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Volumetric Efficiency Improvement by Overflow in Rolling Piston Compressor

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ABSTRACT

In a compressor the existence of the clearance volume is inevitable, even rolling piston compressor is a kind of compact structure compressor, overflow is a method to decrease the effect of clearance volume. In this paper, the overflow design on a rolling piston rotary compressor is discussed, which uses the high-pressure gas in the clearance volume, and discuss its effect on the performance of a compressor by theoretical analyses. The result displays that the volumetric efficiency of the compressor with overflow is visibly higher than those of the conventional compressor in terms of the same operation and dimension parameters. The overflow has beneficial effect on miniaturizing the compressor.

1. INTRODUCTION

Rolling piston type rotary compressors are widely used in variant refrigeration systems including refrigerators, residential and automotive air conditioning systems due to many advantages (Hickman etal, 1984, Ooi, 2005, Yanagisawa, et al, 1985), such as, rolling pistons is more easily to design for operate at high speeds than reciprocating pistons, its structure is fit for compact compressor requirement and not too complicated for manufacture; the lubrication design in rolling-piston compressors can be brief and satisfactorily; rolling-piston compressors are quite tolerant of the entry of slugs of liquid. Therefore, with of compact structure, light weight, low cost and high performance, the rolling piston type rotary compressor is a good candidate used for mini vapor compression refrigeration system(Tothero, et al, 1978).

some volumetric compressors, such as piston compressor, screw compressor, scroll compressor and rotary compressor, the existence of the clearance volume is inevitable, especially in mini compressors, the ratio of clearance volume is larger compared with the conventional scale compressor because of the limitation of compact space and machining accuracy. Studies on the clearance volume have always been important in enhancing the capacity of compressors; such enhancements usually involve decreasing the clearance volume to as low a level as possible and reducing left gas in the space at the end of exhaust stroke.

In principle, the rolling piston type rotary compressor could employ good volume efficiency, however, the suction and export ports demands a certain volume in real design which is clearance volume in the compressor. Moreover, while minimizing the dimensions of compressor for mini cooling system, the rolling piston type rotary compressor is hard to keep high volume efficiency as same as common scale due to compact structure. The improvement of volumetric efficiency is helpful to increase the pumping capacity of a compressor, and to make compact compressor. Besides designing lower clearance volume, reducing the mass in the clearance volume in operation with overflow method (Wang, et al, 2012), the volume efficiency could be improve as well.

Therefore, in this paper, we focus on reducing the mass of the high-pressure gas left in the clearance volume to improve the performance of multi-cylinder compressor.

2. OVERFLOW IN COMPRESSOR

As shown in Figure 1, the 1–2–3–4–1 process represents the ideal thermodynamic cycle in a conventional compressor. The 3–4 is the expansion process, where the gas in the clearance volume expands approximately adiabatically, while its pressure continuously decreases with increasing volume until the gas pressure equals to or be lower than the intake pressure, the intake process 4–1 can occurs, therefore, the existence of the high-pressure gas in the clearance volume reduces suction capacity, resulting in a corresponding decline in pumping performance.

The overflow is served to decrease the mass in the clearance volume , if one chamber of the compressor is at the end of the exhaust process while one of the other chambers is at the end of the intake process or at the initial stage of compression process, the overflow can occur through a channel between the high pressure the clearance volume and the low pressure cylinder in suction.

In Figure 1, 1–1′–2′–3–3′–4′–1 presents the thermal process with overflow. The process 1–1′ represents the process mixing with the overflowed gas, the compression of the mixed gas, and exhaust are illustrated with 1′–2′ and 2′–3. State 3 represents the end of the exhaust process, where the exhaust valve is shut and the overflow begins. Thus, the gas pressure in the clearance volume rapidly drops, as illustrated by line 3–3′. 3′–4′ and 4′–1 show the expansion and intake.
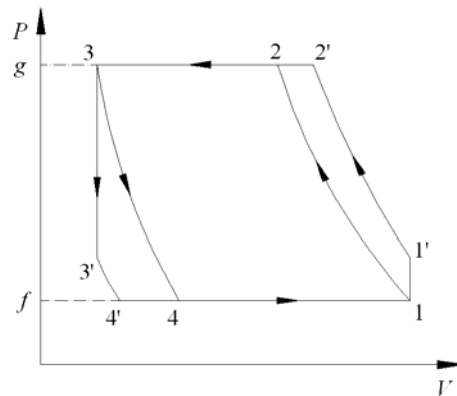

Figure 1   The P–V diagram of a compressor thermodynamic cycle (Zhang, et al, 2012)

2.1 Performance of Conventional Compressor

In principle, the volumetric efficiency of a compressor can be shown by the ratio of effective suction volume (V_e) to the cylinder displacement (V_h).

$$\eta_V = \frac{V_e}{V_h} = \frac{V_1 - V_4}{V_1 - V_3} = 1 - \frac{V_3}{V_1 - V_3}\left(\frac{V_4}{V_3} - 1\right) = 1 - \delta\left(\frac{V_4}{V_3} - 1\right) = 1 - \delta\left(\gamma^{\frac{1}{n}} - 1\right) \tag{1}$$

where δ is the relative clearance volume $V_3/(V_1 - V_3)$, γ is the pressure ratio P_2/P_1, n is the polytropic exponent.

In rela operation, the cylinder displacement of a compressor is calculated from the difference between the volume of the compression cylinder at the end of the compression process (V_2) and the volume of the exhaust cylinder at the end of the exhaust process (V_3),   if $\beta = V_3/V_1$,

$$V_d = V_1\left(\gamma\right)^{-\frac{1}{n}} - V_3 = V_1\left[\left(\gamma\right)^{-\frac{1}{n}} - \beta\right] \tag{2}$$

2.2 Performance of Compressor with Overflow

The volumetric efficiency of the compressor with overflow can be expressed as

$$\eta_V' = \frac{V_e}{V_h} = \frac{V_1 - V_{4'}}{V_1 - V_3} = 1 - \frac{V_3}{V_1 - V_3}\left(\frac{V_{4'}}{V_3} - 1\right) = 1 - \delta\left(\frac{V_{4'}}{V_3} - 1\right) = 1 - \delta\left(\varphi^{\frac{1}{n}} - 1\right) \tag{3}$$

where $\varphi = \dfrac{\gamma\beta + \chi^{1-n}}{\chi + \beta}$, χ is the ratio of the volume of the compression cylinder at the end of overflow to the maximum volume, V1'/V1.

The ratio of volumetric efficiencies with the compressor with overflow and the conventional compressor can be got by Eq. (1) and (3).

The cylinder displacement of the compressor with overflow is increased, and the ratio of cylinder displacements with the compressor with overflow and the conventional compressor,

$$\frac{V_d'}{V_d} = \frac{\chi\left(\varphi\gamma^{-1}\right)^{\frac{1}{n}} - \beta}{\left(\gamma\right)^{-\frac{1}{n}} - \beta} \tag{4}$$
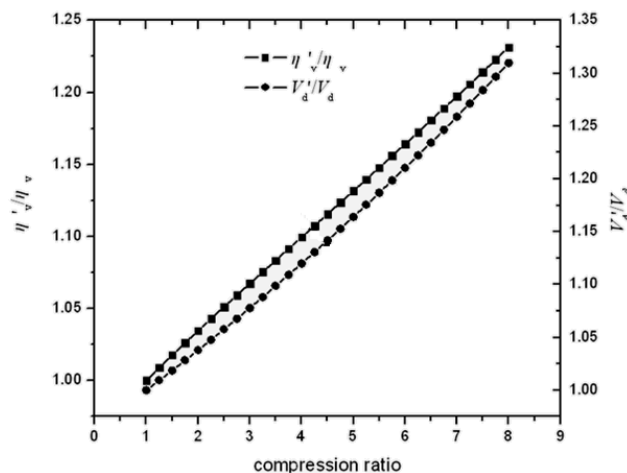

Figure 2 Variation of performance with the compression ratio

Theoretically, the volumetric efficiency decreases with raised compression ratio, the trend of performance drop could be eased by reducing the clearance volume.

Assuming that the relative clearance volume is about 5%, the ratios of volumetric efficiencies and cylinder displacements between the compressor with overflow and the conventional compressor without overflow gradually increase with the increase in compression ratio as shown in Figure 2, the volumetric efficiency and the cylinder displacement improve by about 23% and 31% respectively at compression ratios of 1 to 8.

The analysis results show that the overflow design has a considerable effect on the volumetric efficiency and the cylinder displacement of the compressor, especially at a large compression ratio or relative clearance volume.

3. CLEARANCE VOLUME IN ROLLING PISTON ROTARY COMPRESSOR AND OVERFLOW STRUCTURE

In a rolling piston type rotary compressor, such as in Figure 3, the roller mounted on the eccentric shaft, and a single vane reciprocating moved in the non-rotating cylindrical housing, the sliding vane separates the working cavity into two crescent shaped chambers: a low pressure and a high pressure chamber, each volume varies with the rolling eccentric shaft, the low pressure chamber undergoes expansion and suction, and the high pressure chamber undergoes compression and discharge, the rolling piston compressor completes one compression cycle operation every revolution.

In general, a suction pipe is directly connected to the cylinder suction port without suction valve, the suction process and the compression process is smooth, due to its structure, there is a small top clearance volume in the compression operation, and the volumetric efficiency of the rotary is small as well theoretically.

In real application, the suction and discharge structure and channel demand a certain space, specially for minimized cooling system, the channels or ports need be arranged between the cylinder block and the connecting tube outside of the compressor.
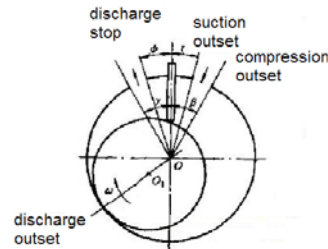

Figure 3 Diagram of a rolling piston rotary compressor

Suppose there is a mini rolling piston rotary compressor, its main geometry parameters are listed in Table 1, where the suction port is placed side plate as in Figure 3, the clearance rate is about 1.0%. R134a is employed for compression in the compressor, which serves for a refrigeration cycle, and the evaporation temperature is 5℃, and the condensation temperature is 50℃. If the suction gas has no superheat degree, and the local flow resistance at the suction and discharge ports is neglected, and there is not any leakage in the compressor, the pressure profile in a compression cycle is shown in Figure 4. In the initial stage, there is a narrow peak due to there is a small distance τ, then some gas is sucked in the chamber, and compressed gradually, once the roller reach a certain angle the chamber is greater than the discharger pressure, compressed gas begin to be pushed out from the discharger port, after the roller rotates over the discharger stop, some gas left in the chamber is compressed theoretically.

Table 1 Parameters of the compressor

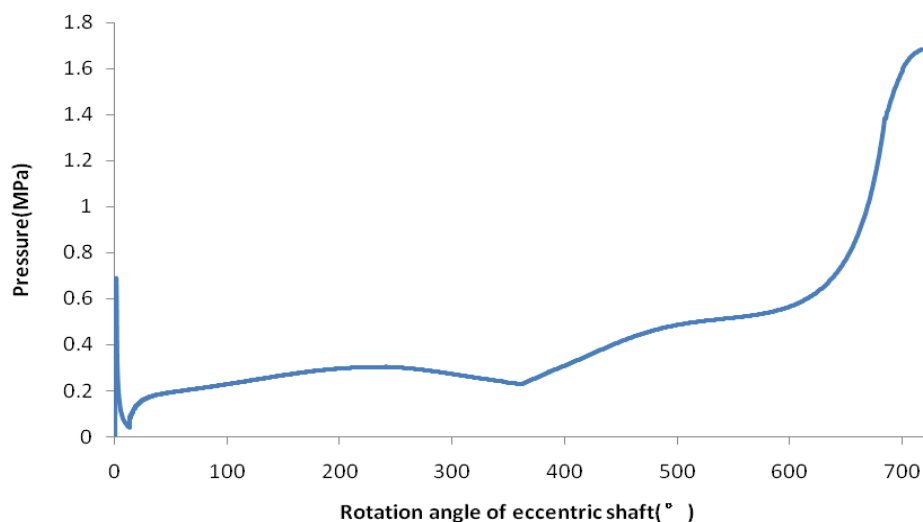| Cavity radius	12mm	Roller radius	10mm
Cavity thickness	11mm	Vane thickness	3mm
Suction port radius	2.5mm	Discharge port radius	1.5mm
Suction port volume	96mm^3	Discharge port volume	80mm^3
Cylinder displacement	14315mm^3	Clearance volume	150mm^3

Figure 4 The pressure Profile in a compression cycle

The overflow process is leading some gas to flow from the high pressure chamber to the low pressure chamber in a certain rotating angles. So we could design a special structure on the sliding vane to connect the high pressure chamber, such as in Figure 5, a related structure could be designed on the side plate to connect the suction chamber, once the slide vane reach the top and the discharge process is close to the end, the special channel on the vane and the related pit on the side plate can be connected, that is, the discharge chamber and the suction chamber are connected, and some gas in the clearance volume leaks to the suction chamber.
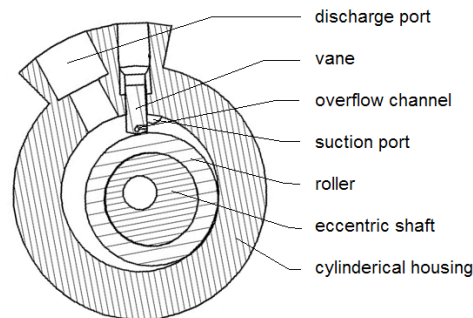

Figure 5 Diagram of a compressor with overflow structure

Suppose the compressor operates in a refrigeration cycle with evaporating temperature 5℃, and condensing temperature 50℃, in Figure 6, the P-V diagram for the compression cycle has be displayed, it is apparent that the compression process is under higher pressure in a cycle with overflow than in a cycle without overflow, that is, the compressor could provide more compressed gas in a cycle. The low pressure zone before suction process is due to the rest space between the outset of suction and the apex point (stop of discharge). Since the area in the P-V diagram equals to the work to compress the gas in a cycle, the work consumed in a cycle with overflow is greater than the work in a common cycle without overflow.
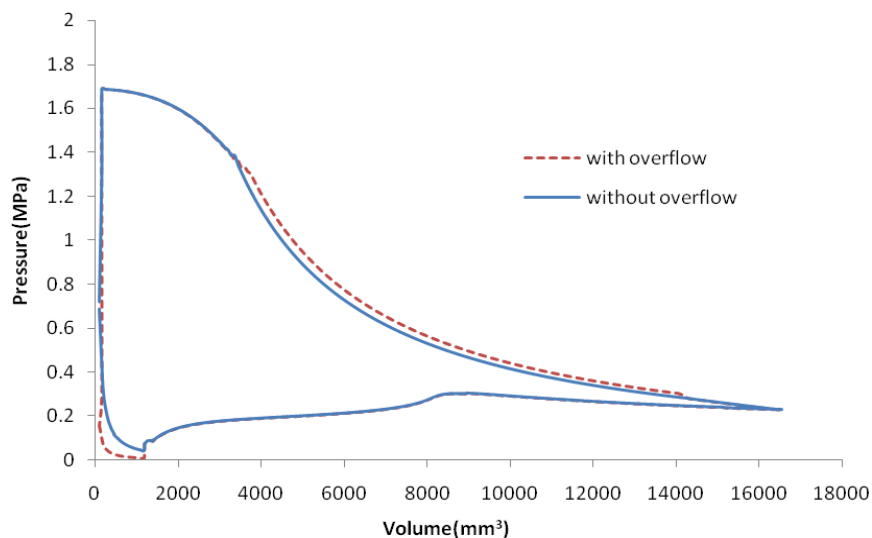

Figure 6 P-V diagrams in a compressor with and without overflow at 1.0% clearance rate

4. VOLUMETRIC EFFICIENCY OF ROTARY COMPRESSOR WITH OVERFLOW

According to thermodynamic analysis, the volumetric efficiency tends to reduce with compression rate rising. Suppose that the compressor in Table 1 operates in a vapor compression refrigeration system with 5℃ evaporating

temperature, if the refrigeration system employs condensing temperature from 45℃ to 65℃, corresponding pressures are from 1.32MPa to 1.89MPa, and pressure ratios by the compressor are from 3.8 to 5.4. The clearance rate in Table 1 is about 1%.

In Figure 7, in common cycle operating without overflow, the volumetric efficiencies display apparent descending tendency with the increasing condensing temperature of refrigeration system, however, in the improvement cycle operating with overflow, the volumetric efficiencies almost are invariable. And the improvement rate of volumetric efficiency is from 6% to 10% in the calculation condition, where the clearance rate is about 1% according to Table 1. The volumetric efficiency is related closely to the cycle cooling capacity in a refrigeration cycle, the raised volumetric efficiency means raised refrigerant amount provided in a cycle, therefore, the overflow benefits for improving the cooling capacity of a refrigeration cycle.
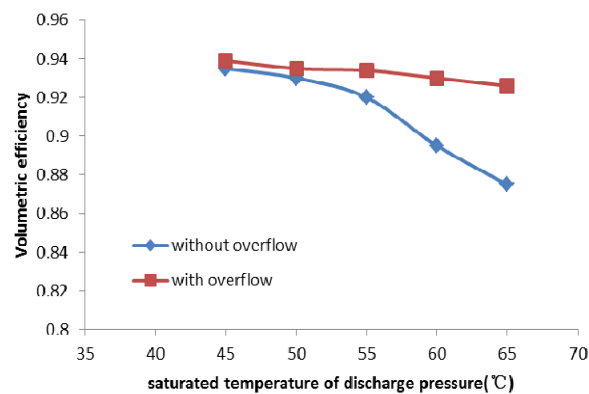

Figure 7 The volumetric efficiency varies with compression rate at 1.0% clearance rate

Figure 8 shows the effect on overflow in the rolling piston type rotary compressor with clearance rate 3.7%. The volumetric efficiency depends on clearance volume directly, if the suction port had to be placed on the cylindrical housing, the suction port would be 530mm^3, and the clearance rate would be 3.7%. The more the clearance, the sharper the volumetric efficiency decreases with high pressure boost in a compressor, however, the effect of overflow is more significant as in Figure 8, the improvement rate of volumetric efficiency is from 6% to 12% if the condensing temperature varies from 45℃ to 65℃.
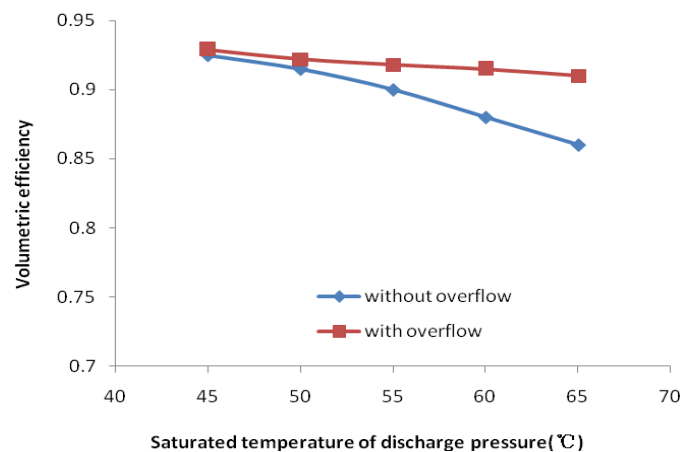

Figure 8 The volumetric efficiency varies with compression rate at 3.7% clearance rate

5. CONCLUSIONS

Overflow is a method to reduce the mass in clearance volume and improve the volumetric efficiency of a compressor. In a rolling piston type rotary compressor, the overflow is possible to realize by specially designed structure. Once the overflow is employed, the volumetric efficiency would be increased as well, especially in high pressure ratio operation, the more the pressure boost in compressor and the more the clearance rate, the more the improvement by overflow.

In this paper, based on the compressor and with pressure ratios 3.8 to 5.4 in this paper, the overflow could provide 6%-10% improvement rate of volumetric efficiency with 1% clearance rate and, and 6%-12% improvement rate of volumetric efficiency with 3.7% clearance rate.

NOMENCLATURE

V_d	Cylinder displacement without overflow	(mm^3)
V_d'	Cylinder displacement with overflow	(mm^3)
V_e	Effective suction volume in principle	(mm^3)
V_h	Cylinder displacement in principle	(mm^3)
V_1	The volume of the compression cylinder at the beginning of the compression process	(mm^3)
V_3	Volume of the exhaust cylinder at the end of the exhaust process	(mm^3)
V_4	Volume of the working cylinder at the end of the expansion process without overflow	(mm^3)
V_4'	Volume of the working cylinder at the end of the expansion process with overflow	(mm^3)
γ	Pressure ratio	
n	Polytropic exponent	
η_v	Volumetric efficiency of the rolling piston type rotary compressor without overflow	
η_v'	Volumetric efficiency of the rolling piston type rotary compressor with overflow	
δ	Relative clearance volume	

REFERENCES

Hickman,C., Neal, W.E.J., Implications of cooling rotary sliding vane heat-pump compressors, *International Journal of Ambient Energy,* 5 (4) (1984) 207-212.

Ooi, K.T., Design optimization of a rolling piston compressor for refrigerator, *Applied Thermal Engineering,* 25(2005), 813-829

Tothero, D.L., Keeney, D.F., A rotary vane compressor for automotive air conditioning applications, in: *International Compressor Engineering Conference.* Purdue University, 1978, pp. 226-232.

Wang W., Zhang, Y.L., Application of Overflow in Multi-cylinder Mini Compressor, *ICE 24-ICMC 2012*, May 2012. Fukuoka, Japan.

Yanagisawa, T., Shimizu, T., Leakage losses with rolling piston type rotary compressor. II. Leakage losses through clearance on rolling piston faces, *International Journal of Refrigeration,* 8 (1985), 152-158.

Zhang,Y.L., Wang, W., Efficiency enhancement in a meso Wankel compressor with overflow, *Proceedings of the Institution of Mechanical Engineers; Part C; Journal of Mechanical Engineering Science*, 2012. 226(6):1537–1554.

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