EXPERIMENTAL INVESTIGATION OF LAMINAR AND TURBULENT DRAG IN CLASSICAL AND QUANTUM OSCILLATORY BOUNDARY LAYER FLOW

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Introduction

Various types of oscillating structures have been important for probing the hydrodynamic properties of quantum fluids since the discovery of superfluidity. The famous Andronikashvili experiment, the basis for the two fluid model, was a measurement of the torsional oscillations of a pile of closely spaced discs and provided the first direct determination of the densities of the normal (ρ_n) and superfluid (ρ_s) fractions in He II. It was soon realized that the ideal picture – according to which the normal fluid is dragged along with the discs because of its finite viscosity while the inviscid superfluid remains stationary and does not participate in the flow – can only hold at sufficiently low oscillation amplitudes. Both the classical viscous boundary layer flows and the quantum flows due to oscillating objects display transitions from laminar to turbulent drag regime. It is interesting to compare classical and quantum cases.

Experimental results and discussion

Experimentally, it is best to use a tool capable of probing both classical and quantum flow that can be changed at will *in situ*. Such a tool indeed exists – the quartz tuning fork. The flow due to its oscillatory motion and transition to turbulent drag regime in classical fluids (cryogenic helium gas and normal liquid helium) has been investigated by our group [1] and some aspects of it were reported at this workshop last year [2]. Based on measurements of the velocity versus the driving force, it has been found that in viscous flow the critical velocity for the crossover from laminar to turbulent drag in the limit $U/\omega \ll \ell \gg \delta$ scales as $U_{\rm cr} \propto \sqrt{\nu\omega}$ over at least two decades of kinematic viscosity ν. Here U is the peak velocity of the fork, ℓ its characteristic size, and ω denotes the angular frequency of the fork. The validity of this scaling was recently tested further by performing measurements with forks of various sizes and oscillating at different frequencies. The scaling can be explained qualitatively by equating the linear and the turbulent drag forces at $U_{\rm cr}$, using the approach described in Ref. [1].

The experiments and analysis has been recently extended from the classical viscous He I to He II (a preliminary report is Ref. [2]). The left panel of Fig. 1 shows no appreciable qualitative change in the character of the dependence of the velocity versus the driving force when crossing T_λ. On decreasing the temperature of He II along the saturated vapor pressure curve further, however, the crossover from laminar to turbulent flow becomes gradually sharper and the character of the curve above the critical velocity changes. This change is seen more clearly in the right panel of Fig. 1, where the drag coefficient $C_{\rm d}$ is plotted for three different temperatures. $C_{\rm d}$ is defined from the equation $F = \frac{1}{2} C_{\rm d} \rho A U^2$, where ρ is the fluid density and A is the projected area of one prong of the fork on a plane normal to the bulk flow. For laminar viscous flow the drag is approximately proportional to U, so that $C_{\rm d} \sim U^{-1}$. We see that in

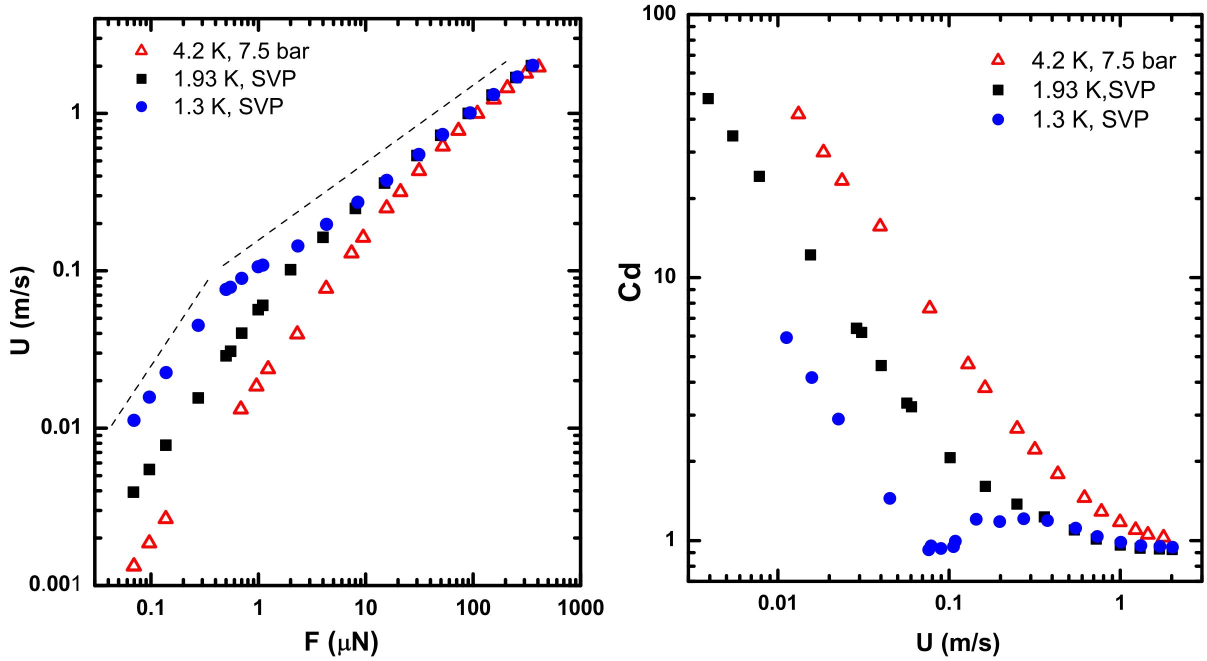

Figure 1: *(Left)* Transition from laminar to turbulent drag regime in ^{4}He, measured with a tuning fork in normal liquid He I and superfluid He II at three temperatures. At low drive level (in the laminar regime) the measured velocity is a linear function of the applied drive; around its critical value the crossover to the turbulent regime occurs, characterized by a driving force proportional to the square of the velocity. The dashed lines indicate the slopes $U \propto F$ and $U \propto \sqrt{F}$. *(Right)* A plot of the drag coefficient C_d versus the velocity of the fork shows that in a classical fluid (He I) there is a gradual change towards a constant value well above the transition to turbulence; while in He II there is a sharp transition at a critical velocity U_cr^S of the superfluid.

classical viscous He I, in the vicinity of U_cr, the measured dependence $C_\mathrm{d}(U)$ gradually levels off and C_d acquires an approximately constant value of order unity. In He II well below T_λ $C_\mathrm{d}(U)$ behaves differently. It displays the laminar part, where the drag is due to the viscous normal fluid only, and then, beyond a sharp minimum, $C_\mathrm{d}(U)$ increases again and displays a broad maximum above which it gradually becomes constant as in the classical case.

This behavior of the drag coefficient $C_\mathrm{d}(U)$ can be understood in the framework of the two-fluid model. The superfluid fraction produces the sharp minimum where the turbulent drag sets in, which is identified as its critical velocity U_cr^S. It was found, at least approximately, frequency independent, in contrast with the behaviour of classical fluid where the critical velocity was found $\propto \sqrt{\omega}$. The phenomenological theoretical model has been developed in collaboration with W.F. Vinen (University of Birmingham, UK); the details will be published shortly.

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