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Development of capacity modulation compressor based on a two stage rotary compressor – part I: Modeling and simulation of compressor performance

Seung-jun Lee [a], Jaesool Shim [b,*], Kyung Chun Kim [c,**]

[a] CAC Laboratory, LG Electronics, Changwon 641-713, South Korea
[b] School of Mechanical Engineering, Yeungnam University, Gyeongsan 712-749, South Korea
[c] School of Mechanical Engineering, Pusan National University, Pusan 609-735, South Korea

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ABSTRACT

Two-stage rotary compressors are gaining popularity because of their ability to reduce operating and energy costs over the entire compressor life cycle. In this work, a capacity modulation compressor based on a two-stage rotary compressor (CMCTR) is developed to improve the performance of the rotary compressor system. The working principle of the CMCTR is presented and the cycle efficiency of the compressor through two-stage compression is numerically investigated. The CMCTR model considers mass and energy balance for a control volume, the internal leakage condition for all leakage paths, the discharge valve motion, and the force and moment balance. For simulation results, the motor efficiency is estimated with respect to shaft power and the pressure during an entire cycle is obtained with respect to the compression volume for saving mode and power mode. The optimum efficiency of the CMCTR is obtained for the modulation for these modes.

Le développement de compresseur à modulation de charge basé sur un compresseur rotatif bi-étagé. 1ère partie : Modélisation et simulation de la performance d'un compresseur

Mots clés : Rotatif ; Compresseur ; Modulation de puissance ; Biétagé ; Simulation

* *Corresponding author*. Tel.: +82 53 810 2465; fax: +82 53 810 4627.
** *Corresponding author*. Tel.: +82 51 510 2324; fax: +82 51 512 9835.
E-mail addresses: jshim@ynu.ac.kr (J. Shim), kckim@pusan.ac.kr (K.C. Kim).
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Nomenclature

A	flow path Area, m^2
A_{eff}	effective area of discharge port, m^2
b	vane thickness, m
c_v	constant volumetric specific heat of gas, $kJ\ kg^{-1\circ}C^{-1}$
C_{damp}	effective damping coefficient, $Ns\ m^{-1}$
COP	coefficient of performance
e	eccentricity of roller, m
F_d	acting force on vane by shell pressure, N
F_{mj}	reacting force of main bearing, N
F_k	force on vane spring, N
F_n	normal force of contact point, N
F_{rj}	reacting force of roller bearing, N
F_{sj}	reacting force of sub bearing, N
F_t	friction force on surface, N
H	enthalpy, $kcal\ kg^{-1}$
k	isentropic exponent
k	spring constant, $N\ m^{-1}$
L	friction loss, W
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
m_p	mass of roller, kg
m_v	mass of vane, kg
MR	modulation rate, %
P_b	pressure in suction chamber, kPa A
P_c	pressure in compression chamber, kPa A
Q	cooling capacity, W
r_c	critical pressure ratio
R	ideal gas constant, $Nm\ K^{-1}$
R	reacting force on bearing, N
y	displacement of valve, kg

Greek symbols

α	contact angle between van and roller, rad
δ	distance between cylinder wall and roller, m
η_{mech}	mechanical efficiency of compressor
η_{motor}	motor efficiency
θ	angle of crankshaft rotation, degree
ρ	refrigerant density, $kg\ m^{-3}$
χ	length of vane extension, m
ω	angular velocity of crankshaft, $rad\ s^{-1}$

1. Introduction

Energy efficient household devices are in demand due to the great increase in the price of energy. In addition, HCFC refrigerants for air conditioning systems need to be replaced in compliance with the Kyoto protocol. For these reasons, the design of highly efficient compressors has become critical for air conditioning and refrigerator systems. To develop an efficient compressor, a great number of numerical simulations and experiments based on performance requirements have been conducted in the field of refrigeration and air conditioning during the past few decades. In 1996, Ooi and Wong presented analytical studies of a rotary compressor for household refrigerators (Ooi and Wong, 1997). Their model allows variations in refrigerating fluid pressure, temperature, and mass flow to be evaluated. In addition, the performance of the machine and cooling capacity were also evaluated. In 2003, Kim et al. analytically studied oil supplied to various lubrication elements for good reliability and high performance in a rotary compressor (Kim and Lancey, 2003). In their study, the total oil flow rate during the operation of a real compressor was estimated for different eccentric bearings. In 2005, Ooi optimized the performance of a rolling piston compressor under preset operational conditions and design constraints. A mathematical model for the compressor was developed with consideration of the geometrical configuration, thermodynamic effects, valve dynamics, and flow and mechanical considerations (Ooi, 2005). In 2008, he introduced a mult-objective optimization technique in compressor design. The optimum solution was based on nine objective functions for the coefficient of performance, refrigerating capacity, motor input power, friction power, adiabatic work, discharge valve loss, suction valve loss, overall size of the compressor, and machine cost (Ooi and Lee, 2008). Although all compressor parts in a conventional piston rolling compressor have been optimized, high performance has not yet been realized. In 2008, Mathison et al. presented a computer model for a hermetic two-stage rotary compressor (Mathison et al., 2008). Their model considered the effects of refrigerant leakage between the compressor chambers, heat transfer between the cylinder wall and the refrigerant gas, and heat loss by natural convection to the surroundings. The model could predict pressure and temperature variations over a crankshaft revolution, and the compressor power input and refrigerant mass flow rate were also calculated. In 2009, Shao et al. improved the performance of an inverter air conditioner using a variable speed compressor (Zhou et al., 2009). He introduced the concepts of frequency at zero refrigerant mass flow rate and power input at zero frequency. He determined the optimal frequency for a high coefficient of performance (COP). In 2009, Zhou et al. developed a synchronal rotary compressor (SRC) to resolve the high friction and severe wear that usually occur in a conventional rotary compressor. He first presented the working principle and structural characteristics using kinematic and force models for a high performance rotary compressor (Shao et al., 2004). However, the air conditioning system could not run continuously at full capacity when the load was less than the design load. If overcooled, a significant amount of energy would be wasted. For this reason, a different cooling capacity is needed to save energy.

In this work, we developed a capacity modulation compressor based on the two-stage rotary design, and a corresponding numerical model. A new principle of capacity modulation is also introduced, which was the basis for a numerical simulation to obtain the performance efficiency. Compression pressure, leakage mass flow rates, and mechanical friction losses were simulated. Finally, the optimum efficiency of the CMCTR was obtained with respect to the modulation rate.

2. The capacity modulation compressor

Analytical and experimental studies have been widely reported regarding the implementation of a variable capacity