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Feasibility study of a bowtie compressor with novel capacity modulation

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Abstract

A novel refrigeration compressor with an integrated method of capacity modulation for use in domestic refrigerators/freezers is proposed and analyzed here. The compressor is called bowtie compressor due to its two sector-shaped, opposing compression chambers forming a bowtie. The bowtie compressor modulates the cooling capacity by changing the piston stroke without changes of the clearance volume for better thermodynamic efficiency. The new compressor includes a unique off-center-line mechanism so that the piston stroke can be varied without creating an extra clearance volume. To investigate the feasibility of the proposed compressor, a simulation model has been developed. A detailed description of the bowtie compressor and its simulation model are presented in this paper. In addition, parametric studies have been carried out to see how the proposed compressor performance can be improved.

Keywords: Domestic refrigerator; Design; Compressor; Oscillating compressor; Capacity reduction; Simulation; Performance

Compresseur « nœud de papillon » muni d'un nouveau dispositif de modulation : Étude de faisabilité

Mots clés : Réfrigérateur domestique ; Conception ; Compresseur ; Compresseur oscillant ; Réduction de puissance ; Simulation ; Performance

1. Introduction

The compressor of typical domestic refrigerators/freezers is designed to deliver the full cooling capacity at a single speed. Since the cooling capacity of domestic refrigerators/freezers varies throughout their operation, the capacity of the compressor has to be modulated to match the cooling loads. Conventional compressors are designed to operate at the maximum cooling load. As a result, they cycle on and off in response to the change of the cooling load. This on-and-off operation is not efficient and consumes unnecessary amounts of energy whenever the compressors are turned back on. One way to increase the efficiency of the compressors is to continuously modulate the compressor capacity based on the demand of the cooling load.

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Nomenclature

A	area (m^2)
$A(t)$	time-dependent heat transfer area (m^2)
BDC	bottom-dead-center
C_D	drag coefficient
C_v	specific heat at constant volume ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
h	enthalpy ($J\,kg^{-1}$)
$h(t)$	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k_s	spring stiffness ($N\,m^{-1}$)
$K(t)$	thermal conductivity of the gas ($W\,m^{-1}\,K^{-1}$)
l	initial length between the centers of the crank and the journal shafts (m)
m	refrigerant mass (kg)
m_{eq}	equivalent mass of the plate spring (kg)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
r_{01}	length of the eccentricity (m)
r_{02}	length of the ground vector (m)
r_{24}	length of the journal shaft vector (m)
r_{25}	length of the vane vector (m)
R	thermal resistance ($K\,W^{-1}$)
$\vec{R}_{01}$	eccentricity vector
$\vec{R}_{13}$	connecting rod vector
$\vec{R}_{25}$	vane vector
rpm	rotation per minute
t	time (s)
T	temperature (K)
TDC	top-dead-center
U_{piston}	mean piston speed ($m\,s^{-1}$)
V	velocity ($m\,s^{-1}$)
$\mathcal{V}$	volume (m^3)
x	x directional coordinate or x distance or control length (cm)

Greek letters

γ	specific heat ratio
η	efficiency
$\mu(t)$	dynamic viscosity of the gas (Pa s)
v	specific volume ($m^3\,kg^{-1}$)
ω	angular velocity (s^{-1})
ω_{12}	angular velocity of the journal shaft (s^{-1})
$\omega_{n,1}$	natural frequency at the first mode shape (s^{-1})
ρ	density ($kg\,m^{-3}$)
θ	angle (radian)
θ_{01}	angle of the eccentricity vector (radian)
θ_{02}	angle of the ground vector (radian)
θ_{12}	angle of the connecting rod vector (radian)

Superscript

$\rightarrow$	vector
$-$	average

Subscripts

amb	ambient
cir	circumference of the valve
comp	compression
cond	condensing
cv	clearance volume
cyl	cylinder
dis	discharge
evap	evaporating
f	flux force
flow	effective flow of the port
friction	friction
gas	gas
high	high-side
in	into the cylinder
leak	leakage
loss	loss
low	low-side
m	mechanical
motor	motor
o	total
oil	oil
o,s,c	overall isentropic compressor
out	out of the cylinder
p	pressure force
piston	piston
port	port
rad	radiation
shell	in the shell
suct	suction
super	superheating
swept	swept
th	throat of a valve port
tr	transitional
v	volumetric
valve	valve
wall	cylinder wall

A typical method for continuous capacity modulation is variable speed control in which a variable speed motor controls the speed of the piston stroke to match the cooling loads. Theoretical studies by Holdcack-Janssen and Kruse [1], and Zubair and Bahel [2] reported that variable speed control is the most energy efficient capacity control method at full and part load conditions in comparison to on/off control, hot gas bypass, clearance volume control, and cylinder unloading. In addition, variable speed control introduces the following other advantages: (1) precise thermal control is possible; (2) the reliability of the compressor is improved due to the reduced number of on/off cycles; (3) the response time for set conditions is fast. However, variable speed control is the most expensive method among the other capacity