Tortuosity of ^4He Films on Aerogel

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Abstract. A torsional oscillator has been used to study the flow of liquid ^4He through silica aerogel. The tortuosity and dissipation of the flow in the fractal aerogel environment has been measured, for both capillary condensed films and a fully saturated cell. The scaling of tortuosity as a function of filling fraction has been investigated. We compare the results of our 88%-porous aerogel to a 92%-porous sample where a transverse sound technique was used. Our more sensitive technique has reduced the scatter in both the frequency and dissipation data. Like in the previous transverse sound experiment, we find tortuosity as a function of filling fraction to scale with an exponent of ~ -1.1 . Further experiments are planned, to find the dependence of the exponent on fractal dimension and porosity of aerogel.

Keywords: superfluidity, aerogel, fractal

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INTRODUCTION

This Paper reports our progress towards using tortuosity of superfluid ^4He films adsorbed onto aerogel, as a method of characterising the microscopic structure of aerogel. This experiment considers capillary condensed films [1], where initial depositions closely follow the morphology of the aerogel's silica matrix, while successive depositions of helium progressively smooth out the small scale irregularities of the film's profile. This effectively de-fractalises the aerogel until it is fully saturated. The scaling of the film's tortuosity with volume of adsorbed helium – or largest filled aerogel pore – can be used as an independent method to characterise aerogel, or indeed other porous media. It may be possible to use this technique to characterise either fractal or non-fractal materials [2].

An inviscid liquid accelerated along a tortuous path while passing round an obstacle exerts force on the obstacle. This force, reflecting the tortuosity of the streamlines, is proportional to their “tortuosity” α , which is sometimes expressed in terms of the “drag factor” χ where $\chi = 1 - \alpha^{-1}$ [3]. It is straightforward to determine the tortuosity of a film of superfluid helium adsorbed inside a porous material by measuring the moment of inertia of a piece of this material with helium inside it.

THE EXPERIMENT

We used a cylindrical (diameter 12.7 mm, height 7.7 mm) aerogel sample of density $\rho_a = 0.269 \text{ g/cm}^3$. Comparison with silica density 2.2 g/cm^3 leads to the aerogel porosity $\phi_a = 0.88$. SAXS revealed mass fractal correlations between the wave numbers $0.016 \text{ \AA}^{-1}$ and

$0.032 \text{ \AA}^{-1}$, and a fractal dimension, $D = 2.0$.

The aerogel is mounted in a typical Manchester torsional oscillator (for more details see [4]). The aerogel was epoxied into a closely fitting cylindrical head made from Stycast 1266, which also had a BeCu torsion stem. A one piece BeCu vibration filter and torsion stem, was fastened to a brass base, from where all temperature regulation was performed. The head unit was made detachable from the filter, to aid manufacture, but primarily to allow easy sample change for future experiments. The filter was driven close to the resonant frequency of the cell head. The high Q-value and disparity between the inertial masses of the oscillator allow the following approximations to be made for the head resonant frequency, ν_R , and bandwidth, ν_B ;

$$\nu_R = \frac{1}{2\pi} \left(\frac{K_1}{I_1} \right)^{1/2}, \quad \nu_B = \frac{1}{2\pi} \frac{\zeta_1 + \zeta_{12}}{I_1}, \quad (1)$$

where K_1 is the torsion constant of the cell head; I_1 the moment of inertia of the cell head; and ζ_1 and ζ_{12} are the damping coefficients of the head's torsion stem and helium in aerogel respectively. We found both ν_R and ν_B for an empty cell to be temperature independent, $\nu_{R0} = 248.626 \text{ Hz}$ and $\nu_{B0} = 6.8 \text{ mHz}$.

For a given helium filling fraction, ϕ_{He} , it is possible to deduce the density of coupled helium, ρ_C [4], and through

$$\alpha(\phi_{\text{He}}) = \left(1 - \frac{\rho_{Cs}(\phi_{\text{He}}) - \rho_0}{\rho_{Cn}(\phi_{\text{He}}) - \rho_0} \right), \quad (2)$$

determine a value for α , where ρ_{Cs} and ρ_{Cn} are the coupled helium density when helium is in the superfluid and normal phase respectively; ρ_0 is the density of helium

solidified on the silica resulting from van der Waals attraction.

EXPERIMENTAL RESULTS AND DISCUSSION

The layer of solid helium on silica makes a temperature independent contribution to I_1 ; the number of moles in this layer is proportional to the surface area of the aerogel and was estimated, using a critical coverage of $35 \mu\text{moles/m}^2$ [5], to be $\rho_0 = 0.013 \text{ g cm}^{-3}$. Further admissions of helium result in liquid films, the profile of which is determined by the van der Waals and capillary terms in the chemical potential [1]. The liquid makes a temperature dependent contribution to I_1 below T_c , reaching a minimum at $T < 0.5 \text{ K}$ when all liquid is superfluid. Above T_c , this contribution is approximately temperature independent.

For a given filling fraction of helium, ϕ_{He} , the contribution to I_1 can be calculated by tracking $v_R(T)$. Above T_c the v_R is temperature independent, but as the temperature is decreased past T_c , v_R increases in a manner which is consistent with the normal component decreasing. However v_R never recovers its empty cell value of $v_{R0} = 248.626 \text{ Hz}$. Below 0.5 K the normal fluid fraction is essentially zero, and the remaining inertia of the superfluid is attributed to tortuosity [6][7]. A more detailed discussion of this analysis for our saturated 88%-porous sample, can be found in [4].

In Fig. 1 we plot $\alpha(\phi)$ for the capillary condensed regime, alongside data for 92%-porous and 93.5%-porous aerogels. We fitted the function $\alpha = \phi_{\text{He}}^{-\epsilon}$ to our data. This is consistent with the physical definition of α , that for a bulk ($\phi = 1$) sample $\alpha = 1$ [3]. We found $\epsilon = 1.060 \pm 0.013$, to be compared with $\epsilon = 1.10 \pm 0.02$ for the 92%-porous aerogel. For comparison, the measured $\alpha(\phi)$ for liquid saturating non-fractal packed powders [8] and fused glass beads [3] of various porosities ϕ , give exponents between $\epsilon = 1/2$ and $\epsilon = 2/3$. The aerogels have a markedly different ϵ to the non-fractal porous media. We found the 88%-porous aerogel to have the same ϵ as the 92%-porous ($D = 2.0$) and 93.5%-porous aerogels within the experimental error, although the 92%-porous and 93.5%-porous aerogels were made by a different manufacturer (Airglass, Sweden). Work is currently under way to determine $\alpha(\phi_{\text{He}})$ for a 98%-porous aerogel.

The values of dissipation for all ϕ_{He} were much smaller than the temperature-independent value of $v_{B0} = 6.8 \text{ mHz}$ for the empty cell.

FIGURE 1. Tortuosity vs. helium filling fraction: (●) our data; (○) data for a 92%-porous sample which employed a transverse sound technique [2]; (△) and for 93.5%-porous aerogel [9]. For comparison helium saturating (*) fused glass beads [3] and (+) packed powders [8] are also shown. Solid lines are produced using an effective-medium theory for saturated porous media [10], for ($\epsilon = 1$) self-similar needles orientated perpendicular to the flow, ($\epsilon = 2/3$) self-similar needles randomly orientated, and ($\epsilon = 1/2$) self-similar spheres. The solid line is a fit to our 88%-porous aerogel data.

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