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FLOW CHARACTERISTICS OF ELECTRONIC EXPANSION VALVES FOR HEAT PUMP SYSTEM USING CARBON DIOXIDE AS A REFRIGERANT

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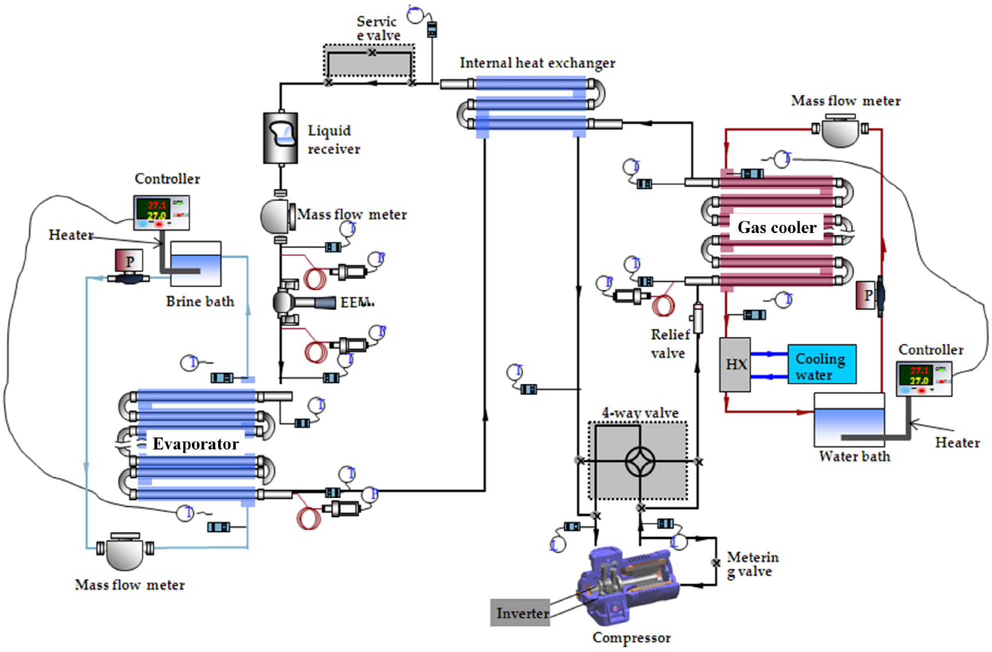
ABSTRACT
An experimental study on the flow characteristics of electronic expansion valves (EEVs) for heat pump system using carbon dioxide as a refrigerant have been carried out in this study. Many researches and efforts have been made to replace chemical refrigerants like Chloro-Fluoro-Carbon (CFC) and Hydro-Chloro-Fluoro-Carbon (HCFC) with natural refrigerants such as carbon dioxide and apply natural refrigerants to chillers or heat pump systems. In this study, we focused on the development of EEV and 4-way valve among the important components of heat pump system using natural refrigerant. The mass flow rate was measured at various EEV inlet temperature and pressure conditions with respect to several EEV openings operated at a heat pump system which has about 10 kW of cooling capacity. The heat pump system consists of a reciprocating compressor, a gas cooler, an evaporator, an EEV, and a 4-way valve which was developed for this study. The inlet temperature and pressure of an EEV was varied from 5°C to 40°C and from 7 MPa to 10 MPa, respectively. The mass flow rate of carbon dioxide through the EEV ranged from 50 g/s to 120 g/s. The mass flow rate of carbon dioxide around the critical point was affected by the inlet temperature and pressure of EEV, valve opening, and density variation. An empirical mass flow rate correlation of carbon dioxide based on the Buckingham π-theorem was developed in this study, and this correlation predicted experimental data within an average absolute deviation of 4.2%. The correlation can be applied to predict the mass flow rate through EEV used in the heat pump system using carbon dioxide as a refrigerant. And the reliability test of developed 4-way valve was conducted. This 4-way valve showed stable operation in the high pressure condition.

NOMENCLATURE

$A_{t,m}$	cross-sectional flow area at throat (m^2)
c_1~c_5	coefficients
D	orifice diameter (m)
L	the length of needle in orifice (m)
$\dot{m}$	mass flow rate of refrigerant (g/s)
P_{in}	inlet pressure of the EEV (MPa)
T_{in}	inlet temperature of the EEV (°C)
ρ	density of refrigerant (kg/m^3)

INTRODUCTION
Phase-out of CFC and HCFC refrigerants has been going on due to their severe environmental problems which are ozone depletion and global warming. Therefore, many studies on the natural refrigerants have been going on for overcoming the environmental problems (1, 2 and 3). Carbon dioxide has emerged as a strong alternative refrigerant in the viewpoint of environmental problems. Although carbon dioxide is environmentally benign, it has an intrinsic weak point. It has low critical temperature and thus high saturation pressure. Especially high working pressure of carbon dioxide is 5 times more than HCFC refrigerants. This has been an obstacle to develop components like EEVs and 4-way valves for heat pump systems.



Graphic 1 Schematic diagram of experimental setup for the test of carbon dioxide components, EEV and 4-way valve

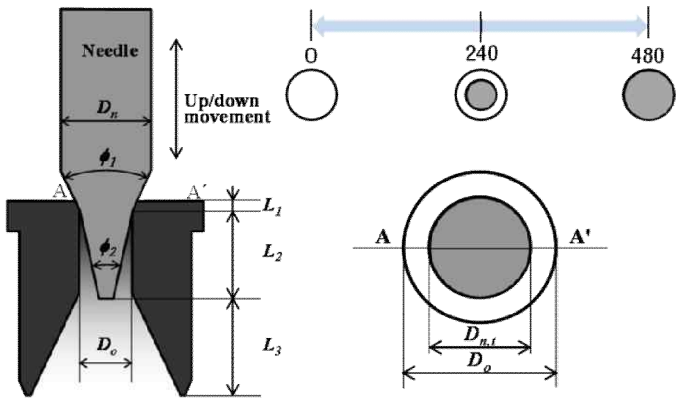
EEV is variable-area expansion device and being widely used in refrigeration systems. Especially, multi type heat pump system needs EEV for controlling mass flow rate of refrigerant to each indoor unit effectively. EEV consists of an orifice, needle, driving step motor, and so on. The needle moves linearly in proportional to electric pulse. The position of needle determines the flow area in orifice, which influences on the flow rate of refrigerant and working pressure of refrigeration system.

A great many studies have been done on the flow characteristics and pressure drop of capillary tubes and thermostatic expansion valves (TXVs). However, a few studies in open literature can be found about the flow through EEVs. Park et al. (4) did an experimental study on the flow characteristics of R22 with six commercial EEVs. They proposed the correlation based on π-theorem, which showed a good agreement with the experimental data with an average deviation of 1.4%. Zhang et al. (5) studied the effect of condensation pressure, evaporation pressure, and degree of subcooling on the flow of R22 and R407C through EEVs. They also presented the correlation based on π-theorem, which predicted their experimental data within standard deviation of 5.2% and concluded that their correlation could be used to predict the mass flow rate through the EEVs of which flow area is less than 2.544 mm^2.

Several studies have been implemented about flow characteristics through short tubes of carbon dioxide. Martin et al. (6) tested the short tube orifices of carbon dioxide with respect to the variation of diameter, length, inlet temperature, and inlet pressure. They developed the empirical model with five independent variables, which expected 98% of the measured data within an interval of ±5%. Liu et al. (7) investigated the carbon dioxide flow through ten sharp-edged short tubes and three chamfered tubes.

Table 1 Specifications of the electronic expansion valve tested in this study

D_0(mm)	D_n(mm)	L_1(mm)	L_2(mm)	L_3(mm)	Φ_1(°)	Φ_2(°)
1.6	3.0	0.2	2.8	3.5	23	50
1.8	3.0	0.2	3.0	3.3	25	50

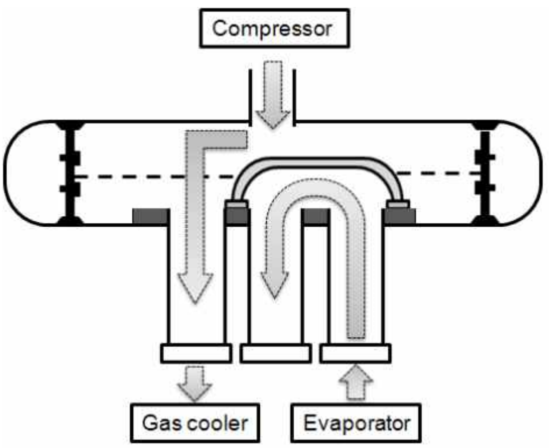


Graphic 2 Cross sectional view of electronic expansion valve

They showed that choked flow existed in all test tubes and the carbon dioxide flow, and the mass flow rate is greatly dependent on upstream pressure and temperature, tube diameter, and tube length. Studies about carbon dioxide through EEVs couldn't be found in open literature, but EEVs for refrigeration systems using carbon dioxide as a refrigerant are developed by several companies such as SAGINOMIYA (Japan), FUJIKOKI (Japan) and OBRIST (Austria).

In this study, we carried out the experimental study on the flow characteristics of EEVs for heat pump system using carbon dioxide as a refrigerant according to previous study (8). And the correlation of the mass flow rate through the EEV was improved by additional experiments. And the 4-way valve developed for this study was tested for its reliability.

(a) 4-way valve



(b) Schematic diagram of 4-way valve

Graphic 3 Photo and schematic diagram of 4-way valve

EXPERIMENTAL SETUP AND TEST METHODS

Graphic 1 shows the schematic diagram of the test rig built for the present study. It consists of compressor, gas cooler, expansion device, and evaporator. Compressor (TCS340/4, Dorin) circulates carbon dioxide through the main loop. Gas cooler, evaporator, and internal heat exchanger are all double-tube type heat exchangers. Water and water/glycol mixture are used as a secondary fluid in gas cooler and evaporator, respectively. This system includes the 4-way valve for testing its performances. Four valves are installed adjacent to 4-way valve as shown in Graphic 1. It enables to change flow directions without the change of roles of gas cooler and evaporator.

RTD (Resistance Temperature Detector) sensor and absolute pressure sensors are installed for measuring temperatures and pressures. The mass flow rate of carbon dioxide are measured by Coriolis mass flow meter (DH025S119SB, Micro motion Inc.).

Cross sectional view of EEV is shown in Graphic 2. The needle moves up and down and the flow area is varied with respect to the position of needle (or the lift of needle). The minimum flow area in the orifice, which is the flow area at orifice throat, influences the mass flow rate through the expansion valve and working pressure in the system. Two types of EEVs are used for the test and detailed specifications are listed in Table 1. The maximum lift is designed to be 2.5 mm, and the pulse rage of step motor is from 0 to 480. 480 pulse means that the needle is positioned at the lowest position, which indicates the smallest flow area. Meanwhile, the needle with zero pulse reaches the highest position, which means the largest flow area. The mass flow rates were measured at six EEV openings in various inlet temperature and pressure conditions.

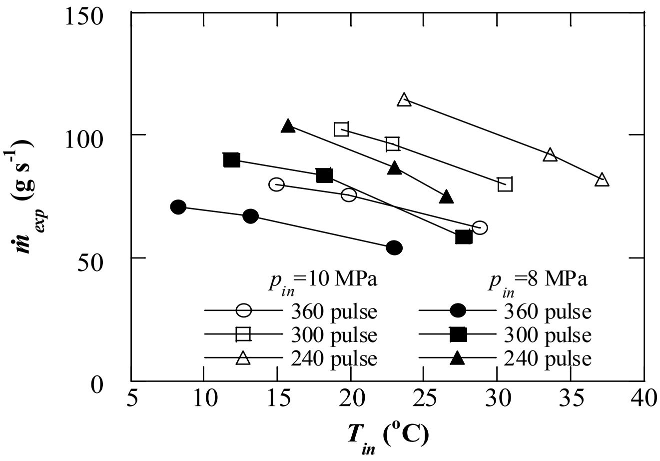
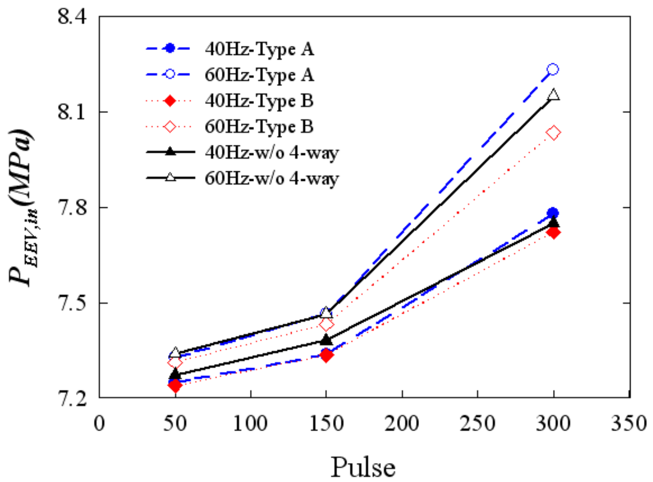


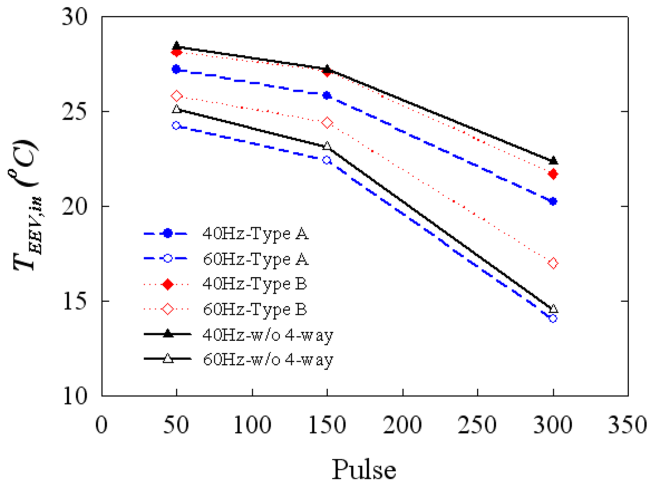
Chart 1 Variations of mass flow rate according to inlet temperature of the EEV

Main parameters are pressure and temperature at the inlet and the outlet of EEV, and the mass flow rate through the EEV. The temperature and pressure of the inlet of EEV were varied from 5°C to 40°C and from 7 MPa to 10 MPa, respectively. The mass flow rate through EEVs ranged from 50 g s^{-1} to 120 g s^{-1}.

Graphic 3 shows the 4-way valve and its schematic diagram used in this study. The inlet of 4-way valve connects the outlet of compressor which has highest pressure in the system. The flow direction and the role of heat exchangers are changed according to the operation mode in the heat pump system. However, the role of gas cooler and evaporator weren't changed in this study by controlling four valves adjacent to 4-way valve for the convenience of the test.



(a) Variations of inlet pressure of EEV according to pulse



(b) Variations of inlet temperature of EEV according to pulse

Chart 2 Comparison of pressure and temperature condition with regard to operation case of 4-way valve

HEAT PUMP SYSTEM INCLUDING 4-WAY VALVE

Chart 1 shows the variation of the mass flow rate through the expansion valve with an orifice diameter of 1.8 mm according to inlet temperature of the EEV. As inlet temperature increases and approaches the critical temperature, the mass flow rate decreases because the density of carbon dioxide decreases drastically around the critical temperature. Chart 1 also shows that the mass flow rate increases according to increasing inlet pressure of the EEV. This is because the inception point of phase change of refrigerant is moved toward EEV outlet, and the ratio of two-phase flow pressure drop to the total pressure drop becomes relatively small. Also, the density of carbon dioxide at high pressure is greater than that at low pressure.

Table 2 Coefficients in developed correlation, Eq. (1)

Coefficients	Value
C_1	1.51×10^{0}
C_2	9.54×10^{-2}
C_3	1.69×10^{-1}
C_4	-4.66×10^{-2}
C_5	-4.32×10^{0}

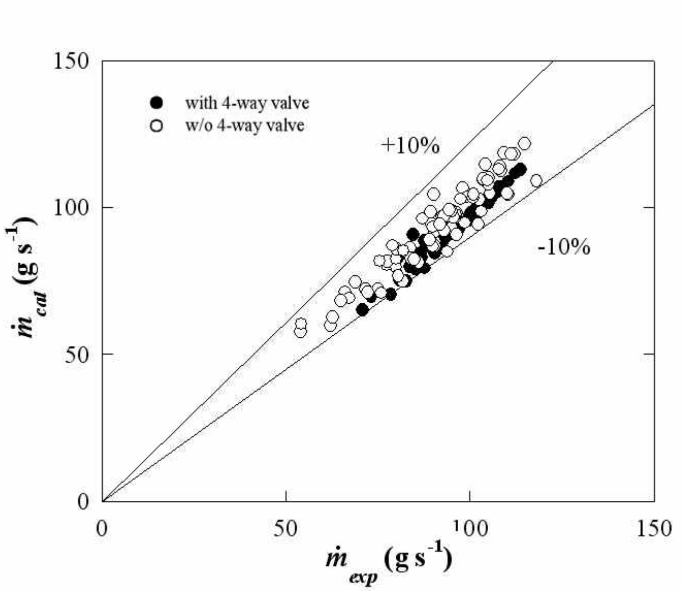


Chart 3 Comparison of mass flow rate between measured data and predicted data by developed correlation

Chart 2 shows the comparisons pressure and temperature condition with regard to operation case of 4-way valve. When 4-way valve is cooling mode position, this case is called type A, and when 4-way valve is the opposite position, it is called type B. But, flow direction of refrigerant doesn't change in both cases by controlling valves. The temperatures of secondary flow of a gas cooler and an evaporator were 30°C and 27°C, respectively. These are general temperature conditions of an indoor unit and an outdoor unit in the heat pump system. The RPM of compressor was varied from 40 Hz to 60 Hz and EEV opening was set as 50, 150 and 300.

Chart 2 shows the test results measured at the lowest and highest compressor frequency case. As shown in Chart 2, there wasn't obtrusive difference with respect to the installation of 4-way valve. At the same frequency of compressor, inlet pressure shows the absolute average deviation of 0.5% and inlet temperature shows the absolute average deviation of 4.9%. This discrepancy is caused by the extension of pipe length extension according to the installation of 4-way valve. The 4-way valve operation was checked thorough this test, and this valve showed stable operation at higher pressure than 10 MPa.

IMPROVEMENT OF CORRELATION FOR MASS FLOW RATE THROUGH EEVS

The correlation to predict the mass flow rate through EEV was developed in the previous study (8). In this study, the correlation was improved by analyzing additional experiments. To do this, all parameters influencing the mass flow rate were included in newly-developed empirical correlation. EEV inlet pressure (P_{in}), EEV inlet temperature (T_{in}), density (ρ) of carbon dioxide, and pressure drop (ΔP) through EEV are considered as parameters to affect the mass flow rate of carbon dioxide through EEV. Geometrical parameters are included in the correlation as following; the length of needle in orifice (L), orifice diameter (D_0), hydraulic diameter at orifice throat (D_m), and flow area at obstruction throat ($A_{t,m}$). The mass flow rate could be expressed as a function of parameters as shown in eq. (1). Five coefficients (c_1-c_5) were calculated with least-squares method and are listed in Table 2.

$$\left(\frac{\dot{m}}{A_{t.m}\sqrt{\rho\Delta P}}\right) = c_1\left(\frac{L}{D_m}\right)^{c_2}\left(\frac{D_m}{D_0}\right)^{c_3}\left(\frac{P_{in}}{P_c}\right)^{c_4}\left(\frac{T_{in}}{T_c}\right)^{c_5} \qquad \text{eq. (1)}$$

Chart 3 shows mass flow rate comparison of experimental data with calculated data by developed correlation and displays separately with respect to 4-way valve installed or not. Almost data are within deviation 10% regardless of 4-way valve. The average absolute deviation of non-existing case of 4-way valve is about 4.8%, and the average absolute deviations of Type A and Type B are 3.5% and 4.2%, respectively.

Chart 4 shows the tendency depending on opening of EEVs by comparing correlations with experiments. As shown in Chart 4, the more EEV closed, the mass flow rate reduced sharply. However, the correlation couldn't reflect this tendency exactly.

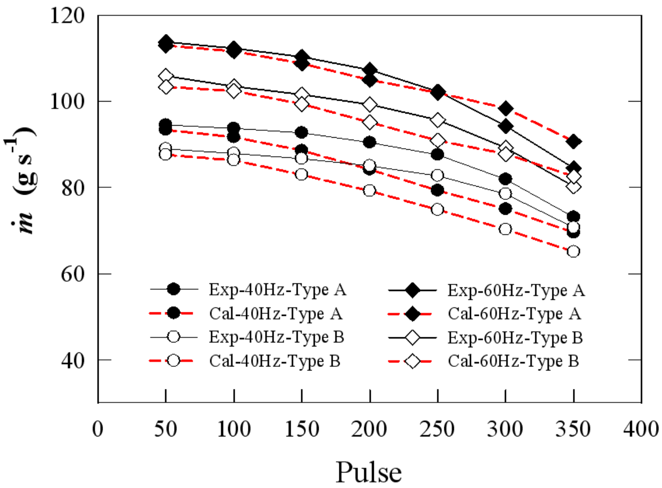


Chart 4 Comparison of mass flow rate between experimental data and correlation data according to opening of EEV

CONCLUSIONS

An experimental study on the flow characteristics of electronic expansion valves (EEVs) for heat pump system using carbon dioxide as a refrigerant have been carried out in this study. And the correlation of mass flow rate through the EEV was developed. This correlation predicted mass flow rate accurately compared with the correlation developed in the previous study (8). And this correlation showed the similar tendency of mass flow rate change according to closing of EEV. The average absolute deviation of non-existing case of 4-way valve is about 4.8%, and the average absolute deviations of Type A and Type B are 3.5% and 4.2%, respectively.

And the reliability test of developed 4-way valve was conducted. This 4-way valve showed stable operation over 10 MPa.

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