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An experimental and numerical study on an inherent capacity modulated linear compressor for home refrigerators

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ABSTRACT

Linear compressors are built based on a free piston system and usually require stroke controllers, since the piston movement is sensitive to the ambient temperature. This paper presents a novel design method for an inherent capacity modulated linear compressor that uses R600a for application in household refrigerators. The compressor is capable of modulating its capacity independently, and this feature secures stable and efficient operation without requiring stroke controllers. Electrical parameters are designed to deliver inherent capacity modulation in accordance with cooling demand variation. 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 show that the cooling capacity was inherently modulated from 55 to 90% over the ambient temperature range, and the inherent modulation is confirmed 70–90% by the experiment.

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Etude expérimentale et numérique sur un compresseur linéaire modulé d'une puissance inhérente pour les réfrigérateurs domestiques

Mots clés : Compresseur ; Piston libre ; Réfrigerateur domestique ; Système frigorifique ; Modélisation

1. Introduction

The refrigerator is one of the most common household appliances in developing and developed countries. As this appliance requires considerable energy to operate, however, the issue of improving its energy efficiency has long been of interest. The compressor consumes the largest portion of the energy, accounting for 80% of the power consumed by the refrigerator. Numerous studies have accordingly been carried out to reduce the energy consumption of compressors, using two different approaches.

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Nomenclature

A_p	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	capacity (μF)
COP	coefficient of performance
f	operating frequency (s^{-1})
f_n	natural frequency (s^{-1})
F_{ga}	gas force (N)
h	enthalpy (J kg^{-1})
i	current (A)
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	mass of piston (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
No.	number of cycle condition
O_1	objective function of displacement
O_2	objective function of velocity
P_c	pressure of cylinder chamber (Pa)
P_{dis}	pressure of discharge (Pa)
P_{suc}	pressure of suction (Pa)
Q	cooling capacity (W)
Q_{cd}	cooling demand of ref. (W)
R_{th}	thermal resistance (Ω)
R	resistance (Ω)
T	temperature (°C)
TDC	top dead center
v	volume (m^3)
V	input voltage (V)
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_o	initial displacement (m)
x_n	nth displacement (m)
$\dot{x}$	velocity (m s^{-1})
$\dot{x}_0$	initial velocity (m s^{-1})
$\dot{x}_n$	nth velocity (m s^{-1})
$\ddot{x}$	acceleration (m s^{-2})

Greek letter

α	motor constant (N A^{-1})
ϵ	tolerance
θ	phase (degree)
θ_0	initial phase (degree)
ω	angular velocity (rad s^{-1})
ω_n	natural angular velocity (rad s^{-1})
ρ	refrigerant density (kg m^{-3})

The first is to improve the performance of the compressor itself. The compressor is thus designed such that its motor efficiency, mechanical efficiency, and thermodynamic efficiency are improved. Linear compressors are among the most efficient compressors, thanks to their low friction loss, simple refrigerant flow path, and highly efficient linear motor. The mechanical loss of a linear compressor is much less than that of conventional reciprocating compressors. Linear compressors only have a friction region between the piston and the cylinder. On the contrary, reciprocating compressors have four friction regions that generate friction loss due to the conversion of rotating energy to reciprocating energy by a crank-driven mechanism. Unger and Walt (1994) made a prototype of a linear compressor and presented its technology for the first time in the world. Lee et al. (2000) introduced a linear compressor for a household refrigerator. They suggested a way to design a highly efficient linear motor. To this end, an application-specific spring was developed. This spring has sufficiently small variation on required piston movement, and it operates under a new method of an oil pumping system based on a linear mechanism. Lee et al. (2008) presented a design guide to improve the mechanical efficiency of linear compressors under a wide range of cooling capacity. They increased the piston diameter and decreased the stroke, sustaining the same volume to reduce friction loss being generated between the piston and the cylinder.

The second approach is to optimize the compressor operation. For instance, 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. Chun and Ahn (2008) applied a PWM (Pulse Width Modulation) inverter to drive the linear motor by adjusting both voltage and frequency according to the load variation. Lee et al. (2008) investigated a capacity modulated linear compressor under a wide range of cooling capacity from 50% to 100%. The cooling capacity was proportionally modulated by the under-stroke operation of the piston with a PWM inverter. The linear compressor was operated with dead volume when the piston was on the under-stoke operation. They show that the varied dead volume was neither experimentally nor theoretically a dominant factor in determining the compression efficiency, because both produced cooling capacity and electrical energy input decrease at the same ratio.

The present authors (Kim et al., 2009) previously investigated the dynamic characteristics in the range of the full capacity of a linear compressor. The dynamic characteristics of the system resonance around the full capacity were examined under 9 different operational conditions of a refrigeration cycle. In general, as the difference between the operating frequency and the natural frequency becomes greater, the COP of the linear compressor in the refrigeration cycle becomes accordingly lower. This means it is very important to link the operating frequency with the natural frequency for improvement of compressor efficiency. For the experiment in the aforementioned study, an inverter control system was used. The stroke controller consisted of a microprocessor and electrical circuits. Power electronic elements were used to convert the AC power source to DC to obtain a certain amount of AC power to reach to the motor. Piston

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