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Hydrodynamic cavitation of binary liquid mixtures in laminar and turbulent flow regimes

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ABSTRACT

Hydrodynamic cavitation of several binary liquid mixtures (diethyl ether – 2-butanol, diethyl ether – ethanol, water – isopropanol) has been performed at different relative mass fractions. Different cavitating flows have been studied downstream two sorts of constrictions: micro-diaphragm profiles, that correspond to shear rate induced cavitation, and micro – venturi profiles, that correspond to sheet cavitation. Using microsystems as 'labs on chip' has made possible these investigations, with a low amount of the mixtures. Moreover, these microsystems have also made possible the inception of cavitation from a laminar single phase flow, because of the small hydraulic diameter of the orifices. Characterization of the binary liquid mixtures is presented with the help of $\sigma(Re)$ diagrams, where σ is the cavitation number and Re is the Reynolds number in the constriction. It has been observed that when the inception of cavitation arises from a laminar single liquid phase regime at a fixed pressure drop, the flow rate is then slightly increased. Moreover, an anomalous behaviour of the pure ethanol liquid has been consistently recorded, with both types of devices. The presence of diethyl ether in the mixture may aid the inception of cavitation because it increases the vapour pressure of the blend and lowers its viscosity. The presence of isopropanol in water increases the viscosity of the blend and shifts the inception of cavitation towards lower Reynolds numbers. The shape of the constriction has also revealed to be a major parameter associated to the two phase flow transition of the mixtures.

1. Introduction

Microfluidics offers unique and unsurpassed opportunities to perform experiments unavailable at macroscale. Down to scales where the laws of hydrodynamics are still valid and where surface effects have not become predominant, the use of 'labs on chip' avoids an excessive consumption of the liquid under test. Microfluidics is generally associated to laminar flows, because of the small hydraulic diameters of the channels. That may be the reason why the number of papers dealing with hydrodynamic cavitation through microchannels is rather low. Peles and coworkers [1–5] were the first to study the hydrodynamic cavitation of water, ethanol and refrigerant liquids downstream microdiaphragms or micro venturis in hybrid silicon – Pyrex microchannels, whose silicon part had been deeply etched. Further experiments were devoted to the heat transfer enhancement involved by cavitating flows in such devices [6]. Rooze et al. [7] have recently studied the possible chemical reactions induced by hydrodynamic cavitation inside milli and microchannels.

In the recent past years, our team has scrutinized the cavitation flow regime of water through several microdiaphragms and microventuris, and has recorded high speed camera movies [8,9]. With the help of these devices exhibiting a cavitating flow regime at flow rates below 1 L/h, it has been established that the transition from a single liquid phase to a two – phase flow is triggered by vortices in the recirculating area downstream the shrinkage of microdiaphragms. Such a transition arises in a low-pressure sheet downstream the throttle of a micro venturi. For these latest devices, the behaviour of the re-entrant jet could eventually be slightly different that in a macroscopic device. The most spectacular effect was the possible delay to the inception of cavitation, due to the metastability of deionized water and to the lack of roughness of the walls. We could then for the first time study hydrodynamic cavitation of nanofluids [8]. The presence of dilute nanoaggregates in the liquid did not give way to noticeable effects on the flow regimes through the venturis. However, above a critical solid volume concentration of $\approx 10^{-4}$, the liquid flowing through

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the diaphragms could not sustain negative pressures as with pure de-ionized water.

So, 'cavitation on chip' may be regarded as a powerful tool in order to progress in fundamental or applicative research in two phase flows. By considering the flow under test over a microsized volume, it becomes possible to use experimental facilities usually devoted to nanosciences. As an example, we could perform a complete thermal mapping of the liquid phase in a cavitating area [10,11]. That was made possible by the correlated benefits offered on the one hand by thermofluorescent nanoparticles seeded in the flow and on the other hand by a confocal microscop able to detect them.

Other recent publications associate microfluidics devices to cavitation [12–14]. However, an increase of the fluid velocity and the corresponding pressure decrease in the flow (Bernoulli'law) is not at the origin of the phase transition mentioned in these papers. Tandiono et al. have applied acoustic cavitation to a microchannel feeded with luminol [12]. Quinto-Su et al. [13] have focused a laser spot on a microchannel in order to promote the role of the height of the microfluidic environment on the bubble dynamics. Zwaan et al. created bubbles by focusing a pulsed laser light into the microvolume of the channels [14].

Hydrodynamic cavitation of rare, expensive or specific liquids is likely to be studied by 'cavitation on chip'. That may be the way to address questions of both fundamental or applicative interest, related to the cavitation process. Former experiments with de ionized water have exhibited some thermal effects [10,11]. The intensity of thermal effects depends on the temperature gap $\Delta T^{\cdot} = \rho_v L_v/(\rho_l c_l)$ where ρ_v and ρ_l are the density of the vapour and liquid phase respectively, L_v is the latent heat and c_l is the specific heat of the liquid. We have $\Delta T^{\cdot} = 0.01$ K for water at ambient temperature but $\Delta T^{\cdot} = 0.6$ K for liquid nitrogen at 77 K. By considering fluids such as diethyl ether, ethanol, isopropanol, and 2-2-butanol one get $\Delta T^{\cdot} = 0.70$ K, 0.90 K, 0.94 K, and 1.12 K respectively, at ambient temperature. However, it is not obvious to perform hydrodynamical cavitation at macroscopic size with such liquids. Some of these fluids, characterized by hydrodynamic cavitation on chips, could offer alternative opportunities to clearly exhibit the role of thermal effects.

For applications devoted to direct injection spark ignition engines, the consequences of alcohol and ether additives are increasingly studied. The objective is to understand the effect of bio-components on fuel spray formation and on spray wall impingement [15]. Moreover, cavitation occurs inside Diesel injector nozzles, that can be used to improve spray atomization [16,17]. Mixtures of biofuels involving diethyl ether and ethanol have been also considered [18,19]. It is obvious that there is a need of experimental data about the cavitation flow characteristics of fluids such as mixtures of alcohols or ether. Moreover, profiles such as microdiaphragms micromachined in a silicon substrate may be considered as being similar to the orifices of injectors.

Another attractive feature of hydrodynamic 'cavitation on chip' is that it makes experimentally possible a broad range of flow regimes, from a perfectly laminar flow regime to a turbulent one. Hydrodynamic cavitation is monitored by a lot of parameters: the vapour pressure P_{vap} of the fluid, the dynamic viscosity μ_l and the density ρ_l of the liquid, the local pressure drop caused by the converging – diverging shrinkage and the corresponding average velocity u of the fluid. Two adimensional numbers are usually considered. The cavitation number σ is defined by $\sigma = (P_{out} - P_{vap})/(\rho_l u^2/2)$ where P_{out} is the pressure at the outlet of the channel and P_{vap} is the vapour pressure of the fluid. That number compares the pressure decrease necessary to reach the vapour pressure, to the dynamic pressure decrease generated by the flow. The Reynolds number *Re* is defined by $Re = \rho_l u d_H/\mu_l$, where d_H is the hydraulic diameter of the constriction. Cavitation is likely to occur for low σ values, that may be regarded as corresponding to high velocities u in the orifice and so as turbulent flow regimes. Neverthless, 'cavitation on chip' may be induced from a laminar flow regime. Let us consider a fluid with $P_{vap} \ll P_{atm}$, emerging at $P_{out} = P_{atm}$. The condition $\sigma < 1$ may be written as

$$d_H < \frac{\mu_l Re}{(2\rho_l P_{atm})^{1/2}} \quad (1)$$

That equation states that the inception of cavitation from a liquid laminar flow ($Re < 2000$) is linked to severe conditions on the diameter of the orifice. Considering water as the working fluid, one get $\sigma < 1$ when $d_H < 140$ μm. Former experiments in microchannels with water have exhibited inception and desinence of cavitation at $\sigma \approx 0.4$, corresponding to transient *Re* values [8]. A viscous liquid as 2-butanol may also help to easily reach the above mentioned condition. The viscosity and density of liquid 2-butanol are $\mu_l = 4$ mPa s and $\rho_l = 809$ kg/m^3, $P_{vap} = 17$ mbar at ambient temperature, so that the condition of Eq. (1) leads to $d_H < 630$ μm. That fluid should take advantage to be hydrodynamically characterized through microdevices. Experimental data concerning such a laminar cavitating flow should be useful, because corresponding simulations could be performed from models more simple than those including turbulence effects. Otherwise, diethyl ether has a low viscosity, and even if its vapour pressure is $P_{vap} \approx 0.5$ bar, the extrapolation of Eq. (1) for that fluid gives $d_H < 50$ μm. For that fluid, the transition towards a two-phase cavitating flow is thus unlikely to be proceeded from a laminar flow.

Binary liquid mixtures at different relative mass fractions may be a solution to browse a large range of σ and *Re* values. For example, it is known, that a small amount of isopropanol diluted in water changes drastically the viscosity of the mixture [20]. There is a lack of data about the cavitation of binary liquid mixtures. Some papers report on the flashing of refrigerant – oil mixtures [21], but oil has a negligible vapour pressure and is unlikely to cavit. In addition, most of the papers deal with complex fuel mixtures, as reported above.

The present article reports on experimental investigations on the hydrodynamic cavitation of three binary liquid mixtures: diethyl ether – 2-butanol, diethyl ether – ethanol and water – isopropanol have been characterized at different mass ratios. Each mixture has been studied with the help of up to four different 'labs on chip'. We have recorded the relationship between the pressure drop and the flow rate in the single liquid phase and in the two-phase flows. Optical snapshots of the flow have been performed using high speed camera movies. Part 1 defines the notations used throughout the text and presents the experimental set up. Part 2 analyzes the results recorded with pure liquids. Part 3 is devoted to the binary mixtures.

2. Cavitating labs on chip and experimental set up

The experimental set up used in the experiments presented below is very similar to the set up described in former experiments devoted to hydrodynamic cavitation in microsystems. In the present paper, we shall only recall the main parameters useful for the understanding of the experiment. Detailed calculations and technical informations about the micromachining of the devices can be found in the papers of Medrano et al. [8,9]. Hydrodynamic cavitation in microsystems is the consequence of Bernoulli law. A constriction of the section of the flow should increase the velocity of the liquid and the resulting decrease of the pressure down to the vapour pressure P_{vap} should trigger the inception of cavitation. The presence of turbulent vortices in the recirculating areas of the flow could also manage the inception of cavitation. Microdiaphragms and microventuris have been micromachined in silicon substrates