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Numerical Analysis on Flow of Automotive Variable Displacement Swash Plate Type Compressor ECV

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Abstract: *Vehicle air conditioner greatly affects the power efficiency and fuel economy of the vehicle, so the operation of the vehicle air conditioner is important.The compressor of the air conditioner has ECV (Electromagnetic Control Valve) which controls the compression ratio of the refrigerant. The compressibility of the refrigerant is an important factor in the performance of the compressor, so ECV of the automotive air conditioner compressor must be precisely controlled. Need to understand functional elements of the ECV with the development of the technology. In Variable Displacement Swash plate type Compressor, we analyze the refrigerant flow characteristics inside the valve on the effect of valve operation.Simulation results show a speed difference of about 44.4m / s and a pressure difference of about 4.44Mpa due to valve operation.*
Keywords: *Vehicle A/C, Swash plate type compressor, ECV, Flow characteristics*

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I. Introduction

Lee YJ et al. [1] investigated that automotive air conditioner compressor needs a lot of engine power.Lee YJ et al. [1] collected data on automotive air conditioner compressor and it showsthat air conditioner compressor is one of the most demanding parts in automobiles. Kim SW et al. [2] investigated that the effect of the air conditioner on the vehicle fuel economy is 9% on an annual average basis, Up to 23% at high temperature conditions.Lee BS et al. [3] investigated that the analysis of the influence of the fuel consumption on the components of the air conditioner. Lee BS et al. [3]showed that fuel consumption occupies 53% annual average fuel consumption and 70% fuel consumption under high temperature conditions [3]. ECV, which controls the amount of compression of a variable swash plate type air conditioner compressor that affects vehicle fuel economy and exhaust gas, is a technical device that improves fuel efficiency and reduces exhaust gas by increasing vehicle efficiency.

ECV(Electromagnetic Control Valve) is an electronically controlled pressure control valve that controls the amount and pressure of refrigerant according to the ECU (Electronic Control Unit) signal of the vehicle to improve the performance of the air conditioner. The core part of the ECV is the bellows, and the length of the bellows is changed by the change of the relationship between the gas pressure around the bellows and the tension of the spring.In this study, we study the operation principle of variable displacement swash air conditioner compressor through electronic pressure control valve (ECV), understand the shape and operation principle through benchmarking (reverse design) for overseasdeveloped products, The flow of the refrigerant is analyzed finitely.

II. Electromagnetic Control Valve(ECV)

The structure of the ECV consists of cylinder valves, solenoids, and bellows. The conceptual diagram of ECV is shown in Fig.1.The solenoid adjusts the position of the valve using the electromagnetic force, and generates an electromagnetic force according to the input current to drive the plunger and control the flow rate.The bellows is a core technology of ECV in the study of Son IS et al. [4].Vehicle ECU(Electronic Control Unit)detects the pressure change of the crankcase of the compressor according to the cooling load of the air conditioner.ECU makes bellows to expand and to shrink. Bellows rapidly expand and shrink to adjust the flow rate of the valve by opening and closing the pipe by axial tensioning and compression.Valve flow control is also available to prevent disturbance of other pressure and torque.

The operation mode of ECV can be divided into low-pressure operation and high-pressure operation and is shown in Fig. 2. In the low-pressure operation mode, the refrigerant moves to ① → Comp. → ② → ③ and the mode of operating by normal compression mode (refrigerant compression function) and the swash plate control function mode in which refrigerant moves to ① → Comp. → ② → ③ → → ⑤. In the high pressure operating mode, the refrigerant moves from ① → Comp. → ② → ③ and there is a mode of operation by normal compression mode (refrigerant compression function) and a swash plate control function mode in which refrigerant moves to ① → ④ → ⑤.The ECV controls the compression rate of the compressor by controlling the angle of the swash plate in swash plate control mode.

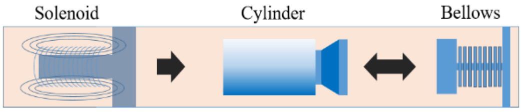

Fig. 1 ECV Conceptual diagram.

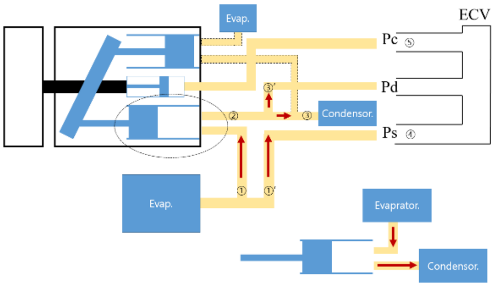

Fig. 2 Explanation of ECV mode.

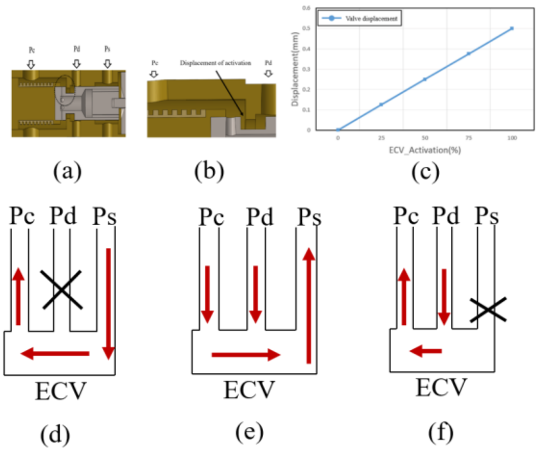

Fig. 3 View of refrigerant passage

Fig. 3. (a) shows the whole cross section of the ECV, which consists of a pressure port (Pc) connected to the crankcase of the compressor, a high-pressure passage (Pd) connected to the refrigerant discharge outlet of the compressor, a suction port Ps. Fig.3. (b) shows an enlarged view of the refrigerant passage.

The flow of refrigerant was analyzed according to the degree of ECV valve opening and closing. The opening and closing degree of the valve is shown in Fig. 3. (c). When the ECV operates at 0%, the low-pressure refrigerant in the suction port Ps moves to the pressure port Pc. The flow diagram of the refrigerant is shown in Fig. 3. (d).

When the ECV is operated at 25%, 50% and 75%, the refrigerant in the crankcase connected to the pressure port (Pc) flows into the Pc and the high pressure (1.6 MPa) Flows into Pd and is combined.Then, the refrigerant flows to the low- pressure refrigerant of the suction port Ps. The flow chart of the refrigerant is shown in Fig. 3. (e).

When the valve is in the 100% operating state, the valve operates at its maximum and flows from the high pressure passage Pd to the shaft port Pc and the low pressure (0.15 Mpa) flow of the suction port Ps flows to the refrigerant inlet of the compressor .The flow diagram of the refrigerant is shown in Fig. 3. (f).

III. Problem setup

This study used the reverse design of Hyundai MOBIS's ECV. Fig. 4 shows the front view of the ECV of Hyundai MOBIS and the parts by disassembling the ECV.Based on the ECV of Hyundai MOBIS, the reverse design is carried out and the cross-sectional structure after assembly is shown in Fig. 5.After the reverse design, the flow of the refrigerant in the system is easily understood according to the operation mode of the ECV.In order to investigate the flow of refrigerant flowing inside the valve, we made the mesh of refrigerant flow passage by referring to the internal shape and dimensions using 3D CAD SOLID WORKS.The operating principle of the valve and the refrigerant flow inside the valve were investigated by predicting the pressure and velocity distribution of the refrigerant acting on the valve by finite volume analysis of the internal passage through which the refrigerant flows using the ANSYS Fluent flow analysis program.In the flow analysis of this study, the bellows structure is omitted.Considering the bellows shape, Lee JH et al. [5] investigated that it is difficult to converge the numerical calculation because the lattice distortion increases in the lattice generation, and the internal shape of the bellows does not affect the flow of the refrigerant.

Fig. 4 ECV Model

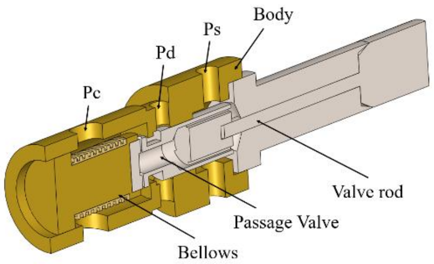

Fig. 5 Geometry of a ECV Valve

IV. Numerical Method

The simulation is conducted using the commercial CFD package Fluent 18.2 by solving the steady-state Reynolds averaged Navier–Stokes equations through the finite control volume method. The refrigerant is set as incompressible flow in this study.The Meshing package in Workbench 18.2 based on Fluent Mesh. Table.1 shows the number of mesh on ECV activation. The turbulence model uses Realizable k-ε model with the pseudo Transient for the simulation

For the analysis, R-134a (CH_2FCF_3) was used as the refrigerant.The refrigerant pressure condition was set at a low pressure based on the evaporation pressure of 0.15 Mpa and the maximum pressure of 0.82 Mpa when the operating rate of the compressor flowing to Ps was 100%.The pressure (0.36 MPa) in the crankcase of the refrigerant flowing into the pressure port Pc was set to a pressure fixed at an operating speed of the compressor of 4000 rpm. The pressure introduced into the high pressure passage (Pd) was set in consideration of the evaporation pressure characteristic of the refrigerant R134a.

Table.1 Mesh size of refrigerant flow

	The number of mesh
0% (0mm)	802918
25% (0.125mm)	3943762
50% (0.250mm)	1732273
75% (0.375mm)	1867950
100% (0.5mm)	1107871

V. Result And Discussion

5.1Pc→Ps flow (0%)

The refrigerant flows from the pressure port Pc to the suction port Ps at a rate of about 0.9 m / s to the pressure port Pc, Flow velocity of about 10.5 m / s was observed in the narrow channel.In the flow of the flow from the pressure port Pc to the suction port Ps, the velocity has increased through the narrow passage in Fig. 6. (a).

The pressure distribution when the refrigerant flows from the pressure port Pc to the suction port Ps is shown in Fig. 6. (b), and the refrigerant flows to the suction port Ps and the pressure of about 0.41 MPa acts on the narrow passage.The flow from the pressure port Pc to the suction port Ps is merged with the refrigerant flowing into the suction port Ps, so that the pressure is lowered.In the narrow channel where refrigerant flows, a vortex is generated at the portion where the pressure change inside the valve occurs, and the flow becomes unstable due to the increase of the turbulent kinetic energy.

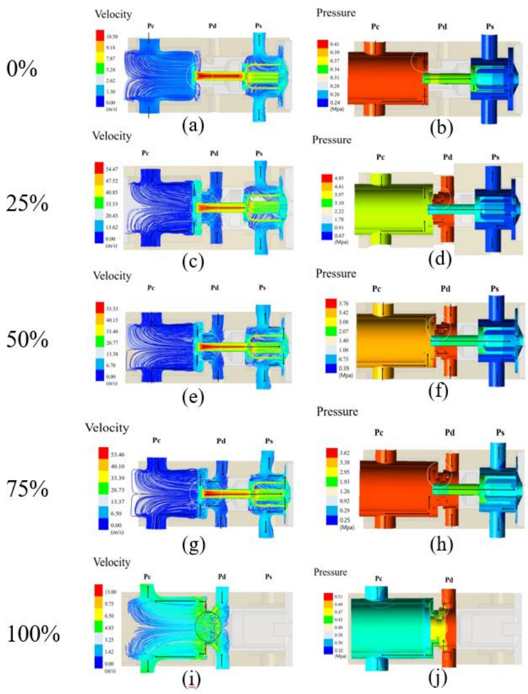

Fig. 6 Flow characteristics

5.2Pc-Pd → Ps flow(25%)

Fig. 6. (c) shows the flow structure into the suction port Ps by combining the refrigerant introduced into the pressure port Pc and the high-pressure passage Pd. The flow rate at a flow rate of about 54.5 m / s in the narrow passage through which the refrigerant flows.

Fig. 6. (d) shows the flow structure to the suction port Ps by combining the refrigerant introduced into the pressure port Pc and the high-pressure passage Pd.A pressure of about 4.85 MPa is applied to the narrow passage through which the refrigerant flows. A vortex is generated in the passage where the refrigerant is combined and moves to Ps, and the flow of the refrigerant becomes unstable due to the increase of the turbulent kinetic energy.

5.3Pc-Pd → Ps flow(50%)

The flow structure to the suction port (Ps) is shown in Fig. 6. (e) by combining the refrigerant introduced into the pressure port (Pc) and the high-pressure passage (Pd).And a flow velocity of about 53.5 m / s in a narrow passage through which the refrigerant flows.Fig. 6. (f) shows the flow structure into the suction port Ps by combining the refrigerant introduced into the pressure port Pc and the high-pressure passage Pd. A pressure of about 3.76 MPa is applied to the narrow passage through which the refrigerant flows.A vortex isgenerated in the passage where the refrigerant is combined and moves to Ps, and the flow of the refrigerant becomes unstable due to the increase of the turbulent kinetic energy.

5.4Pc-Pd → Ps flow (75%)

Fig. 6. (g) shows the flow structure to the suction port Ps by combining the refrigerant introduced into the pressure port Pc and the high-pressure passage Pd.A flow velocity of about 53 m / s in the narrow passage through which the refrigerant flows. The velocity is lower than the flow rate of 50%.The flow structure to the suction port (Ps) is shown in Fig. 6. (h) by combining the refrigerant introduced into the pressure port (Pc) and the high pressure passage (Pd).A pressure of about 3.62 MPa is applied to the narrow passage through which the refrigerant flows. The pressure is reduced when the ECV is 25% and 50%, respectively.A vortex is generated in the passage where the refrigerant is combined and moves to Ps, and the flow of the refrigerant becomes unstable due to the increase of the turbulent kinetic energy.

5.5Pd → Pc flow (100%)

When the valve 100% operates and the passage through the suction port Ps is closed, the refrigerant in the high-pressure passage Pd flows into the pressure port Pc due to the pressure difference. Fig. 6. (i) showsthe flow structure of the refrigerant and the refrigerant a flow rate is about 13 m / s in the narrow channel through which the refrigerant flows.

When the valve 100% operates and the passage through the suction port Ps is closed, the refrigerant in the high-pressure passage Pd flows into the pressure port Pc due to the pressure difference.The pressure distribution when the refrigerant flows is shown in Fig. 6. (j), and the pressure distribution of about 0.51 Mpa is shown in the narrow passage through the refrigerant. The turbulent kinetic energy is the largest in the narrow path from Pd to Pc, and it can be deduced that the vortex is severe in the narrow path and the flow is unstable.

5.6 Results compared with experimental data

Table.2 shows all of the simulation results. The existing experimental data is compared with refrigerant flow simulation in ECV to see how the finite volume analysis through ANSYS CFX differs from the actual ECV internal flow.

The experimental device is an experimental device for measuring the flow rate of the Pc passage, which is the connection path to the crankcase of the compressor.

The experimental apparatus adjusts the opening and closing amount of the ECV by using the PWM controller of the ECU in the same manner as the actual engine control unit (ECU) of the automobile.The specifications of the experimental apparatus are shown in Table 3.

Table.2 Analysis result

0%			Suction velocity	**Inner velocity**	**Inner pressure**
Pc	Pd	Ps			
0.36Mpa	1.6Mpa	0.15Mpa	0.9m/s(Pc),3m/s(Pd), 0.3m/s(Ps)	**10.5m/s**	**0.41Mpa**
25%			0.9m/s(Pc), 3m/s(Pd), 0.3m/s(Ps)	**54.5m/s**	**4.85Mpa**
0.36Mpa	1.6Mpa	0.15Mpa			
50%			0.9m/s(Pc), 3m/s(Pd), 0.3m/s(Ps)	**53.5m/s**	**3.76Mpa**
0.36Mpa	1.6Mpa	0.15Mpa			
75%			0.9m/s(Pc), 3m/s(Pd), 0.3m/s(Ps)	**53m/s**	**3.62Mpa**
0.36Mpa	1.6Mpa	0.15Mpa			
100%			0.9m/s(Pc), 3m/s(Pd)	**13m/s**	**0.51Mpa**
0.36Mpa	1.6Mpa				

Table.3 General specifications of experimental setup

Application	PWM pressure control valve for A/C compressor
Ambient temperature	-40º C~140º C
Burst pressure	90 bar
Operating pressure	27~45 bar
Fluid	Air/refrigerant and oil mixture

Coil resistance	10.2±0.3 Ohm
Dielectric strength	AC600V 50Hz x 1 sec
PWM	400±10 Hz x duty 0~100%
Nominal voltage	12 ±0.1V DC (engine not running) 13.2 V± 0.1V DC (engine running)
Min. voltage	7.5V DC (engine not running)
Max. voltage	16V DC
Max. continuous current	13.5C DC x 100% Duty x -12~135 C
Max. voltage	16V DC

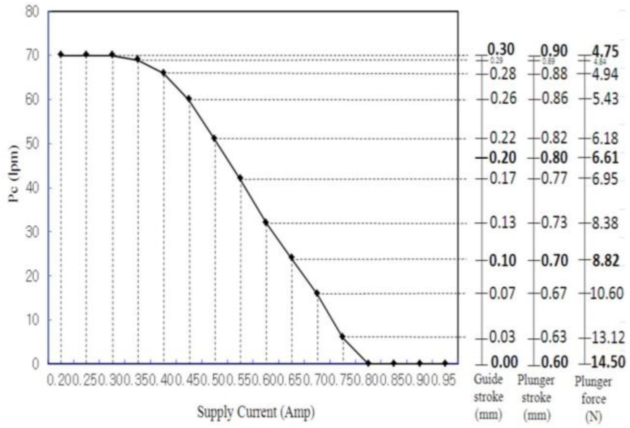

Fig. 7 ECV flow flux analysis[6]

Table.4 Calculation result.

Q	V
5 liter/min	6.33 m/s
10 liter/min	12.65 m/s
20 liter/min	25.30 m/s
30 liter/min	37.95 m/s
40 liter/min	50.60 m/s
50 liter/min	63.26m/s
60 liter/min	75.90m/s
70 liter/min	88.56m/s

Fig. 7Kim BJ et al. [6] shows experimental results showing the flow rate of the Pc channel while changing the length of the plunger and increasing the amount of current.The results are compared with the ECV model with the plunger length of 0.63 mm when the force applied to the plunger is 13.12 N, which is the strongest.At this time, the flow rate of Pc is about 5l/min. Assuming an incompressible flow, the flow rate can be obtainedusing equation (13), which is the flux with the flow rate.The flow velocities calculated using equation (14) and equation (15) for calculating the area of Pc are shown in Table 4.

$\mathrm{Q} = \mathrm{V} \cdot \mathrm{A}$ (13)
$\mathrm{Q} = \mathrm{l/min} = 1.67 \times 10^{-5} m^3/s$(14)
$\mathrm{A} = \pi D^2/4 = 1.32 \times 10^{-5} m^2, D = 4.1\pi mm$(15)

As shown in Fig. 28, when the valve is operated at 100%, the flow velocity in Pc is 6.33 m / s. Therefore, the flow velocity of the Pc flow in the finite volume analysis is about 6 m / s, which is 0.05%.
The difference between the experimental data and the flow rate of the simulation was due to the complicated channel shape, and the vortex due to the peeling occurred.

VI. Conclusion

In this study, we tried to understand the shape and operation principle through the reverse design of ECV, which is an external control valve that regulates the amount of refrigerant in a variable swash plate type compressor. The flow of refrigerant in the valve was predicted by finite volume analysis according to the operation of the valve. The ECV has a complex internal structure and it is difficult to know the internal flow by valve opening and closing.The refrigerant flows in the ECV due to the degree of opening of the high-pressure passage (Pd) of the ECV through the duty control, and the flow is analyzed as follows.

1. There is a sudden change in speed and pressure due to a decrease in the flow passage area when the degree of opening of the high-pressure port Pd is small.
2. The maximum velocity of the refrigerant inside the ECV was interpreted as 54.5 m / s when 25% of the high-pressure passages (Pd) were opened and the maximum pressure was 4.85 Mpa. The greater the degree of opening, the smaller the variation.
3. When the refrigerant flows at high-pressure, it is required to design a component capable of withstanding a pressure of 4.85 MPa or more at a speed of 54.5 m / s of the refrigerant.

Analysis of the results of this study shows that the pressure changes into and out of the ECV are large. Due to the flow velocity and pressure of the refrigerant flowing through the ECV operation, the flow may be separated due to the difference in speed due to the change of the internal shape of the valve. Due to the peeling phenomenon, a vortex is generated in the valve and noise due to flow vortex may appear.

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