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## Performance Evaluation of the Energy Efficiency of Crank-Driven Compressor and Linear Compressor for a Household Refrigerator

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### ABSTRACT

Since conventional crank-driven compressor had many difficulties to increase efficiency due to mechanical loss, new kind of compressor has been paid much of attention by the compressor manufacturers. The free piston compressor mechanism has been one of those kinds. The compressor manufacturers developed an energy efficient free piston linear resonance compressor for a household refrigerator.

In this study, we investigate the energy efficiency of two different types of compressors for a household refrigerator. One of these is conventional crank-driven compressor which is a positive-displacement compressor that has the piston driven by a crankshaft to discharge gas at high pressure. The other is linear compressor which has no crank mechanism and its piston is oscillated by linear motor and helical coil spring. The energy efficiency is tested with a compressor calorimeter. Experimental results show that the new linear compressor has the power consumption reductions about 10% as compared with the brushless direct-current (BLDC) reciprocating compressor. The linear compressor demonstrates excellent energy efficiency by reducing the friction loss since it does not produce any side load between the cylinder and the piston. Due to use of the moving magnet type linear oscillating motor, its motor efficiency goes more than 90%. Additionally, the compressor stroke to piston diameter ratio of the oscillating piston in the free piston linear compressor can be adjusted in order to modulate the cooling capacity of compressor for better system efficiency.

### 1. INTRODUCTION

The compressor is an essential component of the refrigeration system. It circulates refrigerant through the system in a continuous cycle, and accomplishes the required heat lift and rejection through phase change of the refrigerant. The need for efficient compressors has led us to develop a linear compressor to meet goal. The recent worldwide awareness of the global environmental conservation draws attention to the energy saving in household appliances. Especially, the development of high efficiency compressor has been taken much interest, because a refrigerator and air conditioner consumes most of the total electric energy in a house, in which a compressor consume most of the electric energy in the refrigerator.

The reciprocating compressor commonly used in a household refrigerator has many limitations to increase energy efficiency due to the crank mechanism. So compressor manufacturers have been paid efforts to develop new kind of compressor mechanisms. The free piston mechanism is one of those kinds (Koda, 1990 and Unger, 1998). This mechanism has some advantages in tribological aspects over the conventional reciprocating compressor because it does not generate any side force on the piston. A linear compressor is a piston-type compressor in which the piston is driven directly by a linear motor, rather than by a rotary motor coupled to a conversion mechanism as in a conventional, reciprocating compressor. Linear motors are simple devices in which axial forces are generated by currents in a magnetic field (Redlich et al., 1996). Because all the driving forces in a linear compressor act along the linear motion, there is no sideways thrust on the piston. This design substantially reduces bearing loads and allows the use of gas bearing or low viscosity oil. Additional background on the origin and development of linear compressors has been presented elsewhere (Berchowitz, 1973; Unger et al., 1996; Van der Walt et al., 1992, 1994).

Recently, for the energy efficient and smart refrigerators, wide capacity modulation characteristic of the compressors is essential. To satisfy this, the inverter driving operation of a compressor has been widely developed,



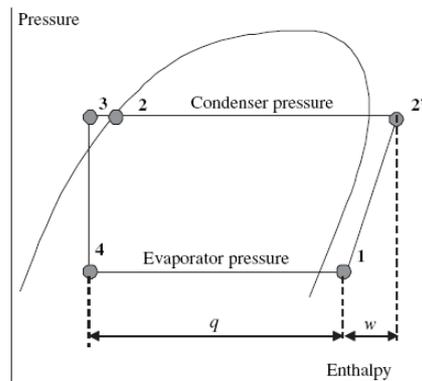


Figure 2: P-h diagram for the measurement of COP

## 2.2 Structure and Capacity Modulation of Linear Compressor

Linear oscillating compressor basically consists of the moving mass (piston), resonant spring and linear motor. In the mechanical system, resonant springs, moving mass, damper, pressure load and motor force compose a basic compression system. If the supporting springs is used to reduce the vibration of compressor body, second oscillation of the compressor body should be considered. Therefore, two degree of freedom model with spring-mass-damping system under periodic motor force can be obtained. Here, damper, which means mechanically dissipated loss, may be classified by the viscous damping loss of piston / cylinder, wind loss and magnet shuttle loss.

Figure 3 shows the structure of the linear compressor affected by gas pressure force and the electromagnetic force of the linear motor in the refrigeration system. It is composed of a mechanical spring, a piston, the refrigerant suction and discharge part, and a linear motor. The stroke of the piston driven by the linear motor is moved from TDC to the bottom dead center and is controlled around the TDC. According to the controlled position of TDC, the location of the piston can have a positive value (+) or a negative value (-) due to the free piston mechanism of the linear compressor. It affects the efficiency and the cooling capacity, which are related to the system resonance (Kim et al., 2009).

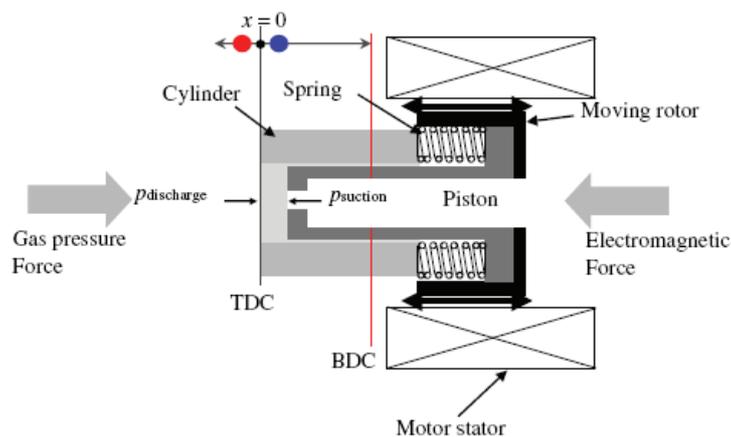


Figure 3: Schematic diagram of the linear compressor system affected by gas pressure force and electromagnetic force

Therefore the efficiency of the compressor itself is very important for energy saving. And the capacity modulation is also important for the energy saving. Even if a capacity variable compressor has the same efficiency, the capacity variable compressor may consume less energy than the capacity invariable compressor owing to the capacity modulation effect. The efficiency of the refrigerator is not only related to the capacity of the compressor, but also proportional to the compressor efficiency. Small capacity of the compressor makes the difference between

condenser pressure and evaporator pressure narrowed in the refrigerator. While the load to the compressor decreases, the cooling capacity does not decrease as much as the load because the density of suction refrigerant increases. Therefore the efficiency of refrigerator increases maximal 12% even though the efficiency of a compressor does not change. The smaller cooling capacity becomes the more capacity modulation effect is acquired and the minimal cooling capacity for keeping temperature is about 50%. The efficiency of the refrigerator is dependent on the cooling capacity of the cycle and the efficiency of the compressor. The capacity modulated efficiency and the efficiency of the compressor are important to predict the efficiency of the refrigerator. The efficiency of the compressor is shown as Equation (3):

$$\eta_{compressor} = \eta_{motor} \times \eta_{mechanical} \times \eta_{compression} \quad (3)$$

where  $\eta_{compressor}$ ,  $\eta_{motor}$ ,  $\eta_{mechanical}$  and  $\eta_{compression}$  are the efficiency of the compressor, the motor, the mechanical part, and the compression, respectively. Each term of equation (3) is measured at several cooling capacity modulation. The motor and mechanical efficiencies are calculated from the losses of the copper, the iron and the friction, etc. at the each cooling capacity.

### 3. RESULTS and DISCUSSION

#### 3.1 Efficiency of Linear Motor

Linear oscillating motor is grossly classified with moving magnet type, moving iron type and moving coil type according to their moving part configuration. Moving coil type motor is used in the SAWAFUJI portable refrigerator, which has very small side force, but it is limited to small size compressor because of coil reliability. And moving iron type linear motor can be produced for low cost, but friction loss by the large side force of motor and large motor size is weak points. Among the various linear motors, we have developed moving magnet linear oscillating motor with Nd magnet for the motor efficiency and size (Redlich, 1995). To minimize the loss of motor, we laminate the core in radial direction. A compact linear motor of which energy efficiency is more than 90% was developed. It has following differences and advantages compared with conventional rotary induction motor.

Figure 4 shows energy efficiency variation as velocity changes (Linear vs. Rotary Induction). Velocity ratio is maximum velocity to modulation velocity ratio of systems. While rotary type induction motor needs large starting torque, the linear motor has very low starting torque. So in case input voltage is very low, linear compressor starts softly. Additionally in spite of a high pressure load, starting has no problem in linear compressor. The efficiency variation of the linear motor as velocity change is less sensitive than rotary induction motor. So linear motor has advantages for capacity modulation. Redlich type linear oscillating motor has much less copper loss than a normal induction motor used for conventional reciprocating compressor, because it does not have unnecessary end-coil and rotor bar which caused lots of copper losses.

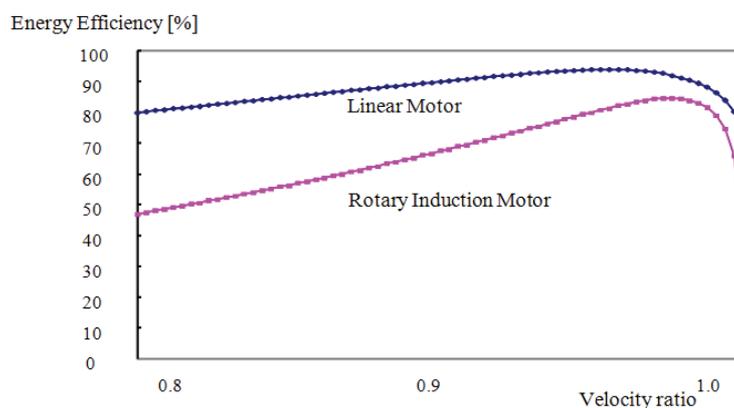


Figure 4: Energy efficiency variation as velocity changes (Linear vs. Rotary Induction)

#### 3.2 Side Force of Resonant Spring and Friction Loss

Mechanically the characteristics of linear oscillating compressor are a free piston mechanism, which has no crank and crank shaft in its mechanism (no crank mechanism). The piston attached on the moving magnet assembly moves

linearly as the magnets of linear motor move. No crank mechanism could make the friction loss of the linear compressor less than half of that of the reciprocating compressor. A helical compression coil spring has selected as a resonant spring for cost effectiveness and high reliability (Oh et al., 1994). When the spring is compressed in the linear compressor, it has the side force that is perpendicular to the compression direction. So resonant springs must be designed to reduce the side force of the spring to the minimum to reduce friction loss and prevent the wear problem between a piston and a cylinder. Figure 5 shows commonly used coil spring (#1) with high side force and spring (#3) designed with very low side force.

For the high energy efficiency, the friction loss has to be as low as possible. In the linear oscillating compressor, the viscous damping loss could be calculated by assuming Newtonian fluid and Couette flow as a reciprocating compressor. In addition the friction loss by viscous damping in the linear compressor can be calculated quantitatively by measuring the velocity in the free damped oscillation as Figure 6. From experiments and theoretical calculation, we could reduce the friction loss in the linear compressor by more than 50% compared with the conventional reciprocating compressor.

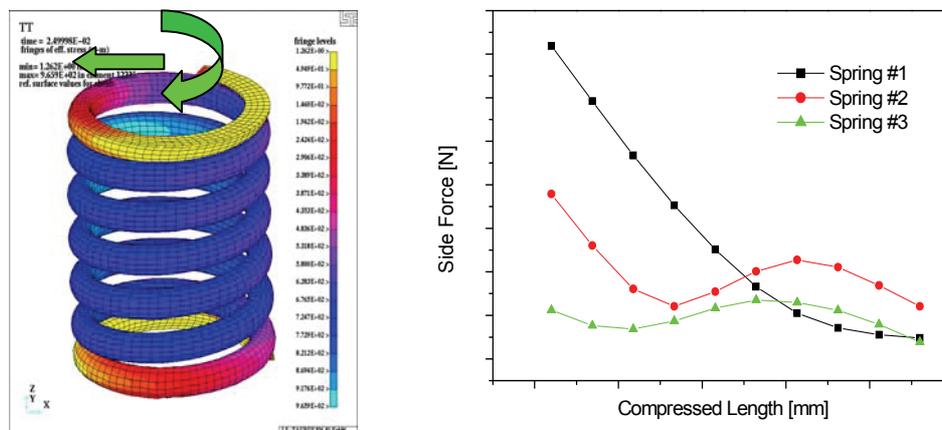


Figure 5: Resonant compression coil spring and its side force

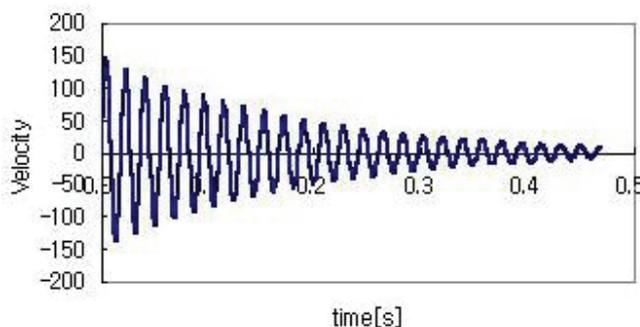


Figure 6: Damping coefficient ( $D_1$ ) measurement in the linear compressor

$$D_1 = \frac{A\mu}{\delta}$$

$$\text{friction loss [W]} = \frac{1}{2} D_1 (\dot{x})^2$$

where:

$\mu$  = dynamic viscosity

$\delta$  = side clearance

### 3.3 New Valve Mechanism

A disk valve and a coil spring are used in the discharge valve system. This kind of valve system can minimize over-compression loss because it has much bigger flow area than conventional reed valves. And the top clearance between the piston and the discharge valve becomes nearly zero, because spring can absorb impact as shown in Figure 7. Therefore it is possible to minimize the re-expansion loss of the compressor and enhance the compression efficiency. In addition we can take larger cooling capacity per unit volume than conventional reciprocating compressor, so we can cut down the size of the compressor. A suction valve is placed on the piston and suction flow path is inside the piston. Thus flow resistance and suction heating loss are much less than conventional reciprocating compressors. With this arrangement (Figure 7), it is possible to use direct suction and minimize the heat exchange between suction and discharge gas (Di Flora et al., 1992).

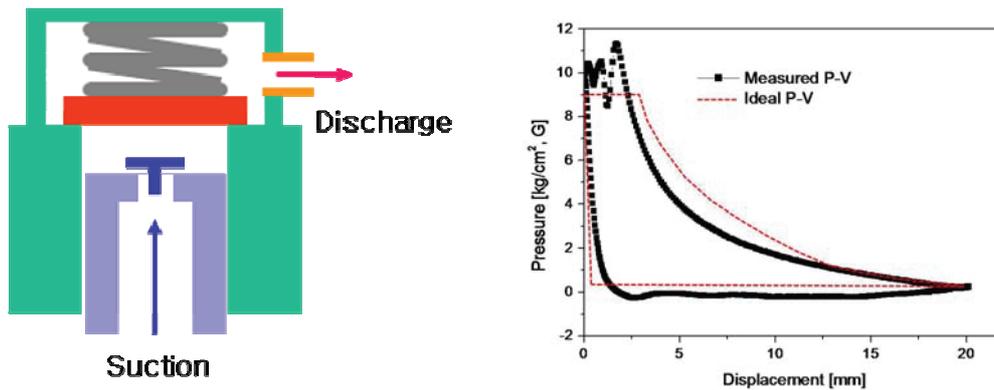


Figure 7: New suction and discharge valve system and P-V diagram measured

### 3.4 Cooling Capacity Modulation

The efficiency of the linear compressor is closely connected with the efficiencies of the motor and the mechanical part. Natural frequency of linear compressor is one of the important operating parameters, which is the function of piston diameter, compressor stroke, mass of the moving part, and charging pressure of working fluid. For the same volume in the linear compressor, the mechanical efficiency increased with increasing piston diameter and with decreasing compressor stroke. As compressor stroke decreases, the motor efficiency decreases according to increasing the input current of motor. Figure 8 shows EER as a function of compressor stroke to piston diameter ratio and cooling capacity ratio in the linear compressor. The EER increased with decreasing compressor stroke to piston diameter ratio due to increasing the mechanical efficiency.

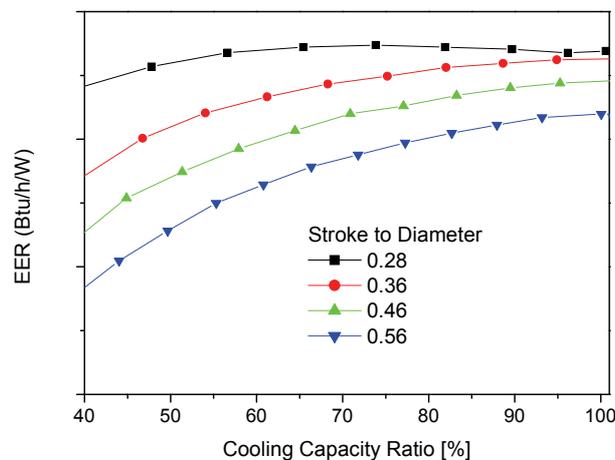
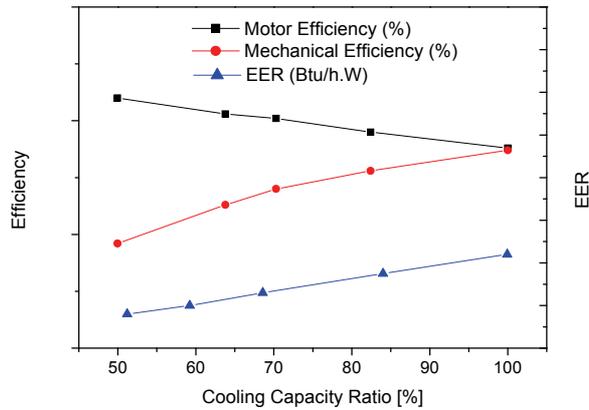
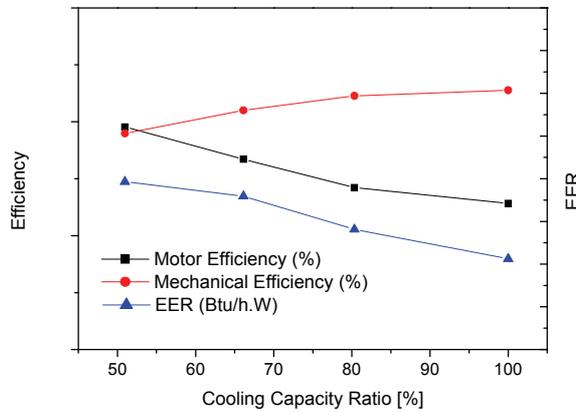


Figure 8: EER as a function of compressor stroke to piston diameter ratio and cooling capacity ratio in the linear compressor

Figure 9(a) shows the general pattern of the mechanical efficiency and the motor efficiency according to the capacity modulation of the linear compressor (i.e. old linear). When the linear compressor is modulated on the small capacity, the motor efficiency increased and the mechanical efficiency decreased. Then, the total efficiency of the linear compressor is proportional to the multiple of the efficiencies of the mechanical part and the motor. The compression efficiency is almost the same for the each capacity modulation and the slopes of the motor and the mechanical efficiencies are closely the same. Then the efficiency of the linear compressor has the maximal value at the cross point of the mechanical efficiency and the motor efficiency. The total efficiency of the compressor shown in Figure 9(a) has the maximal efficiency over the 100% cooling capacity range. However, the total efficiency shown in Figure 9(b) has the maximal efficiency at the 50% cooling capacity when the piston bore is increased and the stroke is decreased. For this case, the cross point of the mechanical efficiency and the motor efficiency is laid on the 50% cooling capacity. From these results, the compressor which is the new linear is optimized to maximize the efficiency of the most useful capacity.



(a) Small bore and large stroke (stroke to dia. ratio: 0.56)



(b) Large bore and small stroke (stroke to dia. ratio: 0.32)

Figure 9: EER related with mechanical and motor efficiency

Figure 10 shows the efficiencies of the new linear, the old linear, and the BLDC reciprocating compressor when compressors are operated in the capacity modulation.

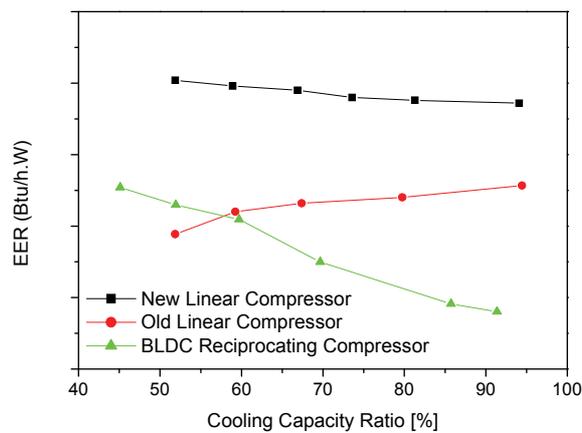


Figure 10: Energy efficiency of developed linear compressor (including drive loss)

The new linear compressor is not only designed to increase the efficiency of the overall range by the improvement of the components, for examples, bearing and valve systems, but also optimized to maximize the efficiency at the 50% cooling capacity. At the full cooling capacity, the efficiency of the new linear compressor is about 75% including the drive loss. It has shown 20% more efficient than the BLDC reciprocating compressor and 8% more efficient than the old linear compressor. Also, the efficiency of the new linear compressor is about 76% at a half cooling capacity. It has shown about 10% more efficient than the BLDC reciprocating compressor and about 15% more efficient than the old linear compressor. The new linear compressor has the large gap of the efficiency comparing with the old linear and the BLDC reciprocating compressor overall cooling capacity modulation range (Lee et al., 2008).

#### 4. CONCLUSIONS

We investigate the energy efficiency of two different types of compressors for a household refrigerator. One of these is conventional crank-driven compressor, the other is linear compressor. The energy efficiency is tested with a compressor calorimeter. The new linear compressor has the power consumption reductions about 10% as compared with the BLDC reciprocating compressor. For high energy efficiency, we have used above mentioned technologies as Redlich type linear motor, low friction loss by free piston mechanism, new valve system, and capacity modulation by the compressor stroke to piston diameter ratio control.

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