Chapter 1

INTRODUCTION

The present study is to investigate a number of low-temperature thermo-fluid dynamic phenomena of superfluid helium ($HeII$) by utilizing the newly developed superfluid shock tube facility. The primary research target are two modes of shock waves, a compression and a thermal shock waves and the λ-phase transition from $HeII$ to HeI induced by shock compression.

A considerable number of studies have been conducted concerning shock waves in $HeII$ [1 $\sim$ 14]. Among them, a great deal of effort has been made on the study of a thermal shock wave, which is a non-linearly developed second sound wave as a genuine temperature wave. In the study of a thermal shock wave, it is usually generated by stepwise strong heating from a heater in $HeII$. Many researchers have selected this method, because input heat flux can be clearly defined and the control of the experimental condition is rather easy even in superfluid experiments. Though this method is quite suitable for the generation of a strong thermal shockwave, only a very weak compression shock wave can be generated by this method. Most studies have focused on thermal shock waves, which is peculiar physical phenomena in $HeII$, but quite a few have been interested in compression shock waves. The reason is that, in general, the physical nature of a compression shock wave is almost same as that in ordinary compressible fluids and that it is very difficult to generate a strong compression shock wave in $HeII$. However, if we consider the problems of highly transient heat transfer in $HeII$ in which strong non-linearity dominates, we understand that the non-linearity not only of a thermal shock wave but of a compression shock wave must be taken into account. In reality, little studies have been conducted concerning non-linearity of a compression shock wave, while a large number of studies have been done for a thermal shock wave.

It is well known that superfluid helium (*HeII*) exhibits several unique properties, such as extremely high apparent thermal conductivity and the ability to flow through even extremely fine channels without any appreciable pressure drop. *HeII* is expected to be an excellent coolant for cooling of superconductive magnets and space devices which require low-temperature environment for high performance. A deep understanding not only of steady *HeII* heat transfer but also of transient heat transfer is needed for further promotion of the practical applications of *HeII* to cryogenic cooling. The quench mechanism of a *HeII* cooled superconductive magnet involving a violent pressure oscillation and boiling heat transfer is not fully understood even now. This is one of the motivation for the present study of the non-linearity of a compression shock wave propagating through *HeII*. However, it is very difficult to generate a strong compression shock wave in *HeII* as mentioned above. Any low-temperature experiments can be only carried out in highly restricted space in a cryostat. This requirement, in turn, brings about the experimental difficulty in a shock wave experiment.

In the second half of the 1970's, Liepmann et al.[15] and Cummings [16] undertook the pioneering researches on a compression shock wave in liquid helium. The original objective of their research had been originally the study of high-speed gasdynamics and had aimed the achievement of an ultra-high Mach number flow with the aid of the cryogenically cooled test section by liquid helium. Then, the experiments were further extended to superfluid helium dynamics researches [17, 18, 19]. With this experimental facility a strong compression shock wave could be generated in *HeII*. Their experiments, in fact, succeeded as pioneering works in the superfluid experiment, but they were far from complete success, in particular, in quantitative data acquisition for further profound quantitative argument. Their cryogenic shock tube was merely a straightforward extension of a conventional shock tube to a cryogenic shock tube. Accordingly, the facility was suffered from difficulties arising in low-temperature environment. In particular, they faced some difficulties in repeated experiments. The main difficulties result from the migration of tiny flacks of broken membrane into a low-pressure tube section and from the contamination of frozen atmosphere on key surfaces in cryogenic sections during membrane replacement processes. Accordingly, successive shock tube operation was impossible within a rather short interval. Furthermore, absolute measurements of the pressure and the temperature could not be performed because of lack of detectors which can be used in the liquid helium temperature environment.

So, we newly developed the superfluid shock tube facility which is a diaphragm-free shock tube equipped with an MO-valve developed by Maeno and Oguchi [20, 21]. The superfluid shock tube was designed to be capable of operating with a $HeII$-filled test section of the low-pressure tube section immersed in $HeII$ in a cryostat. In this noble facility, a gasdynamic shock wave which is generated in a gasdynamic shock tube section impinges on a $HeII$ free surface, and, in part, penetrates into $HeII$ as a transmitted compression shock wave and, at the same time, a thermal shock wave is generated in $HeII$. [22 $\sim$ 26] We could overcome the difficulties described above by using an MO-valve. The diaphragm-free shock tube is capable of a frost-contamination-free operation and a repeated operation within a short interval with a cryogenic fluid. In addition, it even enables a synchronized shock discharge with a number of phenomena due to its excellent reproducibility in operation. There is another technical merit for this facility. It is the windows for visualization study installed at the test section of the shock tube. It is, in general, considered that windows installed to a superfluid cryostat should be avoided because of thermal radiation heat leak through them and of super leak of $HeII$ through a seal of a window glass plate. All these difficulties have been resolved by our group. Visualization can provide us positive understanding of the phenomena. Furthermore, visualization enables us understanding several phenomena appearing simultaneously in a space within an aperture range. In the present study, the Schlieren visualization method is used for visual observation of propagating and reflecting shock waves and other relating phenomena.

This thesis consists of the following four subjects.

(1) Gasdynamic shock wave propagating in low-temperature environment.

The nature of a gasdynamic shock wave propagating in low-temperature environment is investigated to verify the operational characteristic of the newly developed superfluid shock tube facility and to demonstrate its validity for the study subjects. For this purpose, the experimental data are compared with the Rankine-Hugoniot relation which holds between gasdynamic quantities across a shock wave. The impedance matching among $HeII$ and its vapor is also investigated for the transmission of shock waves through a $HeII$ - HeI phase surface.

(2) Characteristics of a compression shock wave propagating through $HeII$.

It is usually very difficult to quantitatively describe shock wave propagation through liquid. This is not only because the total account of available data are rather scarce owing to the difficulty in experiments, but because ordinary liquids do not have high compressibility like gases and thus strong shock waves are hardly generated in liquid and the dynamic nature is not fully described on the basis of the straightforward extension of gasdynamic theory [27, 28]. However, $HeII$ has a very large compressibility compared with other liquids and consequently a clear shock wave can easily been observed. And the behavior can be well described by the two-fluid equation by Landau [29, 30]. This has been verified by the experimental results on thermal shock waves. The Numerical solution to Rankine-Hugoniot relation in $HeII$ will be compared with the present experimental results on a compression shock wave.

(3) Thermal shock wave induced by gasdynamic shock wave impingement.

A large number of studies have been conducted concerning a thermal shock wave in $HeII$. [31 $\sim$ 40] Our group also have been engaged in the researches on thermal shock wave relating phenomena, such as the propagation of a thermal shock wave and the deformation of wave forms by high density quantized vortices. [41 $\sim$ 48] In the conventional method of thermal shock wave generation by stepwise heating from a heater, the strength of a thermal shock wave is highly restricted because of boiling. So, the idea that the thermal shock wave is induced by a gasdynamic shock wave impingement is introduced in this study. Because there is no apparent limit of the heat flux to produce a thermal shock wave, it is expected that a thermal shock wave with strong non-linearity can be generated. And the interaction of both shock waves are possible to be caused.

(4) λ-phase transition induced by shock wave compression.

It is well known that two phases, HeI and $HeII$, exist in liquid helium. In engineering applications of subcooled (pressurized) $HeII$, the phase transition from $HeII$ to HeI crossing the λ-transition line may appear prior to boiling and then the excellent cooling due to super-thermal-conduction of $HeII$ would be lost. Accordingly, it is very important to understand the highly transient heat transfer in subcooled $HeII$ accompanied by the λ-phase transition. Not a few studies have been carried out on the heat-transfer-induced-λ-transition [49 $\sim$ 52] but none of them have paid attention to dynamic aspects of the process. In this study, the λ-phase transition is induced by shock compression to investigate it from dynamic point of view. The process arising in the shock tube facility is an extremely high-speed one with a characteristic time of the order of a few μ sec and would be a non-equilibrium phase transition. This may be the first study on the highly transient λ-phase transition. The transient temperature variation was primarily investigated to confirm the occurrence λ-phase transition.