Formation of vortex turbulence by a heat current in superfluid helium in a long capillary

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Abstract. The propagation of long pulses of the second sound in superfluid helium was experimentally studied. The results of the experiments showed that at the propagation of heat currents of sufficiently high power the process of formation a vortex tangle begins near the heater. It leads to significantly reducing the counterflow of the normal and the superfluid components in helium and, consequently, thermal conductivity of superfluid helium.

Key words: superfluid helium, the thermal conductivity, the counterflow to the normal and the superfluid components, quantum vortices

1. Introduction
The study of turbulence physics is a very actual scientific problem of nowadays. In addition to the problem of describing of the large-scale turbulent processes such as the formation of turbulent state and eddies in the water or in the gas flows, the formation of whirlwinds in the atmospheres of planets and even in space plasma flows, problem of the formation and development of quantum turbulence in superfluid helium remains unsolved. The dynamics of the development of quantum vortices, the interaction between vortexes and the impact of this interaction on the thermal conductivity of superfluid helium remain open. Numerical simulation shows that the formation of high vortex density at heat flux and counterflow of normal and superfluid components in helium can leads to a decreasing in its thermal conductivity. This process leads to a strong heating of helium near the heater, its transition to a normal state and even to local boiling near the heat source. To clarify the picture a set of experiments was done to study the peculiarities of the propagation of powerful thermal pulses depending on their duration.

2. Experimental technique and method
The experiments were carried out on a special insert placed in a helium bath (Fig. 1). The film heater with resistance of $R\approx 150$ $\Omega$ was placed into the quartz capillary with diameter $D\approx 3$ mm. The heater was evaporated on the face of a rectangular quartz prism and we changed the distance of heat propagation from 2 to 150 mm in the capillary by moving the prism along it. At a distance of $H=2$ mm from the end of the capillary, a bolometer with a sensitivity of about 5 V/K was placed. The bolometer allowed to register thermal signals of small amplitude sufficiently accurately. The design of insert allows to study the propagation of pulses in quasi-one-dimensional geometry.
The experiments were carried out at different distances from 3.5 to 130 mm between the heater and the bolometer at a temperature of $T_a = 1.88$ K. It should remind that thermal waves (second sound waves) in superfluid helium have anomalously large dependence of the wave velocity on the amplitude $v = v_0 + \alpha_2 \Delta T$, where $v_0$ is the second sound velocity of the wave with an infinitely small amplitude, $\alpha_2$ – the nonlinearity coefficient of second sound waves and $\Delta T$ – the amplitude of this waves. The nonlinearity coefficient of second sound wave in superfluid helium changes its value and even sign depending on the temperature. So, near $T_a \alpha_2$ is infinitely large negative, at a temperature $T_a = 1.88$ K it becomes equal zero and achieves large positive values at further cooling of helium. Thus, any rectangular thermal pulse with an amplitude of $\Delta T \approx \text{mK}$ at a distance of several mm is transformed into a triangular one with a breakdown at the front or tail of the wave depending on the nonlinearity coefficient. Only at $T = 1.88$ K, where the nonlinearity coefficient of the second sound $\alpha_2 = 0$, the shape of the rectangular pulse is distorted mainly due to its interaction with vortices.

![Figure 1. The experimental insert](image)

The experimental technique allowed to launch into the capillary (waveguide) a test pulse simultaneously with the studied signal from the same heater. In this set of the experiments, we studied the propagation of single powerful thermal pulses of different durations. The effect of pulse duration in the range of 1-1000 $\mu$s on the shape of the recorded signal was investigated in the course of experiments. The amplitude of pulse was 10 V that corresponds to temperature of the thermal pulse of several mK. Figure 2 demonstrated the experimental recordings of the second sound pulses of different durations passing the distance $L \approx 130$ mm from the heater to the bolometer through the waveguide.

3. Results

The pulses of a short duration (less than 200 $\mu$s) undergo a small distortion of the rectangular shape. In the tail part of the pulse the amplitude of the signal begins to decrease. This reduction may be explained as a scattering of the counterflow of the normal and superfluid component of He-II in the pulse on the vortices, generated intensively by this pulse itself. The behavior of recording pulse shape changed drastically in case then signal duration stays longer than 200 $\mu$s. The amplitude of the recorded pulse has the same shape as the shorter signals in the initial 200 $\mu$s, then after 200 $\mu$s the amplitude drops sharply to zero before the entire pulse reaches the bolometer. The time of signal disappearance is the same for all long pulses and is approximately 200-250 $\mu$s. Also an additional peak
on the place of disappearance of the signal is registered. After the end of pulses duration, the bolometer registers a cooling wave.

One of the reasons for this behavior of the long pulses may be local overheating of superfluid helium near the heater and the formation of a vapor film, which prevents the further emitted of heat from the heater. Another possibility may be connected with the difficulty of heat transfer due to the sharply increasing of vortices density, which inhibits the counterflow of the normal and superfluid components in helium.

![Figure 2](image)

**Figure 2.** Records of second sound pulse signals with durations from 1 µs to 1000 µs.

The following experiment was carried out to test the above assumptions. On top of the long second sound pulse with duration of 800 µs, a small testing pulse with a duration of 10 µs and an amplitude of 5 V was launched at different times of delay. The signal records are shown in Fig. 3.

![Figure 3](image)

**Figure 3.** (A) Experimental records of the rectangular pulse with τ=800 µs for different delay times of the testing pulse start (τ₀=10 µs, U₀=5 V); (B) the dependence of the amplitude of the testing pulse on the delay time.
We can see that the testing small pulse is recorded along the entire length of the large pulse, and its amplitude decreases as it approaches the rear part of the long pulse. From this, it can be concluded that the disappearance of the signal is not due to the formation of a vapor film that would not miss the testing signal at all, but may be due to the screening of the counterflow of normal and superfluid components by an increasing concentration of the vortexes near the heater.

4. Conclusion

This experimental study showed that a turning on of sufficiently powerful and long-term heat flow leaded to the growth of a dense vortex tangle near the heater at least at first period of time. This increasing of vortex density inhibits the flow of the normal and superfluid components in helium and greatly reduces its thermal conductivity of superfluid. For more long and more powerful heat pulses the increasing of the vortex density may lead to to local evaporation of helium near the heating source. This assumption is also supported by numerical calculations and computer simulations, the results of which coincide qualitatively and quantitatively with the results obtained in this and previous experiments. However, some features of the behavior of the second sound pulses, such as the appearance of a mysterious peak at the rear of long pulses and the appearance of a cooling wave, are still poorly explained.

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