J Low Temp Phys (2008) 150: 194–199
DOI 10.1007/s10909-007-9533-4

Cavitation in Liquid Helium Observed in a Flow Due to a Vibrating Quartz Fork

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Received: 27 July 2007 / Accepted: 19 October 2007 / Published online: 16 November 2007
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Abstract A quartz fork vibrating at high amplitude is used to study cavitation in He I and He II along the saturated vapor pressure (SVP) curve and at slightly elevated pressures. Cavitation is observed as a breakdown of the resonance response at critical velocity when slowly sweeping the frequency of the drive across the resonance and confirmed by visual observation of a bubble occurring in He II in the space between the prongs of the fork. On decreasing the temperature from 4.2 K along the SVP curve the critical velocity slowly increases from about 0.4 m/s to 1 m/s, until a steep increase up to about 2 m/s occurs within about 20 mK just below the superfluid transition. We discuss our results, including the measured dependence of the critical velocity versus overpressure at fixed bath temperature.

Keywords Cavitation · He I · He II · Quartz crystal

PACS 47.55.dp · 67.55.Fa · 67.57.De

1 Introduction

The vibrating quartz tuning forks such as shown in Fig. 1 proved to be robust, cheap and widely available tools for generating and probing oscillatory boundary layer flows [1–3]. Their peak velocity in helium fluids can be easily varied and detected over seven orders of magnitude, up to very high values of order m/s, limited by their

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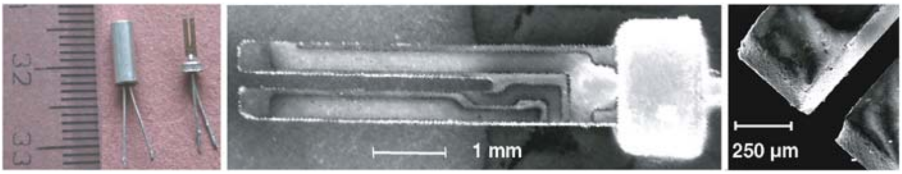

Fig. 1 (Color online) The photograph of an encapsulated and bare quartz tuning fork [4] (*left*), the electron micrograph of the quartz tuning fork with evaporated metallic electrodes (*middle*) and details of its trimmed ends (*right*) showing sharp edges

mechanical and/or electrical strength. An experimental setup described in [2] enables us to experimentally observe additional effects in liquid He I and He II (absent in gaseous He), which we ascribe to cavitation taking place in the vicinity of the vibrating fork.

Liquid helium can be prepared extremely clean, wets almost ideally any solid surface and therefore serves as an ideal model system to study cavitation. Numerous studies have been performed over the last fifty years—see [5] for a comprehensive review of the early experiments on nucleation of bubbles in liquid helium, and [6] for the more recent results. A broader picture is nicely given in a review [7] by Balibar. As many experimental results remain poorly understood, it is of considerable interest to revisit this field using a new tool.

2 Experimental Protocol and Data

Our detection protocol is based on sweeping the fixed driving voltage applied to the quartz tuning fork, of the form $U = U_0 \cos \omega t$, across the resonance peak. At low driving voltages, the response signal from the fork is represented by the absorption and dispersion curves of Lorentzian form [1]. On increasing the driving voltage the response ceases to be of Lorentzian form, the absorption resonant curve widens and the maximum response shifts towards lower frequency. As explained in detail in our previous publication [2], this behavior is observed in both liquid and gaseous helium and is caused by the transition from the laminar to turbulent drag regime. These features occur irrespectively whether the fork is driven in He I, He II or in gaseous helium.

In liquid He I and He II along their saturated vapor pressure curve (SVP) or at slightly elevated pressures an additional pronounced feature occurs, as illustrated in Fig. 2. At high enough drive amplitude U, the observed signal breaks down when the frequency is swept up, first just before reaching the expected maximum in the absorption signal. This event serves for us as a definition of the critical cavitation velocity v_{cav}. When the frequency sweep of the drive is slowly continued (a typical time scale of a sweep is a minute), in most cases the signal recovers at approximately the same frequency difference past the expected maximum (see Fig. 2, top right). When sweeping across the resonance with even higher drive level, the destroyed part of the Lorentzian-like response broadens and the recovery point is in most cases no longer symmetric with respect to the expected maximum response. When repeating

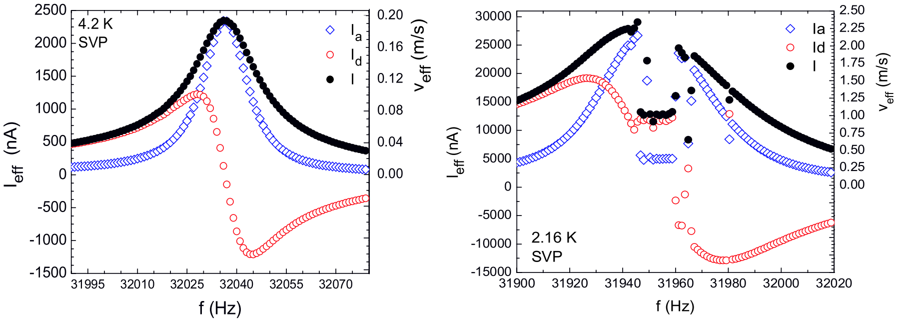

Fig. 2 (Color online) The amplitude, I, (•), in-phase, I_a, (◇, *blue online*) and out-of-phase, I_d, (○, *red online*) current signal measured by the dual-phase SR830 lock-in amplifier when sweeping the driving voltage across its resonant response. The *right axes* show the corresponding values of the rms velocity of the fork, calculated from the current signal, I, using the calibration procedure described in detail in [1]. Up to a critical drive level, the observed curves are of nearly Lorentzian shape (*left*). On increasing the drive amplitude, the observed signal breaks down, first in the vicinity of the maximum response and recovers when the slow sweep passes the maximum response region (*right*)

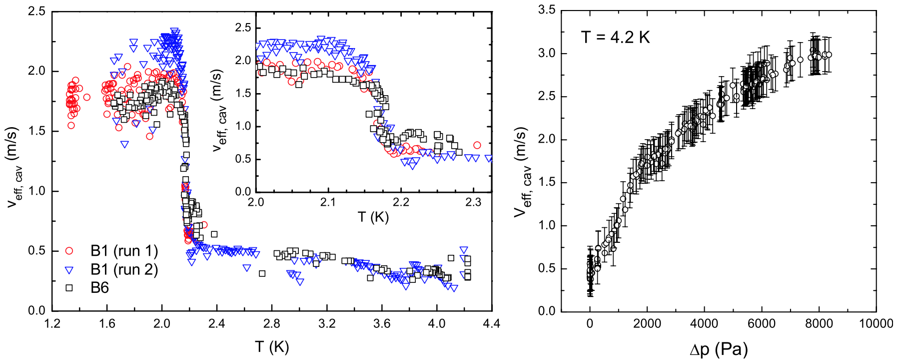

Fig. 3 (Color online) The observed critical cavitation velocity plotted versus the temperature at SVP using two partly encapsulated forks [4] inside the pressure cell. The *inset* magnifies the data in the vicinity of the λ-transition (*left*). The observed critical cavitation velocity plotted versus the applied overpressure in the cell at 4.2 K (*right*)

the sweeps, this peculiar character of the signal persists but the response is generally not exactly reproducible. This character of the signal is observed for both directions of frequency sweeps.

Figure 3 shows the observed temperature dependence $v_{\text{cav}}(T)$. On decreasing the temperature below 4.2 K towards the λ-point, v_{cav} slowly monotonically increases. This is best seen in the data series obtained with a tuning fork in its original can (with only its top removed) placed inside the cylindrical brass pressure cell. Measurements with a bare fork inside the pressure cell and with a bare fork in the open helium bath are in qualitative agreement, but display larger scatter of the data. The most striking feature is a very steep increase in v_{cav} right below the λ-point—here v_{cav} rises by factor 3–5 within about 20 mK. This feature is detailed in the inset of Fig. 3.

We have measured this feature with various forks; it displays a reasonable degree of reproducibility for the data series from different runs as well as for the data obtained with different forks. We believe therefore that this abrupt increase in v_{cav} below the λ-point is firmly established.

Further reduction of temperature down to about 1.3 K seems to have much less effect on v_{cav}; within the rather large scatter it stays roughly constant, but statistically a maximum can be allocated around 1.9 K. Having available the pressure cell [1, 3], we have performed the measurements showing the dependence of v_{cav} versus an externally applied overpressure at 4.2 K (see Fig. 3, right).

It is important to independently confirm that the observed effects are indeed caused by cavitation. The unequivocal proof is the direct visual observation of a bubble occurring between the prongs of the fork in He II [1] where thanks to the extremely large thermal conductivity there are no bubbles in the bulk. In the glass cryostat, we have clearly observed the bubble in the space between the prongs of the fork, attached to their surface. During the frequency sweep such as shown on the right in Fig. 2, the bubble quickly appears when v_{cav} is reached, exists as long as the otherwise Loretzian response is broken and collapses when the Lorentzian-like response recovers. We have not observed any rising bubbles that would originate in the vicinity of the vibrating fork.

3 Discussion

The "breakdown" effects described above never occurred in gaseous helium. Taking into account direct visual observation of a bubble between the prongs of the fork in He II, we therefore naturally assume that the observed effects arise as a consequence of cavitation/boiling processes in liquid He I and He II. The most simple, perhaps naive, explanation would be that due to the Bernoulli equation the local pressure in the flow due to a vibrating quartz fork decreases. The overpressure data at 4.2 K can indeed be fitted by the expected $v_{\mathrm{cav}} \propto \sqrt{\Delta p}$ dependence, however, they lead to a pressure drop comparable with the hydrodynamic static pressure head in the cryostat, far too low for what would be required for homogeneous cavitation. Moreover, this simple approach does not explain the almost step-like change in v_{cav} close to T_λ.

Our experiment with quartz forks whose legs oscillate as cantilevers in antiphase against each other at frequency 32 kHz is geometrically similar to the experiments of Finch and coworkers [8] in that both experiments feature oscillations of solid surfaces perpendicularly to their plane. Finch and coworkers used two identical disks of Clevite PZT-4 ceramics 1/2 inch in diameter and 4.5 cm apart, operated at 91.15 kHz. Cavitation in bulk helium was detected via the acoustic emission associated with the collapse of cavitation bubbles, and also visually at much higher drive amplitudes. The deduced acoustic cavitation thresholds were generally low, comparable (as in our case) to the static pressure head in the helium bath. However, their frequency transfers into a wavelength of about 3 mm, thus the space between the plain ceramics could

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[1] In boiling He I at SVP any visual evidence of cavitation is as yet not conclusive, due to the presence of small bubbles in the bulk.

act as a resonator, where both positive and negative pressure amplitudes might be strongly enhanced thanks to the constructive interference of emitted acoustic waves. Similar improved technique, using a cylindrical acoustic standing wave of frequency 50.58 kHz at $T = 2.09$ K was used by Marston [9]. Bubbles appeared to originate on pressure antinodes, expanded to a large diameter of 0.5–1 mm and eventually fragmented into smaller bubbles.

In case of our fork, the span between the legs is about 20 times less than the wavelength, λ, so it cannot act as an acoustic resonator. The volume where cavitation can take place is recognized as an important factor [5]. In the experiment of Finch and coworkers [8] it was about 20 cm^3. In modern experiments with hemispherical capacitors [5, 7] this volume is much smaller, about $(\lambda/2)^3 \simeq 2 \times 10^{-12}\ \text{m}^3$ and it has become a common notion that here one deals with purely homogeneous nucleation. Note that this volume is only an order of magnitude smaller than the volume between the fork's legs. In He I, however, this volume could be estimated as small as of order $\delta^2 \times L \simeq 10^{-14}\ \text{m}^3$, where δ is the viscous penetration depth and L denotes the linear dimension along the sharp edges of the fork, in the vicinity of which the flow is strongly enhanced. This would suggest homogeneous nucleation, but cavitation occurs here in the vicinity of walls and we believe that in poorly conducting He I we have to take into account thermal effects; these could probably be neglected in He II. Cavitation occurs here at velocity $v_{\text{cav}} \cong 2$ m/s, the applied driving force being [2] about $F \simeq 5 \times 10^{-4}$ N. Assuming that the dissipating energy converts the incoming superfluid into the outflowing normal fluid, at $T \approx 1.3$ K it leads to $V_n \approx 2$ cm/s; at this temperature this is at the same time also an estimate of the counterflow velocity. The temperature gradient associated with this counterflow is probably very small and can be neglected. Thus at least on first approximation it seems fair to assume that in He II (except close below the λ-point, see later) the overheating is negligible. It follows from the Bernoulli equation that the required pressure drop for homogeneous cavitation of about 8 bar would correspond to a flow velocity of about 100 m/s. This is about 30 times higher than our observed *peak* fork velocity. A homogeneous mechanism would therefore require a significant enhancement of the superflow velocity past sharp corners of the fork (see Fig. 1) or due to surface roughness.

In a classical viscous Navier–Stokes fluid He I such a strong flow enhancement is most likely not possible. Based on the thickness of the viscous boundary layer, the enhancement factor round sharp corner [10] would be limited to about 6–7. On the other hand, in normal fluid like He I similar rough estimates for the partly encapsulated fork lead to significant overheating, of order 1 K. This strongly suggests that combined boiling/cavitation rather than pure cavitation occurs. In other words, we might have measured cavitation at significantly higher temperature than that at which the bath was kept. We are currently performing more accurate analysis along these thoughts, taking into account the measured values of force and velocity of the fork.

An interesting situation arises when T_λ is approached from below. About 20 mK below, the order of magnitude estimate of the counterflow velocity mentioned above is still valid, but closer to T_λ the counterflow velocity sharply increases, due to rapidly falling superfluid density. That results in a much larger temperature gradient, possibly in the close vicinity of the fork we might have He I.

Let us comment on Fig. 13 of [7], summarizing the supposedly homogeneous cavitation results in He II. Similarly as in our data, there is a pronounced increase in the cavitation pressure drop around and slightly below the λ-point—theoretical calculations for cavitation predict no anomalies like this. A possible explanation might again be that above the λ-point the cavitation spot could be significantly overheated. This pronounced feature would entirely disappear if the data points around and above T_λ were shifted up by several tenths of a Kelvin. The temperature shift would be gradually smaller as the negative pressure amplitude needed for cavitation to occur gets smaller as the temperature increases. Indeed, acoustic pressurization–depressurization of extremely high amplitude cannot be isothermal and it is plausible that significant heating occurs in the acoustic center.

4 Conclusions

Our preliminary measurements and analysis prove that the oscillating quartz fork represents a handy and simple tool to study cavitation in liquid helium. It probably occurs in the vicinity of sharp corners of the fork, where the fluid flow is strongly enhanced. Based on the measured temperature dependence of the critical cavitation velocity that on decreasing T displays a pronounced steep increase within about 20 mK below T_λ we conclude that in He I the vicinity of the fork is locally overheated and cavitation occurs at temperature which is significantly higher than that at which the surrounding helium bath is kept. The steep increase of the cavitation velocity by factor 3–4 observed just below the superfluid transition can be understood as a consequence of the high convective heat transfer efficiency in superfluid He II. Our data do not allow us to conclude whether the observed cavitation is heterogeneous or homogeneous in nature; homogeneous cavitation would require a superflow velocity enhancement past sharp corners by a factor of about 30.

This paper represents a report on work under progress and our conclusions are at best tentative. There is a call for further experiments and theoretical investigations of the interesting cavitation phenomena in cryogenic helium liquids.

Acknowledgements The authors appreciate technical help of P. Doškářová, L. Doležal and P. Vacek, stimulating discussion with S. Balibar and W.F. Vinen and thank J. Pešička for providing the fork micrographs. This research is supported by research plans MS 0021620834, AVOZ 10100520, by GAČR under 202/05/0218 and GAUK 7953/2007.

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