Visualization Study of the normal-fluid motion in superfluid helium-4

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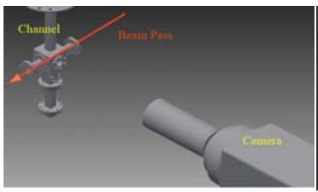
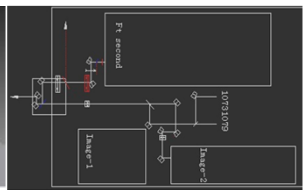
Abstract

Flow visualization in superfluid ^{4}He is challenging, yet crucial for attaining a detailed understanding of quantum turbulence. Two problems have impeded progress: finding and introducing suitable tracers that are small yet visible; and unambiguous interpretation of the tracer motion. Metastable He_2 triplet molecules are excellent tracers in that they form angstrom-sized bubbles in helium and can be imaged using a laser-induced-fluorescence technique [1,2,3]. At temperatures above 1 K, helium molecules solely follow the motion of the normal-fluid component without being affected by quantized vortices [3,4]. In our recent experiments on thermal counterflow, by tracing a thin molecular line created via femtosecond-laser-field ionization technique, we are able to measure the instantaneous normal-fluid velocity field. We show that the obtained velocity probability density function (PDF) in turbulent thermal counterflow obeys a Gaussian distribution. We also discuss the calculated structure function of the novel normal-fluid turbulence in thermal counterflow.

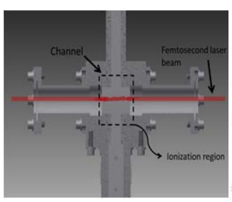
Experiment:

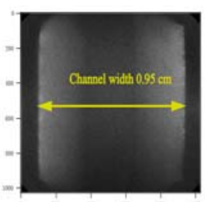
A very thin line of helium molecules is created by a well focused strong femtosecond laser pulse (energy flux ~10^{13} W/cm^2) via laser-field ionization of the ground state helium atoms. A planar heater (around 400 Ohms) is mounted inside the square channel at the bottom closed end to drive a thermal counterflow.

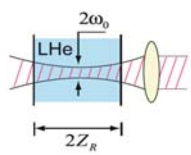




The experimental channel has two side windows attached which allow the laser beams to pass through. A front stepped sapphire window allows us to take images perpendicular to the laser beams and the channel axis. The laser beam is focused by a lens with 75 cm focal length to have a Rayleigh range (Z_R) of 1 cm. The cross section view of the channel is shown below.

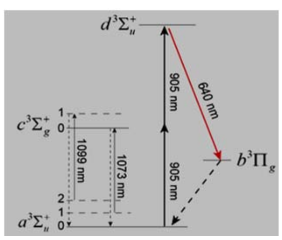






$$\omega(z) = \omega_0\left[1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right]^{\frac{1}{2}}$$

To image the He_2^* molecules in the triplet state, a pulsed laser at 905 nm is used to drive the molecules out of the $a^3\Sigma_u^+$ state to produce 640 nm fluorescent light through a cycling transition [2]. The molecules fall to the a(1) and a(2) excited vibrational levels can be recovered using continuous fiber lasers at 1073 nm and 1099 nm.



Results:

Laminar flow

1)

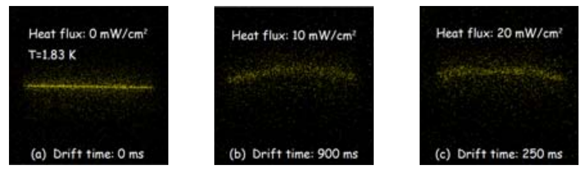


Fig 1a – 1c: typical images of the He_2 excimer lines created via laser-field ionization with low heat fluxes in superfluid helium. A nearly parabolic line shape is observed, indicating the Poiseuille laminar-flow velocity profile of the normal fluid in the flow channel. The drift time denotes the time from line creation to line imaging.

Transition from laminar flow to turbulent flow

2)

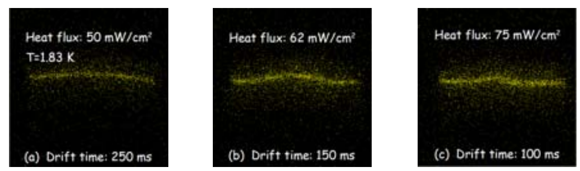


Fig 2a – 2c: the deformation of the excimer lines in the heat flux range as the normal fluid starts to transit from laminar flow to turbulent flow. The tail part of the excimer line becomes clearly flattened due to the mutual friction from the vortices accumulated near the channel walls. These images are all average of 10 images under the same conditions.

Turbulent flow

3)

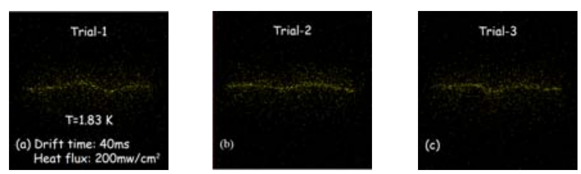


Fig 3a – 3c: single-shot images of the excimer lines exhibiting random distortions in steady-state counterflow at a heat flux of 200 mw/cm^2. The normal-fluid flow is believed to be in the full turbulence regime.

Discussion:

We have determined that it is possible to use laser-induced-fluorescence technique to produce high quality single-shot images of a He_2^* molecule line. We have also shown that, at low heat flux, the normal fluid component of helium-II has a laminar flow profile. Subsequent experiments have been directed toward finding and imaging the laminar-to-turbulent flow transition. Additionally, we are able to measure the normal-fluid velocity field in steady-state counterflow.

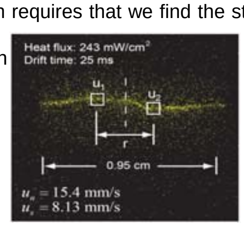
The characterization of steady state counterflow turbulence lies primarily in determining the turbulent energy spectrum, which requires that we find the structure functions of the flow.

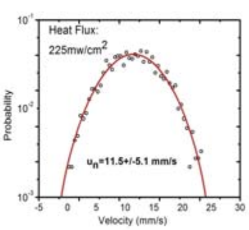
The nth order transverse structure function is given

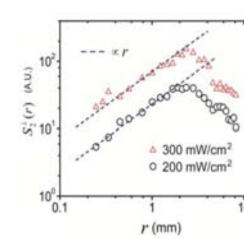
$$S_n^{\perp}(\mathbf{r}) = \left\langle \delta u_{\perp}(\mathbf{r})^n \right\rangle_{av}$$

where:

$$\delta u_{\perp}(\mathbf{r}) = \left[u_2 - u_1\right]_{\perp}$$







The obtained normal-fluid velocity probability density function (PDF) can well be fitted by a Gaussian function, which is different from the observations in typical particle tracking velocimetry (PTV) experiments using micron-sized solidified hydrogen particles [5,6]. We observe that the 2nd order transverse structure function of the normal-fluid turbulence in steady-state thermal counterflow shows a very different behavior from the $r^{2/3}$ scaling, which is typical of homogeneous and isotropic turbulence in classical fluids.

References:

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