

Chapter 1

INTRODUCTION

The study of evaporation phenomena from a liquid-vapor free surface is of considerable importance in various fields of engineering as well as in physics and chemistry. In engineering, there are not a few relating researches, such as those on the evaporation-condensation heat transfer in heat pipes and the evaporation control in vacuum deposition equipment. In the present study, a superfluid helium (He II) environment is used to provide a favorable experimental situation for the study of transient evaporation. It is regarded as a practically pure liquid-vapor system without any non-condensable gases. In the liquid-vapor systems of conventional substances, effects of non-condensable gases cannot be avoid, and, in particular, in the initial transient phase the effects dominate. However, in a He II-vapor system, where all gases except helium are in frozen state due to absolutely low temperature. In addition to the realization of a practically pure system, a He II environment provides another experimental advantage that a He II free surface can be stepwise heated by the impingement of a second sound thermal pulse. A second sound thermal pulse can maintain an extremely sharp wave front in the temperature rise as a result of non-linear development of a finite amplitude second sound wave to a thermal shock. Thus, the impingement of a thermal pulse onto a He II-vapor interface enables an approximately stepwise heating of an interface. It is, thus, another characteristic feature of the present experiment that the experimental procedure can fairly well reproduce the physical situation of stepwise heating of liquid-vapor interface which is usually assumed

in the kinetic theory analysis for a transient evaporation problem[1]. Furthermore, the heating time can be well defined as the duration time of a thermal pulse, and the heat flux can be definitely calculated from the thermal pulse amplitude. Both the characteristic features which are due to shock wave nature of a finite-amplitude thermal pulse exist only in He II. It may be a further advantage of He II environment that a superconductive temperature sensor with a high sensitivity and an extremely quick response can be utilized in the measurement.

One of the main objectives of this thesis is the investigation of evaporation phenomena conducted in a practically pure system in direct comparison of the experimental results with kinetic theory analysis results. It is another objective to obtain the condensation coefficient of He II experimentally. In addition to the transient evaporation investigation, other two studies are conducted in a series of experiment because they are very important to understand He II evaporation phenomena. One is the reflection of a second sound thermal pulse from a He II free surface. The other is He II condensation induced by a pressure wave impingement onto a He II free surface from vapor side. In what follows, the significance and the background of the present study are described.

1.1 Transient Evaporation Phenomena

In order to rigorously investigate the evaporated vapor flow region, molecular interactions between the emitted molecules from liquid and impinging molecules onto liquid phase from vapor must be taken into account in the vicinity of the liquid-vapor interface in vapor phase. The thickness of this interaction layer, the Knudsen layer, is the order of the mean free path of molecules. The existence of the Knudsen layer, in turn, has a significant effect on evaporation phenomena. In order to analyze the inside structure of the Knudsen layer, the analysis must be based on the kinetic theory of gases, in which the Boltzmann equation must be solved. The analytical result of the Boltzmann equation for an evaporation problem is usually

represented in the form of the slip boundary conditions at an interface. There have been many analytical researches on evaporation phenomena on the basis of the kinetic theory of gases. The analytical treatments of steady-state evaporation are conducted by Pao[2][3], Cipolla[4], Sone and Onishi[5]-[7], Matsushita[8] and so on. These solutions given numerically are almost same. Among the existing studies of evaporation phenomena, there have been also many experimental studies of steady-state evaporation from the liquid-vapor interface. The steady-state evaporation from a planar mercury interface is experimentally studied by Adt et al.[9]. The steady-state evaporation and condensation between two parallel surfaces, one of which is evaporating and the other condensing, is experimentally investigated by Shankar and Deshpande[10]. On the other hand, transient evaporation from a liquid surface was numerically studied for the case of weak evaporation in pure vapor by Shanker and Marble[11], for strong evaporation in a pure liquid-vapor system by Sone and Sugimoto[1] and for strong evaporation in the case of binary mixture gas by Onishi and Miura[12]. However, the experimental studies on highly transient evaporation from a liquid-vapor interface excited by stepwise heating of an interface have been little conducted as far as the authors know. This is partly because in most liquid-vapor systems of conventional substances the strong effect of non-condensable gases cannot be avoided in transient evaporation process, and partly because heating of liquid-vapor interface cannot be stepwise done due to thermal dissipation effect in liquid phase. From this point of view, the present study is very important for the verification of the kinetic theory analysis results for the transient evaporation problem.

1.2 Condensation Coefficient

It is also an important research objective of the present experimental evaporation-condensation study to obtain the evaporation and condensation coefficients. These evaporation and condensation coefficients are

defined as

$$\frac{(\text{Actual experimental value of mass flux})}{(\text{Theoretical maximum mass flux})} = \alpha. \quad (1.1)$$

The evaporation and condensation coefficients are the physical properties of substances. Those for many substances are summarized by Pound[13] and Chekmarev[14]. The coefficients for water are measured by many researchers, but the values are scattered in a wide range from 1 to 0.01, and thus, the reliable values for water are not yet available. For these data scattering Eames[15] pointed out the following reasons; the measurement error in the free surface temperature, the experimental environment problem such as non-condensable gases included in the experimental system, the use of the wrong theoretical maximum mass flux that dose not take account of the Knudsen layer effect, that is based on the free molecular theory. The evaporation and the condensation coefficients, in fact, depend on the temperature. This fact is experimentally confirmed for mercury by Adt[9], for rubidium by Huang et al.[16], for water on ice surface by Haynes et al.[17]. Furthermore, in recent years, as the numerical study based on the molecular dynamics has been highly developed, the estimation of these coefficients has been tried. For example, the condensation coefficient of argon is estimated to be 0.8 by Yasuoka et al.[18] and that of methanol $0.2 \sim 0.25$ by Matsumoto et al.[19].

In the kinetic theory analysis for evaporation-condensation problems, in general, there is no distinction between the evaporation coefficient and the condensation coefficient, in which the condensation coefficient is defined as

$$\frac{(\text{Number of condensed molecules among impinging molecules})}{(\text{Total number of impinging molecules on free surface})} = \alpha_c. \quad (1.2)$$

Eq.(1.1) includes the effect of the thermal accommodation coefficient. The accommodation coefficient is defined as the degree of the reflected molecules from a free surface to accommodate to the temperature of the free surface. If the accommodation coefficient is unity, all reflected molecules which strike the free surface rebound with the temperature of the free sur-

face, and in this case $\alpha = \alpha_c$. In this study, the definition of Eq. (1.2) is adopted because the main objective of this study includes the direct comparison of the present experimental results with the kinetic theory analysis result.

The condensation coefficient α_c of He II was first experimentally obtained from the measurement of the distillation rate of He II by Atkins et al.[20]. It was also derived through the comparison of the measured value of the reflection coefficient of a second sound R_{22} , defined as the ratio of the temperature rise of impinging second sound to that of reflected one at a He II free surface, with the theoretical prediction by Hunter and Osborne[21]. The condensation coefficient was also obtained by Kessler and Osborne[22] from a different point of view in which the experimental value of the transformation coefficient, T_{2G} , defined as the ratio of the temperature rise of an evaporation wave to that of an impinging second sound onto a free surface was compared with the theoretical one. It is now understood that the condensation coefficient obtained by Atkins et al.[20] was not correct because they applied the kinetic theory result for free molecular gas to compute the possible maximum evaporation mass flux as pointed out by Hunter and Osborne[21]. And it can be further concluded that the condensation coefficients obtained by Hunter and Osborne[21] and Kessler and Osborne[22] are also not correct. Two facts can be pointed out for this conclusion. One is that the enthalpy flux density of evaporated vapor is not taken into account for the energy balance across the He II-vapor boundary in the derivation of the theoretical values of R_{22} and T_{2G} . The other is that they applied the theory based on the kinetic theory for free molecular gas presented by Hunter and Osborne[21], where the effects of the Knudsen layer are not taken into consideration, to give the evaporation mass flux in the estimation of the theoretical values of R_{22} and T_{2G} . In the present study, the condensation coefficient of He II is estimated from the direct comparison of such experimental results, as the temperature, the pressure and physical quantities which are derived from them, with the most reliable kinetic theory analysis results. In these comparison

the pressure measurement data in the evaporated vapor flow region is very important. In the previous experimental studies, the quantitative measurement of the pressure for the He II evaporation phenomena have never been pursued. The quantitative pressure measurement in the evaporated vapor is first conducted in this study. The temperature dependence of the He II condensation coefficient has never been reported. This report may be the first one describing the temperature dependence of the He II condensation coefficient.

1.3 Reflection of a Second Sound on a Free Surface

It is of great interest how second sound is reflected from a He II free surface. As the second sound is a compression wave of rotons which are quasi-particles excited in the present experimental temperature range, the reflection problem has also got interested in from the viewpoint of quantum mechanics. In low temperature physics, the boundary conditions for the reflection and transmission of these waves are paid attention to, not only in the case of second sound impingement on a He II free surface but also in the cases of the first sound impingement on a He II free surface[23][25] and of the pressure wave impingement on a He II free surface from vapor phase[24][25]. In the past, there have been not a few experimental and theoretical studies on these kinds of reflection and transmission problems. The macroscopic theories of the mode conversion process of sound waves into a number of propagating disturbances across a He II free surface were developed by Pellam[26], Dingle[27] and Chernikova[28]. The boundary conditions for the process were also investigated on the basis of the kinetic theory of gases by Osborne[29] and Hunter and Osborne[21]. Meinhold-Heerlein[30] theoretically considered the superfluid-vapor boundary condition for the mode conversion process by applying thermodynamics for irreversible processes, and this kind of boundary condition was further generalized by Wiechert[32]. A particular solution of it was presented for the linear case by Wiechert and Buchholz[31]. On the other hand, among

the experimental studies, Wiecher and Buchholz[25] measured almost all reflection and transmission coefficients of sound waves through a He II free surface. But, it is now understood that in Wiecher and Buchholz's experiment[25] some calibration errors are included in the measurements of the pressure and the temperature in vapor phase. The only value correctly measured value may be the reflection coefficient R_{22} . The reflection coefficient R_{22} was also measured by Hunter and Osborne[21], Buchholz et al.[33] and Moody[34]. These experimental results of the reflection coefficient R_{22} are almost same. However, as already described in Sec.1.2, the relating theoretical studies are all somehow incorrect. In the present, the experimental value of R_{22} obtained by the direct measurement of the temperature amplitudes of an incident and a reflected thermal pulses is compared with the theoretical value estimated from the most reliable kinetic theory result with the boundary condition where the enthalpy flux density of evaporated vapor is taken into account in the energy balance formular.

1.4 Effect of Super Thermal Conduction on He II Condensation

In He II condensation phenomena the effect of super thermal conduction appears. In the present study, highly transient He II condensation phenomenon is caused by a weak shock wave (evaporation wave) impingement on a He II free surface from vapor phase. As described in Sec.1.3, a number of experimental studies[21], [22], [25] have treated the reflection and the transmission of a pressure wave impinging onto a the He II free surface from the vapor. The reflection coefficient of a pressure wave was measured only by Wiechert and Buchholz[25] with an AC-type microphone pressure transducer. It is, however, found that their pressure measurement data includes significant calibration error, as described in Sec.1.2. In the present study, the pressure amplitude reflection coefficient of an evaporation wave on a He II free surface is directly measured with a DC-type pres-

sure transducer. From the comparison of the experimental result of the reflection coefficient on rigid wall covered with superfluid thin film with that on a He II free surface, the effect of super thermal conduction in He II on condensation is investigated. This study may be the first one describing the effect of the super thermal conduction on He II condensation.