Particle Image Velocimetry Investigations of Turbulence in Superfluid Helium

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Abstract: The present paper overviews the unique aspects of performing PIV experiments in superfluid helium. The paper begins with a brief introduction of the physics of superfluid helium and what PIV may be able to tell us about this unique fluid. This section is followed by a discussion of some of the practical aspects of PIV experimentation with superfluid helium, specifically, the selection and introduction of seeding particles and the unique challenges of the low temperature environment. The paper concludes with a few recent examples of superfluid helium PIV experiments to highlight the discussion.

1. Introduction

Liquid helium at temperatures below about 2.2 K becomes a superfluid with associated unique properties: mass flow without friction; anomalous heat transport by a mechanism known as second sound; and quantized vortex lines in the turbulent state. The existence of these unique characteristics has been extensively investigated using global measurement techniques such as temperature and pressure probes as well as second sound (thermal waves in superfluid helium) attenuation. Such measurements provide useful information about superfluid dynamics; however, they are model dependent and can not directly measure the dynamics of the flow field. For these reasons, researchers have long been interested applying visualization techniques to superfluid helium in order to probe the local velocity field, turbulent vorticity and to study boundary layer phenomena. Particle image velocimetry (PIV) shows promise as a tool that can provide an expanded our understanding of these complex phenomena.

Although the PIV technique has been well developed for classical fluid dynamics studies, its application in superfluid helium fluid dynamics has only just begun and is in some ways more challenging. One of the main hurdles to performing PIV in liquid helium is the development of suitable imaging particles that can be introduced into the liquid and track the flow field. Since liquid helium is a very low density fluid (SG = 0.145) with a small viscosity (μ ~ 1 μPa-s) and exists at extremely low temperatures, many of the conventional particle seeding techniques do not produce a homogeneous dispersed particle distribution suitable for PIV. Two particle seeding techniques that have been successful in liquid helium studies are: 1) the use of commercial (d ~ 1 μm) polystyrene microspheres vacuum processed to minimize coagulation and 2) the condensation and dispersion of solid hydrogen particulates from the gas phase (Zhang, et al., 2004; Bewley, et al., 2007). Still there is concern about how these particles interact with superfluid helium. For example, theoretical predictions (Poole, et al., 2005; Fujiyama, et al., 2005) indicate that the particles should interact with the quantized vortex lines that exist in the turbulent state producing an effective drag force that can lead to unexpected behavior in the visualized flow field. In the extreme, this interaction can lead to particle trapping by vortex lines, which has been observed in some experiments (Bewley, et al., 2006).

After a brief introduction to the unique physical behavior of superfluid helium, the bulk of the present report will focus on how to perform PIV experiments in this unique fluid. The two principal issues contained are how to seed the fluid with tracer particles and technical aspects of how to study low temperature fluid dynamics. The report concludes with a few examples of recent PIV experiments and what they have revealed about superfluid helium.
2. Dynamics of superfluid helium

One of the exceptional characteristics of liquid helium is that it can exist in either of two different phases, normal helium (or He I) and superfluid helium (or He II). These two phases are separated by a pressure dependent phase transition known as the lambda transition, which under saturated pressure occurs at $T_\lambda = 2.176 \text{ K}$. While He I is essentially a Navier-Stokes fluid that obeys the hydrodynamics described by classical fluid dynamics equations, He II displays many unique transport properties, such as a superior thermal conductivity that is many orders of magnitude greater than that of ordinary fluids, and a lowest kinematic viscosity of all known fluids, about three orders of magnitude smaller than that of air. These unique transport properties of He II can be interpreted in terms of the two-fluid model (Landau, 1987). According to this model, He II is comprised of two fully miscible interpenetrating fluid components: the normal fluid and the superfluid. The normal fluid component contains all the thermal excitations and behaves like an ordinary Navier-Stokes fluid with a density $\rho_n$, viscosity $\mu_n$, and specific entropy $s_n$. The superfluid component is thought to be in a macroscopic quantum state. It has a density $\rho_s$, but no viscosity and entropy, i.e. $\mu_s = 0$ and $s_s = 0$. Although the density of He II is nearly constant with temperature, each of the two fluid components has a strong temperature dependence with, for example $(\rho_n/\rho) \sim (T/T_\lambda)^{5.6}$. Also, each fluid component has its own independent velocity field, $\vec{v}_n$ and $\vec{v}_s$, respectively.

If a heat flux $q$ is applied to He II, it is the entropy containing normal fluid component that will carry the heat away from the source. However, at the same time the superfluid component will move in the opposite direction in order to conserve the mass and momentum. This relative motion between the normal fluid and superfluid termed “thermal counterflow” is what gives He II its exceptional heat transport properties. He II has the highest effective thermal conductivity of any known fluid system. Since all the applied heat is carried by the normal fluid, the averaged normal fluid velocity is can be calculated from the expression,

$$\bar{v}_n = \frac{q}{\rho s T}$$  \hspace{1cm} (1)

where $\rho = \rho_n + \rho_s$ is the bulk density of He II, $s = s_n$ is the total entropy, and $T$ is the absolute temperature. Since the normal fluid component has viscosity, one would expect that micron-scale particles such as are used in PIV should track the normal fluid at a velocity $v_p \sim v_n$. However, there are other factors that determine the dynamics of particles in He II mostly associated with the turbulent states of the fluid.

The transition to turbulence that occurs in He II displays a number of unique features. It is believed that the normal fluid component becomes turbulent at a critical Reynolds number ($\text{Re}_{nc} \sim 1200$) much that same as with classical fluids. However, turbulence also can occur in the superfluid component; although because the superfluid is in a quantum state the turbulence manifests itself as a tangle of quantized vortex lines that permeate the fluid. Understanding the behavior of these vortex lines is at the heart of the physical description of He II. For example, the transport of heat in He II is limited by a mechanism known as “mutual friction”, which is attributed to the interaction between the normal fluid component and the superfluid vortex lines. Recent experimental and theoretical evidence similarly suggest that a significant interaction between these vortex lines and micron scale particles may also influence the results obtained from visualization techniques such as PIV. These fundamental issues need to be considered both in terms of the performance of PIV experiments as well as the interpretation of results.
3. Particle seeding for PIV in superfluid helium

Seeding particles in superfluid helium is far from trivial. The low temperature (T ~ 2 K) and low pressure (p ~ 1 kPa) environment solidifies all common gases and liquids. The sole exception is helium. As a result, it is very important to use seeding particles that have been purged of all contaminants. It is also necessary to utilize a particle delivery system that maintains the purity of the seeding particles while they are delivered into the liquid helium bath. There are currently two reasonably successful approaches to particle seeding in superfluid helium. These are: 1) vacuum processed commercially available polystyrene solid particles and 2) particles generated by freezing hydrogen (H\(_2\)) or deuterium (D\(_2\)) gas directly into the liquid helium. Here we discuss both options.

Among the readily available commercial particles, we have found that polymer micro-spheres with mean diameter in the range of 1.7 \(\mu\)m and density of 1100 kg/m\(^3\) have acceptable settling velocity (calculated slip velocity of 1.2 mm/s) and response time constant (\(\tau \sim 1.5\) ms). We have also attempted to use hollow glass bubbles, which are near to neutral density (SG ~ 0.2) but are too large and have too wide a size distribution. To date, we have mainly used the polystyrene particles in our PIV experiments for tracking steady thermal counterflow and transient counterflow induced by second sound and heat diffusion.

We have developed a simple seeding method based on the fluidized bed technique to inject polystyrene particles into liquid helium (Zhang, et al., 2005). As shown in Figure 1, the particles are first heated to over 100 °C for more than eight hours to evaporate any contained moisture. Then high purity helium gas is used to purge the particles followed by evacuation with the vacuum pump to p < 1 Pa. After several purging cycles, the helium gas flows through the porous plate carrying the particles into the liquid helium cryostat. Since these particles have a strong tendency to aggregate together due to their small size, larger (d ~ 100 \(\mu\)m) glass beads are added to the fluidized bed. The upward helium gas velocity is then set between the gravitational settling velocities of the polymer particles and glass beads. Thus, the large size beads are fluidized producing a continuous friction between them, which reduces the aggregation of the polymer particles. A typical seeding result of polymer particles is shown in Figure 2, from which a high particle concentration with no severe particle aggregation can be seen.

![Figure 1. A simple particle seeder using the fluidized-bed technique.](image1)

![Figure 2. A typical seeding result for polystyrene micro-spheres in He II.](image2)
We have also used solidified D$_2$ particles in recent forced flow He II experiments and others have used solidified H$_2$ or H$_2$-D$_2$ particles for counterflow and vortex visualization experiments. The tracking characteristics of solidified H$_2$-D$_2$ particles show the greatest potential for fidelity, fast response and minimal settling due to their near neutral density. By adjusting the ratio of H$_2$ to D$_2$, one can in principle make a particle that is truly neutrally buoyant in He II. However, the solid H$_2$-D$_2$ particle generation process requires special care and control with the resulting particles not necessarily being uniform in size or shape. Furthermore, solid H$_2$ (or H$_2$-D$_2$) particles have a tendency to agglomerate over time into larger structures that become too big for PIV.

Figure 3: Different methods for seeding solid hydrogen particles into liquid helium.

There are various approaches to seeding solid hydrogen particles in liquid helium, see Fig. 3. Nakano and Murakami (1994) used the approach shown in Fig. 3a where the H$_2$-D$_2$ gas is condensed from the vapor phase above the liquid. They reported good seeding producing micron size particles, but the technique is rather inefficient because most of the gas is pumped away with the evacuated helium vapor. Celik (2002) used the approach shown in Fig. 3b, where liquid hydrogen was ejected through a nozzle directly into the liquid helium producing a fine spray that solidified particles. However, in this case, the particle size and distribution was too large and thus not suitable for PIV. The most successful approach to seeding micron-scale solid hydrogen particles into liquid helium was first developed by Boltnev, et al. (2002). Similar techniques have been used by Bewley (2007) and our group (Xu, 2006), see Fig. 3c. The important common feature in all these approaches is to first dilute the hydrogen gas in helium gas at room temperature with a ratio that, depending on the detailed nature of the experiment, can vary between 1/20 and 1/1000. The purpose of the helium gas is to minimize the number of collisions between hydrogen molecules as the gas mixture cools to helium temperature. This ensures that the resulting solid hydrogen particles are of micron-scale and reasonably uniformly distributed within the helium bath. The gas is injected directly into the helium bath producing a cloud of particles that disperses into the bath, see Fig. 4.
To perform Particle Image Velocimetry (PIV) measurements with liquid helium one needs an optical system that can visualize experiments at low temperatures. One of the principal components of such a system is a liquid helium cryostat with optical windows on three sides, as shown in Fig. 5. The cryostat contains the experimental channel for liquid helium flow and heat transport. As an example, the channel we have previously used for He II thermal counterflow PIV experiments is shown in Figure 6. This channel has a cross section area of approximately \( 40 \times 20 \text{ mm}^2 \) and a length of 200 mm although the PIV measurements are conducted in a \( 20 \times 20 \text{ mm}^2 \) view field about 150 mm above the heater that encloses the lower end. In this case, the whole channel is submerged in the He II bath and maintained at a constant temperature between 1.6 K and 2.1 K. The tracer particles are injected from the seeding device into the liquid helium channel and as they pass through the view field, images are captured by the camera and the velocity field is then derived using the PIV analysis software. With this configuration, we have been able to explore many details of the particle velocity generated by thermal counterflow to a spatial resolution of +/- 0.5 mm and a particle velocity range from near zero to over 100 mm/s.

Our visualization system consists of a Nd:YAG dual head pulse laser with a maximum operating rate of 15 Hz and variable emitting energy up to 120 mJ. However, to minimize heating of the fluid we operate the laser at near minimum power. Standard beam expanding optics are used to transform the cylindrical laser beam into a laser sheet that passes through the experimental region illuminating the particles in the view field. A SharpVISION® CCD camera with a spatial resolution of 1300(H)×1030(V) pixels acquires the images at 90 degrees. The unscattered laser light passes through the cryostat and is absorbed at room temperature in a beam dump.
4. Recent PIV experiments in superfluid helium

Here we present a few examples of experimental results on superfluid helium heat and mass transport obtained using the PIV technique. One of the most common and interesting problems in fluid dynamics is that of flow over a bluff body such as a sphere or cylinder. Such flows display complex phenomena such as flow separation and vortex shedding (Schlichting, 1951). Of interest in our investigations was whether these phenomena are present for thermal counterflow where the two fluid components are counter-current. To investigate this idea, we performed a PIV experiment on thermal counterflow over a cylinder in cross flow. To conduct this experiment, we inserted a transparent glass cylinder (OD = 6.35 mm) in the view field of the counterflow channel shown schematically in Fig. 6. The experiment used polystyrene micro-spheres to seed the flow field.

To initiate the experiment, a steady heat flux was applied to the heater at the bottom of the channel resulting in an upward flowing normal fluid component and a downward flowing superfluid component. Figures 7 and 8 show an example of the kind of result obtained. These results are for one temperature and heat flux (T = 2.03 K; q = 11.2 kW/m$^2$). Note the existence of large vortex structures both upstream and downstream of the cylinder. These structures are similar to that seen in flow of classical fluids over cylinders; however there are two important distinctions. First, in the case of counterflow He II these structures exist in front of as well as behind the cylinder. It is suggested that the structures in front of the cylinder may be due to the counterflowing superfluid component interacting with the seeding particles. The other distinction is that these turbulent structures do not detach becoming a vortex street as in the case of classical fluids. We hypothesize that this is because in counterflow He II the net momentum in the fluid is zero even though there is a relative velocity between the two fluid components, see Zhang and Van Sciver, 2005.

![Figure 7: Measured particle velocity field around the 6.35 mm OD cylinder in counterflow He II. q = 11.2 kW/m$^2$ at T = 2.03 K corresponding to Re$_D$ = 21000. The velocity scale at the top is calibrated in pixels/ms (1 pixel/ms = 22 mm/s).](image1)

![Figure 8: Computed stream lines for particle motion for the two heat flux cases in Fig. 7. q = 11.2 kW/m$^2$ at T = 2.03 K corresponding to Re$_D$ = 21000](image2)

A second example of the use of PIV to study turbulence in He II involves the case where the He II is forced to flow through a channel with a net fluid velocity, $u$. The simplest case to consider is that of adiabatic flow at high Reynolds number (Re > 1200) so that the fluid is fully turbulent. We have investigated channel flow in this case by seeding with solid deuterium particles in a horizontal
flow facility containing a square cross section channel, 20 mm x 20 mm for flow rates up to Reynolds numbers of 6.6 x 10^5. Of interest is to study the velocity profile and detailed shape of the boundary layer. It is worth noting that prior to this experiment, no one had visualized the velocity boundary layer in forced flow He II.

Figure 9 shows a contour plot of the velocity profile for a mean velocity of 34.5 mm/s at 2.1 K. The velocity boundary layer is clearly visible at the top and bottom of the view field. From these data we were able to compute the local particle velocity as a function of position perpendicular to the flow direction and as a function of fluid velocity. These results were then normalized versus the average fluid velocity obtained from an independent flow rate measurement. Figure 10 shows this normalized velocity profile versus position where W is the channel width and y is the distance away from the channel wall and normal to the flow direction. Clearly visible is the velocity boundary layer near the channel wall. As can be seen in the figure, these results are in reasonable agreement with Nikuradse’s n^th power law velocity distribution function.

Figure 9: Averaged velocity field of the deuterium particles in forced flow He II at 2.1 K, u = 35.5 mm/s corresponding to a Reynolds number Re = 5.4 x 10^5.

Figure 10: Normalized velocity profile at 2.1 K for different Reynolds number.

5. Summary

The Particle Image Velocimetry technique has only recently been applied to flow visualization experimentation on liquid helium. PIV with liquid helium requires unusual experimental conditions driven largely by the low temperature and partial vacuum environment. Suitable solutions to these challenges have been obtained allowing a series of successful experiments that are yielding important new information about this unique fluid system.

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7. References
