TRANSITION TO TURBULENCE IN ^{4}HE DUE TO MECHANICAL OSCILLATORS

David Schmoranzer[1], Martial Defoort[2], Sébastien Dufresnes[2], Eddy Collin[2], Henri Godfrin[2] & Ladislav Skrbek[1]

[1]*Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague, Czech Republic*
[2]*Institut Néel, CNRS et Université Joseph Fourier, BP 166, F-38042 Grenoble Cedex 9, France*

Abstract We report on recent experiments on the transition to turbulence observed in both normal and superfluid ^{4}He, including purely quantum turbulence at very low temperatures down to 10 mK. The transition to both classical and quantum turbulence has been investigated using mechanical oscillators in the form of quartz tuning forks and micromechanical goalpost structures. We investigate the differences between the transition to classical turbulence in normal He and to quantum turbulence in its superfluid phase, and discuss the changing characteristics of the dependence of drag coefficient vs. velocity with changing normal fluid and superfluid density fractions.

INTRODUCTION

Developments of low temperature physics achieved during the twentieth century have led, among other, to the opening of a new field of research – cryogenic fluid dynamics, and specifically, superfluidity. The matter of interest are some quite peculiar properties known to exist only in the liquid phases of the two stable isotopes of helium, ^{3}He and ^{4}He, of which we will only consider the latter. Upon cooling below a certain critical temperature (2.17 K at saturated vapour pressure), liquid ^{4}He (historically called He I) undergoes a second order phase trasition to become a quantum liquid or a superfluid (called He II), which can no longer be described by conventional fluid mechanics of classical physics.

In the temperature range from 2.17 K down to approximately 0.7 K, the conventional picture of a liquid is replaced by the so-called two-fluid model, meaning that superfluid He II is phenomenologically described as an intimate inseparable mixture of two components – the normal component and the superfluid component, whose density ratio is given solely by temperature. The normal component behaves as any classical liquid would (with properties similar to He I), while the superfluid component carries no entropy and is inviscid, resulting in frictionless flow. These two components have their individual velocity fields, which can be considered independent at low velocities. At higher flow velocities, a special type of turbulence may form in the superfluid component – quantum turbulence – resulting in mutual friction between the two components and dissipation of energy, while the likelihood of existence of classical turbulence in the normal component may be determined by classical criteria such as the Reynolds number.

Below approximately 0.7 K, the two-fluid model breaks up, as there remains so little normal component that it cannot be described as a continuum anymore. Hence for lower temperatures, we are left with the superfluid component only, in which thermal excitations (that what is left of the normal component) propagate balistically. Upon further cooling, their concentration drops as T^3 and below 100 mK, one might say that for all practical purposes only pure superfluid remains. It is in this pure superfluid that we may have the best picture of quantum turbulence, and it is known to consist of a complex tangle of discreet vortex lines called quantized vortices, which due to quantum mechanical restrictions all have the same circulation around their thin cores (diameter ≈1 Å), known as the circulation quantum, $\kappa = h/m$, determined from the Planck constant, h, and the mass of one superfluid particle, m. For a review on superfluidity, see Refs. [9, 17].

SENSORS, TECHNIQUES AND RESULTS

Since the lowest temperatures mentioned above require the use of highly specialized devices such as dilution refrigerators, one is typically confined to a relatively small volume of fluid, ranging from units of millilitres to around one litre. For this reason, the use of various oscillating objects, such as spheres[15, 12], grids[6, 10], wire loops[18, 4], and tuning forks[1, 13, 3, 5] has become the cornerstone of very low temperature experimentation[17]. One typically drives these oscillators either magnetically or piezoelectrically at their resonant frequencies to determine the damping due to the surrounding medium (after comparison with vacuum values) and to determine the relevant drag coefficients. Provided that care is taken to suppress all other mechanisms that would dissipate the kinetic energy of the oscillator, such as acoustic emission[14, 2], the drag coefficient can be used to determine the critical parameters for the transition to turbulence.

As far as purely quantum turbulence is concerned, at the moment no generally accepted criterion for the transition to occur exists. It is currently believed that we may use simply the flow velocity, or in some specific cases, quantities defined more or less analogically to the classical Reynolds number. Presently open questions about the transition to quantum turbulence are numerous, and include topics such as multiple distinctly observed transitions vs. a single transition to turbulence, hysteresis, the scaling of critical velocity with frequency of oscillations (similarly to various predictions for critical Keulegan-Carpenter vs. Stokes number[11, 16]), and if oscillator size and geometry can significantly affect the critical velocity, or whether it is a quantity intrinsic to the quantum fluid in question – determined only by the dynamics of quantized vortices.

The application of micro- and nano- machining technologies to the design and manufacture of probes for studies of superfluid turbulence gave rise to a new class of oscillating devices – goalpost structures made of Si or Si_3N_4 with a superconducting coating. Driven using the magnetomotive scheme, the micro- and nano- wires are promising experimental tools for three reasons. First, using nano-engineered mechanical systems (NEMS) such as the silicon nanowires discussed in Ref. [8], we hope to access the dynamics of quantized vortices on the smallest scales so far and at the highest frequencies in the MHz range. Second, using silicon microwires[7] can also help us better understand the discrepancies between results previously obtained with tuning forks operated typically at tens of kHz and vibrating wire loops resonating usually around 1 kHz. Micromachining makes it easy to join these two frequency regions and thus to distinguish between frequency effects and the influence of oscillator geometry. Finally, at higher frequencies, an additional benefit of reduced oscillator dimensions is the suppression of acoustic emission, which is found to be a dominant dissipation mechanism[14, 2] for tuning forks at frequencies above 60-70 kHz.

The presented data include preliminary measurements of the drag coefficient and critical velocities in both normal and superfluid ^{4}He using silicon microwires. The results are compared to data obtained with tuning forks in the same experimental arrangement, as well as previous measurements using both tuning forks and vibrating wire resonators. We focus on the apparent differences in the transition mechanisms in oscillatory classical flows and superflows, illustrating them on the changes of the drag coefficient vs. velocity dependence with temperature (with concentrations of the normal and superfluid component of He II).

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