Decay of grid turbulence in superfluid helium-4: Mesh dependence

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Abstract. Temporal decay of grid turbulence is experimentally studied in superfluid $^4$He in a large square channel. The second sound attenuation method is used to measure the turbulent vortex line density ($L$) with a phase locked tracking technique to minimize frequency shift effects induced by temperature fluctuations. Two different grids (0.8 mm and 3.0 mm mesh) are pulled to generate turbulence. Different power laws for decaying behavior are predicted by a theory. According to this theory, $L$ should decay as $t^{-11/10}$ when the length scale of energy containing eddies grows from the grid mesh size to the size of the channel. At later time, after the energy containing eddy size becomes comparable to the channel, $L$ should follow $t^{-3/2}$. Our recent experimental data exhibit evidence for $t^{-11/10}$ during the early time and $t^{-2}$ instead of $t^{-3/2}$ for later time. Moreover, a consistent bump/plateau feature is prominent between the two decay regimes for smaller (0.8 mm) grid mesh holes but absent with a grid mesh hole of 3.0 mm. This implies that in the large channel different types of turbulence are generated, depending on mesh hole size (mesh Reynolds number) compared to channel Reynolds number.

1. Introduction
There has been intense interest in grid- and thermal counterflow-generated quantum turbulence (QT) in liquid $^4$He contained in channels of late [1–5]. There is an accumulating set of data which seems to hold the promise of understanding some of the similarities and differences between classical and quantum turbulence in such situations. Some theories and simulations have been advanced to begin this understanding [5–9].

A quasi-classical theory predicts the decay of vortex line density of grid turbulence [9, 10]. From the classical energy spectrum, the line density of grid turbulence in a confined geometry is expected to exhibit power law behaviors which evolve with time (with development of length scale of the turbulent eddies). When the energy containing eddies are smaller than channel size (early time), the line density should decay as $t^{-11/10}$. After the eddy size becomes comparable to the size of the confinement (later time), the decay should follow $t^{-3/2}$ behavior which developed from the classical Komogorov-like energy spectrum [9, 11].

We contribute pulled-grid data from by far the largest square channel ever used (4.5 cm x 4.5 cm inner dimension of the channel) for QT over the temperature range 1.5 K to 2.1 K using 2 different grid mesh sizes. Second sound attenuation is used to probe the turbulent intensity. This paper focuses on mesh size and mesh surface finish. The decay of turbulence generated by two square hole mesh grids (Fig. 1) are found to be qualitatively different. However, the decay
of turbulence from the grid which is first (a) finished with #220 grit (50 micron) abrasive paper and then later (b) electro-polished to an atomically smooth surface is found to be unchanged.

One interesting aspect of many data is an apparent increase in QT intensity which occurs during the general decay of the QT after the heat has been terminated (in the case of counterflow) or after the pulled grid has stopped (in our work). This appears as a bump in the otherwise monotonic decay of the turbulent intensity under these conditions. We find that the size of this bump is dependent on mesh size in our so-far limited studies. This is surprising since it is not commonly expected that mesh size plays a critical role in the nature of the QT generated. This discovery suggests that, at least in the range of mesh size (0.8 mm and 3.0 mm) and mesh Reynolds numbers ($3 \times 10^4$ and $10^5$ respectively), fundamentally different types of turbulent structures are being generated in the two situations.

2. Experimental setup and procedure

A versatile apparatus has been constructed to investigate quantum turbulence decay inside a 4.5 cm square-cross-section channel. In this paper, we present results with two different square-grid meshes (Fig. 1) pulled through superfluid $^4$He to generate turbulence. The whole apparatus assembly, including the channel, is submerged in a stationary helium bath (Fig. 2). The relatively long length (40 cm) of this channel allows high velocities of grid motion and minimizes possible interfering effects from the top and bottom channel ends on the second sound signal. The size of second sound transducers (diameter= 3.8 cm), mounted on opposite sides of the channel facing each other, are comparable to the channel width. For sensitive temperature regulation, a Ruthenium oxide thermometer and a resistive heater are installed on the channel. They are attached to the outside, on opposite walls, 10 cm from the bottom of channel. All the decay data is taken when the channel is completely submerged in liquid helium II. The bath temperature is regulated by a resistance bridge AVS-46 [12] and a homemade PID controller. Typical temperature regulation range is $\pm 0.06$ mK at 1.8 K except near the instant of grid motion, where the temperature may vary up to $\pm 0.2$ mK.
The channel and support structure is made of commercial extruded aluminum square pipe to lower its mass. The main support structure immediately above the channel is made of the same commercial pipe material, cut into a triangular lattice shape maintaining robust support through both rotational and translational strains with less mass and little heat leak. Plates with partial sections of finger stocks are placed in between apparatus structures to help center and stabilize them in the dewar.

To extend the run time by reducing heat leak from radiation and conduction, the experimental setup is placed in a double dewar system. The inner dewar contains the main experimental apparatus, including the channel and the regulation heater, etc. The bath temperature of the inner dewar may be varied for the turbulence study between 1.5 - 2.1 K. The outer dewar contains a helium bath at 4.2 K that behaves as a radiation shield (lowering heat leak) and greatly reduces the heat leak coming down the support structure for the inner dewar by thermally connecting the neck of the inner dewar with the outer dewar bath.

A motor system and actuator rod for pulling the grid are mounted on top of the cryostat. A commercial motor controller (Roboclaw 2x15A) [13] and batteries for the system are also mounted right next to the controller. All cables and wires are kept as short as possible to minimize electrical noise. A linear servo motor is used along with an encoder and a tachometer for position and velocity measurements of the actuator rod. The encoder is an optical quadrature encoder that is used for position feedback to establish constant velocities for the grid. A PID control feedback mechanism is used to reach and maintain a given velocity. A Labview code was written to set PID constants, desired stroke distance, velocity profile, and maximum accelerations so the grid could be pulled at constant speed over the longest possible distance.
thus promoting the creation of isotropic and homogeneous turbulence in the neighborhood of the sound transducers. A linear power supply was used initially for the motor controller, but it introduced intolerable cross talk noise into other signals, such as temperature and position measurements, so they were replaced with batteries. However, the lower capacity of the batteries limited the maximum velocity of the grid to 60 cm/s.

Two different grids are used for turbulence generation. Both grids have a square cross sectional outline (Fig. 1) with 4.4 cm side length, and the same transparency, 67%. The gap between grid and the channel wall is about 0.4 mm on each side and the grid has corner bumpers made of Stycast 2850FT [14]. Those bumpers are designed to keep the grid in the center of the channel and minimize rotation of the grid and therefore interference with the transducers when passing them.

The amplitude of a second sound resonance produced spanning the turbulence is measured and converted into turbulence intensity [15, 16]. During the experiment, resonance frequencies could be shifted by temperature fluctuations, since the speed of second sound is strongly temperature dependent ($v_{ss} = f\lambda$, where $v_{ss}$: second sound velocity, $f$: frequency, and $\lambda$: wavelength). This leads to apparent but fictitious vortex line density measurements. To overcome this issue, a second sound tracking system was developed [17] and used in the system. With this technique, the transmitting signal frequency adjusts (tracks) so it always stays on the peak of a desired resonance. A similar tracking scheme was used in other second sound experiments [18, 19]. Our tracking system is a positive feedback circuit. Instead of providing a fixed frequency signal input to drive the second sound resonance, a stable AC oscillation is self-generated inside a closed loop circuit which includes the second sound cavity. When the circuit condition satisfies the Barkhausen criterion [20], the output signal can occur without an external signal generator. It can be designed to oscillate only at a desired resonant frequency and maintaining a constant transmitter signal amplitude.

One directional grid stroke motion is used with constant velocity to produce turbulence. The grid starts from the bottom of the channel and is pulled up at a desired speed by the linear servo motor. The stroke length is 37 cm, which gives a final grid location $\sim 0.8$ cm below the top of the channel. Once a grid motion is completed, it takes about 5 - 10 minutes to collect the data and return the grid to the original bottom position with speed of 5 cm/s. The SS signal data is taken by the tracking system for the whole duration of the procedure above. Before another motion, the system is allowed to settle for $\sim 5$ minutes to ensure the turbulence generated in previous motions is completely decayed to the same background level (remnant vorticity). The line density is calculated from individual second sound attenuation data from each grid motion.

3. Results and conclusions
We report electro-polishing the grid surfaces made no significant difference in the measured turbulence decay, while changing mesh size showed rather striking and interesting effects on decay behaviors. Figure 3 shows typical vortex line density measurements after grid pulls of 30 cm/s at 1.65 K (the peak in the second sound velocity vs. temperature curve) for two different grid hole sizes (0.8 mm and 3.0 mm). The tracked resonance is 21.6 kHz with Q-value of 1600. The $t=0$ for vortex line density calculation is set when the grid is passing through the center of transducers assuming that is the average time when turbulence is generated initially throughout the space between the large transducers. The plots are averages of 12 independent grid pulls as described above. Measurements show high reproducible tendency between each grid pull and look very similar at 1.5 K, 1.8 K, and 2.1 K [5]. The straight lines on the log-log plots represent slopes that both are predicted by theory and fit different parts of the data.

The early decay ($t<0.3$ s) is not shown because of the grid position effect on the sound signal [5] and re-locking time of the lock-in amplifier used in the tracking circuit [17]. The $t^{-11/10}$ dashed line for early time and $t^{-3/2}$ for later decay are for comparison with the theory [9]. The
later time slope tends toward $t^{-3/2}$ for counterflow turbulence decay (1 cm square channel) [21,22] and our 1 cm square channel measurements [1,5]. These 1 cm channel data display the bump as in our smaller grid hole data in the 4.5 cm channel shown in Figure 3. Another straight line $t^{-2}$ is a better fit to both of our data sets in the large channel at later time. It had been suggested that the $t^{-2}$ later time behavior was due to the bump pushing up the turbulent intensity before the later time decay was measured. By comparing with smaller channel data, we believe the later time behavior depends on the channel size (bigger channel means faster decay), since the smaller grid mesh has a prominent bump and the larger grid mesh does not, but both decay faster than $t^{-3/2}$. This is unexpected. It could be interpreted that the turbulence in the larger channel contains a non-Kolmogorov-like energy spectrum. This is quite different from classical grid turbulence. Clearly more grid mesh sizes need to be studied.

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