Observation of the spiral flow and vortex induced by a suction pump in superfluid $^4$He

H Yano’, K Ohyama, K Obara and O Ishikawa
Graduate School of Science, Osaka City University, Osaka 558-8585, Japan
E-mail: hideo@sci.osaka-cu.ac.jp

Abstract. A suction flow generates a whirlpool, namely a bathtub vortex, in a classical fluid; in contrast, rotating containers, which are usually used for studies of superfluid helium, can produce only simple solid rotation. In the present work, the superfluid flow and concentrated quantized vortices induced by a cryogenic motor immersed in superfluid $^4$He were investigated. Using a motor with six blades in a cylinder caused the free surface of the superfluid $^4$He to take on a parabolic shape, indicating that the motor produces a rotating superfluid flow. To drive a suction flow in superfluid helium, the motor was mounted in a cylindrical container with a small hole at the center of the top and a slit at the side, acting as a superfluid pump. This pump was successfully used to generate a spiral flow and a vortex with a funnel-shaped core in superfluid $^4$He, suggesting that the resulting suction flow transports and centralizes quantized vortices to the suction hole, increasing the vortex circulation and sucking the free surface of the superfluid down.

1. Introduction
Superfluid vortices have been investigated extensively because they have a simpler structure than classical vortices in viscous fluids [1]. Hall and Vinen have suggested that in uniformly rotated superfluid helium, the arrangement of vortex lines can be found by minimizing the free energy of the rotating system [2]. Vinen also performed an experiment to observe quantized circulation under rotation [3]. When a container containing liquid helium is rotated, a regular arrangement of aligned quantized vortices forms [4]. Even under very high-speed rotations on the order of $10^6$ revolutions per second (rps), quantized vortices remain aligned [5], indicating that a simple rotating flow cannot centralize quantized vortices in the fluid.

In a viscous fluid under rotation, the vorticity is, or virtual element vortices are, also distributed uniformly throughout the fluid. However, an additive axial flow may produce a whirlpool, namely a bathtub vortex, in a rotating fluid [6]. A flow drained through a pipe drives a concentration gradient in the fluid, transporting and centralizing each element vortex in the fluid during this process. Consequently, the vorticity increases near the drain, producing a large vortex in the fluid.

Superflow is also expected to transport and centralize quantized vortices and produce a large vortex, though such a large vortex has not yet been studied for superfluid helium. The centralization may produce a vortex bundle, or even might produce a quantized vortex with a winding number larger than one. A new state of quantized vortices enables to extend the study of the superfluidity of helium. In this study, a large vortex with a funnel-shaped core was successfully generated in superfluid helium by producing a suction superflow. This paper reports an experimental setup of a cryogenic motor and a superfluid pump and discuss the vortex and superfluid flow induced by the pump in superfluid helium.
Figure 1. Schematics of (a) the cryogenic motor and (b) the setup of the rotating flow experiment. The outer part of the cryogenic motor is a permanent magnet rotor. The rotor is connected to the stator via a sliding bearing. In the rotating flow experiment, the cryogenic motor with six attached blades is mounted in the cylinder. The rotating superfluid flow produces a centrifugal force, resulting in the formation of a parabolic meniscus (see text). 

2. Cryogenic motor
The cryogenic motor used in this study was a brushless motor with a stator coil, as shown in Fig. 1(a). An electrode brush is not acceptable for cryogenic use, because it produces friction heat and electric sparks. The stator coil is composed of a wound copper wire or a superconducting NbTi wire. A rotor composed of a permanent magnet is connected to the stator by a revolving ceramic shaft. The shaft is supported by a sleeve with no grease and spins smoothly even at low temperatures. To control the rotation of the brushless motor, a position sensor is required. A Hall device (SHARP, LT135A) that operates at low temperatures was used as a position sensor. The magnetic properties of the stator were also measured to ensure that the stator ferrite does not show magnetic hysteresis at low temperatures.

Through these adjustments, the motor was successfully rotated at low temperatures. The rotational velocity ranged from 2 to 40 rps at a temperature of 2 K for the copper coil. The rotor of the cryogenic motor spins smoothly at high velocities, though the friction between the shaft and the sleeve causes the rather stepping motion of the rotor at 2 rps. The dissipation power of the motor in saturated vapor at 2 K increases linearly with the rotational velocity at a rate of 0.25 W per 40 rps, allowing the motor to operate in superfluid helium.

3. Rotating superfluid flow driven by cryogenic motor
To produce a rotating flow in superfluid helium, the cryogenic motor was mounted in a cylinder with an inner diameter of 65 mm, as shown in Fig. 1(b). Six blades were attached to the rotor of the motor to agitate the liquid helium in the cylinder. The cylinder was mounted in a conventional glass dewar and filled with liquid helium. A thermometer was immersed in the liquid helium at the outside wall of the cylinder near the bottom to measure the temperature. By pumping helium vapor in the container, liquid helium can be cooled to a superfluid state. The temperature can reach a minimum of 1.6 K in this cryostat system, corresponding to a superfluid ratio of $\rho_s/\rho \approx 0.8$, where $\rho_s$ and $\rho$ are the densities of the superfluid helium and the liquid helium, respectively.

After the helium was cooled to a superfluid state, the rotor was rotated with the blades immersed in the superfluid helium to create a rotating flow.
Figure 2. Rotational velocity of normal liquid and superfluid helium flow. The data were taken at temperatures above 1.6 K, which corresponds to superfluid components ranged from $\rho_s/\rho = 0$ to 0.8 for the superfluid state. The solid line indicates a rotational velocity of the flow equal to the rotor velocity.

Figure 3. Dissipation power of the cryogenic motor rotating in normal liquid and superfluid helium. The dissipation powers for the two states are very similar. The solid line indicates the intrinsic dissipation of the motor measured in saturated vapor at 2 K.

in the superfluid helium, and it was found that the surface of the fluid took on a parabolic shape in the cylinder. The formation of a parabolic meniscus has been also observed in superfluid helium in a rotating container [7], indicating that the rotating blades produce a solid rotating flow even in a superfluid state. During the rotation, remnant vortices attached to the blades are expected to be stretched by boundary superflows along the surfaces of the blades, producing a macroscopic rotating flow in the cylinder. The parabolic meniscus forms because of the centrifugal force produced by the rotation, and its height $h$ from the bottom is given by

$$ h = \frac{R^2 \omega^2}{2g}, $$

where $R$ is the distance from the axis of rotation, $\omega$ is the angular velocity of the rotation, and $g$ is the acceleration due to gravity.

The parabolic meniscus was photographed to estimate the velocity of the rotating flow from Eq. (1), and the flow velocity was found to be nearly equal to the rotor velocity, as shown in Fig. 2. Moreover, although a viscous laminar drag decreases in a superfluid state, the rotation velocities for the superfluid state in the range from $\rho_s/\rho = 0$ to 0.8 were almost equal to those for the normal fluid. Interestingly, the dissipation powers of the motor for the two states were also very similar, as shown in Fig. 3. The dissipation powers were estimated from the applied currents and the induced voltages of the motor to increase in the fluid whatever its state. The rotational flow velocity appears to be influenced little by the viscosity of the normal fluid. However, the rotating flows are slightly slower than the rotor velocity for both states, suggesting that a stationary cylinder wall may decrease the flow velocity. Quantized vortices attached to the wall in the superfluid may contribute to the drag braking force observed in studies of oscillating objects, such as a tuning fork or a vibrating wire, in superfluid helium [8, 9].
Figure 4. Suction vortex experiment. (a) Schematic of the suction pump and superfluid flows (arrows). The cylinder length of the pump is 90 mm, and the hole diameter and the side slit gap are 5 mm and 2 mm, respectively. (b) Photograph of a suction vortex produced by the pump in superfluid helium at a temperature of 1.6 K. As shown in this photograph, superfluid flows from the side slit to the top hole of the cylinder may enhance vortex circulation above the hole, sucking the free surface down to the hole.

4. Superfluid flow and vortex

A solid rotating fluid with angular velocity $\omega$ produces a centrifugal force that causes a pressure difference $\Delta p$ given by

$$\Delta p = \frac{1}{8} \rho \omega^2 R^2,$$

where $\rho$ is the fluid density and $R$ is the distance from the axis of rotation. The pressure difference in a rotating superfluid may provide the feature of a superfluid pump, namely, a centrifugal pump. A cryogenic motor was mounted in a cylinder with a small hole at the center of the top and a slit along the side, as shown in Fig. 4(a). The cylinder containing the motor was immersed in superfluid helium. The rotating flow in the cylinder ejects the superfluid out through the side slit and forces the fluid in through the top hole, which acts as a drain, as a result of the pressure difference given by Eq. (2), generating the superfluid circulation loop shown in Fig 4(a).

Interestingly, a tornado-like vortex emerged in the superfluid helium above the top hole of the cylinder during the rotation of the motor, as shown in Fig. 4(b). The fluid ejected from the side slit has an angular momentum as a result of the vorticity generated by the rotating flow in the cylinder, causing it to flow to the upper area above the cylinder. Because the flow transports the vorticity of the fluid, the flow drained into the hole appears to centralize the vorticity, enhancing the vortex circulation [6]. The enhanced circulation just above the drain hole produces a large vortex that sucks the free surface of the helium fluid. Therefore, the tornado-like vortex is visualized as a pipe, as shown in Fig. 4(b). Thus, a large vortex with a funnel-shaped core was successfully generated in superfluid helium. The motion of the surface of the vortex core reveals the existence of a spiral flow around the core. The vortex core extends to the drain hole with a diameter of approximately half that of the hole. The descent height $h - h_0$ of the core surface of a suction vortex is given at a distance $R$ from the axis by

$$h - h_0 \approx -\frac{\Gamma^2}{8\pi^2 \rho R^2},$$

where $h_0$ and $\Gamma$ are the normal level of the fluid and the circulation, respectively. The circulation of the vortex was estimated from Eq. (3) to be on the order of $10^3 \text{ mm}^2/\text{s}$ or $10^4 \kappa$, where $\kappa$ is the circulation of a single quantized vortex of superfluid $^4\text{He}$. Thus, a suction flow enables the generation of a vortex with a high circulation even in a superfluid.
5. Summary
The superfluid flow and vortex induced by a newly proposed suction pump in superfluid \(^4\)He were investigated in this study. A cryogenic motor immersed in superfluid helium in a cylindrical container produces a rotating flow in the cylinder. The pressure difference in the rotating superfluid generates a superflow circulation outside of the cylinder, acting as a superfluid pump. The suction superflow into the pump was successfully used to generate a vortex with a high circulation much larger than that of the single quantized vortex in superfluid \(^4\)He. It is expected that this new method will find wide applications in superfluid studies.

Acknowledgments
The authors are very grateful to K. Fujimoto, M. Tsubota, and H. Takeuchi for their stimulating discussions. The research was supported by JSPS KAKENHI Grant Numbers 15H03694 and 17K18761.

References
[1] Donnelly R J 1991 Quantized Vortices in Helium II (Cambridge, England: Cambridge University Press)
[2] Hall H E and Vinen W F 1956 Proc. Roy. Soc. A 238 215
[3] Vinen W F 1961 Proc. Roy. Soc. A 260 218
[4] Yarmchuk E J, Gordon M J V and Packard R E 1979 Phys. Rev. Lett. 43 214
[5] Gomez L F et al. 2014 Science 345 906
[6] Andersen A, Bohr T, Stenum B, Rasmussen J J and Lautrup B 2003 Phys. Rev. Lett. 91 104502
[7] Andronikashvili E L and Mamaladze Y G 1966 Rev. Mod. Phys. 38 567
[8] Blažková M, Schmoranzer D, Skrbek L and Vinen W F 2009 Phys. Rev. B 79 054522
[9] Hashimoto N, Goto R, Yano H, Obara K, Ishikawa O and Hata T 2007 Phys. Rev. B 76 020504(R)