LIQUID HELIUM FLOWS AROUND AN OSCILLATING CYLINDER

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Abstract The complementary flows of normal viscous liquid helium (He I) and of superfluid helium (He II) around an oscillating obstacle, of rectangular cross-section, have been studied experimentally by using the particle tracking velocimetry technique, with solid deuterium particles. The observed particle behaviour in He II is very similar to that seen in He I. It seems therefore that, without some kind of special forcing acting differently on each superfluid helium component, on length scales which the experiment can access, the oscillating quantum flow mimics the classical one.

INTRODUCTION

Superfluid ^{4}He (also called He II) is a quantum liquid that exists at temperatures below about 2.17 K, while, at larger temperatures, liquid ^{4}He is known as normal ^{4}He, or He I, as it behaves as a classical viscous fluid, see, e.g., [8, 1] and references therein.

He II can be phenomenologically understood as a mixture of two fluids: the inviscid superfluid component that can be described by a macroscopically ordered quantum wave function, and the viscous normal component, representing the gas of elementary excitations, i.e., rotons and phonons. Moreover, the normal to superfluid density ratio is temperature dependent (He II can be often considered entirely superfluid at temperatures below 1 K).

One of the consequences of the quantum nature of superfluid ^{4}He is the existence of singly quantized vortices with fixed circulation $\kappa = 9.997 \cdot 10^{-8}$ m^2/s. On *quantum length scales*, i.e., on length scales smaller than the mean distance between quantized vortices, the superflow is subjected to severe quantum mechanical restrictions and differs in a fundamental way from any conventional viscous flow. At larger, *quasiclassical*, length scales, however, the superflow, containing tangled bundles of quantized vortices, could, in principle, mimic a classical viscous flow. This indeed takes place, for example, in the well known case of a rotating bucket of He II, recently visualized [2], mimicking the solid body rotation displayed by any viscous fluid.

Generally, on quantum length scales the normal and superfluid velocity fields are always different, although it has to be kept in mind that this follows from the two-fluid description of a single fluid behaviour. While thermal forcing of He II results in a *counterflow* of normal and superfluid components, where the normal and superfluid velocity fields are different at *all* length scales, mechanical forcing acts on both components similarly and can generate a *coflow*, where normal and superfluid velocity fields are, on quasiclassical scales, identical. In particular, an interesting emerging question concerns large vortical structures shed by oscillating structures: do they appear identical in classical and quantum flows?

RESULTS AND DISCUSSION

To answer this intriguing question, we use the Prague experimental visualization set-up described in detail in our previous publications [4, 5, 6, 7]. In short, the experiment takes place in a low-loss cryostat with optical access to the experimental volume at its bottom. The flow of liquid helium is visualized by using the particle tracking velocimetry technique [3]. Deuterium is injected in gaseous form into the helium bath, where it solidifies to create small snowflakes having diameters of the order of a few micrometers. These particles are illuminated by a light sheet less than 1 mm thick, generated by a continuous solid-state laser. Their positions are captured, at 100 fps, by a digital camera with a 1280×800 px spatial resolution, which corresponds to a field of view of 34×21 mm. The captured particle positions are connected into trajectories and these tracks (see an example in Figure 1) are studied statistically.

In this experiment, flows of He II around an almost harmonically oscillating obstacle – 10 mm wide and 3 mm high rectangular cylinder – are visualized at frequencies in the range $0.05 - 1.0$ Hz and oscillation amplitudes of 5 and 10 mm, corresponding to Reynolds numbers (calculated as a product of the relevant Keleugean-Carpenter number and Stokes numbers) ranging approximately from 40 to $4 \cdot 10^4$, based on the viscosity of the normal component of He II.

In order to quantitatively analyze the particle-position data sets (as shown in Figure 1) we introduce the parameter θ, with the dimension of vorticity, which depends on the position $\mathbf{R}$, on a chosen grid of the two-dimensional field of view, and on the motion phase φ, defined as

$$\theta(\mathbf{R}, \varphi) = \frac{1}{N} \sum_{|\mathbf{R}-r_i|<R_M} \; \sum_{|\varphi-\varphi_i|<\Phi} \frac{(\mathbf{R}-\mathbf{r}_i) \times \mathbf{v}_i}{|\,\mathbf{R}-\mathbf{r}_i\,|^2} \,, \tag{1}$$

where N is the number of trajectory points, φ_i indicates the motion phase of the i-th particle, $\mathbf{r}_i$ denotes its position and $\mathbf{v}_i$ is its velocity, calculated from the positions. The chosen parameters are $R_M = 200$ px and $\Phi = 7.5°$. A sample map of $\theta(\mathbf{R}, \varphi = 90° \pm 15°)$ is shown in Figure 1. One can appreciate that, for infinite density of particles, in the limits $R_M \to 0$

and $\Phi \to 0$, the parameter $\theta(\mathbf{R}, \varphi) \to \omega(\mathbf{R}, \varphi)$, where ω is the vorticity. Note that, although θ is calculated as an integral quantity, it is here plotted as a local quantity, see again Figure 1.

Our preliminary results show that the macroscopic vortices shed by the cylinder oscillating in superfluid ^{4}He are very similar to those expected to occur in a classical fluid. Besides, the squared average of the parameter θ appears to be linearly proportional to the imposed motion frequency, while the corresponding temperature dependence has yet to be investigated in detail. We shall report our findings, together with a more comprehensive discussion, elsewhere.

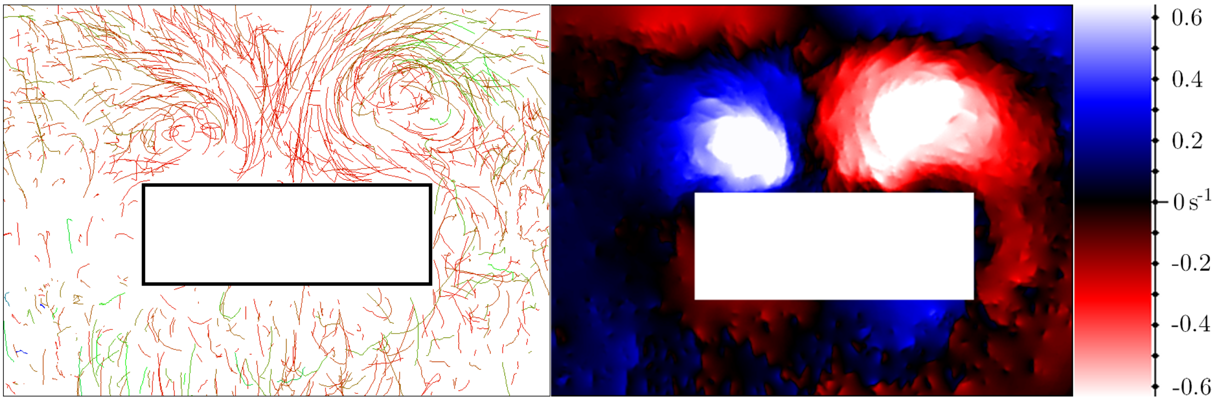

Figure 1. Left: Particle trajectories shown near the bottom position of the cylinder cycle, $\varphi = 90° \pm 15°$; oscillation frequency $f = 0.5$ Hz; temperature $T = 1.3$ K; 21 mm wide and 16 mm high field of view. The cylinder is shown as a white rectangle. Colours refer to trajectory lengths. Right: The corresponding map of the θ parameter calculated for the same data set.

CONCLUSIONS

To summarize, preliminary results of a classical experiment, performed, however, for the first time in normal viscous He I, as well as, at various temperatures below 2.17 K, in superfluid ^{4}He, have been reported. The resulting flow patterns, obtained from the observed particle trajectories, display large vortical structures shed by the sharp corners of the oscillating cylinder, which in He I and He II appear almost identical. This strongly suggest that, without some kind of special forcing acting on each component of superfluid ^{4}He differently, on the quasiclassical length scales that the experiment can access, the oscillating quantum coflow mimics the classical one.

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