Flow regimes of the superfluid helium caused by oscillating quartz tuning fork.

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Abstract. The laminar-turbulent flow transition in HeII was studied with an oscillating quartz tuning fork. At temperatures from 200 mK to 3.0 K a current-voltage characteristic were recorded with varying driving voltage from $10^{-5}$ to 10 V. A resonance frequency and a width of the resonance curve were also registered. It is found that at temperatures below ~0.8 K the laminar-turbulent transition proceeds through an intermediate region clearly seen in the current – voltage characteristic curves. In this case the resonance curve changes in its shape – there appears a plateau near the maximum. An increase in the resonance curve width suggests the existence of excess dissipation related to the generation of quantized vortices in HeII in the vicinity of the oscillating surface. Estimation of the possible size of the vortices may suggest that these are generated on the oscillating surface roughness.

1. Introduction

Turbulence in liquids is generally originated under conditions where the laminar flow loses its hydrodynamic stability [1-2]. The laminar-turbulent transition is associated with the competition between inertial forces and viscous forces in a liquid. That is why of particular interest is the development of turbulence in a superfluid liquid where the viscous processes are of specific character. Unlike the classical liquids the superfluid helium demonstrates a two-fluid behaviour: its normal component behaves as an ordinary viscous liquid while the superfluid component has no viscous dissipation. Besides, the behaviour of the latter component follows the quantum law and its rotation can be only in the form of quantized vortices. The situation becomes the most interesting at low temperatures where the normal component density is negligible.

The origination of turbulence in HeII at low temperatures was previously investigated by studying a steady – state motion of various geometric bodies immersed in HeII: a sphere [3], a vibrating wire [4] or a grid [5]. All the experiments displayed the laminar – turbulent transition but the results were in quantitative discrepancy. So there was a good reason to perform similar experiments by using a new technique – an oscillating quartz tuning fork. The technique has been recently developed, the piezoquartz fork has been calculated [6] and the experiments on HeII at high temperature (above 1.3 K) have been made under conditions where the normal component is still important in the turbulence development [8]. The experiments performed by the new technique but at low temperatures (down to 200 mK) are reported in the present paper.

2. Experimental Procedure

The superfluid liquid motion was excited and detected with an oscillating piezoelectric quartz resonator of the form of a quartz tuning fork [8] (the fork leg height and section being 3.9 mm and 0.28x0.39 mm, respectively). The generator excitation voltage $\hat{U} = U(f) \cos(\omega t)$, where $\omega$ was the angular oscillation frequency was applied to the fork immersed in HeII (Fig. 1). The voltage value was proportional to the force causing the resonator to oscillate. Current $I$ excited in the resonator was measured with a two phase lock-in analyzer (5208) by the resistance $R = 1$ kOhm voltage drop. The current proportional to the fork oscillation rate varied between $10^{-10}$ and $10^{-6}$ A. In the experiment...
several quartz resonators (of industrial production) were used with a resonance frequency close to \( f = \frac{\omega}{2\pi} = 2^{15} \text{Hz} = 32768 \text{Hz} \), a frequency spread not more than 1 Hz and \( Q = 10^5 \) at room temperature in vacuum.

The quartz resonator was placed in a special leak-tight cell filled at room temperature with \(^4\text{He}\) under high pressure; then the filling capillary was pinched and soldered. The absence of the filling capillary eliminated any fluid flux in it and hence its effect on the measurements. After the low temperature condensation of helium, the quantity of the substance in the cell was sufficient for the fork to be immersed completely in the liquid studied which was at the saturated vapour pressure.

![Figure 1](image)  
*Figure 1.* The block-diagram for measurements of characteristics of the quartz resonator immersed in HeII.

The measurements were made in two temperature ranges: at temperatures from 200 mK to 1.3 K (with a dilution refrigerator) and of 1.6 to 3.0 K (when the dilution refrigerator operated in the evaporation cryostat regime) measured were the root mean square value of output signal \( I \) (rms) as a function of excitation voltage amplitude (peak-to-peak) were measured as well as resonance frequency \( f_0 \) and resonance curve width \( \Delta f \) at different temperatures.

### 3. Intermediate flow regime at low temperatures

The laminar-turbulent transition features were studied by analyzing the measured current – voltage characteristic curves for the oscillating fork immersed in He II and by using the data on excitation voltage dependence of \( f_0 \) and \( \Delta f \). The typical results obtained are summed up in Fig. 2 for high (1.49 K) and low (0.35 K) temperatures. For the high temperature (Fig. 2a) the current – voltage characteristic (a lower diagram) is similar to that obtained in [7-8].

At low excitation voltage one can observe a linear characteristic (regime I, Fig. 2a) without any voltage dependence of resonance frequency and line width. This regime corresponds to the laminar flow of the normal component and the potential flow of the superfluid one. At a certain critical value of \( U \) the linear dependence \( I \sim U \) changes to a nonlinear one \( I \sim U^{1/2} \) (regime II, Fig. 2a) what is followed by a considerable decrease in resonance frequency and an increase in the line width. The latter suggests that the dissipative loss in the liquid nearby the oscillating surface increases. All the above features are typical of the transition to turbulence.

Of a quite different behaviour is the laminar-turbulent transition at low temperatures (Fig. 2b). In this case in addition to regime I and II, the \( I-C \) curve (a lower diagram) shows an intermediate regime III where the \( U \)-dependence of \( I \) changes its behaviour from linear to \( I \sim U^{1/2} \) with increasing \( U \). In the intermediate region changes undergo also the dependences of \( \Delta f \) and \( f_0 \) on \( U \): the resonance line width increases by a higher power low than that at high temperatures and a decrease in the resonance frequency is of some intermediate character. Note that a similar intermediate regime was also observed in the experiments with an oscillating grid [5] where it was suggested that there appeared a new mechanism of dissipation associated with the vortex formation at the grid surface.
Figure 2. Current – voltage characteristic and frequency characteristics as a function of applied voltage for two temperatures: a – 1.49 K; b – 0.355 K; in the current – voltage characteristic curves the solid line corresponds to \( I \sim U \) and the dashed one to \( I \sim U^{1/2} \).

4. Analysis of the resonance curves. Excess dissipation

In the laminar - turbulent transition the resonance curves of the oscillating fork change significantly their shape. The evolution of the resonance curves with increasing \( U \) at constant temperature is shown in Fig. 3. Figure 3a corresponds to \( U = 1 \) mV, i.e. the laminar flow, and the resonance curve is well described by the Lorentzian. For the intermediate flow regime (\( U = 10 \) mV) the resonance curve displays an anomaly – almost a flat (plateau) nearby the maximum. In this region the resonance curve differ from the Lorentzian (a dashed line) due to the appearance of excess dissipation. The existence of excess dissipation is more pronounced in the turbulent regime (Fig. 3c, \( U = 1 \) V), where the resonance line becomes abruptly wider.

The excess dissipation can be naturally attributed to the formation of quantized vortices in the superfluid component nearby the fork oscillating surface. The possible size of a ring vortex was estimated in [9] by the measured values of vortex formation critical velocity. The estimation shows that at \( T \leq 0.9 \) K the vortex ring diameter is not depended on temperature and amounts to \( \sim 5 \) mkm.
This value is substantially smaller than the typical depth of viscous wave penetration at the oscillation frequency used in the experiment. This suggests that at low temperatures quantized vortices ring may be formed and dissipated in a boundary layer near the oscillating fork surface. The special purpose optical measurements demonstrated that the size of fork surface roughness was coincident with that of the vortex ring. This suggests that the oscillating surface irregularities generate quantized vortices, causing the excess dissipation to appear in the nonlinear region.

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