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Research Paper

Theoretical and experimental study on thermodynamic performance of single screw refrigeration compressor with Multicolumn Envelope Meshing Pair

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HIGHLIGHTS

- Theoretical model was established to predict the performance of SSRC with MEMP.
- Experiments prove that SSRC with MEMP has higher volume displacement.
- Thermodynamic performances of the SSRC with MEMP have been analyzed.
- Theoretical model was validated to have reasonable error by experimental study.
- SSRC with MEMP is proved high volumetric efficiency and more power consumption.

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ABSTRACT

In single screw refrigeration compressor (SSRC), the Multicolumn Envelope Meshing Pair (MEMP) was proposed to reduce the wear of the meshing pair. However, the application of this new type meshing pair will change the thermodynamic performance of SSRC. It is necessary to research the thermodynamic performance of the SSRC with MEMP to evaluate the value of the proposed MEMP. In this paper, a theoretical calculation model describing the working process of the SSRC with MEMP is established to predict the thermodynamic performance of the SSRC. Experimental investigations on the performance of a SSRC with MEMP under different conditions are also carried out to verify the theoretical calculation model. Obtained results show that the theoretical calculation results are in good agreement with the experimental ones, which means that the presented theoretical calculation model is a powerful tool for performance analysis of the SSRC with MEMP. With the validated model, thermodynamic performances of the SSRC with MEMP have been analyzed. The SSRC with MEMP is proved to have high volume displacement and volumetric efficiency but needs slightly more shaft power. The maximum increment of shaft power and volumetric efficiency of SSRC with MEMP is 5.06% and 3.7% respectively in all working conditions.

1. Introduction

Single screw compressor was first invented by Zimmern in 1960s [1], and then it was introduced to the field of refrigeration soon in the mid of 1970s by Grasso company and J&E Hall company [2–4]. Now the single screw refrigeration compressor (SSRC) is widely used in refrigeration and air conditioning systems [5]. Although a newly produced SSRC has a higher performance than the reciprocating piston compressor and the screw compressor [6,7], the exhaust capacity of it will decrease sharply several hundred hours after initial operation [8]. The reason is that the star-wheel tooth flank of the existing SSRC with the straight line envelope meshing pair (LEMP) wears rapidly and the clearance between the star-wheel and the screw increases quickly. In order to enhance the wear-resistance of the meshing pair, a new Multicolumn Envelope Meshing Pair (MEMP) was deduced by Wu from 2007 to 2009 [9–11] on the basis of column envelope profile proposed by Zimmern and multi-straight line envelope profile proposed by Feng et al. [12].

In the past few years, a series of studies have been carried out for the design method and the performance of this new type meshing pair MEMP. Wu and Huang et al. researched the design method of Multicolumn Envelope Meshing Pair and simulated the surface

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Nomenclature

a	central distance between the star-wheel and the screw rotor (m)
b	width (m)
b'	clearance width (m)
C	heat capacity (J/K)
c	specific heat (J/(kg K))
c_r	spiral coefficient
d	diameter (m)
d/D	diameter ratio
F_1	heat leakage coefficient (W/K)
g	gravitational acceleration (m/s^2)
h	enthalpy (J/kg)
i	the number of directly measured parameter
j	the directly measuring parameter
L	length (m)
$\dot{M}$	the measured mass flow rate
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
n	the total number of directly measured parameters
p	pressure (Pa)
Δp	pressure difference(Pa)
Q	heat (J)
R	equivalent radius (m)
R_2	star-wheel radius (m)
r	the indirect measurement result
S	area (m^2)
T	temperature (K)
t	time (s)
U	perimeter of flow channel section (m)
u	velocity (m/s)
V	volume (m^3)
v_{12}	relative speed of screw groove and star-wheel tooth (m/s)
W	friction power (J)
x	dryness
z	height (m)

Subscripts

1,2,...9	state point
a	equivalent
a1	area formed by VF and boundary curves of the exhaust port
a2	area formed by VB and boundary curves of the exhaust port
c	saturation condition
d	end angle
e	environment
ed	effective exhaust area
g	refrigerant gas
gs	temperature rise
h	hydraulic
in	state of medium enter the system
l	refrigerant liquid
mid	VF pass over the point 1
o	lubricating oil
out	state of medium leave the system
r	the indirect measurement result
s	start/suction
sd	refrigerant gas after flowing through the motor
j_i	the directly measuring parameter
wall-oil	wall-oil film

Greeks

α	heat transfer coefficient (W/(m^2 K))
Δ	the absolute accuracy
δ	the total relative accuracy
ε	expansion coefficient
θ	rotational angle of star-wheel (rad)
κ	flow coefficient
λ	correction coefficient
λ_g	refrigerant gas Thermal conductivity W/(m K)
μ	viscosity (Pa s)
v	specific volume (m^3/kg)
ρ	density (kg/m^3)
τ	viscous force (N)

profile of the groove bottom to analyze the processability of the MEMP [13–16]. Li and Huang et al. analyzed the tooth wear resistance of the MEMP through the experimental method and proved that this MEMP could significantly improve the wear resistance of the compressor [17,18]. However, leakage path shapes of the LEMP and the MEMP compared by Wu show that the leakage paths were changed [19]. So in our previous paper, the leakage characteristics of the compressor with MEMP had been investigated [20]. Obtained results show that the leakage of the SSRC with MEMP was a little bit smaller than that of the SSRC with LEMP. Although this new type meshing pair MEMP was proved to have good wear resistance and better performance of leakage, whether the performance of the SSRC with MEMP is good or bad also cannot be evaluated. In the existing research, several scholars had investigated the performance of the single screw compressor [21–27], but the meshing pairs of the compressor used in there studies are also the LEMP. The meshing properties and structural characteristics of the MEMP are very different from those of the LEMP, which will seriously impact the thermodynamic performance of the SSRC, so the investigation method based on LEMP is no longer applicable. Thus, it is necessary to investigate the thermodynamic performance of the SSRC with MEMP, to better evaluate the value of the proposed MEMP.

In this paper, a theoretical calculation model describing the working process of the SSRC with MEMP is established. In order to verify the model, an oil-injection SSRC with MEMP has been developed and experimental investigations on the performance of this SSRC under different conditions have been carried out. The contrast of the theoretical calculation results and the experimental test results shows that the presented theoretical calculation model is a powerful tool for performance analysis of the SSRC with MEMP. With the validated model, the thermodynamic performances of the SSRC with MEMP have been analyzed. The SSRC with MEMP is proved to have high volume displacement and volumetric efficiency but needs more shaft power.

2. Mathematical modeling

2.1. Geometrical parameters

As shown in Fig. 1, the SSRC depends on the meshing movement of a screw and two star-wheels symmetrically located with the screw to realize suction, compression and exhaust process. The working chamber used in the process to realize gas transmission is formed by the screw groove, the upper plane of star-wheel tooth