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Numerical Analysis on Performance Variation of Linear Compressor Equipped with Economizer

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Abstract

An economizer is often used in a scroll-type or a rotary-type compressor to increase the efficiency of the refrigeration cycle. This study used computational fluid dynamics to analyze improvement in the efficiency of a refrigeration cycle when an economizer was applied to a linear compressor. According to the study's numerical analysis, the economizer was found to have decreased subcooling of the refrigeration cycle and reduced the temperature of the refrigerant inside the compression chamber, thereby enhancing the coefficient of performance by about 12.6%.

Keywords: Linear compressor, refrigerator, cycle simulation, numerical analysis, computational fluid dynamics (CFD).

1. Introduction

Refrigerators and air conditioners used at home or in industrial settings are built with a refrigeration cycle as shown in Fig. 1. A refrigerator accounts for 20-40% of a household's overall power consumption, and the compressor used in a refrigerator, in particular, takes up a substantial portion (as much as 80%) of the entire amount of electricity consumed by the refrigerator [1].

Refrigerators for home use typically use a piston-type, reciprocating compressor. A typical reciprocating compressor has a motor and a piston connected via a connecting rod, and converts the motor's rotational motion into the piston's reciprocating motion to compress the refrigerant. However, reciprocating compressors come with a disadvantage, in that their compression efficiency deteriorates due to friction between the motor and connecting rod, between the connecting rod and the piston, and between the piston and the cylinder due to the piston's reciprocating motion. To address this issue, linear compressors are used instead of reciprocating compressors. Unlike a reciprocating compressor, a linear compressor does not use a connecting rod, but rather utilizes a high-force magnetic motor. This keeps frictional losses to a minimum and results in smaller flow resistance, thereby providing 28% higher efficiency than a reciprocating compressor.

Research on reciprocating compressors has been going on since the 1950s, ranging from studies involving simple mathematical models to those on how to enhance efficiency [2]. Some have dealt with partial modeling [3-5] while others have modeled an entire compressor and made predictions through numerical analysis [6-7].

One of the developed improvements is an economizer, which is used as a way to reduce energy consumption and to enhance compressor efficiency. The economizer expands some portion of the refrigerant from the condenser and exchanges heat with refrigerant flowing into an expansion valve, to increase subcooling while reducing compression work [8]. Until now, research on economizers has mainly dealt with scroll and rotary-type compressors. Ma et al. [9] applied a sub-cooler and flash tank to a scroll compressor and experimentally proved that the coefficient of performance (COP) of the flash tank could be raised by about 4.3%. Navarro et al. [10] used vapor injection in a scroll compressor and raised the COP by 10%. Meanwhile, Wang et al. [11] bypassed some condensed refrigerant in a scroll compressor to another compressor, thereby improving the COP by approximately 16%. Self et al. [12] demonstrated that the major factors influencing COP when an economizer is applied include evaporation pressure, subcooling, economizer pressure and superheating.

Meanwhile, there has been active research on linear compressors as well. Kim et al. [13, 14] performed a numerical analysis of an inherent capacity-modulated (ICM) linear compressor through experiment. Kim et al. [15] carried out an experimental numerical analysis to investigate the dynamic characteristics of linear compressors. Yang et al. [16] applied a linear compressor to a sterling cryogenic refrigerator to study a fuzzy controller's performance against phase or stroke. However, no study has so far dealt with an economizer in a linear compressor.

Therefore in this study, an economizer was applied to a linear compressor for the purpose of enhancing the compressor's efficiency. To that end, the efficiency of a refrigeration cycle equipped with an economizer was analyzed using computational fluid dynamics (CFD). The study presents a P-V diagram, the compression work and cooling capacity of the refrigeration cycle, and analysis of the COP increase as well.

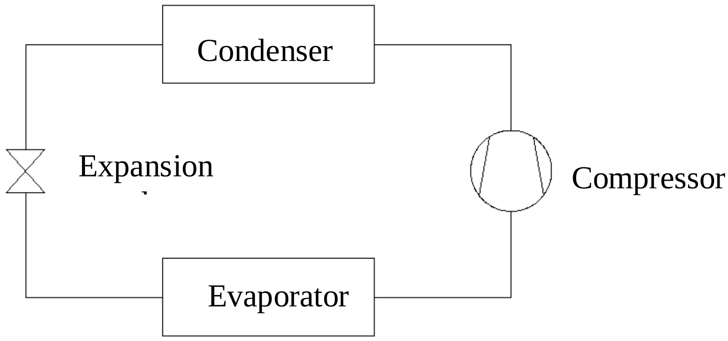


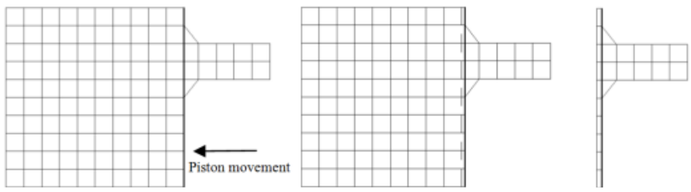
Fig. 1 Schematic diagram of the typical refrigeration cycle

2. Numerical Method

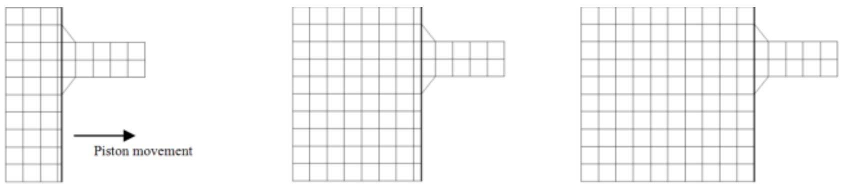
The fluid flow considered in this study is a three-dimensional, compressible and unsteady state, and turbulent flow. The turbulence model adopted was a realizable k-ε model and axisymmetric model was assumed. In addition, the actual material property of isobutene (R600a) [17] was used, and a layering technique of a dynamic mesh supported in Fluent [18] was also used, as shown in Fig. 2, to illustrate the compression chamber's expansion-compression process. The initial internal temperature of the cylinder was 25 ℃ and the heat transfer from the wall was assumed to be adiabatic.

Fig. 3 shows a schematic diagram of the compressor used for this study's numerical analysis. It was assumed that the stroke of the piston was 12.4mm and the piston frequency was 56.5 Hz. The compression-expansion process was described by using dynamic meshes for a moving part and a stationary part as shown in Fig. 4. Fig. 5 shows the opening and closing timings of the discharge valve and suction valve based on the cylinder pressure. Upon compression, the discharge valve opens when the cylinder pressure is raised to 416,030 Pa. The pressure at the suction pipe was assumed to be 48,550 Pa, and for the model when an economizer was applied, the pressure was assumed to be 38,840 Pa. For meshes, 84,000 hybrid meshes made up of hexahedral and tetrahedral meshes were used, while Fluent was used for the numerical analysis of the compressor. Furthermore, the time step was set at 10-5 seconds for accurate calculation of the cooling capacity and compression work.

To obtain the enthalpy difference between the model equipped with an economizer and the model without an economizer, a system analysis was performed by using an engineering equation solver (EES). R600a provided by EES [19] was used for a refrigerant, and the compressor efficiency, condensation temperature and evaporation temperature were assumed to be 90%, 31℃, and -29℃, respectively. In addition, the study also assumed that the superheating and subcooling were at 5℃, and the refrigerant mass flow at the gas injection port was 20% of the entire mass flow, whereas the efficiency of the plate heat exchanger was 80%.



(a)



(b)

Fig.2 Layering mesh (a: compression process, b: expansion process)

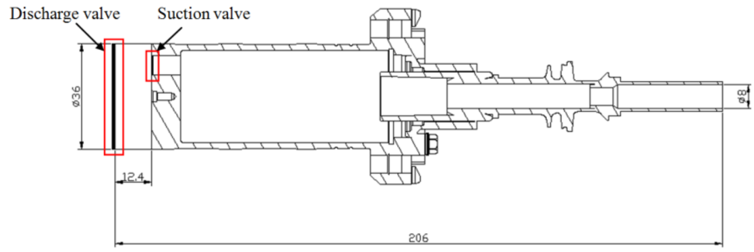


Fig.3 Schematic diagram of the numerical analysis model

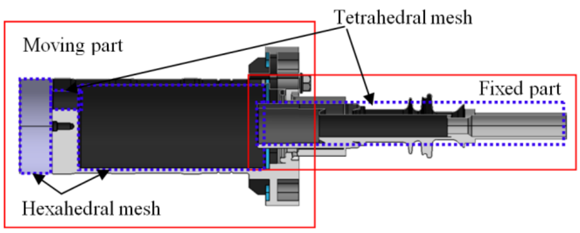


Fig.4 Moving and fixed zones

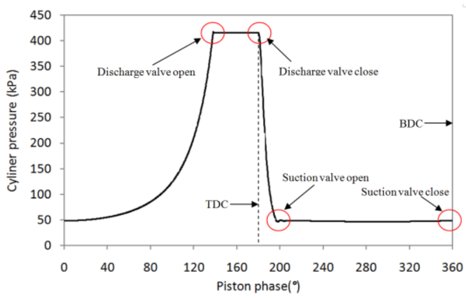
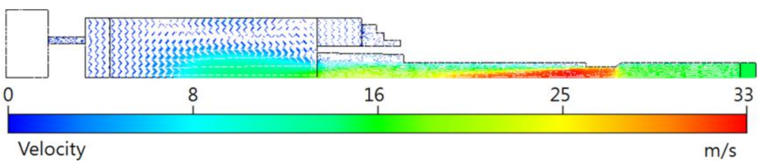
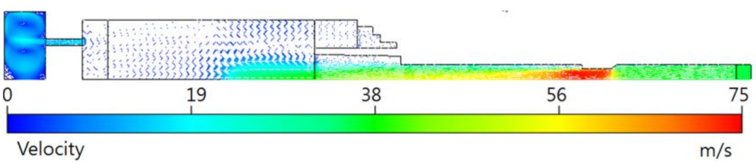


Fig.5 Valve timing with piston phase angle



(a) Piston phase angle= 34°



(a) Piston phase angle= 340°

Fig.6 Changes in internal flow of the cylinder at varying piston phase angles

3. Results and Discussion

3.1Numerical analysis on internal flow of the cylinder

Fig. 6 shows how internal flow typically changes during a piston's compression-expansion process. As shown in Fig. 6 (a), the piston's phase angle is 34° during compression, with the suction valve closed. During compression, the volume inside the piston increases, making the refrigerant from the suction pipe flow faster. At the same time, as shown in Fig. 6 (b), expansion takes place at the piston phase angle of 340°, during which time the refrigerant flows into the cylinder through the suction valve. The flow inside the cylinder consists of two recirculation zones, and the refrigerant flows in at 10 m/s on average. Fig. 7 represents the velocity vector for the refrigerant when the gas injection port opened at the piston phase angle of 95°. At this time, the average flow velocity is 128 m/s, indicating that fast injection is performed. The duration of injection varies depending on the diameter of the injection port.

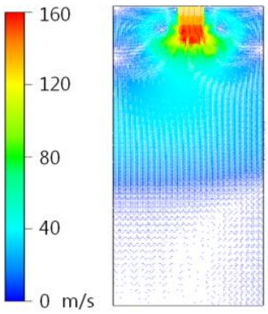


Fig.7 Velocity vector of the cylinder flow upon gas injection at piston phase angle 95°

3.2 Variations of suction valve flow rate and pressure

Fig. 8 shows changes in the flow rate of the suction valve with and without an economizer. For the model equipped with an economizer, the refrigerant pressure at the suction pipe is 38,840 Pa, which is about 20% lower than the model without an economizer. Therefore, the flow into the cylinder through the suction valve decreases, and the time it takes for the suction valve to open gets delayed by about 3.5°as well. For a model using an economizer, the gas injection starts when the cylinder pressure reaches about 142,120 Pa. At this time, the piston's phase angle is 94.4°, and the phase angle upon completion of gas injection is 95.9°. This means that the gas injection is completed within a very short time, taking only about 0.1ms. The duration of injection can be adjusted according to the injection timing and the injection port's diameter.

Fig. 9 shows the mean refrigerant mass flow per cycle into the suction valve and the gas injection port. For the model with an economizer, 79.4% of the entire volume of refrigerant flows in through the suction valve, while 20% of the refrigerant flows in through the gas injection port. This is because the injection valve opens at a phase angle delayed by 3.5°compared to the model without an economizer, making the flow of the refrigerant smaller by about 0.6%.

Fig. 10 shows pressure change at the suction valve with and without an economizer. The model equipped with an economizer has about 20% lower pressure formed depending on the piston phase than the model without an economizer. A low suction valve pressure upon opening indicates that the refrigerant flow through the suction valve is not fast enough. Therefore, the mass flow of the suction valve in the model with an economizer is decreased in proportion to the suction pipe pressure.

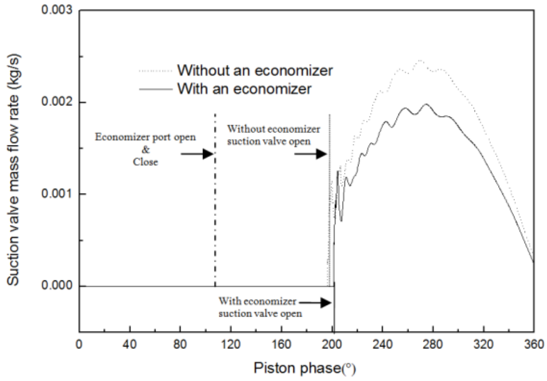


Fig.8 Change in the suction valve flow with and without an economizer

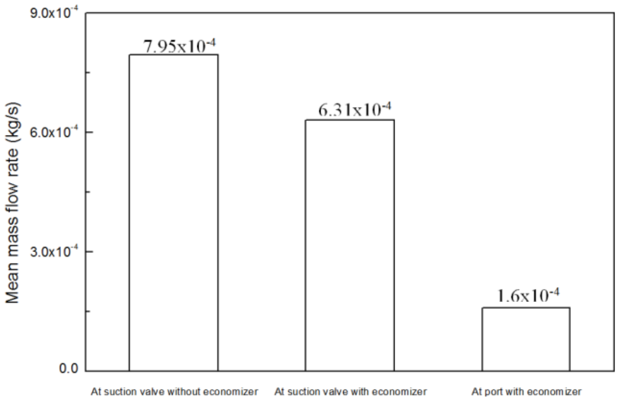


Fig.9 Change in 1 cycle mean mass flow rate with and without an economizer

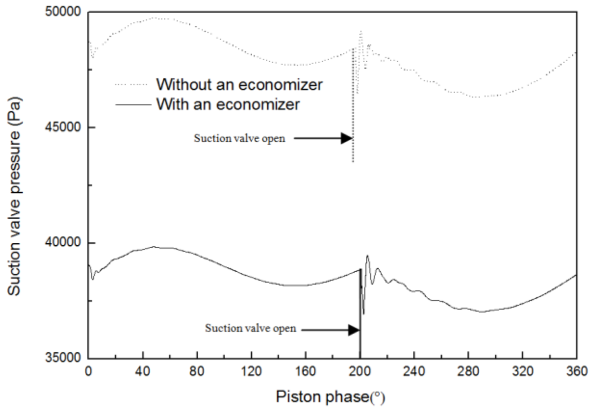


Fig.10 Change in suction valve pressure with and without an economizer

3.3 Comparison of cooling capacity and compression work with and without an economizer

A P-V diagram for the two models – one equipped with an economizer and the other not equipped with an economizer – is shown in Fig. 11. The model with an economizer undergoes compression when the suction pipe pressure is 20 % lower than that of the model without an economizer. When the cylinder volume becomes 5.89x10-6 m3, cold refrigerant flows in from the gas injection port. When the gas injection is completed, compression continues at about 2% lower pressure than the model without an economizer, causing the opening timing of the discharge valve to be delayed by about 1.6°. Meanwhile, the opening timing for the suction valve during the expansion process is delayed by about 3.5°, as the suction pipe pressure of the model with an economizer is about 20% lower than that of the model without an economizer. Therefore, with respect to the compression work, the model with an economizer is more advantageous for the compression process but less advantageous for the expansion process. However, the entire compression work is 0.3% smaller in the model using an economizer.

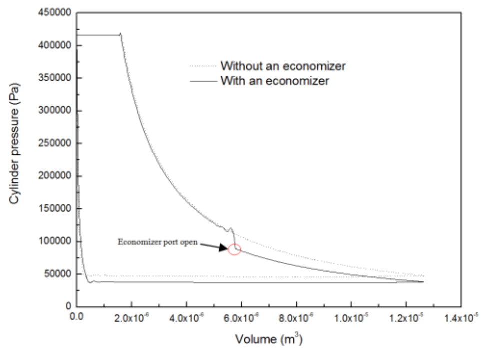


Fig.11 Change in the P-V diagram with and without an economizer

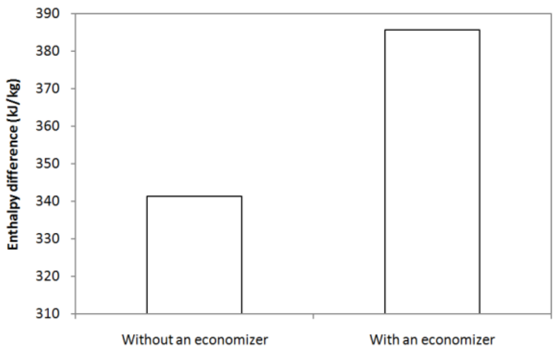


Fig.12 Enthalpy difference between the model with an economizer and the model without an economizer

The enthalpy difference between the model with an economizer and the model without an economizer at the inlet and outlet of the evaporator is shown in Fig. 12. Some of the refrigerant discharged from the condenser gets bypassed through the expansion valve and then exchanges heat with the refrigerant flowing into the compressor inlet. As a result, the refrigeration cycle's subcooling increases, making the temperature fall by 23.9℃ compared to that of the model without an economizer. This makes the difference between the inlet and outlet of the evaporator greater, which in turn enhances the refrigeration performance.

Table 1 shows the cooling capacity, compression work and COP of the models with and without an economizer obtained from the CFD analysis. The cooling capacity of the model equipped with an economizer increases by about 12.2% in proportion to the mean mass flow rate of the suction valve. Typically, compression work increases when a larger amount of refrigerant flows into a compression chamber. However, the model with an economizer uses a gas injection refrigerant at a lower temperature and thus has better refrigeration performance, resulting in about 0.3% less compression work. Therefore, the COP is enhanced by about 12.6%.

Table 1. Performance variation between the models with and without an economizer

	Without an economizer	With an economizer
Cooling capacity (W)	271.4	304.6
Compression work (W)	79.0	78.7
COP	3.44	3.87

4. Conclusion

This study aimed to apply an economizer to a linear compressor in order to enhance its efficiency. To that end, the study presented the efficiency of a refrigeration cycle equipped with an economizer by using a P-V diagram, compression work, cooling capacity and COP, using CFD. The following conclusions were drawn from this study.

1. The injection velocity based on the discharge pressure at the gas injection port was 128 m/s and the duration of injection could be adjusted by changing the diameter of the injection port. When the injection is performed faster, it is less influenced by change in the cylinder pressure.
2. In the model with an economizer, the mass flow rate into the cylinder via the suction valve was designed to account for 80% of the entire mass, but the piston's phase angle to open the suction valve was delayed by 3.5°, causing 79.4% of the entire refrigerant flow in.
3. In the model with an economizer, due to the cooling effect, which causes a reduction in the temperature of the refrigerant within the gas injection cylinder and an increase in the subcooling of the cycle, COP was enhanced by about 12.6% compared to the model without an economizer.

In the future, it is necessary to experimentally validate compressor performance by equipping a linear compressor with an economizer and then controlling gas injection.

5. Acknowledgement

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