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Modulation characteristics of a linear compressor for evaporating and condensing temperature variations for household refrigerators

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ABSTRACT

Linear compressors are sensitive to both condensing and evaporating temperatures since they do not have mechanical restrictions to piston movement. Linear compressors used in refrigerators are subjected to a wide range of compression loads, because of the condensing temperature change caused by the ambient temperature variations and the evaporating temperature change due to the freezer compartment temperature. The compartment temperature is influenced by door opening, product loading, defrosting and setting temperature. This paper presents modulation characteristics of an inherent capacity-modulated linear compressor for evaporating temperature variations representing compartment temperature change. A numerical model and a prototype compressor were developed. The prototype compressor was evaluated over an evaporating temperature from −35 to −15 °C. The results were compared with the compressor performance variations over a condensing temperature from 30 to 50 °C. The cooling capacity increased by 241 and 50 W for 20 °C increment of the evaporating and condensing temperature, respectively.

Caractéristiques de modulation d’un compresseur linéaire pour des variations de température d’évaporation et de condensation de réfrigérateurs domestiques

Mots clés : Compresseur linéaire ; Piston libre ; Réfrigérateur domestique ; modélisation ; Systéme frigorifique

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Nomenclature

A_p	cross sectional area of piston (m^2)
BDC	bottom dead center
C_f	friction damping coefficient ($N\ ms^{-1}$)
c_t	total damping coefficient ($N\ ms^{-1}$)
C	capacitance (μF)
CCR	cooling capacity ratio
COP	coefficient of performance
f_n	natural frequency (s^{-1})
f_{sys}	system resonant frequency (s^{-1})
F_{gas}	gas force (N)
i	current (A)
I_m	imaginary part
I	peak current (A)
k_{gas}	spring constant of gas ($N\ m^{-1}$)
k_s	spring constant ($N\ m^{-1}$)
k_t	total spring constant ($N\ m^{-1}$)
L	inductance (mH)
m_p	mass of piston (kg)
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	input voltage (V)
V	peak voltage (V)
$\dot{W}$	input power (W)
x	displacement (m)
X	peak displacement (m) reactance (Ω)
X_o	initial displacement (m)
$\dot{x}$	velocity ($m\ s^{-1}$)
$\dot{x}_0$	initial velocity ($m\ s^{-1}$)
$\ddot{x}_0$	acceleration ($m\ s^{-2}$)
Z	impedance (Ω)
Greek letter	
α	motor constant ($N\ A^{-1}$)
θ	phase (degree)
θ_0	initial phase (degree)
ω	angular velocity ($rad\ s^{-1}$)
ρ	refrigerant density ($kg\ m^{-3}$)
η	efficiency

1. Introduction

A linear compressor has high efficiency characterized by its simple flow path, low friction loss, and highly efficient linear motor. On the other hand, compressor performance is sensitive to both condensing and evaporating temperature variations because the stroke of the piston, which does not have mechanical restrictions, is variable. Moreover, linear compressors used in home refrigerators are subjected to a wide range of compression loads associated with the evaporating and condensing temperature. The evaporating temperature is varied by door opening, product loading, defrosting, and freezer compartment temperature. The condensing temperature is influenced by the ambient temperature.

Lee et al. (2000) introduced a linear compressor for use in household refrigerators. They applied TRIACs, which controls the AC voltage in order to control the piston displacement of the compressor.

Lee et al. (2008) investigated a capacity modulated linear compressor under a wide range (50–100%) of cooling capacity. Since the stroke of a piston in the linear compressor is not fixed due to a mass-spring system, they defined the under-stroke as the difference between maximum piston stroke and reduced piston stroke for capacity modulation is called under-stroke. The cooling capacity was proportionally modulated by the under-stroke operation of the piston with a pulse width modulation (PWM) inverter. The linear compressor was operated with dead volume when the piston was in the under-stoke operation. It was shown that the varied dead volume was neither experimentally nor theoretically a dominant factor in determining the compression efficiency, because both the produced cooling capacity and the electrical energy input decrease at the same ratio. A comprehensive model of a linear compressor for electronics cooling was previously presented by Bradshaw et al. (2011) then proved the energy recovery characteristics of a linear compressor as compared to those of a reciprocating compressor. Bradshaw et al. (2013) showed that the overall isentropic efficiency of the linear compressor remained relatively unaffected by an increase in dead volume up to a certain point. It was analyzed that the linear compressor has a higher ability to store energy due to the higher stiffness of mechanical springs which is analogous capacitance in an electrical system. This characteristic behavior allows a linear compressor to be used for efficient capacity control roughly from 35 to 100%.

The present authors (Kim et al., 2009) previously investigated the dynamic characteristics in the range of the full capacity of a linear compressor. 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, a PWM inverter was used to obtain the resonance system. The system consisted of a micro processor and electrical circuits. Power electronic elements were used to convert the AC power source to DC to induce a certain amount of AC power to reach to the motor. Piston controllers such as inverters and TRIACs are expensive to apply, need power to run, and require complicated control logic, since the piston movement is influenced by many different cycle conditions. Furthermore, for optimal performance and to minimize power consumption by