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ABSTRACT

A mathematical model has been built which includes thermodynamic, mechanical and generator models. Then, the starting procedure of scroll expander driven by compressed air has been simulated. The rotating speed and stable time influenced by the suction pressure, discharge pressure and load resistance have been analyzed. The results show that the starting procedure of scroll expander is determined by the suction and discharge parameters, the load and the geometric parameters of expander. The rotating speed is affected by the driving force of air and the resistance of generator. The rotating speed increases but the increment decrease with the starting time until the expander runs steadily. The stable time and final rotating speed increase with the increase of both suction pressure and electric resistance but decrease with the increase of the discharge pressure.

1. INTRODUCTION

Because of the consumption of fossil fuels and environment problems in recent years, the low-grade energy recovery technique has brought many researchers' interest. The small scale energy recovery system makes important contribution to energy crisis and environment pollution which is normally used in the vehicle and mobile equipment. Scroll machine with the high efficiency, simple structure and small scale, is often used as compressor in the refrigeration system and heat pump system (Zhao *et al*., 2005 and Ma *et al.,* 2007). Scroll expander could be used as the energy recovery machine in the small energy recovery system. In recent years, scroll expander is normally applied in the low-temperature waste heat recovery system (Pererson *et al.,* 2007 and Kim *et al.*, 2007), fuel cell system (Zhao *et al.,* 2006) and carbon dioxide refrigeration system (Kim *et al.*, 2008). Most of the research on scroll expander is concentrated on the steady performances either simulation or experiment. Because the small scale system has the characteristics of start up and shutdown frequently, the starting procedure is very important to research the dynamic characteristics of the system.

In the previous reports, there is little research has been focused on the starting procedure of the scroll expander. In this paper, a mathematical model considering the leakage and heat transfer, air force, generator and resistance has been built to simulate the starting procedure of scroll expander driven by compressed air. The effect of suction pressure, discharge pressure and load resistance has been analyzed. The results could be used to analyze the dynamic characteristics of scroll expander. A properly improved model could be used to research the shutdown and adjustment procedure.

2. THEORETICAL ANALYSIS

The scroll expander is often connected with the generator in the small energy recovery system. The energy recovered from compressed air could be transformed into electric energy directly. The schematic diagram is shown in Fig.1. The working volumes of scroll expander are composed of fixed scroll and orbiting scroll. The high pressure air flows into the center of scrolls and pushes the orbiting scroll rotation. The electric resistance consumes the power and influences the rotary moment of generator and expander. When the driving force is larger than the resistance of load, the expander accelerates. When the driving force is equal to the resistance, the rotating speed reaches maximum and the expander runs stably. Leakage and heat transfer between chambers occur in all the process which affect the actual expansion process. The starting procedure and stable parameters of expander is determined by the suction pressure, discharge pressure and load resistance.

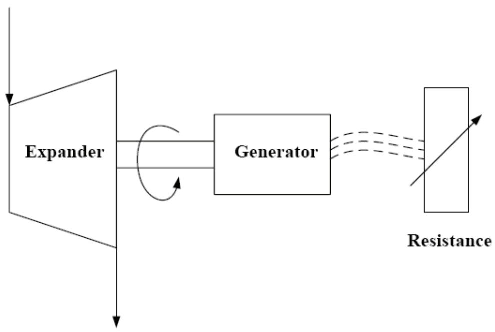

Fig. 1 Scroll expander generator system

2.1 Energy conservation

The working process of scroll expander is an energy conversion process from high pressure air to mechanical energy. Taking the chamber as control volume and ignoring the variation of kinetic energy and potential energy flowing in and out the control volume, the energy conservation of control volume can be expressed by following equation (Gao *et al.*, 2004).

$$\frac{dT}{dt}=\frac{1}{mc_v}\left\{-T\left(\frac{\partial p}{\partial T}\right)_v\left[\frac{dV}{dt}-v\left(\frac{dm_i}{dt}-\frac{dm_o}{dt}\right)\right]+\sum\frac{dm_i}{dt}(h_i-h)\right\} \tag{1}$$

2.2 Leakage model

The leakage is a significant factor influencing the performance of scroll expander. The leakage simulation could predict the working process and analyze the behavior of scroll expander. The leakage includes two parts. One is the leakage through the axial clearance between the scroll and bottom plate and the other is the leakage through the radial clearance between sidewall of scrolls. According to the throttle nozzle model (Gu *et al.,* 1998), the following equations can be given.

$$\frac{dm_{tj}}{dt} = f_t \frac{C_t L_{tj}}{v_j}[\frac{2k}{k-1} p_j v_j (\varepsilon^{\frac{2}{k}} - \varepsilon^{\frac{k+1}{k}})]^{1/2} \tag{2}$$

$$\frac{dm_{lj}}{dt} = f_r \frac{2C_r H}{v_j}[\frac{2k}{k-1} p_j v_j (\varepsilon^{\frac{2}{k}} - \varepsilon^{\frac{k+1}{k}})]^{1/2} \tag{3}$$

The pressure ratio ε is defined as following:

$$\varepsilon = \begin{cases} \frac{p_{j+1}}{p_j} & , \text{ if } \frac{p_{j+1}}{p_j} \geq (\frac{2}{k+1})^{\frac{k}{k-1}} \\ (\frac{2}{k+1})^{\frac{k}{k-1}} & , \text{ if } \frac{p_{j+1}}{p_j} < (\frac{2}{k+1})^{\frac{k}{k-1}} \end{cases} \tag{4}$$

2.3 Heat transfer model

The heat transfer influences the energy flowing in and out of chamber and influences the working process of scroll expander. Because of the temperature gradient of expansion process, the heat transfer occurs between different chambers. The heat depends on the air temperature in adjacent chambers and the geometric parameters of expander. The heat transfer process is described by following (Gu *et al.,* 1998):

$$\frac{dQ}{dt} = \left(\frac{1}{\alpha_1} + \frac{b}{\lambda} + \frac{1}{\alpha_2} \right)^{-1} A\Delta T \tag{5}$$

$$\alpha = 0.023 \frac{\lambda}{D} Re^{0.8} Pr^n \tag{6}$$

2.4 Mechanical model

The rotation of scroll expander is driven by the air force which includes the radial air force, the axial air force and the tangential air force. The rotating speed is decided by the driving force and the resistance force. The high pressure air flowing into center chambers pushes the orbiting scroll rotation. With the increase of rotating speed, the pressure in chamber and the air force change at the same time. When the driven moment is equal to the resistance moment, the air would not accelerate the orbiting scroll and the rotating speed keeps invariant. The rotary moment describes by following equation.

$$M_d = \frac{r}{2} aH \sum_{i=1}^{N} \left[4(i-1)\pi + 2\theta \right] (p_i - p_{i+1}) \tag{7}$$

2.5 Generator model

The generator coupled with scroll expander could transform the mechanical energy into electric energy. The power could be used for electrical apparatus such as storage battery, the motor, and other electric loads. The electric load influences the rotating speed of generator and scroll expander. When the relation between voltage and rotating speed of generator has be given, the resistance moment depends on the voltage, the resistance, the efficiency and rotating speed of generator which can be expressed by following equation.

$$M_l = 9.549 \frac{U^2}{nR\eta_g} \tag{8}$$

The driving and resistance moment influence the rotating speed of scroll expander. The moment of inertia depends on the geometric parameter of orbiting scroll, shaft, and rotor of generator. The rotating speed increases when the driving moment is larger than resistance moment, while the rotating speed decreases when they have the opposite relation. It could be described by following equation.

$$\left(M_d - M_l\right) = J\beta \tag{9}$$

3. RESULTS AND DISCUSSION

The starting procedure of scroll expander is affected by a lot of factors, such as the suction and discharge pressure and temperature, the leakage and heat transfer of the expander, the geometric parameters of expander and generator, the resistance of electric load and so on. In order to describe the starting procedure of scroll expander, a mathematic model has been built to analyze the variation of transient rotating speed, stable time, final rotating speed affected by the starting time. The calculation condition is shown in following table.

Table 1 Parameters of calculation condition

Parameter	Value
Suction pressure(kPa)	500-700
Suction temperature(K)	323.15
Discharge pressure(kPa)	100-200
Electric resistance(Ω)	15-38
Environment temperature(K)	283.15

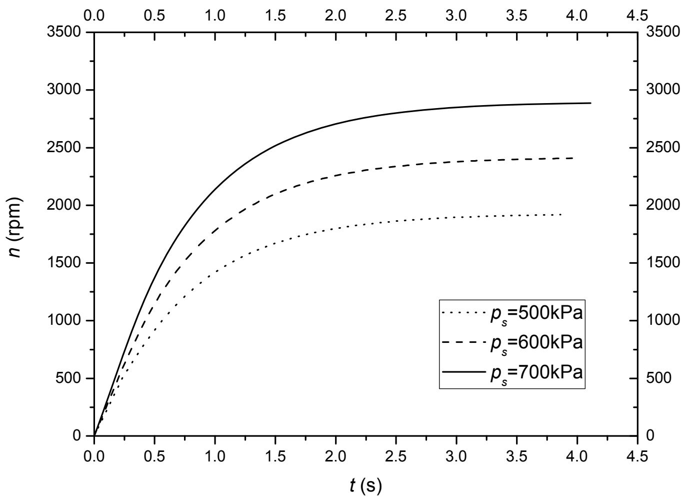

Fig.2 Starting procedure of scroll expander

Fig. 2 shows the variation of rotating speed in the starting procedure when the suction pressure is 500-700kPa, the electric resistance is 30Ω and the discharge pressure is 100kPa. When the high pressure air flows into the center chamber, the driven moment increases suddenly but the resistance moment is almost invariant because of the inactive orbiting scroll. The large difference of driven and resistance moment leads to the large rotational acceleration and the rotating speed increases rapidly. With the increase of rotating speed, the generator and electric resistance start to work and the resistance moment increases gradually. Although the rotational acceleration increases still, the increment decreases. When the driven moment is equal to the resistance moment, the rotating speed reaches the final value and the starting procedure is finished. The leakage and heat transfer occurs in all the process. When the rotating speed is instable, the pressure and temperature in chambers are varying and the leakage and heat transfer change also. When the starting procedure finishes, the values keep invariant. Because of the fluctuation of air force, the rotating speed periodically changes but the variable quantity is small when the rotating speed is stable.

Fig. 3 shows the effect of suction pressure on the stable time and final rotating speed when the discharge pressure is 100kPa and the electric resistance is 30Ω. The suction pressure determines the driven force of air. The scroll expander could recover more energy from air and get the larger rotating speed when the suction pressure is large, but it need the more time to stable at the same time. According to the figure, the stable time and final rotating speed increase with the increase of suction pressure. With the suction pressure increasing from 500 kPa to 700 kPa, the stable time increases from 3.86 s to 4.11 s and the final rotating speed increases from 1919 rpm to 2887 rpm correspondingly.

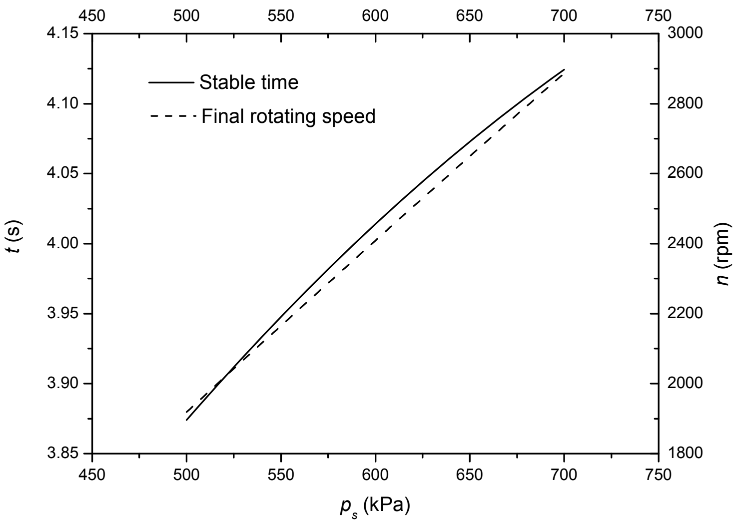

Fig.3 Stable time and final rotating speed vs. suction pressure

Fig. 4 shows the variant of stable time and rotating speed influenced by the discharge pressure. When the discharge pressure increases, the pressure difference between intake port and exhaust port decrease. Therefore the effect of discharge pressure on the starting procedure is opposite comparing to the suction pressure. The stable time and final rotating speed decreases with the increase of discharge pressure basing on the simulation. With the discharge pressure increasing from 100 kPa to 200 kPa, the stable time decreases from 4.01 seconds to 3.70 seconds and the final rotating speed decreases from 2011 rpm to 1682 rpm correspondingly.

Fig. 5 shows the influence of electric resistance on the starting procedure. The electric resistance provides different resistance moment for the generator and expander. With the increasing of electric resistance, the resistance moment decreases and the scroll expander could reach higher rotating speed. The electric resistance could also be used to control the rotating speed of scroll expander and generator. With the increasing of electric resistance from 15Ω to 38Ω, the stable time increases from 2.20 s to 4.97 s and the final rotating speed increases from 1304 rpm to 2961 rpm.

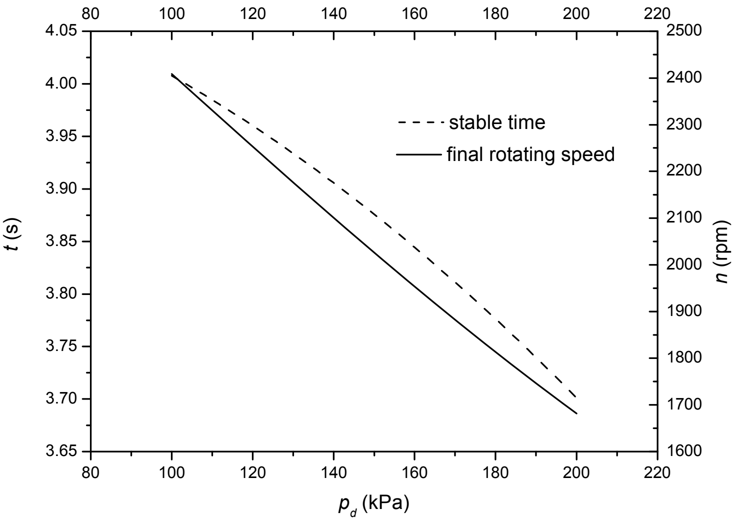

Fig.4 Stable time and final rotating speed vs. discharge pressure

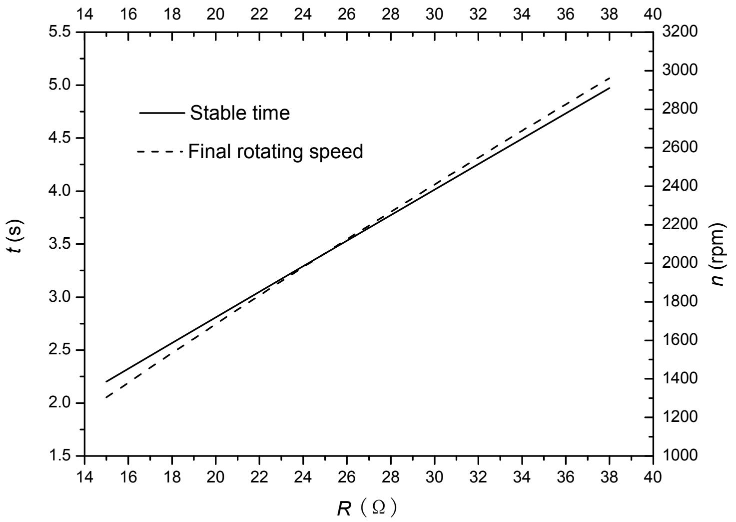

Fig.5 Stable time and final rotating speed vs. electric resistance

4. CONCLUSION

In order to simulate the starting procedure of scroll expander, a mathematic model has been built. The effects of suction pressure, discharge pressure and electric resistance have been analyzed. The following conclusions have been gotten.

- The starting procedure of scroll expander is influenced by the suction and discharge conditions, the geometric parameters and the characteristic of generator. The rotating speed increases rapidly at the beginning of starting procedure and then the increment decreases until the rotating speed is stabilized.
- The stable time and final rotating speed increase with the increase of suction pressure. With the

suction pressure increasing from 500 kPa to 700 kPa, the stable time increases from 3.86 seconds to 4.11 seconds and the final rotating speed increases from 1919 rpm to 2887 rpm.

- The stable time and final rotating speed decrease with the increase of discharge pressure, With the discharge pressure increasing from 100 kPa to 200 kPa, the stable time decreases from 4.01 s to 3.70 sand the final rotating speed decreases from 2011 rpm to 1682 rpm.
- The stable time and final rotating speed increase with the increase of electric resistance. With the increasing of electric resistance from 15Ω to 38Ω, the stable time increases from 2.20 seconds to 4.97 seconds and the final rotating speed increases from 1304 rpm to 2961 rpm.

NOMENCLATURE

a	Radius of basic circle (m)	t	Time (s)
A	Area (m^2)	T	Temperature (K)
b	Thickness of scroll (m)	U	Voltage (V)
c_v	Specific heat ($kJ.kg^{-1}.K^{-1}$)	v	Specific volume ($m^3.kg^{-1}$)
C	Clearance (m)	V	Volume (m^3)
D	Equivalent diameter (m)	α	heat transfer coefficient($W.m^{-2}K^{-1}$)
f	Flow coefficient	β	Angular acceleration ($rad.s^{-1}$)
h	Specific enthalpy ($kJ.kg^{-1}$)	η	Efficiency
H	Height of scroll (m)	θ	Rotation angle (rad)
J	Rotation inertia ($kg.m^2$)	λ	Thermal conductivity ($W.m^{-1}K^{-1}$)
k	Expansion index	**Subscripts**	
L	Length of clearance (m)	d	Driven
m	Mass of air (kg)	i	Flowing in
M	Moment (N.m)	j	Number of chamber
n	Rotating speed (rpm)	l	load
p	Pressure (Pa)	o	Flowing out of
Q	Heat (W)	r	Radial
R	Electric resistance (Ω)	t	Tangential

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