FORMATION OF A CENTRAL VORTEX IN ROTATING LIQUID HELIUM

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A description is given of experiments made to study the macroscopic central vortex in rotating helium. It is demonstrated that this vortex is formed only in rotating He I, owing to the existence of a two-phase liquid-vapor system, and is completely classical in character. This viewpoint is confirmed by modeling the phenomenon in rotating water. Nevertheless, this "classical formation" may be frozen-in upon the transition through the λ-point of the rotating He I and its transformation into rotating He II. The macroscopic vortex is found to be unstable in He II, and vanishes with the passage of time.

1. In the course of studying the properties of rotating helium near the λ-point, on both the high-temperature and low-temperature sides, the Tbilisi[1,2] group observed phenomena which indicate the possibility of the survival in a classical fluid of types of motion characteristic of quantum systems, and, on the other hand, in a quantum system, of types of motion characteristic of classical systems. Among these phenomena, an important place is occupied by the central vortex, found some time ago in He II by É. L. Andronikashvili[3]. Subsequently, an analogous phenomenon was also observed by Lane and his co-workers[4] in He I.

A very important question regarding the nature of the Andronikashvili vortex is whether it is quantum or classical, and whether it preserves its quantum properties through the transition from rotating He II into He I or, alternatively, retains classical properties through the transition from rotating He I into rotating He II. The present paper is devoted to the clarification of these problems.

2. The apparatus consisted of a Plexiglas beaker with polished walls. The diameter of the beaker was 25 mm; its height, 110 mm. The beaker was placed within a helium Dewar and partially filled with liquid helium at a temperature of 4.2° K.

The bottom of the beaker rested upon a pointed bearing, and its cover was connected with an axle which extended out through a packing gland sealed into the top of the Dewar. A multiple-step pulley attached to the axle was connected via a drive belt with a second multiple pulley mounted on the shaft of an SD-09 M synchronous motor. The rotational speed was determined with the aid of an electronic circuit to which pulses from an FSK-1 photoresistor were applied at each revolution. The number of pulses within a given time interval was counted by an electromechanical counter. The meniscus of the liquid helium was illuminated by a daylight lamp through the Dewar slits.

Observations of the state of the meniscus were made visually, and its configuration was photographed. The experiment was carried out at various rates of rotation, corresponding to linear velocities of from 15 to 105 cm/sec. The apparatus was set into rotation, and the vapor pressure over the free surface of the helium was reduced by pumping. During the pumping process, the state of the liquid was observed continuously.

As a result of these experiments the following points were established.

A. The Andronikashvili vortex regularly arises in He I when the latter is in a state of vigorous boiling (see Fig. 1). The process of development of the vortex is almost instantaneous: it appears suddenly along the entire length of the beaker. The impression is given that the vortex develops from the top downward. After the appearance of the vortex the rotating liquid ceases to boil. The vortex, which has a body diameter of ~2 mm, undergoes intense transverse oscillations ~10 mm in amplitude (at a rotational frequency $\omega_0 = 50$ $\sec^{-1}$). As the rotation rate increases, however, the amplitude of the vortex oscillations diminishes. The appearance of the vortex occurs at various temperatures, depending upon the pumping rate. When the rate of reduction in pressure (within the helium Dewar) is 10 mm Hg per second, the vortex appears at a temperature of 3° K; at ~3 mm Hg per second it appears just at the λ-point; at a rate of 1 mm Hg per second it does not appear at all.

B. At the transition of the liquid into the superfluid state the oscillations of the vortex cease at once (even at low rotational speeds), and the vortex column extends along the axis of rotation. At a rate of reduction of pressure of 10 mm Hg per second, the vortex begins to disappear smoothly 70 seconds after the transition to the superfluid state. The vortex first becomes detached from the bottom of the beaker, and then diminishes in length at a rate of 10 mm/sec. After the disappearance of the vortex, a conical indentation remains permanently at the center of the liquid meniscus, as was reported at the time of his observations by Andronikashvili[5]. This conical depression persists without material change even to the lowest temperatures (1.2°K) reached in the present experiment.

C. As has already been remarked, the Andronikashvili vortex does not appear when the temperature of the rotating He I is reduced sufficiently slowly (1 mm Hg per second). In this case, however, certain peculiar features are observed: at temperatures near the λ-point (but slightly higher) the liquid meniscus becomes metastable; elongated bubbles of gas grow downward into the liquid from the center of the meniscus, break off, and are then reabsorbed by the liquid. Immediately after the transition through the λ-point the meniscus becomes quiescent, and assumes its characteristic form with the conical depression at its center.

D. If the temperature of the rotating He II is allowed to rise smoothly by closing off the pumping line (in this case the helium does not boil, even above the λ-point), the conical depression persists, even in the He I, up to a temperature of 3°K. Even a brief halt in the rotation of the beaker is sufficient, with $T > T_\lambda$, to cause the conical depression to vanish, and the meniscus to resume its usual parabolic form.

E. Under the conditions prevailing in our experiment, it proved impossible to generate an Andronikashvili vortex in He II.

3. The experiments which we performed under rotating helium led us to the opinion that the Andronikashvili vortex can arise also in a rotating classical fluid (such as water) when it is in a state of boiling.

To verify this hypothesis we constructed the following experiment. A voltage was applied to

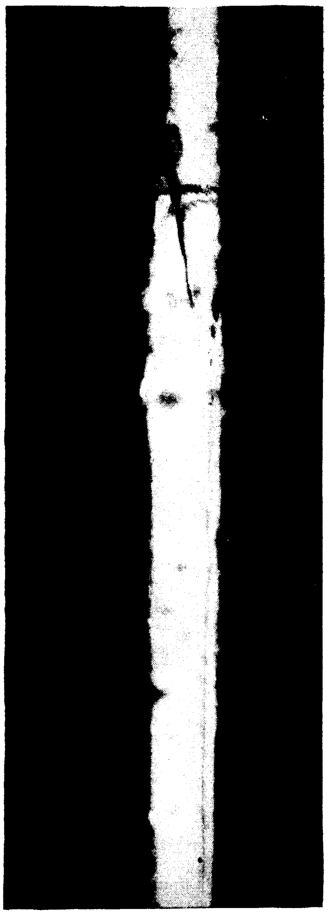


FIG. 1. Andronikashvili vortex in He I (rotational frequency $\omega_0 = 73.5\ \mathrm{sec}^{-1}$).

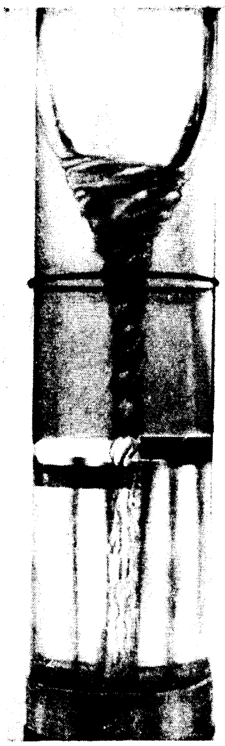


FIG. 2. Central vortex in water ($\omega_0 = 55\ \mathrm{sec}^{-1}$).

electrodes introduced into a rotating beaker filled with water. The resulting passage of an electric current led to heating of the water. When the boiling point was reached in the rotating water, a central vortex was formed (see Fig. 2) whose behavior corresponded completely with that of the vortex in helium (i.e., with increasing rotation rate, the magnitude of the deviations from the axis of rotation diminished). As the vigorously boiling water unwound, the vortex grew gradually upward from the bottom until it met the liquid meniscus. At this instant, gas bubbles ceased to appear in the body of the liquid.

The process of disappearance of the central vortex in rotating water begins rapidly after the heating current is cut off. It first becomes smaller in diameter, then breaks up into separate bubbles, and within 10—15 sec all traces of the formation have vanished.

4. The phenomena observed in water and in helium can be explained with the aid of the following considerations.

As is well known, the distribution of pressure P in a rotating liquid is expressed by the following relation

$$P - P_0 = -\rho g z + \tfrac{1}{2}\rho\omega_0^2 r^2,$$

where P_0 is the pressure at the free surface, ρ is the density of the liquid, r and z are cylindrical coordinates, z is measured upwards from the vortex of the meniscus, g is the acceleration of gravity, and ω_0 is the rotational frequency.

Thus, along a given radius within the liquid the pressure decreases from the periphery to the center (the isobaric surfaces have the form of paraboloids of revolution). Gas bubbles forming in the body of the liquid must therefore have a velocity component (the greater, the higher the rate of rotation) directed towards the axis of rotation. When a large concentration of gas bubbles is present, they combine, forming a hollow at the rotational axis.

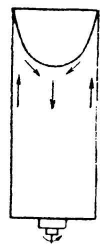
5. If the consideration developed in Sec. 4 correctly describe the phenomenon, then for formation of an Andronikashvili vortex it is sufficient to have a two-phase gas-liquid system.

This proposition was verified with the aid of the following experiment: a grid consisting of a brass disk, in which a number of holes were drilled, was placed 5 mm above the bottom of a beaker filled with water. Air was introduced below this grid through a fine German silver tube. The air bubbles streaming through the rotating water concentrated themselves along the axis of rotation and formed an internal zone resembling to a certain degree a vortex.

6. From the considerations presented above, as well as from a comparison of the results obtained in helium and in water, it follows that the Andronikashvili vortex and the central vortex formed in water are identical in nature: all of the properties of these vortices, and all of the factors in their formation, are identical. An exception is provided by the kinetics of formation of the vortices. However, the means for inducing boiling in the two liquids are likewise different: in helium, intense boiling is achieved by reducing the pressure of the overlying vapor, in water, by heating the liquid.

A possible reason for the differing directions of growth of the central vortices in water and in helium may lie in a difference in the convection patterns in the two liquids. The character of the convection currents arising in rotating He I can be established by means of the following considerations. As is well known, the density of He I increases as its temperature is reduced; consequently, the layers of the liquid cooled by pumping must move downward. (This consideration also applies to water, when its temperature is above 4° C.) As a consequence of the fact that during the pumping process the walls of the beaker containing the helium are always at a higher temperature than the helium itself, at the walls there arises a flow directed towards the surface, and along the axis of rotation, one directed downward (see Fig. 3).

FIG. 3. Pattern of convection currents arising in He I under pumping.



In the case of the water, the walls of the vessel will be colder than the adjacent liquid layers, due to the fact that the water is being heated. Here, therefore, we have the opposite convection pattern; at the walls there will be a downward flow, and at the center a flow directed upward.

In order to establish in water the convection currents illustrated schematically in Fig. 3, we constructed a special apparatus. Two types of heaters were used. One of these consisted of two parallel disks placed at the bottom of the beaker. The second type was in the form of two coaxial cylinders situated at the periphery of the beaker and extending up to the surface of the water. Thus, in the first case the water was heated at the bottom of the beaker, and in the second, the heating of the water began at the sides of the vessel.

If a heater of the first type is used in conjunction with a reduction in the vapor pressure over the rotating water, a pattern is produced which closely resembles the formation of a vortex without pumping. This means that the convection field illustrated in Fig. 3 is strongly altered by a current of liquid flowing from the heater. If, however, a heater of the second type is used, with pumping, the development of the central vortex, in the water proceeds as in the case of He I. At the moment the liquid begins to boil, the vertex of the meniscus is observed to enter an unstable state (a tendency to extend towards the bottom of the beaker). When the vortex appears, a more prominent stem is formed at the meniscus and gradually extends toward the bottom. Under intensive heating and pumping, the vortex appears instantaneously along its whole length.

7. Reviewing the facts presented above, we may draw the following conclusions:

a) the Andronikashvili vortex constitutes a classical formation, independent of the special characteristics of liquid helium;

b) a two-phase (liquid-gas) system, set into rotation, is required for the formation of the Andronikashvili vortex;

c) the kinetics of the formation and disappearance of the Andronikashvili vortex are governed by the direction of the convection currents in the rotating liquid;

d) this mechanism for formation of the vortex, based upon the distribution of pressure within a rotating liquid, and upon the presence within this medium of a gaseous phase, is capable of accounting for all of the results obtained by us, both for water and for He I and He II. One exception is the relatively long persistence of the vortex in He II.

It was found to be impossible, in the present experiments, to devise a means of insuring the formation of a central macroscopic vortex in rotating He II, as observed by Lane.

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