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On the Visualization of Thermal Counterflow of He II Past a Circular Cylinder

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Abstract Thermal counterflow of superfluid ^{4}He is investigated experimentally in the proximity of a 3 mm diameter cylinder by analyzing the motions of micrometer-sized solid particles, focusing especially on the occurrence of macroscopic vortices. The influence of heating an opaque brass cylinder by the light source is studied, as thermal counterflow is generated from its surface, and compared with the case of a transparent plexiglass cylinder of the same size. Additionally, we report our preliminary investigation of vertical counterflow around the transparent cylinder. We find that care should be taken when applying conventional visualization techniques—particle image velocimetry and particle tracking velocimetry—as spurious vortical structures might be identified in quantum flows displaying two-fluid behavior.

Keywords Turbulence · ^{4}He · Thermal counterflow · Flow visualization

1 Introduction

Significant progress in understanding the two-fluid hydrodynamics of He II [1, 2] has recently been achieved by using modern visualization methods [3], such as PIV (particle image velocimetry) and PTV (particle tracking velocimetry). These techniques are indeed very valuable quantitative tools in classical fluid mechanics research and have been applied to study many scientific and industrial problems [4]. PIV can estimate the fluid velocity in a section of the flow field, by assuming a single, smoothly varying velocity field. PTV allows the measurement of Lagrangian quantities, i.e., the velocity and its derivatives, in the visualized flow field. In both techniques, small particles are suspended in the fluid and employed to trace its motion. They reflect the

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light of an appropriate source, e.g., a laser beam, and their time-dependent positions are captured by suitable sensors, e.g., a digital camera, and processed by purpose-made software. PTV allows determining the Lagrangian trajectories of the visualized particles, while PIV, which requires a larger number of particles, does not allow the direct calculation of the velocity of each visualized particle but provides a statistical estimate of the Eulerian velocity field in chosen locations, called interrogation areas, with a small number ($\simeq$10) of particles.

Although the application of visualization methods to cryogenic flows is difficult for both technical (optical access to the experimental volume, choice of suitable particles) and, in the case of quantum flows, fundamental reasons (two velocity fields, interaction of particles with quantized vortices), it has already led to the direct visualization of quantized vortices in He II [5]. Important results have been obtained in thermal counterflow [1, 2] and include, among others [6–8], the observation of vortical structures around a cylinder [9]. Still, in comparison with classical fluid dynamics, the implementation of modern visualization methods to study quantum flows is in its infancy, sometimes posing more questions than giving clear answers. For example, the vortical structures observed around cylinders in thermal counterflow (despite the attempt to explain them theoretically [10]) deserve further attention and study. There is a clear call for more detailed experimental analysis by flow visualization. In order to fulfill such a need, an experimental apparatus has been devised [11] and corresponding results, recently obtained in thermal counterflow, are here reported and discussed.

2 Experimental Apparatus and Protocol

A low-loss, custom-built cryostat is equipped with 25 mm diameter windows, which enable optical access to the experimental volume. The current experiments are performed in a square glass channel, of 25 mm sides and about 100 mm long, inserted in the tail of the optical cryostat. The windows are placed about 50 mm above the bottom of the channel. A purpose-made seeding system supplies micrometer-sized solid particles, obtained by mixing hydrogen, deuterium, and helium gases at room temperature and injecting the mixture into the helium bath. A continuous-wave solid-state laser and suitable lenses are used to obtain a laser sheet of less than 1 mm thickness and height of about 10 mm. A digital camera is situated perpendicularly to the laser sheet and its 1 MP CMOS sensor (1280 $\times$ 800 pixels) is focused on a 12.8 mm width and 8 mm height field of view by using an appropriate macro lens. Such a setup enables us to use the PIV and PTV techniques in a plane parallel to the vertical counterflow direction, in the middle of the experimental volume, i.e., as far as possible from its boundaries. The vertical thermal counterflow is generated by a flat square heater of sides of about 25 mm, placed on the bottom of the glass channel.

Once liquid helium is transferred into the cryostat, a pumping unit is used to lower its temperature. The gaseous mixture is then injected and the helium bath stabilized at a chosen temperature. As the particles are not neutrally buoyant, images are recorded before switching on the heater, in order to estimate their settling velocities and dimensions [11]. The heater is then switched on, images collected and the particle tracks calculated by using an open-source algorithm [12]. In each image, there are usually up to few hundred particles. Several thousand trajectories, with up to few hundred points, are computed for each movie, recorded for this study at 50 fps or 100 fps (note that particle tracks do not generally start at the same time). The corresponding particle velocities are estimated by purpose-made computer codes, developed by us, while the PIV analysis is performed by using the commercial software Dynamic Studio; for further details, see our publications [11, 13].

3 Results and Discussion

After establishing and testing the experimental setup [11], our investigations have been focused on the analysis of the Lagrangian dynamics of particles in thermal counterflow [13]; recently we began to study quantum flows past bluff bodies. As a first step, thermal counterflow in the proximity of a circular cylinder is being investigated; this article serves as a progress report on this activity.

A 3 mm diameter brass cylinder is placed in the middle of our glass channel, spanning its entire width. The thin laser sheet is perpendicular to the axis of the cylinder, passing through the middle of the experimental volume. One of the aims of the discussed experiments is to verify that, in contrast to classical flows past bluff bodies, macroscopic vortices are shed both in the normal fluid flow direction and in the superfluid flow direction, as reported by Zhang and Van Sciver [9].

During the first experiments, fast radial motions of a number of particles were observed in the vicinity of the brass cylinder. In order to explain the experimental outcome, it was hypothesized that a radial thermal counterflow is generated at the cylinder surface, when the latter is heated by the laser light (the cylinder surface was painted in black to avoid reflections). We consequently decided to investigate this issue more closely, by switching off the heater at the bottom of the channel and studying particle motions in the proximity of the brass cylinder, heated solely by the light source.

The main considerations relevant to such a thermal counterflow, generated at the heated cylinder surface, are as follows. The used laser power was $P \approx 50$ mW, of the same order of that employed in other thermal counterflow experiments [11, 13]. Assuming for simplicity that the intensity profile of the laser sheet is a step function, instead of being Gaussian, the power reaching the cylinder surface can be geometrically evaluated to be about 1.5 mW. This means that the thermal irradiation from the illuminated surface, π times larger than the cylinder radius, can be estimated to be around 320 W/m^2 in the proximity of the cylinder surface, this value being of the same order of that usually generated by the flat heater in previous counterflow experiments [11, 13], i.e., about 500 W/m^2. Note that the thermal conductance of brass and black paint are negligible, compared with the extremely high thermal conductance of He II. We also assume that the surface absorbs all the incoming light, even though this is not entirely true due to its non-zero reflectivity.

We have studied the thermal counterflow generated by the heated cylinder by using the PTV technique. The statistical distribution of the radial particle velocity v_r/v_r^{sd} at temperature $T \approx 1.9$ K is shown in Fig. 1 as black squares; v_r^{sd} is the standard

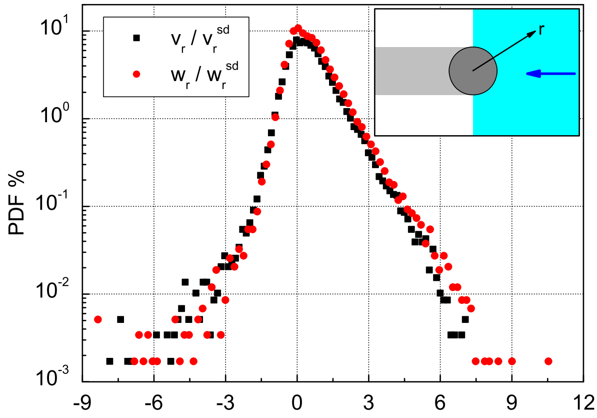

Fig. 1 *Black squares*: probability density function *PDF* of the radial particle velocity v_r/v_r^{sd}, where v_r^{sd} is the standard deviation of v_r; *red circles*: *PDF* of w_r/w_r^{sd}, where w_r^{sd} is the standard deviation of $w_r = v_r(r/R_c)$, r indicates the particle distance from the cylinder axis, and R_c is the cylinder radius. Data taken at temperature $T \approx 1.9$ K and laser power $P \approx 50$ mW (opaque cylinder, bottom heater switched off). *PDF* shown as a percentage of the total number of points, which is about 50000. Tracks with at least 5 points. The *inset* schematically shows, in *light blue*, the area of the field of view used to calculate v_r; the *blue arrow* indicates the laser light direction and the *black arrow* denotes the position r of a generic particle; the shadow behind the circular cylinder is shown in *gray*, while the cylinder is displayed in *dark gray* (Color figure online)

deviation of $v_r = v_x(r_x/r) + v_y(r_y/r)$, where v_x is the particle horizontal velocity (positive if directed to the right of the field of view), v_y indicates the vertical particle velocity (positive if directed upwards), and r is the particle radial distance from the cylinder axis, r_x and r_y being its horizontal and vertical components, respectively (note that the range of r depends on the movie, i.e., on the distances of the detected particle positions from the cylinder axis, within the observed area). The latter radial velocities have been obtained considering only the heated side of the cylinder (the field of view has been divided into two parts by a vertical line passing through the cylinder axis and perpendicular to the laser sheet, see also the inset of Fig. 1). As the local heat flux is inversely proportional to the distance r from the cylinder axis, we can normalize the radial velocity v_r as $w_r = v_r(r/R_c)$, where $R_c = 1.5$ mm is the radius of the cylinder. The distribution of w_r/w_r^{sd}, where w_r^{sd} is the standard deviation of w_r, is also displayed in Fig. 1 (red circles) and is similar to that of v_r/v_r^{sd}, thus proving the negligible effect of r on the shown outcome. The average velocity of the particles moving away from the cylinder is found to be 1.2 ± 1 mm/s. The corresponding heat flux q per unit area can be estimated to be about 240 W/m^2, which represents 3/4 of the value reported above. This is consistent with several thermal counterflow experiments, where the measured particle velocity is generally smaller than the calculated normal fluid velocity, see, e.g., our previous work [11].

We consequently conclude that, in the range of investigated parameters, the particle motion is indeed affected by the thermal counterflow due to the heated cylinder surface. In order to reduce this effect, in further investigations a transparent plexiglass cylinder has been used. As expected, fast radial motions of the particles have not been observed from the transparent cylinder surface. Note also that the used laser power

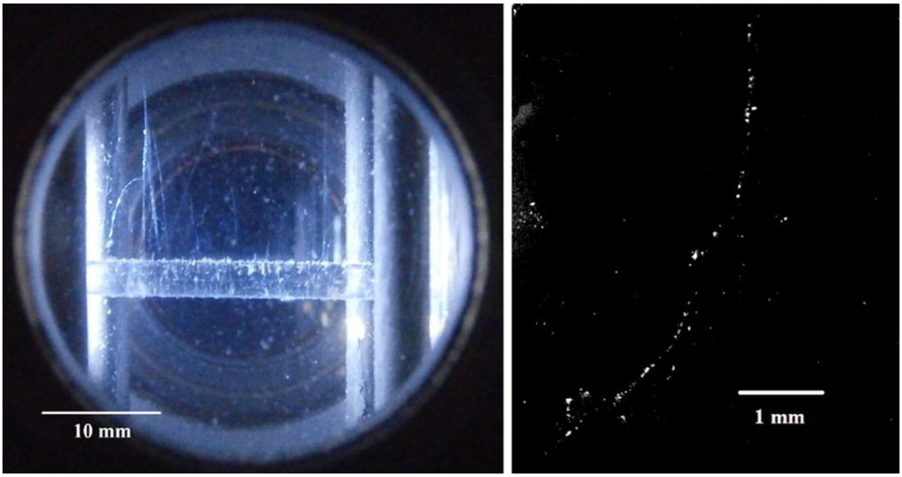

Fig. 2 *Left*: picture of hydrogen filaments in the vicinity of the transparent cylinder, at temperature $T \approx 2.16$ K. *Right*: picture of one of these structures, at $T \approx 2.15$ K (Color figure online)

does not appear to affect particle motions, as the obtained tracks, in the absence of other heat sources, are mostly in the vertical direction, i.e., due only to the density mismatch between particle and liquid.

In Fig. 2, the picture on the left, taken just below the λ-transition, shows the transparent cylinder. To the left of the cylinder one notices long filaments, made of hydrogen particles in this case, which resemble quantized vortices. On the right of Fig. 2 one of these filaments, illuminated by the laser sheet, is shown as recorded by our camera. Such structures have always been observed in He II and more frequently when hydrogen particles are used, especially at temperatures close to the λ-transition. As discussed in our previous work [11], it is not yet clear why similar filaments are observed less frequently with deuterium particles.

The top part of Fig. 3 displays particle trajectories obtained by processing the data of one of our experiments on steady-state thermal counterflow past the transparent cylinder. It is clearly seen that most particles move around the obstacle and macroscopic vortical structures are not observed. The outcome also applies to other experimental conditions and, to date, we have not yet found clear evidence of macroscopic vortices in our investigations. This may be related to the employed heat flux, smaller than that used by Zhang and Van Sciver [9], and to the small field of view. Further experiments are being performed to address these issues.

In a few cases, the number of particles was large enough to allow for the application of the PIV technique used by Zhang and Van Sciver [9]. The PIV results obtained from the same data is shown in the bottom part of Fig. 3 (the PIV analysis was performed on the entire movie and the outcome can then be considered as the mean flow in the studied conditions). A large vortical structure is seen in the top left of the figure. This macroscopic vortex, not apparent in the corresponding PTV outcome, seems to be an artifact of the technique which, as mentioned above, is best suited to analyze a single, smoothly-varying flow field. Thermal counterflow is, however, characterized by two velocity fields and these are likely to generate spurious vortical structures in

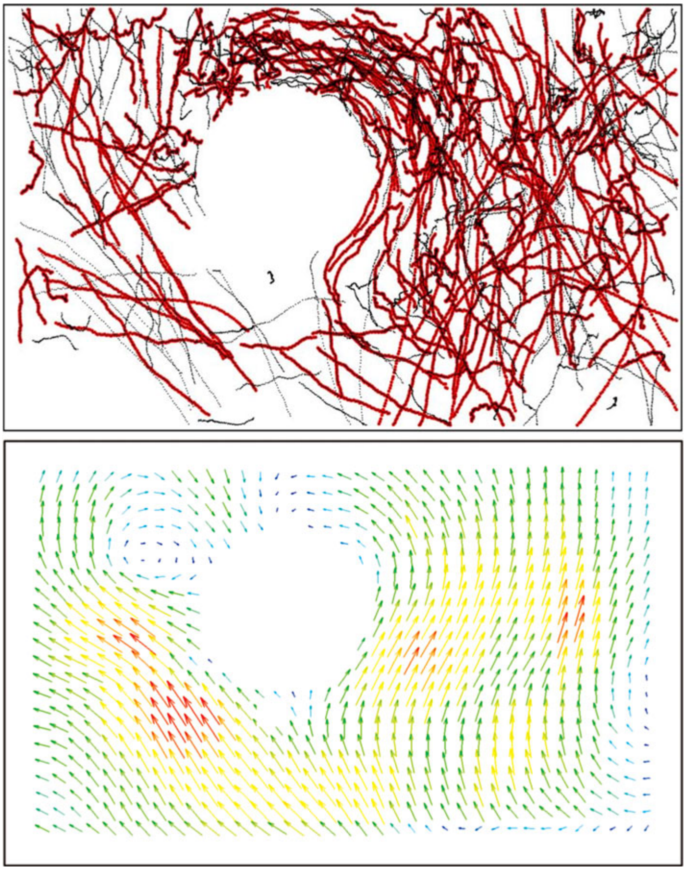

Fig. 3 *Top*: Hydrogen particle tracks obtained at temperature $T = 2.02$ K and heat flux $q = 477$ W/m^2 (transparent cylinder, bottom heater switched on, most particles move up, in the normal fluid flow direction). *Black circles*: 394 trajectories with at least 75 points; *red circles*: 183 tracks with at least 100 points. 2000 images taken at 100 fps; 13.2 mm width and 8.2 mm height field of view. *Bottom*: PIV results of the same data set. The *square interrogation areas* are of 128 pixel sides, corresponding to 1.3 mm, with 75 % overlap. The vector sizes and colors are proportional to the velocity magnitude, whose maximum, shown is *red*, corresponds to about 4 mm/s (Color figure online)

the PIV results, since for each interrogation area, which usually contains information of both fields, a single velocity vector is calculated. This experimental outcome clearly shows that extreme care should be taken when applying the PIV technique to study thermal counterflow. Note also that due to the relatively small number of particles used, the interrogation areas are quite large compared to the field of view (as detailed, for example, in the caption of Fig. 3) and this may also lead to the detection of spurious flows.

Similar results have also been obtained with the brass cylinder, as shown in Fig. 4. In this case the heater was switched off (a radial heat flux is generated at the opaque cylinder surface) and the images were taken just below the λ-transition a few moments after the injection of the particles in He I (the injection tube ends above the

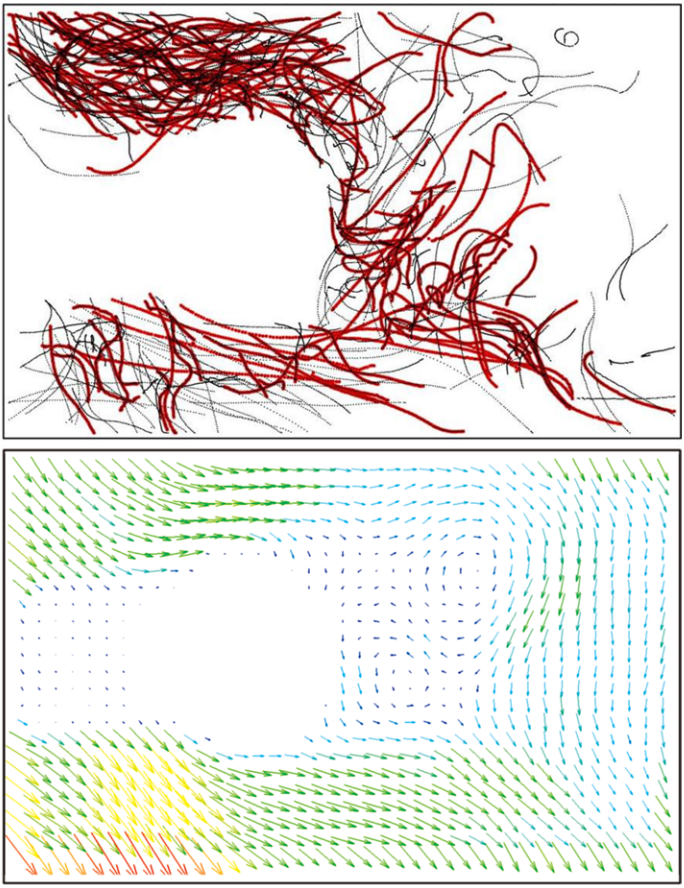

Fig. 4 *Top*: Deuterium particle tracks obtained at temperature $T \approx 2.16$ K (opaque cylinder, bottom heater switched off, radial heat flux at the brass cylinder surface of about 320 W/m^2, most particles move down, as they have just been injected from above, and to the right of the field of view). *Black circles*: 347 trajectories with at least 75 points; *red circles*: 134 tracks with at least 100 points. 1000 images taken at 50 fps; 13.3 mm width and 8.3 mm height field of view. *Bottom*: PIV results of the same data set. The square interrogation areas are of 64 pixel sides, corresponding to 0.7 mm, with 75 % overlap. The vector sizes and colors are proportional to the velocity magnitude, whose maximum, shown is *red*, corresponds to about 4 mm/s (Color figure online)

cylinder, outside the field of view). Note that the two macroscopic vortices seen to the right of the cylinder in the bottom part of Fig. 4 are not visible in the PTV data, while a spiralling particle track can be seen on the top right corner of the top part of Fig. 4.

4 Conclusions and Future Work

The motion of solid particles in thermal counterflow in the proximity of a circular cylinder has been investigated by using the particle image velocimetry (PIV) and particle tracking velocimetry (PTV) techniques. It was shown that it is preferable if the bluff body is made of a transparent material to avoid parasitic flows. Additionally, it was found that the application of the PIV technique for the study of quantum flows requires special attention, as macroscopic vortices, not apparent in the PTV data, may be identified in the PIV results. In the future, we intend to perform visualization investigations of oscillating bodies in superfluid ^{4}He, in order to clarify the issue of the existence of macroscopic vortical structures in quantum turbulence.

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