Experimental Study of Shock Waves in Superfluid Helium Induced by a Gasdynamic Shock Wave Impingement

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Abstract: Two modes of shock waves, a compression shock wave and a thermal shock wave, propagating in He II have been investigated. The shock waves are at a time generated by the impingement of a gasdynamic shock wave onto a He II free surface in the newly developed superfluid shock tube facility. Superconductive temperature sensors, piezo-type pressure transducers and visualization photograph were used for the measurement of them and the phenomena induced by them were investigated in detail. It is found that the compression by a compression shock wave in He II causes temperature drop because He II has negative thermal expansion coefficient. The thermal shock wave is found to be of a single triangular waveform with a limited shock strength. The waveform is similar to that generated by stepwise strong heating from an electrical heater for relatively long heating time. In the experiments at the temperatures near the lambda temperature, no thermal shock wave is sometimes detected in shock compressed He II. It can be understood that shock compression makes He II convert to He I in which no thermal shock wave is excited.

1. INTRODUCTION

Superfluid helium (He II) has been used as an excellent coolant for the cooling of superconducting magnets and infrared detectors in space. He II being a t liquid phase below lambda temperature (about 2.17K under saturated vapor pressure condition) has several unique properties that can not be explained by ordinary thermo-fluid mechanics. Among the properties, the existence of a temperature wave known as the second sound is a typical example. Many studies of thermal shock wave that is the nonlinear form of the temperature wave, have been done from physical and engineering interest. However, there are still unsolved open problems relating thermal shock wave. It is one of such problem that a large amplitude thermal shock wave is reduced to a single peak wave with a limited shock strength in spite of increasing the heat input. It is very important to understand this process for practical uses and more wide applications. For instance, in case that superconducting magnet quenching occurs, a strong heat pulse transmits through He II, and strong pressure oscillation is accompanied by boiling. Furthermore, as for the compression shock wave, very little studies have been done because of such experimental difficulties in strong pressure wave generation and quantitative measurement, etc. In this study, for the purpose of investigating two strong modes of shock waves, we have chosen an experimental method that can generate strong shock waves. For this purposes the newly developed superfluid shock tube facility is used, in which a gasdynamic shock wave generated in helium vapor impinges onto He II free surface. Upon the impingement a compression shock wave penetrates through the He II free surface, and a thermal shock wave is generated by heating from the gasdynamic shock and propagates into He II. Liepman et. al[1] and Cummings[2] have originally adopted this method to obtain large Mach number and large Reynolds number flows in cryogenic helium vapor. The present facility is considered as a further extension of it.

2. EXPERIMENTAL APPARATUS

2-1 The Superfluid shock tube facility

The schematic overview of the superfluid shock tube facility and the cross-sectional view of the test section of cryogenic shock tube are illustrated in Fig.1 and Fig.2 respectively. The shock tube facility consists of two major parts, a diaphragm-free shock tube with an M-O quick opening valve and a cryostat for maintaining He II.

The adoption of the quick opening valve is the very technical advantage of our shock tube in order to solve the technical problem that air and water vapor migration into the shock tube during a diaphragm replacement process causes frost contamination on inside wall of a shock tube. The shock tube consists of two parts, the high pressure chamber and the low pressure tube. In the former high pressure helium gas is charged as the driver gas. The latter has a rectangular cross section (35 x 25 mm) and is equipped with two pairs of optical windows with a diameter of 25 mm in the test section. It is charged with saturated helium vapor as the driven gas. The test section where shock waves are measured, located in the lower portion of the low pressure tube, is filled with He II. The measurement of the pressure variation is made by three piezo-electric pressure transducers located in He II and in helium vapor. The propagation speed of gas dynamic shock wave is measured by upper two pressure transducers of the three.

For the measurement of the temperature variation, we used superconductive temperature sensors schematically illustrated in Fig.3.

2-2 Measurement of the temperature variation

The temperature variation is measured through the variation in the electric resistance of the superconductive sensing element with a length of 2 mm. The sensing element consists of thin films of gold and tin with a thickness of 230Å and 1000Å, both of which are vacuum-deposited on the surface of a glass fiber with a diameter of 40μ m. This sensor is calibrated by referring to He II temperature regulated through the saturated vapor pressure controller.

Accurate measurement of the temperature up to 1mK is possible with this sensor. Owing to the high sensitivity and quick response of the sensor, the measurement of the temperature variation induced by very fast compression shock waves is possible.

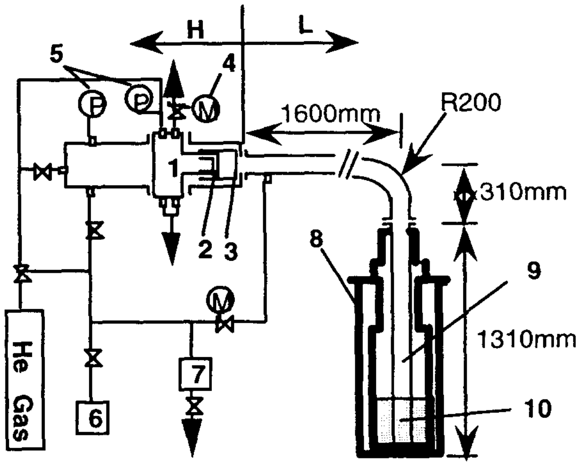

Fig.1. Schematic overview of the superfluid shock tube facility. H; High pressure chamber, L; low pressure tube, 1; M-O main valve, 2; Sub-piston, 3; Main-piston, 4; Electro-magnetic pilot value, 5; Pressure gauges, 6; Rotary vacuum pump, 7; Buffer tank, 8; Cryostat, 9 and 10; Test section filled with helium vapor and He II respectively.

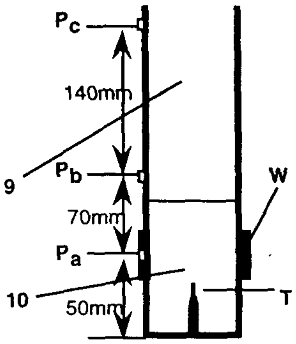

Fig.2. Enlarged cross-section of the test section. W; Optical window, T; Superconductive temperature sensor, Pa, Pb, Pc; Pressure transducers.

3. RESULT AND DISSCUSION

3-1. Theoretical predictions of shock wave

We introduce the approximation made by Khalatnikov[3], which have been frequently compared

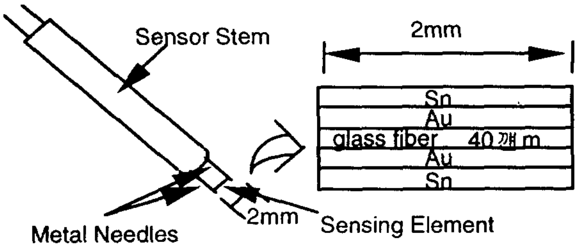

Fig.3. Superconductive temperature sensor

with experimental data. It is a weak shock wave approximation for both the thermal and compression shock waves. It is assumed that the jumps in all quantities across a shock wave are very small and the jumps in the temperature, the pressure and the connterflow velocity chosen as the independent variables are taken into account only up to second-order. The result for the temperature jumps is given for the thermal and the compression shock waves, respectively by

$$\Delta T = 2(M-1)\left[\frac{\partial}{\partial T}\ln\left(\frac{a_2^3 C_p}{T}\right)\right]^{-1} \qquad (1)$$

$$\Delta T = 0 \qquad (2)$$

The equation (2) indicates that no temperature jump is induced in a compression shock wave in He II in the level of the approximation. The denominator of Eg. (1) can be either positive or negative depending on the temperature. It is positive for T <1.88 K under the saturated vapor pressure condition, which means that the thermal shock becomes a front shock wave as ordinary shock waves. And for T>1.88 K, it has negative sign, a back shock wave is formed and the temperature drops across back side of a thermal pulse.

3-2. Typical time variation induced by a gasdynamic shock wave impingement onto He II free surface

A typical waveform detected by the pressure transducer and the superconductive temperature sensor in He II is shown in Fig.4. After a gas dynamic shock impinges into He II, a transmitted compression shock (C.S) propagates through He II and is detected firstly by the pressure transducer (Pa) and then by the superconductive temperature sensor (T). It is evident that the temperature jump in a compression shock is negative and the Khalatnikov approximation does not hold in the level of the present experiments.

The negative temperature variation is a natural consequence of compressed He II because it has negative thermal expansion coefficient. The second temperature and pressure jumps result from the reflected shock (R.C). The thermal shock wave signal (T.S) with a positive temperature jump can be recognized only by the temperature sensor after the detection of the expansion fan (E.F), because the speed of the second sound is much slower than that of the first sound. The triangular profile of the thermal shock suggests that intense heat is imposed after the impingement to generate high density quantum vortices which causes strong wave form deformation as a result of interaction.

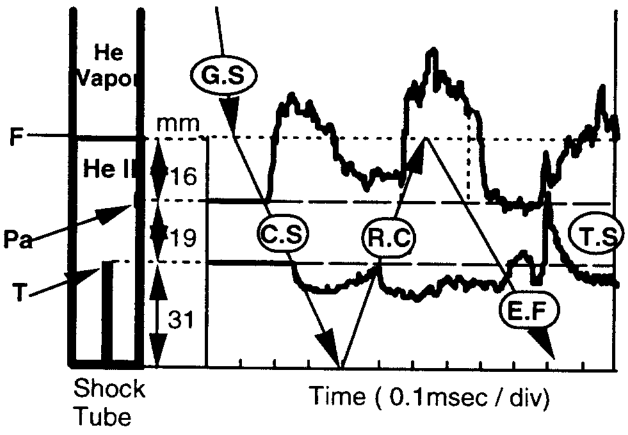

Fig.4.Typical waveforms detected by a pressure transducer (Pa) and a superconductive temperature sensor (T) after the impingement of a gas dynamic shock wave onto a He II free surface (F). The geometrical arrangement of the free surface, the pressure and the temperature sensors and the bottom of the test section is also drawn in this figure. Driver gas: helium gas (700KPa, 300K), driven gas: saturated vapor of He II at 2.7KPa, initial He II temperature: 1.95K. The speed of the gas dynamic shock wave (G.S): 354.3m/sec. The speed of the transmitted compression shock (C.S): 245.2m/sec. The speed of the compression shock reflected from the end wall (R.C): 276.5m/sec. · E.F: Expansion fan transformed from R.C reflected at the free surface. The velocity of the thermal shock wave (T.S): 20m/sec.

3-3 Differences of temperature jump by compression shock waves

Fig.5 shows the temperature profile induced by a transmitted compression shock wave (C.S) and a reflected compression shock wave (R.C) at 2.15K. This temperature profile is different from that shown in Fig.4, in the point that the temperature rises by compression shock waves. From these temperature rises, it is suggested that He II before compression by a transmitted compression shock, converts to He I by shock compression because He I has the positive thermal expansion coefficient. Of course, the sign of the thermal expansion coefficient changes from negative to positive at slightly higher temperatures than the lambda temperature. From this fact, He I conversion can not be judged only from the sign of temperature variation by compression shock waves. In order to verify this fact, we investigate the pressure and temperature variations induced by transmitted compression shock waves for several different He II initial temperatures in Fig.6. These data points are plotted on the phase diagram of He together with a number of isentropic curves starting from the same initial temperature as an approximation. In He II, compression causes temperature drop almost along the isentropic curves provided that the compressed state is far from lambda line as shown Fig.4. But the data measured near lambda line shows different tendency. Of course, temperature drop is still induced by very weak compression in He II and so is true in He I state at the slightly higher temperature region than lambda line.

Consequently, the change from drop to rise in temperature does not occur exactly on the lambda line.

Accordingly, it is the nonexistence of thermal shock wave to confirm the conversion from He II to He I.

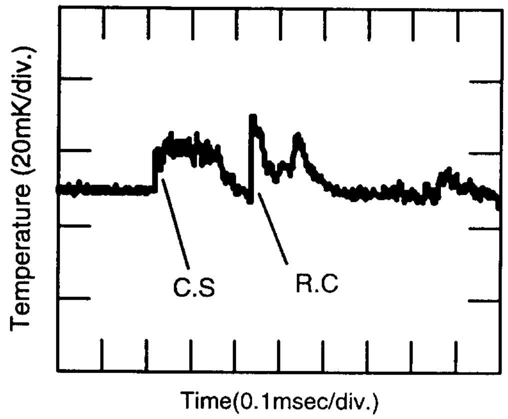

Fig.5. Time variation of the temperature induced by compression shock waves in the case of He II to He I conversion by shock compression. Initial He II temperature: 2.15K, Pressure rise by the transmitted shock wave: 0.60Mpa.

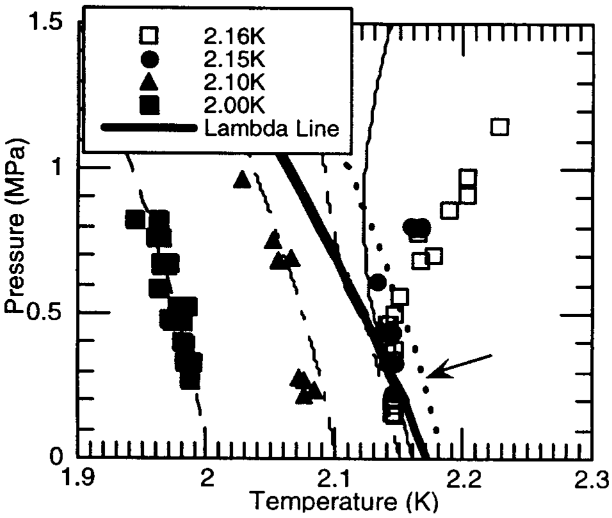

Fig.6. The pressure and the temperature jumps induced by transmitted compression shock wave. The data are plotted on phase diagram of He together with isentropic curves as an approximation. The dotted curve (arrow indication) indicates the change of the sign of thermal expansion coefficient. In the lower temperature region than the curve, the sign of thermal expansion coefficient has negative though the state is in He I.

3-4 Generation of thermal shock wave

3-4-1 Thermal boundary layer

Shown in Fig. 7 are photographs of free surface region taken at 0.1 msec after the impingement of a gas dynamic shock wave. Since the propagation of the transmitted compression shock wave is very fast, it is seen through the lower window. The point of this photograph is that the thickened discontinuity surface around the original He II free surface. It is thought that violent evaporation occurs responding to sudden heating by the compressed gas dynamic shock wave in the very initial phase. After this initial phase, the thermodynamic state of the interface region turns to supercritical state because of quite large temperature estimated about 30K from the Rankine-Hougoniot relation and pressure rises due to shock compression. The dark zone in the free surface region must result from the critical opalescence phenomenon in the pseudo critical state. It is considered that the region with very large temperature gradient in which the critical opalescence occurs develops between the original free surfaceand bulk He II, which may be called as the thermal boundary layer. The thermal boundary layer consists of three different thermodynamic states of helium, that is compressed vapor to compressed He II via compressed He I. It is considered that in the thermal boundary layer thermal conduction is a dominant heat transport process. However, such a heat transport mechanism as piston effect may be effective to supply heat through the supercritical state to He II to generate the thermal shock wave. It is understood that the mechanism of the wave deformation with limiting shock strength is the strong interaction of high density quantized vortices which develops as a result of intense heating with the thermal shock wave. The generation of the quantized vortices is responsible for poor heat transfer in the thermal boundary layer. As the results, the amplitude of thermal shock is quite limited.

3-4-2 Amplitude of thermal shock wave

Fig.8 shows the temperature amplitude of thermal shock which may be regarded as the shock strength of the thermal shock wave plotted against the pressure jump observed in corresponding transmitted compression shock for two initial temperatures 2.00 K and 2.14 K. It is seen that the strength increases almost linearly with the pressure jump in the case of 2.00 K. However, near the lambda temperature at 2.14 K, the temperature amplitude reaches the maximum value at the pressure jump around 0.2 MPa, and it vanishes above 0.5 MPa. That is to say, the thermal shock practically disappears above 0.5 MPa.

It is understood from this discussion that thermal shock wave does not exist even at 2.14K as the result of conversion of He II to He I due to

strong compression behind the compression shock wave.

4. SUMMARY

It is found that the pressure rise by a compression shock wave in He II causes temperature drop because He II has negative thermal expansion coefficient. The thermal shock wave is found to be of a single triangular waveform with limited shock strength. The waveform is similar to that generated by stepwise strong heating from an electrical heater for relatively long heating time.

There is a thermal boundary layer with a thickness of several mm between the impinging supercritical helium vapor and the compressed He II. In the experiments near lambda temperature, no thermal shock wave is detected in shock compressed He II. It can be understood that shock compression makes He II convert to He I in which no thermal shock wave is excited.

(a) (b)

Fig.7. Visualization photograph of the free surface region
taken by Schlieren method, (a) before impingement and (b) 0.1msec after the impingement. F: initial free surface, C.S: transmitted compression shock wave compressing He II up to about 0.5MPa. Please note the discontinuity of free surface region is getting thicker within very short time.

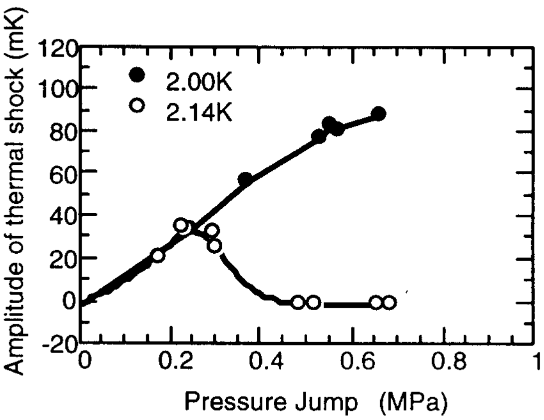

Fig.8. Amplitude of thermal shock wave as a function
of pressure jump of the transmitted compression shock
wave

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