International Journal of Multiphase Flow 58 (2014) 301–312

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Velocity measurements based on shadowgraph-like image correlations in a cavitating micro-channel flow

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ARTICLE INFO

Article history:
Received 29 March 2013
Received in revised form 10 September 2013
Accepted 10 October 2013
Available online 23 October 2013

Keywords:
Cavitation
Shadowgraph
Turbulence
Channel flow
Correlation
Image correlation
Diesel injector

ABSTRACT

Cavitation is generally known for its drawbacks (noise, vibration, damage). However, it may play a beneficial role in the particular case of fuel injection, by enhancing atomization processes or reducing nozzle fouling. Studying cavitation in real injection configuration is therefore of great interest, yet tricky because of high pressure, high speed velocity, small dimensions and lack of optical access for instance. In this paper, the authors proposed a simplified and transparent 2D micro-channel (200–400 μm), supplied with test oil at lower pressure (6 MPa), allowing the use of non-intrusive and accurate optical measurement techniques. A shadowgraph-like imaging arrangement is presented. It makes it possible to visualize vapour formations as well as density gradients (refractive index gradients) in the liquid phase, including scrambled grey-level structures connected to turbulence. This optical technique has been already discussed in a previous paper (Mauger et al., 2012), together with a Schlieren and an interferometric imaging technique. In this paper, the grey-level structures connected with turbulence are considered more specifically to derive information on flow velocity. The grey-level structure displacement is visualized through couples of images recorded within a very short time delay (about 300 ns). At first, space and space–time correlation functions are calculated to characterize the evolution of grey-level structures. Space–time correlations provide structure velocity that slightly under-estimates the real flow velocity deduced from flowmeter measurements. Since the grey-level structures remain correlated in time, a second velocity measurement method is applied. An image correlation algorithm similar to those currently used in Particle Image Velocimetry (PIV) is used to extract velocity information, without seeding particles. In addition to the mean velocity of grey-level structures, this second method provides structure velocity fluctuations. In particular, an increase in structure velocity fluctuations is observed at the channel outlet for a critical normalized length of vapour cavities equals to 40–50%, as expected for the real flow velocity fluctuations. The present study is completed by a parametric study on channel height and oil temperature. It is concluded that none of them significantly impact the critical normalized length for which the fluctuation increase is observed, even though the magnitude of these fluctuations is larger for the higher channel.

1. Introduction

Over the years, automotive industry standards have increasingly forced manufacturers to produce eco-friendly vehicles. During the last decades, heat engines have been improved, becoming less pollutant yet more efficient. The optimization of the thermodynamic cycle has played a key role in the improvement process. More precisely, increased knowledge of the internal aerodynamics of cylinders and enhanced injection systems have made it possible to better control fuel evaporation and mixture, and therefore fuel combustion. Nevertheless, in many respects, the atomization process at the injector outlet – in particular, the influence of the internal flow on atomization – is still not well understood.

The spray characteristics of Diesel injectors depend on the atomization processes in cylinders, and therefore, they depend on the velocity profile and turbulence inside the nozzle and at the nozzle exit (Birouk and Lekic, 2009). The spray characteristics are then likely influenced by the presence of cavitation in nozzle orifices. Using a backlit micro-PIV system in a real size transparent VCO nozzle, Chaves (2008) highlights that cavitation appears at the sharp edge inlet of the injection orifice. Vapour cavities extend along the orifice and bubbles seem to collapse in a very deterministic

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.10.004

and localized manner. Velocity fields are also measured by using Particle Image Velocimetry (PIV). However, the introduction of seeding particles in the flow is potentially problematic: Particles can act as cavitation nuclei and, consequently, modify the conditions of cavitation inception. Different cavitation regimes are described in the literature, namely no cavitation, developing cavitation, super-cavitation and hydraulic flip (Sou et al., 2007). Most authors (Birouk and Lekic, 2009; Sou et al., 2007; Hiroyasu, 1991; Soteriou et al., 1995; Wu et al., 1995; Hiroyasu, 2000; Tamaki et al., 2001) show that the most favourable regime for spray atomization is super-cavitation while hydraulic flip is the worst in this respect (Sou et al., 2007; Hiroyasu, 1991; Bergwerk, 1959). It is considered that super-cavitation is reached when the vapour cavity length is 70–100% the orifice length (Sou et al., 2007). In super-cavitation condition, at least two mechanisms are supposed to influence spray formation. Firstly, cavitation may increase flow turbulence (Tamaki et al., 2001; He and Ruiz, 1995) through bubble collapse and pressure waves. Secondly, bubbles may reach the channel outlet and enhance directly the liquid jet atomization when they collapse (Sou et al., 2007). In order to provide useful information on the internal flow inside injection orifices, different experimental setups are presented in the literature. Flow investigation in a realistic geometry and real injection conditions is a difficult task because of high pressure, high velocities, small dimensions, lack of optical access and strong unsteadiness. As a result, most experimental investigations are carried out at lower pressure injection, in a simplified geometry and/or in up-scaled orifices. In a large-scale channel, He and Ruiz (1995) measure both cavitating and non-cavitating flows by means of a Laser Doppler Velocimeter (LDV). When cavitation occurs, they notice a difference in the mean streamwise velocity component profile near the inlet and a 10–20% increase in turbulence intensity behind vapour cavities. In order to investigate the relationship between vapour cavity length and turbulence, high speed visualizations and Particle Image Velocimetry (PIV) measurements are conducted by Stanley et al. (2008) in an up-scaled, sharp-edged, acrylic nozzle. In super-cavitation regime, vapour bubbles convected through the nozzle exit have a significant influence on the liquid jet structure and enhance the aerodynamic shear break-up of the jet. Turbulent Kinetic Energy (TKE) is shown to be strongly linked to vapour cavity length inside the nozzle. Sou et al. (2007) also use LDV in a 2D up-scaled channel. They suggest that the strong turbulence induced by the collapse of cavitation clouds near the exit plays a major role in ligament formation. They visualize cavitation in the nozzle and ligament formation at liquid jet interface simultaneously using a high-speed camera. They find that the formation of a ligament is often (but not systematically) preceded by the collapse of a cavitation cloud at the channel outlet. It seems that the size of a ligament is roughly proportional to the size of the vapour formation preceding it. However, Sou et al. (2008) report that the formation of ligaments induced by a collapse of bubbles is less observed in a cylindrical configuration than in a channel configuration. This can be explained by the greater difficulty in observing a flow in a cylindrical configuration. For that reason, 2D channel configurations are preferred by some authors to study cavitation formation. Winklhofer et al. (2001) investigate a cavitating flow in a micro-channel with backlit imaging. They measure velocity profiles with a fluorescence tracing method. Velocity profile measurements show that vapour formation in the channel inlet increases flow velocities near the liquid–vapour interface. Winklhofer et al. (2001) also reconstruct the pressure field inside the channel by means of a Mach–Zehnder interferometer arrangement. For different cavitation regimes, they compare the pressure field and hydraulic behaviour. They notice that the flow is choked after super-cavitation. These studies suggest that the turbulence induced by cavitation plays a major role in spray formation. It is clear that super-cavitation is the most favourable regime to enhance atomization. Further investigations are required to highlight cavitation/atomization dependency.

Although observing cavitation inside nozzle orifices is a difficult task, experimental data, especially at the nozzle outlet, are needed to enhance our general knowledge on high pressure injection processes and to provide reliable initial conditions for numerical simulations (Ménard et al., 2007; Gorokhovski and Herrmann, 2008; Marcer et al., 2008; Lebas et al., 2009). Obtaining quantitative information as velocity profiles is even more complicated. Consequently, a simplified experimental configuration is considered in this paper. A 2D micro-channel permanent flow is visualized by using a shadowgraph-like imaging setup, based on a backlit illumination and sensitive to refractive index gradients. This setup has already been used together with alternative imaging techniques to study cavitation inception, under conditions close to those of direct injection in a 400 μm high micro-channel (Mauger et al., 2012). In this paper, couples of shadowgraph-like images are considered to perform velocity measurements in a 2D micro-channel, without seeding particles. The experimental setup is presented in Section 2. Shadowgraph-like images of the channel flow are presented in Section 3 together with the result of space and space–time correlations. Section 4 is dedicated to the measurement of mean velocities and fluctuations, based on an image correlation algorithm for a channel height between 200 μm and 400 μm.

2. Experimental setup

In the present study, cavitating flow is investigated in a quasi-2D orifice (micro-channel). The micro-channel consists of two separated metal sheets, sandwiched between a pair of glass windows (Fig. 1). It is continuously supplied with fuel (test oil SHELL V-Oel-1404) through holes directly drilled into the glass windows. Oil pressure levels are measured 40 mm upstream and downstream of the channel using metal thin film sensors. A variable area meter measures the flow rate. Oil temperature is regulated by an air/oil heat exchanger and controlled by a T-type thermocouple. In the following, the flow temperature upstream the channel is $T = 24\,^\circ\mathrm{C}$.

The use of two separated metal sheets makes it possible to better control channel geometry and wall roughness. A Scanning Electron Microscope (SEM) is used to measure channel dimensions. The channel is about 388 μm high and 1475 μm long, with an area reduction of 5% between the inlet and the outlet. The channel depth is $L = 2$ mm. Channel inlets are very sharp ($r \simeq 10$ μm). The surfaces constituting the channel walls have been mirror-polished. Their roughness is characterized by using an optical profilometer, by a mean arithmetic roughness parameter $R_a < 0.1$ μm.

Different flow conditions are obtained maintaining upstream pressure p_{up} constant and varying downstream pressure p_{down}. Depending on the imposed pressure drop $\Delta p = p_{up} - p_{down}$, three flow regimes are identified, namely single-phase flow, cavitating flow and choked flow. Cavitating flow is divided in three steps:

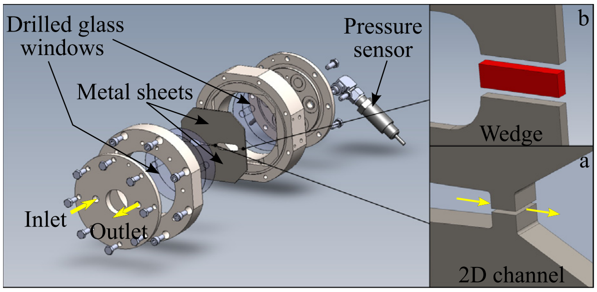

Fig. 1. Exploded view of the 2D micro-channel.