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An experimental and numerical study on dynamic characteristic of linear compressor in refrigeration system

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ABSTRACT

This paper presents experimental and numerical results of the dynamic characteristic and COP of a linear compressor in a refrigeration system using R600 refrigerant. The numerical analysis consists of a model and a simulation that includes the linear compressor. In this study, the dynamic characteristic of the natural frequency of the linear compressor is validated by comparing the simulation results with the experimental results. To investigate the effect of system resonance on the performance of linear compressor, COP is evaluated under evaporator pressure in the range of 48.3–63.2 kPa abs, and condenser pressure in the range of 439.0–573.3 kPa abs. Based on the results, the system resonance at the TDC was varied within a range of 3% under the test conditions. COP and its sensitivity were found to vary within 3% according to the operating frequency of the system ranging from 48.5 to 51.5 Hz.

Etude expérimentale et numérique sur les caractéristiques dynamiques d’un compresseur linéaire dans un système frigorifique

Mots clés : Système frigorifique ; Système à compression ; Compresseur linéaire ; Butane ; Expérimentation ; Modélisation ; Simulation ; COP ; Résonance ; Fréquence

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Nomenclature

A	area of piston (m^2)
BDC	bottom dead center
c_f	friction damping coefficient (N m s^{-1})
c_g	equivalent viscous damping coefficient of gas (N m s^{-1})
C	capacity (uF)
COP	coefficient of performance
f	operating frequency (s^{-1})
f_n	natural frequency (s^{-1})
$F(x)$	gas force (N)
F_e	electromagnetic force (N)
h	enthalpy (J kg^{-1})
i	current (A)
I_0	initial current (A)
k_g	equivalent spring constant of gas (N m^{-1})
k_m	spring constant (N m^{-1})
L	inductance (mH)
m	mass of piston (kg)
No.	number of cycle condition
O_1	objective function of displacement
O_2	objective function of velocity
P	pressure (Pa)
$p_{\mathrm{discharge}}$	pressure of discharge (Pa)
p_{suction}	pressure of suction (Pa)
ΔP	difference pressure between discharge and suction (Pa)
Q	cooling capacity (W)
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_0	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^{-1})

Greek letter

α	motor constant (N A^{-1})
ε	tolerance (Ω)
Φ	phase (degree)
Φ_0	initial phase (degree)
ω	angular velocity (rad s^{-1})w
ω_n	natural angular velocity (rad s^{-1})

1. Introduction

A linear compressor is a compressor with a positive displacement of free piston directly driven by a linear motor. It has been considered as a substitute for the reciprocating compressor because of its efficient energy consumption in the vapor compression cycle. However, it had many technical difficulties when it was applied to a real vapor compression cycle. The dynamic characteristic and control of the linear compressor depend significantly on the refrigeration application.

Unger and Walt (1994) first made a prototype of the linear compressor and presented its technology. Yang and Huang (1998) presented a new dual fuzzy controller for the linear compressor with a split-stirling cryocooler. Here, fuzzy control was adopted to the complex system consisting of a stroke and a phase in the cryocooler system. Choe and Kim (2000) analyzed the nonlinear dynamics in the linear compressor as well as the steady state response characteristics and the jump phenomenon in the linear compressor. The gas dynamics was described with an equivalent spring constant and a viscous damping coefficient. The jump phenomenon of the linear compressor was tested experimentally, and the dynamic characteristics of the jump phenomenon were investigated by nonlinear analysis. Koh et al. (2002) presented a study on the characteristics of the linear compressor for the Stirling cryocooler. They also modeled the gas dynamic characteristics with an equivalent spring and also studied the operating parameters of its performance. Masuyama et al. (2006) researched a Stirling type pulse tube refrigerator with an active phase control. They controlled the phase angle between the mass flow and the pressure inside the pulse tube to improve the performance of the refrigerator.

In a similar study on the reciprocating compressor in refrigeration systems, Tassou and Qureshi (1998) reported the comparative performance evaluation of the positive displacement compressor in refrigeration applications and evaluated the COP of the reciprocating compressor according to various operating frequencies of the compressor. Srinivasa et al. (2002) showed a computationally efficient model of the refrigeration compressor gas dynamics and studied the model coupled with the gas dynamics equation and acoustic plenum models of the reciprocating compressor.

However, in a real application, the dynamic characteristic of the system resonance around the TDC is very important when the linear compressor is operated. The system resonance related to the natural frequency of linear compressor can affect the COP of the refrigeration system. Previous studies did investigate the system resonance around the TDC, and it could improve the energy consumption of the refrigeration system with a linear compressor in a real application.

In this study, it is shown that the system resonance is the most important factor of the dynamic characteristics and efficient performance of the vapor refrigeration system when the linear compressor is applied. A natural frequency is the same as the operating frequency at the TDC, where the volumetric loss by dead volume is the smallest in the reciprocating piston mechanism. The dynamic characteristic of the system resonance around the TDC is examined under various cycle conditions because the stroke position around the TDC and the pressure of the various cycle conditions mainly affect the system resonance.

To investigate the system resonance, the experimental and the numerical studies on the linear compressor were performed under various cycle conditions. As stated, the modeling of the new approach including the system