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Yuan, Yikai; Wu, Jianhua; Yang, Jingtao; and Gao, Qiang, "Investigation on the Pressure Pulsation in the Discharge Muffler of Rotary Compressors" (2006). International Compressor Engineering Conference. Paper 1749.  
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Investigation on the Pressure Pulsation in Discharge Muffler of Rotary Compressors

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ABSTRACT

Gas pulsation in the discharge side of rotary compressor is one of the main sources of noise, so the discharge muffler is widely used to decrease the gas pulsation and noise level. Investigations on pressure pulsation in the muffler can provide not only a method to evaluate the muffler design and modification, but also a base for advanced study of noise in rotary compressor. In this paper the mathematical model of pressure pulsation in the muffler is built up by Helmholtz resonator approach and coupled with the valve dynamic model and thermodynamic model in the cylinder to simulate the gas pulsation. The pressure pulsation in various cavities of mufflers are calculated and analyzed in time and frequency domain, which shows pressure pulsation in outlet cavity is decreased much more than that in inlet cavity. Experiments are also carried out to prove that the calculation models are reliable.

1. INTRODUCTION

Room air conditioner (RAC) is widely used to make our lives comfortable; on the other hand it brings problems about energy and environment, for example the noise of rotary compressor.

Former experiment results have discovered that noise is generated as the compressed refrigerant is abruptly discharged into various spaces within rotary compressor, and with further frequency analysis pressure pulsation excited and acoustically amplified in various inner spaces is the major source of noise [¹]. Pressure pulsation in the discharge side can not only cause noise problem, but also affect the efficiency and reliability [²]. Usually rotary compressor is equipped with discharge muffler to decrease pressure pulsation and noise level. The section area is changing suddenly at several places in the flow direction of muffler, which can cause reflection and interference of pressure waves so that gas pulsation is attenuated. In the process of muffler design the first and key step is to investigate pressure pulsation in the discharge side, then estimate the natural frequency of the discharge system to avoid resonance [²]. Study of pressure pulsation in the discharge side can help engineers understand its mechanism and find effective ways to reduce it, and the most important is to provide a method to evaluate muffler design and modification.

2. PRESSURE PULSATION IN THE MUFFLER

2.1 Gas pulsation and discharge muffler

Discharge system of rotary compressor is shown in Figure 1. During each cycle of compressor operation, refrigerant gas in low pressure is charged into the cylinder, and compressed to a certain pressure that is large enough to make the valve open, then discharged out of the cylinder into the discharge muffler and the following discharge manifolds.
Since the discharge valve is intermittently open for a small fraction of time during compressor running, besides the valve plate is fluctuating, gas flow through the valve port is discontinuous. To the refrigerant gas in the discharge cavities, this intermittently discharged gas is an excitation source, so the gas pressure keeps oscillating as long as the compressor is running.

The reactive type muffler used in rotary compressor is shown in Figure 2, which is composed of several larger cavities and short necks. When the gas flow arrivals at the position where the section area is sharply changing, pressure waves in certain frequencies reflect which cause interference. This makes the gas flow out of the muffler smooth, namely the pressure pulsation is decreased. Thus the vibration and noise level of rotary compressor is attenuated.

2.2 Mathematic Model

Since the discharged gas flow is not constant, the effect of gas inertia to pressure pulsation must be taken into consideration. When building the mathematic model, quantity level of pressure oscillation and dimensions of cavities should be paid much attention to. To the muffler depicted in Figure 2, Helmholtz resonator approach is an appropriate choice, which has no restriction about the system’s configuration.

As is shown in Figure 3, basic model of Helmholtz resonator approach is composed of two parts: a volume and a short neck, which can be treated as a linear vibration system: gas in the volume is compressible and inertialess, like the spring; gas in the neck is incompressible, like a plug namely the mass element.

When using Helmholtz resonator approach, there are some assumptions should be considered [3][4].

1) Gas flow consists of two parts: one is average flow, another is pulsation flow; gas pressure is the superposition of a mean
pressure and an acoustic pressure;

2) Acoustic pressure is relative small compared to the mean pressure;

3) The dimensions should be smaller than 1/4 wavelength of the interested frequencies of sound.

Applying Newton’s second law to the gas in the neck

\[ L A \rho_0 \ddot{x} = \ddot{p} A - D \dot{x} \]  

(1)

where \( x \) is the displacement of the mass element, \( A \) is the cross section area, \( \rho_0 \) is the gas density, \( D \) is damping coefficient, and \( L \) is the effective length.

The acoustic pressure changes in the cavity can be written as

\[ \ddot{p} = \frac{a_0^2}{V} \int_0^t \dot{m} \dot{t} - \frac{a_0^2}{V} \rho_0 A \dot{x} \]  

(2)

where \( V \) is the volume of the cavity, \( a_0 \) is the sound velocity of refrigerant gas, \( \dot{m} \) is the mass flow rate into the cavity.

In Figure 4 there is the pump structure of a rotary compressor, which is double discharging type with two discharge mufflers. Discharged gas in the lower muffler flows through the axial holes in the cylinder to the upper muffler, then meets the discharged gas in the upper muffler and goes into the shell space together.

Because of the restriction imposed by main bear and bolts, the whole flow domain in the upper muffler is divided into 5 cavities and 5 necks. The lower muffler is the same as the upper one. Together with the two discharge ports in the main bear muffler and two holes in the cylinder, the resonator model of the discharge muffler system is built as a combination of 10 volumes and 14 necks as shown in Figure 5, which is a complicated vibration system with 14 degrees of freedom. “V_m” means the cavity and “n_m” means the neck, for example “n_13” and “n_14” refers to the discharge ports in the upper muffler.
For the convenience of solution, equation (1) and (2) is modified \([4]\). Parameter \(u = \dot{x}\) is used to take the place of parameter \(x\) in equation (1)

\[
LA\rho\ddot{u} = \ddot{p}A - Du
\]

where \(u\) is the velocity of the gas plug in the neck. Differentiating both sides of equation (2) yields

\[
\frac{dp}{dt} = \frac{\alpha_0^2}{V} \dot{m} - \frac{\alpha_0^2}{V} \rho_0 A \dot{x} = \frac{\alpha_0^2}{V} \dot{m} - \frac{\alpha_1^2}{V} \rho_0 A u
\]

Equation (3) is the governing equation of dynamic character of gas plug in the neck, and equation (4) explains relations between pressure change in the volume, mass flow rate into the volume and velocity of gas plug. Applying the above two equations to the resonator model depicted in Figure 5, then the governing equations set of pressure pulsation is set up.

Since the volume of single cavity in the muffler is so small compared with the shell spaces, pressure in the shell space is considered as constant. Namely in the resonator model in Figure 5, the pressure imposed on the outer side of “n14” and “n13” is unchangeable as the boundary condition for solution.

### 3. COUPLING SOLUTION

In the discharge process of rotary compressor, gas force due to the pressure difference between the cylinder and muffler pushes the valve open; on the other side, valve displacement and pressure difference affects the mass flow through the valve and vise versa. This interaction effect keeps continuing during the discharge process, so the gas pulsation model of muffler should be coupled with both the valve dynamic model and the cylinder thermodynamic model \([5]\), and all the differential equations have to be solved simultaneously.

### 4. EXPERIMENT TEST

Testing apparatus of pressure pulsation consists of two parts: pressure measurement and data acquisition. Pressure measurement parts is responsible for measuring and switching pressure signal to electrical signal; data acquisition parts is responsible for collecting and switching electrical signal to digital signal, then sending the digital signal to computer for data processing.

As is shown in Figure 6, pressure pulsation experiment apparatus consists of pressure transducer, signal amplifier, signal acquisition board and computer. In the experiment pressure transducers are mounted on the muffler to measure the pressure change in “V1” and “V10” shown in Figure 5, which are the cavities that are just on top of the valve ports, and Figure 7 is the actual assembling picture.
5. ANALYSIS OF EXPERIMENT AND SIMULATION RESULTS

The rotary compressor investigated in this paper uses R22 as refrigerant, and the experiment is carried out under the conditions $P_d=2.145$ MPa, $T_d=371$K, $P_s=0.624$ MPa, $T_s=291.5$K and the driving power is 220 V/50 Hz.

5.1 Comparison Analysis

Pressure pulsation measured in “V10” (in the main bear muffler) and “V1” (in the sub bear muffler) are compared with experiment ones and shown in Figure 8 and Figure 9 respectively.

![Figure 8: Pressure pulsation in V1](image)

![Figure 9: Pressure pulsation in V10](image)
When the discharge valve is open, refrigerant gas in “V1” or “V10” which is relative steady originally is excited and the pressure rises up sharply and quickly, and reaches the highest peak, then goes down as the valve closes gradually. When the valve closed completely, gas pressure keeps oscillating but decreasing until the valve opens again.

Applying FFT (Fast Fourier Transform) method to the results in time domain. Referring to the concept of sound pressure level in acoustic theory, pressure level of refrigerant gas is defined as $L_p = 20 \log \left( \frac{p}{P_{ref}} \right)$ (dB), where $P_{ref} = 2 \times 10^{-5}$ Pa. Then the results shown in Figure 8 and Figure 9 are transformed to the frequency spectra shown in Figure 10 and Figure 11 respectively.

From the above analysis, it is found that the simulated results agree reasonably well the experiment ones, which proves the Helmholtz resonator model reliable even though the discharge system is of such complicated configuration.

5.2 Simulated Results Analysis

To a well-designed muffler, its effects on pressure pulsation concentrates on two aspects: in time domain, pressure pulsation in outlet chamber is decreased than that in inlet chamber, and some fluctuation is disappear; in frequency domain, amplitude of pressure pulsation in high frequency band is decreased.
Pressure pulsation comparison between the inlet and outlet chamber reveals: in time domain, pressure pulsation in V6 is reduced much, especially the peaks; in frequency domain, around 1000 Hz the amplitude of pressure pulsation in V6 is decreased much more than in V10. From the acoustical point of view, the discharge muffler is actually a low pass filter, which prevents high frequency pulsation from transmitting through.

6. CONCLUSIONS

Helmholtz resonator approach is used to simulate the pressure pulsation in the discharge muffler of rotary compressor, and experiment results validate the mathematic model. In the discharge muffler, the pressure pulsation in outlet chamber is much decreased than in inlet chamber. Studies on the pressure pulsation carried out in this paper is an efficient method to evaluate the muffler design and modification.

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