Journal of Low Temperature Physics manuscript No.
(will be inserted by the editor)

E. Zemma · J. Luzuriaga

Anomalous trajectories of H_2 solid particles observed near a sphere oscillating in superfluid turbulent ^{4}He.

Received: date / Accepted: date

Abstract Using a relatively low cost apparatus, consisting of a glass dewar and a digital camera capable of taking images at 240 frames per second we have observed trajectories of frozen H_2 particles which follow the flow of liquid helium below 2 K, around a sphere oscillating at 38 Hz. In some of the images the motion is compatible with laminar flow, while at high amplitudes, where we can reach Reynolds numbers of a few thousand in the normal component, the flow is clearly turbulent. In some of the videos taken we find particles being suddenly accelerated to several times the velocity of the oscillating sphere.

Keywords Quantum fluids · Turbulence · Superfluid Helium · Flow visualization · Oscillating Sphere

PACS 67.25.-k , 67.25.dk, 67.25.dg, 47.37.+q

1 Introduction

Turbulence in superfluids has been studied for a long time [1, 2] and there is still a strong interest in the subject [3–8] with new experimental techniques for flow visualization [9, 10] being developed and adapted to quantum fluids.

Experiments and simulations have shown that quantum turbulence involves the rearrangement of quantized vortices in a cascade mechanism [6, 7, 11, 12]. A method available to image this process makes use of the fact

E. Zemma
Centro Atómico Bariloche, (8400)S.C. Bariloche, CNEA, Inst. Balseiro UNC, CONICET, Argentina
E-mail: zemma@cab.cnea.gov.ar

J. Luzuriaga
Centro Atómico Bariloche, (8400)S.C. Bariloche, CNEA, Inst. Balseiro UNC, Argentina

that there is a force that holds a particle close to a vortex core [9, 13–15]. We can then infer the location of vortex lines and analyze their dynamics by observing the motions of micrometer sized solid hydrogen particles which attach to them. Using particle tracers valuable information has been gathered about vortices in superfluid helium, and reconnection events, where two vortices merge at a point, change topology by exchanging parts, and separate have been shown to produce high, atypical velocities [13, 16, 17]. Tracers have also been used to image counterflow [18, 19] and turbulent flow in channels [10, 20, 21] and in rotating flow past a body [22] but Vinen [8] has recently pointed out that flow visualization past oscillating objects, a type of turbulence with a classical analogue, is in need of development.

Many experiments with oscillating bodies have been performed [23–38] but in general they have been focused on studying the onset or other characteristics of turbulence.

We have been able to film particles flowing around an oscillating sphere submerged in superfluid helium and we report our first results in the present paper. In the turbulent regime, when analyzing the instantaneous velocities of the particles, we find instances of much higher speeds than the oscillating sphere. This anomalous behavior remains unexplained. Instances of sudden acceleration have been reported for intermittency in normal fluids [39] and for particles caught in a suddenly accelerated vortex core [13], however our experiments are not equivalent to these cases.

2 Experimental Details

Experiments were performed in a conventional glass helium cryostat of 6 cm internal diameter and 1.2 m of height. The silvering is suppressed forming a window of 2 cm width over the whole length. The nitrogen outer Dewar which is normally present was removed to allow a clear view inside. The helium bath was pumped and a rubber diaphragm regulator was used to stabilize the temperature. The helium vapor pressure, measured with a calibrated gauge, was used to estimate the temperature. The heat exchange with the outside is rather large because of the removal of the outer nitrogen Dewar. By measuring the rate of evaporation and using the latent heat of evaporation of the helium we estimate the heat flux to be between 800 mW and 450 mW, depending on the distance of the helium surface to the top of the cryostat and the temperature and pumping rate. This arrangement allows imaging of the flow of liquid helium by using tracer particles which can be directly seen through the glass window.

We are interested in visualizing the flow past a sphere, with emphasis on the behavior in the turbulent regime. We used a sphere of radius 0.45 cm oscillating at 38 Hz, this oscillation was maintained by an ac current passed through a coil fixed to the cryostat and a permanent magnet attached to the sphere. The spherical oscillator used is held by a flexible stem or reed made from a strip of BeCu alloy 5 mm wide and 0.05 mm thick. Close to the resonance frequency, we could attain displacements of 0.5 millimeters. For the sinusoidal displacement of the sphere, it implies a maximum velocity ≈ 0.1 m/s and an associated Reynolds number Re of around 10^4 at ≈ 2 K where most of our videos were taken. We consider the density of the normal component alone when computing *Re*, and have found previously that the transition to turbulence is dominated by *Re* defined in this way [38].

Images were collected with a fast camera [40], up to 1000 frames per second (fps) although for higher resolution we generally used a rate of 240 fps. The camera is fixed on a platform outside the dewar and the zoom and focus set to maximize the size of the oscillating sphere. Solid particles are formed when a hydrogen-helium gas mixture is injected into the liquid helium following the procedure outlined by Bewley and co-authors [**?**,13,16]. We filmed each injection to detect the movement of particles in the fluid. The mixture is prepared with hydrogen and helium gases whose proportions can vary, thus changing the particle size.

To illuminate the tracer particles we used a green laser beam. The frozen H_2 particles are not expected to absorb significant energy in the visible [41]. The laser is on the outside of the equipment, and the light passes through an optical fiber which ends less than a centimeter away from the oscillating sphere, illuminating the particles perpendicular to the line of sight of the camera. The fiber is polished at the end, giving a three dimensional cone of light, which also partly diffuses in the white sphere. Other reflections where minimized by using a black screen in the background. A still taken from the videos is shown in Fig. 1.

Experiments were performed between 1.7 and 2 K. Dissipation in the superfluid component in this range of temperatures is mainly produced by mutual friction between the quantized vortices and normal fluid [42].

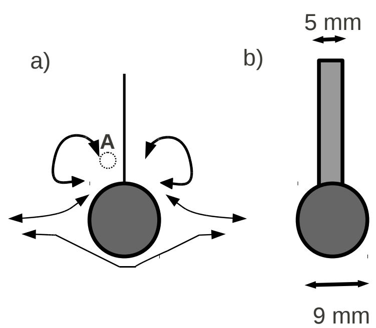
In Fig. 1 we show in a) a front and in b) a side view of the sphere, with a rough sketch of the circulation expected, and the relevant dimensions in millimeters. The flow will be different from that of a free sphere because of the presence of the flexible CuBe stem which acts as the spring of the mechanical oscillator. The stem is 5 mm wide, so that its section is not negligible, and should affect the flow.

3 Experimental Results

We have found that a mixture of one part of hydrogen to 50 parts of helium gives good results. The injection pressure is generally 500 Torr, and around a hundred cubic centimeters of gas are injected each time. We wait until the perturbations caused by the injection die out before using the video footage of particle motion.

In general we have few particles present at a time, and we analyze the motion of individual particles across several successive video frames by digitizing their positions in the frame. All videos shown are taken at 240 fps, so the time interval is 4.17 ms between frames and we use this quantity as our time reference to calculate velocities. The distances in the images are calibrated with respect to the measured dimensions of the optical fiber. The particles analyzed here are between 70 and 200 microns in size, as estimated by the size of their images.

For some regions of the sphere, and for several cycles of oscillation, we have observed motion that is consistent with laminar flow. In Fig. 2 we show



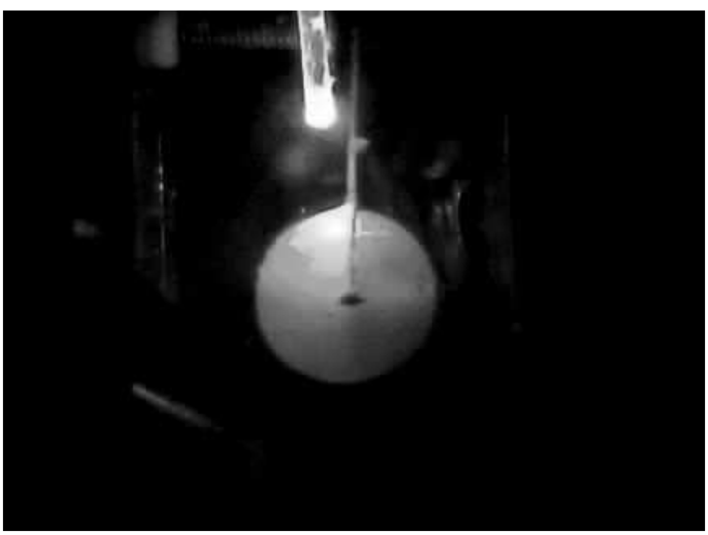


Fig. 1 Left: Schematic view of the sphere: a) View seen from the camera, a rough draft of the expected liquid path round the sphere is indicated; b) Side view showing the dimensions in millimeters and the approximate relative size of the flexible stem. The point marked with A shows the region where most of the paths shown below originate. Right: Still picture, showing the particle analyzed in Fig. 2

the velocity of the sphere and an isolated particle through several video frames.

The flow round a sphere in the laminar regime can be calculated using the potential flow approximation and gives [43]

$$\mathbf{v} = \frac{1}{2}\frac{R^3}{r^3}\left[3\mathbf{n}(\mathbf{u}\cdot\mathbf{n}) - \mathbf{u}\right] \tag{1}$$

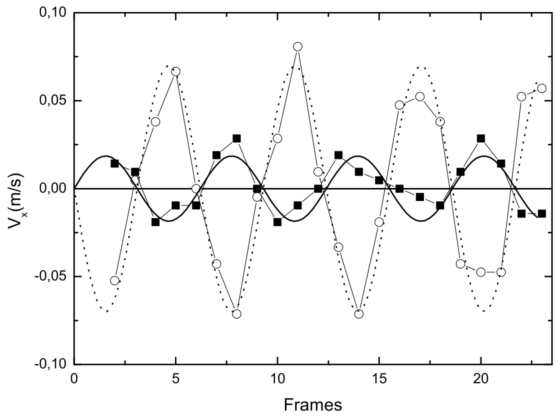


Fig. 2 Particle and sphere velocity at low amplitudes, showing the behavior expected in the laminar regime. Open circles: measured velocity of the sphere, filled squares: measured velocity of a particle near the border of the sphere, dotted lines: sinusoidal fit to the sphere velocity, filled lines: expected velocity from Eq.1. The signals are 180°out of phase, in the laboratory system of reference, where the liquid is static at large distance from the oscillating sphere.

where **v** is the fluid velocity, **u** is the speed of the sphere, and and **n** is a unit vector parallel to the radius of the sphere. The particle studied is around one millimeter away from the sphere at $\theta \approx 60°$, where θ is the angle between **v** and **u**. In this position, we expect from Eq. 1 that the flow parallel to the motion of the sphere (the x direction in the system of coordinates we use) is out of phase with the motion of the sphere and with a magnitude reduced by a factor of about five. In the figure we show in full lines a sinusoidal fit to the motion of the sphere. In dotted line we plot this fit, with the opposite phase and multiplied by 0.2 and we see that it agrees within experimental error with the observed motion of the particle. In this regime both the normal fluid and the superfluid are expected to move in phase except very close to the surface of the sphere. Therefore the particle seems to behave as if it is being dragged by the viscous normal component.

When the sphere moves at large amplitudes, the videos show clearly that many particles follow erratic paths, and very different trajectories can be observed. Sudden changes in velocity can be seen, looking as if the particle acquires momentum suddenly, in many cases moving distances which are several times the amplitude of oscillation of the sphere. We have concentrated the analysis in these cases, and found that when quantifying the particle speeds we obtain values that can be several times greater than the velocity of the sphere.

The trajectories of some selected particles are shown in Fig. 3.

The points represent the positions within the frame in millimeters, taken at the 4.17 ms time step given by the camera, and it can be seen that in some instances there is a larger gap between positions indicating a higher velocity.

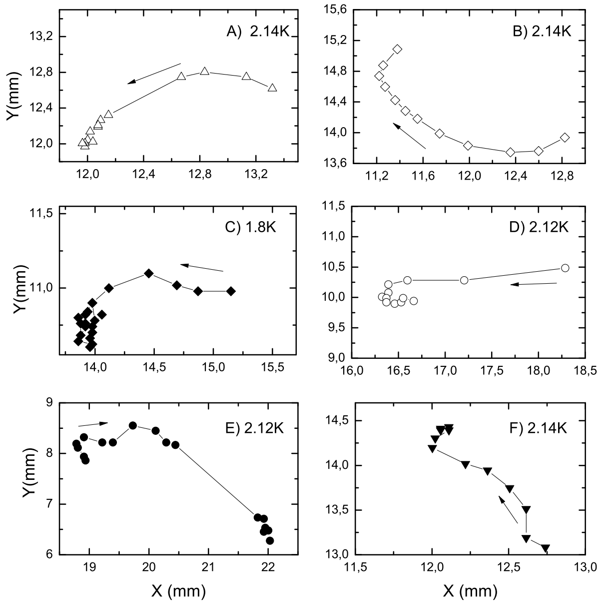


Fig. 3 Selected particle trajectories for high amplitudes of oscillation. Each point corresponds to a single frame, being separated by 4.2 milliseconds in time.The temperatures are indicated in the graphs and the arrows show the direction of the movement. Velocities inferred from this graph are shown in Fig. 4

We have plotted the absolute value (modulus) of the velocity vector obtained from the trajectories as a function of time and results are shown in Fig. 4. The velocities show sudden changes, sometimes over a couple of frames and sometimes over a single frame. This is due to the random characteristic of turbulent flow, and we only observe this behavior when the amplitude of oscillation is high, but a surprising feature of the data is that the velocities of the particles can be much higher than the maximum velocity of the oscillating sphere.

We have plotted in Fig. 5 the maximum velocities observed for the particles, against the maximum velocity attained by the sphere in its sinusoidal motion. Both quantities have been estimated from the videos, and we have added data for some particles not included in the previous graphs.

It can be seen that there is no obvious trend, but in a few cases the particles are several times faster than the oscillating sphere. In other cases the difference is less, but particle velocities are generally higher, being above the full line in the graph, which is identical with the velocity of the sphere. It can be recalled that in the laminar regime the maximum velocity of the particle in the laboratory reference frame would be half that of the sphere.

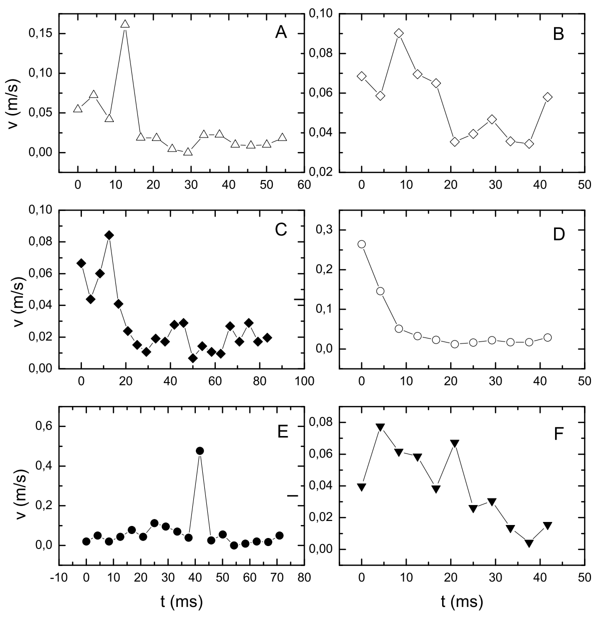


Fig. 4 Modulus of the particle velocities *vs* time, corresponding to the trajectories shown in Fig. 3 represented by the same symbols and the figures are labeled by the same letters. Each point represents the speed calculated between pairs of video frames and large variations can be seen over a few frames.

4 Discussion

The sudden acceleration of suspended particles due to reconnecting vortices has been observed by Bewley *et al* [13], but there is a large difference in the size of the events. Their vortex reconnections are seen in image frames of millimeter sizes, while ours are over a centimeter. This makes it problematic to identify the acceleration seen here with vortex reconnections, but it is possible that we could be seeing particles attached to a vortex core which accelerates in the turbulent flow, although it would seem that our particles are rather large (around a hundred microns) for being strongly attached to a vortex core. We are generating vorticity at around the scale of our sphere so we would be seeing a particle caught in the core of a large superfluid vortex driven by the turbulence.

Another possibility is an analogy with intermittent events in the normal component, which has also been seen in classical turbulence. Instances of sudden vortex formation in normal fluids have been reported by Douady *et al* [39] by Titon and Cadot [44] in flow driven by counterrotating paddles. Voth*et al* [45] have reported sudden very short time accelerations in a similar

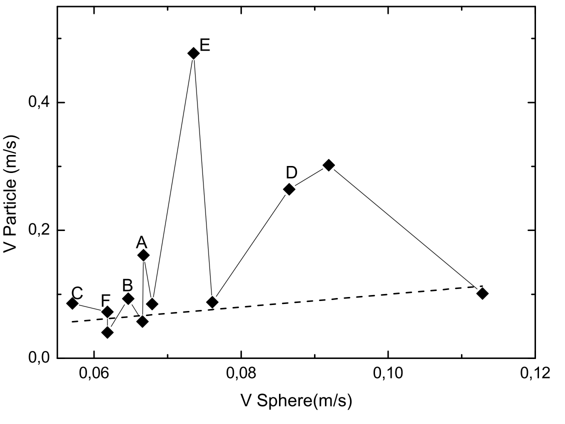


Fig. 5 Maximum particle velocities observed as a function of the peak velocity of the sphere, for the events where a sudden acceleration was observed. The capital letters refer to the labels of particles represented in figures 3 and 4. The dotted line represents the maximum speed of the sphere, which is seen to lie well below some of the points. No apparent trend is seen with the sphere velocity.

geometry. It could be that this normal fluid effect is at work in the normal fraction of the helium, which is rather high. On the other hand, flow visualization around a sphere oscillating in a normal fluid [46] has yielded no events similar to those seen here.

5 Acknowledgments

We gratefully acknowledge helpful correspondence from C. Barenghi, D. Lathrop, L. Skrbek, M. Tsubota and W. J. Vinen as well as fruitful discussions with H. Godfrin. This work was partially supported by grant PICT00-03-08937 from ANPCyT, Argentina and 06/C252 grant from U.N. Cuyo.

References

1. J. Tough, "Chapter 3: Superfluid turbulence," in *Progress in Low Temperature Physics* (D. Brewer, ed.), vol. 8 of *Progress in Low Temperature Physics*, pp. 133 – 219, Elsevier, 1982.
2. R. J. Donnelly and C. E. Swanson, *Journal of Fluid Mechanics*, **173**, 387 (1986).
3. R. J. Donnelly, *Physica B: Condensed Matter*, **329-333**,1 (2003). Proceedings of the 23rd International Conference on Low Temperature Physics.
4. W. F. Vinen, *Journal of Low Temperature Physics*, **145**,7 (2006). 10.1007/s10909-006-9240-6.
5. W. F. Vinen, *Philosophical Transactions of the Royal Society*,**366**,2925 (2008).
6. M. Paoletti and D. Lathrop, *Annu. Rev. Condens. Matter Phys.*, **2**,213 (2011).
7. M. Tsubota, *International Journal of Emerging Multidisciplinary Fluid Sciences*, **1**,229 (2009).
8. W. Vinen, *Journal of Low Temperature Physics*, **161**, 419 (2010).

9. R. Donnelly, A. Karpetis, J. Niemela, K. Sreenivasan, W. Vinen, and C. White, *Journal of low temperature physics*, **126**,327 (2002).
10. S. W. Van Sciver and C. F. Barenghi, *Progress in Low Temperature Physics*, **16**,247 (2009).
11. M. Paoletti, M. Fisher, and D. Lathrop, *Physica D: Nonlinear Phenomena*, **239**,1367 (2010).
12. D. Kivotides, J. C. Vassilicos, D. C. Samuels, and C. F. Barenghi, *Phys. Rev. Lett.*, **86**, 3080 (2001).
13. G. Bewley, D. Lathrop, and K. Sreenivasan, *Nature*, **441**,588 (2006).
14. C. F. Barenghi, D. Kivotides, and Y. A. Sergeev, *Journal of Low Temperature Physics*, **148**,293 (2007).
15. C. F. Barenghi and Y. A. Sergeev, *Physical Review B*, **80**,024514 (2009).
16. G. P. Bewley, *Cryogenics*, **49**, 549 (2009). Flow Visualization at Low Temperature.
17. G. Bewley, K. Sreenivasan, and D. Lathrop, *Experiments in Fluids*, **44** 887 (2008).
18. T. Zhang and S. W. Van Sciver, *Nature Physics*, **1**, 36 (2005).
19. M. La Mantia, T. Chagovets, M. Rotter, and L. Skrbek, ‘ *Review of Scientific Instruments*, **83**, 055109 (2012).
20. D. Y. Chung and P. Critchlow, *Physical Review Letters*, **14**,892 (1965).
21. T. Chagovets and S. Van Sciver, *Physics of Fluids*, **23**,107102 (2011).
22. T. A. Kitchens, W. A. Steyert, R. D. Taylor, and P. P. Craig, *Phys. Rev. Lett.*, **14**,942 (1965).
23. L. Skrbek and W. Vinen, *Progress in Low Temperature Physics*, **16**,195 (2009).
24. J. Jäger, B. Schuderer, and W. Schoepe, ‘ *Phys. Rev. Lett.*, **74**,566 (1995).
25. J. Luzuriaga, *Journal of Low Temperature Physics*, **108**, 267 (1997).
26. W. Schoepe, *Journal of Low Temperature Physics*,**150**,724 (2008).
27. M. Blažková, D. Schmoranzer, L. Skrbek, and W. F. Vinen, *Phys. Rev. B*, **79**,054522 (2009).
28. M. Blažková, M. Clovecko, E. Gao, L. Skrbek, and P. Skyba, *Journal of Low Temperature Physics*, **148**, 305 (2007). 10.1007/s10909-007-9389-7.
29. M. Blažková, T. Chagovets, M. Rotter, D. Schmoranzer, and L. Skrbek, *Journal of Low Temperature Physics*, **150**, 194 (2008).
30. W. F. Vinen, L. Skrbek, and H. A. Nichol, *Journal of Low Temperature Physics*, **135**,423 (2004).
31. H. A. Nichol, L. Skrbek, P. C. Hendry, and P. V. E. McClintock, *Phys. Rev. Lett.*, **92**,244501 (2004).
32. H. A. Nichol, L. Skrbek, P. C. Hendry, and P. V. E. McClintock, *Phys. Rev. E*,**70**, 056307 (2004).
33. D. Charalambous, L. Skrbek, P. C. Hendry, P. V. E. McClintock, and W. F. Vinen, *Phys. Rev. E*, **74**, (2006).
34. V. Efimov, D. Garg, M. Giltrow, P. McClintock, L. Skrbek, and W. Vinen, *Journal of Low Temperature Physics*, **158**,462 (2010).
35. H. Yano, A. Handa, H. Nakagawa, M. Nakagawa, K. Obara, O. Ishikawa, and T. Hata, *Journal of Physics and Chemistry of Solids*, **66**,1501 (2005). Proceedings of the ISSP International Symposium (ISSP-9)on Quantum Condensed Systems.
36. H. Yano, N. Hashimoto, A. Handa, M. Nakagawa, K. Obara, O. Ishikawa, and T. Hata, *Phys. Rev. B*,**75** 012502 (2007).
37. H. Yano, Y. Nago, R. Goto, K. Obara, O. Ishikawa, and T. Hata, *Phys. Rev. B*, **81**, 220507 (2010).
38. E. Zemma and J. Luzuriaga, *Journal of Low Temperature Physics*,**166**, 171 (2012).
39. S. Douady, Y. Couder, and M. Brachet, *Physical review letters*, **67**,983 (1991).
40. CASIO, *Exilim EX ZR100.* digital camera.
41. R. Penney and T. K. Hunt, *Phys. Rev.*, **169**,228 (1968).
42. M. S. Paoletti, M. E. Fisher, K. R. Sreenivasan, and D. P. Lathrop, *Phys. Rev. Lett.*, **101**, 154501 (2008).
43. L. D. Landau and E. M. Lifshitz, *A Course in Theoretical Physics - Fluid Mechanics*, vol. 6. Pergamon Press Ltd., 1987.

44. J. Titon and O. Cadot, *Physical Review E*, **67**,027301 (2003).
45. G. A. Voth, A. la Porta, A. M. Crawford, J. Alexander, and E. Bodenschatz, *Journal of Fluid Mechanics*, **469**, 121 (2002).
46. F. Otto, E. K. Riegler, and G. A. Voth, *Physics of Fluids*, **20** 093304 (2008).