Generalization of the critical angle refractometry for the characterization of clouds of bubbles

Fabrice Onofri[1], Jonathan Worms[2], Mariusz Krzysiek[3], Janusz Mroczka[4]

1: IUSTI-UMR CNRS 6595, University of Provence, France, Fabrice.Onofri@polytech.univ-mrs.fr
2: IUSTI-CEA DFRC, University of Provence, France, Jonathan.Worms@ecl2006.ec-lyon.fr
3: Chair of Electronic and Photonic Metrology, Technical University of Wroclaw, Poland,mariusz.krzysiek@kmeif.pwr.wroc.pl
4: Chair of Electronic and Photonic Metrology, Technical University of Wroclaw, Poland, Mroczka@kmeif.pwr.wroc.pl

Keywords: bubbles, distribution, size, refractive index, composition, critical scattering.

Bubbly flows occur in many industrial and natural processes. Understanding the evolution and properties of bubbly flows is, therefore, of major technological as well as scientific interest. Thus, experimental data and diagnosis tools are still required. In the present paper, we introduce a new optical technique for the simultaneous characterization of the size distribution and the relative refractive index (i.e. composition) of a cloud of bubbles. It is based on a generalisation of the Critical Angle Refractometry (Marston, 1979, Onofri F., 1999).

1. Scattering of a single bubble

From Descartes' refraction optics laws we know that there exists an angle of incidence $\varphi_c=\sin^{-1}(m/m')$, for rays passing from a medium of higher refractive index m' to a medium with a lower refractive m, leading to an abrupt transition to total reflection for $\varphi > \varphi_c$. For a spherical bubble, the same phenomenon occurs at the so-called "critical angle" (CA), $\theta_c = \pi - 2\varphi_c$. In the framework of the wave optics, the total reflection can be treated by a procedure similar to Airy's theory of the rainbow: a Kirchhoff-type approximation is applied to the amplitude distribution along a virtual reflected wave front. This "Physical Optics Approximation (POA)" (Marston, 1979), improves significantly the description of the CA scattering pattern which is characterized by low angular frequency fringes, Fig. 1. In a previous work (Onofri F., 1999), we have derived analytical relations from the first order term of the POA, to infer simultaneously, from an experimental CA scattering pattern: the size and the relative refractive index of a bubble. In the present paper, this earlier work is extended to analyze the CA scattering pattern produced by a cloud of bubbles and finally, the properties of the bubbles. In fact, this requires a much higher precision in the description of the relative amplitude of the scattering pattern. So, we have performed numerical comparisons between the POA (p=0, and p=0 and p=1), the Lorenz-Mie Theory (LMT) and a zero order approximation of the near-critical-angle scattering that is based of the Complex Angular Moment (CAM) theory (Fiedler-Ferrari et al., 1991). Our conclusions are that the POA provides only a good estimation of the position of the fringes, and CAM is only interesting for large bubbles (D>500µm).

2. Scattering of a cloud of bubbles

Classically, in the limit of a single scattering regime, the scattering of a cloud of particles can be considered as an incoherent summation of the contribution of all bubbles that are illuminated. For a given size distribution, the CA scattering diagram can be calculated for various mean sizes (D=25-1000µm), size distribution widths (σ_D/D=0-100%) and refractive indexes (m/m'=1.32-1.52). The key results are that the major influence of each parameter on the CA scattering pattern is: i) for refractive index: an homothetic angular translation of the whole pattern; ii) for the mean diameter : the angular width (spreading /compression) and iii) for the size distribution width : the contrast, the "visibility", of the CA fringes. So that, one can expect to characterize the bubbles properties from the measurement of the global angular position, the angular width and the visibility of the CA scattering pattern.

3. Experimental test and results

The experimental setup is quite similar to the one developed for the analysis of single bubbles (Onofri F., 1999), except that the laser beam is expanded to light large number of bubbles at the same time. 1 good agreement is found between experimental and numerical CA intensity profiles (Fig. 1), provided that the number of bubbles in the probe volume is statistically enough and that they are spherical.

4. References

Marston, P. L. (1979), J. Opt. Soc. Am. A 69, 1205-1211.
Onofri F. (1999), Part. and Part. Syst. Charact. 16, 119-127.
Fiedler-Ferrari, N., Nussenzweig, H. M., and Wiscombe, W. J. (1991), Physical Review A 43, 1005-1038.
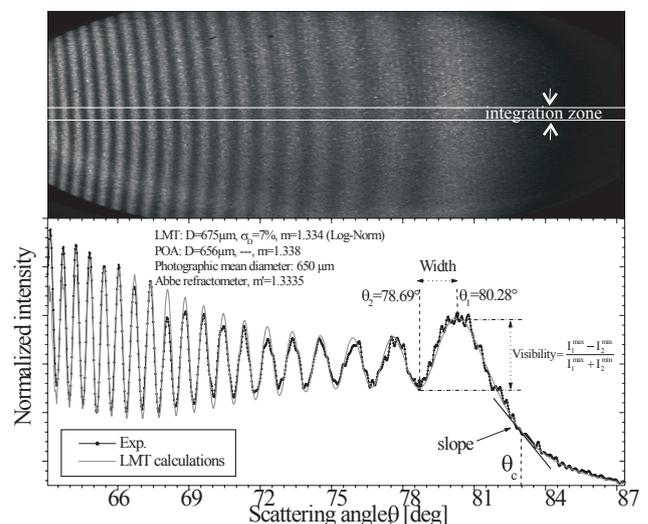
Fig. 1 Critical scattering patterns: experimental and numerical.