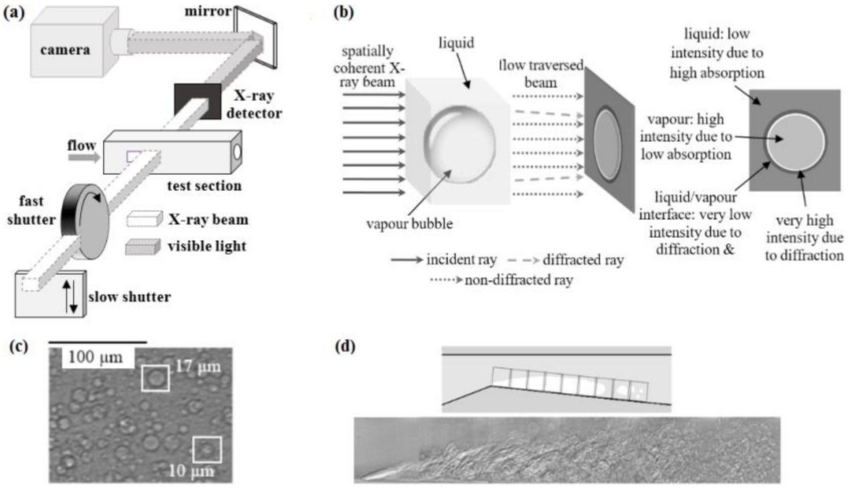

Figure 2: X-ray imaging - (a): X-ray imaging set-up; (b): X-ray absorption and phase-enhanced mechanisms; (c) seeding particles; (d) cavity decomposition into several acquisition windows

The images were recorded at a frequency of 12,070Hz, while 3.68µs separates two images of the same pair. The spatial resolution is 704 × 688 px² with a pixel size of 2 µm. Since the beam has a cross-section of only 1.7x1.3mm², each sheet cavity had to be divided into several windows recorded successively but not simultaneously. In other words, 3770 image pairs of the first window, which corresponds to the beginning of the cavity, were recorded. The test section was then shifted parallel to the divergent floor to the second position where the same number of pairs were recorded and so forth until the end of the two-phase cavity (figure 2(d)).

Silver-coated hollow glass spheres with an average diameter of 17µm were added to the flow and used as tracers of the liquid phase (figure 2(c)).

3 Measurements and results

Thanks to this method, each image contains simultaneous information about the flow structures and the dynamics of each phase. To analyse these information, an image processing-based algorithm was developed to separate the seeding particles from the vapour phase. In fact, from each X-ray radiograph, three new images are created: *(i)* an image of particles for measurements of the liquid phase velocities; *(ii)* an image of bubbles for vapour phase velocity measurements, and *(iii)* an image of the vapour structures with neither interfaces nor particles, used for vapour volume fraction measurements. Figure 3 shows an example of the obtained images as well as the measurements obtained for one position (window) within the sheet cavity. Note that various validation methods were also developed and all measurement uncertainties due to processing were estimated [11].

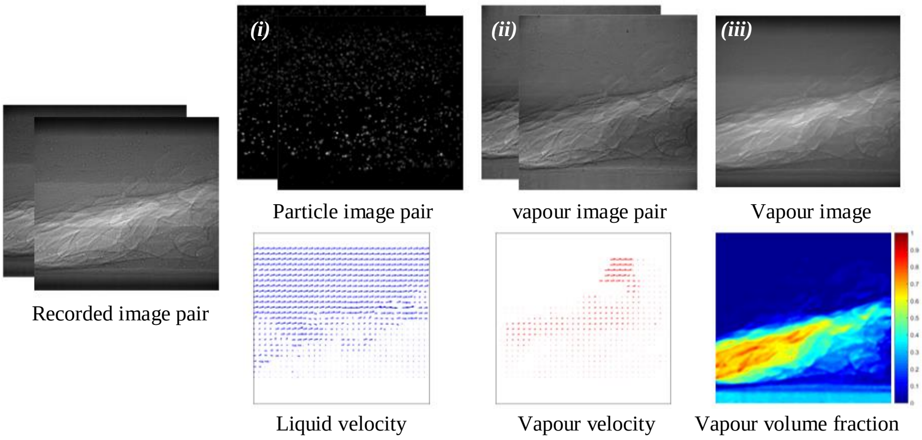

Figure 3:velocity and vapour volume fraction measurements within a cavitating flow

Phase-locked averaging was performed to obtain the space-time evolution of unsteady cavities. Figures 4(a) and 4(b) show the evolution of the vapour volume fraction for a flow with a cavitation number of 1.97 and a volume flow rate Q of 35.09 l/min. These flow conditions produced a cavity oscillation frequency f_{cav} of 510 Hz (Strouhal number St of 0.28), which corresponds to a 13-step discretization of the flow mean cycle.

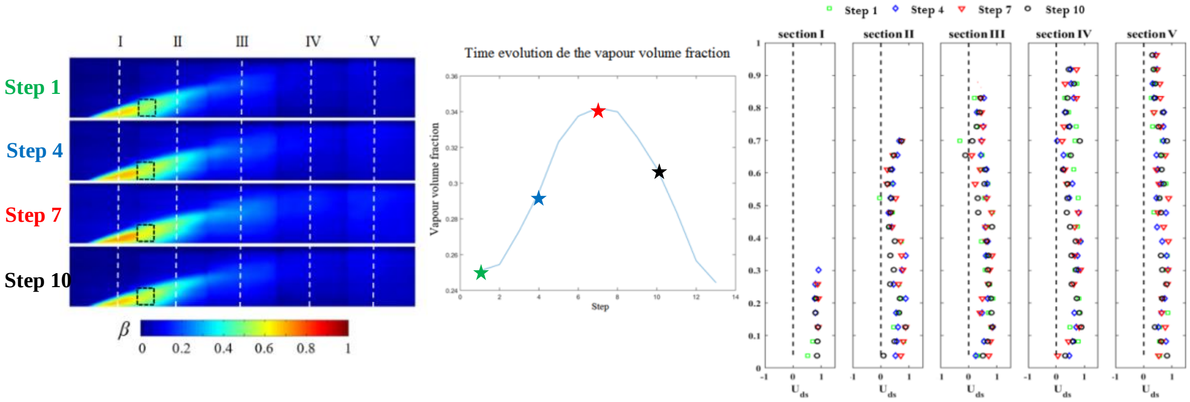

Figure 4: phase-locked averaging for unsteady cavitating flow, (a) space-time evolution of vapour volume fraction; (b) time evolution of the vapour volume fraction within the dashed square in (a); (c) dimensionless slip velocity profiles in sections I to V

The analysis of instantaneous and phased-locked average velocity profiles for several flow configurations and within different positions shows non-negligible differences between the liquid and vapor velocities and thus highlights the existence of a noteworthy slippage between the liquid and the vapour phases inside sheet cavities.

The analysis of the dimensionless slip velocities $U_{ds} = (U_l - U_v)/U_v$, where U_l and U_v are respectively liquid and vapour velocities according to flow main direction, showed that, regardless of the time evolution step or the horizontal position within the cavity, the phases behave similarly with respect to each other. Figure 4(c) shows dimensionless slip velocity profiles for different steps and several sections within unsteady cavitation.

The analysis on the turbulence is performed with respect to the existing models used in RANS simulations, the local velocity of the mixture U is defined as follow: $U = (1-\propto)U_l + \propto U_v$, with $\propto$ the local vapour volume fraction, while the mixture density $\rho = (1-\propto)\rho_l + \propto \rho_v$ and the turbulent shear stress $\tau = -\rho\overline{U'V'}$, with $U' = U - \overline{U}$ and $\overline{U}$ is the local velocity phase-locked average.

Figure 5(a) shows the distribution of the ratio of the turbulent shear stress by the kinetic energy, $\frac{\tau}{k} = -\rho\overline{U'V'}/k$, within the sheet cavity. As it could be observed, this quantity varies significantly with the void fraction (Figure 5(b)), i.e. the density as well as the position in the cavity. In regions corresponding to the attached cavity, $\frac{\tau}{k}$ was plotted as a function of the mixture density and compared with the standard model from *k-ω SST* model and the one obtained from Reboud's modification (Figure 5(c)). The former model corresponds to Bradshaw's assumption where the shear stress is a linear function of the kinetic energy and the density, $\tau = \rho a_1 k$, with a_1 a constant. In Reboud's modification, ρ is replaced by $f(\rho) = \rho_v + (1-\propto)^m(\rho_l - \rho_v)$; $\tau = f(\rho)a_1 k$.

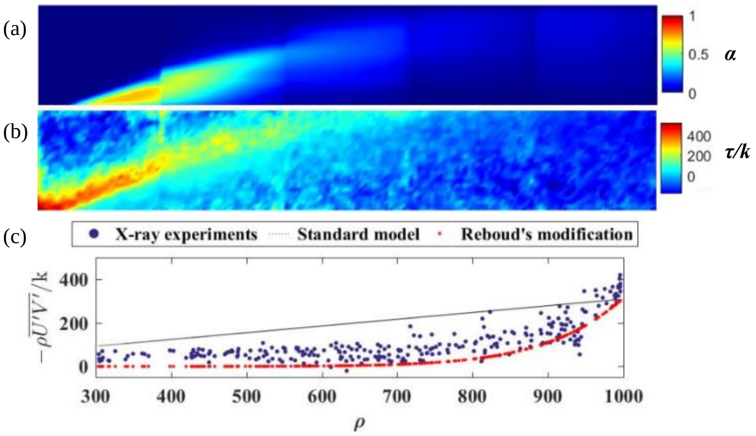

Figure 5: turbulence analysis - (a) vapour volume fraction distribution; (b) distribution of *τ/k* (c) comparison between experimental results and Reboud's arbitrary modification

It is clear from this plot, that the results obtained from the experiments are very close to those suggested by Reboud's correction, which explains why this arbitrary modification provides significant improvements in the numerical simulations of the periodical unsteady behaviour of cavitating flows. It is worth noting that this observation was found in all flow configurations that were tested. More work is currently undertaken to analyse the turbulence quantities according to the local void fraction, the size of the sheet cavity, and the steps of the periodic cavitation cycle. The results will be used to improve the modelling of cavitation.

4 Conclusion

With the aim of improving the general understanding of cavitation, a new experimental method was developed in order to have simultaneous access to both the dynamics and the composition of cavitating flows. Thanks to synchrotron X-ray imaging, the space-time distribution of the vapour volume fraction and both the liquid and the vapour velocities are obtained. The measurements within a flow in a Venturi-type test section showed a significant slippage between both phases. Furthermore, the simultaneous information obtained by this technique allowed for the first time an analysis of the turbulence inside sheet cavities, even in regions with high void fraction. A nice agreement between the current results and Reboud's empirical correction was observed, explaining *a posteriori* why this modification leads to major improvements in the simulation of cloud cavitation.

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