Visualization of two-fluid flows of superfluid helium-4

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Abstract

Quantum fluids have been studied experimentally for many years and have by now become a major focus of low-temperature physics (ref. 1 and references therein). Applications of the subject are widely ranged, from engineering, where superfluid 4He is used as a coolant for superconducting magnets and the formation of cosmic strings (5, 6). More recently, superfluidity has been used to describe the collective behavior of birds (7) and a cosmological model has been used to obtain perfluidity has been used to describe the collective behavior of birds (7) and a cosmological model has been used to obtain results relevant to superfluid turbulence (8). The latter form of turbulence, occurring in quantum fluids, is indeed an especially interesting topic because of its quantum peculiarities and its similarity to classical turbulence. Superfluids, in which turbulence can be directly visualized and studied, include superfluid 4He and atomic Bose–Einstein condensates (9). Due to the limit of small sample volumes, the experimental study of turbulence in Bose–Einstein condensates has hardly begun. The development of visualization techniques applicable to superfluid 4He is thus essential, if our understanding of quantum turbulence is to make significant progress in the near future.

Superfluid 4He is viewed as consisting of two interpenetrating fluids. The gas of thermal excitations forms the normal component, which can be considered as a viscous fluid. The superfluid component is inviscid and its rotational motion is possible only in the presence of topological defects, in the form of quantized vortex filaments. Turbulence in the superfluid component therefore takes the form of a tangle of quantized vortex lines. Turbulence in the normal fluid is more conventional, although the interaction between the normal fluid and the vortices leads to the nonclassical force of mutual friction between the two fluids. Turbulence in such a system can exhibit a behavior that is similar to that found in a classical fluid; but it may take forms that are unknown in classical fluid mechanics: for example, forms relevant to a fluid in which there is no viscous dissipation, and those that depend on the coexistence of the two fluids. Study of quantum turbulence can therefore enrich our knowledge of turbulence in general, as well as being interesting in its own right.

Visualization Techniques

Flow visualization techniques have been developed to a high degree of precision and speed for classical fluid dynamics investigations. However, for liquid helium, such techniques have not kept pace, in part due to the extremely low temperature and low density of the fluid. A number of early efforts were devoted to producing macroscopic particles for qualitative investigations (10–12) and the challenge of producing neutrally buoyant particles that faithfully follow the complex flow fields has been the main impediment to quantitative advancement. In addition, several attempts have been made to visualize fluid dynamics in superfluid helium with microscopic tracers, which include neutron absorption tomography, using 3He particles (13), and acoustic cavitation imaging, using electron bubbles (14). These small particles are expected to follow the fluid motion, because Stokes drag, from the normal-fluid flow, is deemed to dominate other forces. However, these methods have specific challenges. Neutron absorption tomography requires a finely collimated neutron beam and the ability to raster the neutron beam through the region of interest. The electron-bubble cavitation method relies on the generation of strong ultrasonic sound waves in helium that inevitably disturb the flow to be studied. Recently, the groups represented by the present authors have successfully developed a number of liquid helium flow-visualization techniques: particle image velocimetry (PIV) and particle tracking velocimetry (PTV) techniques, using micron-sized solid particles (15–21), and a laser-induced fluorescence imaging technique, using angstrom-sized He3 excited molecules (22, 23).

PIV and PTV Techniques. PIV and PTV are valuable, quantitative tools that have been applied to study many scientific and industrial problems (24). PIV can estimate the fluid velocity in a section of the flow field, by assuming a single, smoothly varying velocity field, whereas PTV allows the measurement of Lagrangian quantities, i.e., the local velocity and its derivatives. With both techniques the particles are suspended in the fluid and reflect the light from a laser sheet that illuminates the flow field of interest. The time-dependent positions of the particles are thus captured and analyzed by a suitable digital imaging system. The particles for liquid helium experimentation can be broadly classified into two categories: solid particles, as are often used in classical fluid dynamics experiments, and solidified particles, produced by injecting gases (usually hydrogen or deuterium) into liquid helium. Micron-sized solid particles have been successfully used in conjunction with the PIV technique to observe broad, average properties of the turbulent state of superfluid helium (15, 25, 26). However, such particles have proved to be too dense to explore the detailed structure of quantum turbulence. As a result, most recent experiments have used solidified hydrogen (or deuterium) particles (16–21). To produce these particles, a gaseous mixture of helium and hydrogen in a volume ratio of ~100:1 is injected directly into liquid helium. A cloud of solid particles with diameters typically of a few microns can be produced.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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www.pnas.org/cgi/doi/10.1073/pnas.1312546111

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Although solids from other gases, such as argon, methane, nitrogen, and propane, have been tested (27), hydrogen and deuterium produce particles that are close to neutrally buoyant.

**H₂ Fluorescence Imaging Technique.** Recently, a new visualization technique, using excited H₂⁺ triplet molecules, was developed (22, 23). These molecules can be produced in large numbers in liquid helium, following the ionization or excitation of ground state helium atoms (28, 29). The singlet state molecules radiatively decay in a few nanoseconds (30), but the triplet state molecules are metastable with a radiative lifetime of about 13 s (31). These triplet molecules form bubbles in liquid helium with a radius of about 6 Å (32) and can be used as tracers. To image the H₂⁺ triplet molecules, a cycling-transition laser-induced fluorescence technique, first developed by McKinsey et al. (33) and McKinsey and coworkers (34), has been used. A laser pulse at 905 nm can excite helium molecules from their triplet ground state 3Σ⁺ to the excited electronic state 1Σ⁺. Over 90% of the molecules in the d state quickly decay to an intermediate b¹Π state, emitting detectable fluorescent photons at 640 nm (35). A filter can be used to block unwanted laser light, to achieve low background. From the b¹Π state, molecules quench back to the 3Σ⁺ state, and the process can be repeated so each molecule produces many fluorescence photons.

**Particle Motion in Superfluid Helium.** In superfluid helium-4, vorticity is concentrated along the filamentary cores of quantized vortex lines, and the velocity circulation around any such line is equal to \( \kappa = \hbar / m_A \approx 3 \times 10^{-3} \text{ cm}^2/\text{s} \), where \( \hbar \) is Planck’s constant and \( m_A \) indicates the mass of a \(^4\text{He} \) atom. A particle positioned on a quantized vortex line in superfluid helium displaces liquid that has high kinetic energy, and, as a result, there is an energy binding the particle to a vortex line. The micron-sized particles used in the PTV and PTV experiments can consequently get trapped on quantized vortex lines, besides tracing normal-fluid flows (to date these experiments have been performed at temperatures above about 1.5 K, mainly due to heat load concerns). Moreover, as detailed below, imaging trapped particles allows the study of interesting vortex-line dynamics. However, in flows where the normal fluid, the superfluid, and the vortices have different velocity fields, the behavior of these particles might become difficult to interpret (19, 36, 37). On the other hand, H₂⁺ molecular tracers are entrained solely by the normal-fluid component above 1 K, due to their small binding energy on vortices (38). This makes them suitable for unambiguously probing various normal-fluid flows; and, as revealed in recent experiments, H₂⁺ molecules can attach to quantized vortex lines below 0.2 K (39), which has the potential to allow for vortex-line imaging at low temperatures. More generally, it is clear that special care should be taken when choosing the tracer particles, keeping especially in mind that particle size should always be smaller than relevant flow length scales (19, 36).

**Progress on Flow Visualization in Helium**

**Vortex-Line Imaging Experiments.** Bewley et al. (16) first observed solid hydrogen particles trapped on quantized vortex lines, using the PTV facilities at University of Maryland (Fig. 1). The particle tracking technique was then further developed to investigate vortex reconnection in superfluid helium. Reconnection was first predicted by Feynmann in 1955 as a process by which dissipation could be allowed even in pure superfluid (40). Experiments, which strongly suggest the occurrence of vortex reconnection, were performed by Bewley et al. (41) and Paoletti et al. (17) in 2008, supporting both the existence of this topological change and the details of the predicted vortex motions. Fig. 2 shows an example in which two vortices, marked with particles as solid lines, meet and cross, exchanging topology and rapidly retracting. The vortex rapid retraction leads to a high particle velocity \( v \), which is characterized by the predicted \( v^{-3} \) power-law distribution (17, 42). This clearly distinguishes quantum turbulence from classical turbulent flows, as the velocity distribution of the latter has a nearly Gaussian shape (43). Such a power-law shape of the tails of the velocity distributions was later confirmed in two-fluid flow experiments (20, 21) and in superfluid numerical simulations (44–47). Note, however, that the reasons why the tails of the velocity distributions obtained in two-fluid flow (17, 20, 21, 42) are consistent with those computed in the absence of normal-fluid flow (44–47) are still not entirely understood and further investigations are consequently required to address the issue.

**Thermal Counterflow Experiments.** Thermal counterflow is a unique flow mode that exists only in the superfluid phase of helium, even though its study might be also relevant to the understanding of heat transport, e.g., in the form of turbulent convection (52, 53). The condition can be easily established by applying heat at

![Fig. 1.](image-url)

**Fig. 1.** Intensity inverted images showing hydrogen ice particles trapped on quantized vortex lines in superfluid helium (16). The concentration of hydrogen ice can be varied such that (A) only isolated particles are trapped on vortices, (B) multiple particles form dotted lines on vortices, or finally (C) solid hydrogen skeletons perturb the dynamics of the vortices and stabilize branches and crossings. The natural state is for crossings to reconnect.

![Fig. 2.](image-url)

**Fig. 2.** Images at low ice concentration confirm vortex line reconnection and allow one to quantify the dynamics of the intervortex separation \( \delta (t) \) (42).
the closed end of a flow channel containing superfluid helium. The normal-fluid component carries the heat and moves away from the heater at a mean velocity \( v_n = q / \rho S T \), where \( q \) is the heat flux, \( \rho \) is the helium density, \( T \) denotes the temperature, and \( S \) represents the specific entropy of helium (54). The superfluid component moves toward the heat source, serving to eliminate any net mass flow. It has been known for many years that, above a (small) critical value of heat flux, the superfluid component in counterflow becomes turbulent. This results in a tangle of quantized vortex lines, whose dynamical behavior is an essential ingredient of quantum turbulence (55). Counterflow allows a controlled forcing of the superfluid state away from equilibrium.

A number of flow visualization experiments have been performed in thermal counterflow. Early PIV experiments indicated that average particle velocities were typically less than the normal-fluid velocity field in counterflow. A thin line of \( \text{He}_2^+ \) tracers was created via laser-field ionization in helium. To achieve the required high electric field for ionizing ground state helium atoms, laser intensity as high as \( 10^{13} \text{ W/cm}^2 \) is needed (58). Such a high instantaneous laser intensity can be achieved by focusing a femtosecond laser pulse through a tiny cross-section. The molecule density so created is high enough to allow high-quality single-shot imaging of the tracer line. Fig. 4 shows fluorescence images of \( \text{He}_2^+ \) tracer lines that have been successfully generated and imaged in counterflow, at 1.85 K, with a 35-fs laser pulse, at 55 mJ. At low heat fluxes, a straight tracer line deforms into a parabolic shape, indicating the Poiseuille laminar velocity profile of the normal fluid. At large heat fluxes, the tracer line distorts, possibly due to the turbulent eddies in the normal fluid. The local normal-fluid velocity could then be estimated by dividing the center displacement of a small line segment by the drift time. Structure functions of the turbulent flow could be computed based on the derived velocities (59), which should allow us to gain information on the turbulent energy spectrum. By creating multiple lines to include crosses or grid tracer structure, measurements of normal-fluid vorticity and other complex velocity derivatives can be made.

To unambiguously examine the normal-fluid motion in thermal counterflow, the \( \text{He}_2^+ \) molecule visualization technique was recently used (23). The \( \text{He}_2^+ \) tracers were produced by a tungsten field-emission source in a glass counterflow channel. A focused pump laser pulse at 910 nm was used to tag a line of molecules across the channel by driving the molecules to a long-lived vibrational level \( a(1) \) (Fig. 3A). This tagged line was imaged subsequently, using a probe laser pulse at 925 nm. Up to 40 images were superimposed at each given pump–probe delay time to achieve a good image quality. Typical summed images are shown in Fig. 3B, suggesting a flat averaged normal-fluid velocity profile that should be expected for turbulent flow, in a long enough channel. The observed rapid growth of the averaged line width with time further supports the claim that the normal-fluid flow is turbulent (23). Note that, due to the mutual friction between the two fluid components, dissipation occurs at all length scales in the normal fluid, which contrasts with the situation in classical turbulence, where dissipation is deemed to take place only below a small length scale, called the Kolmogorov length scale (54). The experiment revealed a unique normal-fluid turbulence in counterflow (57).

Normal-Fluid Turbulence in Counterflow. The unique type of turbulence just discussed obviously calls for further attention. Studying it not only will likely broaden our understanding of turbulence in general, but also might have practical significance because the turbulent normal-fluid flow could, e.g., alter our understanding of heat transfer. An experiment has been specifically designed at Florida State University to examine the normal-fluid velocity field in counterflow. A thin line of \( \text{He}_2^+ \) tracers is created via laser-field ionization in helium. To achieve the required high electric field for ionizing ground state helium atoms, laser intensity as high as \( 10^{13} \text{ W/cm}^2 \) is needed (58). Such a high instantaneous laser intensity can be achieved by focusing a femtosecond laser pulse through a tiny cross-section. The molecule density so created is high enough to allow high-quality single-shot imaging of the tracer line. Fig. 4 shows fluorescence images of \( \text{He}_2^+ \) tracer lines that have been successfully generated and imaged in counterflow, at 1.85 K, with a 35-fs laser pulse, at 55 mJ. At low heat fluxes, a straight tracer line deforms into a parabolic shape, indicating the Poiseuille laminar velocity profile of the normal fluid. At large heat fluxes, the tracer line distorts, possibly due to the turbulent eddies in the normal fluid. The local normal-fluid velocity could then be estimated by dividing the center displacement of a small line segment by the drift time. Structure functions of the turbulent flow could be computed based on the derived velocities (59), which should allow us to gain information on the turbulent energy spectrum. By creating multiple lines to include crosses or grid tracer structure, measurements of normal-fluid vorticity and other complex velocity derivatives can be made.
Particle Acceleration Measurements. The Lagrangian dynamics of solid deuterium particles, at length scales comparable to the mean distance $\ell$ between quantized vortices, have been recently studied in steady-state thermal counterflow at Charles University by using the PTV technique (20, 21). It was unexpectedly found that the normalized distribution of the particle acceleration appears to follow a classical-like behavior (21). Fig. 5 displays the normalized probability density function (PDF) of the instantaneous particle acceleration in the vertical direction, that of the imposed counterflow, in different experimental conditions, at length scales about one order of magnitude smaller than those reported previously (21). The result was obtained by collecting images at frame rates that allow the study of the particle dynamics at scales smaller than $\ell$. The latter scales can be quantified by introducing the nondimensional time $\tau = t_1/t_2$, where $t_1$ is the time used for the calculation of accelerations along the tracks, $t_2 = \ell/V_{abs}$, and $V_{abs}$ denotes the mean particle velocity. It can be seen that the agreement with a log-normal fit used for classical turbulent flows (60, 61) to hold also for $\tau > 0.1$, i.e., at length scales about one order of magnitude smaller than $\ell$. Note, however, that, as suggested in ref. 21, the classical fit seems not to agree with the experimental data at large accelerations, for the smallest times. The distribution tails of the particle acceleration in the horizontal direction display indeed more noticeable departures from the classical shapes, as the particle dynamics are dominated by the imposed vertical velocities (56). The outcome, whose details will be reported elsewhere, represents unique experimental evidence that the mean distance between quantized vortices can be seen as the length scale distinguishing classical-like from quantum behavior.

Flow-Across-Obstacle Experiments. An important, classical fluid dynamical condition is that of the flow past solid objects, such as cylinders and spheres, with the associated drag crisis (62). Initial studies using solid particles and the PIV technique showed the existence of large-scale turbulent eddies, both behind and in front of a cylinder in thermal counterflow (15). Such a behavior has no classical analog. More recently, Chagovets and Van Sciver discussed the existence of two distinct velocity fields in counterflow around a cylinder (63). At low relative velocities, typically
\(v_n < 1 \text{ cm/s},\) the normal-fluid flow appears as a laminar flow, whereas the particles tracking the superflow are more typically trapped on the vortex lines (Fig. 6). At higher relative velocity, the fields of the two fluid components are no longer separable, and the particle motion begins to display the large-scale eddies first observed using solid particles (15). As with channel flow (19), this transition is deemed to occur as a result of Stokes drag, due to the normal-fluid flow, being sufficient to dislodge the trapped particles from the superfluid vortex lines. Other related visualization studies include preliminary results on the flow past an oscillating sphere (64) and additional investigations on the occurrence of macroscopic vortices in the proximity of cylinders in counterflow (65).

**Forced Flow Experiments.** Another basic, classical problem that can be used to determine the extent to which superfluid dynamics display classical behavior is the pressure gradient in turbulent pipe flow. Unlike counterflow, in forced flow of turbulent superfluid helium the two fluid components are believed to be coupled together by the mutual friction force such that the flow velocity \(U_{\text{aver}}\) equals the velocities of the two fluids. This leads to a turbulent friction factor that scales with the classical Reynolds number \(Re = U_{\text{aver}}W/\nu_n\), where \(W\) is a relevant flow scale and \(\nu_n\) denotes the kinematic viscosity of the normal-fluid component (66). To display such a behavior, the fluid would be expected to have a velocity boundary layer similar to that seen in classical fluids (67). At Florida State University, Xu and Van Sciver made PIV measurements of the velocity profile near the wall in forced flow of superfluid helium at \(Re \approx 10^5\) (68). The experimental apparatus used calibrated bellows pumps driven by linear actuators to produce a known average flow rate in a square cross-section channel, of side \(W = 20\) mm. The channel is horizontal, in a specially designed cryostat that allows optical access to the flow field. The results from these experiments showed a velocity distribution that is essentially classical in character, with a measurable velocity boundary layer that scales with \(Re\) (Fig. 7). Further investigations are consequently needed to clarify whether a parameter range exists where forced flow superfluid dynamics are different from classical hydrodynamics and also to assess in which conditions the influence of the physical boundaries on quantum flows can be neglected.

**Conclusion and Future Work**

The study of quantum turbulence has in recent years benefited from the use of flow visualization techniques, which led researchers to appreciate more clearly similarities and differences between classical and quantum flows (69). These very powerful tools produced, at the same time, results that are posing more questions than giving clear answers, showing thus that the probed phenomena are indeed worth investigating. Thermal counterflow is a well-known quantum flow, characterized by a unique form of heat transport, whose links to classical turbulent convection (52, 53) are yet to be explored in detail. Similarly, the newly discovered normal-fluid turbulence characterized by a unique form of heat transport, whose links to classical turbulent convection (52, 53) are yet to be explored in detail. Similarly, the newly discovered normal-fluid turbulence characterized by a unique form of heat transport, whose links to classical turbulent convection (52, 53) are yet to be explored in detail. 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