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PERFORMANCE PREDICTION AND TEST RESULT OF A ROLLING PISTON TYPE COMPRESSOR

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ABSTRACT

This paper describes the theoretical and experimental analysis used to evaluate the performance of rolling piston type compressor. Thermodynamic properties of refrigerant in compression chamber are theoretically analysed using simple thermodynamic model which consists of 3-step processes that are adiabatic compression process, isochoric heat transfer process and leakage process. Also based upon this model, the coefficients of heat transfer for compression process are obtained by experimental results of a specially installed test compressor.

INTRODUCTION

Generally two approaches have been used for the performance analysis of rotary compressors and modeling the thermodynamic behavior of the working fluid. One is polytropic process model and the other is the 1st law of thermodynamics model. In order to see the internal gas properties in compression chamber, it is necessary to study kinematic motion of compressor, leakage with oil flow and heat transfer etc.. But it is difficult to calculate its properties by theoretical analysis.

In case of the polytropic process model with constant polytropic index n , some deviations occur between computation and corresponding experiment. Some experimental investigations show that polytropic index n varies with rotating angle of rolling piston, operating condition and geometry of compressor. It is too complicated to model and calculate the influence of several parameters on compression process and to do parametric study on its factors. So to gain a better description of the thermodynamic behavior of rotary compressors, many models about heat transfer during the compression process have been presented by applying the 1st law of themodynamics. In most of these papers, the heat transfer model was made by an assumption, that is, heat transfer was proportional to the product of heat transfer area and temperature difference between cylinder wall and gas. But it is difficult and complex to evaluate a proper heat transfer coefficient according to the boundary condition such as oil film and leakage and to describe the accurate situation of compression chamber under the operation.

The purpose of this paper is to present a model which can describe the compression process including the heat transfer, leakage and geometric effect of inner cylinder. In this model, real compression process is assumed to be divided into three simple independent processes. The first step of this model is adiabatic compression process with no heat transfer and no leakage. The second step is heat transfer process from/to cylinder wall with no volume change and no leakage. The last step is leakage process without heat transfer and volume change. In order to get the P-V diagram, valve motion and heat transfer coefficient, pressure and temperature were obtained at the suction pipe, compression chamber, plenum and cylinder while the test compressor was operated by calorimeter under the standard condition.

ANALYTICAL MODELING

Suction process

Mass flow between suction pipe and suction chamber is assumed to be nozzle flow. Mass flow rate per unit area, $\dot{g}$, is

$$\dot{g}=\sqrt{\frac{2k}{k-1}\,\rho_u\,P_u\left(\frac{P_d}{P_u}\right)^{\frac{2}{k}}\left\{1-\left(\frac{P_d}{P_u}\right)^{\frac{k-1}{k}}\right\}} \qquad (1)$$

Then mass flow rate $\dot{m}$ through suction port and suction pressure, Ps, are written as follows.

$$\dot{m}=A_{eff}\,\dot{g} \qquad (2)$$

$$P_s=mRT_s \qquad (3)$$

Compression process

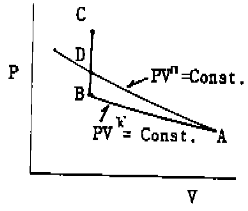

Fig 1. 3 Step Model

To obtain the pressure,temperature and other properties at a certain time, following model is used. From the known P(t) and T(t), P(t+Δt) and T(t+Δt) after an infinitesimal time Δt is caculated by next 3 steps.

1. A → B : adiabatic compression process
2. B → C : heat transfer process at isochoric condition
3. C → D : leakage process

This model which consists of 3 steps is applied over entire range of compression.

1. Adiabatic compression step.

Now the step from point A to B is assumed to be compression process with no heat transfer and no leakage. Then pressure and temperature at point B are

$$T_B=T_A\left(\frac{V_A}{V_B}\right)^{k-1} \qquad (4)$$

$$P_B=P_A\left(\frac{T_A}{T_B}\right)^{\frac{k}{k-1}} \qquad (5)$$

2. Isochoric heat transfer step

Heat transfer occurs between refrigerant and peripheral area of compression chamber. Actually temperature of that area is not constant with crank angle because temperatures of cylinder wall, roller, vane and cylinder head vary with time and also oil in the cylinder affects heat transfer. But in this paper, representative wall temperature Tw is assumed to be a time-independent constant as average value. Under the assumption of isochoric heat transfer process from point B to C, increment of internal energy is equal to heat flux $\dot{Q}$ between heat transfer area and refrigerant.

$$mC_v(T_C - T_B) = C_h A (T_w - T_B)\Delta t \qquad (6)$$

From equation (6) ,Pc and Tc are calculated.

3. Leakage step

From point C to D,leakage occurs between high pressure region and low under isochoric condition. Leakage flow is calculated under the assumption of nozzle flow.

$$\dot{m} = C_d A_l \sqrt{\rho_c^2 \left(\frac{P_s}{P_c}\right) \frac{2k}{k-1} R T_c \left\{ 1 - \left(\frac{P_s}{P_c}\right)^{\frac{k-1}{k}} \right\}} \qquad (7)$$

After leak occurs, the mass and specific volume of point D are written as

$$m_D = m_C - \dot{m}\Delta t$$

$$v_D = \frac{V_D}{m_D}$$

Using above equations, T and P are evaluated.

Properties of final state D after 3 step process (A-B-C-D) are equivalent to those obtained by polytropic process (A-D).

Discharge process

The behavior of valve system is assumed to be 1 DOF. Then the valve dynamic equation is written as follows.

$$M_v\,(dx/dt)^2 + C\,(dx/dt) + K\,x = A_f\,(P_p - P_c) \qquad (8)$$

Discharge mass is calculated from the valve displacement and mass flow rate equation.

EXPERIMENT

The purpose of this experiment is to extract the factors which are needed for the analytical modeling. In this experiment, following factors are measured:

1. crank angle measurement
2. suction pressure in suction chamber
3. compression pressure in compression chamber
4. discharge pressure
5. valve displacement
6. cylinder wall temperature
7. shell cavity pressure
8. suction gas temperature
9. discharge gas temperature

To measure the above experimental factors accurately,the original rotary compressor of household refrigerator was modified. Fig.2 describes the experimental apparatus. Table 1. shows the running condition used for the experiment. With the results which were measured under the steady state operating condition, the pressure-volume diagram in compression chamber was obtained. This P-V diagram is shown in Fig.3.

APPLICATION RESULT

In the application of 3 step model,several ways of application can be considered. It is possible to change the order of each step or to use constant or variable heat transfer coefficient during the compression process. Changing the order of leakage step and isochoric heat transfer step after adiabatic compression step was negligible. And for the coefficient of heat transfer, Ch , constant value was applied to the model at first. Also the variable Ch using experimental data of pressure signal in the compression chamber was extracted. At each crank angle Ch was reversely obtained by applying the experimental pressure signal to 3 step model.

1.Simulation result with constant Ch

Ch is not constant through the crank angle because of the varying heat transfer area, flow condition of gas and the effect of oil etc.. But constant Ch was taken regardless of angle. Appropriate value of constant Ch was taken from considering the previously announced result of papers [1,2,3,4]. In the Fig.4,5,6,7,8,9 crank angle starts from 40° and ends before the angle of valve opening. Suction port position is at 40° and compression process is mainly dealt with. Fig.4 shows pressure-volume diagram at Ch=100 W/(m^2*K). From this it is known that the ascent is not so steep at the beginning of compression compared with Fig.3,experimental P-V diagram. So it gives less work than experiment. And valve opening time is delayed a little also. Fig.5 shows the change of mass of gas in a compression chamber before discharge.Mass in the control volume decreases with angle , because of leakage which is very little compared with discharge mass as well known. From Fig.6 the change of specific volume in the compression chamber is shown. Specific volume decreases rapidly before valve opening. And Fig 7 shows the rise of gas temperature with angle.

From the above results, it can be known that the P-V diagram which is obtained by simulation with constant Ch gives about 10 % error for the prediction of work,as shown in Fig.3, 4. And changing Ch a little does not affect much the trend of underestimated compression work and delayed valve opening time. So 3 step model is not suitable for the prediction model if constant Ch is used.

2.Reverse extraction of Ch from experiment

Ch can be reversely extracted from the application of experimental pressure data to the 3 step model proposed. The values of Ch and temperature varying with angle from experimental data are obtained. Pressure and specific volume are known from experiment and previous step, so temperature can be obtained at a heat transfer step. Next,Ch can be calculated from eq.(4). Fig.8 shows gas temperature reversely extracted from experimental pressure signal. Ch does not ascend smoothly. And it shows very sharp peaks but gives the trend of nearly linear rising,that is different from Fig.7 which shows parabolical trend. Fig.9 shows the relation between heat transfer coefficient Ch and angle and also has very steep peaks. So obtained values are too high compared with real physical values. In the vicinity of 120° very high values are obtained. Because gas temperature is nearly equal to wall temperature in the neighbor of 120°. It can be known from eq. (4). The sharpness of temperature and Ch may be attributed to the pulsating experimental pressure data.

If pressure increases smoothly before valve opening, more accurate result may be obtained. It may be proposed to curve-fit pressure data obtained from experiment. With the curve-fitted pressure data smoother and exact temperature and Ch may be obtained. By the parametric study on Ch for the wall temperature and angle,3 step model may be more useful for the prediction of compression work. The above 3 step model makes it easy to obtain heat transfer coefficient approximately only if P-V diagram, wall temperature and thermodynamic properties of suction gas are given by experiment.

CONCLUSION AND DISCUSSION

1. In the compression process, thermodynamic properties of refrigerant such as temperature and pressure in the compression chamber were obtained by using the constant heat transfer coefficient Ch. But the result was not recommendable.

2. By applying this model approximate Ch can be obtained easily from P-V diagram, wall temperature and suction condition given by experiment.

3. In order to apply this model effectively to the prediction of temperature and pressure in compression chamber, it would be recommended to use curve-fitted Ch from experimental data rather than to use constant value of Ch.

4. Ch and temperature are affected much sensitively by the experimental pressure data -angle. For the application of 3 step modeling to obtain Ch and temperature , exact relation between experimental pressure data and angle is very important. So it is important to get the reference angle than usual.

ACKNOWLEDGEMENT

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NOMENCLATURE

$\dot{g}$	mass flow rate per unit area	k	specific heat ratio
ρ	density	P	pressure
T	temperature	Aeff	effective flow area for suction
$\dot{m}$	mass flow rate	V	volume
v	specific volume	Cv	isochoric specific heat capacity
$\dot{Q}$	heat transfer	Tw	wall temperature

Ch	heat transfer coefficient	Cd	leak coefficient
Al	effective leak area	R	gas constant
Mv	mass of valve	C	damping coefficient
x	valve displacement	K	spring constant
Af	effective force area		

SUBSCRIPTS

u	upstream	d	downstream
s	suction	c	compression
p	plenum		

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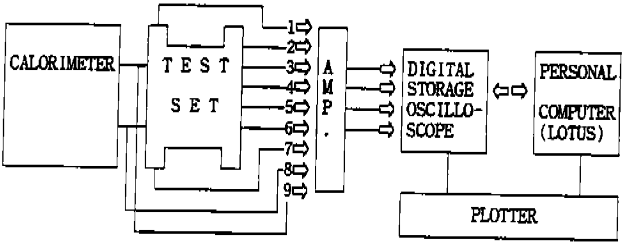
TABLE 1. Operating Condition

Operating Condition	
Suction Pressure(Ps)	0.1 Kgf/㎠(G)
Suction temperature	32 ℃
Discharge pressure(Pd)	9.0 Kgf/㎠(G)
Input Voltage	220 Volt
Input Frequency	60 Hz
Refrigerant	R12



1:Crank angle measurement
2:Suction pressure measurement
3:Compression pressure measurement
4:Discharge pressure measurement
5:Valve displacement measurement
6:Cylinder wall temperature
7:Shell cavity pressure
8:Suction temperature
9:Discharge temperature

Fig.2 EXPERIMENTAL APPARATUS

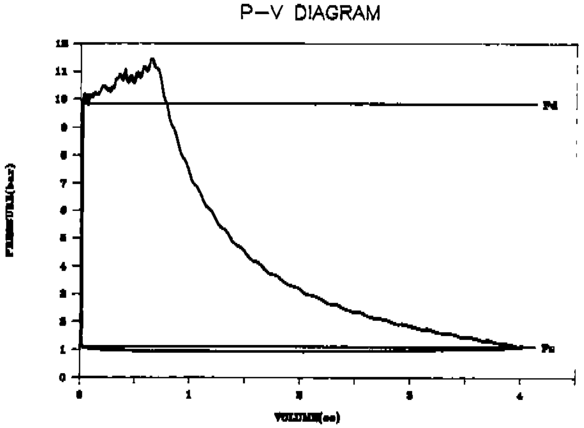


Fig.3 Pressure-volume diagram from experiment

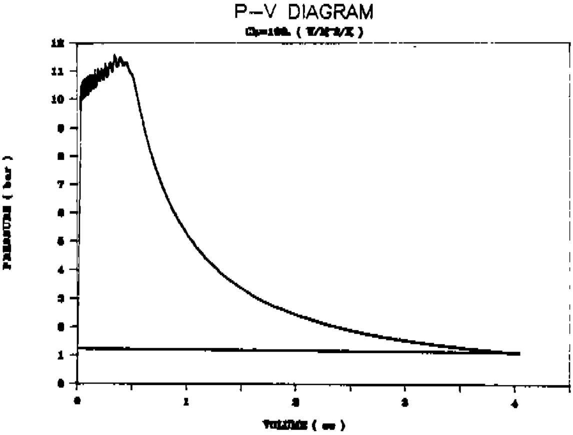


Fig.4 Pressure-volume diagram for the constant Ch

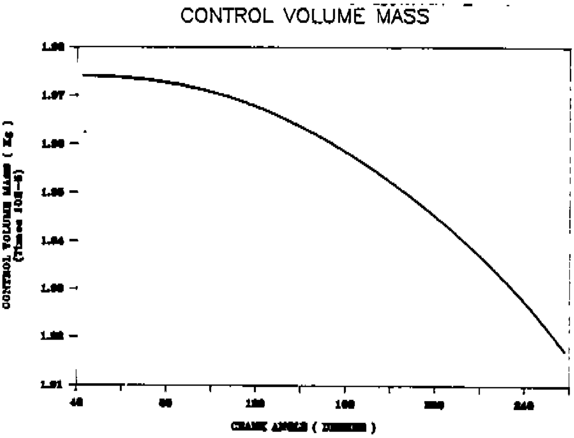


Fig.5 Mass of compression gas for the constant Ch

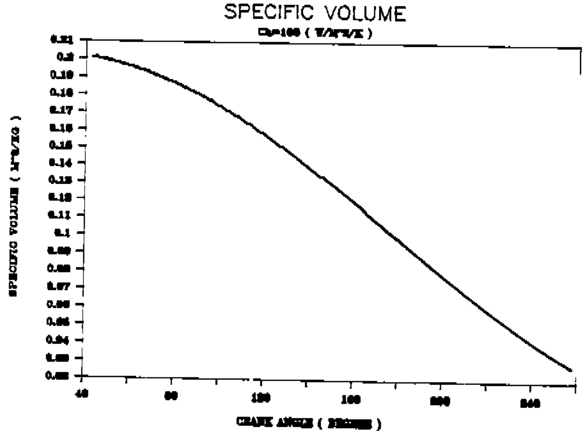


Fig.6 Specific volume in compression chamber for the constant Ch

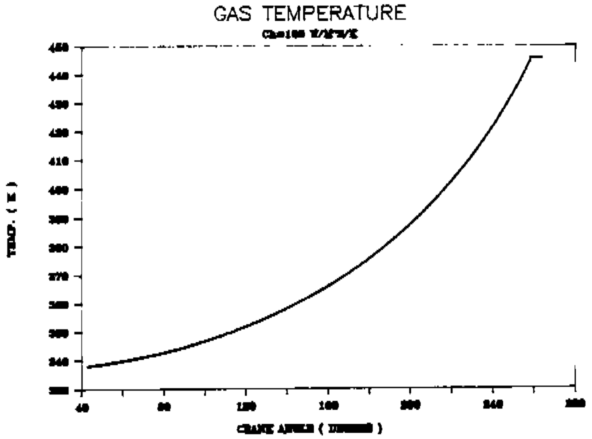


Fig.7 Compression gas temperature for the constant Ch

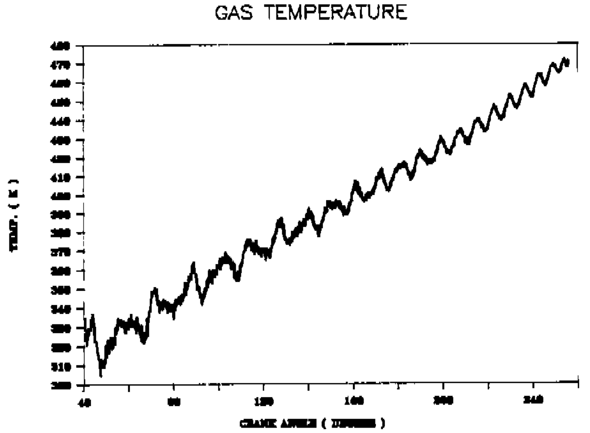


Fig.8 Gas temperature reversely extracted from experiment

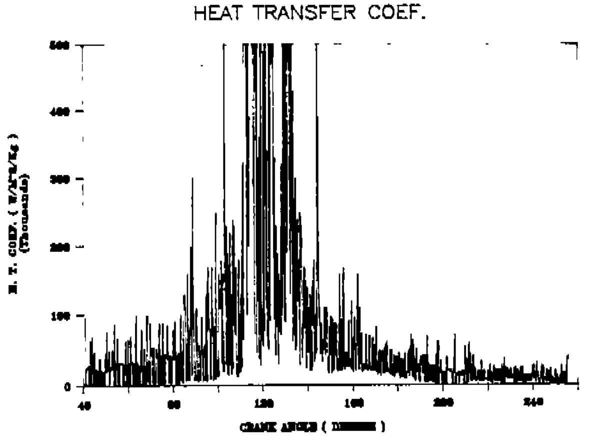


Fig.9 Heat transfer coefficient reversely extracted from experiment