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Condensation Induced by Rarefaction Waves and Reflected Rarefaction Waves①

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ABSTRACT

In this paper, homogeneous condensation induced by unsteady rarefaction waves and reflected rarefaction waves in vapor–gas mixture was investigated experimentally. It is shown that the temperature of condensation onset during very fast unsteady expansion in vapor–gas mixture is much lower than that during equilibrium process in the atmosphere. It is of interest to indicate that the size of droplets approximates a constant, but the number density and the mass density of droplets change rapidly in the region of static flow.

Key words: Shock tube, Rarefaction waves, Condensation

I. INTRODUCTION

Usually, the process both occurrence and disapparance of cloud and fog in the atmosphere can be described by equilibrium thermodynamics. In the area of weather modification such as rain stimulation and hail mitigation by artificial means, the process of very fast unsteady changes in gas, water vapor and droplets mixture is important. Unfortunately, we do not exactly know the inherent characters of this process now. due to the phenomena of the fast unsteady condensation and evaporation are contacted with supersonic tube, turbine and combustion engine et al. many studies have been made. By using the methods of expansion cloud–chamber and diffusion cloud–chamber, supersonic tube and expansion tube Kotake and Glass (1981), Peters and Paikert (1989) investigated the processes of unsteady nucleation and condensation in vapor–gas mixture. Marble (1969), Netteton (1977) reviewed the phenomena of evaporation Goossens et al. (1986), (1988) and Smolders et al. (1989, 1992) studied the structure of a shock wave in fog and the evaporation caused by passage of the shock wave.

In this paper, we studied homogeneous condensation in vapor–gas mixture induced by unsteady rarefaction waves and rareflected rarefaction waves in shock tube. Our purpose is to investigate the process of phase transformation during very fast unsteady condensation in vapor–gas mixture. A two–wavelengths light extinction method was used to calculate droplet size and droplet concentration. The homogeneous condensation process, including changes of number density and mass density of droplets, was observed.

II. EXPERIMENTAL METHOD AND FACILITY

The experiments were conducted in a conventional shock tube with a square cross–section

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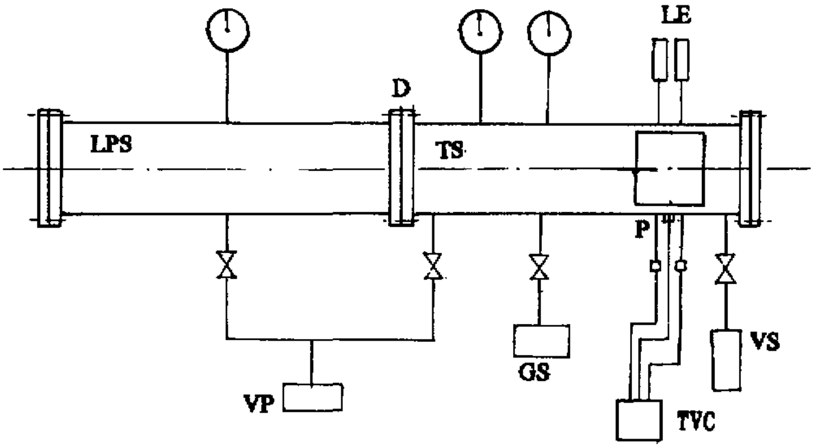

Fig. 1. Schematic of experimental facilities. TS–test section, LPS–lower pressure section, D–diaphragm, VP–vacuum pump, VS–vapor supply, GS–gas supply, LE–two wavelengths light extinction facility, P–pressure transducer, TVC–transient wave converter.

of 94 × 94 mm^2 as shown in Fig. 1. The driver section is 2.35 m long, and the driven section is 2.0 m long. There is a mylar diaphragm between driver and driven section. In order to perform the interaction of rarefaction waves and reflected rarefaction waves with vapor–gas mixture, the driver section is used as a test–section. and a viewing window of 100 × 120 mm^{2}is located 15 mm apart from the end of test–section. Two semiconductor lasers (λ_1 = 670 μm, λ_2 = 780 μm) are used together with two photodiodes as a light detector for measuring droplet

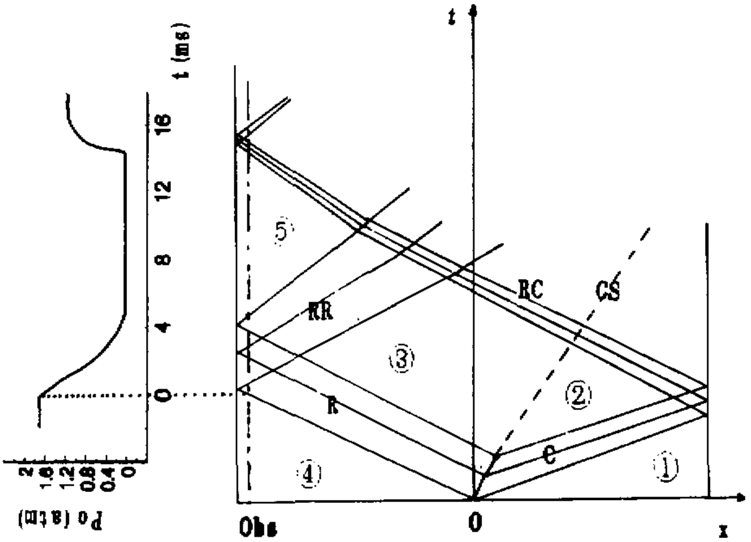

Fig. 2. Schematic of wave pattern and pressure change at point Obs C–compression wave, CS–contact surface, R–rarefaction wave, RC–reflected compression wave, RR–reflected rarefaction wave, Obs–observatoion point.

size and droplet number density. The pressure in the interaction region of rarefaction waves and reflected rarefaction waves is measured by a piezoelectrical pressure and the light are simultaneously recorded on a transient wave converter and a micro–computer.

Firstly, the pressure in the test–section is evacuated to a certain value, then, a vapor–gas mixture is filled to it. Finally, the mylar diaphragm is rupture by using electrical heating of a wire which is attached to the surface of it. Fig. 2 shows the wave pattern at schematic $x - t$ plane after a mylar diaphragm breaks, where x is distance and t is time, and the corresponding change of pressure in p–t diagram at the point Obs.

The vapor–gas mixture is expanded adiabatically through the rarefaction waves and reflected rarefaction waves before condensation happening. The onset of condensation and the growth of the droplets are detected by means of the two–wavelengths light extinction method, called DQ method, described by Goossens in 1988. The DQ method is based on the principle that the extinction of a plane light wave in a cloud of droplets is a function of wavelength. With this method, the mean droplet radius and droplet number density can be calculated and the width of the droplet size distribution function can be estimated. According to Lambert–Beer's Law, the intensity of light beam passing a scattering medium over a distance L is described as follows:

$$I = I_0 \exp(-\beta L) \ , \tag{1}$$

considering that the scattering medium consists of droplets with a certain size distribution, and a number density N, and the refractive indices of the media are given. The extinction coefficient β can be written as

$$\beta = N\pi < r^2 Q > \ , \tag{2}$$

where Q is the extinction efficiency, r is droplet radius and $< r^2 Q >$ denotes the average extinction cross–section. The extinction efficiency Q is a known function of r / λ and can be calculated for spherical particles by using Mie theory.

The dispersion quotient DQ is defined by Goossens et al. as a ratio of the extinction coefficients β_1 to β_2 measured by two different wavelengths. It can be written as

$$DQ = \frac{\beta_1}{\beta_2} = \frac{< r^2 Q_1 >}{< r^2 Q_2 >} \ . \tag{3}$$

Usually, the droplet size distribution $F(r)$ is proposed to satisfy a zeroth order log normal distribution with a model droplet radius r_m and width parameter ε

$$F(r) = \frac{1}{\sqrt{2\pi}\,\varepsilon r_m} \exp\left[- \left(\frac{\ln\left(\frac{r}{r_m}\right)}{\varepsilon\sqrt{2}} \right)^2 - \frac{\varepsilon^2}{2} \right] . \tag{4}$$

For a constant ε, the value of DQ first strongly decreases with increasing of particle size and goes to an absolute minimum. The value of the minimum of DQ depends on ε. When the droplets formed by condensation become sufficiently large, the minimum DQ value can accurately be measured.

In the present experiments, we assume that the condensed droplets have equal size at the same time (Hastings and Hodgson, 1979). With measured two different wave length light extinction, the droplet radius r and the number density N can be calculated from Eq.(1) and Eq.(2). The mass of droplets per unit volume ρ_p can be expressed in the droplet number density N and the density of water material ρ_w by:

$$\rho_p = \frac{4}{3}\pi < r^3 > \rho_w N \ , \tag{5}$$

where $\frac{4}{3}\pi < r^3 >$ is the averaged volume of droplets.

III. EXPERIMENTAL RESULT AND DISCUSSION

Typical experimental results of homogeneous condensation due to unsteady expansion in vapor–gas mixture are shown in Fig. 3, and states before and after the rupture of diaphragm are given in Table 1.

Table 1.

p_1(atm)	p_4(atm)	p_{41}	T_4(K)	p_5(atm)	T_5(K)
0.1	1.7	17.0	298.0	0.0455	105.96

Where p_1 is the initial pressure in driven section of shock tube, p_4 and T_4 are the initial pressure and temperature in test–section of shock tube, respectively. p_{41} is the ratio of the pressure p_4 to the pressure p_1. p_5 and T_5 are pressure and temperature in the region behind the end of reflected rarefaction waves, respectively. It is noted that the parameters in Table 1 present the condition of isentropic flow in which no condensation occurs.

The signals of pressure and two–wavelengths light extinction are illustrated in Fig. 3a in which the condensation of vapor–gas mixture takes place under the effect of unsteady rarefaction waves and reflected rarefaction waves. Then, reflected compression waves cause the water droplets to evaporate. The expansion of this mixture gas is regarded as isentropic before the onset of condensation happening. So the temperature of the onset can be calculated from isentropic relation

$$\left(\frac{T_c}{T_4}\right)^{\frac{1}{2}} = \left(\frac{\rho_c}{\rho_4}\right)^{\frac{r-1}{2}} = \left(\frac{P_c}{P_4}\right)^{\frac{r-1}{2r}} \ , \tag{6}$$

where subscript c represents the state of condensation taking place. As soon as condensation occurs, the state of gas–droplet mixture no longer obeys the isentropic relation, because latent heat is released.

The temperature T_c(111 K) is calculated with p_4, T_4 and p_c. The pressure p_c (0.05 atm) is observed at state of the onset of condensation. The droplet radius r, number density N and mass density ρ_p are calculated and shown in Fig.s 3b, 3c 3d. It follows from Fig. 3 that droplet size grows up so quickly that it takes almost no time from zero to a constant that equals about 0.51 μm in the beginning of condensation. On the other hand, it takes about 2.0 ms for both the number and the mass density of droplets changing from zero to the first peak. In the region between the end of reflected rarefaction waves and the beginning of reflected compression waves, in which the gas–droplet mixture is at rest, the droplet radius r almost remains the constant, but the number density and mass density of droplets decrease obviously after the first peak, then both of them rapidly increase to the second peak at 13.7 ms. It takes about 7.7 ms for this process. This phenomenon is interesting and represents the non–equilibrium condensation process of vapor–gas mixture.

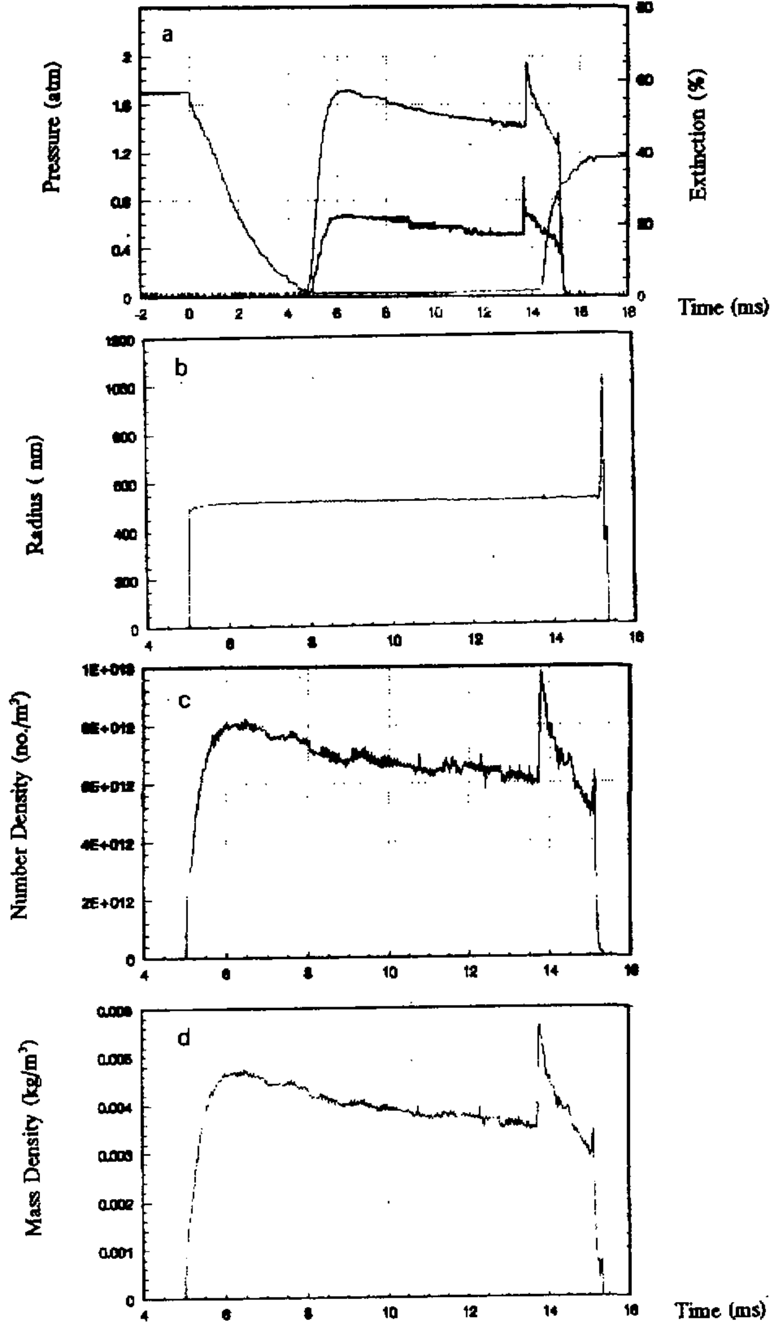

Fig. 3. Typical recordings of rarefaction waves and reflected rarefaction waves induced condensation of vapor–gas mixture. The initial conditions as follows: P1 = 0.1 atm, P4 = 1.7 atm, T = 298 K. (Fig. 3a–pressure and light extinction, Fig. 3b–droplet radius, Fig. 3c–number density, Fig. 3d–mass density).

From the experimental results above, it is evident that the unsteady condensation of vapor–gas mixture is different from the condensation occurred in the natural atmospheric environment. In the natural atmospheric environment, water vapor and supercooled droplets usually become ice crystals at about–40°C. But in the process of very fast unsteady expansion with rapid decrease of temperature, the temperature of condensation onset is much lower than that in the natural atmospheric environment. This delay process may be considered as the result from an additional resistance of the pressure decrease against the condensation of water vapor. But it is difficult to explain another interesting phenomenon that the number density and mass density of droplets decrease from 6.0 ms to 13.7 ms both of them rapidly increase to the second peak at 13.7 ms. This phenomenon is happened in the region of static flow where the pressure almost remains a constant. We try to give an explanation to this phenomenon by using the viewpoint of non–equilibrium thermodynamics.

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