Experiment of Non-equilibrium Condensation on the Cold Wall in Alternative Freon Vapor Flow behind Shock Waves

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Abstract
The aim of the present study is to investigate the non-equilibrium condensation of alternative Freon vapor on the cold wall behind the shock waves. To clarify the relation between the shock wave propagation and the phase change of vapor behind the shock wave on the shock tube side wall, the liquid film thickness and heat flux are measured. Experiments were carried out by using a diaphragmless and a low temperature shock tube that can be cooled down to 100K by using liquid nitrogen. The time dependent thickness of liquid film was measured by an optical interferometric method based on multiple reflections of a He-Ne laser beam at the interface of the thin liquid film and the transparent optical glass. The condensation heat flux was measured by a platinum thermo-sensor. It is found that the liquid film thickness and the condensation heat flux rapidly change behind the reflected shock waves. It is also found that for the same initial temperature, a higher \( \rho_0 \) led to a faster growth of the liquid film, however it is not cleared the difference in the liquid film growth behind the reflected shock wave.

Key words
Diaphragmless Shock Tube, Non-equilibrium Condensation, Liquid Film, Heat Flux, Multiphase Flows

1. Introduction
Non-equilibrium vapor condensation is one of fundamental problems of thermo-fluid dynamics. It is connected with applied problems such as two-phase flow, boiling, cavitation, combustion and semi-conductor production. A shock-tube is a suitable device for performing not only homogeneous condensation, but also heterogeneous condensation.

Condensation and evaporation phenomena are observed in various engineering fields. For example, they are observed around an acro-plane passing through rain clouds and in internal flows of a high speed pump or a vapor turbine. If these interferences are further intensified, erosion or vibration of pump blades will be caused, in the worst case equipment or pipelines will be damaged. In order to prevent the above phenomena, it is important to clarify the impact of condensation shock wave.

Especially, at a low temperature, as the speed of sound in the vapor becomes low, shock waves easily occur [1]. To make clear the relation of the shock wave and these phase changes, the condensation liquid film thickness and heat flux behind the incident and the reflected shock waves on the shock tube side walls were measured at a low temperature.

A limited number of papers were reported on the relation of the condensing non-equilibrium liquid film and the shock waves. On the shock tube end wall, non-equilibrium liquid film was measured by using an interferometric method behind the reflected shock wave, the mass transfer condensation coefficient of methanol was also estimated by Fujikawa[2]. At the side wall, similar experiments were performed behind the incident and reflected shock waves by Teske[3]. For a retrograde fluid, the liquid film growth behind the incident shock wave was researched by Kobayashi[4]. These researches were performed at the room temperature condition.

This experiment was performed at a low temperature to prevent the inflow of air, a diaphragmless shock tube was used to improve the experimental procedure. At a low temperature experiment, it is very important to improve uniformity of temperature distribution in the vacuum shield chamber.

This study is also hoped to apply to a Liquid Air Cycle Engine. Liquid Air Cycle Engine is a type of spacecraft propulsion engine that attempts to increase its efficiency by gathering part of its oxidizer from the atmosphere. It uses cryogenic hydrogen fuel to liquefy the air. In a LOX/LH₂ bipropellant rocket the liquid oxygen needed for combustion is the majority of the weight of the spacecraft on lift-off, so if some of this can be collected from the air on the way, it might drastically lower the take-off weight of the spacecraft.

2. Experimental Setup and Measurement

2.1 Diaphragmless cryogenic shock tube
In this study, experiments were carried out by using a diaphragmless cryogenic shock tube. Schematic diagram of the shock tube and the position of pressure transducers are shown in Fig.1. Instead of a diaphragm, the shock tube has two pistons in the high pressure chamber. When the electromagnetic valve is opened, these pistons quickly move and driver gas flows into the low pressure tube to form a shock wave, then the shock wave propagates through the horizontal tube, the bend tube of 150mm curvature, and the vertical tube, and reaches the test section.

In order to cool down the test section, liquid nitrogen is poured into a cooling chamber set above the test section. The pressure signals of the incident and reflected shock waves are monitored by two piezoelectric transducers installed in the test section. The initial pressure of vapor is measured by a K-type thermocouple. Nitrogen is used as a driver gas and HFC-134a, known as an alternative fluorocarbon, is used as a driven gas. Table 1 shows the general properties of HFC-134a. This test gas can be
condensed easily by controlling the initial pressure ratio ($p_4/p_1$) and the initial temperature ($T_1$).

This shock tube is free from pollution by broken diaphragm particles or water vapor. It allows continuous operation in the low temperature conditions without any pollution[5].

**Table 1 The general properties of HFC-134a**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Name</td>
<td>1,2,2,2-Tetrafluoroethane</td>
</tr>
<tr>
<td>Chemical Formation</td>
<td>CH$_2$F-CF$_3$</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>102.031</td>
</tr>
<tr>
<td>Freezing Point [K]</td>
<td>172.0 (at 101.325kPa)</td>
</tr>
<tr>
<td>Boiling Point [K]</td>
<td>249.67 (at 101.325kPa)</td>
</tr>
<tr>
<td>Specific Heat Ratio</td>
<td>1.186</td>
</tr>
<tr>
<td>Heat of Vaporization [kJ/kg]</td>
<td>177.99 (at 298.15K)</td>
</tr>
</tbody>
</table>

2.2 Platinum thin film thermo-sensor and bridge circuit

The heat flux of cold wall is measured by using a platinum thin film thermo-sensor installed in the test section. The resistance of the platinum thermo-sensor varies with the temperature change. The platinum thermo-sensor is in connection with a balanced bridge circuit as shown in Fig.2. If the bridge circuit is out of balance by changing of the platinum thermo-sensor’s resistance, an output voltage of the bridge circuit will generate.

As for measuring the heat flux by applying the platinum thin film thermo-sensor, it is considered as a problem governed by the simple one-dimensional heat equation. The following assumptions are made in the present analysis.

1. The heat flow in the thin film is simply one-dimensional in the vertical direction
2. The cold wall is thick enough to be considered as a semi-infinite body.

Heat flux is calculated by using Eqs.(1) and (2)

\[
q(t) = \frac{2\sqrt{\rho v K}}{\sqrt{\pi R_0 \alpha p}} \left[ \sum_{i=1}^{n} \left( \frac{\rho_v(t_i) - \rho_v(t_{i-1})}{\sqrt{T_i - T_{i-1}} + \sqrt{T_n - T_{n-1}}} \right) \right]
\]

\[
\beta = \frac{R_2 V_c}{(R + R_2)(R1 + R3)} \quad V_c = 12V
\]

3. Theory of Interferometric Measurement for Film Condensation

Liquid film thickness is measured by using the optical interferometric method based on the multiple reflection of a He-Ne laser beam at the solid-liquid boundary of the thin liquid film.

Fig.3 shows a changing thermodynamic state by a shock wave. ① indicates the arrival moment of the incident shock wave. Just after the incident shock wave arrives at the observation window, the pressure, temperature and density of the vapor increases step wisely from an initial low state to a high one following the Rankine-Hugoniot relations. The test gas pressure and temperature jump to the state 2a, where the condensation will not occur. The temperature of the vapor close to the cold wall decreases rapidly because of a large difference in heat capacities between the vapor and the cold wall, then, the vapor begins to condense and forms the liquid film on the cold wall. (1 to 2b) [6].
The concept of the interferometric measurement method of the liquid film thickness is shown in Fig.4. The laser beam is partly transmitted and partly reflected by the interface of the windows. The optical system results in an interference pattern, and the light intensity is detected by a photo-diode to the shift of the interference fringes. The practical interference system is shown in Fig.5. The shock tube has two optical windows for heat insulation, it is necessary to develop the complicated expression for the strict value of the liquid film thickness, however, in this study the simple model is applied and the following Eqs (3), (4) and (5) are used. [7].

![Fig.4 Interferometric measurement method](image)

![Fig.5 Optical interference system](image)

\[ I(t) = \frac{r_{1s}^2 + r_{2s}^2 + 2r_{1s}r_{2s} \cos \phi}{1 + r_{1s}^2r_{2s}^2 + 2r_{1s}r_{2s} \cos \phi} \]  
(3)

\[ \phi = \frac{4 \pi I \Delta I(t) \cos \phi}{\lambda} \]  
(4)

\[ r_{1s} = \frac{n_s \cos \theta_s - n_i \cos \theta_i}{n_s \cos \theta_s + n_i \cos \theta_i}, \quad r_{2s} = \frac{n_s \cos \theta_s - n_i \cos \theta_i}{n_s \cos \theta_s + n_i \cos \theta_i} \]  
(5)

The time dependent thickness of the liquid film growth is calculated by using Eqs.(6) and (7)

\[ \Delta I(t) = \frac{\lambda}{4 \pi I \cos \phi} \cdot \cos \left[ \frac{c_i (I_{\text{max}} + I_{\text{min}} - I(t)) - c_s}{c_i (I_{\text{max}} - I_{\text{min}}) \Delta I(t)} \right] - \phi_0 \]  
(6)

\[ Q(t) = \frac{K(t) - K_{\text{min}}}{K_{\text{max}} - K_{\text{min}}} \]  
(7)

4. Experiment Results and Discussion

4.1 Measurement of condensed liquid film growth
By using Nitrogen as the driver gas and HFC-134a as the driven gas, the representative time variations of the pressure and the reflected light intensity are shown in Fig.6. Fig.6 (a) shows the pressure variations of the two pressure transducers, \( M_i \) is estimated from the distance and the rapid rise time difference between the two pressure transducers and \( p_2 \) is determined from pressure rise of the upper pressure transducer.

![Fig.6 Typical experiment of the HFC-134a condensation](image)
upper transducer, \( p_1 \) is determined from the pressure rise of the lower pressure transducer. Record of the reflected light intensities and the pressure signal is shown in Fig. 6(b). The two vertical dotted lines indicate the arrival times of the incident and reflected shock waves at the observation window measured from the rapid pressure rise time difference between two pressure transducers. In this figure, the reflected light signal seems to rapidly change at the same time as the arrival of the incident shock wave. Oscillation of reflected light signal decays behind the reflected shock wave at 2.29 ms, the reason of which is considered to be caused by the turbulent motion on the liquid film surface behind the reflected shock wave. Future work will be required to carry out the flow field visualization experiments. Using the interferometric measurement method, a normalized liquid film thickness after the passing of half wave-length of reflected light intensity was determined, as shown in Fig. 6(c). Condensation on the wall is accompanied by an instantaneous increase in pressure behind the incident shock wave. When the reflected shock wave reaches the observation window, the condensation is enforced again. In the experimental data, the speed of liquid film growth behind the incident and reflected shock waves are 477 nm/ms and 301 nm/ms respectively. As shown in Fig. 6(c), the solid circles show fringe liquid film thickness data in the constructive interference conditions of the laser, liquid film thickness at the fringe points is calculated using Eq. (8), the normalized liquid film thickness data are lower than fringe liquid film data, but are very close to each other.

\[
\delta_l = \frac{m\lambda}{2n_l \cos \theta_l} \quad (m=1, 2, \cdots)
\]

(8)

### 4.2 Measurement of heat flux

In this experiment, the heat flux is measured by the platinum thermo-sensor installed in the test section. The heat flux is obtained from the output voltage of the bridge circuit. Bridge circuit output voltage data are shown in Fig. 7. The heat flux is also measured from the condensed mass flux, the results of the heat fluxes are shown in Fig. 8. The two methods do not show very close results, however, they show the same tendency. These results show that the condensation heat flux increases behind the arrival of incident shock wave at first, then it decreases 0.75 ms behind incident shock wave, after that it increases again behind the arrival of the reflected shock wave.

The flow of HFC-134a vapor disappears behind the reflected shock wave, because the temperature behind the reflected shock wave \( T_2 \) is higher than 300 K. The high temperature causes the rapid heat flux increase behind the reflected shock wave.

### 4.3 Comparison of liquid film growth and heat flux in the same initial temperature

To attempt controlling the growth of liquid film, experiments are performed for different initial pressures keeping the initial temperature constant. The output voltage of the photo-diode, the time dependent condensed liquid film thickness and the heat flux by using the platinum thermo-sensor are shown in Figs. 9-10. The results suggest that the liquid film growth and heat flux do not depend strongly on the initial pressure \( \rho_4, p_1 \) at the same initial temperature \( T_i \). Under this experimental condition, some parameters such as \( \rho_4, p_1, \gamma, M_i \) can be regarded as signal parameter, there are no obvious relations between these signal physical quantities and the growth of liquid film behind the shock waves from the experimental data. It is important to find new parameters to relate the growth of liquid film. From the experimental result, the pressure behind the incident shock wave \( p_2 \) is supposed to be an important parameter. It includes the initial pressure, the incident shock wave mach number, the initial temperature as shown in Eqs. (9) and (10).

\[
p_2 = \frac{2\gamma \cdot M_i^2 - (\gamma - 1)}{\gamma + 1} \cdot p_1 \quad (9)
\]

\[
M_i = \frac{u}{\sqrt{\gamma \cdot RTN}} \quad (10)
\]

At the same initial temperature condition, when the pressure behind the incident shock wave increases, the liquid films behind the incident shock wave will grow faster. The degree of super saturation \( \rho_2 - \rho_{sat} \) is another
important parameter of this study. When the super saturation increases at the same initial temperature, the liquid films behind the incident shock waves will growth faster for the different initial pressure conditions. It is apparent that for faster liquid film growth, a larger heat flux is obtained. However, can not be seen obvious difference in the liquid film growth behind the reflected shock waves for different pressures behind incident shock wave. In Fig.9, normalized output voltage waveforms can be seen behind both the incident and reflected shock waves, however, in Fig.10, normalized output voltage waveforms can be seen only behind the incident shockwaves.

Fig. 9 Liquid film growth and heat flux (191K)

(A)Reflected light intensity detected by the photo-diode

(B)Time dependent liquid film thickness

(C)Heat flux by using platinum thermo-sensor

Fig. 10 Liquid film growth and heat flux (200K)

4.4 Comparison of liquid film growth and heat flux in the same pressure ratio

Experiments are also performed for different initial temperatures with keeping the initial pressure ratio to be constant. The results are shown in Fig. 11. From results, it is found that the reflected light intensity waveform does not exist behind the incident shock wave for higher initial temperature. However, liquid film growths the same trend behind the reflected shock wave. It is also found that the heat flux rapidly increases behind the reflected shock wave.
5. Conclusions
In this study, a non-diaphragm shock tube and a laser interference system were re-constructed for HFC-134a vapor condensation experiment at low temperatures.

By using an optical interference method, the liquid film thickness on the cold glass window behind the incident and reflect shock waves were measured. The liquid film growth rates showed obvious changes behind the reflected shock wave. The condensation heat flux was calculated from the liquid film mass flow rate and was also measured directly by using a platinum thermo-sensor. The same qualitative tendency in the heat flux data was observed for both methods. The relation between the liquid film growth rate and the initial temperature behind the incident shock wave was investigated. For the same initial temperature, a larger $p_2$ led to a faster growth of the liquid film behind the incident shock wave, however the difference of the liquid film growth behind the reflected shock wave could not be recognized.

Nomenclature
- $c_{ab}$: Constant number
- $I(t)$: Time dependent energy-reflectivity
- $K(t)$: Time dependent output voltage from the photo-diode
- $M$: Molecular weight
- $n$: Refractive index
- $q(t)$: Time dependent heat flux
- $Q(t)$: Time dependent relative energy-reflectivity
- $r$: Reflectivity
- $R_0$: Resistance value
- $v_{out}(t)$: Time dependent Output voltage of bridge circuit
- $\lambda$: Wavelength of the He-Ne laser
- $\alpha$: Temperature coefficient of the resistance
- $\beta$: Sensitivity of voltage
- $\gamma$: Heat capacity ratio
- $\delta$: Growth of liquid film
- $\theta$: Incident angle of laser
- $k$: Thermal conductivity
- $\rho$: Density of the base material
- $\phi$: Phase delay

Subscripts
- $l$: Liquid
- $s$: Solid
- $v$: Vapor
- $sat$: saturation
- $1(4)$: Initial state of driven (drive) gas
- $2(5)$: Area behind the incident (reflected) shock wave

References