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# Performance characteristics of a capacity-modulated linear compressor for home refrigerators

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ABSTRACT

A linear compressor requires stroke controllers, as the piston movement is sensitive to the ambient temperature. This paper presents the performance characteristics of an inherent capacity-modulated (ICM) linear compressor. The compressor is capable of modulating its capacity independently without requiring stroke controllers. Electric parameters are designed to deliver inherent capacity modulation in accordance with variations in the cooling demand. An inherent capacity modulation method according to cooling demand levels was proposed and a prototype compressor was constructed. Its performance was evaluated with the cooling capacity ratio varying from 50 to 100% at an evaporating temperature of −26 °C and a condensing temperature of 38 °C. The total efficiency of the ICM linear compressor was as high as that of an electrical resonant system. This shows that the COP difference between the ICM linear compressor and the linear compressor controlled by an electrical resonance system appeared to be less than 1% over a wide cooling capacity ratio range of 50–100%. The results for the conventional linear compressor did not account for the power consumed by the electronic drive, so thus the ICM linear compressor had the potential improvement for energy saving.



# Caractéristiques de la performance d’un compresseur linéaire à modulation de puissance pour les réfrigérateurs domestiques

*Mots clés* : compresseur linéaire ; piston libre ; réfrigérateur domestique ; modulation de puissance intégrée ; système frigorifique

## 1. Introduction

Energy regulations for reducing energy consumption to protect the global environment have been reinforced for home refrigerators. A refrigerator requires a considerable amount of energy to operate, and the compressor consumes the largest portion of the energy, accounting for 80% of its power consumption. A linear compressor is one of the most efficient types due to its low friction loss, simple refrigerant flow path, and highly efficient linear motor. Lee et al. (2000) investigated a linear

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**Nomenclature**

| | |
|---|---|
| $A_p$ | cross sectional area of piston ($m^2$) |
| BDC | bottom dead center |
| $C_f$ | friction damping coefficient ($N\ m\ s^{-1}$) |
| $C_g$ | gas damping coefficient ($N\ m\ s^{-1}$) |
| C | capacitor ($\mu F$) |
| CCR | cooling capacity ratio |
| COP | coefficient of performance |
| $f$ | operating frequency ($s^{-1}$) |
| $f_n$ | natural frequency ($s^{-1}$) |
| $F_{gas}$ | gas force (N) |
| $h$ | enthalpy ($J\ kg^{-1}$) |
| $i$ | current (A) |
| $I_m$ | imaginary part |
| $I_p$ | peak current (A) |
| $k_{gas}$ | spring constant of gas ($N\ m^{-1}$) |
| $k_s$ | spring constant ($N\ m^{-1}$) |
| L | inductance (mH) |
| $m_p$ | mass of piston (kg) |
| $\dot{m}$ | mass flow rate ($kg\ s^{-1}$) |
| $P_c$ | pressure of cylinder chamber (Pa) |
| $P_{dis}$ | pressure of discharge (Pa) |
| $P_{suc}$ | pressure of suction (Pa) |
| $\dot{Q}$ | cooling capacity (W) |
| Real | real part |
| R | resistance (Ω) |
| T | temperature (°C) |
| TDC | top dead center |
| V | volume ($m^3$), input voltage (V) |
| $\dot{W}$ | input power (W) |
| X | displacement (m) |
| $X_{bot}$ | piston's bottom position (m) |
| $X_p$ | peak displacement (m) |
| $X_{top}$ | piston's top position (m) |
| $X_0$ | initial displacement (m) |
| $\dot{x}$ | velocity ($m\ s^{-1}$) |
| $\dot{x}_0$ | initial velocity ($m\ s^{-1}$) |
| $\ddot{x}$ | acceleration ($m\ s^{-2}$) |
| Z | Impedance (Ω) |
| *Greek letter* | |
| $\alpha$ | motor constant ($N\ A^{-1}$) |
| $\theta$ | phase (degree) |
| $\theta_0$ | initial phase (degree) |
| $\omega$ | angular velocity ($rad\ s^{-1}$) |
| $\rho$ | refrigerant density ($kg\ m^{-3}$) |
| $\eta$ | efficiency |

compressor for a household refrigerator and introduced several key components, such as a highly efficient linear motor, an application-specific spring, and a new type of oil pumping system based on a linear mechanism. Lee et al. (2008) described a design guide to improve the total efficiency mainly through the three components of the motor, mechanisms, and compression in the low-cooling-capacity zone to represent a high cooling-capacity modulation rate. They increased the piston diameter and decreased the stroke, sustaining the same volume to reduce the friction loss being generated between the piston and the cylinder. Jeong et al. (2010) carried out research on the efficiency of the moving-magnet type of linear motor. They determined the main factors affecting the motor efficiency, which were motor core, the magnet assembly and the surrounding structure, all of which were subject to magnetic flux variations.

Capacity modulation of a compressor has been investigated using various methods. Lee et al. (2000) applied Triac, which controls the AC voltage in order to control the piston stroke of the compressor. Lee et al. (2008) applied a PWM (Pulse Width Modulation) inverter to convert an AC power source to DC to ensure that certain amount of AC power reaches the motor. The present authors (Kim et al., 2009) introduced the dynamic responses in the range up to the full capacity of a linear compressor. The dynamic characteristics of the system resonance at nearly full capacity were evaluated under nine different operational refrigeration cycle conditions. They proved that it is very important to link the operating frequency to the system resonant frequency to improve the compressor efficiency. For the experiment in the aforementioned study, an inverter control system was used. The stroke controller consisted of a micro-processor and electric circuits. Stroke control devices such as an inverter and Triac are expensive to apply, need power to run, and require complicated control logic, given that the piston displacement is influenced by many different cycle conditions. Furthermore, the linear compressor driven by the position controller should be optimized specifically to the refrigeration cycle each moment for optimal performance and to minimize power consumption by modulating the cooling capacity according to the variable refrigerator conditions.

The present authors (Kim et al., 2011) also presented a novel design method for an inherent capacity-modulated linear compressor, referred as the inherent capacity modulation (ICM) linear compressor, which uses R600a for application in household refrigerators. The electric parameters are designed to deliver inherent capacity modulation in accordance with variations in the cooling demand. The mechanical parameters are tuned to establish an efficient resonance system. A numerical model was developed and a prototype compressor was constructed. The prototype compressor was evaluated over a condensing temperature range of 15–50 °C, which corresponds to an ambient temperature range of 5–43 °C. The simulation results showed that the cooling capacity was inherently modulated from 55 to 90% over the ambient temperature range, and the inherent modulation was confirmed to be 70–90% in the experiment. Hence, the experimental results proved the inherent capacity modulation over a condensing temperature range of 35–50 °C, which corresponds to an ambient temperature range of 27–43 °C. The modulation range between the simulation and measurement was different because suction temperature of 32.2 °C and sub-cooler temperature of 32.2 °C were set to measure the cooling capacity and compare capacity modulation under variation of the condensing temperature. That is, the condensing temperature is limited to over 32.2 °C to prevent two phase state refrigerant from entering into an expansion valve.