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The Innovative Green Technology for Refrigerators - Development of Innovative Linear Compressor -

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ABSTRACT

Since 2000, LGE has produced the Linear Compressors for household refrigerators, and several million linear compressors have been operating in Korea and Europe. For producing the Linear Compressors, LGE has solved lots of reliability problems, for example, accurate driving of the free piston.

For the capacity modulation, the displacement modulation operation is used in the LG linear compressor, instead of changing operating frequency. As expected, the small displacement operation leads to large dead volume. There is a misunderstanding that the efficiency of linear compressors in the small cooling capacity is lower, because it has a large dead-volume. However, LGE found that the dead volume doesn't influence the efficiency of compressor; on the other hand, the most important factors are the motor and mechanical efficiency.

Deeper analysis of the motor and mechanical efficiency with the variation of the piston diameter and displacement shows that the efficiency with a large dead volume can be much higher.

Finally, LGE created the *Innovative Linear Compressor*, which has much higher efficiency in the small cooling capacity. Also, the refrigerator with this linear compressor shows that the power consumption reduction by 25% can be achieved, as compared with the reciprocating compressors, and CO₂ reduction of the linear compressor is equivalent to the absorption by 9 pines. Based on the outstanding CO₂ reduction, LG linear compressors will be the one of Green technology to keep the global clean.

1. INTRODUCTION

The linear compressor uses the resonant free piston reducing the mechanical loss instead of the crank mechanism of the reciprocating compressor. Also, the linear motor using the permanent magnet has higher efficiency than other type of motor. From these reasons, the linear compressor has higher efficiency than other reciprocating compressor at the large cooling capacity.

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, and utilized in Japan. The typical type of a compressor is the reciprocating compressor with BLDC inverter. By changing operating frequency, the BLDC inverter reciprocating compressor is operated on 40~110% range of the cooling capacity.

On the other hand, the linear compressor is modulated by *the control of the stroke*. The characteristics of the mechanical part, the motor, and the compression efficiency with respect to capacity modulation are totally different from those of the BLDC reciprocating compressor.

In this paper, the characteristics of the capacity modulation of the LG linear compressor will be mentioned. Also, the efficiency improvement method at small cooling capacity will be discussed.

Based on our researches, we created the innovative linear compressor, which has the outstanding characteristics in efficiency, easy control, and acoustic noise.

2. CHARACTERISTICS of CAPACITY MODULATION of LINEAR COMPRESSOR

2.1 Capacity Modulation for Energy Saving

Usually, the compressor in a refrigerator consumes more than 80% of the total energy of the refrigerator. Therefore the efficiency of the compressor itself is very important for energy saving. But 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%.

2.2 Capacity Modulation of Linear Compressor

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

2.2.1 Compressor efficiency

The efficiency of the compressor is shown as Equation (1)

$$\eta_{compressor} = \eta_{motor} \times \eta_{mechanical} \times \eta_{compression} \quad (1)$$

where $\eta_{compressor}$, η_{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 (1) 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, et al. at the each cooling capacity.

2.2.2 Compression efficiency vs. dead volume

For the efficiency of the compression, the P-V diagram is simulated and experimented at the several cooling capacity. For the linear compressor, the cooling capacity is modulated by the controlled stroke of the free piston. When the stroke of the piston is fully operated, the cooling capacity is maximized as shown in Fig. 1. The cooling capacity is proportionally modulated by the under-stroke operation of the piston. The linear compressor is operated with the dead volume when the piston is operated on the under-stroke. This is the natural characteristics of the linear compressor.

Fig. 2(a) and (b) show the P-V diagram of the linear compressor. There are the P-V diagram of the 100% cooling capacity and the 50% cooling capacity, respectively. The dotted line shows the P-V diagram with the ideal valve system of the simulation and the solid line shows the P-V diagram of the actual valve system of the experiment.

For the consideration of the compression efficiency by the cooling capacity modulation, the ratio of the cooling capacity to the P-V work is compared with the P-V diagram in Table. 1. From Table. 1, the ratio of the cooling capacity to the P-V work is almost the same with each other. There is a little difference between the ratio of the 100% cooling capacity to a half cooling capacity from these results. Therefore the dead volume is not a dominant factor of the efficiency of the compression. From these results, the efficiency of the linear compressor is closely connected with the efficiencies of the motor and the mechanical part.

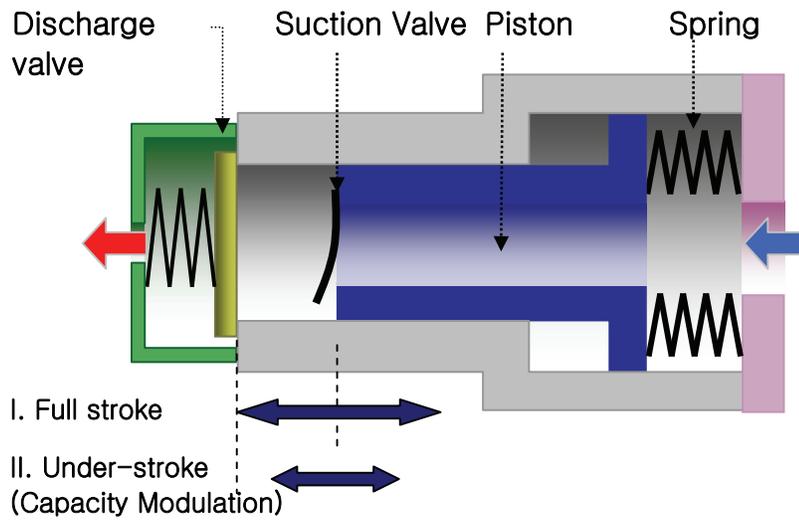


Figure 1: Schematic diagram of linear compressor

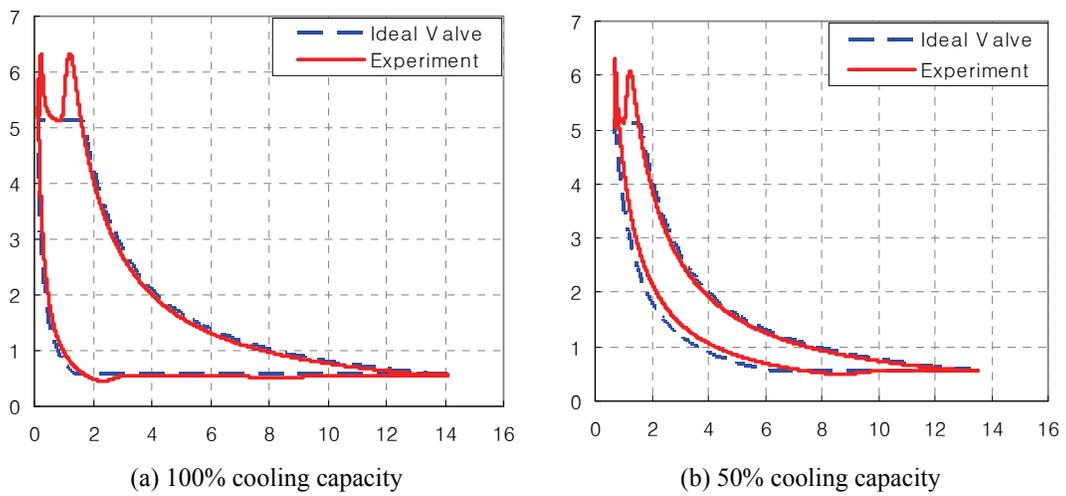


Figure 2: Capacity modulation of linear compressor (P-V diagram)

Table 1: Ratio of the cooling capacity to the P-V work

	100% Cooling	50% Cooling
Dead Volume [cc]	0.1	0.7
Ideal Valve (Simulated)	3.296	3.296
Experiment	3.113	3.139

2.2.3 Mechanical & motor efficiencies vs. cooling capacity

Fig. 3(a) shows the general pattern of the mechanical efficiency and the motor efficiency according to the capacity modulation of the linear compressor. 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 Fig. 3(a) has the maximal efficiency over the 100% cooling capacity range. However, the total efficiency shown in Fig. 3(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 is optimized to maximize the efficiency of the most useful capacity.

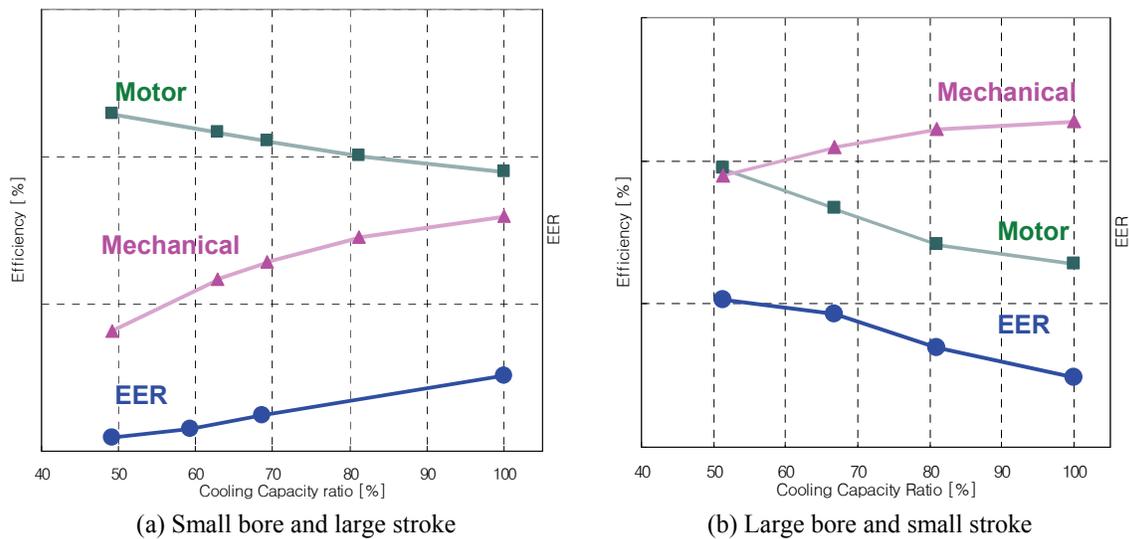


Figure 3: EER related with mechanical and motor efficiency

3. DEVELOPMENT of INNOVATIVE LINEAR COMPRESSOR

Figure 4 shows the efficiencies of the innovative linear, the old linear, and the BLDC reciprocating compressor when compressors are operated in the capacity modulation. LGE developed the innovative linear compressor with superior efficiency for the overall capacity modulation. The innovative 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 innovative 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 innovative 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 innovative linear compressor has the large gap of the efficiency comparing with the old linear and the BLDC reciprocating compressor overall cooling capacity modulation range.

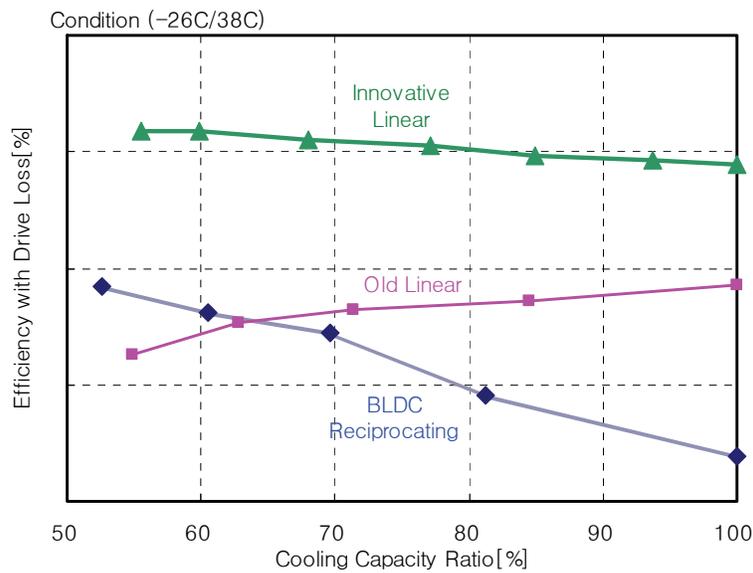


Figure 4: Energy efficiency of developed linear compressor (including drive loss)

4. CONCLUSIONS

The innovative linear compressor by LGE has the power consumption reductions by 25% and 12%, as compared with the conventional constant speed and the BLDC reciprocating compressor, respectively. The technology for energy saving of appliances is important to reduce CO₂, which causes the global warming problem. When the conventional reciprocating compressor in a refrigerator, which consumes 720kWh/Year, is replaced with the innovative linear compressor by LGE, the emitted CO₂ is reduced by almost 90kg/Year (for Korean electric power production). This amount of CO₂ reduction is equal to the absorption of CO₂ by 9 pines, because a pine absorbs 10kg CO₂ for a year. Because the energy consumption of a refrigerator has large portion in the household, the innovative linear compressor will be the one of *the Green Technology* to protect the global warming.



Figure 5: CO₂ reduction by the innovative linear compressor

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