Heat Transfer and Boiling of Liquid Helium Oscillation in Narrow Rectangular Duct

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Summary Small temperature fluctuations in saturated super fluid He II (at 1.9K) was measured by using the small thermistors operated by a lock-in amplifier. The experiments were performed in a rectangular channel (13×13×200 mm) in which the heater was set at the bottom. We found that the periodic temperature oscillation and the pulsive boiling sound appear. They are synchronizing and the oscillating frequencies strongly depend on the helium pressure and the heat flux. When the He pressure decreases, the oscillation frequency decreases. However, the decay rate is independent of the heat flux. This physical mechanism will be discussed in the presentation with PIV analysis.

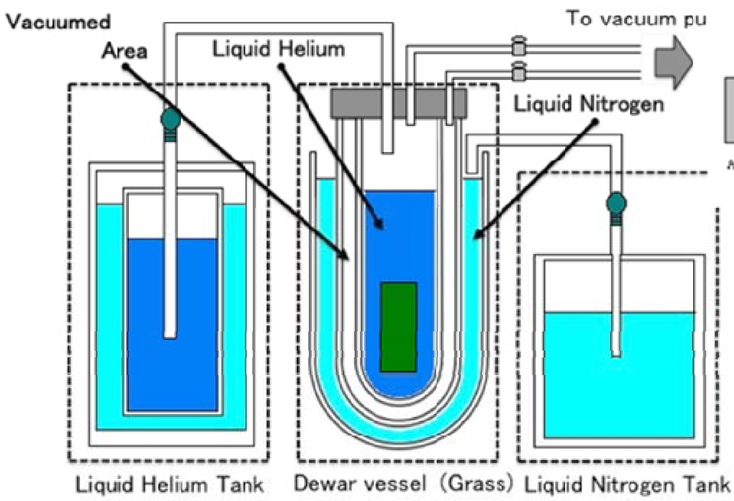
INTRODUCTION

When the liquid helium has its temperature below 2.2K, it becomes a super fluid, and indicates the unique properties. For instance, there exits the mass flow without friction, anomalous heat transport by a mechanism known as second sound, and quantized vortex lines in the turbulent state. These characteristics have been investigated by temperature fluctuation measurement and the second sound attenuation technique. However, they are model dependent and do not give the dynamical information of the fluid flow. For this reason, we have been interested in applying the visualization technique to the super fluid helium in order to obtain the local velocity fluctuation, and study the statistical characteristics.

Small temperature fluctuations in saturated super fluid He II (at 1.9K) was measured by using the small thermistors operated by a lock-in amplifier. The experiments were performed in a rectangular channel (13×13×200 mm) in which the heater was set at the bottom. We found that the periodic temperature oscillation and the pulsive boiling sound appear. They are synchronizing and the oscillating frequencies strongly depend on the helium pressure and the heat flux. When the He pressure decreases, the oscillation frequency decreases. However, the decay rate is independent of the heat flux. This physical mechanism will be discussed in the presentation with PIV analysis.

EXPERIMENTAL CONDITIONS

Figure 1 shows the schematic view of our experimental apparatus. In the glass dewar, the rectangular duct (cross section is $A = 1.69[\mathrm{cm}^2]$, length is $L = 20[\mathrm{cm}]$) made of GFRP is set. The liquid He temperature is set at 1.9K. The heater is located at the bottom, which generates the thermal counter flow. We measure the temperature inside the duct by small thermistors at three locations. From the temperature gradient, the heat flux carried by the normal fluid is calculated, which is compared to the heater supplied power $q[\mathrm{W/cm}^2]$. Small temperature fluctuations are measured by thermistors. We can observe cyclic sounds inside the dewar, which may be generated by the bubble generation due to the boiling. The sounds are recorded by microphone positioned on the top of glass dewar.



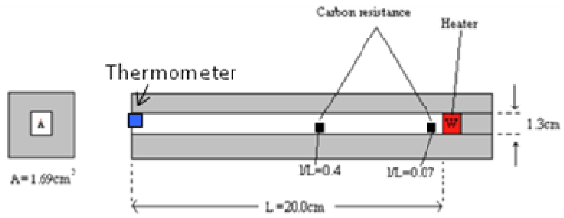


Figure 1 Schematic view of the glass dewar and the rectangular duct for thermal counter flow.

Figure 2 Tracer particles in liquid He at 1.6K

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CCD camera (1018×1008[pixels]) is used for visualizing the area $47[\mathrm{mm}] \times 47[\mathrm{mm}]$. Double pulse YAG laser is operated to generate the laser sheet whose thickness is about $1[\mathrm{mm}]$. We used the polystyrene microspheres whose density is $\rho_p = 145[\mathrm{kg/cm}^3]$ and its diameter is $d_p = 50[\mu\mathrm{m}]$. Figure 2 shows the visualized particles. They are carried by the thermal counter flow jet, but small density difference from the density of super fluid, the particles goes down gradually. We are thinking that this point should be improved in the next experiment.

RESULTS AND DISCUSSIONS

PIV measurement of He II forced flow with constant heat flux is performed. A constant heat flux up to 4.0 kW/m^2 was applied to a steady state forced flow through the channel using the heater. The heat can be transported by both the thermal counter flow and forced convection. The portion of the heat q conducted by thermal counter flow induces a the normal fluid velocity component, which can be expressed as $v = \rho sT$, where ρ is fluid density and s is entropy. We first measured the steady state temperature profiles at different heat fluxes along the flow direction and compared with the theoretical prediction. From this result, we can assume that the heat is transferred by forced convection can be neglected and essentially all the heat is transferred by the thermal counter flow in the same direction.

Particle image velocimetry (PIV) is a potential tool to measure the local velocity and it promises us to give a deep understanding of complex super fluid motions [1]. PIV is a standard technique in classical fluid researches. But its application to super fluid has just started, and there remains several problems. The most difficult one is the development of proper imaging particles that can be spread in homogeneous over the liquid and track the flow field. Liquid helium is a very low density fluid with small viscosity, and it exists in low temperature. These conditions prevent the conventional particle spreading techniques developed so far in classical fluid. On the successful application of tracer particles, there have been two challenges of PIV measurement in super fluid turbulence. One is the use of commercial (d~1μm) polystyrene microspheres and the other is the condensation and dispersion of solid hydrogen particulates from the gas phase. In the present study, we tried the former approach. From the PIV measurement we found the relation: $v[mm/s] = 50.6 \cdot q[w/cm^2]$ which is consistent with the normal fluid velocity calculated by the heater power.

Increasing the heat flux, we observed the film boiling phenomena in He II. Although this phenomenon was found in 1960's, little is known among this research community. In the boiling process, the pressure above lambda pressure (5kPa) is a decisive factor which boiling mode appears. Above the lambda pressure, the film boiling is related with the co-existence of three phases, that is He II, He I and helium vapor. Below the lambda pressure, the film boiling should be accompanied with only two phases; He II and helium vapor. The boiling curve for He II may be different from that of ordinary fluid, but the detailed things are not clarified. In He II boiling, the detached vapor bubbles cannot be seen due to extremely large effective thermal conductivity, and the nucleate boiling is only observed in a transition state at the beginning of film boiling [2].

In Fig.3, the temperature fluctuations measured inside the duct are plotted. The solid red line is the temperature near the heater, and the blue one is that at the exit. The periodic oscillation is clearly observed near the heater, but it disappears at the duct exit. This temperature oscillation may due to the film boiling of He II. Changing the heat flux, we investigate the temperature fluctuations. The oscillating frequency is affected by the heat flux. It becomes large for larger heater power. But it is found that the oscillating frequency is more strongly affected by helium pressure. In the film boiling there appears also a cyclic sound. The sound is associated with the bubble in the boiling. We measured the sound by microphone set up at the test section. The solid green line indicates the sound oscillations. Temperature and sound oscillations are synchronizing with each other.

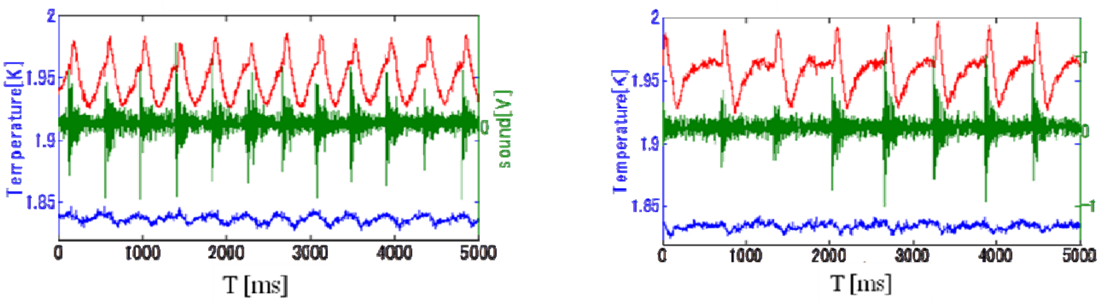

Figure 3 Temperature fluctuations inside duct measure by small thermistor. Solid red line is the temperature close to the heater and blue one is near the exit. Green solid line represents the sound fluctuations. The right handside and left handside are results measured at the same heat flux but different pressure condition.

[1] T.Xu and W.V.Sciver, PIV application in He II forced flow research, Teion Kogaku, vol.43,100-108, 2008
[2] S. Takada, Heat transfer mechanism of He II film boiling in a narrow channel, Ph.D thesis, Tsukuba Univ., 2009.