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Features of the formation of the vortex system and cavitation in superfluid solutions ^{3}He - ^{4}He

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The work examines the features of the formation a system of vortices, turbulent fluid flow and cavitation that arises at the oscillation of the quartz tuning fork placed in superfluid ^{4}He and solutions ^{3}He in ^{4}He. With an increasing of excitation a shift of the resonance frequency of tuning fork and the increase of resonance width arises, which indicates the transition to the vortex state of fluid and turbulent flow regime. It is shown that in superfluid solutions the increase of the impurity concentration of ^{3}He leads to the increasing of the stability the liquid with respect to the formation of vortices and the transition to the turbulent state. The formation of gas bubbles in superfluid solution (cavitation) was fixed at the biggest exciting force, more than 10^{-4} N, in the "open" tuning fork. Cavitation was not registered in the tuning fork with constrained geometry.

Keywords: superfluid solutions, turbulence, quartz tuning fork

У роботі розглядаються особливості формування системи вихорів, турбулентний потік і кавітація, що виникають при коливанні кварцового резонатора в надплинному ^{4}He і розчинах ^{3}He в ^{4}He. У міру зростання збудження виникає зсув резонансної частоти камертона і збільшення ширини резонансу, що вказує на перехід до турбулентного режиму течії. Показано, що в надплинних розчинах збільшення концентрації домішок ^{3}He призводить до збільшення стійкості рідини по відношенню до утворення вихорів і переходу до турбулентного стану. При найбільшій збуджуючій силі, більше ніж 10^{-4} Н, у «відкритому» камертоні в надплинному розчині було зафіксовано утворення бульбашок газу (кавітація). У камертоні з обмеженою геометрією кавітация не була зареєстрована.

Ключові слова: надплинні розчини, турбулентність, кварцовий камертон.

В работе рассматриваются особенности формирования системы вихрей, турбулентный поток и кавитация, которые возникают при колебании кварцевого резонатора, помещенного в сверхтекучий ^{4}He и растворы ^{3}He в ^{4}He. По мере роста возбуждения возникает сдвиг резонансной частоты камертона и увеличение ширины резонанса, что указывает на переход к вихревому состоянию жидкости и турбулентному режиму течения. Показано, что в сверхтекучих растворах увеличение концентрации примесей ^{3}He приводит к увеличению устойчивости жидкости по отношению к образованию вихрей и переходу к турбулентному состоянию. При наибольшей возбуждающей силе, большей чем 10^{-4} Н, в «открытом» камертоне в сверхтекучем растворе было зафиксировано образование пузырьков газа (кавитация). В камертоне с ограниченной геометрией кавитация не была зарегистрирована.

Ключевые слова: сверхтекучие растворы, турбулентность, кварцевый камертон.

Introduction

When an oscillating body is immersed in the liquid, in the beginning, at low velocities of the oscillation, a laminar flow occurs in the fluid, which velocity v is proportional to the exciting force F. If the exciting force, which acting on the body, is increased further, initially the solitary vortices appear in the fluid, which can then develop into a vortex tangle and then the turbulent state will be formed in the liquid. Maximum excitation force and thus the liquid flow velocity results in a local breakage and formation of vapor bubbles, namely cavitation. In simple liquids the formation of the gas phase depends on the impurities, dissolved gases, defects, roughness of the walls, the effect of background radiation and cosmic particles. All these factors make nucleation easier (it acquires the heterogeneous nature) and lead to a decrease in the critical breaking pressure. Obtaining of the homogeneous cavitation, which acts as an intrinsic property of a clean system and can occur very far from thermodynamic equilibrium at high negative pressure, is an important physical problems. Liquid helium is a clean system, which is free from impurities and perfectly wets almost every solid surface. It is convenient to use to study the characteristics and conditions of the transition from laminar to turbulent flow of the liquid and the emergence of a homogeneous cavitation. Virtually the only factor affecting these processes are the impurity particles of ^{3}He. ^{3}He atoms are deposited on the core of the vortices, which there are always in a small amount in the helium, and the number of which increases with the transition to turbulent flow regime, thereby increasing its size and weight. Previous studies of the transient characteristics were performed in a pure ^{4}He and 5% solution of ^{3}He in ^{4}He [1, 2]. In the present work, the solution of 15% ^{3}He in ^{4}He was studied for a more complete understanding of the effect of impurity particles ^{3}He on the conditions of the transition from laminar to turbulent flow of a liquid. For the first time the conditions of cavitation in superfluid mixtures of helium isotopes were installed.

Experimental technique

Method of oscillating quartz tuning fork, which is placed in the liquid, was used for studies of transients in the fluid flow. The amplitude - frequency characteristics of the tuning forks of the industrial production of the fundamental frequency of about 32 kHz, oscillating in a 15% solution of ^{3}He in ^{4}He was measured. Data, which was obtained in pure ^{4}He and 5% solution of ^{3}He in ^{4}He, was used for comparison [1, 2]. Tuning forks have identical geometrical dimensions: height feet L = 3.79 mm, thickness H = 0.59 mm, width W = 0.3 mm and the distance between the legs of D = 0.3 mm. Tuning forks with a hole in the factory-made cap to fill it with the fluid were used to study the effect constrained geometry. The tuning forks with cap - “closed” and without cap - “open” were investigated. The inner diameter of cap was 2.8 mm. Tuning forks were placed in two copper cylindrical cell filled with the test liquid. The cells were attached to the cold plate of the evaporation ^{3}He refrigerator. The amplitude-frequency characteristics of the tuning forks were measured by scanning the frequency of using a continuous sine wave generator MCP SP F80 in the voltage range from 0.001 to 20 V. A special amplifier voltage up to 500 V (peak-to-peak) was made for higher amplitude voltage required for the measurement of cavitation. The output signal from the tuning fork with a reference signals were fed to the synchronous amplifier (5208 Two Phase Lock-in Analyzer). More information can be found in [3].

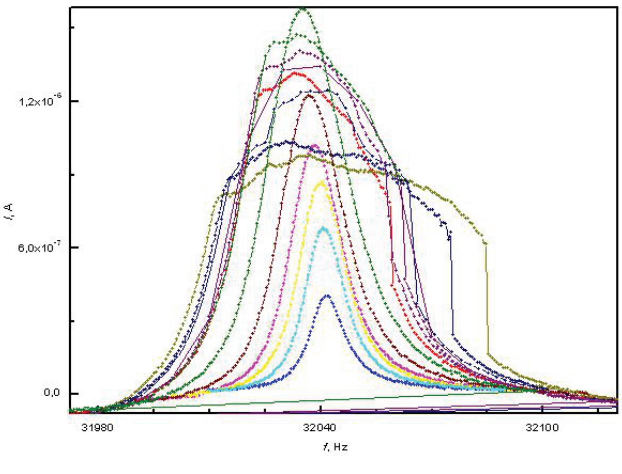

Fig. 1. The amplitude-frequency characteristics of the “open” tuning fork at various driving voltage from 1 to 100 V at the temperature T = 1.7 K.

In the experiment the RMS amplitude of the output signal I as a function of frequency and the resonance curves width at half-maximum Δf of the resonance were measured at constant driving voltage U and constant stabilized temperature of the cell. Initially we measured the frequency response in vacuum which allowed, in accordance with [4], to find out a piezoelectric constant of the tuning fork a. This constant allows us to move from electrical parameters – I_0 signal amplitude at resonance and the drive voltage U_0, to the physical parameters of the system – the vibration velocity of the fork tines v $(v = I_0 / a)$ and the exciting force F $(F = aU / 2)$.

The transition from laminar to turbulent flow in the liquid helium. Influence of impurity ^{3}He and confined geometry

Fig. 1 shows a typical primary data of the amplitude-frequency dependencies (the resonance curves) of a tuning fork, that is immersed in a 15% solution of ^{3}He in ^{4}He at a constant temperature, pressure and at change of the driving voltage. In the analysis of the curves, there are three area of the excitation voltage: 1 - at low voltages a linear dependence of the amplitude of the resonance against exciting force and constancy of the resonance frequency is observed; 2 - with a further increase of the voltage there are a shift of the resonance frequency and an increase its width; 3 - at high voltages applied to the tuning fork deformation in the shapes of the resonance curve and the failures are observed.

For each of the forks the dependence of the velocity of the oscillations of the fork tines against the applied force at a constant temperature has been built. It was found that the first area of the excitation voltage corresponds to

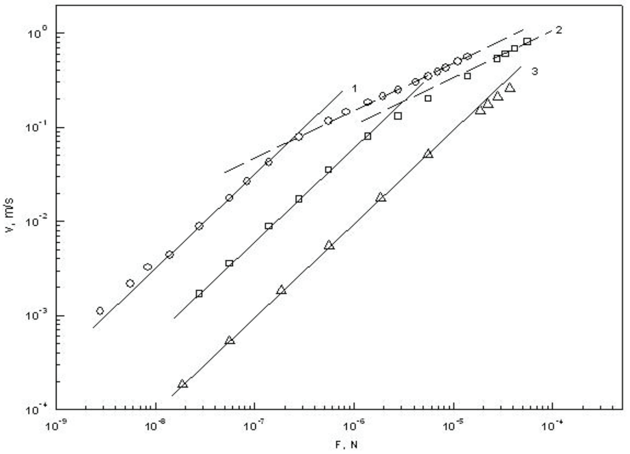

Fig. 2. The dependencies of the vibration velocity of the fork tines at various driving forces at T = 1.15 K. 1 - pure ^{4}He; 2 - 5% solution of ^{3}He - ^{4}He; 3 - 15% solution of ^{3}He - ^{4}He. The solid lines correspond to the dependence of v ~ F, dotted - dependence v^2 ~ F.

the laminar flow of the liquid , the second - the nonlinear nature of the flow, which can be explained by the transition from laminar to turbulent flow, and which is accompanied by the appearance of vortices, and the third - corresponds to the onset the process of cavitation in the liquid.

Figure 2 shows the dependencies v (F) for the temperature T = 1.15 K for the "closed" forks in pure 4He, 5% and 15% solutions of ^{3}He in ^{4}He. For a qualitative comparison, the figure has the line, which is corresponding to the linear dependence of v ~ F (laminar flow), and the dependence $v^2 \sim F$ (turbulent flow), in accordance with [5]. As you can see, the growth of the impurity ^{3}He leads to an increase in the excitation power required for the transition to a turbulent state. Simultaneously, one can see the growth the critical velocity of the transition to this state, which indicates an increase of stability of liquid helium versus the number of impurities. The same behavior in the pure 4He occurs when the temperature rises, it corresponds to increasing the density of the normal component of the superfluid helium [1]. The increasing of the concentration of ^{3}He from 5% to 15% leads to increases the stability of the solution relatively to the formation of vortices. In fact, in the 15% solution of ^{3}He in ^{4}He experimentally observed only beginning of the transition (curve 3 in Fig. 2) at the maximum applied excitation force. However, dependencies shown in Fig. 2, do not answer the question, resulting in increased stability due to the addition of liquid ^{3}He – increasing the density of the normal component in the superfluid solution or an increase in the number of impurity ^{3}He quasiparticles [1, 2], because both magnitudes have changed. The density of the normal component of ^{4}He is ≈ 0.0036 g/cm^3, in a 5% solution of ^{3}He in ^{4}He ρ_n is ≈ 0.016 g/cm^3, and in a 15% solution of ^{3}He in ^{4}He ρ_n is ≈ 0.046 g/cm^3.

To elucidate the role of impurity quasiparticles ^{3}He and the confined geometry (the can of the tuning fork) at the transition from laminar to turbulent flow in a superfluid helium were measured the amplitude-frequency dependences of the "open" and "closed" forks at temperatures 1.1 K and 1.7 K in 15% solution of ^{3}He in ^{4}He. The results of the measurements as dependencies *v(F)* are shown in Fig. 3. In this figure, the open points correspond to a tuning fork with unlimited geometry and closed points are the tuning fork with can. The measurement results show that the dependencies of *v(F),* corresponding to the solution of the same concentration but at two different temperatures, is close to the case of "open" unlimited tuning fork, and as in the case of "closed" limited tuning fork. Thus, the impact of changes in the density of the normal component in this case is not noticeable. From this we can conclude that in the case of measurements at constant temperature and varying concentrations of ^{3}He (Fig. 2) the stability of the liquid ^{3}He-^{4}He solution with respect to the appearance of vortices and the establishing turbulent state is associated with an increase in the number of ^{3}He impurities and their interaction with the vortices.

Note that dependencies on the Figure 3 show a significant effect of the geometry on conditions vibrations of the tuning fork in superfluid solution ^{3}He and ^{4}He. The difference between the curves v (F) of "open" and "closed" tuning forks is because the resonant value of v (F) ~ 1/Δf [6]. As was established in [7], at temperatures above 1 K in the ^{4}He resonance width Δf is determined only by viscous dissipation, which in this temperature range is the same for the "open" and "closed" tuning forks. Therefore, in ^{4}He dependencies of v(F) for "open" and "closed" tuning forks are virtually identical at temperatures above 1 K. Only at temperatures below 1 K in the ^{4}He begins to dominate the dissipation of vibrations of a tuning fork associated with the emission of the first sound. The first sound wave does not develop and the contribution of radiation to the damping of the tuning fork is close to zero in the vibrations of the tuning fork in the presence of the can due to the proximity of the walls. Therefore, there is a contrast, which associated with the surrounding geometry. In solutions of ^{3}He in ^{4}He situation is much more complex – after the superfluid transition the second sound waves occurs, the same occurs the contribution to the dissipation due to radiation of the tuning fork [3], because the wavelength of the second sound is less than the first and the cover is no longer limiting its spread. Accordingly, the dissipation of the tuning forks in solutions of ^{3}He - ^{4}He becomes sensitive to the surrounding geometry because of engagement with the standing waves of the acoustic waves. Therefore, for a 15% solution of ^{3}He - ^{4}He difference between "open" and "closed" forks evident even at temperatures higher than 1 K, as we can see in Fig. 3.

The occurrence of cavitation

The amplitude-frequency characteristics of the "open" fork on Figure 1 shows that at the driving voltage ≈ 50 V resonance curves start to deform and broaden. As follows from [8], such change in the shape of the resonance curves corresponds to the appearance of bubbles gas phase in the liquid, namely cavitation. The v(F) dependence of the "open" fork in Fig. 3 shows that transition to cavitation mode occurs at excitation more than 10^{-4} N and it is accompanied by a sharp decrease in the flow velocity of fluid. By comparing the results of [8] in pure ^{4}He with our results for the solution of 15% of ^{3}He in ^{4}He obtained at the same temperature in the superfluid phase of helium, we can note a strong difference in the value of the critical velocity of onset of cavitation – in the case of pure ^{4}He it is ≈ 2 m/s, in solution is ≈ 0.4 m/s. Thus, we can assume that the quasiparticles of ^{3}He by interacting with the core of vortices facilitate the conditions of occurrence of the gaseous phase in the solution.

Note one more result, which follows from the

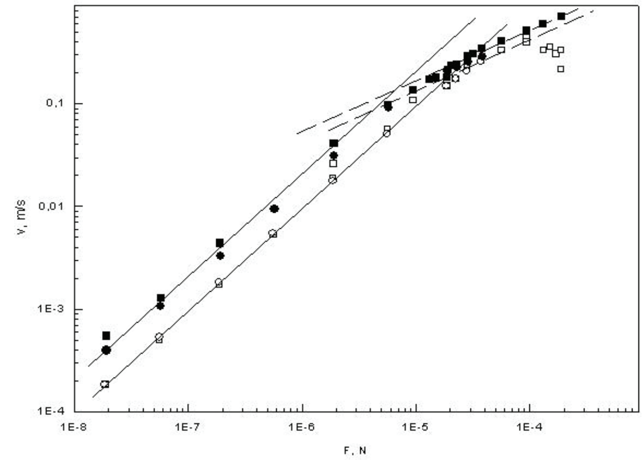

Fig. 3. The dependencies of the vibration velocity of the fork tines at various driving forces at T = 1.1 K and 1.7 K in a 15% solution of ^{3}He - ^{4}He. The solid lines correspond to the dependence of v ~ F, dotted - dependence v^2 ~ F. The filled symbols correspond to a tuning fork with limited geometries and transparent - with unlimited.

dependencies v(F) in Fig. 3. By comparing the dependence of the “open” and “closed” forks at high excitation forces, it is clear that cavitation occurs only in the “open” tuning fork, and there are no cavitation in the restriction. We can assume that for the occurrence of cavitation in the “closed” tuning fork requires large excitation force, but the using of such force leads to the risk of destruction of the fork. Note that in [8] the measurement of cavitation in the “closed” tuning fork were not carried out.

Conclusion

We have measured the properties of a vibrating quartz tuning fork immersed in superfluid ^{3}He - ^{4}He solutions. The vortex formation that occurs during the transition from laminar to turbulent flow in the superfluid solution was found. It was found that at low excitation voltage applied to the tuning fork, there is laminar flow of liquid. With increasing of excitation a shift of the resonance frequency of tuning fork and the increase of its resonance width arises, which indicates the transition to the vortex state of fluid and turbulent flow regime. With further increase of the excited forces to a tuning fork the beginning of cavitation is observed, which manifests itself in the form of distortion and broadening of the resonance curves of the amplitude-frequency characteristics.

It is shown that in superfluid solutions the increase the impurity concentration of ^{3}He leads to increased stability of the liquid with respect to the formation of vortices and the transition to the turbulent state.

It was found that in 15% solution of ^{3}He - ^{4}He the dependencies the vibrations velocity of the tuning fork against exciting force at different temperatures are close under identical conditions of space limitations fork. The absence of the confining cap increases the stability of the liquid with the later transition to the turbulent state at the high excitation forces. When the exciting force more than 10^{-4} N in the “open” tuning fork, the formation of gas bubbles in superfluid solution, namely cavitation, in liquid was fixed. In the tuning fork with constrained geometry cavitation was not registered. To clarify the causes of this phenomenon requires further study.

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