CFD analysis of linear compressors considering load conditions

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Abstract. This paper is a study on computational fluid dynamics (CFD) analysis of linear compressor considering load conditions. In the conventional CFD analysis of the linear compressor, the load condition was not considered in the behaviour of the piston. In some papers, behaviour of piston is assumed as sinusoidal motion provided by user defined function (UDF). In the reciprocating type compressor, the stroke of the piston is restrained by the rod, while the stroke of the linear compressor is not restrained, and the stroke changes depending on the load condition. The greater the pressure difference between the discharge refrigerant and the suction refrigerant, the more the centre point of the stroke is pushed backward. And the behaviour of the piston is not a complete sine wave. For this reason, when the load condition changes in the CFD analysis of the linear compressor, it may happen that the ANSYS code is changed or unfortunately the modelling is changed. In addition, a separate analysis or calculation is required to find a stroke that meets the load condition, which may contain errors. In this study, the coupled mechanical equations and electrical equations are solved using the UDF, and the behaviour of the piston is solved considering the pressure difference across the piston. Using the above method, the stroke of the piston with respect to the motor specification of the analytical model can be calculated according to the input voltage, and the piston behaviour can be realized considering the thrust amount due to the pressure difference.

1. Introduction
Recently, global depletion of resources and global warming have accelerated, and the importance of energy saving is emphasized in many industries. It is a relevant step to reduce household appliances energy consumption to meet the regulation in decreasing the global energy consumption. Household refrigerator must operate 24 hours a day and this requires the largest proportion of energy consumption in the house. Furthermore, the compressor consumes the most of the energy required by the household refrigerator. Thus, various kinds of the research and development are continuously carried out to increase the efficiency of the compressor in the household refrigerator manufacturers and related universities.

An analytical approach using CFD is one of the efficient tools in research and development of refrigerator compressor. CFD analysis helps predict the phenomena occurring in compressor sensitive to heat or fluid flow, and identify the variations by easily changing parameters. In addition, by using the fluid structure interaction (FSI) technique, the behaviour of the valve is simulated to develop an
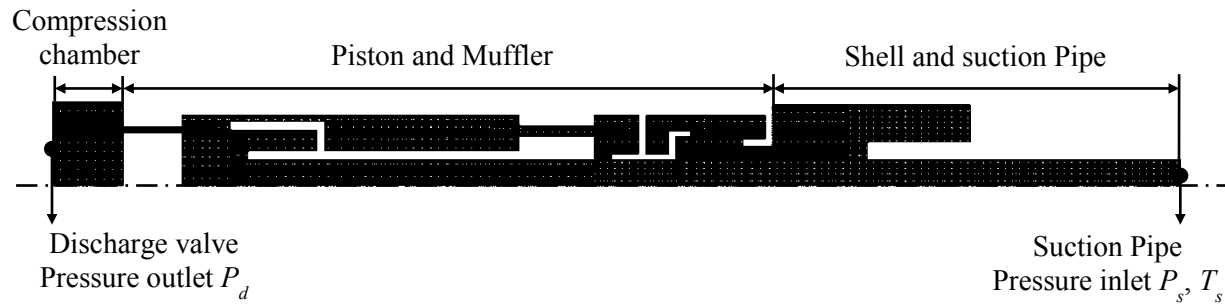
Figure 1. Fluid domain in CFD analysis of the linear compressor.

analysis technique that is closer to the actual phenomenon. Oh et al. (2016) studied the effects of CFD on the muffler shape of a linear compressor. The influence of the temperature and pressure of the refrigerant on the compressor efficiency according to the change of the muffler shape was analysed and the design direction was suggested. Suh et al. (2006) analysed the suction valve movement and the pressure of the refrigerant before compression process according to the muffler shape of the linear compressor using FSI technique. The effect of muffler frequency and acoustic supercharging effect on compressor efficiency according to muffler shape was shown. Kim et al. (2011) studied the capacity variable characteristics of linear compressors. It was analysed through the numerical method by equation and conducted experiments with the prototype compressor. They explained linear compressors require a new design approach because the stroke mechanism changes as load conditions change by the free piston system.

In this study, the UDF is used for the piston behaviour in the flow analysis of the linear compressor. In the UDF, the stroke is calculated by two coupled equations, the mechanical equation of the piston and the electrical equation of the motor. When the sine wave voltage is applied, the two coupled equations are solved using the Runge-Kutta method and the velocity of the piston is calculated. In the above process, stroke shift, which is characteristic of linear compressors, can be reflected.

2. Numerical Methodology
In this study, the mechanical equations of the piston and the electric equations of the motor are used to realize the behaviour of the piston over time in the transient analysis, and the two equations are coupled.

$$m\ddot{x} + c\dot{x} + kx = f + \alpha\dot{q}$$
$$L\ddot{q} + R\dot{q} + \frac{1}{C}q + \alpha\dot{x} = V$$

Where, forcing term of the mechanical equation is reflected in the force applied to the piston by the compressed gas, which plays an important role in simulating the actual behaviour of the linear compressor piston. There are two advantages to solve the two coupled equations to realize the behaviour of the piston. Firstly, it is possible to realize the behaviour of the piston. Unlike a reciprocating compressor (using crankshafts and rods), the stroke of a piston is not constrained, and a linear compressor is subjected to a force in the opposite direction of compression due to the difference between the pressure in the piston-cylinder compression chamber and the pressure inside of the piston. Stroke shift occurs when the piston is pushed backward. This explains the stroke applied gas force and the stroke neglected gas force are not equal at the same input voltage, and in the former case, the stroke is shifted backward. In this method, similar to the actual piston can be reflected in the analysis, and furthermore, the maximum stroke and the maximum cooling capacity in a limited geometry can be calculated. Secondly, the electrical work can be calculated. If the stroke of a piston is implemented as a sinusoidal wave, the efficiency is calculated by using the compression work as input of the compressor. On the other hand, when the electrical equations are solved together, the power consumed by the motor can be calculated, and the efficiency of the compressor can also be calculated using the
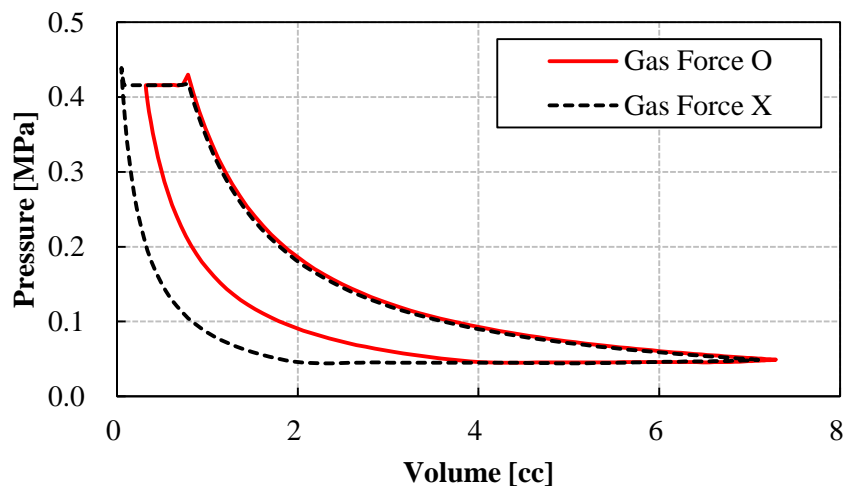
Figure 2. P-V Diagram with and without gas force.

electric power. It shows that the efficiency of the compressor and the motor is changed according to the specification of the motor. This provides the optimum point of the motor.

ANSYS Fluent V.15 was adopted for CFD simulations. Two-dimensional axisymmetric domain was used to reduce the number of cells and to simplify the structure. As shown in Figure 1, the domain is considered to be the back of the shell where the refrigerant entering through the suction pipe diffusion, the interior of the piston, and the compression chamber. The interpretation domain was assumed to be unsteady, viscous flow, compressible real gas model and κ-ε turbulence model. We set the simulation fluid as a real-gas-isobutane based on physical property in Refprop. A square cell was used and dynamic mesh including layering was used to implement motion of the piston. Numerical values used in the boundary conditions were obtained by experiments. The boundary condition corresponding to the suction pipe was 298 K temperature, 48,000 Pa pressure, and mass flow inlet condition was given. For the fully open discharge valve, the temperature 348 K, the pressure 415,000 Pa and the pressure-outlet condition was given. The temperature of the surface of the parts such as piston, muffler, shell, etc. was given as the boundary condition obtained from the experiment. The SIMPLE scheme is used by the pressure-velocity coupling algorithm. We apply a second upwind line to the interpolation between the node and the node. The total numbers of nodes and elements in the fluid model were about 65,000 and 128,000, respectively. Each time step needed about 5e-5 seconds to run calculation.

The operating process of the compressor applied to the CFD analysis consists of compression, discharge, expansion and suction. Discharge occurs when the discharge valve opens when the pressure in the compression chamber reaches P_d. Likewise, suction is achieved by opening the suction valve when the pressure in the compression chamber reaches P_s. Where P_d and P_s are the pressures corresponding to the temperatures of the condenser and the evaporator for a particular operating condition of the refrigerator. Compression and expansion processes are polytropic processes. The valve is assumed to be a fully-open, fully-closed ideal valve. The actual suction port is eccentric in the central axis of the piston, so that the area is the same as the donut shape in order to reflect this in the axis-symmetry.

Table 1. Result comparison with and without gas force

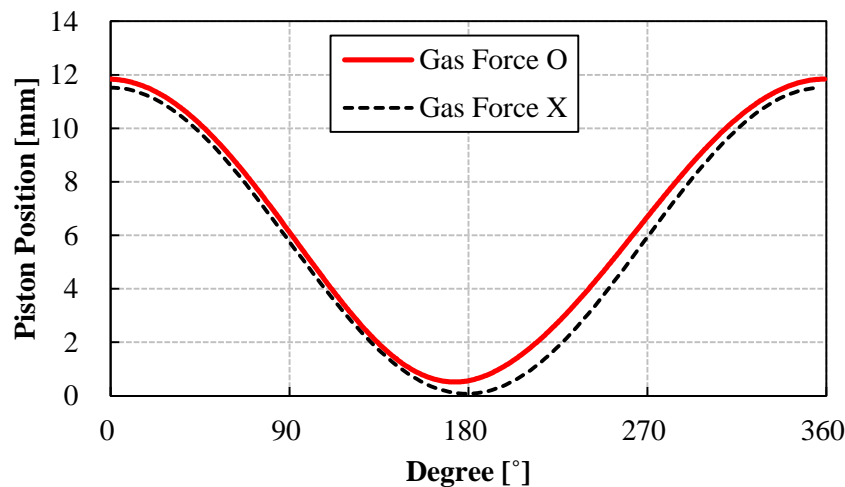|	Cooling Capacity (W)	Compression Work (W)	C.O.P.
With gas force	116.6	36.3	3.21
Without gas force	199.5	62.7	3.18

Figure 3. Stroke curve with and without gas force.

3. Result and Discussion

3.1. Effect of gas force on P-V diagram
In this section, we compare the case where the gas force acts and the case where the gas force does not act. In both cases, the stroke is calculated by the coupled two equations, the mechanical equations of the piston and the electrical equations of the motor, and depends on the presence or absence of forcing term *f* by the gas in the mechanical equation of the piston. And the same voltage was applied. Figure 2 is a pressure-volume (P-V) diagram for the compression chamber of a piston-cylinder. The P-V curve with a gas force is shifted to the right for a P-V diagram without a gas force as presented in Figure 2. We can see that the bottom dead centre (BDC) that starts compression and the top dead centre (TDC) that ends discharge move to the right. It can be seen that the characteristics of the linear compressor, in which the piston is subjected to the force in the opposite direction of compression by the gas force and the stroke is shifted, is well reflected by the analysis. As the P-V diagram changes, the cooling capacity and compression work also change, as shown in Table 1. When the gas force is applied, both the cooling capacity and the compression work are seen to decrease because the stroke is reduced by the gas force. Theoretically, even though the stroke changes, C.O.P., which is calculated using compression work, does not change, but it can be a necessary result to predict the maximum cooling capacity of a linear compressor through the above discussion. Due to the free piston, which is a characteristic of a linear compressor, pushing back occurs when a gas force is applied and piston can move a maximum stroke greater than twice the compression chamber distance corresponding to the initial position of the piston.

3.2. Effect of gas force on piston behaviour at same input voltage
Figure 3 shows the behaviour of the piston with and without gas force. The behaviour of the piston by the gas force is not perfect sinusoidal form. This is similar to the case where the angular velocity is not the same in the compression and expansion process of the reciprocating compressor. The compression process was slightly shorter and the expansion process was slightly longer as shown in Figure 3. This means that the gas force is reflected, the phase of TDC becomes faster. Also, the difference in TDC position is larger than BDC position. The centre positions of the strokes are 6.2 mm and 5.8 mm, respectively, when gas force is applied and when it is neglected. It shows the centre position is pushed BDC direction by 0.4 mm as the gas force acts. If the diameter of the pistons becomes larger or the spring stiffness becomes weaker, the centre position will be pushed more. Also, the larger the pressure differences between the condenser and the evaporator, the greater the pushed back amount. This can be an important factor in configuring the geometry of a linear compressor and can provide the information required to match the compressor and the refrigerator. When designing the initial position
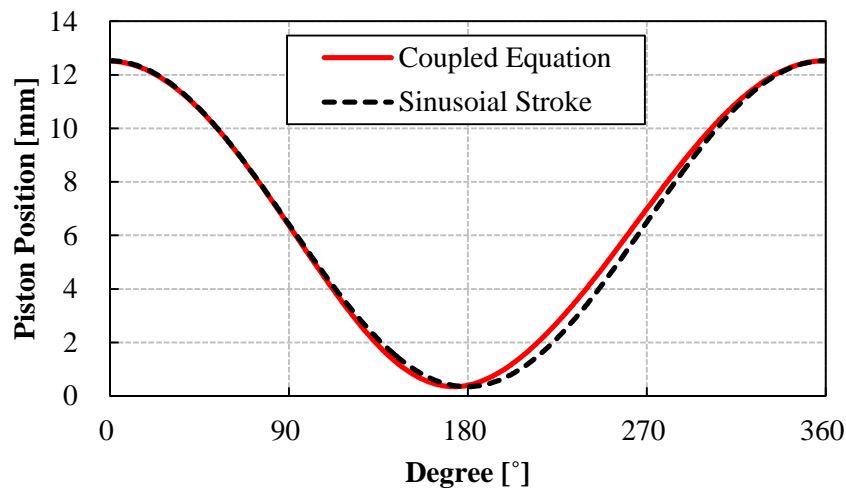
Figure 4. Piston positions about two cases. (calculated by coupled equations, and sinusoidal stroke)

of the piston and the stroke amplitude required for the maximum cooling capacity, it is necessary to reflect the amount of push back by the gas force, so that mechanical collision and reliability deterioration can be prevented.

3.3. Effect of gas force on piston behaviour at same amplitude stroke
In the previous section, we compared the results with and without the gas force on the same voltage in calculating stroke using coupled electrical and mechanical equations. In this section, the results are compared by giving a sinusoidal stroke waveform with the same amplitude as the stroke calculated by the two coupled equations, the mechanical equation and the electrical equation. In both cases, compression work, and C.O.P. were the same. In the compression chamber, if the piston positions are the same, pressure is the same due to the polytropic process, regardless of the stroke waveform. Figure 4 shows the stroke curves for two cases calculated by coupled equations, and sinusoidal stroke. While the TDC phase of the sinusoidal stroke is 180 degrees, the TDC phase of the coupled equation stroke is slightly faster. In addition, the waveform of the stroke obtained from coupled equation is distorted rather than a perfect sine form. In this paper, although the suction valve and the discharge valve are considered to be ideally opened and closed, the phase of the TDC is important considering the system that can reflect the actual valve behaviour. If the TDC phase becomes faster, the discharge valve will open quickly. And, as the phase of TDC reaches faster, both of the time required for backward movement of piston and required for suction becomes longer. This may affect the time at which the suction valve opens and closes. Designing the suction valve, it is necessary to consider the shift of the TDC phase, in particular to match the time of opening and closing the valve. In the future, the system reflected the actual valve behaviour will be further analyzed.

3.4. Motor efficiency calculation through electric work
The compression work can be obtained by the P-V diagram, when it is assumed that the motion of the piston is represented as a sinusoidal wave via CFD analysis of the linear compressor. The efficiency of the compressor with the compression work as input includes the following two types of loss. The first is the pressure drop caused by the structural reason and the flow loss due to the vortex in the refrigerant passage. The second is the heat loss due to the temperature of the boundary condition. This does not include motor loss. On the other hand, the electrical work can be estimated by the input voltage and the calculated current value, when it is assumed that the stroke is implemented by solving the mechanical and the electrical equations. The motor efficiency is 91.7% in the specification of the linear compressor applied to the analysis in this paper. If the stroke analysis method using the coupling equation is used, it is helpful to study the motor efficiency and specification for the optimum operating point.

4. Conclusion

In this paper, we introduce the technique of solving the mechanical equation of the piston and the electrical equation of the motor which are coupled through the Runge-Kutta method and setting the behaviour of the piston. This leads us to the following conclusions.

- The actual behaviour of the piston differs from the perfect sine curve, which should be reflected in the analysis.
- To give the behaviour of the piston including the force, should solve the mechanical equations of the piston and the electrical equation of the motor.
- The interpretation of the stroke shift allows for more accurate information on designing and optimizing the linear compressor.
- Computing and designing the maximum cooling capacity of the compressor without considering the gas force can cause mechanical collision and cause reliability problems.
- The electric work and the motor efficiency can be found by solving the electrical equation together.

Nomenclature

m mass of system
c total damping coefficient of system
k stiffness of system
α thrust constant
f gas force
q quantity of electric charge
L inductance of motor
R resistance of motor
C capacitance of motor
V input voltage

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