Experimental study on the oblique shock waves and expansion waves in the supersonic carbon dioxide two-phase flow

Yosuke KAWAMURA* and Masafumi NAKAGAWA*

* Department of Mechanical Engineering, Toyohashi University of Technology
1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan
E-mail: kawamura@nak.me.tut.ac.jp

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Abstract
Recently, with the appearance of the two-phase flow ejector in refrigeration air conditioning and heat pump systems, the efficiency of the cycle has largely been improved in comparison with that of conventional cooling and heating systems. We have been developing an ejector for the refrigeration cycle and fundamentally researching the behavior of two-dimensional expansion waves and oblique shock waves to clarify the characteristics of waves occurring during high-speed two-phase flow. In previous studies, it was revealed that an oblique shock wave is generated at the nozzle exit of the ejector and affects the flow field of the supersonic two-phase flow inside the mixing section in the ejector. This is because the speed of sound for a two-phase flow is low compared to that for a single-phase flow. In the present study, we elucidate the behavior of oblique shock waves and expansion waves of supersonic two-phase flow by experiments using carbon dioxide refrigerant. The angle of the oblique shock waves and the expansion waves were experimentally measured, and corresponded well with those calculated using a theoretical model.

Key words: Multiphase flow, Supersonic flow, Shock waves, Expansion waves, Carbon-dioxide

1. Introduction

In recent years, the heat-pump cycle, which uses natural refrigerants such as the carbon-dioxide (hereinafter CO₂) with low environmental loads, has been gaining attention. By utilizing a two-phase flow ejector (A.L.Lee, 1975, D.Buyadgie et al., 2010) with the heat pump cycle, the coefficient of performance can be significantly improved. However, the behavior of shock waves and the expansion waves produced inside the ejector significantly affects the ejector’s performance. One of the most important functions of the two-phase flow ejector is to compress the extracted refrigerant vapor from the evaporator and to assist the compressor. The recovered pressure largely depends on the kinetic energy of the two-phase flow at the mixing section (Ogata and Nishino, 2015).

Generally, the characteristics of shock waves and expansion waves in the two-phase flow are greatly different from those in the single-phase flow. This is because the so-called relaxation phenomenon peculiar to a two-phase flow occurs in between the vapor phase and the liquid phase. Among the past studies on the shock waves propagating in the single component two-phase flow, there are many experiments using a shock tube (Kobayashi et al., 1982, Tanaka et al., 1994). In addition, for the shock wave in the nozzle, many experimental studies use the humid air as the working fluid (S.B.Kwon et al., 1988, Kawagoe et al., 1989). However, the studies on shock waves and expansion waves in the nozzle using the carbon dioxide refrigerant near to a critical point scarcely exist, and at this condition, the gas-liquid density ratio and the surface tension are comparably small. Thus, it is thought that shock waves and expansion waves in the carbon dioxide refrigerant differ from those in the humid air.

We have been developing an ejector for the refrigeration cycle (Nakagawa et al, 1998, Nakagawa, 2004.) and fundamentally researching the characteristics of two-dimensional expansion waves (Nakagawa and Harada, 2007, Nakagawa et al, 2008.) and oblique shock waves (Kawamura et al, 2015.) to clarify the characteristics of waves that
occur in high-speed two-phase flow.

The purpose of this study is to clarify the characteristics of shock waves and expansion waves occurring in a supersonic two-phase flow by the experiment using natural refrigerant CO$_2$ as the working fluid.

2. Experimental apparatus

In this study, we prepared three types of two-dimensional nozzles, as shown in Fig. 1 and Table 1. Homogeneous equilibrium model (HEM) which assumed an isentropic change (hereinafter IHE model (Nakagawa and Morimune, 2003, R.T. Lahey, 2013)) was used for the design of the nozzles. These nozzles were cut from a 0.8-[mm]-thick stainless steel plate with a wire electric discharge machine. Except for the measuring section, each nozzle had the same shape. In the measuring section, the inclined wall of each nozzle was deflected by $\theta = 0^\circ$, $6^\circ$, and $-6^\circ$ on the basis of on half of the divergent angle $\alpha = 3^\circ$. The nozzles were called Nozzle 0, Nozzle 1, and Nozzle 2, respectively. Here, the shape of Nozzle 1 is determined by the deflection angle $\theta$. The flow in the nozzle must not be choked by the deflection. In other words, the deflection angle depends on half of the divergent angle of the nozzle. Thus, we set the deflection angle $\theta$ of Nozzle 1 as $6^\circ$.

In this study, many measurement points were necessary to measure an occurrence of the shock waves and the expansion waves. Therefore, we supplemented a number of pressure measurement points using a thermocouple. The symbols in the nozzle diagram shown in Fig. 1 indicate the sampling points. Here, the filled square (■), triangle (▲), and inverted triangle (▼) indicate the sampling points of the thermocouple. Using the experiments, we calculated the saturated pressure from the saturated temperature of the two-phase flow measured by the thermocouple. The calculated saturated pressure is given by REFPROP V.8 of NIST’s software (Eric et al., 2007). On the other hand, the unfilled square (□) and triangle (△) indicate the sampling points of the pressure gauge.

![Fig. 1 Nozzle geometry and measurement points.](image)

<table>
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<th>Table 1 Dimension of the two-dimensional nozzle.</th>
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<td>Convergent section length</td>
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<td>Divergent section length</td>
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<tr>
<td>Measuring section length</td>
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<td>Mixing section length</td>
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The test section shown in Fig. 2 constitutes a two-dimensional rectangular duct with two high-adiabatic Bakelite plates and one test nozzle plate. A K-type thermocouple was buried in the bottom Bakelite plate. In addition, a hole was established to measure the pressure on the upper Bakelite plate. A capillary tube connected to a pressure gauge was fixed to the upper brass plate.

Figure 3 shows the features of the blow-down testing apparatus set up for this study. It mainly consisted of a high-pressure tank, test section, and gas cylinders of nitrogen (hereinafter N\textsubscript{2}) and CO\textsubscript{2}. The test section, which included the nozzles, was incorporated into the apparatus. The CO\textsubscript{2} liquid refrigerant blew down from the high-pressure tank, and the liquid-phase flow went through the nozzle into the test section. N\textsubscript{2} gas, whose density is smaller than that of CO\textsubscript{2}, was used to compress the high-pressure tank from the top. The flow rate of compressed N\textsubscript{2} gas was measured at the orifice. Then, the volumetric flow rate of the flushing CO\textsubscript{2} was calculated from that of N\textsubscript{2}. The pressure of CO\textsubscript{2} at the inlet of the nozzle was controlled by the decompression valve at the high-pressure N\textsubscript{2} gas cylinder. The temperature of CO\textsubscript{2} was adjusted by adjusting the temperature of the hot water that ran through the heat-exchanger pipe in the high-pressure tank. The inlet pressure ranged from 8 to 11 [MPa], and the temperature ranged from 20 to 40 [°C]. We used the pressure gauge (Accuracy : ±1.0\%F.S.) and thermocouple (Accuracy : ±0.5°C) provided in the test section to measure the pressure distribution associated with the generation of the oblique shock waves and the expansion waves.

4. Experimental result
4.1 Pressure distribution in the nozzles

In the experiments, the pressure \(p_{in}\) was changed from 8 to 11 [MPa] and the temperature \(t_{in}\) was changed from 20 to 40 [°C] at the nozzle inlet. The experimental results obtained with \(p_{in} = 10\) [MPa] and \(t_{in} = 30\) [°C] are shown in Fig. 4. Each graph in Fig. 4 indicates the static pressure profile in the nozzle for each nozzle. The vertical axes of the graphs show the measured static pressure, and the horizontal axes show the distance from the nozzle throat. The upper sub-figures on these graphs indicate a diagram of each nozzle. In these graphs, the filled and unfilled symbols indicate the pressure measured by the thermocouple and the pressure gauge, respectively. In addition, the symbol with a filled star indicates the nozzle throat pressure calculated using a second approximation from four downstream measurement points. Furthermore, the dashed curves indicate the decompression curves calculated using the IHE model.

The experimental results shown in Fig. 4(a) indicate that the measured pressure decreases along each theoretical curve, and this pressure decrement continues to the position of \(z = 40\) [mm] of the diffuser section. This means that the CO\textsubscript{2} flow was in a supersonic state from the nozzle throat to \(z = 40\) [mm]. In other words, it can be said that the flow field in the measuring section was in a supersonic state. However, from the results for each nozzle, it can be seen that the pressure exhibited the same decompression gradient for all nozzles except at the measuring sections. This means that the flow field was also in a supersonic state from the nozzle throat to \(z = 40\) [mm] for Nozzle 1 and Nozzle 2.
Fig. 4 Pressure changes in the interiors of the test section.
4.2 Pressure distribution near the deflection point

From the abovementioned results, we focused on the pressure distribution of the measuring section. Each graph shown in Fig. 5 indicates the static pressure profile near the measuring section for each nozzle. In each graph, the filled and unfilled circles (● and ○, respectively) indicate a pressure change in the nozzle centerline of the experimental results using Nozzle 0.

Firstly, according to the experimental results for Nozzle 1 shown in Fig. 5(a), the pressure increases further upstream from \( z = 15 \) [mm] of the deflection point of the lower wall. Furthermore, the lower-wall pressure increases further upstream in comparison with the centerline and the upper-wall pressure. The measurement range of the pressure gauge is from 0 to 5 [MPa]. Thus, the measurement error of these pressure gauges becomes ± 50 [kPa]. In addition, the thermometry error of the thermocouple in this experimental condition when the value of thermocouples changed to the saturated pressure is approximately ± 30~50 [kPa]. The pressure increment in the measuring section obtained from the experiment is large enough than the value of the measurement error. From these results, it can be said that this pressure increment was caused by an oblique shock waves.

Fig. 5 Pressure change near the measuring section.
Secondly, according to the experimental results for Nozzle 2 shown in Fig. 5(b), the pressure decreases (contrary to the results for Nozzle 1) further upstream from \( z = 15 \) [mm] of the deflection point of the lower wall. In addition, a decompression gradient is gradually exhibited in the order of the lower wall, centerline, and upper wall. From these results, it can be said that this pressure decrease was caused by an expansion waves.

Lastly, the pressure change of Nozzle 1 and Nozzle 2 was very slow and was not like the typical step-formed pressure increment and decrement expected from gas dynamics. This means that the oblique shock waves and the expansion waves of the two-phase flow forming the dispersed pressure field were measured in these experiments.

5. Conclusion

Shock waves and expansion waves occurring in the supersonic CO\(_2\) two-phase flow in the nozzles are experimentally investigated and the following characteristics of the shock waves and the expansion waves are found:

- By the experimental result of Nozzle1, the oblique shock waves with the gradual increment pressure were measured. Because those are largely different from the single-phase flow shock waves, the characteristic two-phase flow oblique shock waves are measured by the present experiment.
- From pressure distribution measured by this experiment, the front edges of oblique shock waves and expansion waves goes upstream from the deflection point of the wall. The dispersion of the waves is thought to take place by the peculiar two-phase flow relaxation phenomenon in between the vapor phase and the liquid phase.

References


