NUMERICAL ANALYSIS OF THE PERFORMANCE OF A COMPRESSOR WITH SUCTION ORIFICE POSITION USING A RIGID BODY MODEL FOR REED VALVES

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ABSTRACT

The refrigeration system is an indispensable field in our everyday life and needs continuous research. Since the refrigerator consumes a large amount of power in the home, it needs to improve the efficiency of the compressor. In this paper, a numerical analysis is carried out using a 3D valve model to investigate the performance change of refrigerator according to suction orifice position. As a result, it has been found that as the suction orifice is located farther from the center, the cooling capacity becomes greater and the EER also higher.

Keywords: compressor, rigid body model, suction orifice, cooling capacity, compressor work, EER.

INTRODUCTION

Due to industrial developments and population growth, not only environmental problems but also energy consumption rates are increasing rapidly. In order to solve this problem, energy efficiency has been a great concern and continuously improved [1].

The refrigeration industry is an eco-sustainable sector, and it is helping the industry and everyday life. Air conditioners and refrigerators as a typical household appliance have been widely used. The power consumption of a refrigerator is about 0.042kW, and the power consumption of air conditioner is 1.2kW. However, the air conditioner is only used during hot summer days, while the refrigerator continues to operate all four seasons. Therefore, although the rated power consumption of the refrigerator is not high, the power consumption can not be ignored.

(a) Reciprocating compressor

(b) Linear compressor

Figure-1. Typical refrigerator compressors.

The refrigerator power consumption usually depends on the energy efficiency of the compressor.

Therefore, Hasanuzzaman *et al*. [2] studied heat transfer in the refrigerator and tried to reduce the power consumption of the refrigerator. Schanin [3] conducted a study on reducing the power consumption of a refrigerator compressor through a control system.

Compressors include rotary compressors [4], scroll compressors, reciprocating compressors, and linear compressors. Among them, reciprocating compressors and linear compressors are widely used in household refrigerators. Figure-1 (a) is a schematic of a reciprocating compressor. The reciprocating compressor converts rotational motion of a crankshaft into linear motion through a connecting rod. Figure-1 (b) is a schematic of a linear compressor. The piston of a linear compressor linearly moves by a linear motor. In addition, suction and discharge valves are located at the upper end of the chamber for a reciprocating compressor, while they might be located in a straight line, parallel to the flow direction, for a linear compressor.
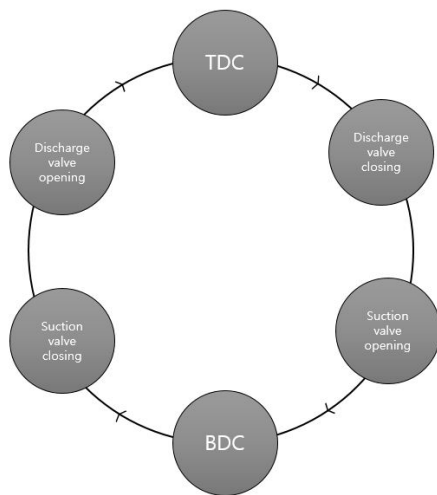
Many researchers have performed studies on refrigerator compressors. Silva and Deschamps [5] suggested that refrigerant leakage through the discharge valve clearance reduces compressor efficiency over the suction valve clearance. Bae and Oh [6] studied the piston behavior of linear compressors through CFD (Computational Fluid Dynamics).

Figure-2 shows the valve opening and closing during compression and expansion processes of the compressor. First, the suction valve is opened before the BDC so that the refrigerant flows into the compression chamber. Next, the refrigerant is compressed after the suction valve closes past the BDC. Then, the discharge valve is opened before the TDC, and the compressed refrigerant at high temperature and high pressure is discharged through the discharge valve. Finally, after TDC, the discharge valve closes and the refrigerant undergoes expansion process. The compressor repeats this cycle. For a refrigerator compressor, suction and discharge valves are
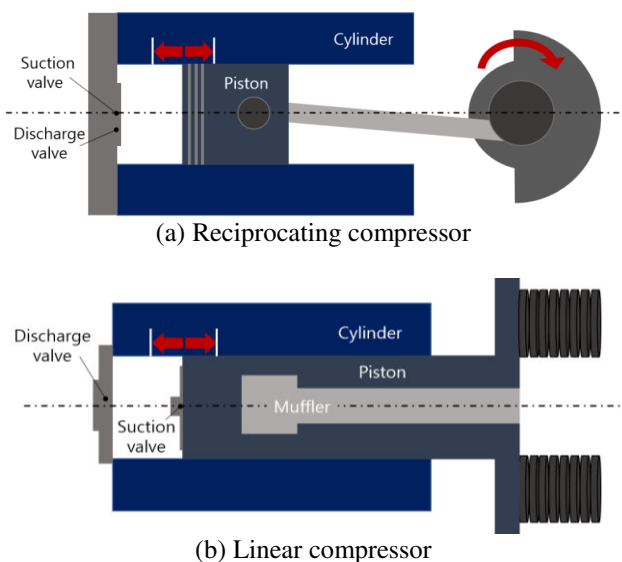
Figure-2. Valve opening and closing timing.

critical to compressor performance.

Many researchers have conducted a number of studies on compressor valves. Willian and Cesar [7] numerically predicted the suction valve behavior of a reciprocating compressor using finite element method. They have optimized the structure of the intake valve system. Jomde *et al.* [8] also investigated the compressor efficiency variation with the suction valve thickness of the linear compressor. Hwang *et al*. [9] investigated the discharge valve behavior of the linear compressor through the FSI model and predicted the EER (Energy Efficiency Ratio) [10] of the refrigerator. Park and Lee [11] numerically analysed the performance changes of the linear compressor using the rigid valve model.

However, the effect of suction orifice position on compressor performance has not been studied yet. Therefore, in this study, the change of the compressor performance according to the suction orifice position was examined. For this, 3D rigid-body valve models were used and cooling capacity, compression work and EER were determined with varying suction orifice position.

NUMERICAL METHODS

(a) Case 1   (b) Case 2

(c) Case 3
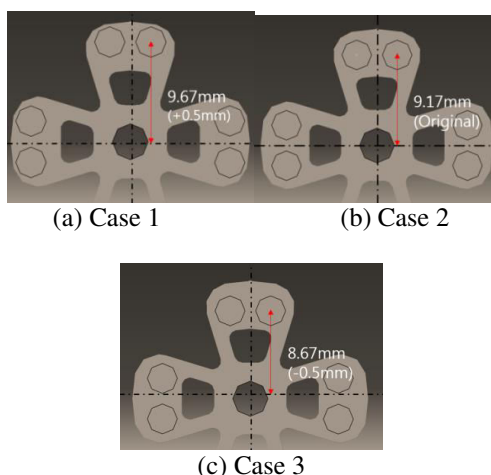
Figure-3. Locations of suction orifices.
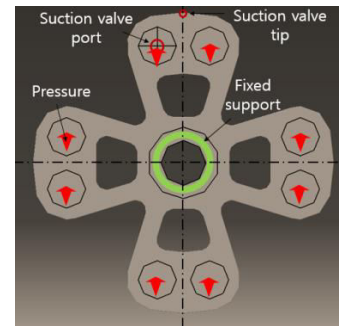
Figure-4. Constraints for structural analysis
of the reed valve.

Table-1. Material properties of the suction valve.

| Material	Sandvik 20C
Density	7800 kg/m^3
Young's Modulus	210 GPa
Poisson's Ratio	0.3
Tensile Yield strength	1200 MPa
Compressive Yield strength	1200 MPa

In this paper, three locations of suction orifice are considered as shown in Figure-3 and the EER of the refrigerator according to the orifice position is obtained. Valve modeling was done by Catia [12]. In case 1, the suction orifice is located 0.5 mm higher in the radial direction compared to the case 2. In case 3, it is located 0.5 mm lower than that of case 2.

Figure-4 shows the constraints for the structural analysis of the reed valve. For the load condition, a pressure of 1 kPa to 5 kPa was applied to the suction port and a fixed condition was provided on the side where the screw and the reed valve were in contact. Also, the deformation amount of the suction valve was determined based on the center of the suction port.

The material of the reed valve is Sandvik 20C [13] and its properties are shown in Table-1.

Figure-5 (a) and (b) show deformation and stress when a pressure of 1 kPa is applied to the suction port of case 2. The deformation was 0.17 mm, which was the largest at the end of the reed valve, and the stress was the highest at the bottom part of the reed valve, 53.5 MPa.

Figure-6 shows the fourth mode obtained through the modal analysis of the reed valve [14]. At this time, the natural frequency was 392.8Hz.

(a) Deformation (b) Stress
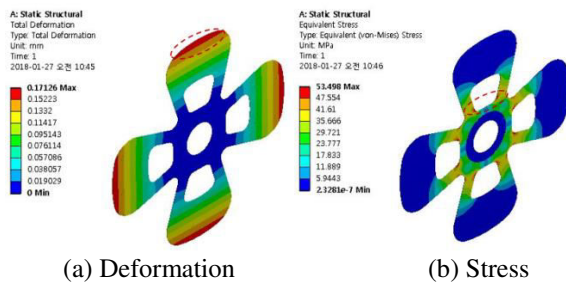
Figure-5. Deformation and von Mises stress of the reed valve.
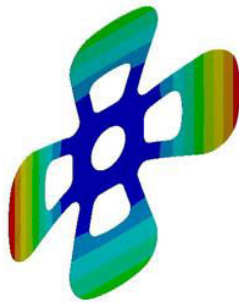

Figure-6. Modal shape of the reed valve.

Equation (1) shows the one-dimensional vibration equation. Here, the spring constant is given by equation (2).

$$F = m_e \ddot{x} + c\dot{x} + kx \qquad (1)$$

$$k = \frac{F}{x} \qquad (2)$$

The spring constant was calculated from the equation (2) as in Figure-7 using the deformation of the reed valve and the pressure load of the suction port.

The effective mass was obtained using spring constant and natural frequency as shown in Equation (3). The damping coefficient of the reed valve was calculated as shown in Equation (4). At this time, the damping ratio ξ is assumed to be 0.1.
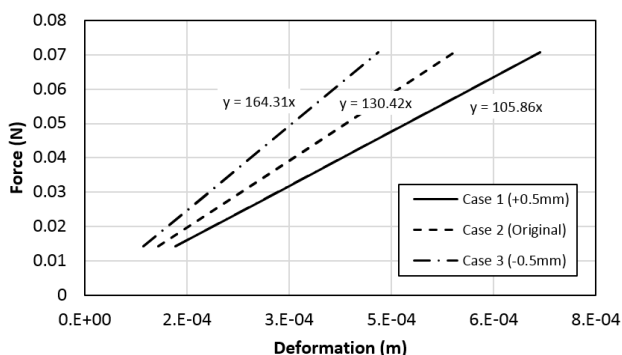
Figure-7. Spring constants of the suction valve.

Table-2. Spring constant, effective mass and damping coefficient of the suction valve according to orifice position.

Model	Spring constant (N/m)	Effective mass (kg)	Damping coefficient
Case 1	105.8	1.737E-05	0.857E-02
Case 2	130.4	2.141E-05	1.056E-02
Case 3	164.3	2.697E-05	1.331E-02

(a) Front view (1/8 model)

(b) Mesh system
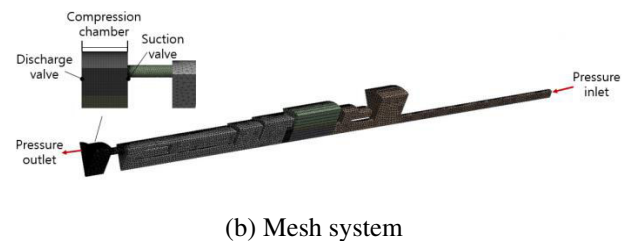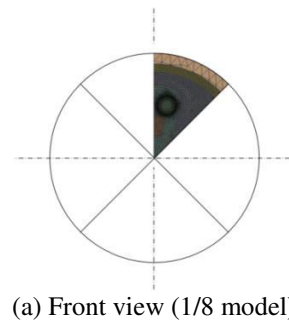
Figure-8. 3D rigid body valve model.

$$m_e = \frac{k}{(2\pi f)^2} \qquad (3)$$

$$c = \xi\sqrt{m_e k} \qquad (4)$$

The spring constant, effective mass and damping coefficient of the reed valve according to the location of the suction orifice are shown in Table-2.

In this paper, a three - dimensional rigid body model is used to predict the behavior of the suction valve. In order to simplify the analysis, the 3D valve model was cut to 1/8as shown in Figure-8 (a). Figure-8 (b) shows the mesh system of the valve model. Mesh was created using Ansys meshing [15] and about 170,000 cells were used.

Three-dimensional CFD analysis was performed using Fluent [16]. The turbulence model uses a realizable k - ε model and UDF (User Defined Function) is used to describe the piston motion inside the compressor. The refrigerant used for the numerical analysis is R600a used in household refrigerator. The behaviors of the discharge valve and the suction valve were simulated by a rigid body model.

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RESULTS AND DISCUSSIONS

Valve lift according to suction orifice position

Figure-9 shows the variation of valve lift with piston phase angle for a cycle. The discharge valve opens once while the suction valve opens twice. This is caused by the stiffness of the suction valve. The suction valve lift is about two times larger than that of the discharge valve. This is because the diameter of the discharge valve is much larger than that of the suction valve and the flow area of the discharge valve is much larger. There is almost no change in the discharge valve lift while the suction valve lift increases as the suction orifice moves farther from the center. This means that the amount of refrigerant
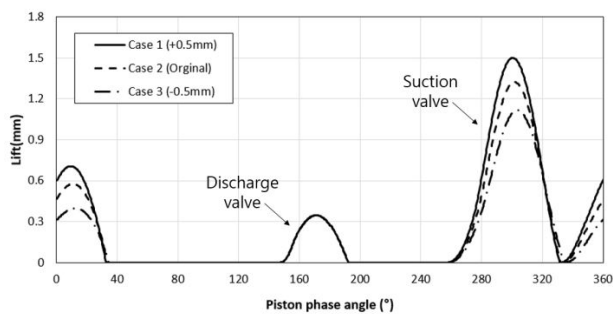

Figure-9. Variation of valvelifts with piston phase angle.

entering the compression chamber through the suction valve increases.

Cooling capacity according to suction orifice position

Figure-10 shows the variation of mass flow rate of suction valve with piston phase angle. The farther away the orifice is from the center, the more the mass flow increases. In addition, the time for the mass flow rate to reach a maximum is advanced. This is due to the fact that as the orifice moves away from the center, as shown in Figure-9, the lift peak of the suction valve advances. As the suction valve mass flow rate increases, the cooling power increases proportionally.

Figure-11 shows the cooling capacity according to the suction orifice position. As the suction orifice position moves away from the center, the suction valve is opened more and the cooling power is increased. The cooling capacities of case 1 and case 2 were increased by
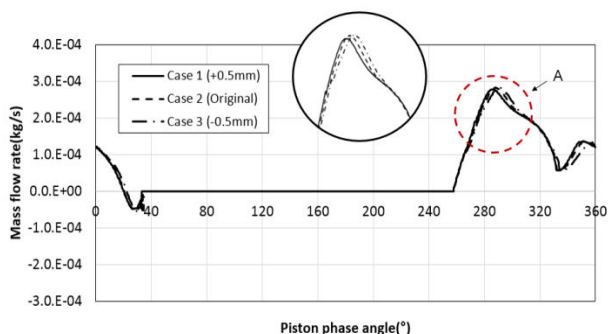

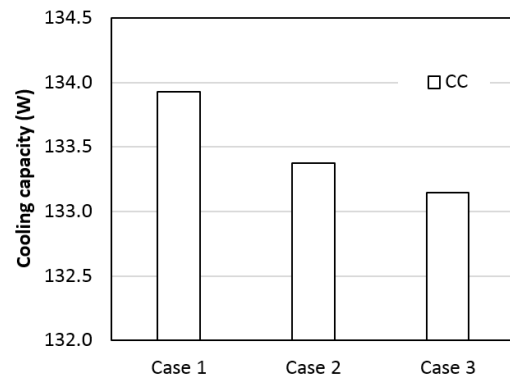**Figure-10.** Mass flow rate according to orifice location.

Figure-11. Cooling capacity according to orifice location 0.59% and 0.17% compared to case 3, respectively.

Compression work and EER according to suction orifice position

Figure-12 shows the P-V diagrams of the compressor according to the position of the orifice. The difference between compression and expansion curves was insignificant according to the position of suction orifice. However, case 3 shows the lowest suction pressure during suction process.

Figure-13 shows the variation of compression work with case. The compression works were obtained by integrating the PV diagrams. Case 2 has the smallest compression work and case 1 shows the largest. Compression work, cooling power and EER according to the orifice location are summarized in Table-3. Case 1 has the smallest compression work, but the cooling capacity is relatively small. As a result, the EER of case 1 is the highest. The EER of case 1 is about 0.05 higher than case 3.
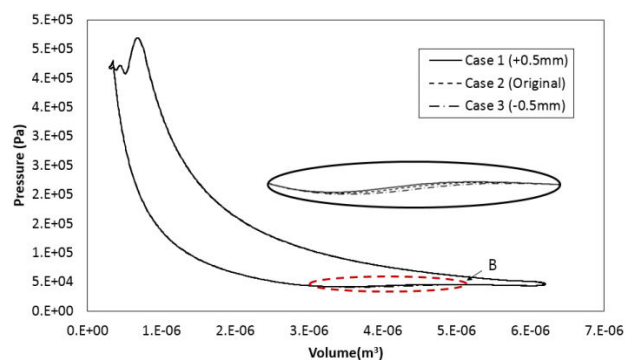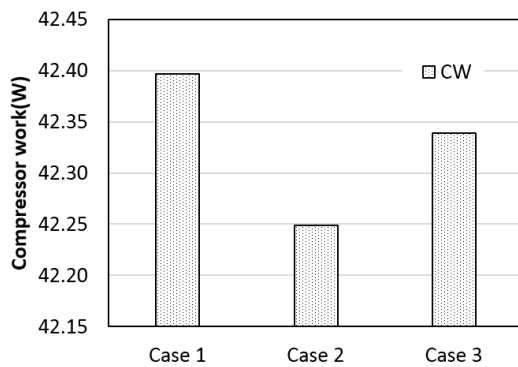

Figure-12. P-V diagrams according to orifice location

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Figure-13. Compressor work with orifice location.

Table-3. CW, CC and EER with orifice location.

Model	Compressor work	Cooling capacity	Energy efficiency ratio
Case 1	42.40 W	133.93 W	10.772
Case 2	42.25 W	133.37 W	10.765
Case 3	42.34 W	133.15 W	10.724

CONCLUSIONS

In this paper, we investigated the performance change of refrigerator according to the position of suction orifice using CFD. The following conclusions were drawn from this study.

a) As the position of the suction orifice moves away from the center, the lift of the suction valve increases and the mass flow rate also increases.
b) Case 2 has the smallest compression work and case 1 has the largest compression work. However, the variation of compression work with case is relatively small compared to cooling power.
c) Thus, EER is the highest in case 1, but it is about 0.05 larger than case 3.

In the future, further EER improvement needs to be achieved by optimizing other suction system structure.

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