Habilitation thesis

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Particle dynamics in quantum turbulence

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“Vi sono più cose in cielo e in terra, Orazio,
di quante se ne sognano nella vostra filosofia”
William Shakespeare, *Amleto*

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Motivation

I am currently a researcher at the Department of Low Temperature Physics, which I joined in October 2009, few months after I was awarded a Ph.D. degree from the University of London (United Kingdom). My Ph.D. research project was devoted to investigations of the hydrodynamic forces acting on flapping wings, such as fish fins. I specifically developed dedicated computer programs and performed relevant wind-tunnel experiments in order to address this interdisciplinary problem. My scientific background is therefore mainly on fluid mechanics.

The design and implementation of a novel experimental apparatus to analyse by visualisation cryogenic flows of normal and superfluid ^{4}He was initially the focus of my work at the Department of Low Temperature Physics. The implemented setup, unique in Europe at the time, is now being used, under my supervision, to perform valuable scientific investigations. The dynamics of relatively small particles in selected quantum (superfluid) flows is being studied by using classical (room-temperature) visualization techniques, which have been suitably modified in order to be applied to low-temperature flows. Current analyses are mainly focused on the investigation of the similarities and differences between classical (viscous) and quantum turbulent flows, an interesting and challenging line of scientific research.

This would not have been possible without Professor Ladislav Skrbek, a leading scientist within the condensed matter physics and fluid mechanics communities. He established the Prague low-temperature visualization laboratory, which I am currently in charge of. When I came to Prague in 2009, I only had a quite vague notion of superfluid helium. The idea of Professor Skrbek was indeed to investigate quantum flows by using classical visualization techniques, which were more familiar to me than to him, and, at the time, I was happy to join his research group, mainly because I was looking for a challenging job opportunity in science.

My initial task was to contribute to the design of the experimental setup, taking advantage of the available resources, granted to Professor Skrbek, and, although I can be considered to be the main responsible of the current appearance of the apparatus, its design greatly benefitted from the vast low-temperature knowledge of Dr. Miloš Rotter, who, since then, has been involved in almost all cryogenic visualization experiments performed in Prague.

At the end of 2009 we actually had the privilege of starting from scratch. For example, the equipment customarily used to visualize flows includes at least a camera and a light source, and it was mainly my responsibility to choose the most suitable ones among the latter devices. However, only some parts of the apparatus could be directly purchased because low-temperature flow visualization was at the time – and, to some extent, still is – a relatively new experimental technique. We therefore designed by ourselves some other parts, such as the optical cryostat, which was manufactured on the basis of our drawings. Indeed, in order to visualize a flow, optical access to the experimental volume is needed and we decided to design the latter volume in such a way that several types of quantum flows – as many as possible – could be experimentally investigated by visualization.

The most critical part of the apparatus, which was also designed by us, is the particle seeding system. Liquid helium is a transparent fluid (its refraction index is comparable to that of air) and opaque particles are therefore needed to visualize its flows. However, particles that can be dispersed in liquid ^{4}He to this end cannot be easily purchased and, consequently, on the basis of our knowledge, we devised a purpose-made system in order to generate adequate flow-probing particles.

The following step, once all relevant equipment was delivered to us and suitably assembled, was to test the cryogenic visualization setup. Its implementation included, first of all, a number of water experiments, which were mostly performed by me, mainly to investigate the capabilities of the purchased camera and light source. Additionally, it is worth noting here that the processing of visualization data is far from being trivial because, on each collected image, particles have to be found and, then, starting from the obtained positions, relevant statistical calculations, including, for example, those concerning particle velocities and accelerations, can be performed, by using dedicated computer programs.

Although numerous image processing schemes are readily available and routinely employed, they have in general to be suitably modified in order to be applied to the analysis of actual movies, that is, I performed a rather exhaustive testing of various particle tracking algorithms and developed, in the meantime, several purpose-made computer codes. Programming constitutes indeed a crucial part of data processing, which, by the way, takes usually much more time than the experiments themselves – several months compared to few days – leaving aside for a moment the experiment preparation, which can also take a relatively long time.

Nevertheless, back then, I was the one who had to get meaningful information from the collected images and, in order to do so, the first step was, as mentioned above, to test the devised visualization system on a number of classical water flows, including, for example, the flow past a circular cylinder. This was followed by more stringent low-temperature tests, performed, under the supervision of Professor Skrbek and Dr. Rotter, by me and Dr. Timofej Chagovets, who gained valuable experience at Florida State University (United States of America), where a cryogenic flow visualization laboratory was established by Professor Steven Van Sciver some years earlier.

After few attempts, we were able to generate suitably small particles, made of solid hydrogen and deuterium, and to visualize their flow-induced motions in superfluid ^{4}He. The collected movies were then processed, mostly by me, and, after some trials, I developed a data processing procedure that could be applied to the analysis of quantum flows, as, for example, the obtained statistical distributions of the particle velocities could be positively compared with those computed by other researchers. Note in passing that the developed procedure has been modified over the past years not only by me but also by Dr. Daniel Duda, who has been recently awarded a Ph.D. degree from Charles University, under the supervision of Professor Skrbek (I was his thesis consultant).

The cryogenic visualization setup design and implementation took approximately two years and, in the process, I also gained valuable low-temperature expertise and became familiar with quantum fluids and, more broadly, with condensed matter physics. Once it was demonstrated that the apparatus works, it was time to perform actual scientific experiments and the present habilitation thesis can be viewed as a summary of the most relevant results that have been obtained by using the devised setup.

The following chapter specifically outlines these results and introduces the publications that I have chosen to show my contribution to our current understanding of the underlying physics. The work also demonstrates that, by applying classical visualization techniques to the study of cryogenic flows, I have gradually established myself as an independent researcher in condensed matter physics.

Additionally, in order to further support my application to become associate professor, I mention here that I was awarded in 2015 a three-year Czech Science Foundation grant, on boundary effects in quantum flows, and that I have recently started a collaboration with Dr. Mathieu Gibert, who just established a low-temperature visualization laboratory in Grenoble (France). My scientific activity has also been acknowledged by a number of invited talks at international conferences, such as the prestigious March meeting of the American Physical Society, in 2016.

My teaching activity in Prague has been, however, less remarkable. I am in charge of two graduate courses at the faculty, one on fluid turbulence and the other on flow visualization, and, together with Professor Skrbek, I am organizing regular seminars on quantum fluids, which are also offered as a course. I have successfully supervised the Bachelor and Master theses of Patrik Švančara, who just started his Ph.D. study under my guidance, and I am currently supervising the final-year project of Petra Hrubcová, an undergraduate student. I am also the supervisor of the Master thesis of Jan Hodic, who has not yet been able to defend his mathematical work. His first unsuccessful attempt had, nevertheless, at least a positive consequence for me because it made possible starting a collaboration with Dr. Vít Průša and Dr. Jaroslav Hron, at the Mathematical Institute of Charles University, on the computational modelling of quantum flows.

In Prague I also had the chance to continue the investigation of flapping flight, in collaboration with my former Ph.D. supervisor, Professor Peter Dabnichki, currently at the Royal Melbourne Institute of Technology (Australia), and to be involved in the analysis on turbulent convection data, collected at the Institute of Scientific Instruments in Brno (Czech Republic) by Dr. Pavel Urban and his collaborators.

I finally would like to thank here my colleagues at the Department of Low Temperature Physics, especially Professor Ladislav Skrbek, Dr. Miloš Rotter and Dr. David Schmoranzer. Without their help and advice it would not have been possible for me to pursue an independent scientific career in condensed matter physics.

Particle dynamics in quantum turbulence

Properties of natural phenomena often depend on the scale at which they are investigated. Features that appear similar at a certain scale may look entirely different at another scale, leading to the possibility of discovering hidden connections between apparently dissimilar phenomena. In other words, the same bricks can be used to build different houses or, similarly, the same house can be built by using different bricks.

During the last few years I have applied this research approach to the study of quantum turbulence, which can loosely be defined as the most general form of motion of quantum fluids displaying superfluidity. The investigation of quantum flows is indeed a challenging line of scientific enquiry that is not only interesting in its own right but is also contributing to our general understanding of fluid turbulence, one of the open problem of modern physics, as it highlights close similarities as well as distinct differences between flows of quantum and viscous fluids [1-3].

Liquid ^{4}He is, in this context, a unique working medium because it can display both quantum and viscous features. It is characterized by extremely low values of kinematic viscosity, three orders of magnitude smaller than those of air, that is, as low as 10^{-8} m^2/s [4], and, between about 4.2 and 2.2 K, at the saturated vapour pressure, it behaves as a classical viscous fluid, such as water (in this phase, it is called He I). Additionally, at approximately 2.17 K, it undergoes the phase transition to the superfluid state and becomes a quantum fluid, known as He II or superfluid ^{4}He. Its observed properties change dramatically – for example, the liquid heat capacity displays a sharp peak at the transition – and its turbulent flows can often be described by using an effective (temperature-dependent) kinematic viscosity.

This behaviour can be understood, at least to a certain extent, if both small and large scales of superfluid ^{4}He flows are considered. A phenomenological (large-scale) model is usually employed, as it can account for various experimental findings. It is known as the two-fluid model and assumes that He II consists of two components. While the normal fluid component is described, within the model, as a gas of thermal excitations carrying the entire entropy content of the liquid, the superfluid component represents a collective state of matter (described by a macroscopic wave function) with zero viscosity. The density ratio of the two components is strongly temperature dependent and, at the superfluid transition temperature, He II consists solely of the normal fluid component. By decreasing the temperature, the relative amount of normal fluid decreases and, below 1 K, it is usually assumed that only the superfluid component remains, that is, He II can be regarded as an inviscid fluid.

In order to describe the small-scale behaviour of superfluid ^{4}He flows quantum mechanics can be used and this leads to the conclusion that the superfluid component may flow potentially, at relatively low velocities. Additionally, the existence of quantized vortices (line-like topological defects within the superfluid component) is postulated to account for the vorticity observed in quantum flows. These vortices are, in He II, singly quantized in units of the quantum of circulation $\kappa = 9.97 \times 10^{-8}$ m^2/s and have been visualized by decorating their angstrom-sized core with small solid particles that became trapped onto them [5]. Many experiments and numerical simulations have shown that the dynamics of quantized vortices in two-fluid flows of superfluid ^{4}He is very rich, including vortex reconnections and generation of vortex rings. Turbulent flows of He II can therefore be seen, above 1 K, as resulting from the interaction between the two-component fluid and the tangle of quantized vortices.

This type of turbulence occurring in superfluid ^{4}He can be experimentally generated in various ways, as discussed, e.g. by Varga *et al.* [6]. A common approach, which is relatively easy to implement, is to drive the flow thermally, by using, for example, a heater placed inside the He II bath, resulting in the so-called thermal counterflow. Once the heater is switched on, the normal component moves away from it, while the superfluid component flows in the opposite direction, toward the heater, in order to conserve the null mass flow rate (note that this description is strictly valid only on average, that is, at length scales larger than the mean distance between quantized vortices). Superfluid ^{4}He can also be driven mechanically, by using, for example, an oscillating cylinder [7], and the resulting flow type is named coflow [8] because the two components move, again on average, at large enough length scales, in the same direction.

It is then apparent that, as mentioned above, the description of turbulent flows of He II depends on the length scale at which these flows are investigated. The smallest physical length scale is the size of the quantized vortex core, of the order of 1 Å, while the mean distance ℓ between quantized vortices is usually appreciably larger, of the order of 100 μm, and it is therefore much easier to access experimentally, compared to the vortex core size. Additionally, the length scale ℓ, which is often called the quantum length scale of the flow, is crucial in defining the relation between quantum and classical turbulence because it has been observed that, at scales larger than ℓ, many flow features appear to be classical-like [1-3], while, at smaller scales, the quantum description of He II flows cannot be neglected in the interpretation of the obtained experimental data, as neatly proven by my recent work [9].

To date, the latter paper can indeed be regarded as my most relevant contribution to our understanding of quantum turbulence. Relatively small solid particles, of micrometre size, are suspended in He II. Their flow-induced motions are suitably visualized, i.e. the particles are illuminated by a laser sheet and corresponding images are collected by a camera placed perpendicularly to the light sheet; see Ref. [10] for a detailed description of the cryogenic visualization setup. Then, by using the particle tracking velocimetry technique [11], it is possible to compute the particle trajectories and, consequently, relevant statistical properties of the observed particle dynamics, such as velocity and velocity increment distributions, can be calculated, within the Lagrangian framework (indicating that a flow observer follows a fluid particle as it moves in space and time).

In Ref. [9] it is specifically shown that the statistical distributions of the velocities of the flow-probing particles are characterized, in steady-state thermal counterflow, at length scales smaller than the mean distance between quantized vortices, by a non-classical broadening of the tails, which can be explained by taking into account the interactions between particles and quantized vortices. At scales larger than ℓ, the distribution shapes are instead found to be nearly Gaussian, as it is usually observed in turbulent flows of viscous fluids, see, e.g. Ref. [12].

It is then possible to say that the house, representing the shape of the statistical distribution of particle velocities in classical turbulence, can also be built by using quantum bricks, which are the quantized vortices. Similarly, a more recent work [13] proves that these quantum bricks can be used to build different quantum houses, i.e. different large-scale quantum flows.

Indeed, as mentioned above, the large-scale appearance of thermal counterflow is found to be different from that of coflow because, in the latter case, the two components of He II flow, on average, in the same direction, while the opposite is true for counterflow, again on average, i.e. at scales larger than ℓ.

Ref. [13] reports that the tails of the particle velocity distributions obtained in the proximity of a cylinder oscillating in He II, that is, in coflow, display the same power-law shape of those calculated in thermal counterflow at scales smaller than the mean distance between the vortices. Additionally, millimetre-sized vortical structures are shed at the edges of the oscillating cylinder, while large vortices have yet to be clearly detected in thermal counterflow, where, once more, large means larger than ℓ.

In other words, it was proven experimentally, for the first time, that the differences observed at large scales between coflow and counterflow disappear at scales smaller than ℓ, at least when the velocity statistical distributions of the flow-probing particles are considered.

At this point one could remark that the nearly Gaussian form of the large-scale velocity distributions obtained in both quantum and viscous flows can also be seen as a consequence of the central limit theorem, that is, other flow features should be studied in order to give a more convincing proof that the probed flows are indeed turbulent ones.

Following this thought, a suitable research direction seemed to be the detailed investigation of particle velocity increments, which can be said to be proportional to accelerations, if the time between the corresponding positions along the trajectories is small enough. One of the first results I have obtained in Prague is indeed related to Lagrangian accelerations [14]. It was shown that in steady-state thermal counterflow the statistical distributions of the particle accelerations display a classical-like shape, which, by the way, is strongly non-Gaussian.

The latter outcome was, however, not explicitly linked to the length scale probed by the particles and only after it was clear that particle velocity distributions display quantum tails solely at scales smaller than the mean distance between quantized vortices [9] it was decided to study velocity increments in more detail. It was found that velocity increment distributions are also characterized at scales smaller than ℓ by power-law tails, which can be explained by taking into account the interaction between particles and quantized vortices, and that eventually, at larger scales, their appearance become classical-like [15].

From the particle statistics computed to date, it follows therefore that quantum flows seem to behave as classical flows solely at large enough length scales. It is believed that, at these large scales, the quantized vortex dynamics is smoothed in such a way that the resulting flow behaviour is quite similar to that reported to occur in turbulent flows of viscous fluids [1-3]. The mutual friction force, arising from the scattering of thermal excitations by quantized vortices, is expected to cause the dynamical locking of the two components of superfluid ^{4}He, at large enough length scales, especially in the case of coflow [8].

However, for thermal counterflow, it is not straightforward to perform a direct comparison with similar flows of viscous fluids, although some of its large-scale features can be said to be classical-like. Apart from the just mentioned particle velocity and acceleration distributions, it was also observed that the vorticity temporal decay follows, at relatively late times, the classical –3/2 power law not only in coflow [16-18] but also in counterflow [6,19,20]. Thermally driven flows of superfluid ^{4}He seem, nevertheless, to lack direct (large-scale) classical analogues – possibly because He II is characterized by an extremely large heat conductivity – and might therefore display quantum features also at large scales, as recently suggested [21,22].

The quest for large-scale quantum features of thermal counterflow is indeed one of the most lively research areas in quantum turbulence and a definite answer is still lacking, although, from the Lagrangian statistics computed to date, it is possible to state unambiguously that particles probing (large scale) quantum flows appear to behave as they were tracking classical flows, regardless of the mechanism of flow generation.

The outcome is, as mentioned above, especially evident in the case of coflow [1-3] and I have also given my contribution to this line of scientific enquiry [7,23,24]. Small mechanical oscillators have been used to study the dynamics of quantum fluids for many years [8] but the features of the flows they generate are largely unknown at scales smaller than (or of the same order of) the oscillator size, mainly because such scales are difficult to access experimentally.

An option to address the issue is to make the oscillator bigger and this is indeed what led to the results reported in Ref. [7]. The flows due to a relatively large cylinder (of rectangular cross section) oscillating in liquid ^{4}He were visualized and it was shown that the vortical structures shed at the cylinder edges in He II are very similar to those observed in He I, at large enough length scales, smaller than the cylinder dimensions but larger than relevant dissipative length scales (the mean distance between quantized vortices in He II and the Kolmogorov scale in He I).

Additionally, in order to characterize, from the computed particle trajectories, the strength of the observed large-scale vortical structures, a parameter loosely related to the flow vorticity, named Lagrangian pseudovorticity, has been introduced in Ref. [7]. Corresponding numerical values have been found to be significantly smaller in He II, comparted to those calculated in He I, at length scales smaller than the dissipative ones, while, at larger scales, this quantitative difference was less noticeable, reinforcing therefore the notion of the small-scale quantum nature of He II flows, suggested in Ref. [9]. The next step was to compute relevant statistical velocity distributions, which, as discussed in Ref. [13], display power-law tails at length scales smaller than ℓ, similarly to what has been observed in thermal counterflow.

The flows due to a quartz tuning fork – a type of smaller and much faster oscillator widely used in quantum turbulence research [8] – have also been recently visualized [23]. It has been found that, at the probed (relatively large) length scales, the flow patterns obtained in He II cannot be distinguished from those observed in He I and that, additionally, they are consistent with those reported to occur in the proximity of a similarly shaped cylinder oscillating in water.

The result is substantiated by the computed Lagrangian pseudovorticity maps [23] but, mostly due to the appreciably larger oscillator velocities, it was not possible, in the case of the tuning fork experiments, to access experimentally scales smaller than ℓ. Similarly, for other coflow experiments, visualizing the flows of He II occurring between two grids oscillating in phase, it has been found that the shapes of the particle velocity and velocity increment distributions are classical-like at the probed scales, appreciably larger than the flow quantum scale [24].

The main aim of the latter series of experiments [24] was to probe a large-scale coflow of He II more similar to thermal counterflow than to the flows observed in the proximity of an oscillation cylinder [7] or close to a tuning fork [23]. This was achieved by investigating the flows occurring between two grids oscillating in phase, in the region where the millimetre-sized vortices shed by the oscillators should have lost their coherence. It was found that, for the purpose-made coflow, characterized by the absence of large-scale vortical structures, the obtained velocity and velocity increment statistical distributions are classical-like, at length scales appreciably larger than the estimated quantum length scale of the flow, as shown already for thermal counterflow [9,14,15], which also appears to be characterized by the absence of large-scale vortical structures. It follows therefore that the latter flow property is most likely not responsible for the large-scale quantum features of thermal counterflow suggested recently in Refs. [21,22].

In any case, at scales smaller than the mean distance between quantized vortices, the observed behaviour of the flow-probing particles can be explained on the basis of the quantum description of He II flows, that is, as mentioned above, by taking into account the interactions between particles and quantized vortices; see, for example, Ref. [13] and references therein. In short, it is possible to argue that the superfluid acceleration, due to the velocity field of the quantized vortices, is felt by the particles, also in the absence of viscosity, thanks to inertial and added mass forces [15,25]. Particles are then attracted to the vortices and can become trapped onto them. They can probe therefore the occurrence of vortex reconnections and, as suggested in Ref. [26], the power-law shape of the particle velocity distribution tails can be interpreted as a result of the vortex reconnections probed by the particles.

Particle trapping is, however, a dynamical process, that is, particles that become trapped onto vortices can be detrapped at a later time and vice versa, especially if the imposed large-scale flow is strong enough. It was indeed observed that, in thermal counterflow, at relatively large values of heat flux, most particles move away from the heater, in the direction of the normal fluid flow, and interact with the vortex tangle, as it is apparent from the fact that the corresponding particle tracks are not straight. Instead, at smaller heat fluxes, particle trajectories in the normal fluid flow direction appear straighter than those in the superflow direction, indicating therefore that, at these smaller heat fluxes, particles tend to stay trapped onto vortices for longer times; see Ref. [27] for a detailed discussion.

The onset of turbulence in thermal counterflow is indeed the focus of Ref. [27]. The values of heat flux at which the onset occurs have been experimentally estimated from visualization data for a relatively wide channel and have been found to be consistent with our current understanding of this phenomenon, i.e. the obtained value of onset velocity is smaller than those reported in the literature for smaller channels. This can be intuitively explained by saying that, as the channel size increases, it is easier for the incoming flow to perturb the state of a quantized vortex attached to the channel walls and crossing its width, i.e. a quantized vortex that is initially approximately perpendicular to the incoming flow (it is generally believed that quantized vortices are already present in any macroscopic sample of apparently quiescent He II; see, e.g. Ref. [8] for an introduction to quantized vortex nucleation). The transition of He II flows to the turbulent state is actually a topic that deserves to be investigated in more detail, as, for example, the respective roles of the two fluid components, interacting with the quantized vortex tangle, have yet to be exhaustively addressed, mainly because it is not easy to access experimentally low fluid velocities; see again Ref. [27] for further considerations on this topic.

Another line of research that, as pointed out in Ref. [27], has received little attention to date is that focusing on the influence of solid boundaries on the development of quantum flows, despite the fact that wall-bounded flows of viscous fluids have been investigated for many years [28]. I have actually been awarded in 2015 a Czech Science Foundation grant in order to address this open problem. The first project result strongly suggests that boundary layers might also exist in quantum flows, consistently with a number of related numerical findings. Visualization results obtained in steady-state thermal counterflow show that quantized vortices seem not to be homogenously distributed in the channel where the flow occurs and appear to preferentially concentrate close to its walls [29]. The latter paper can indeed be regarded as the first dedicated experimental study on wall-bounded quantum flows.

The introduction of a new experimental technique to estimate the mean distance between quantized vortices made this results possible. In previous publications, such as in Ref. [9], the bulk values of ℓ have been taken from numerical simulations and it was shown that, for particles probing length scales larger than the quantum length scale, the corresponding particle velocity distributions have nearly Gaussian shapes, while, at smaller scales, the distributions are characterized by wide, power-law tails. The velocity distribution flatness therefore decreases as the length scale increases until, at scales of the order of ℓ, its value becomes equal to three, that of the Gaussian distribution.

It follows consequently that it is possible to estimate the mean distance between quantized vortices not only from numerical simulations or second-sound measurements, as in Ref. [6], but also from the particle velocity flatness trends and this is indeed what has been shown in Ref. [29]. The flatness values obtained in the boundary proximity reach the Gaussian one at quantum length scales smaller than those found in the bulk, supporting therefore the view that close to the channel wall there are more vortices than in the bulk; see Ref. [29] for further details.

Within the project on boundary effects in quantum flows, I am also currently investigating, together with my students, how the distance from the flow source affects the flow behaviour, which is presently unknown, especially in the case of thermal counterflow. In the past it has always been assumed that the distance from the heater had a negligible influence on the development of counterflow, due to the extremely large heat conductivity of the liquid, but preliminary results actually show that, in the heater proximity, the vortex tangle is denser than in the bulk. This series of experiments might, additionally, shed light on the possible relations, if any, between thermal counterflow and turbulent convection in viscous fluids, which, by the way, I also had the chance to investigate in collaboration with colleagues from the Czech Academy of Sciences [30,31].

Future lines of scientific enquiry, based on the results I have obtained to date, could follow various routes and here I mention just three of them. The flow-induced particle behaviour at scales smaller than the mean distance between quantized vortices has yet to be thoroughly analysed, especially in the case of mechanically driven flows [7]. Its investigation could be instrumental in clarifying the mechanisms of energy dissipation in quantum turbulence, which are believed to be strictly related to quantized vortex dynamics. The quest for the large-scale quantum features of thermal counterflow could possibly be addressed by increasing the sizes of the current data sets, in order to calculate higher order statistical flow properties, such as structure functions [21]. A series of experiments on particle preferential concentration in quantum flows, which I have recently performed together with some French colleagues, within a project partly founded by the European Union, can indeed be seen as a step in this direction. The use of other experimental tools, such as second sound sensors [6] and accelerometers, could also be pursed in view of obtaining complimentary flow data. For example, by using a force sensor, it could be possible to link the large vortices shed by a cylinder oscillating in He II to the corresponding forces acting on the oscillator.

In summary, the experimental investigation of turbulent flows of He II has been the focus of my work in Prague and I believe that it could definitely keep me busy for some more years because, as I have tried to show here, the study of particle dynamics in quantum turbulence is not only interesting in its own right but is also contributing to our general understanding of quantum turbulence, leaving aside its close relation with classical hydromechanics.

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[25] M. La Mantia and P. Dabnichki, *Structural response of oscillating foil in water*, Eng. Anal. Bound. Elem. 37, 957 (2013).

[26] M. S. Paoletti, M. E. Fisher, K. R. Sreenivasan and D. P. Lathrop, *Velocity statistics distinguish quantum turbulence from classical turbulence*, Phys. Rev. Lett. 101, 154501 (2008).

[27] M. La Mantia, *Particle trajectories in thermal counterflow of superfluid helium in a wide channel of square cross section*, Phys. Fluids 28, 024102 (2016).

[28] I. Marusic, B. J. McKeon, P. A. Monkewitz, H. M. Nagib, A. J. Smits and K. R. Sreenivasan, *Wall-bounded turbulent flows at high Reynolds numbers: recent advances and key issues*, Phys. Fluids 22, 065103 (2010).

[29] M. La Mantia, *Particle dynamics in wall-bounded thermal counterflow of superfluid helium*, Phys. Fluids 29, 065102 (2017).

[30] P. Urban, P. Hanzelka, V. Musilová, T. Králík, M. La Mantia, A. Srnka and L Skrbek, *Heat transfer in cryogenic helium gas by turbulent Rayleigh-Bénard convection in a cylindrical cell of aspect ratio 1*, New J. Phys. 16, 053042 (2014).

[31] V. Musilová, T. Králík, M. La Mantia, M. Macek, P. Urban and L. Skrbek, *Reynolds number scaling in cryogenic turbulent Rayleigh-Bénard convection in a cylindrical aspect ratio one cell*, J. Fluid Mech. 832, 721 (2017).

Relevant publications

Some papers of mine introduced above [7,9-11,13-15,23-25,27,29] are presented below in order of appearance, for the sake of clarity. The brief (up to two pages) introduction to each article has the aim of showing its relevance within the research activity outlined above, that is, I have chosen the papers that are more relevant to highlight my contribution to our current understanding of particle dynamics in quantum turbulence and to support my application to become associate professor.

[23] D. Duda, M. La Mantia and L Skrbek, *Streaming flow due to a quartz tuning fork oscillating in normal and superfluid ^{4}He*, Phys. Rev. B (2017) 33

[24] P. Švančara and M. La Mantia, *Flows of liquid ^{4}He due to oscillating grids*, J. Fluid Mech. (2017) 34

[25] M. La Mantia and P. Dabnichki, *Structural response of oscillating foil in water*, Eng. Anal. Bound. Elem. (2013) 35

[27] M. La Mantia, *Particle trajectories in thermal counterflow of superfluid helium in a wide channel of square cross section*, Phys. Fluids (2016) 36

[29] M. La Mantia, *Particle dynamics in wall-bounded thermal counterflow of superfluid helium*, Phys. Fluids (2017) 38

Copies of the papers are appended, in order of appearance, at the end of the thesis, which is 39-page long (the appendix is 117-page long).

[7] D. Duda, P. Švančara, M. La Mantia, M. Rotter and L. Skrbek, *Visualization of viscous and quantum flows of liquid ^{4}He due to an oscillating cylinder of rectangular cross section*, Phys. Rev. B 92, 064519 (2015).

The flows due to a relatively large cylinder oscillating in liquid ^{4}He have been studied by visualizing the motion of small particles suspended in the fluid and large-scale vortical structures, shed at the cylinder sharp edges, have been observed, both in viscous He I and superfluid He II. In order to characterize, from the computed particle trajectories, the strength of these vortices, a parameter loosely related to the flow vorticity has been introduced. Corresponding numerical values have been found to be significantly smaller in He II, comparted to those calculated in He I, at length scales smaller than the dissipative ones (the mean distance ℓ between quantized vortices in He II and the Kolmogorov length scale in He I), while, at larger scales, this quantitative difference was less noticeable.

The outcome has reinforced the notion of the small-scale quantum nature of He II flows, as discussed in Ref. [9], and, additionally, has suggested that such small-scale behaviour does not depend appreciably on the flow generation mechanism, as it was later confirmed by a direct comparison with results obtained in thermal counterflow [13].

Note that the dissipative scale estimation presented in the article relies on a number of assumptions (such as the chosen value of effective kinematic viscosity of He II) that have been mainly justified on the basis of their consistency with the obtained experimental data. It follows therefore that, although in the range of investigated parameters the made assumptions appear to hold, their general validity has yet to be firmly assessed, including the relation, if any, between the flow quantum length scale and the Kolmogorov dissipative scale, as I have recently pointed out in Ref. [29].

Additionally, it is useful to highlight here that the mean distance between quantized vortices has been called dissipative length scale because of its apparent analogy with the Kolmogorov scale, below which the fluid motion is dissipated into heat by the action of the fluid viscosity. Quantum flows of He II may instead exist all the way down to the size ξ of the quantized vortex core, which is usually much smaller than ℓ, and their dissipation is expected to occur at scales of the order of ξ via sound emission, although its mechanisms are yet to be fully understood [1-3].

In other words, the mean distance between quantized vortices cannot be strictly regarded as a dissipative length scale but, on the basis of our current understanding of the underlying physics, it indicates the change between classical-like and quantum behaviours and, in the latter sense, it can be viewed as analogue to the Kolmogorov dissipative scale, above which, in the so-called inertial range, turbulent flows of viscous fluids are observed to have similar features, regardless of their large-scale generation (and small-scale dissipation) mechanisms.

[9] M. La Mantia and L. Skrbek, *Quantum, or classical turbulence?* Europhys. Lett. 105, 46002 (2014).

The work represents, to date, my most relevant contribution to our understanding of quantum turbulence. It clearly shows that the power-law shape observed in thermal counterflow for the particle velocity distributions [26] solely occurs at scales smaller than the mean distance ℓ between quantized vortices. Additionally, it has been found that these distributions display a nearly Gaussian form at scales larger than ℓ, similarly to what is reported to occur in turbulent flows of viscous fluids, see, e.g. [12].

By removing particle positions from the obtained trajectories it has been possible to achieve the outcome, that is, to access increasingly larger flow scales and to show the gradual disappearance of the particle velocity distribution power-law tails (that results in the decrease of the distribution flatness). The experimentally probed scales, estimated from the mean distance travelled by the particles between subsequent positions, have been specifically found to straddle two orders of magnitude across the flow quantum scale ℓ, which, in the case of bulk thermal counterflow, is known with sufficient accuracy from second-sound measurements and numerical simulations, see, for example, Ref. [6]. In other words, the quantum scale of the studied flow has been found to be approximately ten times larger than the smallest flow scale that can be accessed by the particles, i.e. their mean size, equal to few micrometres.

The obtained results also suggest that, if the mean distance between quantized vortices is unknown, it can be estimated from the velocity distribution flatness because the latter is equal to three for the Gaussian distribution. Indeed, the minimum scale at which the flatness reaches the Gaussian value can be identified as the flow quantum scale and I have recently applied this technique to estimate ℓ in wall-bounded thermal counterflow [29].

The paper is 6-page long.

[10] M. La Mantia, T. V. Chagovets, M. Rotter and L. Skrbek, *Testing the performance of a cryogenic visualization system on thermal counterflow by using hydrogen and deuterium solid tracers*, Rev. Sci. Instrum. 83, 055109 (2012).

As mentioned above, I have given a significant contribution to the design and implementation of the Prague cryogenic visualization setup, which has been established by Professor Ladislav Skrbek and is described in this article. The setup has been successfully employed in the last few years, as it is apparent from my publication list, and I am currently in charge of it.

The paper describes the setup main components, including its purpose-made optical cryostat and particle seeding system, and discusses the first results that have been obtained with it, in steady-state thermal counterflow.

The way employed to estimate the size of the flow-probing particles, from their settling velocities, in the absence of other flow sources, is addressed in detail. It is also mentioned that the size and shape of the generated particles may vary, depending on the seeding procedure and particle density, and that therefore the latter can have an appreciable influence on the quality of the performed measurements. The seeding system parameters leading to the generation of micrometre-sized particles have been specifically chosen after several trails. However, a systematic study of the seeding system performance has yet to be performed and it is currently being carried out, under my supervision, by Patrik Švančara, within a research project founded by the Charles University Grant Agency.

Two types of particles, characterized by different densities, have been used during the reported tests. One type is made of solid hydrogen, which is lighter than liquid ^{4}He, while the other is of solid deuterium, heavier than the fluid. It has been specifically found that the aggregation process of solid hydrogen is different from that observed for solid deuterium, as a function of time (solid hydrogen particles tend to aggregate in filaments, which may resemble quantized vortices, while deuterium ones form clusters of approximately spherical shape). The reasons of this behaviour are yet to be thoroughly investigated, mainly because particles larger than few micrometres are, in general, not useful for typical cryogenic flow visualization experiments, usually performed before particles become too big, compared to relevant flow scales.

The mean velocity of micrometre-sized particles in the normal fluid flow direction has been found to be consistent with that expected in thermal counterflow, for the normal fluid, at low enough values of applied heat flux (it is indeed known that, as discussed, for example, in Ref. [14], particles tend to be less likely to be trapped onto quantized vortices at large velocities). Similarly, the obtained particle velocity distributions appears to display power-law tails, although, due to the relatively small size of the data sets collected at the time, the paper scientific results can only be regarded as a qualitative ones, that is, the article main aim was to demonstrate that the Prague cryogenic visualization setup works.

The paper is 8-page long.

[11] W. Guo, M. La Mantia, D. P. Lathrop and S. W. Van Sciver, *Visualization of two-fluid flows of superfluid helium-4*, Proc. Natl. Acad. Sci. USA 111, 4653 (2014).

The review belongs to a special issue dedicated to quantum turbulence. It has been written by the researchers that, at the time, devoted more effort to the experimental investigation by visualization of flows of liquid ^{4}He. It is worth mentioning that, to date, two other laboratories have joined this challenging research field. One is located in Japan, at Nagoya University, and is led by Professor Yoshiyuki Tsuji, while the other has been recently established by Dr. Mathieu Gibert in Grenoble (France), at the Institute Néel.

The article introduces relevant experimental techniques, including the one based on the use of metastable helium molecules, developed by Dr. Wei Guo, currently at Florida State University (United States of America), and his collaborators, and the particle tracking velocimetry technique that I have been using in Prague for several years.

The review does not only discuss already published works but also reports new results. I have specifically presented the first evidence that a departure from the classical-like form is observed, in steady-state thermal counterflow and at small enough length scales, also for the particle velocity increment distributions, which, as mentioned above, can be said to be proportional to particle accelerations [14].

Future lines of scientific enquiry have also been discussed in the paper and special emphasis has been given to the still open issue regarding the large-scale quantum features of thermal counterflow, which have yet to be found, although recent results indicate that they might indeed exist [21,22].

The paper is 6-page long.

[13] M. La Mantia, P. Švančara, D. Duda and L. Skrbek, *Small-scale universality of particle dynamics in quantum turbulence*, Phys. Rev. B 94, 184512 (2016).

Three different quantum flows have been experimentally investigated by using the particle tracking velocimetry technique, at length scales straddling two orders of magnitude across the mean distance between quantized vortices: thermal counterflow in the bulk, as far away as possible from fluid boundaries [9,15], thermal counterflow in the proximity of a wall, approximately ten times closer to the fluid boundary than in the previous case [29], and flow due an oscillating cylinder, which is a mechanically driven flow [7].

These flows are known to have different features at large enough length scales, as, for example, relatively large vortical structures, similar to those observed in coflow [7,23], have yet to be directly seen in thermal counterflow. The velocity statistical distributions of the flow-probing particles have instead been found to display the same power-law shape at scales smaller than the quantum length scale of the flow, regardless of the large-scale flow generation mechanism. The outcome constitutes what in the article is called the small-scale universality of particle dynamics in quantum turbulence, which can be said to be analogous to that observed in turbulent flows of viscous fluids, following Kolmogorov pioneering work.

In summary, the obtained experimental results support the view that particle dynamics in quantum flows is solely influence by the interactions between particles and quantized vortices, at small enough scales. A rather simple model of particle-vortex interactions, based on the assumption that particles trapped onto vortices can probe the occurrence of vortex reconnections, is specifically presented in the article and, when applied to the studied flows, its predictions have been found to agree quite well with corresponding experimental values.

The paper is 9-page long. © American Physical Society

[14] M. La Mantia, D. Duda, M. Rotter and L. Skrbek, *Lagrangian accelerations of particles in superfluid turbulence*, J. Fluid Mech. 717, R9 (2013).

The article presents the first scientific results obtained by using the Prague cryogenic visualization setup. The normalized statistical distributions of the particle accelerations have been found to display classical-like shapes, in steady-state thermal counterflow, at length scales of the order of the mean distance between quantized vortices.

The outcome, when taken together with the results discussed in Ref. [9], clearly shows that, in the range of experimental parameters investigated to date, the large-scale behaviour of thermal counterflow is similar to that observed in turbulent flows of viscous fluids, that is, other flow features should be probed in order to assess the quantum nature of large-scale counterflow, following, for example, Ref. [21].

A simple model of particle dynamics is also discussed in the paper in order to account for the observed increase of the particle acceleration amplitude as the fluid temperature T decreases (or the applied heat flux q increases). The model results have been found to qualitatively agree with the experimental findings, supporting therefore the view that, as q increases (or T decreases), particles should be less likely to be trapped onto vortices and, consequently, less likely to move at a relatively constant velocity.

This follows from the fact that, according to the model, the ratio between the viscous drag force acting on a particle and the pressure gradient force attracting this particle to a quantized vortex also increases with decreasing T and increasing q. In other words, at large enough heat fluxes (or low enough temperatures) particle dynamics is still affected by the presence of quantized vortices, as it is testified by the acceleration amplitude increase, but trapping events becomes less likely to occur.

The paper is 11-page long. © Cambridge University Press

[15] M. La Mantia and L. Skrbek, *Quantum turbulence visualized by particle dynamics*, Phys. Rev. B 90, 014519 (2014).

The main result of the article consists in showing that the normalized distributions of particle accelerations in thermal counterflow appear to display power-law tails at scales smaller than the mean distance ℓ between quantized vortices. The outcome has been explained by taking into account particle-vortex interactions, following Ref. [9], that is, it also supports the small-scale quantum nature of thermal counterflow.

Additionally, it has been observed that, at larger scales, which, however, are still smaller than ℓ, the acceleration distribution form becomes classical-like. The reason why this shape change occurs at scales smaller than the mean distance between the vortices is yet to be completely understood. It could be due to the relatively simple method used to calculate accelerations from velocities, as pointed out in Ref. [29], or to the fact that the classical and quantum shapes of the acceleration distributions are more similar to each other than in the case of the particle velocity distribution forms, as noted in Ref. [14]. Nevertheless, the point here is that the acceleration distributions have been found to display a quantum shape at small enough length scales.

As the probed length scale is increased above the mean distance between the vortices, the acceleration distribution forms gradually become closer to the shape of the Gaussian distribution, as it is reported to occur in classical turbulent flows, where the Gaussian form is obtained at scales of the order of the flow integral length scale, which is comparable to the experimental volume size, see, for example, Ref. [12]. In the present case, the Gaussian shape has been, however, not obtained likely because the largest probed length scale results appreciably smaller than the flow integral length scale. The latter outcome might, nevertheless, be an indirect indication of the existence of macroscopic vortices in thermal counterflow, at scales larger than ℓ, due to the possible occurrence of a Kolmogorov-like inertial range of scales between ℓ and the flow integral scale.

Furthermore, the just mentioned results have been obtained by using two types of particles, characterized by different densities. One type is made of solid hydrogen, which is lighter than liquid ^{4}He, while the other is of solid deuterium, heavier than the fluid. It follows therefore that, due to the added mass effect, hydrogen particles should accelerate, on average, more than deuterium ones and this is indeed what has been found experimentally.

A dedicated model of particle dynamics has been specifically developed to account for the added mass effect in quantum flows and its predictions have been found to be in good qualitative agreement with the experimental findings. Note in passing that particle density has a less significant effect on the statistical distributions mentioned above because the latter are normalized.

Finally, it is worth mentioning that, as discussed, for example, in Ref. [13], particles are attracted to vortex cores regardless of their density, also in the absence of viscosity, but their dynamical response to this pressure gradient force depends on the particle inertia and on the other forces acting on the particle, such as the Stokes drag. This has been neatly proven by my recent works [13-15], which, at least in my opinion, have given a significant contribution to our current understanding of particle dynamics in quantum flows, by taking into account previously overlooked effects, such as the added mass influence on the observed particle motions.

The paper is 7-page long.

[23] D. Duda, M. La Mantia and L Skrbek, *Streaming flow due to a quartz tuning fork oscillating in normal and superfluid ^{4}He*, Phys. Rev. B 96, 024519 (2017).

Quartz tuning forks have been used to study quantum flows for decades, see, e.g. Ref. [8] and references therein. However, the flow features in the proximity of these small and fast mechanical oscillators, which are mostly employed as quantum turbulence probes, are yet to be entirely understood, mainly because they are characterized by a rather complex geometry. The article discusses the first visualization experiments of the flows generated by a (relatively large and slow) quartz tuning fork, performed by using the particle tracking velocimetry technique.

The main outcome is that the observed flows appear to be classical-like, at the probed length scales, which have been found to be larger than the mean distance between quantized vortices (smaller scales could not be accessed experimentally mainly because the fork oscillation frequency was much larger than the camera frame rate). In other words, from a general point of view, the results presented in the paper can be viewed as a further experimental confirmation of the classical-like nature of large-scale coflow.

The observed flow type belongs to the wide class of streaming flows, which are due to high-frequency oscillations in a fluid, that is, the time average of a fluctuating flow can often result in a non-zero mean. The flow features observed in He II have been found not only to be very similar to those seen in He I but also to those due to a cylinder of square cross section oscillating in water.

Additionally, the result, which has been specifically obtained by computing the particle Lagrangian velocities in the fork proximity and by plotting corresponding pseudovorticity maps, following Ref. [7], clearly demonstrates that the flows due to a quartz tuning fork influence the surrounding fluid up to a distance of the order of the oscillator size, giving therefore a useful piece of information on the properties of this widely used quantum turbulence probe.

The paper is 8-page long. © American Physical Society

[24] P. Švančara and M. La Mantia, *Flows of liquid ^{4}He due to oscillating grids*, J. Fluid Mech. 832, 578 (2017).

The flows of He II occurring between two grids oscillating in phase have been investigated by using the particle tracking velocimetry technique and it has been found that the shapes of the particle velocity and velocity increment distributions are classical-like at the probed scales, appreciably larger than the flow quantum scale.

From a general point of view, these results are quite similar to those reported in Ref. [23], that is, they can be viewed as a further experimental confirmation of the classical-like nature of large-scale coflow. However, they have also, at least in my opinion, more interesting implications, related to the current quest for large-scale quantum features of thermal counterflow.

The flows occurring between the oscillating grids have been studied in the region where the millimetre-sized vortices shed by the oscillators should have lost their coherence. It was found that, in this region, the purpose-made coflow is characterized by the absence of large-scale vortical structures and therefore is more similar to thermal counterflow than to the flows observed in the proximity of an oscillation cylinder [7] or close to a tuning fork [23]. It consequently follows that the apparent absence of coherent vortical structures is most likely not responsible for the large-scale quantum features of thermal counterflow suggested recently in Refs. [21,22].

Additionally, the claim that the studied coflow has been investigated at scales larger than the mean distance ℓ between quantized vortices is mostly based on the distribution forms, which are found to be classical-like, but it is also substantiated by a first-order estimate of the quantum scale, which has been found to be of the order of the mean particle size.

The paper is 22-page long.

[25] M. La Mantia and P. Dabnichki, *Structural response of oscillating foil in water*, Eng. Anal. Bound. Elem. 37, 957 (2013).

My Ph.D. research project was devoted to experimental and numerical investigations of the unsteady forces generated by flapping wings, such as penguin flippers. The computational study reported in the following article, which has been written when I was already working in Prague, is closely related to these investigations and specifically addresses the added mass effect, which has been found to give a significant contribution to the forces acting on bodies accelerating in dense fluids. The effect, which is purely inertial and does not depend on the fluid viscosity, is also very relevant to the understanding of particle dynamics in quantum flows, as outlined above and discussed in Refs. [13,15].

The main outcome of the article is that light wings are subjected to forces larger than those acting on heavy wings, when other flapping flight conditions are fixed, because the latter wings are characterized by smaller accelerations per unit mass compared to those of the former ones. It follows that rigid, heavy wings appear to be more suitable for the propulsion mode corresponding to steady cruise, as the applied bending stresses are smaller than those obtained for lighter, more flexible wings. The added mass effect could instead be exploited when required, by using lighter propulsors, which can generate larger forces.

Anyway, leaving aside the specific outcome discussed in the paper, I have decided to include this work in the present dissertation thesis because it clearly shows the relation between my Ph.D. project and my current research activity, focusing on the dynamics of particles in quantum flows.

The paper is 10-page long. © Elsevier Ltd.

[27] M. La Mantia, *Particle trajectories in thermal counterflow of superfluid helium in a wide channel of square cross section*, Phys. Fluids 28, 024102 (2016).

The transition to the turbulent state in thermal counterflow has been investigated by using the particle tracking velocimetry technique. In order to study particle dynamics at low heat fluxes a more sensitive camera has been used, compared to that employed in previous experiments, such as those discussed in Ref. [9]. However, the smaller sizes of the collected data sets and the slower camera frame rate did not allow performing statistical analyses similar to those previously carried out.

The particle trajectories appearance has been specifically studied as a function of applied heat flux q and it has been found that particle tracks have the tendency to become less straight as q increases. The outcome has been explained following the argument already discussed, for example, in Ref. [14], that is, theoretical predictions and experimental findings are consistent with the view that particles are more likely to be trapped onto vortices at small heat fluxes, due to the relatively more significant influence on particle dynamics of the pressure gradient force (attracting particles to vortices), compared to other forces, such as the Stokes drag.

The visual inspection of particle trajectories has also been instrumental in identifying the value of counterflow velocity at which the transition to the turbulent state most likely occurs in the range of investigated parameters, that is, for the wide counterflow channel employed in these experiments. The turbulence onset velocity has been specifically found to be smaller than those reported in the literature for smaller channels and, as mentioned above, the outcome has been explained on the basis of our current understanding of the underlying physics.

Additionally, consistently with my previous works and in agreement with the obtained experimental results, it has been argued that particle motions are not solely affected by the normal fluid flow, as it has been often stated in the literature, but also by the accelerating superflow in the proximity of quantized vortices. It has been therefore suggested that the thermal counterflow velocity, which takes into account the steady flows of both components, should be used to characterize counterflow particle dynamics, instead of the previously employed normal fluid velocity that, in general, cannot account for all the contributions to particle motions.

In the article I have also outlined a number of related open problems that I am currently investigating within a research project founded by the Czech Science Foundation, including the influence of solid boundaries on quantum flows, which is yet to be thoroughly analysed, and the effect of the distance from the heat source on the development of thermal counterflow, which is still largely unknown.

The paper is 12-page long.

[29] M. La Mantia, *Particle dynamics in wall-bounded thermal counterflow of superfluid helium*, Phys. Fluids 29, 065102 (2017).

The work can be regarded as the first dedicated experimental study on the effect of solid boundaries on particle dynamics in thermal counterflow. Bulk results, obtained as far away as possible from solid boundaries [9,15], have been specifically compared to those obtained in the proximity of a wall, approximately ten times closer to the boundary than in the previous case, at length scales straddling two orders of magnitude across the quantum length scale of the flow.

The normalized statistical distributions of the particle velocities (and velocity increments) have been found to be wider (that is, to display more apparent tails) in the bulk, compared to those obtained in the wall proximity, at approximately the same value of R, defined as the ratio between the experimental length scale (probed by the particles) and the mean distance ℓ between quantized vortices (estimated on the basis of bulk numerical simulations), for $R < 1$.

Additionally, the wall-bounded velocity distribution flatness has been found to reach the Gaussian value, indicating classical-like behaviour, at a length scale ratio R approximately 1.5 times smaller than that computed in the bulk for hydrogen particles. The latter case has been taken as a term of comparison because the velocity distribution shape change, from quantum to classical-like, has been observed at $R \approx 1$, by using the quantum length scale numerically estimated in the bulk [9,15].

After noting that the length scales probed by the particles is approximately constant, I have argued that in the wall proximity there should be more quantized vortices than in the bulk, consistently with a number of numerical simulations, because the velocity distribution shape change should occur at $R \approx 1$, that is, the used bulk values of ℓ seem not to be the correct ones close to the boundary and, therefore, the wall quantum length scale should be approximately 1.5 times smaller than the bulk one, in the range of investigated parameters.

The outcome has been physically explained by assuming that the normal component flows faster in the bulk than in the boundary proximity, while the flow of the superfluid component does not depend on its distance from the wall. Additionally, the mutual friction force, arising from the scattering of thermal excitations – the normal fluid component – from quantized vortices, has been taken into account. This force is proportional to the magnitude of the local, but still large-scale, difference between the velocities of the two components and, due to its action, there should be more quantized vortices in regions where this local velocity difference magnitude is smaller, i.e. close to the boundary. In the bulk, the larger mutual friction force is indeed expected to cause the local increase of the total length of quantized vortices, which then expand and move to the walls.

I have also noted that the bulk velocity distribution flatness obtained with deuterium particles reaches the Gaussian value at a length scale ratio slightly larger than one. Consistently with my previous work [15], I have explained the outcome considering that deuterium particles are expected to accelerate less than hydrogen ones, that is, the former should actually experience a vortex tangle less dense than that probed by the latter.

In the article a number of open issues are also outlined, including the estimation of the quantum boundary layer thickness, as a function of applied heat flux, which will require further experiments, and the relation, if any, between the quantum length scale and the Kolmogorov dissipative scale, which is yet to be firmly established, as already noted in Ref. [7].

The paper is 9-page long.