VOL. 10, NO. 10, JUNE 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

NUMERICAL ANALYSIS ON THE PERFORMANCE OF REFRIGERATION COMPRESSORS WITH VARYING OPERATION FREQUENCIES

S. J. Park and Y. L. Lee
Department of Mechanical Engineering, Kongju National University, Korea
E-Mail: ylee@kongju.ac.kr

ABSTRACT

Reciprocating compressors have high energy consumption due to friction between component parts. Linear compressors with fewer parts than reciprocating compressors are able to minimize friction and deliver energy efficient performance. This study examines the impact of changing frequencies in compressors used in household refrigerators on overall cooling capacity and COP. For this, two frequency settings of 56.5 Hz and 100 Hz were tested to predict changes in cooling capacity, compression work, and COP. Results from the numerical analysis showed that low frequency resulted in reduced cooling capacity and compression work but enhanced COP. Higher frequency resulted in lower COP but higher cooling capacity, allowing for higher output from the same volume.

Keywords: refrigeration compressor, operation frequency, COP, cooling capacity, CFD.

INTRODUCTION

Compressors are devices that compress refrigerant in the cooling cycle to produce high temperature and pressure; they are commonly used in household refrigerators, air conditioners and industrial low temperature warehouses. Refrigerators are used in a majority of households and industrial facilities and the compressor takes up about 80% of energy consumption in a typical refrigerating unit (1).

Compressors commonly used in refrigerators can be classified into reciprocating compressors, scroll compressors, screw compressors and linear compressors. Reciprocating compressors utilize connecting rods to convert the rotating motion in the motor into the reciprocating motion of the piston that compresses the refrigerant. However, the reciprocating compressor has a great amount of friction between its component parts, which acts to lower compressing efficiency. Therefore, linear compressors are typically used in smaller refrigerators as a solution to this friction problem. Linear compressors use motors powered by strong magnets, allowing for the connecting rods used in reciprocating compressors to be removed. Thus, friction loss is minimized and the lower flow resistance makes this type of compressor 26% more efficient than the reciprocating compressor.

The study of compressors has been steadily advancing since the 1950s. Amid ongoing studies on enhancing compression efficiency using simple one dimensional mathematical models (2), there have been studies on partial modelling (3~5) and modelling of the entire compressor(6,7) to make predictions based on numerical analysis.

Economizers are currently used in compressors in order to maximize energy efficiency and enhance the Coefficient of performance (COP).Before the refrigerant is fed into the expansion valve; economizers divert some of the refrigerant into the secondary expansion valve, where it is expanded. It is then combined with the remaining refrigerant before it goes into the main expansion valve to enable heat exchange between the two, increasing super cooling and thus the endothermal capacity. The refrigerant coming out of the secondary expansion valve is fed into the compression chamber during the compression process, lowering the temperature of the refrigerant to reduce the compression work and thus enhance COP (8). There have been studies utilizing economizers in scroll and rotary type compressors to enhance the COP. Ma *et al.* (9) applied a sub-cooler and flush-tank to a scroll compressor with experimental results proving an approximate 4% rise in the COP of the flush tank. Navarr *et al*. (10) applied vapor injection (VI) to a scroll compressor to enhance COP by about 10%, while Wang *et al*. (11) enhanced COP in a scroll compressor by about 16% by bypassing a portion of the condensed refrigerant into the compressor. Self (12) analysed the variables affecting COP when applying an economizer to a vapor compressor and arranged variable impacts in order of evaporation pressure (36.6%), super cooling (14.9%), economizer pressure (1.3%) and superheating (0.8). Another well covered area of research is the linear compressor. Kim *et al*. (13, 14) studied performance changes in refrigerator ICM (Inherent Capacity-Modulated) linear compressors through numerical analysis and experiments, while Kim *et al.* (15) examined the dynamic characteristics of a linear compressor through numerical analysis and experiments. Yang *et al*. (16) conducted a study on the application of a linear compressor to a split-Stirling cryocooler and the resulting phases and strokes.

There have also been studies on compressor frequency variation for high speed operation. Park (17) predicted through numerical analysis that cooling capacity goes down when compressor frequency is adjusted to above 90 Hz. Michael *et al*. (18) conducted an experiment

ARPN Journal of Engineering and Applied Sciences

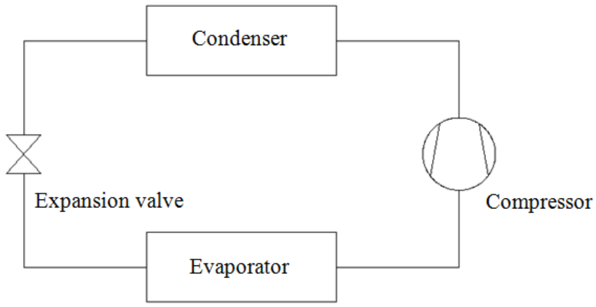


Figure-1. Schematic diagram of the typical refrigeration cycle.

on frequency variation using a scroll compressor to show that total efficiency dropped 1% at 60 Hz compared to that at 50 Hz. However, our review has found a lack of existing research conducted on frequency variations in linear compressors.

Thus, this study aims to predict the impact of operation frequency variation on performance in compressors. For this, we examined changes in internal flow depending on frequency variation and predicted cooling capacity from the inflow of refrigerant from the suction valve. Finally, a P-V diagram was used to predict compression work in order to calculate changes in COP.

Analysis method and conditions

The fluid flow considered in this numerical analysis was axi-symmetric, compressible, unsteady, turbulent. The actual physical properties of isobutene (R600a) (19) were used, while the Fluent supported dynamic mesh layering method, as shown in Figure-2, was used to describe the suction-expansion-compression-discharge process within the compression chamber. The initial temperature within the cylinder was 25° C and the heat transfer on the cylinder wall surface was assumed to be at insulation condition.

Figure-3 shows a schematic diagram of the compressor used in the numerical analysis. Piston frequencies were assumed to be 56.5 Hz and 100 Hz, respectively. The suction, compression, expansion and discharge process is described using dynamic mesh and divided into the moving zone and fixed zone, as shown in Figure-4. The cell height at which layering occurs is 0.3 mm. Figure-5 shows the internal pressure within the cylinder according to the piston phase and the discharge valve is described as open when cylinder pressure rises above the designated discharge pressure and closed when phase angle is at TDC (Top dead center).

84, 000 hexahedral and tetrahedral meshes were used, while Fluent was used in the compressor modelling and numerical analysis. Inflow from the inlet valve, pressure and cylinder internal pressure were monitored at intervals of $5\text{x}10^{-6}$ seconds to calculate cooling capacity and compression work.

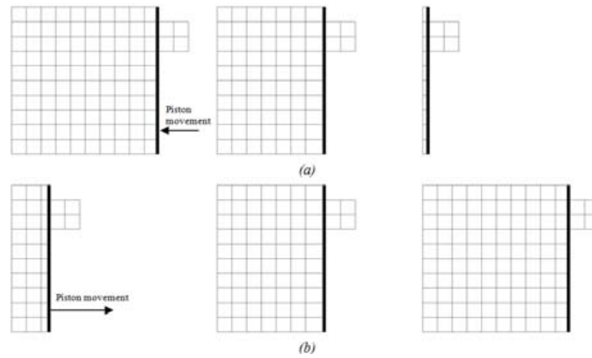


Figure-2. Layering mesh (a: compression process, b: expansion process).

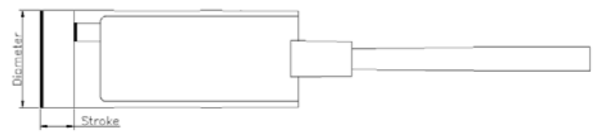


Figure-3. Schematic of the numerical analysis model.

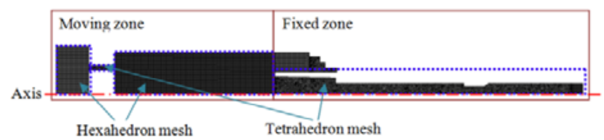


Figure-4. Mesh system.

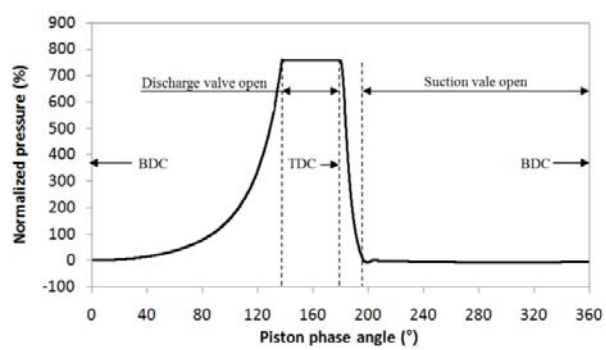


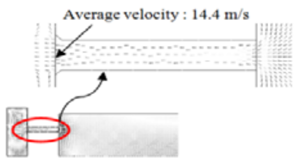
Figure-5. Valve timing with piston phase angle.

RESULTS AND DISCUSSIONS

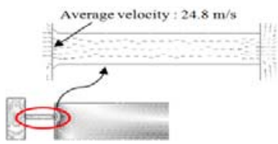
Numerical analysis of cylinder internal flow depending on operation frequency variation

Figure-6 shows the internal flows of the 56.5 Hz and 100 Hz models at piston phase angle 269° during the suction process. The 100 Hz model exhibited a refrigerant influx velocity of 24 m/s at the suction valve, which was 73.1% faster than that of the 56.5 Hz model. This meant that volume efficiency was reduced by about 3.9% at high

VOL. 10, NO. 10, JUNE 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences



(a) 56.5 Hz piston phase angle = 269°



(b) 100 Hz piston phase angle = 269°

Figure-6. Change in internal flow of the cylinder at varying piston phase angles.

(a) 56.5 Hz piston phase angle = 269°

(b) 100 Hz piston phase angle = 269°

Figure-7. Change in internal pressure of the cylinder with varying piston phase angles.

speed. When the velocity of the refrigerant entering through the suction valve increases, the cooling capacity also increases.

Figure-7 shows the changes in internal flow within the cylinder during the suction process at piston phase angle 269° . The difference in pressure between the compression chamber and within the piston was 407 Pa in the 56.5 Hz model and 1,256 Pa in the 100 Hz model, making the latter about 2.1 times higher than the former. This causes the velocity of the refrigerant influx into the compression to rise.

Numerical analysis of changes in suction valve flow and pressure depending on operation frequency variation

Figure-8 shows changes in refrigerant flow at the suction valve depending on changes in the operation frequency. When the operation frequency went up from 56.5 Hz to 100 Hz, the pattern of refrigerant suction into the suction valve remained similar but the mass flow increased with changes in the piston phase angle, resulting in a 67.6% increase in mass flow.

Figure-9 shows pressure changes in the suction valve according to changes in operation frequency. The

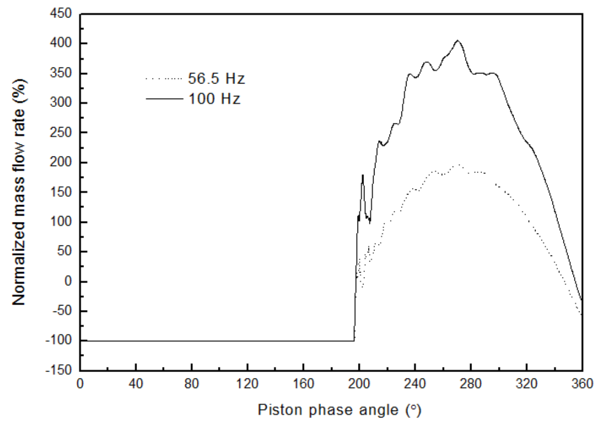


Figure-8. Variation of piston phase angle with normalized suction valve mass flow rate for 56.5 and 100 Hz.

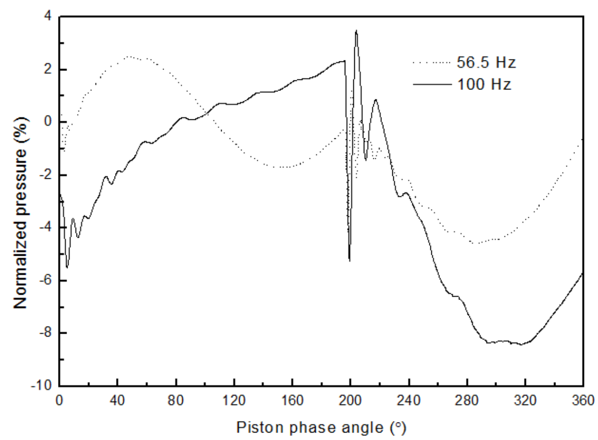


Figure-9. Variation of piston phase angle with normalized suction valve pressure for 56.5 and 100 Hz.

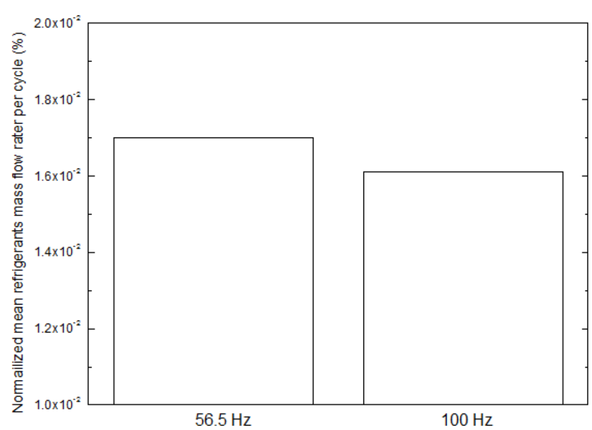


Figure-10. Variation of normalized mean refrigerants mass flow rate per cycle for 56.5 and 100 Hz.

lowest and highest pressures at 56.5 Hz were 4.6% lower than the suction pressure and 2.5 % higher than the suction pressure, respectively, while the corresponding values at 100 Hz were 8.4 % lower and 3.5 % higher than the suction pressure, respectively. The shapes of the two models were identical but a simple increase in frequency from 56.5 Hz to 100 Hz lowered the minimum pressure and raised the highest pressure, increasing the inflow at the suction valve.

Figure-10 shows the mass of the refrigerant flowing into the cylinder per cycle. The period for a single cycle at 56.5 Hz was 0.017 seconds; this period was 0.01 seconds at 100 Hz. The mass of refrigerant inflow per cycle went down about 5.6% at 100 Hz. This was because the shorter cycle meant less refrigerant flowing into the cylinder, reducing the volume efficiency. This shows that when frequency is increased in a compressor, the volume efficiency is lowered. Thus an optimal refrigerant suction system has to be designed in order to enhance volume efficiency during high speed operation.

Numerical analysis of performance depending on operation frequency variation

Figure-11 shows the P-V diagram for varying operation frequencies. Pressure difference did not occur as the system was designed to open the suction valve at the operating pressure, close the suction valve and open the discharge valve at the designated discharge pressure.

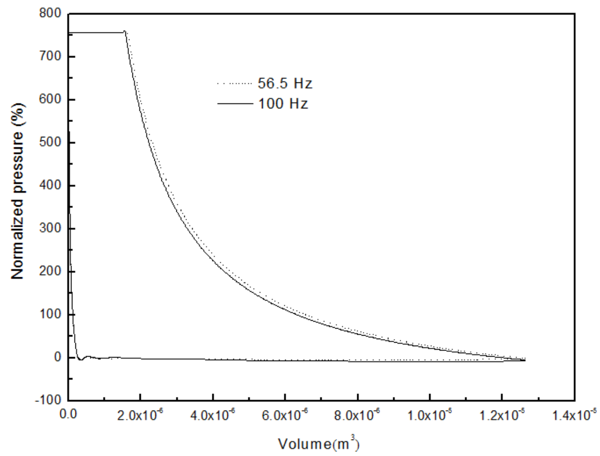


Figure-11. Variation of cylinder volume with normalized cylinder pressure for 56.5 and 100 Hz.

Table-1. Comparison of cooling capacity, compression work and COP.

	56.5 Hz model	100Hz model	Difference between 56.5 Hz model and 100 z model
Frequency	100%	177.0%	77.0%
Cooling capacity	100%	167.6%	67.6%
Compression work	100%	171.9%	71.9%
COP	100%	97.5%	-2.5%

However, the timing of the opening of the discharge valves varied slightly, as the valve opened at the piston phase angle of 138 ° for 56.5 Hz, and at 139 ° for 100 Hz, making the latter about 0.6 % slower. The delay in the opening of the discharge valve was due to insufficient influx of refrigerant into the cylinder, causing about 4% difference in pressure during the compression process. This was due to the lowered volume efficiency in the 100 Hz model.

Table-1 shows differences in cooling capacity, compression work and COP in the 56.5 Hz and 100 Hz models. When the frequency was increased by 77% from 56.5 Hz to 100 Hz, cooling capacity was enhanced by 67.6 % but compression work rose by 71.9 %, resulting in an overall 2.5% drop in COP. Although the rise in compression work should be accompanied by a corresponding rise in cooling capacity, the reduction of volume efficiency led to a drop in the refrigerant influx at the suction valve, resulting in a 2.5% drop in COP. However, at a higher operation frequency, the volume required to achieve the same cooling capacity is only 60% of that required at a lower frequency. This means that refrigerator space can be used more efficiently just by adjusting the operation frequency.

CONCLUSIONS

This study was conducted under the aim of understanding the impact of operation frequency change on compressor performance for refrigerator compressors. In order to do this, CFD was used to analyse axi-symmetric, unsteady and turbulent flows in the compressor cycle and predict the cooling capacity, compression work and COP. This study yielded the following conclusions.

a) When operation frequency increases from 56.5 Hz to 100 Hz, the refrigerant velocity and pressure change are increased due to the rise in piston speed. Maximum refrigerant speed goes up about 73 % while refrigerant pressure change in a single cycle increases by 68 %. Mass flow increases, enhancing the cooling capacity but COP drops as volume efficiency is reduced.

b) When operation frequency increases from 56.5 Hz to 100 Hz, mass flow increases about 67.6%. This means a 5.6 % drop in volume efficiency. Thus, the optimal refrigerant suction system has to be designed in order to enhance volume efficiency during high speed operation.

c) When compressor operation frequency increases from 56.5 Hz to 100 Hz, cooling capacity is enhanced by 67.6 % but compression work rises 71.9 %, resulting in an overall 2.5% drop in COP. However, at a higher operation frequency, the volume required to achieve the same cooling capacity is only 60% of that required at a lower frequency. This means that refrigerator space can be used more efficiently just by adjusting the operation frequency.

d) Finally, this study points to the necessity of future studies regarding methods to improve volume efficiency in high speed refrigerant compressors.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0024805) and by the Human Resources Development program (No. 20134030200230) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

REFERENCES

[1] Lee H. K., Song G. Y., Park J. S., Hong E.P. and Jung W. H. 2000. Development of the Linear Compressor for a Household Refrigerator. Proceedings Internal Compressor Engineering Conference, Purdue University. pp. 31-38.

[2] MacLaren J. F. T. 1972. A Review of Simple Mathematical Models of Valves in Reciprocating Compressors. Proceedings Internal Compressor Engineering Conference, Purdue University. pp. 180-187.

[3] Prakash R. and Singh R. 1974. Mathematical Modeling and Simulation of Refrigerating Compressor. Proceedings Internal Compressor Engineering Conference. pp. 274-285.

[4] Singh R. 1978. First Law Analysis of a Compressor using a Computer Simulation Model. Proceedings Internal Compressor Engineering Conference. pp. 577-586.

[5] Morel T. and Keribar R. 1988. Comprehensive Model of a Reciprocating Compressor Application to Component Design Issues. Proceedings Internal Compressor Engineering Conference. pp. 375-380.

[6] Dhar M. and Soedel W. 1978. Compressor Simulation Program with Gas Pulation. Proceedings Internal Compressor Engineering Conference.

[7] Singh P. J. 1984. A Digital Reciprocating Compressor Simulation Program Including Suction and Discharge Piping. Proceedings Internal Compressor Engineering Conference, pp. 129-138.

[8] Lee H., Ki S. H., Jung S. S. and Rhee W. H. 2008. The Innovative Green Technology for Refrigerators Development of Innovative Linear Compressor. Proceedings Internal Compressor Engineering Conference, Purdue University.

[9] Ma G. Y. and Zhao H. X. 2008. Experimental study of a heat pump system withflash-tank coupled with scroll compressor. Energy and Buildings. 40: 697-701.

[10]Navarro E., Redon A., Gonzálvez-Macia J., Martinez-Galvan I.O. and Corberán J.M. 2013. Characterization of a vapor injection scroll compressor as a function of low, intermediate and high pressures and temperature conditions. International Journal of Refrigeration. 36(7): 1821-1829.

[11]Wang B., Han L., Shi W. and Li X. 2012. Modulation method of scroll compressor based on suction gas bypass. Applied Thermal Engineering. 37: 183-189.

[12]Self S. J., Reddy B. V. and Rosen M. A. 2013. Ground source heat pumps for heating: Parametric energy analysis of a vapor compression cycle utilizing an economizer arrangement. Applied Thermal Engineering. Issue 2, Vol. 52, pp. 245-254.

[13]Kim J. K., Roh C. K., Kim H. and Jeong J. H. 2011. An Experimental and Numerical Study on an Inherent Capacity Modulated Linear Compressor for Home Refrigerators. International Journal of Refrigeration. 34: 1415-1423.

[14]Kim J. K. and Jeong J. H. 2013. Performance Characteristics of a Capacity-Modulated Linear Compressor for Home Refrigerators. International Journal of Refrigeration, Bol. 36, pp. 776-785.

[15]Kim H., Roh C. K. and Kim H. K. 2009. An Experimental and Numerical Study on Dynamic Characteristic of Linear Compressor in Refrigeration System. International Journal of Refrigeration. 31: 1536-1543.

ARPN Journal of Engineering and Applied Sciences

[16]Yang Y.P. and Huang B. J. 1998. Fuzzy Control on the Phase and Stroke of a Linear Compressor of a Split-Stirling Cryocooler. Cryogenics. 38: 231-2387.

[17]Park Y.C. 2010. Transient Analysis of a Variable Speed Rotary Compressor. Energy Conversion and Management. 51: 277-287.

[18]Michael M. C. and Jack S. 2008. Impact of Power Frequency on the Performance of a Scroll Compressor. International Compressor Engineering Conference. Pp. 1335-1336.

[19]2013. Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures Database V 7.0, national Institute of Standards and Technology.

[20]Ansys Fluent 14.1, 2012.