Experimental Study of Conical Rotary Compressor for High Pressure Ratio Applications

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Abstract The Conical Rotary Compressor (CRC) is a positive displacement machine characterized by internal meshing, variable pitch, and variable rotor profile. Compared to twin screw machines, the CRC has a shorter leakage line length, no leakage triangle, no discharge port, and co-directional thermal expansion, providing advantages when operating at high pressure ratios (Pi). Over-compression or under-compression can be avoided by matching external Pi with internal Pi, which depends on the volumetric index (Vi) of the CRC. However, higher Vi values lead to increased manufacturing complexity and cost. For this study, a CRC with Vi 6.8 was selected, and Vi was modified by reducing the inner rotor length from the discharge side. Experiments were conducted at five different Vi values (6.8, 5.8, 4.6, 4, and 3) with Pi varying from 11 to 41. The results showed that 75% isentropic efficiency and 95% volumetric efficiency were achieved at a pressure ratio of 21. The isentropic efficiency and volumetric efficiency remained higher than 45% and 75%, respectively, even at a pressure ratio of 41. Performance began to decrease when Vi was lower than 4, resulting in significant under-compression. The efficiency contour and Vi contour obtained from this study can be used for performance prediction and optimization of CRC design.

Keywords Conical rotatory compressor · Volume ratio · High pressure ratio · Experimental study

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Nomenclature

q	Diameter ratio (/)
wrap number	Number of rotations of outer rotor profile over length (/)
D1	Pitch diameter (mm)
L	Rotor length (mm)
omega	Cutting tool coefficient (/)
Vi	Volume ratio = $\frac{V\_suc}{V\_dis}$ (/)
Pi	Pressure ratio = $\frac{P\_out}{P\_in}$ (/)

1 Introduction

The transportation of natural gas through pipeline networks is an environmentally friendly and cost-effective method of delivery. However, in the past, natural gas was often wasted through flaring or venting during pipeline maintenance and construction, resulting in both financial and environmental losses. To minimize waste and pollution, natural gas can be recompressed back into the pipeline section or tanks. Typically, a Pressure Index (Pi) of 20–40 is required for this application, which can be achieved using high Volume Index (Vi) in Positive Displacement Machines (PDM) such as piston and twin-screw compressors. Nevertheless, it can be challenging to attain high Pi in a single stage due to leakage and high discharge temperatures in both piston and twin-screw compressors. Pi of twin screw compressor in one stage can reach up to approximately 15:1 with oil cooling [1]. High Pi could be achieved by multistage, but this will add complexity and cost to the system.

The Conical Rotary Compressor (CRC) is an innovative rotary compressor that utilizes a variable pitch and rotor profile to achieve high Vi, thereby improving performance at high Pi operating conditions. Its working mechanism, rotor profile design [2], and quasi one-dimensional chamber model [3] have been described. While chamber model analysis is effective for predicting PDM performance [4, 5], the leakage and heat transfer models need to be fine-tuned with experimental results to accurately predict high pressure ratio conditions. Choked flow can occur when the pressure ratio exceeds the critical pressure ratio, which is 0.53 for air. Computational Fluid Dynamics (CFD) is another powerful tool used for PDM performance prediction [6, 7]. However, both the chamber model and CFD require experimental validation to produce reliable results. This study conducted experiments to investigate the capability of the CRC with different Vi for high Pi applications. The performance of the CRC with five different Vi (3, 4, 4.6, 5.8, and 6.8) at Pi between 11 and 41 was evaluated to aid the selection of suitable Vi for different Pi applications.

Table 1 Suction chamber volume and Vi changing with design parameters

Parameters	Symbol	V_suc	Vi
Cutting tool	$omega$	Increase	Constant
Diameter ratio	q	Decrease	Increase
Wrap number	$Lambda$	Decrease	Increase
Pitch diameter	$D1$	Increase	Constant
Rotor length	L	Increase	Constant

2 Rotor Design

The design of CRC rotor profile and its geometry calculation has been explained [2]. In this section, the suction chamber volume and Vi of the CRC are analyzed based on the design parameters. Five different Vi values are selected, and the rotor length is calculated accordingly. Additionally, the sealing line length, a key factor in performance, is quantified for all five cases.

2.1 Rotor Geometry

Seven parameters are defined for CRC rotor design, which are lobe combination, pitch diameter, variable or constant pitch type, cutting tool coefficient, wrap number, rotor length and diameter ratio. Table 1 shows suction chamber volume and Vi changing with design parameters. Geometrical parameters such as suction chamber and discharge volume, volume index, sealing line length can be calculated with in-house software VertSim [2].

Normalized chamber volume is calculated with changing of rotational angle as shown in Fig. 1. The working process of CRC consists of suction, compression and discharge. Because the rotor pitch and rotor diameter decrease along the rotor length, the chamber volume decreases with the rotational angle. Around 50% suction chamber volume is sacrificed because suction chamber is not closed at the point maximum chamber volume reached. Therefore, it is necessary to design suction and discharge port plates to further increase suction chamber volume and Vi.

2.2 Vi Calculation

As shown in Table 1, Vi is only dependent on diameter ratio and wrap number. The relationship between Vi, diameter ratio and wrap number are illustrated by Fig. 2. Vi increases with increasing wrap number and diameter. At wrap number 1.5, Vi is equal to diameter ratio. Any of the three parameters can be interpolated from the known two parameters.

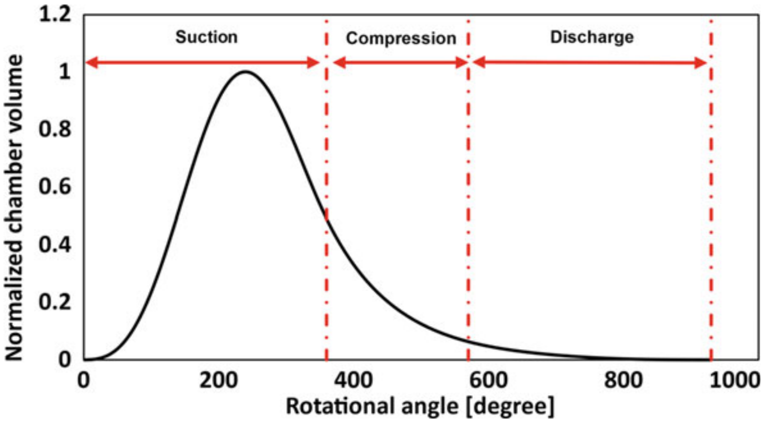

Fig. 1 Normalized chamber volume changing with rotational angle

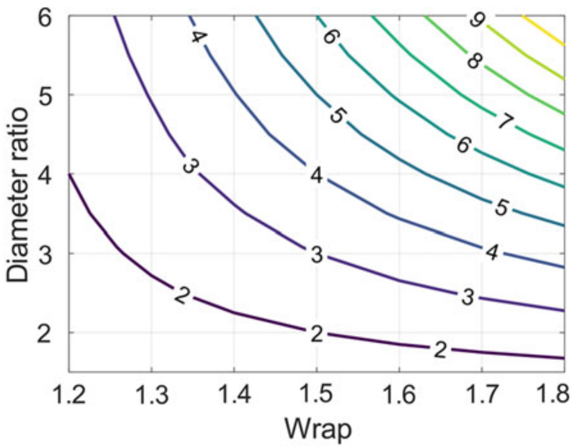

Fig. 2 Vi contour

For the convenience of this experimental study, instead of making new pair of rotors with different Vi, inner rotor was reduced in length from discharge end. Discharge chamber volume increases with reducing the inner rotor length while suction chamber volume stays the same. In this way, Vi decreases with a shorter inner rotor. The relationship between Vi and rotor length is shown in Fig. 3. Five Vi cases were selected for this test, which were 3.0, 4.0, 4.6, 5.8 and 6.8.

In this study, Vi is calculated without considering oil volume fraction which also occupied the chamber volume. Therefore, Vi could be higher when running with high oil volume flow rate. For example, Vi could increase from 6.8 to 8.0 with oil flow rate of 5 lpm. This will not be introduced here considering the length of this paper.

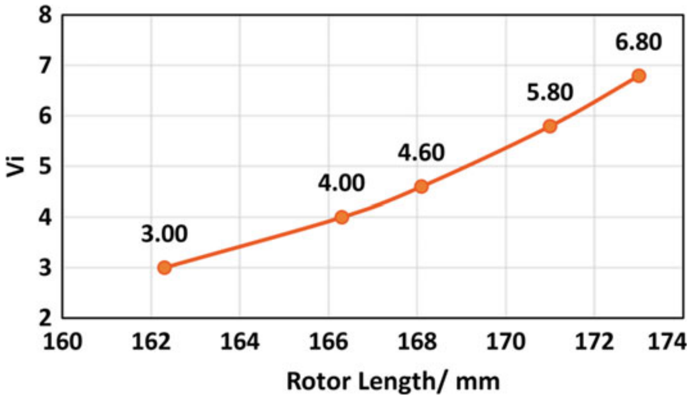

Fig. 3 Vi changing with rotor length

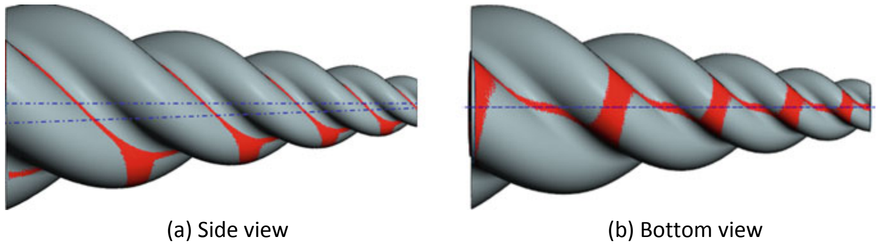

Fig. 4 Contact band between inner and outer rotor with enlarged inner rotor surface

2.3 Sealing Line Length

Leakage can negatively impact the performance of CRC. Sealing line should be continuous between inner and outer rotor and as short as possible. CRC has two types of leakage paths which are axial path and radial path. The contact band is amplified by offset inner rotor surface as shown in Fig. 4. Continuous sealing lines are formed between inner and outer rotors and the sealing line length between chambers is decreasing along rotor length.

Six leakage paths were defined as shown in Fig. 5. Considering $C1$ is the control chamber, which can connect with maximum six neighbor chambers. Discharged side paths C12, C22 and C3 have a more significant effect on volumetric efficiency and isentropic efficiency.

The discharge side sealing line length of C12, C22 and C3 are calculated for five different Vi cases as illustrated by Fig. 6. The leakage line length increases with the decreasing of Vi.

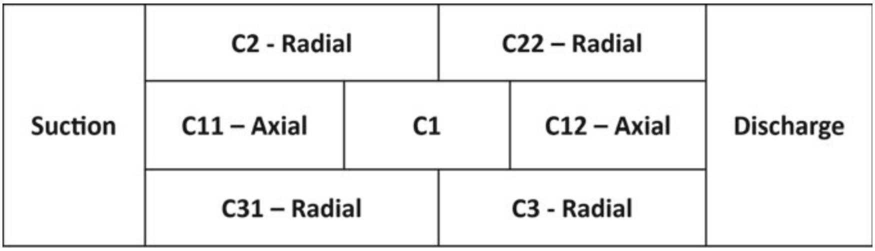

Fig. 5 Leakage paths

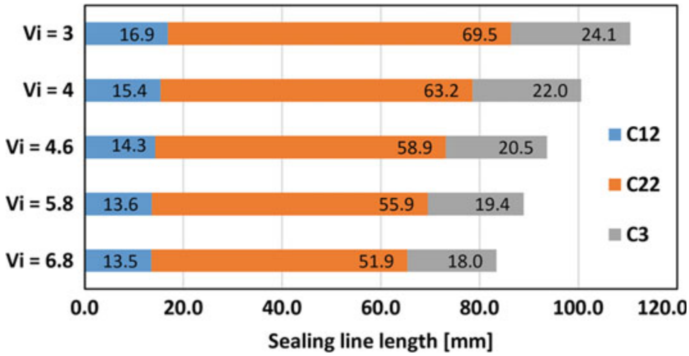

Fig. 6 Leakage line length comparison

3 Experimental Results

An experimental study of conical rotary compressor for high Pi applications is presented in this session. In theory, optimal performance of positive displacement machine is reached when internal Pi matches with external Pi. External Pi is defined as discharge pressure over suction pressure and internal pressure ratio for air testing is calculated based on Vi as $Pi_{internal} = Vi^{1.4}$. However, the internal pressure ratio could be higher than theory because of internal leakage. The experimental parameters explored consists of Pi and Vi. The pressure ratio is varied between 11 and 41 and the Vi is varied between 3 and 6.8.

3.1 Test Rig

The test rig schematic is outlined in Fig. 7. Same CRC is used for the test which starts from initial Vi of 6.8. CRC with Vi of 5.8, 4.6, 4 and 3 is modified by reducing the length of inner rotor. Air volume flow rate is measured at compressor suction side. Discharge pressure is regulated with pressure relief valve, symbol 15. In the

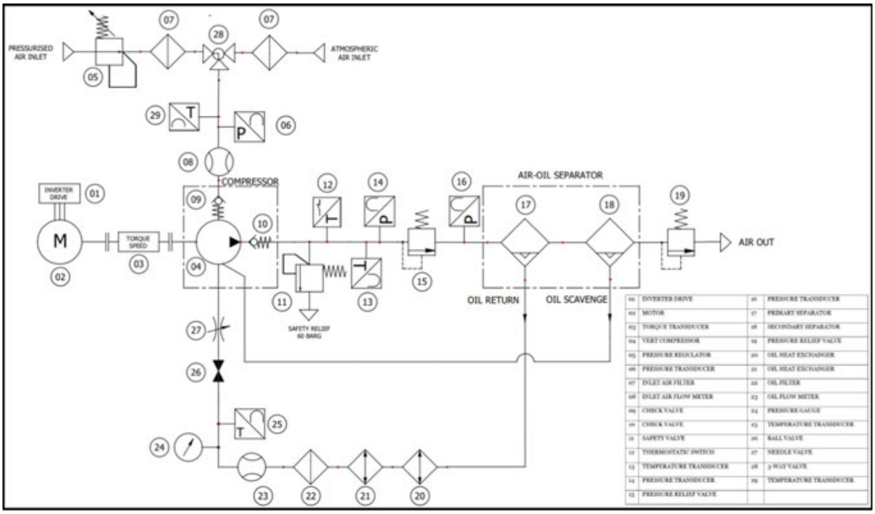

Fig. 7 Test rig schematic

Table 2 Operating condition

Parameters	Unit	Value
Speed	rpm	3000
Suction pressure	barG	0
Discharge pressure	barG	10–40
Suction temperature	K	288
Discharge temperature	K	333–363
Oil injection temperature	K	313
Oil flow rate	lpm	3–5

meantime, torque, oil flow rate, oil injection pressure and discharge temperature are measured.

The operating conditions are presented in Table 2. Suction pressure is atmosphere pressure. Discharge pressure sweep tests were operating from 10 to 40 barG. Oil injection flow rate is from 3 to 5 lpm and temperature is 313 K.

3.2 Performance Comparison of CRC with Different Vi

Volumetric efficiency and isentropic efficiency varying with discharge pressure are compared for CRC with Vi of 3, 4, 4.6, 5.8 and 6.8 as shown in Fig. 8. Both volumetric efficiency and isentropic efficiency have optimal operating point which are 97.52% and 76.98% respectively at around 20 barG.

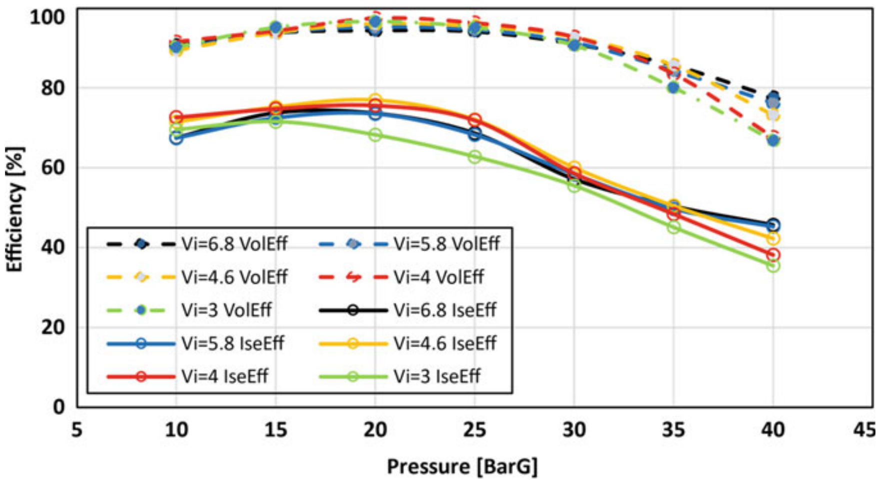

Fig. 8 Efficiency changing with discharge pressure

For isentropic efficiency, when discharge pressure is lower than 35 barG, Vi of 4.6 is better than other cases. Vi of 3 has the lowest performance because of under-compression. Vi of 5.8 and 6.8 cases have lower efficiency comparing with lower Vi case when discharge pressure is lower 30 barG. As discussed in Sect. 2.3, cases with higher Vi values have shorter sealing line lengths, which typically results in better sealing. Therefore, lower efficiency in cases with high Vi values is possible for over-compression to occur. Vi of 5.8 and 6.8 cases only have better efficiency after 35 barG.

For volumetric efficiency, all cases have comparable values higher than 90% at pressures below 30 barG. Volumetric efficiency drops quickly after 30 barG and higher Vi have higher volumetric efficiency beyond 35 barG.

3.3 Efficiency Comparison at Same Pressure Ratio

All five Vi cases have optimal volumetric efficiency and isentropic efficiency at discharge pressure 20 barG. Therefore, efficiency changing with Vi at this pressure is compared in Fig. 9. In theory, all five cases are under-compression at this discharge pressure. Therefore, the best efficiency should be achieved at Vi of 6.8 where less under-compression than other cases. However, isentropic efficiency increases with Vi then decreases and approaches 80% at Vi of 4.6. Over-compression could happen due to leakage at Vi of 5.8 and 6.8. Volumetric efficiency stays higher than 90% and peaks at Vi of 4.

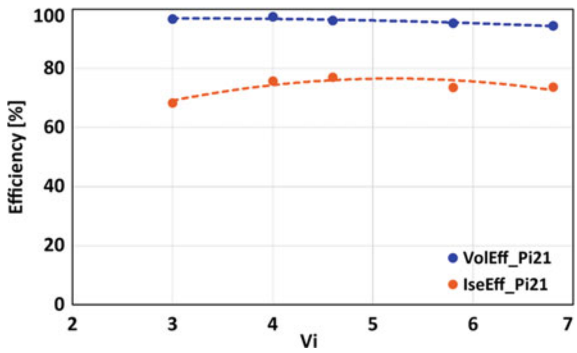

Fig. 9 Efficiency changing with Vi at pressure ratio 21

3.4 Efficiency Contour

Efficiency contours with different Vi and Pi are compared as shown in Fig. 10. These contours can help for selection of Vi and Pi to achieve better volumetric efficiency and isentropic efficiency.

Volumetric efficiency can be higher than 93% for all cases operating at pressure ratio between 13 and 27. As high as 97% volumetric efficiency can be achieved when Vi between 3.2 and 4.1 operating at pressure ratio between 19 and 22. The optimal volumetric efficiency is achieved when the external pressure ratio is 2.0–2.5 times that of the internal pressure ratio.

Isentropic efficiency of 76% is achieved when Vi is between 4.1 and 5.0 operating at pressure ratio around 20. Volumetric efficiency and isentropic efficiency drop quicker at low Vi side than high Vi side which can be visualized from the density of contour lines.

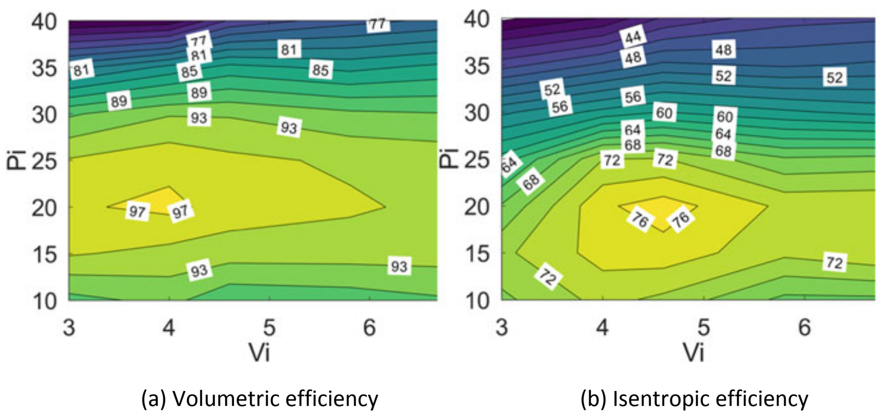

Fig. 10 Efficiency contour

4 Conclusions

This paper details the selection of an initial CRC with a volumetric index (Vi) of 6.8, which was subsequently modified by reducing the length of its inner rotor to obtain different Vi values of 5.8, 4.6, 4, and 3. The resulting sealing line lengths were calculated and compared across all five cases. To investigate the impact of Vi and pressure index (Pi) on CRC performance, experiments were conducted at varying Pi values between 11 and 41, and volumetric efficiency and isentropic efficiency were compared, resulting in the generation of efficiency contours. Based on the experimental findings, the authors conclude that:

- The CRC demonstrates capability for high Pi applications.
- Over-compression may occur when the theoretical internal Pi is lower than the external Pi due to leakage.
- The optimal volumetric efficiency (greater than 95%) envelope can be achieved with a Vi between 3.2 and 4.1 and operating at Pi between 19 and 22.
- The optimal isentropic efficiency (greater than 74%) envelope is achieved when Vi is between 4.1 and 5.0, and operating at Pi between 18 and 22.
- The CRC can achieve high volumetric efficiency (greater than 90%) across a wide range of Vi at Pi of 21.
- A CRC with a lower Vi may be selected for Pi values lower than 35 to reduce manufacturing complexity.

In future work, the experimental results will be utilized to refine the chamber model, with consideration given to the calculation of the volumetric index (Vi) by incorporating the oil volume fraction.

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