

## THE EFFECT OF BUBBLES ON DEVELOPED TURBULENCE

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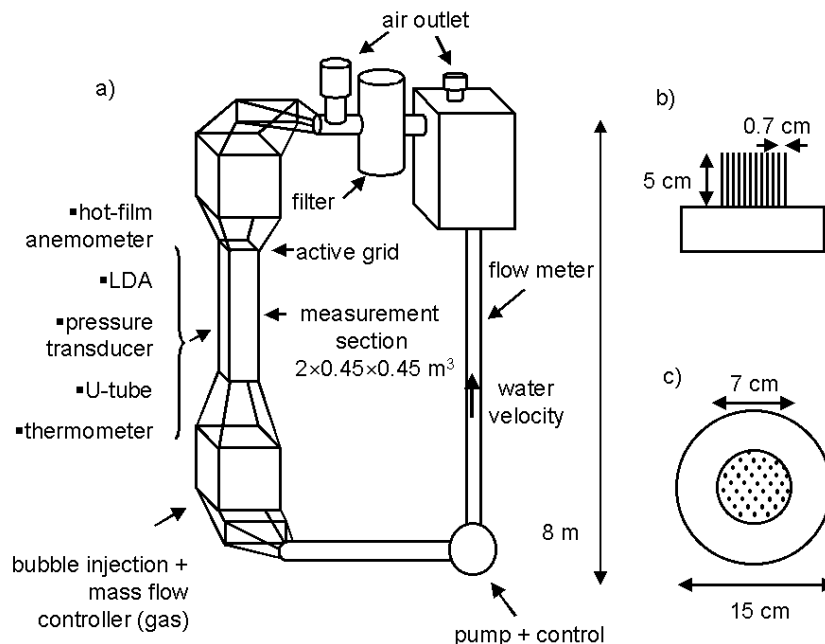
**Summary** We report on measurements of energy spectra, second and higher order structure functions in bubbly turbulence. The void fraction is up to 2.9 % with an mean equivalent bubble size of 3-5 mm. We find the results of [I. Mazzitelli, D. Lohse, F. Toschi, Phys. Fluids, **15** L5 (2003)] qualitatively confirmed, i.e. a more pronounced energy enhancement on small scales than on large scales due to the presence of the bubbles, leading to a less steep slope in the spectrum as compared to the Kolmogorov  $-5/3$  law.

### INTRODUCTION

Hitherto findings on the statistical properties of turbulent two phase flow are inconclusive and controversial. Lance and Bataille [1] found that for increasing gas fraction  $\alpha$  the Kolmogorov energy spectrum exponent  $-5/3$  is progressively substituted by  $-8/3$ . They argue that the steeper spectrum originates from the energy production within the bubble wakes. In contrast, Mudde *et al.* [2] found the classical  $-5/3$  power law in a bubble column even for a gas volume fraction of 25%. Numerical work [3] suggests that there is an energy input at small scales, but an energy reduction at large scales, leading to a less steep spectrum. In order to clarify this controversy, we propose that the role of data analysis has to be carefully analyzed.

### EXPERIMENTS

The measurements of turbulent bubbly flow are conducted in the Twente Water Channel shown in Fig. 1. The flow through the test section is directed vertically downwards with mean velocities up to 0.5 m/s. The device is equipped with an active grid, which allows for Taylor-Reynolds numbers  $Re_\lambda$  up to 200. Gas bubbles with an equivalent size of 3-5 mm can be immersed into the flow by islands of needles (Fig. 1 (b,c)). These bubbles rising upwards against the water flow. Void fractions up to 10 % can be achieved. Hot-film anemometry is used to measure the energy spectra and the



**Figure 1.** Experimental setup. (a) Vertical recirculation loop with test section, bubble injection unit, elbow pump, and reservoir. (b,c) The bubble injection unit consists of nine islands with needles (top view and side view). The gas flow is controlled by a mass flow controller.

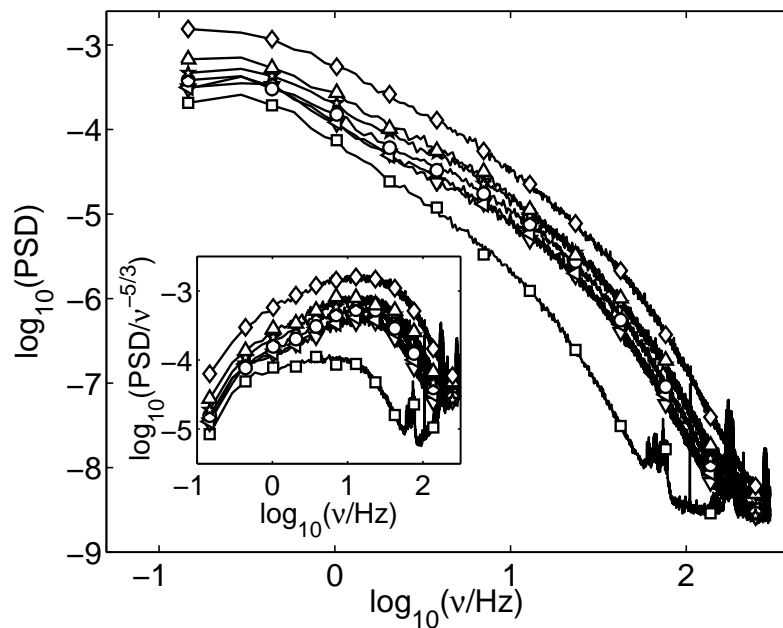
longitudinal velocity structure functions. The application of hot-films in bubbly flows consists of the following steps: (i) characterization of the bubble-probe interaction; (ii) detection of these interactions in the signal and its disentanglement from it; (iii) conditional statistics on the segmented signal. The interaction of a bubble with the hot-film probe has been investigated thoroughly in several experimental studies. Nevertheless, its detection in turbulent flow remains an intricate task. The intrinsic difficulty arises from the large variability of the gas signal and the increasing complexity of the fluid

signal for increasing gas fraction and Reynolds number. Furthermore, it has been shown that the obtained statistical properties of the flow sensitively depend on the accuracy and robustness of the applied method. Thus, the reliability of the algorithm is of prime importance in particular for higher order statistics.

In this paper, we apply an algorithm for hot-film time series based on stochastic pattern recognition [4, 5]. The algorithm consists of an optimal signal decomposition using an adaptive wavelet transform. The classification is done with a neural network based trained classifier. We used the data of bubble-probe interactions of the high-speed imaging for supervised learning. The output of the algorithm is a phase indication function. The robustness and accuracy of the algorithm is carefully evaluated. The typical recognition accuracy is 95-97%.

## RESULTS

Based on the indication function, we discuss methods to obtain conditional statistics, e.g. energy spectra, second and higher order structure functions. The effect of bubbles on the energy spectrum is shown in Fig. 2 for void fractions up to 2.9%. We find the results of [3] qualitatively confirmed, i.e. a more pronounced energy enhancement on small scales than on large scales due to the presence of the bubbles, leading to a less steep slope in the spectrum as compared to the Kolmogorov -5/3 law [6]. In contrast to [1] we did not find a -8/3 power law.



**Figure 2.** Power spectral density. The dependence on the void fraction is indicated by the following symbols:  $\square$  0% (single phase flow);  $\triangleleft$  0.5%;  $\circ$  0.7%;  $\nabla$  1.0%;  $\triangle$  1.5%;  $\triangleup$  2.0%;  $\diamond$  2.9%. The inserted graph shows the power spectral density compensated by  $\nu^{-5/3}$ .

## References

- [1] M. Lance and J. Bataille, *J. Fluid Mech.* **222**, 95 (1991).
- [2] R. F. Mudde, J. S. Groen, and H. E. A. van den Akker, *Chem. Eng. Science* **52**, 4217 (1997).
- [3] I. Mazzitelli, D. Lohse, and F. Toschi, *Phys. Fluids* **15**, L5 (2003).
- [4] J. Rensen, S. Luther, J. de Vries, and D. Lohse, *Int. J. Multiphase Flow* (submitted).
- [5] S. Luther and J. Rensen, *Int. J. Multiphase Flow* (submitted).
- [6] J. M. Rensen, S. Luther, and D. Lohse, *J. Fluid Mech.* (accepted).