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Ken Shaun Yap
Nanyang Technological University, Singapore, Singapore / TUM CREATE, ksyap2@e.ntu.edu.sg

Kim Tiow Ooi
Nanyang Technological University, Singapore, Singapore, mktooi@ntu.edu.sg

Anutosh Chakraborty
Nanyang Technological University, Singapore, Singapore, AChakraborty@ntu.edu.sg

Introduction of the Novel Cross Vane Expander-Compressor Unit for Vapour Compression Cycle

Ken Shaun YAP[1,2a]*, Kim Tiow OOI[1b], Anutosh CHAKRABORTY[1c]

[1] School of Mechanical and Aerospace Engineering, Nanyang Technological University,
50 Nanyang Avenue, Singapore 639798.
[2]TUM CREATE (Technische Universität München - Campus for Research Excellence
And Technological Enterprise), 1 CREATE Way, #10-02, CREATE Tower, Singapore 138602.

[a]Phone: +65 6592 3755, email: ksyap2@e.ntu.edu.sg
[b]Phone: +65 6790 5511, e-mail: mktooi@ntu.edu.sg
[c]Phone: +65 6790 4222, email: achakraborty@ntu.edu.sg

* Corresponding Author

ABSTRACT

A new type of expander-compressor system called Cross Vane expander-compressor (CVEC) was introduced. This device replaces the expansion valve and compressor in conventional refrigeration systems to reduce the energy consumption and improve the coefficient of performance (COP) of the system. As opposed to many expander-compressor systems in the literature, whereby a separated expander is coupled to a separated compressor of the same or different mechanism, the novel Cross Vane mechanism performs both the function of expander and compressor in a single mechanism. Therefore, one machine is built rather than two as required in the former system. This has significant advantages on the manufacturing process and mechanical efficiency. In this paper, the design and working principle of CVEC are presented and the comparison between the novel CVEC and various types of rotary expander-compressor systems are discussed.

1. INTRODUCTION

With the growing concern over the rapidly increasing oil prices and the need to curb greenhouse gas emissions, energy-efficient refrigeration systems are needed. One of the most promising methods to reduce the energy consumption of refrigeration system is the replacement of expansion valve with an expander. The energy recovered from the expansion process is used to supplement the energy required by the compressor, thereby improving the coefficient of performance (COP) of the system as a whole. There are many types of expander-compressor system available in the literature. Nickl *et al.* (2005) developed a three-stage expander which drives an auxiliary compressor in a CO_2 transcritical cycle. Kim *et al.* (2008) designed a scroll type expander-compressor unit and simulated its performance in two-stage compression CO_2 cycle. Kovacevic *et al.* (2006) designed and analysed a twin screw expander-compressor unit for work recovery in high pressure refrigeration system. Kohsokabe *et al.* (2006) developed an expander-compressor unit by joining a scroll type expander and a rolling piston type compressor by a shaft and studied its performance. Teh and Ooi (2006) invented a highly energy-efficient compressor mechanism named Revolving Vane (RV) mechanism, and an improved version called RV-i mechanism was subsequently introduced (Teh and Ooi, 2008a and 2008b). This mechanism was later used to develop an expander (Subiantoro and Ooi, 2010) and a prototype was fabricated and tested in an open air circuit (Subiantoro *et al.*, 2012).

Almost all of these systems found in the literature are a combination of expander and compressor of the same or different mechanism coupled via a connecting shaft. This arrangement makes the systems more complicated and costly, and presents a challenge to its further commercialization. Therefore, a single mechanism that performs both the function of expander and compressor simultaneously would be ideal. Recently, a new type of expander-compressor mechanism called the Cross Vane mechanism was invented by the authors (provisional patent number: 61/638,740). This mechanism is employed in the design of expander-compressor unit called the Cross Vane expander-compressor (CVEC) to replace the compressor and expansion valve in conventional refrigeration systems. The machine consists of only three major components: the outer cylinder-vane-shaft assembly, the inner cylinder, and the split bush. This reduces the physical size of the machine, which makes it more compact and hence, it is easier to be implemented. In addition, unlike most of the expander-compressor systems, CVEC is a single integrated unit, instead of two machines. This has significant implication on its mechanical efficiency, as the former has frictional losses contributed by two machines, whereas in CVEC, frictional losses are contributed by only one machine. Hence, a higher mechanical efficiency is expected of CVEC as compared to a system of compressor and expander coupled via a connecting shaft.

2. DESIGN AND WORKING PRINCIPLE

2.1 The Design

In its basic form, the CVEC has 3 major components: a) the outer cylinder-vane-shaft assembly, b) the inner cylinder, and c) the split bush as shown in Figure 1. The vane is rigidly fixed to the shaft and the outer cylinder as one assembly. The outer cylinder-vane-shaft assembly is then assembled eccentrically with the inner cylinder and split bush, such that a line contact always exists between the shaft and the inner wall of the inner cylinder, and between the outer wall of inner cylinder and the inner wall of outer cylinder as shown in Figure 2. As a result, the suction and discharge chamber of the expander, and the suction and compression chamber of the compressor are formed.

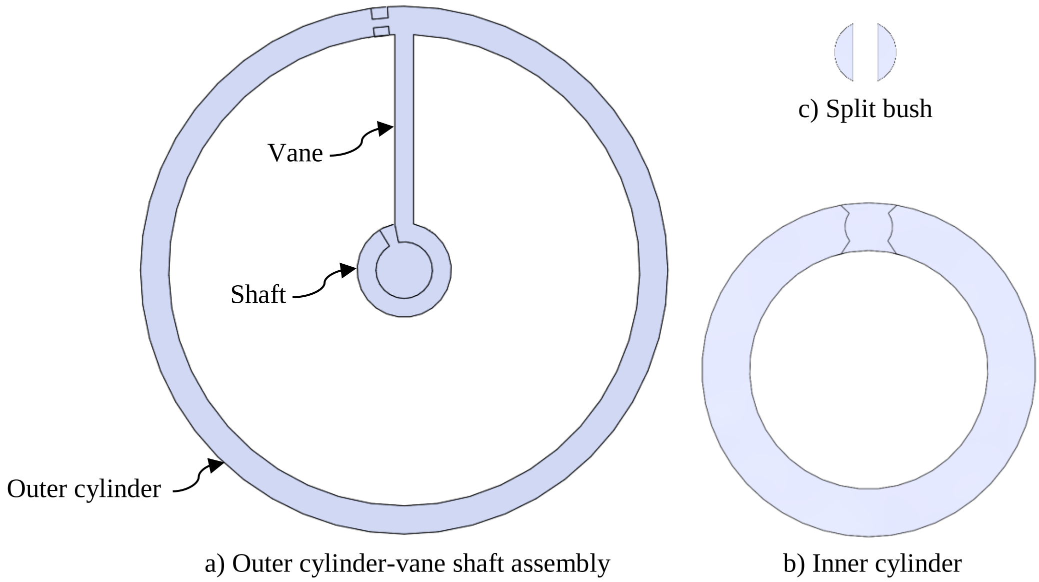

Figure 1: Components of CVEC

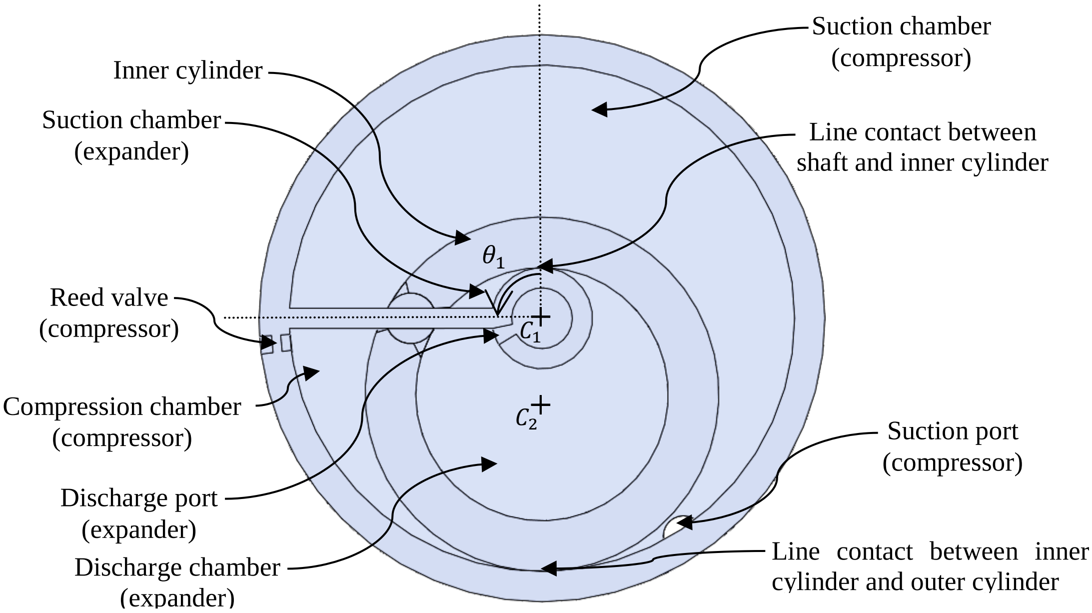

Figure 2: Front sectional view of CVEC

The outer cylinder-vane-shaft assembly and inner cylinder are supported individually and concentrically on bearing pairs as shown in Figure 3. This arrangement allows them to rotate about their respective axes of rotation. A drive shaft will also be integrated with the shaft concentrically which is coupled to a prime mover, such as an electric motor. During operation, the rotation of shaft causes the vane to revolve which in turn rotates the outer cylinder and the inner cylinder. The motion causes the volumes trapped within the suction and compression chamber of the compressor to vary, resulting in suction, compression and discharge of the working fluid. Similarly, the volumes trapped within the suction and discharge chamber of the expander varies too, resulting in suction, expansion, and discharge of the working fluid. Both the compressor and expander operate concurrently.

The shaft is where the suction and discharge ports of the expander are located. They are placed at the opposite ends of the shaft to avoid interaction between the suction fluid and discharge fluid as shown in Figure 3. The suction port can be seen extending from the shaft and through the bearing in which the suction valve is located. The role of the expander's suction valve is to control the point where the suction process ends and the beginning of expansion process. This is one of the many ways in which the suction and expansion process can be controlled. Other methods include the use of externally controlled valve such as solenoid or pneumatically controlled valve.

The discharge port of the compressor is located at the outer cylinder; therefore a reed valve is located just before the discharge port to control the end of compression process and the beginning of discharge process (see Figure 2). In addition, the reed valve also ensures the unidirectional flow of the working fluid from the compression chamber to the discharge port of the compressor and finally out to the discharge reservoir (within the housing). The suction port of the compressor is located at the bearing as shown Figure 2 and 3.

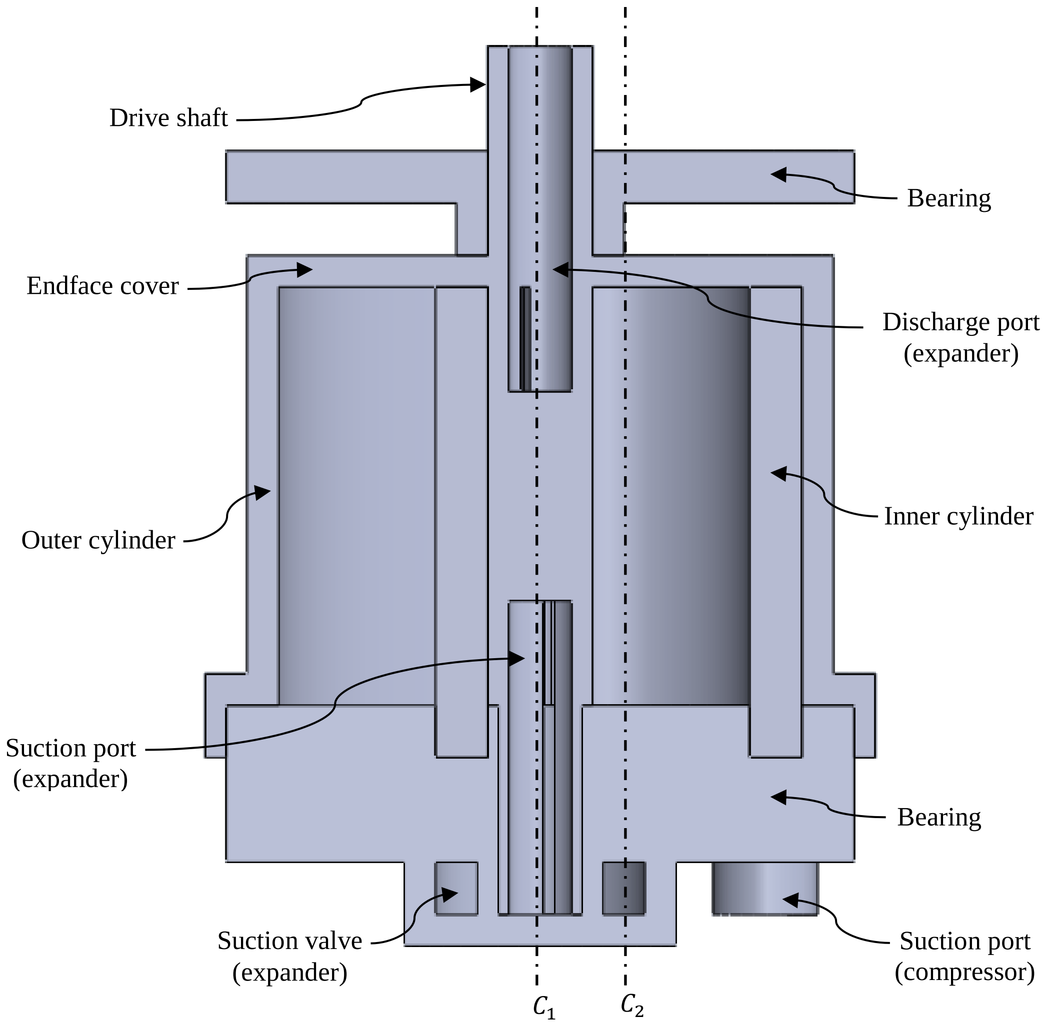

Figure 3: Side sectional view of cantilever type CVEC

2.2 The Working Principle

The operating process of the expander and compressor of CVEC is illustrated in Figure 4. The expander is located at the inner chambers whereas the compressor is located at the outer chambers. The compressor work is supported by the prime mover and also the expansion work generated in the expander. Therefore, lesser work is required from the prime mover and the efficiency of the refrigeration system is increased.

A brief explanation of the expander operating process is as follow: (a) suction and discharge begin; (b) suction and discharge continue; (c) suction and discharge continue; (d) suction ends, expansion begins and discharge continues; (e) expansion and discharge continue; (f) expansion and discharge continue. The cycle repeats.

From Figure 4, it can be seen that the compressor and expander cycles are 180° out of phase from each other, whereby the compressor cycle starts at Figure 3e. A brief explanation of the operating process of the compressor is as follow: (e) compression and suction begin; (f) compression and suction continue; (a) compression and suction continue; (b) compression ends, discharge begins and suction continues (c) discharge and suction continue; (d) discharge and suction continue. The cycle repeats.

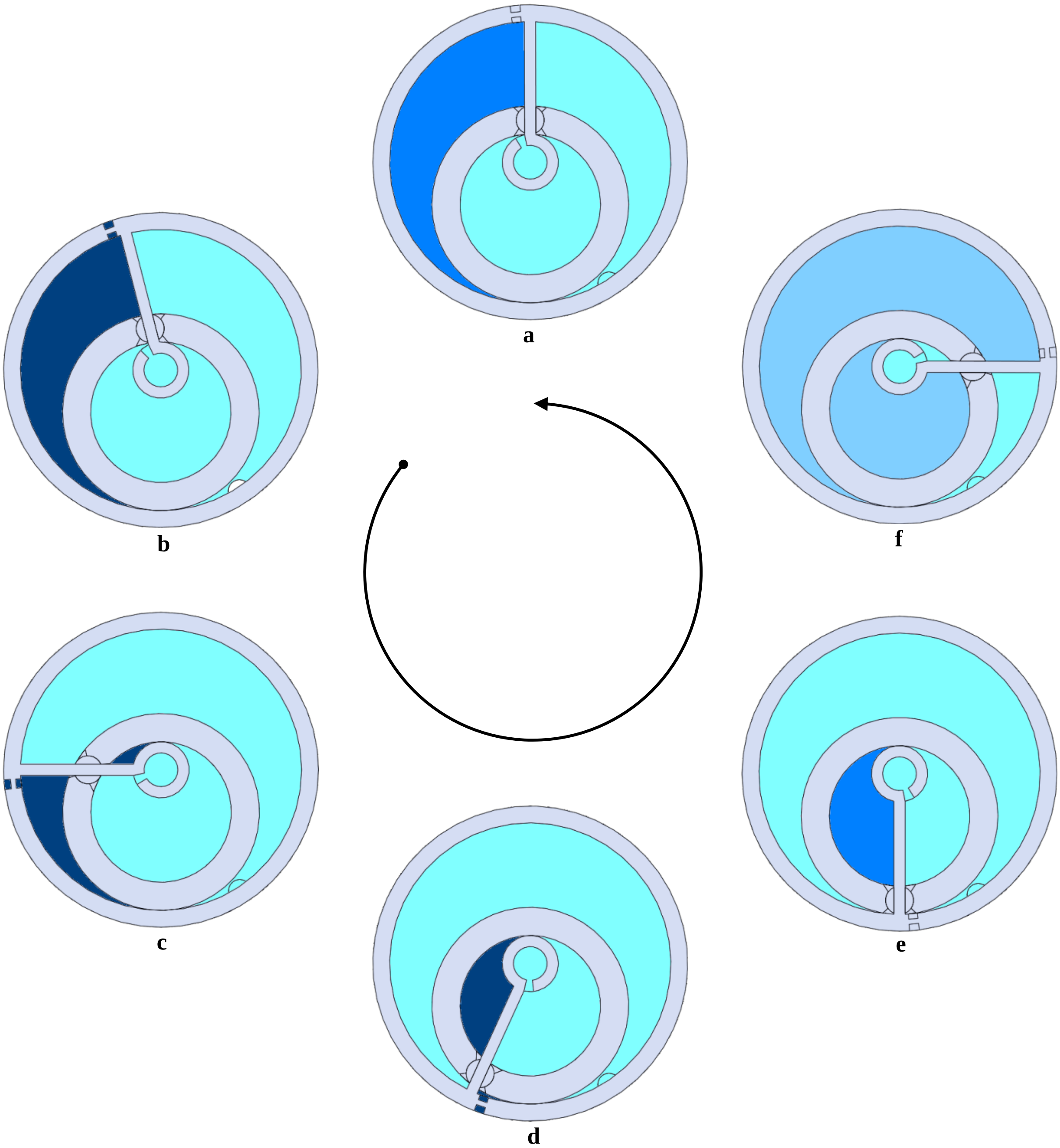

Figure 4: The working principle of CVEC

3. DISCUSSION OF THE DESIGN

Design comparison between CVEC and other existing rotary expander-compressor systems is shown in Table 1.

Table 1: Comparison between various types of rotary expander-compressor systems and CVEC

Feature	Screw Expander – Screw Compressor	Scroll Expander – Scroll Compressor	Scroll Expander – Rolling Piston Compressor	CVEC
Number of major components	**3 components**.	**5 components**.	**8 components**.	**3 components**.
Simplicity of component geometry	**Helical profile** requires an exquisite accuracy in manufacturing.	**Spiral profile** requires high precision in manufacturing.	**Spiral profile** of the scroll expander requires high precision in manufacturing.	Components are mainly **cylindrical and concentric**, and can be made by turning operation.
Moment of inertia of rotating components	Thick and massive rotors results in **high moment of inertia**.	Thin and light scroll resulting in **low moment of inertia**	Thick and massive eccentric part of the rolling piston compressor results in **high moment of inertia**.	Thin, small and light outer cylinder-vane-shaft assembly and inner cylinder resulting in **low moment of inertia**.
Working fluid capacity	**Lower** fluid intake per rotation for a given size and mass.	**Lower** fluid intake per rotation for a given size and mass.	**Lower** fluid intake per rotation for a given size and mass.	**Higher** sweep volume per rotation for a given size and mass.
Mechanical efficiency	Relatively **low** mechanical efficiency due to longer screw profile.	Relatively **low** mechanical efficiency due to two machines required.	Relatively **low** mechanical efficiency due to two machines required.	Relatively **high** mechanical efficiency due to one machine required.
Torque matching	Peak torque of compressor and expander **cannot be matched easily**.	Peak torque of compressor and expander **can be matched by adjusting the shaft**.	Peak torque of compressor and expander **can be matched by adjusting the shaft**.	Peak torque of compressor and expander **cannot be matched easily**.
Configuration of suction and discharge ports	The arrangement of suction and discharge ports of expander and compressor is **less complicated**.	The arrangement of suction and discharge ports of expander and compressor is **less complicated**.	The arrangement of suction and discharge ports of expander and compressor is **less complicated**.	The arrangement of suction and discharge ports of expander and compressor is **more complicated**.

Preliminary theoretical investigation has been conducted using R-134a as the working fluid. The studies show that the mechanical efficiency of CVEC is 96.5%, and that an energy saving of up to 18.0% is achievable when the expander-compressor unit is used in refrigeration cycle. Apart from its relatively higher mechanical efficiency as compared to other existing expander-compressor systems, the machine also reduces the peak power requirement of the system. Therefore, a smaller electric motor is needed to run the system which leads to further cost reduction. The theoretical work and the results of the numerical simulation will be presented in the second paper entitled: Modelling and Simulation of the Dynamics of Cross Vane Expander-Compressor Unit for Vapour Compression Cycle (Yap *et al.*, 2014), which will be published in the same proceedings.

4. CONCLUSIONS

The novel Cross Vane Expander-Compressor mechanism design is introduced in this paper. In its basic form, the CVEC has 3 major components: the outer cylinder-vane-shaft assembly, the inner cylinder, and the split bush. The device replaces both the expansion valve and compressor in a conventional refrigeration system. Expansion power is recovered by the expander to partially drive the compressor, thereby reducing the energy consumption and improves the COP of the refrigeration system. Since the machine performs the function of expander and compressor in a single mechanism, the mechanical losses associated with CVEC is expected to be lower than other types of rotary expander-compressor systems, whereby the separated expander is directly coupled to a separated compressor.

Additional advantages of CVEC as compared to other types of rotary expander-compressor systems are:

- Fewer major components.
- Simplicity of component geometry.
- Lower moment of inertia of rotating components.
- Higher working fluid capacity given the same size.

However, the disadvantages associated with CVEC are:

- Challenge in torque matching.
- Complexity and space limitation in the design of suction and discharge ports.

NOMENCLATURE

θ	rotational angle	(rad)
C	centre	(-)

Subscript

1	about the shaft
2	about the inner cylinder

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