PDPA Characterization of the Droplet Mist in a HeII Two-Phase Flow

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Optical observations of HeII two-phase flow in the Cryoloop experiment show a transition from stratified to mist flow at high vapor velocities (several m/s). We present results on the size and velocity distributions of the droplets as measured by Phase Doppler Particle Analysis (PDPA). They allow us to evaluate the mass transported by droplets, an important issue to understand the improved wall heat transfer in these experiments.

INTRODUCTION

The superconducting magnets of the Large Hadron Collider will be cooled by surrounding pressurized superfluid 4He, itself cooled by a pipe containing a two-phase (vapor-superfluid) flow of 4He, the cooling power being provided by the latent heat of vaporization. A key factor of efficiency is the heat transfer from the magnet bath to the flowing saturated superfluid liquid. The primary goal of the Cryoloop experiment developed at CEA-Grenoble was to investigate this transfer under realistic conditions.

Our measurements show that, at high vapor quality, corresponding to a large vapor velocity, heat transfer is significantly better than expected from the liquid level in the pipe [1]. This improvement correlates with the apparition of a stratified mist of droplets above the liquid [2], suggesting that droplet deposition leads to the formation of a liquid film above the liquid free surface. Surface capacitive probes glued on the walls indicate that the film thickness is less than 10 µm, and thermal resistance values, that its height should reach 5-10 mm above the free surface [1].

In order to check the consistency of this scenario, we need to estimate the volume flux of droplets impinging on the pipe walls. Previously, we mapped out the interfacial area of the droplet mist using quantitative light scattering of a laser beam propagating along an horizontal diameter, combined with full field CCD pictures of a cross section of the pipe [2]. Converting this quantity into a volume flux requires to know the sizes and velocities of the droplets. This can be carried out using Phase Doppler Particle Analysis (PDPA). This technique is widely used to characterize classical sprays, but, to our knowledge, was never used before for helium.

APPLICATION OF PHASE DOPPLER PARTICLE ANALYSIS TO HELIUM

We use a commercial PDPA (Aerometrics) [3]. A HeNe laser beam is split into two coherent beams propagating in a horizontal plane, nearly normaly to the pipe axis (Figure 1). The two beams cross within the pipe, defining a small probe volume, where their interference modulates the light intensity along the pipe axis, with a period related to the angle 2θ between the two beams (25 mrad in most of our experiments). The light scattered by droplets crossing the volume is measured by three photomultipliers,

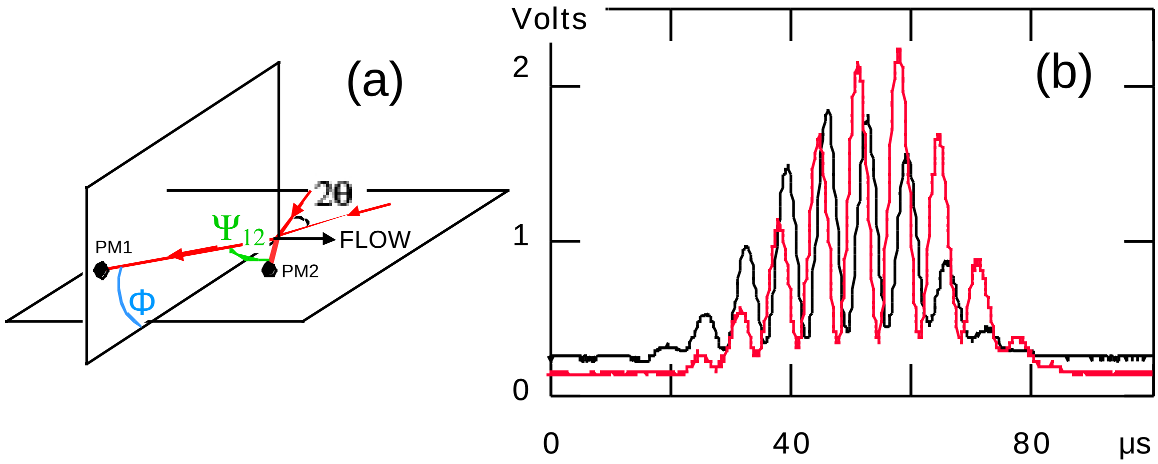

Figure 1 (a) Scattering geometry for PDPA. Only one pair of photomultipliers (PM) is shown; (b) Typical Doppler burst (for the two PM's of the pair) at a local velocity of 4 m/s.

which observe the probe volume at an angle φabove the horizontal plane, and small angles ψ_i, i=1-3, with respect to the vertical plane normal to the pipe. Each droplet gives rise to an intensity burst on the PM's, modulated at a frequency proportional to its speed along the pipe (Figure 1b). In the regime of geometrical optics, the phase shift between the different pairs of PM's is proportional (modulo 2π) to the droplet diameter d and the difference of angles ψ between the pair. The specificity of liquid helium is its small refractive index (n~1.025), which implies that droplets larger than several microns in diameter scatter light mainly close to the forward direction [4]. We therefore use a scattering angle φ of 15°, small enough to give significant scattering (by refraction), but large enough for diffraction to be negligible. In these conditions, and in the regime of geometrical optics, the phase shifts are given by :

$$2\pi \frac{d}{\lambda}\theta \frac{\psi}{\sqrt{4(1-n)^2+\phi^2}} \approx 2\pi \frac{d}{\lambda}\frac{\theta\psi}{\phi}$$

where λ is the wavelength. The PDPA software analyzes in real time each Doppler burst and yields the velocity and diameter of the corresponding droplet, the event being validated only if the two pairs of PM 1-2 and 1-3 give consistent results. We checked the validity of the above expression for our droplets by using a model system : it consists in a rotating cell containing polystyrene beads suspended in benzyl alcohol, which gives a contrast of optical indices similar to that for liquid helium-helium vapor. Due to the strong refraction at the air-benzyl alcohol interface, θ, φ, ψ inside the liquid differ from their values for helium. However, for our case of nearly normal detection and incidence, the ratio φ/ψ is conserved, while the reduction in θ is compensated for by that in λ, allowing direct test of the above relationship. For beads with diameters of 3, 6, 23, and 90 µm covering the range relevant for our experiment, the obtained diameters were within 20% of their actual values.

RESULTS

We here present results for a run at a fixed total mass flow of 5.5 g/s. The optical measurements were performed at 10 m downstream from the line inlet, where a heater is used to vary the quality. Power ranges from about 70 W (slightly above the threshold to observe the mist) up to 120 W (corresponding to dry out). Figure 2 shows the cross section of the pipe, with the mist illuminated by a white light sheet, and the studied laser beam locations, respectively 16 and 8 mm above the pipe bottom.

The average vapor velocity is obtained from the vapor mass flow, given by the applied power, plus the heat losses (~10 W), and the vapor density, fixed by the temperature (here 1.79 K or 1.85 K). Figure 3a presents droplet diameter distributions for different vapor velocities. A fairly exponential distribution is found over the range 4-100 µm. On the pipe axis, the trend is that the average size decreases from

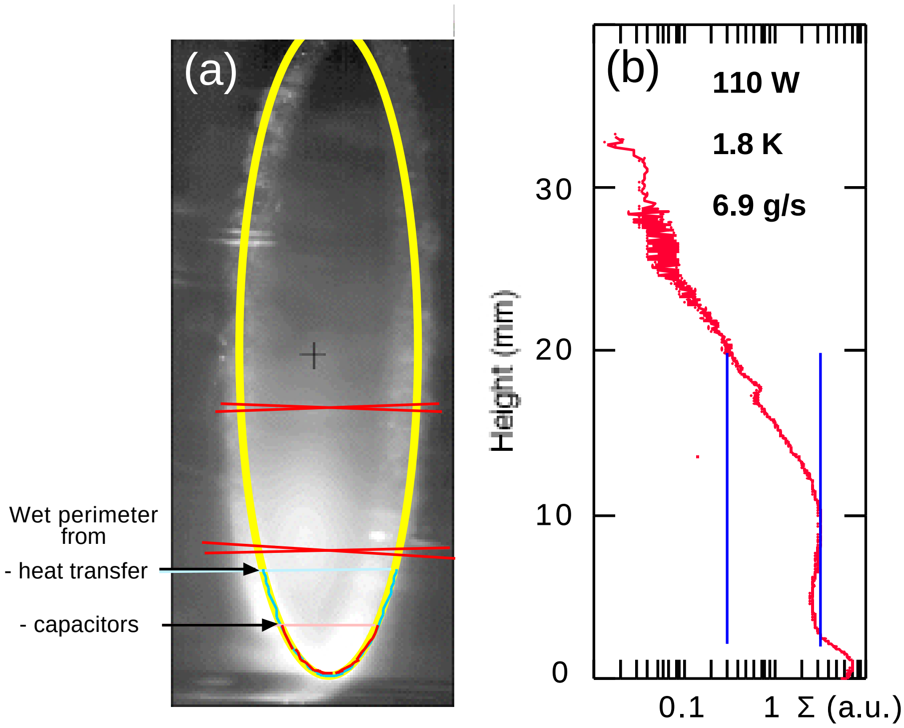

Figure 2 (a) Cross section of the pipe, showing the mist distribution as revealed by sheet illumination normaly to the pipe, and observation at 15° from normal. The two laser beam locations are indicated, as well as the wet perimeter, as deduced from either the capacitors or the thermal resistance; (b) Vertical profile of the interfacial area per unit volume, Σ, deduced from sheet illumination at 1.8 K, 110 W, and 6.9 g/s. For these conditions, Σ increases by a factor of ten between the pipe axis and the pipe bottom.

20 to 10 µm with increasing velocity (from 8 to 12 m/s). The order of magnitude of the decrease is not inconsistent with the v^{-2} law expected from the classical argument in shear atomization that the droplet diameter d corresponds to a constant Weber number $We=\rho v^2 d/\sigma$, where σ is the surface tension. However, our size range (10-20 µm) corresponds to a critical Weber number for drop breakup of order 2, quite smaller than the value of 12 usually reported [5].

Assuming that the size distributions of validated and non validated events are identical, we can compute from the total number of counts, the run duration, the transverse section of the probe volume, and the diameter distribution, the volumes and surfaces (per unit volume) transported by the droplets. On the pipe axis, the latter quantity (i.e. the interfacial area Σ)can be cross-checked with respect to the global (photometric) measurements previously reported [2]. Both results agree within a (systematic) factor of two, which could result from a misevaluation of the transverse section of the probe volume. At the lower height, larger sizes are observed. This is consistent with the fact that the local vapor velocity, hence the atomization, is smaller close to the interface than on the pipe axis (see below). In this case indeed, droplets just issued from the liquid are expected to be larger in size than those falling back from the middle of the tube.

Figure 3b shows the distribution of the component of the droplet velocity along the pipe axis. While data shown correspond to the whole size distribution, velocity histograms for selected size classes show no dependence on size for the small droplets, only the larger droplets having a slightly smaller speed. This shows that the (dominating) small droplets are advected at the vapor velocity. The data on the pipe axis at a given temperature (1.79K) thus show that the mean local vapor velocity increases with the applied power. This local velocity is found about 20% larger than the average velocity computed from the vapor mass flow deduced from the heating power. This is consistent with the observed decrease of the vapor velocity close to the interface (compare the data for 1.85 K and 86 W at two different heights in Figure 3b).

For given flow conditions, the fluctuations of the droplet velocities are due to the gas turbulence. Assuming an isotropic turbulence, we can therefore estimate the r.m.s radial velocity from the width of the axial velocity distribution. On the pipe axis, the relative width of the distribution is constant and of order 20 %. In contrast, the fluctuations at the lower height are stronger. Therefore, despite the lower

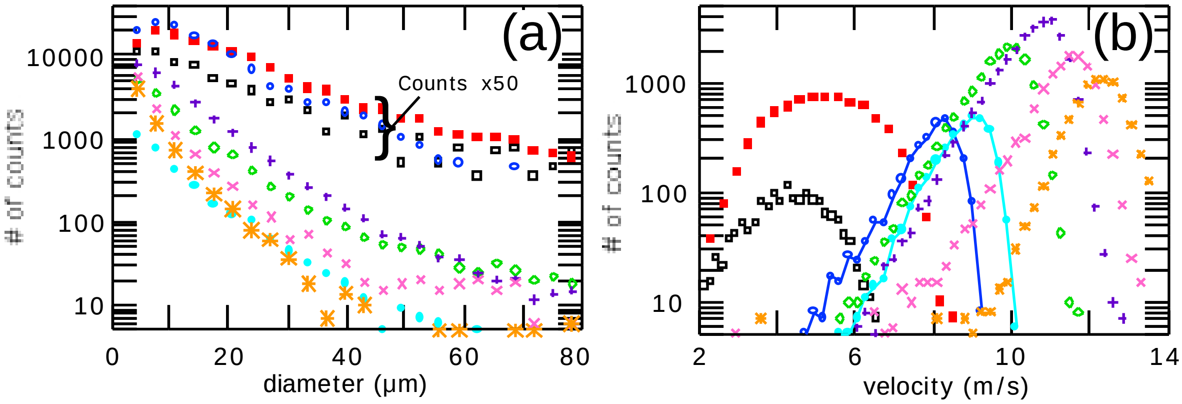

Figure 3 (a) size and (b) velocity distributions for different inlet powers and temperatures, at two positions : low height, 1.85 K : □ 73 W, ■ 86 W; half diameter 1.85 K : ❍ 86 W, 1.79 K : ● 74 W, ✧ 86 W, ✚ 96 W ✕ 105 W, ✳ 112 W ; Vertical scale gives the number of validated counts in 10 s, which, first, increases with the local velocity, before decreasing due to drying out. Validation rate is between 30 and 60% for all data shown.

axial velocity, the estimated radial velocity is comparable to (or larger than) that on the pipe axis (~ 1 m/s for all our data).

We now estimate the liquid flow due to droplets impinging on the walls. For the experiments of Figure 3, the maximal flow at half diameter is for 96 W and of order 0.02 (mm^3/mm^2)/s, corresponding to a cooling power of 6 mW/cm^2. The heat fluxes used to measure the thermal transfer range from 1 mW up to 50 mW/cm^2, as deduced from the measured temperature differences and the thermal resistance in the absence of mist [1]. This flow may then be expected to have a negligible influence on the measured transfer. On the other hand, closer to the interface, the droplet interfacial density is about ten times larger (Figure 2b). Combined with a factor of two increase in the diameter, this gives a cooling power twice as large as the maximal heat flux used, so that the droplets impinging in this region should deposit a film on the walls. These results are qualitatively consistent with the vertical extension of the effective wet area (Figure 2a). We expect a decrease in the efficiency of the thermal transfer at the largest heat fluxes, as the film is burnt by the applied heat flux. We might have observed the beginning of this process [1], but, unfortunately, could not check it by using still larger heat fluxes, as we then reached the lambda transition of the pressurized helium.

CONCLUSION

We have demonstrated the ability of the PDPA technique to characterize the flow of droplets in two-phase HeII. Our findings are consistent with the idea that the improved heat transfer is due to the droplets impinging the walls close to the bottom of the pipe. More systematic experiments should allow to confirm this mechanism. This will be one purpose of the future set-up [6], in which the liquid flow rate, and hence, the maximal vapor velocity, will be varied over a very wide range. An other prospect is to use the efficiency of the PDPA technique to characterize the droplet size and spatial distributions as function of the vapor velocity, an information of wide interest in the general context of two-phase flows.

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