PARTICLE TRAJECTORIES IN THERMAL COUNTERFLOW OF SUPERFLUID HELIUM

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Abstract The motion of micrometer-sized particles in a quantum flow – thermal counterflow of superfluid helium – is studied experimentally by using the particle tracking velocimetry technique, at various values of temperature and applied heat flux. The trajectory appearance changes as the imposed thermal counterflow velocity increases, i.e., the particle tracks appear, at low velocities, straighter than at larger ones, suggesting thus the transition to turbulence of the investigated flow.

INTRODUCTION

Quantum turbulence, which occurs in quantum fluids displaying superfluidity, such as superfluid ^{4}He, is a fast developing branch of fluid dynamics and combines quantum physics with classical fluid mechanics [11, 2].
Liquid ^{4}He is called normal helium, or He I, at temperatures larger than approximately 2.17 K, at the saturated vapor pressure, as it behaves as a classical viscous fluid. If the temperature decreases further, liquid ^{4}He changes dramatically its properties. It is then known as He II, or superfluid ^{4}He, and its viscosity can be considered null at 0 K, i.e., He II does not behave as a classical viscous fluid. The two-fluid model can be used to account for its behaviour and it describes superfluid ^{4}He as made of two fluids. The normal component of He II can be considered as a viscous fluid, carrying the entire entropy content of the liquid, while the superfluid component of He II is assumed inviscid. The total density ρ of the liquid, defined as the sum of the densities of its normal and superfluid components, ρ_n and ρ_s, respectively, depends weakly on temperature, while the densities ρ_n and ρ_s display a much stronger temperature dependence (He II can be often considered entirely superfluid at temperatures below 1 K).
If, at finite temperature, a closed volume of superfluid ^{4}He is suitably heated, the superfluid component moves towards the heater, while the normal component flows away from it. This phenomenon is called thermal counterflow and its strength is often quantified by the velocity $v_{ns} = q/(\rho_s \sigma T)$, where q is the applied heat flux per unit area, σ indicates the entropy per unit volume and T denotes the temperature.
The superfluid component of He II can be usefully described by a macroscopic wave function, leading to the result that quantized vortices, i.e., line singularities where the superfluid density is null, can exist in superfluid helium. These vortices, whose strength is quantized, usually arrange themselves in a tangle and the dynamical behaviour of such a tangle constitutes an essential ingredient of quantum turbulence.
Recent progress in quantum turbulence has been achieved by the implementation of flow visualization techniques to the study of quantum flows of He II, see, e.g., [5]. Fundamental results have been obtained by visualizing the dynamics of hydrogen and deuterium particles of micrometer size. Their motion is very complex, as particles interact with both the normal and superfluid velocity fields simultaneously and may become trapped (and/or de-trapped) onto the cores of quantized vortices. Both the normal and superfluid velocity fields can become turbulent and are coupled by the action of the mutual friction force [11, 2, 5]. The application of the particle tracking velocimetry (PTV) technique resulted specifically in the discovery of non-classical velocity statistics in thermal counterflow [10, 6, 7], among other results, e.g., [3, 4]. Recently, we have also shown the crossover between classical and quantum features in the velocity and acceleration distributions of thermal counterflow [8, 9].

RESULTS AND DISCUSSION

We use the Prague experimental visualization set-up already described in our previous publications [6, 7, 8, 9]. It consists of a custom-built optical cryostat, a purpose-made seeding system supplying micrometer-sized solid particles (generated by mixing helium and deuterium, or hydrogen, gases at room temperature and injecting the mixture into the helium bath), a continuous-wave laser and cylindrical optics, in order to obtain a thin laser sheet of about 10 mm high and less than 1 mm thick, and a sensitive digital camera situated perpendicularly to the laser sheet, focused on a 9.6 mm (2560 px) by 8.1 mm (2160 px) field of view. The PTV technique is used for the measurement of Lagrangian quantities in a vertical plane, in the middle of our square experimental channel of 25 mm sides and about 100 mm long. The gaseous mixture is injected into the helium bath, which is later brought to some chosen temperature. The heater, placed on the bottom of the channel (the imposed flow is in the vertical direction), is then switched on, images collected at 48 fps, and the obtained particle tracks are processed by purpose-made computer programs (see our previous publications [6, 7, 8, 9] for further details on the experimental apparatus and protocol).
We have performed several thermal counterflow experiments, at various values of applied heat flux, between approximately 50 W/m^2 and 500 W/m^2, and temperature, between about 1.3 K and 2.1 K. We have found that the appearance

of the particle trajectories changes as the imposed thermal counterflow velocity increases. At values of v_{ns} smaller than ca. 1 mm/s, the trajectories of the particles, especially those moving upwards, in the direction of the normal fluid flow, appear to follow straight lines, while the tracks of the particles moving downwards, in the direction of the superfluid flow, are less straight. At larger values of counterflow velocity, the character of all the trajectories appear to be very similar, as already reported in our previous publications [6, 7, 8, 9]. In other words, as v_{ns} increases, the particles seem to interact more frequently with quantized vortices and this becomes apparent in the paths followed by the particles, as shown, e.g., in Figure 1 for several movies taken at $T = 1.95$ K. The critical velocity for the onset of turbulence has been reported in [1] and is consisted with the one found by us, although our channel is larger that those used in previous experiments. Note, however, that the transition to turbulence in quantum flows has been found often to depend on the channel size, see again [1], that is, to depend on the flow boundaries.

To summarize, the preliminary results presented here show that, in thermal counterflow of superfluid ^{4}He, the obtained particle trajectories appear straighter as the imposed velocity decreases, suggesting thus the transition to turbulence of the investigated flow for values of v_{ns} larger than ca. 1 mm/s. Further analysis is in progress and a comprehensive report will be submitted for publication elsewhere.

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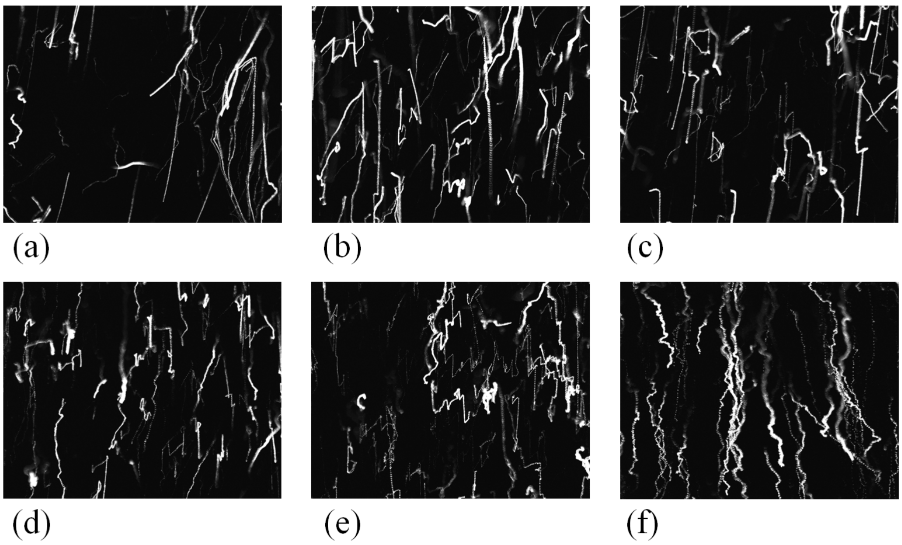

Figure 1. Each image represents a movie taken at $T = 1.95$ K; (a) $q = 97$ W/m^2, $v_{ns} = 0.80$ mm/s; (b) $q = 121$ W/m^2, $v_{ns} = 1.00$ mm/s; (c) $q = 146$ W/m^2, $v_{ns} = 1.21$ mm/s; (d) $q = 193$ W/m^2, $v_{ns} = 1.60$ mm/s; (e) $q = 242$ W/m^2, $v_{ns} = 2.01$ mm/s; (f) $q = 484$ W/m^2, $v_{ns} = 4.01$ mm/s. The intensity of each pixel in all the images is obtained as the root mean square of the corresponding pixel intensities of all the frames taken in the specified experimental conditions.

References

[1] S. Babuin, M. Stammeier, E. Varga, M. Rotter, and L. Skrbek. Quantum turbulence of bellows-driven ^{4}He superflow: steady state. *Phys. Rev. B*, **86**:134515, 2012.

[2] C. F. Barenghi, L. Skrbek, and K. R. Sreenivasan. Introduction to quantum turbulence. *Proc. Natl Acad. Sci. USA*, **111**:4647–4652, 2014.

[3] G. P. Bewley, M. S. Paoletti, K. R. Sreenivasan, and D. P. Lathrop. Characterization of reconnecting vortices in superfluid helium. *Proc. Natl Acad. Sci. USA*, **105**:13707–13710, 2008.

[4] E. Fonda, D. P. Meichle, N. T. Ouellette, S. Hormoz, and D. P. Lathrop. Direct observation of Kelvin waves excited by quantized vortex reconnection. *Proc. Natl Acad. Sci. USA*, **111**:4707–4710, 2014.

[5] W. Guo, M. La Mantia, D. P. Lathrop, and S. W. Van Sciver. Visualization of two-fluid flows of superfluid helium-4. *Proc. Natl Acad. Sci. USA*, **111**:4653–4658, 2014.

[6] M. La Mantia, T. V. Chagovets, M. Rotter, and L. Skrbek. Testing the performance of a cryogenic visualization system on thermal counterflow by using hydrogen and deuterium solid tracers. *Rev. Sci. Instrum.*, **83**:055109, 2012.

[7] M. La Mantia, D. Duda, M. Rotter, and L. Skrbek. Lagrangian accelerations of particles in superfluid turbulence. *J. Fluid Mech.*, **717**:R9, 2013.

[8] M. La Mantia and L. Skrbek. Quantum, or classical turbulence? *EPL*, **105**:46002, 2014.

[9] M. La Mantia and L. Skrbek. Quantum turbulence visualized by particle dynamics. *Phys. Rev. B*, **90**:014519, 2014.

[10] M. S. Paoletti, M. E. Fisher, K. R. Sreenivasan, and D. P. Lathrop. Velocity statistics distinguish quantum turbulence from classical turbulence. *Phys. Rev. Lett.*, **101**:154501, 2008.

[11] L. Skrbek and K. R. Sreenivasan. Developed quantum turbulence and its decay. *Phys. Fluids*, **24**:011301, 2012.