Journal of Low Temperature Physics, Vol. 126, Nos. 1/2, January 2002 (© 2002)

The Use of Particle Image Velocimetry in the Study of Turbulence in Liquid Helium

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Experiments are described in which Particle Image Velocimetry has been used to study turbulent flow in helium I. The possibility that this technique might be applied usefully to superfluid helium is explored briefly.

PACS numbers: 47.27, 67.40.V.

1. INTRODUCTION

Particle Image Velocimetry (PIV) has been used extensively in the study of turbulent flow in conventional classical fluids[1]. The principle of the technique is as follows. Small, neutrally-buoyant, tracer particles are added to the fluid. A short light pulse from each of two lasers (with different colours, red and green, say) is focussed into a narrow sheet within the fluid, the two pulses being separated in time by a few milliseconds. The light scattered in a direction normal to the sheet by the tracer particles within the sheet is focussed so that it forms an image of the particles in a colour CCD camera. Each particle produces two images, one red one green, separated by a distance that is a measure of the component of the velocity in the plane of the light sheet with which the particle is moving; the separation is therefore a measure of the component of the local fluid velocity. Analysis requires that the pair of images belonging to a given particle be identified, and this is achieved by a cross-correlation technique based on the assumption that particles within a small interrogation area are moving with approximately the same velocity. The two laser pulses must have different colours in order that the direction of the velocity component within each interrogation area be unambiguously determined.

2. EXPERIMENTS USING PIV IN THE STUDY OF TURBULENT FLOW IN HELIUM I

The experiment is shown schematically in Figure 1. The cryostat contains a vertical channel of length 250mm and square, 50mm×50mm, cross-section, in which a turbulent flow is generated by the motion of a grid from one end of the channel to the other at a uniform speed. The channel is fitted with a set of windows through which the laser pulses and the scattered light can pass; each window has an effective diameter of 20mm and is situated half way along the channel. The biplane square grid has a solidity of 0.44, and grid speeds range from 0.5 to 5 ms^{-1}. After the cryostat has been filled the channel contains no free helium surface.

The particle tracers are hollow glass spheres. As supplied, these spheres have diameters ranging from 1μm to 10μm. When they are added to the helium, the heavier spheres fall quickly to the bottom of the channel, leaving the lighter spheres, used for the PIV, effectively suspended in the helium. The suspended particles are comparable in size with the smallest length scale in the turbulence, so that they do not respond to motion on these smallest scales. Their settling velocity and inertial effects are measured in terms of the Froude and Stokes numbers respectively[2,3], which are estimated[4] to be of the order of five percent over most of the duration, so that these particles indeed follow the fluid motion faithfully.

The pulses from the two lasers have lengths of 10ns and they are at wavelengths 640nm(red) and 532nm (green). The pair of pulses are separated in time by a few milliseconds. The thickness of the focussed vertical light sheet in the channel is approximately 500μm. The CCD camera has 1524×1012 pixels. Each pixel corresponds to 9μm at the position of the light sheet, and the whole recorded image corresponds to an area of 14mm×9mm. The interrogation areas are 64×64 pixels, with an overlap of 32 pixels. Each image yields 45×29 velocity vectors, the smaller number relating to the direction along the length of the channel.

3. EXPERIMENTAL RESULTS

Our experiments so far have been carried out at a temperature of 4.2K. A typical PIV image and the deduced velocity vector plot are shown in

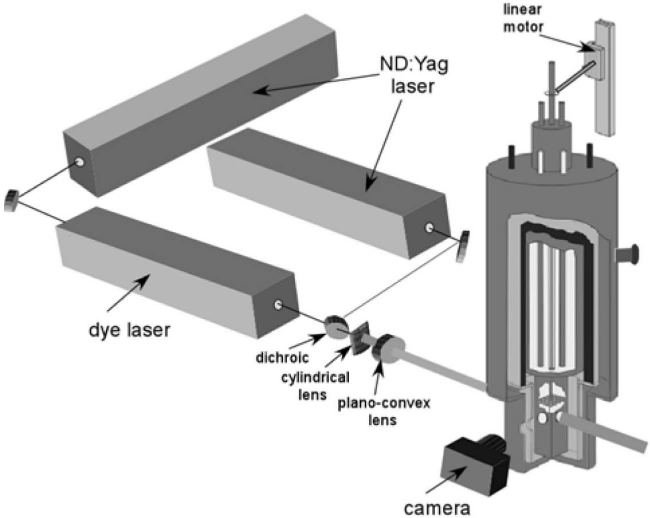

Fig. 1. Schematic of the PIV experiment. The linear motor pulls an external magnet which couples to the grid.

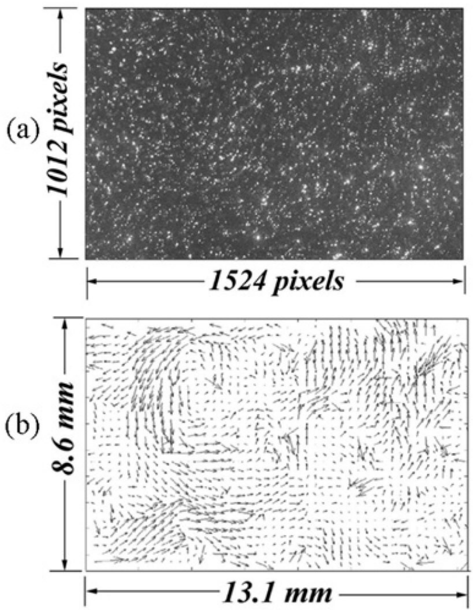

Fig. 2. Typical PIV image and corresponding velocity vector plot taken in helium at t_M=40 and $R_M = 3.3 \times 10^4$.

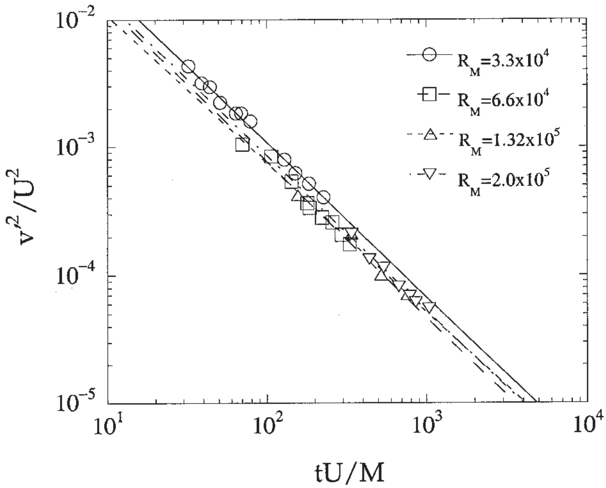

Fig. 3. Time decay of the mean square transverse velocity fluctuation, v'^2, at three different Reynolds numbers. The lines through the data are the least-square power-law fits.

Figure 2. In analysing our data we average over twenty such images, each obtained at a fixed time after passage of the grid. If U is the speed of the grid and M is its mesh, an appropriate dimensionless time is $t_M = tU/M$, and an appropriate Reynolds number is $R_M = MU/\nu$, where ν is the kinematic viscosity of the helium.

A number of results have been obtained from our PIV images. (1) We have measured the time decay of the mean square turbulent transverse velocity, v'^2, normalized by U^2 (Fig. 3.). If these data are fitted to a power law $\alpha t_M^{-\beta}$, we find that α is typically about 0.2 and β is typically about 1.2 (with a statistical uncertainty of less than ± 0.1). (2) We have obtained the "longitudinal" integral length scale L_i by evaluating the area under the normalized correlation function $\langle v'(r)v'(r+a)\rangle$, where the displacement a is parallel to the grid. The results can be compared with earlier wind tunnel data [5] by converting space in those experiments to time in ours through the flow velocity U. Agreement is within an experimental error of 0.25-0.5 mm for L_i. (3) We have computed the quantity $\epsilon L/v'^3$, where ϵ is the energy dissipation rate. Experiments[6,7] and direct numerical simulations[8] indicate that for conventional classical fluids this quantity tends to a constant value of order unity for large enough Reynolds number ($R_\lambda \approx R_M^{0.5} \geq 70$); our data for helium I indicate a similar behaviour for R_λ up to 350 (Fig. 4.).

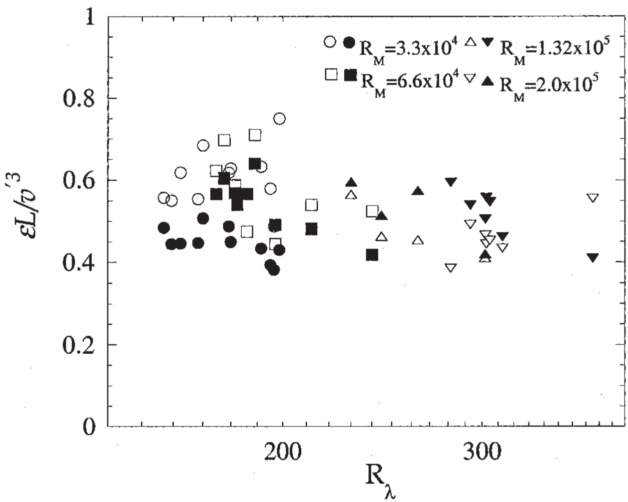

Fig. 4. $\epsilon L/v'^3$ as a function of R_λ.

A full analysis of our results will be published elsewhere, but it can be stated here that they indicate a behaviour consistent with that observed in any classical fluid.

4. POSSIBLE EXPERIMENTS USING PIV WITH SUPERFLUID HELIUM

There are two velocity fields in superfluid ^{4}He, corresponding to the normal and the superfluid components. In addition there may be quantized vortex lines in the superfluid component, and these lines may determine a third velocity field. *A priori* it is not obvious how a seed particle will respond in the presence of these velocity fields. Detailed calculations suggest that the response is generally complicated and depends on the size of the particles, on the frequency with which the turbulent velocity at a particular point in space changes with time, on the viscosity and density of the normal fluid, and on the extent to which vortex lines can trap the particles. Careful and systematic experiments would be required to check these predictions, with a range of seed particles having well-defined shapes and sizes.

However, there is one particular situation where the behaviour may be more simple. It has been shown by Stalp *et al*[9,10] that grid turbulence in superfluid helium above 1K can be described by a classical model. According to this model the superfluid contains a large density of vortex lines, which, through the action of mutual friction, lock the two fluids together on length scales larger than the spacing between the vortex lines. The locked fluids behave like a single classical fluid. Since the velocities of the two fluids are equal in this locked situation, and since the vortex lines must move with a velocity field that is closely equal to this common velocity, there can be little doubt that suitable tracer particles ought to respond classically to this common velocity. Experimental study with PIV could therefore provide valuable confirmation that the classical model does indeed provide a good description of grid turbulence in superfluid helium.

The use by Stalp *et al*[9,11] of second sound as a probe for the decay of vortex lines in superfluid grid turbulence has led to the observation of turbulent decay over a period much larger than that achieved so far in helium I by PIV, so that a more complete picture of the evolution of the turbulence can be obtained. The use of second sound remains therefore a powerful technique, but PIV could provide useful supplementary evidence and information.

ACKNOWLEDGEMENTS

We are grateful to Ladislav Skrbek for helpful discussions. Our research was funded by NSF grant # DMR-9529609.

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