New experimental set-up to analyse cryogenic flows by visualisation

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Abstract. The first laboratory in Europe for visualisation of liquid helium flows is currently being established at the Charles University in Prague. The use of such a valuable experimental approach for the analysis of cryogenic flows of normal and superfluid \( ^4 \)He is introduced and its specific features discussed. More importantly, it is shown that the newly implemented flow visualisation equipment is potentially capable of obtaining novel results, i.e. further understanding of the involved physics.

1. Introduction
Flow visualisation techniques have been recently applied at very low temperatures for the investigation of various liquid helium flows [1, 2]. Quantitative techniques, such as PIV (Particle Image Velocimetry) and PTV (Particle Tracking Velocimetry), have been indeed proven very fruitful in many scientific and industrial areas of research during the last decades [3]. However, such a promising experimental approach is still in its infancy in the analysis of cryogenic flows and the ways to optimise it are yet to be fully investigated due to a number of technical and fundamental difficulties, e.g. the optical access to the helium bath and choice of suitable tracer particles.

Gaseous and liquid \(^4\)He are generally used as working fluids in cryogenic fluid mechanics. At the pressure of 1 bar \(^4\)He is gaseous, if the temperature is larger than 4.2 K. At lower temperatures it becomes liquid and, if the temperature is larger than 2.17 K, liquid \(^4\)He is called normal helium or He I. This fluid is characterised by extremely low values of the kinematic viscosity (of the order of \(10^{-4}\) cm\(^2\)/s), compared to those of air (of the order of \(10^{-1}\) cm\(^2\)/s) and water (of the order of \(10^{-2}\) cm\(^2\)/s) [4]. If the temperature decreases further, liquid \(^4\)He is called He II. Its viscosity can be considered null at 0 K, i.e. the fluid is assumed inviscid in the zero-temperature limit: this is why He II is also called superfluid.

The unique properties of He II are described by the two-fluid model, e.g. see [5, 6]. It is assumed that He II is made of two fluids, normal and superfluid helium. The former is viscous and carries entropy while the latter is inviscid and does not carry entropy. The total density \(\rho\) of He II is defined as the sum of the densities of its normal and superfluid components, \(\rho_n\) and \(\rho_s\), respectively, and depends weakly on temperature. \(\rho_n\) and \(\rho_s\) have instead a much stronger dependence on temperature. The ratio between \(\rho_n\) and \(\rho\) increases indeed steeply as the temperature decreases and, for example, is equal to 0.986 at 1.1 K [7]. In other words, He II can be considered entirely superfluid at temperatures below 1 K. To highlight the uniqueness of He II an example can be made on the basis of the just sketched two-fluid model. If a volume of He II is heated, the normal component flows away from the heater while
the superfluid component moves towards the heater in order to have a null flow rate, i.e. to conserve the mass of He II. This phenomenon is called thermal counterflow and has not any equivalent in classical fluid mechanics.

Besides, the superfluid component of He II has been described as a quantum fluid, that is, by a macroscopic wave function, see again [5, 6] for further details. This leads to the result that superfluid flow is irrotational, i.e. $\omega = \text{curl } v_s = 0$, where $\omega$ is the flow vorticity and the superfluid velocity $v_s$ is proportional to the gradient of the wave function phase. It follows that for a simply connected fluid region the circulation of the superfluid velocity is null. If the region is instead multiply connected, the circulation is not null and equal to an integer multiple of the quantum of circulation $k$, which is the ratio of the Planck constant and $^4$He atomic mass, i.e. $k = 9.98 \times 10^{-4} \text{ cm}^2/\text{s}$ [7]. This result can be seen as a quantum restriction to the superfluid motion. In other words, just quantised vortices – line singularities where the superfluid density is null – can exist in superfluid helium. These vortices usually arrange themselves in a tangle and such a tangle of vortices constitutes what is generally called quantum turbulence.

The description of superfluid helium (He II) as a quantum fluid is specifically relevant for the implementation of flow visualisation techniques at low temperatures. For example, the complex interactions between tracer particles, quantised vortices and macroscopic eddies in cryogenic flows are far from being completely understood and novel experiments are required to verify the current theoretical understanding of these coupled phenomena [8, 9]. Moreover, the interesting and puzzling results recently obtained in overseas laboratories [1, 2] are posing more questions than giving answers, e.g. the mechanisms of particles’ trapping into the quantised vortices’ cores and the vortical structures observed around cylinders in thermal counterflow deserve further attention and study. These outcomes show consequently the need of more detailed experimental analyses by flow visualisation, which is being proven as a very valuable technique to study cryogenic flows.

2. Experimental apparatus

In order to fulfil such a need of novel experimental data we are currently establishing the first laboratory in Europe for flow visualisation at low temperatures. Experimental investigation of selected cryogenic flows over wide ranges of governing dynamical parameters, spanning from laminar to developed turbulent regime, using all forms of cryogenic $^4$He as working fluids are being planned. All these classical and quantum flows will be mainly probed by using quantitative flow visualisation techniques, i.e. PIV and PTV. The cryogenic flows will be obtained by various means. Flows around bodies oscillating in stationary fluid will be studied, due to their relative simplicity of implementation at low temperatures. A bellows system, connected to a precise linear motor [10], will be used to generate flows of various velocities around bluff bodies and heaters will be employed to obtain thermal counterflow, the aim of these experiments being also the comparisons of dynamically similar flows in normal and superfluid $^4$He.

The flow visualisation equipment, which already is available in our laboratory, consists of the following parts. A custom-made low-loss cryostat equipped with five sets of 25 mm diameter windows that minimise the heat input into the helium bath, enabling horizontal as well as vertical optical access, was designed and manufactured, see Figure 1. A seeding system with a fast computer-controlled valve to supply the helium bath with the desired amount of hydrogen and deuterium micron-sized solid tracers was built and is being tested. These low-temperature related parts are to be used with an off-the-shelf 5 W continuous wave solid state laser, a very fast digital camera (up to 6273 fps at full resolution, i.e. 1 MP) and relevant hardware and software to implement the PIV and PTV techniques for cryogenic flows, purchased from Dantec Dynamics.
Our facility is being designed to perform novel experiments, that is, not to be just a copy of existing systems but to be potentially capable of obtaining new results. For example, the much faster camera will most likely allow a more detailed analysis of cryogenic flows’ dynamics, compared to [1, 2]. As already mentioned, the complex interactions between tracer particles, quantised vortices and macroscopic eddies could be studied experimentally in unprecedented detail and, for example, the theoretical models that predict the conditions for particles’ trapping into the quantised vortices’ cores verified [8, 9]. This may also have an impact on the study of turbulent multiphase flows, which is a very active field of research in classical fluid mechanics [11, 12]. Besides, the PTV technique, especially chosen to study quantum flows, has so far been rarely used for such applications and the use of PIV also appears controversial for these peculiar flows. In other words, particularly for turbulent flows, it is not completely clear if and when the PIV computed velocities are those of the normal component of He II or those of the superfluid portion of it or a mixture of the two. This is particularly evident in the case of thermal counterflow that, as mentioned above, is characterised by the fact that the normal and superfluid component of He II are flowing in opposite directions. A plausible option would then be to study the same flow by using both techniques and consequently assess which technique is the most suitable at low temperatures. However, a number of technical difficulties have to be tackled. For example, even though the set-up was carefully designed, the seeding system needs to be tuned in order to obtain the most suitable tracers. The PIV and PTV equipment is also currently being tested on various experiments in water, such as well-known flows past bluff bodies and around oscillating objects, see next Section. The first results at low temperatures are expected in the coming months. More precisely, thermal counterflow experiments are being planned, similar to those discussed in [2], as well as experiments on cryogenic flows around oscillating objects, such as cylinders and spheres, which to our best knowledge have not been yet analysed by visualisation.
3. Visualisation of water flows

Figure 2 shows the mean velocity field for a slightly bent water jet, directed downwards, as calculated by the Dynamic Studio software (200 images were taken at the maximum frame rate and a 2D PIV analysis with micron-sized buoyant particles was performed). It can be noted that the camera field of view is quite small, ca. 4 cm². Besides, the Reynolds number is equal to ca. 18,000, i.e. the flow is turbulent, as the jet diameter \( \approx 12 \) mm and its mean velocity \( \approx 1.5 \) m/s. In other words, such a flow field could not have been probed with a much slower camera. In Figure 3 the corresponding mean vorticity field is plotted and the clock-wise region of vorticity can be explained by considering that the jet was slightly bent to the left of the field of view, see Figure 2. This might appear clearer if it is assumed that the jet is made by two smaller jets, close to each other. The first one, on the right of the field of view, is directed vertically downwards while the second one, less energetic than the first one and similarly directed downwards, is also bent to the left of the field of view. The interaction between these two close jets can then justify the presence of two local minima with negative vorticity.

![Figure 2: Velocity field for a slightly bent water jet (Re \( \approx 18,000 \)).](image1)

![Figure 3: Vorticity field for a slightly bent water jet (Re \( \approx 18,000 \)).](image2)
Figure 4 displays the mean vorticity field of the flow past a circular cylinder, as calculated by the Dynamic Studio software (100 images were taken at the maximum frame rate). The cylinder, placed at the left of the field of view, is in a slightly bent water jet, directed horizontally from the left to the right of the field of view. The Reynolds number is in this case equal to ca. 1,000, as the cylinder diameter = 5 mm and jet mean velocity $\approx 0.2$ m/s, i.e. the flow is still turbulent.

Figure 4: Vorticity field for the flow past a cylinder in a slightly bent water jet (Re $\approx 1,000$).

Figure 5: Particles’ tracks for the flow past a cylinder in a slightly bent water jet (Re $\approx 1,000$). The legend indicates the minimum number of points for the tracks shown in that colour.

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In Figure 5 relevant particles tracks are plotted, as computed by processing the results obtained by the Dynamic Studio software. The colour code for the tracks indicates the minimum number of points for the tracks shown in that colour. For example, there are ca. 1,400 tracks with at least 25 points and ca. 300 with at least 75 points. It can be seen that the recirculation zone behind the cylinder is well captured by both visualisation techniques.

Figure 6 shows the instantaneous vorticity field generated by a cylinder oscillating harmonically in water, as calculated by the Dynamic Studio software (images taken at 1000 fps). The cylinder was oscillating vertically (the lowest position of the harmonic cycle was just above the bottom of the field of view) and the vorticity field was computed just after the cylinder left the field of view moving upwards. The Reynolds number $Re \approx 100$, as the cylinder diameter $= 5$ mm and its maximum velocity $\approx 0.02$ m/s. The oscillation frequency was set to ca. 0.5 Hz and its amplitude to 0.02 m. This corresponds to a viscous penetration depth $\delta = (2\nu/\omega)^{0.5} \approx 0.8$ mm, where $\nu$ is the water kinematic viscosity, $10^{-6}$ m$^2$/s, and $\omega$ the cylinder oscillation frequency in rad/s. Vortices rotating in opposite direction were consecutively shed by the cylinder, i.e. a Von Karman vortex street is clearly visible. Besides, the weak clock-wise vortex at the bottom left of the figure was shed at the end of the previous stroke, when the cylinder reached its lowest position, and pushed away while the cylinder moved upwards.

![Vorticity Field](image)

**Figure 6**: Instantaneous vorticity field for the flow past an oscillating cylinder ($Re \approx 100$).

In Figure 7 the vorticity field at the same point of the harmonic cycle, i.e. the cylinder just left the field of view moving upwards, is shown for $Re \approx 20$, as the cylinder maximum velocity $\approx 0.004$ m/s and its oscillation frequency $\approx 0.1$ Hz (the cylinder diameter and oscillation amplitude did not change), the viscous penetration depth being in this case equal to ca. 1.8 mm. Images were taken at 100 fps and processed by the Dynamic Studio software, as above. Single vortices were not shed and a region of vorticity can be seen behind the cylinder, i.e. the boundary layer. It has also to be noted that the vorticity absolute value is about one order of magnitude smaller than that shown in Figure 6.
Further investigations, at different oscillation velocities and by using different cylinder section geometries, e.g. square instead of circular, are being currently performed and planned, their aim being also a systematic study of the characteristics of the wake shed by oscillating bodies [13-15].

Figure 7: Instantaneous vorticity field for the flow past an oscillating cylinder (Re ≈ 20).

However, the results presented in this Section are well known, at least qualitatively. The main purpose of these experiments in water is to explore the capabilities of the visualisation system that is soon going to be used to analyse various cryogenic flows, as detailed in the previous Section. More precisely, it was briefly shown that the chosen visualisation apparatus appears to be well suited for the task of analysing cryogenic flows, at least in the range of investigated parameters, as the latter are similar to those expected at low temperatures [16].

4. Conclusion
In summary, the use of flow visualisation at low temperature seems to be a very promising experimental tool that is certainly capable of improving our general knowledge of classical and quantum flows. Flow instabilities, the fine details of the transition to turbulence and the properties of developed and decaying classical and quantum turbulent flows could be studied systematically over wide ranges of dynamical parameters by using cryogenic helium, a remarkable working fluid with well-known, unique and easily tuneable properties.

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