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Development and Evaluation of a Pulse Driven-type Electromagnetic Control Expansion Valve applied to a Small Scale Refrigerant Cycle (Part II: Experimental evaluation of pressure drop)

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Abstract: *The application of a new pulse driven-type electromagnetic control expansion valve to an R744 cycle is proposed and the characteristics of the valve are experimentally examined in this paper. First, the structure of the valve is simulated by elements such as ducts, a pin hole, a groove and an orifice. The pressure drops caused by each element that makes up a valve are estimated individually, and summed up to discern the total pressure drop. Especially, the influence of the machining tolerance is estimated because the parts that make up the valve are very fine. Then an experiment for the pressure drop measurement is conducted by constructing a refrigerator cycle. The experimental results are then compared to theoretically estimated results. Both results show similar tendencies of a similar order against the mass flow rate, even though a refrigerant has a very complicated gas-liquid two-phase fluid flow. The pressure drop can be controlled by an electromagnetic control valve for the designated range. As a result, it was shown that the pulse driven-type electromagnetic control expansion valve proposed in this paper can be applied to control the pressure drop in a way suitable for fulfilling cooling demand.*
Keywords: *Electric expansion valve, Electromagnetic control, Refrigerator, Pulse drive,* CO_2*(R744)*

I. Introduction

Low temperature heat, such as that applied to an air conditioning unit or a fridge, is obtained from a heat pump or refrigerator using a refrigerant cycle, even though other energy conversion systems such as thermoacoustic refrigerators with thermoacoustic engines have been proposed [1-5]. The cycle contains a refrigerant as a working fluid, but a majority of currently used refrigerants are harmful to the environment, including causing problems such as the greenhouse effect. Accordingly, a heat pump using CO_2(R744) as a working fluid has been practically used in recent years. R744 is a natural refrigerant which has a lower impact on the greenhouse effect when compared to conventional artificial refrigerants. However, the electric consumption of the heat pump that uses R744 becomes higher than that of a conventional refrigerant cycle with an artificial refrigerant, because the refrigerant needs high compression pressure in the cycle. Therefore, the development of an energy-conserving heat pump using R744 has been expected.

The refrigerant cycle consists of a compressor, a condenser, a decompression device, an evaporator and a working fluid. A capillary tube or an expansion valve is generally employed as a decompression device. The optimum design and control of the elements that make up the system, such as electric expansion valves, which are suitable for operation conditions have been investigated [6]. The application of a new pulse driven-type electromagnetic control expansion valve to an R744 cycle is proposed, and the characteristics of the valve are theoretically evaluated [7]. An electromagnetic control expansion valve is experimentally examined in this paper. The valve can control the pressure drop of a refrigerant continuously from the liquid to the two-phase state appropriate to the desired level of cooling. The motion of the pressure control elements inside the valve is much quicker than those of conventional systems using stepping motors. It contributes to the optimum operation of the refrigerator. The R744 cycle has a higher decompression and lower volume flow rate than other conventional refrigerant cycles at equal system capacity. The decompression of the refrigerant is caused at a microchanel and an orifice inside a valve. The flow patterns of CO_2 passing through a microchanel or a short orifice are very complicated, because the fluid starts boiling and expands when it passes through these elements. The flow characteristics, especially for a pressure drop in a microchanel, have been examined in detail [8-16].

A pulse driven-type electromagnetic controlled expansion valve is one of the most promising pieces of decompression equipment for refrigerant cycles. In this paper, the application of the valve to an R744 cycle is proposed, and the characteristics of the valve are experimentally examined and compared to the theoretically obtained results for the future design of the valve.

II. Experimental Apparatus and Procedure

Figure 1 shows a schematic layout of the experimental apparatus employed in this experiment. The system consists of a compressor, a condenser, an electromagnetic control expansion valve as a test piece and an evaporator. The mass flow rate is measured by a Coriolis mass flow meter. The mass flow rate of the refrigerant is controlled by a compressor with an inverter. The mass flow rate of refrigerant is also influenced by the pressure drop of the expansion valve and the filling amount of the refrigerant to the circuit. The principal local pressures and temperatures are measured by semiconductor pressure transducers and thermocouples, respectively. These pressures and temperatures are recorded by a multi-channel data logger. The schematic configuration and photo of the test section are shown in Fig. 2. The test section consists of a cylinder with a pin hole and a V-shaped groove, a plunger and an orifice. The plunger is moved upwards and downwards by a solenoid which is controlled by pulse signal. If the plunger moves to the upper position, it contacts the cylinder. Refrigerant passes through only a V-shaped groove and flows toward to the orifice, as shown in Fig. 2(a). On the other hand, the plunger also contacts the orifice when it moves to its lowest position. Refrigerant can not flow into the orifice and is stopped, even though the gap between cylinder and plunger becomes large in this case. During the movement of the plunger between the upper and lower positions, refrigerant passes through narrow paths with varying cross sections. The pressure drop can be controlled by the position of the plunger, and its position is controlled by pulse driven electromagnetic devices. Accordingly, the refrigerant sustains its pressure drop when it passes through the expansion valve.

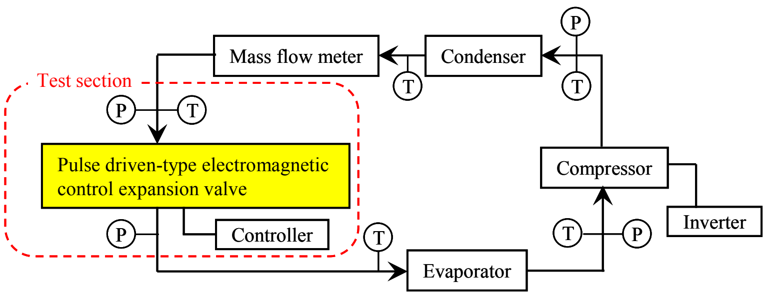
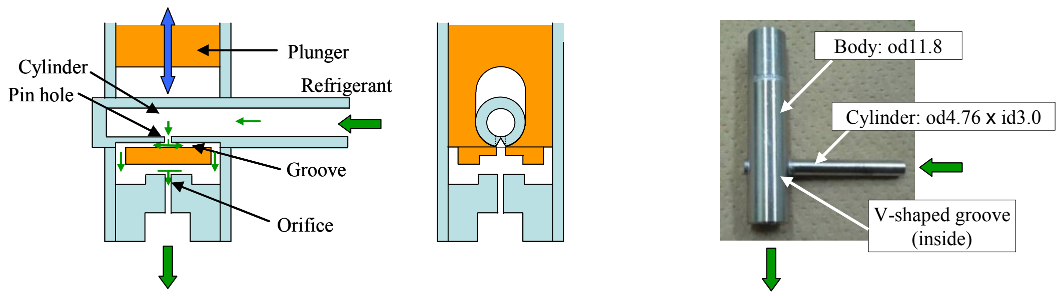


Figure 1 Schematic layout of experimental apparatus



(a) Detail of valve (upper position of plunger) (b) Photo of test piece

Figure 2 Pulse driven-type electromagnetic control expansion valve

R744 was used as the refrigerant. Inlet pressure, inlet temperature and directing outlet pressure, namely pressure drops are chosen based on the empirical conditions for a small scale CO_2 refrigerator. Figure 3 shows a part of the Mollier chart of R744. The red striped area shows the inlet pressure and temperature of R744 to the valve. The blue striped area shows the outlet condition of the R744. The temperature difference of the fluid between inlet and outlet is around 10 ºC, and the quality of the gas, x, becomes between $0<x<0.2$. The mass flow rate is set based on empirical conditions.

The inlet temperature of R744 to the valve is controlled by the cooling amount of the condenser. And the inlet pressure and mass flow rates are controlled by the filling amount of refrigerant and the compressor which is operated by an inverter control. The position of the plunger shown in Fig. 2(a) is fixed at the upper position in this experiment. Accordingly, the characteristics of the pressure drop caused by the V-shaped groove, rapid-contraction and rapid-expansion effects at its inlet and exit interfaces are examined. After the steady state condition is achieved, local pressures and temperatures are measured and recorded.

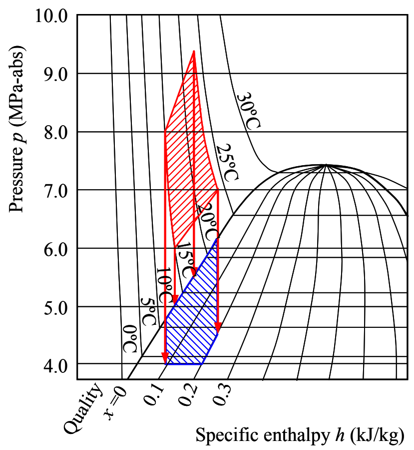


Figure 3 A part of the R744 Mollier chart for the experimental conditions

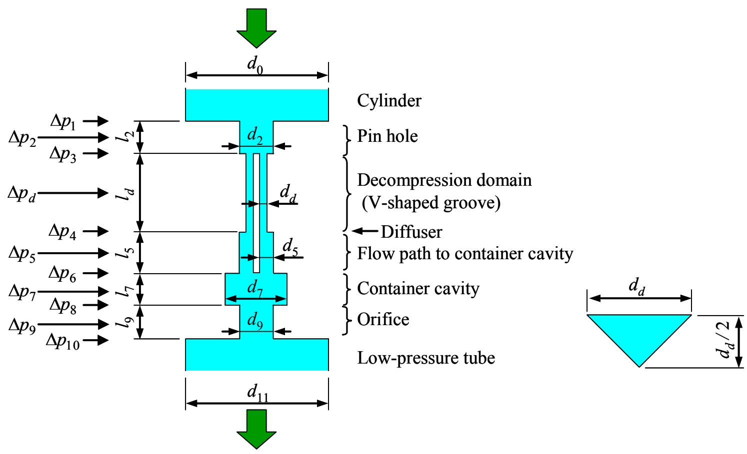
III. Experimental Results and Discussion

3.1 Theoretical estimation of pressure drop in the expansion valve

Before the experiment, the pressure drop caused by the proposed expansion valve is theoretically estimated. The details of the estimation are shown in reference 7. The configuration of the valve is simulated by fundamental elements, as shown in Fig. 4. The specifications of the elements are shown in Table 1. Especially, the processing accuracy of the groove is introduced in the estimation, because the groove has a very fine structure. The pressure drops caused by the elements that make up the valve are estimated individually, and the overall pressure drop is estimated.

The theoretically obtained overall pressure drop and experimental results are shown in Fig. 5. It is difficult to estimate the local quality inside a valve by experiment. The principal pressure drop was caused by the V-shaped groove and its entrance and exit interface [7]. Therefore the quality at the exit of the V-shaped groove and after there are assumed to be x = 0, 0.1 and 0.2 in the simulation. x = 0 means that the refrigerant did not start to boil after it passed the valve. These results are shown in Fig. 5(a) - (c), respectively.

The gradient of the theoretically estimated pressure drop becomes more gentle as the quality increases, because the density of the refrigerant becomes smaller even though the flow velocity increases. The pressure drop rises quickly and sharply as the groove width grows narrower. This is especially typical for the case of d_d = 0.30 mm.



(a) Flow model of refrigerant (b) Cross section of V-shaped groove

Figure 4 Flow model for pulse driven-type electromagnetic control expansion valve

Table 1 Specification of the valve for theoretical estimation

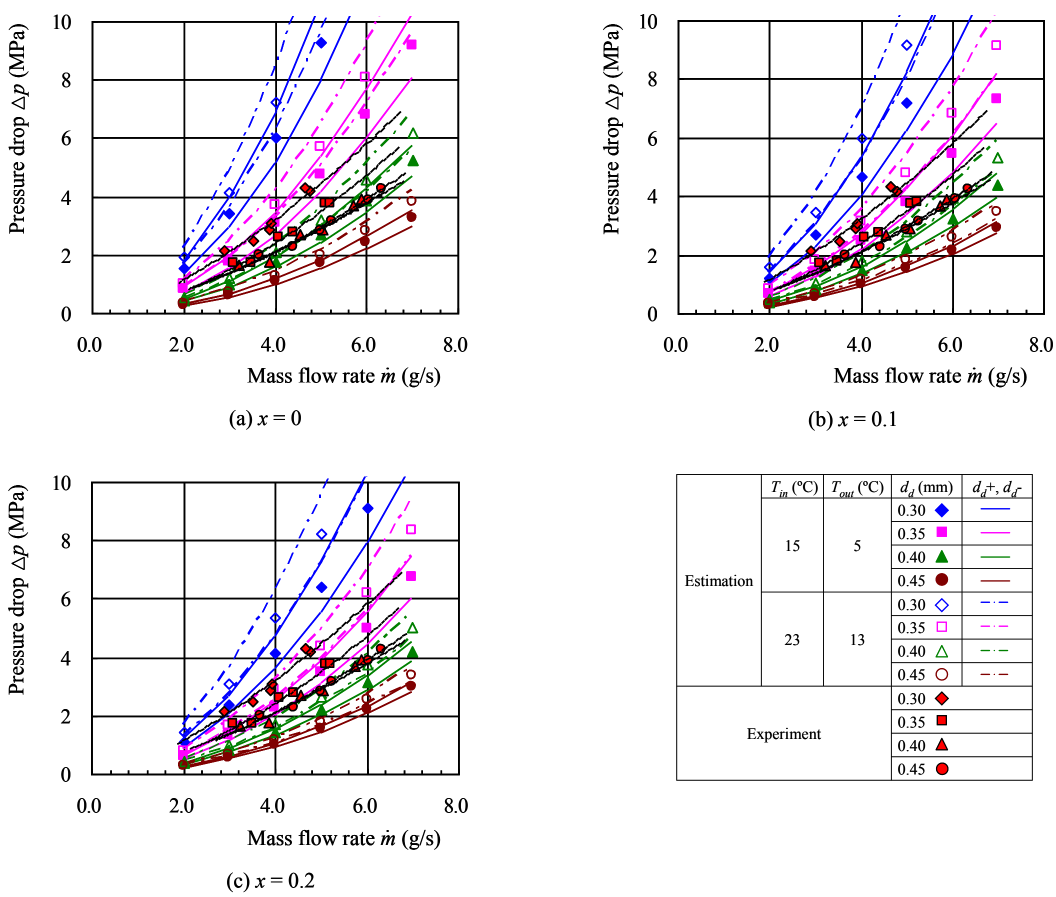
Index	Elements	Hydraulic diameter d (mm)	Length l (mm)
0	Cylinder	3.0	
1	Rapid-contraction		
2	Pin hole	0.6	0.88

3	Rapid-contraction		
d	Decompression domain	(d_d) 0.3 - 0.45	3.8 x 2
4	Rapid-expansion		
5	Flow path to container cavity	1.1	2.8 x 2
6	Rapid-contraction		
7	Container cavity	1.85	4.1 x 2
8	Rapid-contraction		
9	Orifice	0.6	4.0
10	Rapid-expansion		
11	Low pressure tube	2.76	
	Processing accuracy of V-shaped groove	±0.01 mm for d_d	

3.2 Experimental results of pressure drop

The experimental conditions are shown in Table 2. The width of the V-shaped groove varied from 0.30 mm to 0.45 mm every 0.05 mm steps. These conditions are chosen corresponding to the theoretical conditions of each other. The experimental results are shown in Fig. 5, too. The experimentally obtained quality at the exit of the valve, estimated using a Mollier chart, was not distinguished in the figure. During the experiment, the qualities of the refrigerant at the exit of the valve were $0<x<0.2$. The pressure drops obtained by the experiment were lower than those of the theoretical results except $d_d = 0.45$ mm. However, the tendency of both results was the same. The pressure drop required is around 5 MPa or less. The theoretically estimated pressure drops for narrower grooves are quite different from the experimental value, especially for $d_d = 0.30$ mm. The gradient of the results obtained by $d_d = 0.30$ mm is very sensitive against the mass flow rate. It means that it is difficult to control the pressure drop carefully. On the other hand, it is insufficient to raise the pressure drop by using $d_d =$ 0.40 mm and 0.45 mm. $d_d = 0.35$ mm may be suitable for the control of the pressure drop. The pressure drop can be reduced by opening the V-shaped groove by the pulse driven electromagnetic control valve.

The pressure drop can be controlled by an electromagnetic control valve for the designed range. As a result, it was shown that the pulse driven-type electromagnetic control expansion valve proposed in this paper can be applied to control the pressure drop in a way suitable for fulfilling cooling demand.



(a) $x = 0$ (b) $x = 0.1$ (c) $x = 0.2$

Figure 5 Experimentally obtained pressure drop and theoretical estimation

Table 2 Experimental conditions for refrigerating cycle and V-shaped groove

Refrigerant	R744 (CO_2)
Inlet pressure: p_0	6 - 9 MPa
Inlet temperature: T_{in}	15, 23 ºC
Outlet pressure: p_{11}	4 - 6 MPa
Mass flow rate: $\dot{m}$	2.0 - 7.0 (g/s)
V-shaped groove width and length: d_d, l	0.3 - 0.45 mm, 0.05 mm steps, 3.8 mm x 2
Pin hole diameter and length	0.6 mm, 0.88 mm
Orifice diameter and length	0.6 mm, 4.0 mm

IV. Conclusions

The application of a new pulse driven-type electromagnetic control expansion valve for the R744 cycle is proposed, and the characteristics of the valve are experimentally examined in this paper. The experimental results were compared with the theoretically estimated results. The influence of the machining tolerance on the pressure drop is also estimated. The experimental results show lower values compared to theoretical results. Particularly, the difference between them becomes greater when the groove width is narrower, because the flow pattern is very complicated when it becomes a two-phase fluid flow and passes through a narrow duct. However, both results show similar tendencies of about the same order against the mass flow rate, even though it becomes a very complicated fluid flow. Then the validity of this estimation is verified by the experiment. The pressure drop can be controlled by an electromagnetic control valve. As a result, it was shown that the pulse driven-type electromagnetic control expansion valve proposed in this paper can control the pressure drop in a way suitable for fulfilling cooling demand.

V. Nomenclature

d: Hydraulic diameter of duct [m]
h: Specific enthalpy [J/kg]
l: Length [m]
$\dot{m}$: Mass flow rate [kg/s]
p: Pressure [Pa]
T: Temperature [ºC]
x: Quality [-]

Subscripts
0-11: index of position
d: V-shaped groove

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