Critical Velocities in Superfluid Helium Flow Through 10-μm-Diameter Pinholes*

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The dissipation mechanism which usually limits superfluid flow to about 30 cm/sec in large pinholes is found to be suppressed by compressed-rouge superfluid filters placed in the flow path on each side of the orifice. The much larger "intrinsic" critical velocity is then observed for the first time in "large" channels.

Measurements of the critical velocity for onset of dissipation in flow of superfluid helium have been reported in channels ranging in width from about 10^4 to 10^{-3} μm.[1,2] In porous materials with channels 0.2 μm wide and smaller, Reppy and co-workers[3,4] and Notarys[5] have found a temperature-dependent "intrinsic" critical velocity, which decreases to zero at the lambda temperature as the superfluid density $\rho_s(T)$. The temperature and pressure dependence of this intrinsic critical velocity are in accord with calculations by Iordanskii[6] and by Langer and Fisher[7,4] of dissipation due to homogeneous nucleation of quantized vortex rings, except that the measured velocities are about an order of magnitude smaller than predicted. Otherwise, except very near T_λ[8] and in film flow, the measured critical velocities are independent of temperature but decrease with increasing channel width, and are typically not exactly reproducible from day to day.[8] They might reasonably be called "extrinsic." Several theoretical models for the dissipation mechanism in the extrinsic regime have been proposed,[9-12] based on Feynman's[13] idea of quantized vortex-ring creation at the channel wall.

The present experiments on flow through pinholes of approximately 10-μm diam show intrinsic behavior, with velocities exceeding 500 cm/sec at the lowest temperatures, provided the orifice is guarded by rouge superleaks in series on each side. Without the superleaks, typical extrinsic behavior is observed, with velocities comparable to those reported previously in similar geometries.[14,15]

The apparatus is shown schematically in Fig. 1. An inner and an outer reservoir are connected only through the pinhole. Both are evacuated at room temperature with a mechanical pump, sealed during cooling, and then partially filled by condensing commercial helium gas which is first passed through a liquid-nitrogen-cooled charcoal trap. The potential difference to drive superfluid through the pinhole is produced by displacing liquid in the inner reservoir with a plunger or, through the thermomechanical effect, by turning on or off a heater in one or the other reservoir. An annular capacitor connected in the tank circuit of a tunnel diode oscillator senses the liquid level in the outer reservoir. The oscillator frequency is counted, usually for 1-sec intervals, and successive counts are subtracted to yield data proportional to the rate of flow through the orifice. Samples of such data in Fig. 2 show flow following rapid displacement of the plunger.

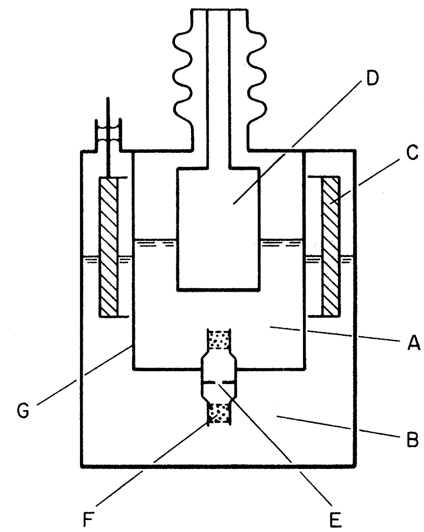

FIG. 1. Schematic diagram of the apparatus: *A*, inner helium reservoir; *B*, outer reservoir; *C*, capacitor; *D*, plunger; *E*, pinhole; *F*, rouge plug; *G*, oxygen-free high-conductivity copper wall.

The first measurements were made without rouge plugs with orifice plate No. 1 (100 holes of 10.6-μm diam in 10-μm-thick electroformed nickel[16]). The critical velocity obtained on a given day for a given direction of flow was reproducible within a few percent and independent of temperature, at least in the range 1.32 to 1.82 K. However, after each time the apparatus was cycled to room temperature a different value was obtained: The critical velocities measured on three days for inward and outward flow, respec-

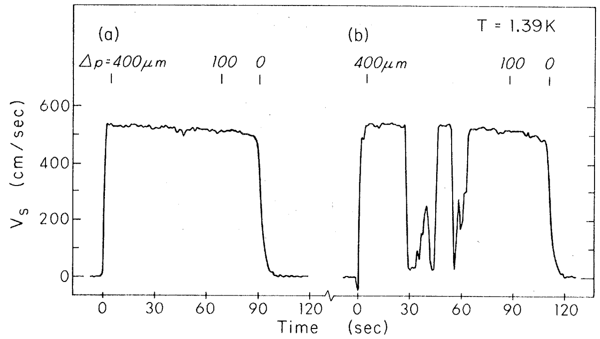

FIG. 2. Data for two runs, showing superfluid velocity as a function of time during decay of an initial pressure head. The head in micrometers of He is indicated at several points.

tively, are 23.8 and 25.9, 37.4 and 35.1, and 18.9 and 14.3 cm/sec. In the last case, cycling the apparatus above T_λ increased the subsequent flow rate by 30%, but repetition of the cycling produced no further change. The pressure dependence of the supercritical flow rate also varied widely from day to day: The ratio of velocities at 1000 and 35 μm of helium head ranged from 1.01 to 1.8. Additional measurements with orifice plate A (single conical hole of 7.7 μm minimum diameter in 20-μm-thick nickel foil[17]) showed similar behavior, although with larger fluctuations in each run. Two superleaks were made by compressing jeweler's rouge into 0.17-cm-i.d. stainless steel forms. These were sealed in the flow path a few millimeters either side of the orifice plate. Measurements were made with orifice plate C (similar to A, 9.4-μm diam) on two occasions, with the apparatus warmed to room temperature but not disassembled between. Orifice plate D (similar to A, 7.2-μm diam) was used on one occasion. In this configuration, the velocities for the two directions of flow and before and after cycling to room temperature are equal within experimental error, which is about 2% near 1.39 K.

Data for a typical run are shown in Fig. 2(a). The time at which the potential difference has reached zero is identified approximately as the inflection point at the right end of the curve. Following this there is subcritical exponential decay of the remaining level difference and of a proportional temperature difference, which was generated by the superflow.[8] This thermal effect is smaller at lower temperatures, and inertial overshoot is observed below 1.3 K. The minimum observable pressure head is limited to about 10 μm of He, at the lowest temperatures by instru-

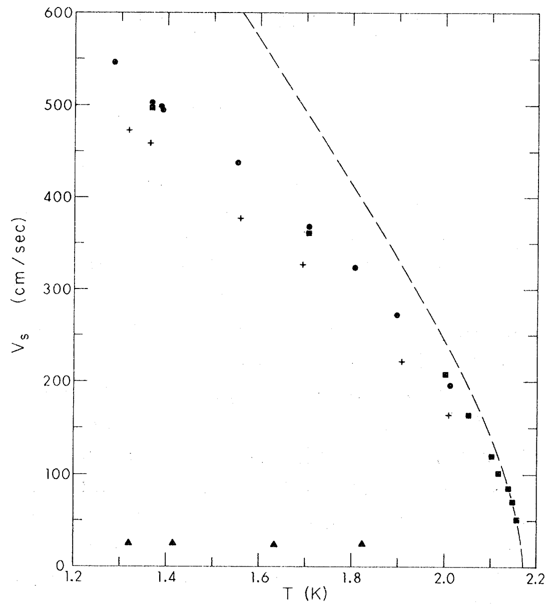

FIG. 3. Superfluid velocity as a function of temperature at a pressure head of 35 μm of He, for several orifices. Circles and squares: orifice C on two dates three days apart; crosses: orifice D; triangles: orifice No. 1, without rouge plugs. The dashed line is the function $\rho_s(T)/pT$ with arbitrary normalization.

mental time resolution, and at the highest temperatures by uncertainty in identifying the inflection point. The largest head used is about 1 mm. Within this range, the dependence of velocity on pressure head is at least approximately logarithmic, with

$$\delta = v^{-1}(\partial v/\partial \ln p) = 0.026 \pm 0.003$$

at 1.39 K, and $\delta = 0.04 \pm 0.01$ at 2.05 K. The measured velocities at a head of 35 μm (0.5 dyne/cm^2) are plotted against temperature in Fig. 3. Each point represents the average of between 2 and 20 runs. (For each orifice there is a 15% systematic uncertainty in velocity, due to error in measuring the hole area.) The results are very similar to the published data for 0.2-μm-diam channels.[3-5]

The Iordanskii-Langer-Fisher theory, together with Anderson's corollary,[18] gives the prediction[5]

$$\ln(\Delta p/\Delta p_0) = \Gamma - E(v_s)/kT,$$

where the free energy of a stationary vortex ring is

$$E(v_s) = (\rho_s \kappa^3/16\pi\alpha v_s)(\eta - \tfrac{3}{2})(\eta - \tfrac{1}{2}),$$

if the rings are nucleated where the local velocity is αv_s. Here Δp_0 is a nominal pressure head, $\kappa = h/m$ is the quantum of circulation, and Γ is constant to a fair approximation in the experimentally accessible regime.[19] Near T_λ, η is nearly constant[4] and so at fixed Δp, $v_s \sim \rho_s(T)/T$. This function is plotted for comparison in Fig. 3. At lower temperatures, η must be smaller, which probably accounts for the divergence of the data from the curve.

If Γ and α are treated as adjustable parameters, the present data require $\alpha \approx 20$. The microscopically observable shape of the orifice suggests $\alpha \approx 1.5$ to 2 at the wall in the section of minimum circumference. The discrepancy may result, in part, from small-scale roughness or it may indicate that nucleation is not actually homogeneous, but rather partial rings are nucleated at a wall.[20]

One other phenomenon was observed with orifice C and is illustrated in Fig. 2(b). The flow rate sometimes dropped temporarily from the intrinsic value to a value typical of extrinsic behavior. This slow flow was never observed at pressure heads less than 120 μm. It was common at 1.55 K and colder, but was not observed above 1.8 K.

Why do rouge plugs inhibit the extrinsic dissipation mechanism? Known or plausible effects of these superleaks include the following: (a) They inhibit normal-fluid flow. However, this is very small and certainly nonturbulent in their absence. (b) They may filter out pre-existing superfluid vorticity. (c) They filter out dust, except for that trapped between the superleaks on assembly. The characteristic irreproducibility from day to day of the extrinsic critical velocity suggests a contamination mechanism. If the same mechanism causes the slow flow intervals when the superleaks are present, the irregularity suggests that only one or two free particles may be involved (although it may be a purely hydrodynamic metastability). By far the largest force which would act on an uncharged free dust particle near the orifice is the superfluid Bernoulli force. Consequently, the particle would be drawn to the wall in the region of greatest velocity. It might partially block the orifice, but also it may provide a site of easy quantized vortex generation. To test this suggestion of a dust mechanism, it would be desirable to make further measurements with relatively large orifices, taking particular care to exclude both room dust and frozen air.

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