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Prediction of Leakage Flow of Radial Clearance in a Rolling Piston Rotary Compressor

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ABSTRACT

The functional formula of the flow coefficients for the radial clearance in a rolling piston rotary compressor was developed by the experiments and Computational Fluid Dynamics (CFD) to improve the accuracy of a compressor simulation program. The experiments and CFD simulation were conducted to obtain the flow coefficients at the radial clearance under the assumptions of incompressible flow and steady state. The experiments were carried out with the variation of pressure ratio and low upstream pressure using the nitrogen as a working fluid. The CFD simulation was adopted to calculate the flow coefficients at the radial clearance with change of the radial clearance and high upstream pressure. The results of CFD calculation were compared with the experimental results for verifying the reliability of CFD simulation. The functional formula obtained from the results of the CFD calculation was applied to compressor performance simulation for calculating the leakage flow through the radial clearance. The results of compressor simulation with the functional formula showed tolerable errors with the experimental data of the compressor calorimeter in terms of EER (Energy Efficiency Ratio). Thus, the function of the flow coefficients may be acceptable for prediction of leakage through the radial clearance under the various conditions.

1. INTRODUCTION

A rolling piston type rotary compressor has been widely used as a core component in the air-conditioning and refrigeration system. This is mainly due to the advantages like design simplicity, compactness, light weight, low cost and high performance. However, the steep rise in concern for energy conservation and environmental problem demanded the development of a higher efficiency compressor. Among the influenced factors for performance of the rolling piston type rotary compressor, the refrigerant leakage is very important from the point of view of volumetric efficiency. Especially, the leakage through the radial clearance constitutes the major contributions (Pandeya, P and Soedel, W. 1978).

Previous researches show that the leakage through the radial clearance has been calculated using simplified model. This model was applied to calculate the leakage through the radial clearance and predict the performance of a rolling piston rotary compressor.

The base model for predicting the leakage in the radial clearance is the incompressible flow of a gas through a convergent divergent nozzle with isentropic flow. This isentropic model has been applied to calculate the mass flow rate through the radial clearance.

In order to consider the fluid friction loss, several researches modeled this case of leakage assuming compressible flow of pure refrigerant gas. Yanagisawa and Shimisu (1985) designed the radial clearance between the rolling piston and the cylinder wall as a convergent nozzle and a straight friction channel. This paper suggests the general flow coefficient (0.3) to calculate the mass flow rate in the radial clearance. Ian H. Bell et al (2013) studied leakage through the radial clearance by applying the frictional correction term to the isentropic nozzle model with the Reynolds number.

Furthermore, previous researches established model of mass flow rate through the radial clearance with oil-refrigerant mixture (Ferreira, R.T.S et al., 1984), (Dias, J.P. et al, 2011), (Gasche, J.L. et al, 2012). The flow models of these researches are good to predict the mass flow rate through the radial clearance, but these of model were relatively complicated to apply to compressor simulation and insufficient consideration for operating condition of compressor. B.C. Min et al (2014) developed the simple functional formula of flow coefficient for a discharge valve system with consideration about diameter of discharge port and lift height of the discharge valve to simplify the prediction for the mass flow rate in the discharge valve system for simulating the performance of compressor.

In this work, the functional formula of the flow coefficients at the radial clearance was derived from experiments and CFD simulation under a wide range of operating conditions and developed for simplifying the application to compressor simulation. The comparison between functional formula and 0.3 (Yanagisawa and Shimisu (1985) for predicting mass flow rate through the radial clearance was done with the simulation of compressor performance. Consequently, functional formula of the flow coefficient could be helpful to predict the performance of a compressor for various operating conditions.

2. NUMERICAL ANALYSIS

In this paper, the model of mass flow rate through the radial clearance can be described by the simple orifice flow. The flow through the radial clearance is assumed as the isentropic and one-dimensional flow. Eq. (2) and Eq. (3) were used to calculate the mass flow rate through the radial clearance. The mass flow rate through the nozzle can be classified into two divisions with criteria of the critical pressure ratio as Eq. (1). At first, when the pressure ratio is bigger than the critical pressure ratio, mass flow rate is calculated by using the Eq. (2) under the no-choke condition. However, when the flow reaches choke condition, Eq. (3) is used to calculate the mass flow rate through the radial clearance.

$$P_{cr} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (1)$$

For $P_{cr} < P_d/P_u$

$$\dot{m} = C_v P_u A \sqrt{\frac{2k}{(k-1)RT_u} \left[\left(\frac{P_d}{P_u} \right)^{\frac{2}{k}} - \left(\frac{P_d}{P_u} \right)^{\frac{k+1}{k}} \right]} \quad (2)$$

For $P_{cr} \geq P_d/P_u$

$$\dot{m} = C_v P_u A \sqrt{\frac{k}{RT_u} \left(\frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}}} \quad (3)$$

C_v is flow coefficient in each equation. The major influence factors for the actual mass flow rate are presented as the flow area, pressure and temperature condition in this equation. To develop the functional formula of flow coefficient, these factors were considered.

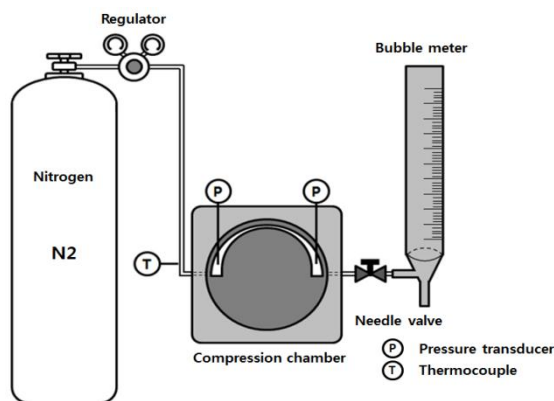


Figure 1: Schematic diagram of experimental set-up

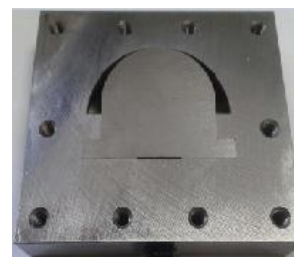


Figure 2: Compression chamber simulator

3. EXPERIMENTAL SET-UP

The experiment variables were determined based on the equation of the isentropic nozzle flow. Figure 1 and Figure 2 show the experimental apparatus used to measure the mass flow rate, pressure and temperature through the radial clearance. The roller is fixed in the cylinder to maintain the gap of clearance, δ . The radial clearance is confirmed by clearance gauge and SEM (Scanning Electron Microscope). The side of top and bottom in cylinder is packed by using the hard sheet packing. A. Levy (1964) investigated accuracy of bubble meter according to the range of mass flow rate. Since the mass flow rate under the 1 L/s was measured within 1% error, the mass flow rate was measured by bubble meter in this experiment. The upstream pressure was controlled by using the regulator with the pressure transducer. And, the downstream pressure was controlled by using the needle valve with the pressure transducer. The ambient temperature was not changed during the experiments. Nitrogen is used as a working fluid.

4. CFD SIMULATION

In this study, CFD simulation was done as a tool to investigate the mass flow rate through the radial clearance. Since the width of the radial clearance is quite small (typically, 10-60 μ m), it is difficult to measure the actual area and mass flow rate in this experiment. Therefore, CFD simulation was conducted using Fluent 14.5 to obtain the mass flow rate with various operating conditions. Table 1 shows the conditions of CFD simulation. Figure 3 shows geometry of radial clearance. In order to make the pipe flow fully developed, the length of pipe was sufficiently long.

5. RESULTS AND DISCUSSION

5.1 Validation of CFD simulation

The CFD simulation results were compared with the experimental results to validate the reliability. In the condition of high upstream pressure (30 bar), the measurement of mass flow rate with the bubble meter may have large uncertainty. Thus, the validated CFD simulation under the condition of low upstream pressure was used for predicting the flow coefficient through the radial clearance. Figure 4 shows the comparison results of mass flow rate at the radial clearance with variable upstream pressure condition. The maximum error of comparison result is within 10%, when the upstream pressure is upper than 8 bar. Although the maximum error of mass flow rate is 10%, the difference of mass flow rate is near the 0.01 g/s in the each case.

The mass flow rate through the radial clearance obtained by CFD simulation has acceptable reliability for applying to prediction of the mass flow rate through the radial clearance.

Thus, the mass flow rate through the radial clearance under the various operating conditions was obtained by the CFD simulation. The functional formula is derived from the results of CFD simulation.

Table 1: Conditions for the CFD simulation

| | |
|---------------------------|-----------------------------|
| | Incompressible steady-state |
| Viscous model | Realizable k-ε model |
| Inlet boundary condition | Pressure inlet |
| Outlet boundary condition | Pressure outlet |



Figure 3 Geometry for the CFD simulation

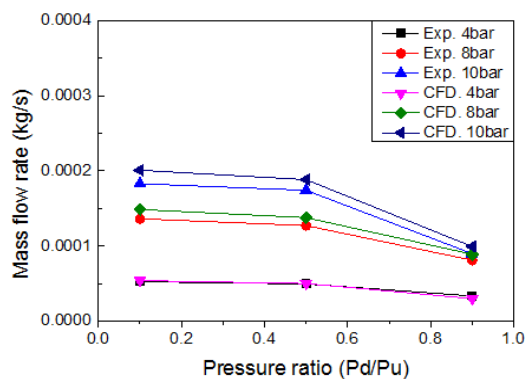


Figure 4 Comparison of mass flow rates from experimental and CFD simulation

5.2 Functional formula of flow coefficients

The influence factors for determining the flow coefficient are area of radial clearance, pressure ratio and upstream pressure. Figure 5 shows the flow coefficient with a change of each influence factor. The trend of flow coefficient is directly proportional to the width of radial clearance and upstream pressure. The rate of change of flow coefficient is different with choke condition. However, the flow coefficient is not affected by the height of radial clearance, even though the area of the radial clearance was changed. It seems that the effective area with the change of height in radial clearance has a linear correlation with the mass flow rate through the radial clearance.

Thus, the functional formula was developed by considering the width of radial clearance, upstream pressure and pressure ratio. Eq. (4) was derived from the results of CFD simulation to obtain the flow coefficients under the various conditions.

This equation of the flow coefficients was applied to compressor simulation in order to calculate the mass flow rate through the radial clearance. The mass flow rate was calculated by Eq. (2) and Eq. (3) with consideration of choke condition as Eq. (1). Where, P_r is the pressure ratio, w is the width of a radial clearance and P_u is the upstream pressure.

$$C_v = f_1(w) + f_2(w)P_{ub} + f_3(w)P_r + f_4(w)P_{ub}^2 + f_5(w)P_r^2 + f_6(w)P_{ub}P_r \quad (4)$$

$$f_n(w) = aw^4 + bw^3 + cw^2 + dw \quad (n = 1, 2, 3, 4, 5, 6) \quad (5)$$

Table 2: Constants for Eq. (5)

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|----------|----------|----------|----------|----------|----------|
| a | 1.7E-07 | -5.3E-08 | 3.1E-07 | 1.2E-09 | -1.5E-07 | 1.6E-09 |
| b | -2.0E-05 | 6.9E-06 | -3.2E-05 | -1.5E-07 | 1.2E-05 | -5.5E-07 |
| c | 6.1E-04 | -2.9E-04 | 8.3E-04 | 5.9E-06 | 1.4E-04 | 3.9E-05 |
| d | 7.E-03 | 4.8E-03 | 4.2E-04 | -8.9E-05 | -2.4E-02 | -6.0E-04 |

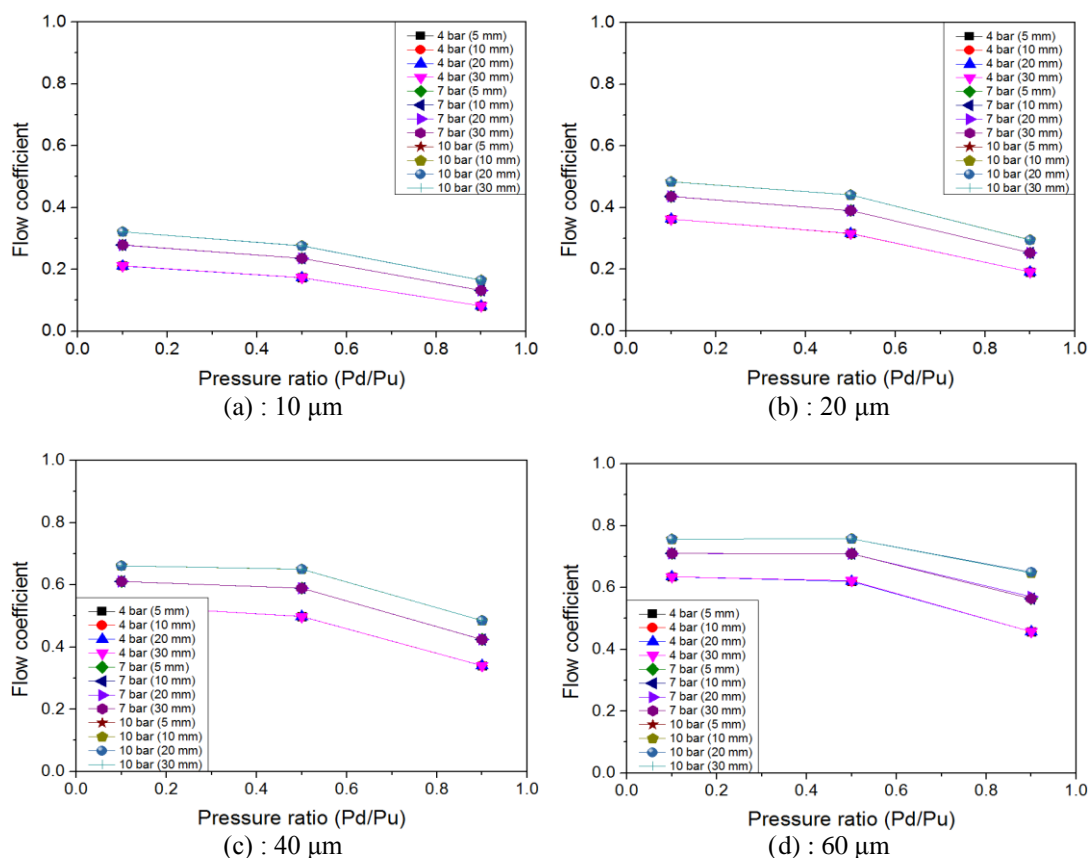


Figure 5 Flow coefficient in the radial clearance for each width of radial clearance

5.3 Application of functional formula to performance analysis of compressor

The compressor performance simulation with the functional formula was conducted the several operating conditions. This simulation data was compared with the results of simulation with $C_v = 0.3$ (Yanagisawa, T. and Shimisu, T., 1985) for calculating the mass flow rate and the results of calorimeter experiments. Table 3 shows the operating conditions and specifications of compressor for using in compressor performance simulation and experiments. Figure 7 shows the Energy Efficiency Ratio with varying operating conditions.

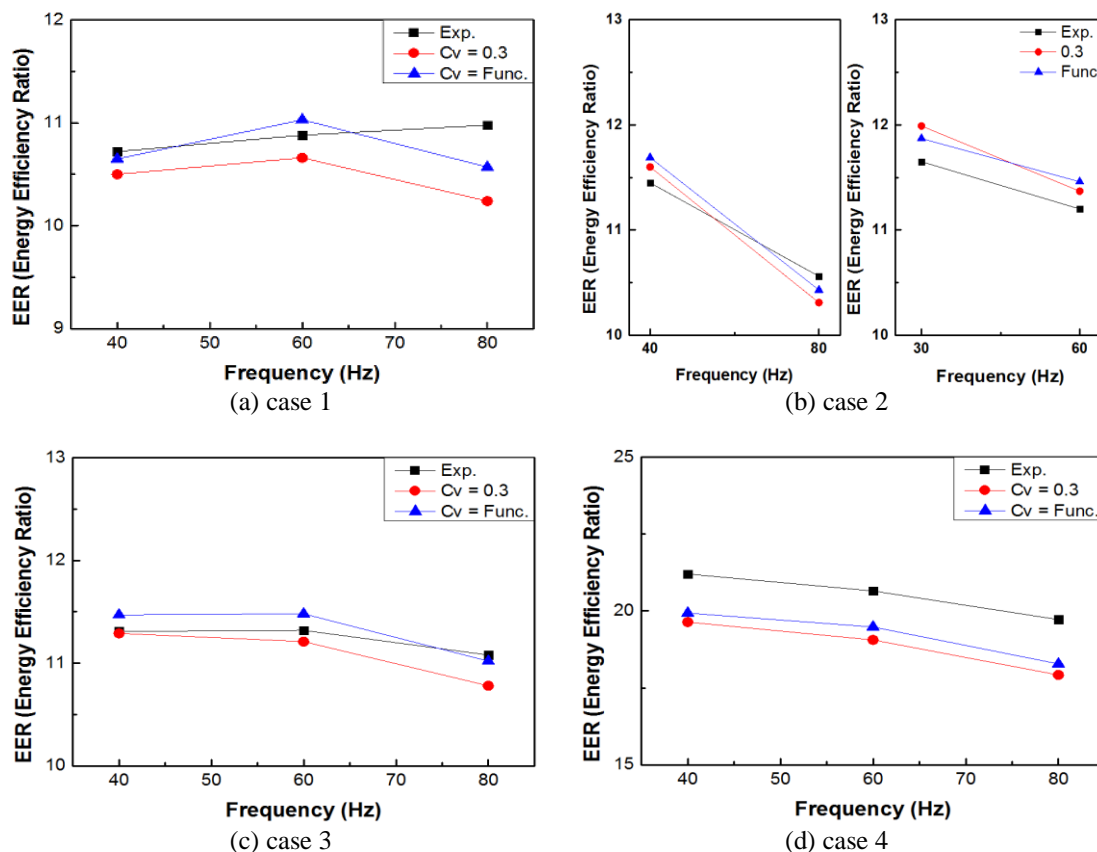
The comparison results of experiments and compressor performance simulation with the functional formula and 0.3 showed tolerable errors of 3 % in the case 1 and 3 except for 80 Hz condition. Since over compression in the compression chamber occurred the insufficient the leakage flow rate through the radial clearance, the results of high frequency of 80 Hz in the case 1, 3 have a higher error than 3 %. The simulation results applying the functional formula and 0.3 showed 3.7 % and 6.7 % errors respectively with comparison to results of experiment under the 80 Hz of operating condition.

In the case 2, the results of simulation with functional formula and 0.3 showed acceptable error of 3 % with the results of calorimeter experiments. The pressure ratio of case 4 is different from other case. The error between functional formula and 0.3 was upper than 5% under the various Hz condition. The simulation results applying the functional formula and 0.3 showed 7 % and 9 % errors respectively with comparison to results of experiment in the case 4. Although the compressor input power was increased with increase of the leakage through the radial clearance, it seems that the cooling capacity was more increased with the increase of the volume efficiency according to the compressor performance simulation.

The functional formula may be acceptable for predict the performance of compressor because that of equation considered for high upstream pressure and various width of radial clearance.

Table 3: Operating conditions and specifications of compressor for numerical simulation

| | Case 1 | Case 2 | | Case 3 | Case 4 |
|------------------------------------|---------------|---------------|----|-------------|-------------|
| Suction pressure (bar, absolute) | 9.95 | 9.95 | | 9.95 | 10.15 |
| Discharge pressure (bar, absolute) | 33.8 | 33.8 | | 33.8 | 23.37 |
| Capacity of Comp. (cc) | 10.2 | 24 | 42 | 14.1 | 14.1 |
| Comp. type | Single rotary | 2stage rotary | | Twin rotary | Twin rotary |

**Figure 6** The results of numerical compressor simulation

6. CONCLUSIONS

In this work, the flow coefficient through the radial clearance in the rolling piston type rotary compressor was functionalized with various operating condition. The results are summarized as follows.

The functional formula of flow coefficient ($= C_v$) in the radial clearance consist of the width of radial clearance, pressure ratio and upstream pressure. The range of flow coefficient is from 0.08 to 0.85 under the various width of radial clearance ($10 \mu\text{m} - 60 \mu\text{m}$) and upstream pressure (4 bar – 30 bar). When the width of radial clearance was the $20 \mu\text{m}$ with the various upstream pressure and height, the average value of flow coefficient was 0.3. But, flow coefficient was different from 0.3 under the various operating condition. The results of compressor performance simulation with the functional formula showed good agreement with the results of experiments.

The developed functional formula is helpful for predict the performance of compressor in the design process of novel compressor under the various operating condition.

NOMENCLATURE

| | | |
|-----------------|--|-------------------|
| A | Area of the radial clearance | (m ²) |
| C _v | Flow coefficient of the radial clearance | (-) |
| k | Specific heat ratio | (-) |
| \dot{m} | Mass flow rate | (kg/s) |
| P _{cr} | Critical pressure ratio | (-) |
| P _d | Downstream pressure | (Pa) |
| P _r | Pressure ratio | (-) |
| P _u | Upstream pressure | (Pa) |
| P _{ub} | Upstream pressure | (bar) |
| R | Gas constant | ((N*m)/(kg*K)) |
| T _u | Upstream temperature | (K) |
| w | Width of the radial clearance | (μm) |

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