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# Twenty Years of Compressor Innovation at NTU, Singapore

Kim Tiow Ooi
*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*,
mktooi@ntu.edu.sg

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Kim Tiow OOI

School of Mechanical and Aerospace Engineering, Nanyang Technological University,
50 Nanyang Avenue, Singapore 639798.
Phone: +65 6790 5511, fax: +65 6791 1859, e-mail: mktooi@ntu.edu.sg

## ABSTRACT

In this paper, innovations in refrigeration compressors and their mechanisms which were conceptualized (and some of these were commercialized) at Nanyang Technological University in Singapore over the past twenty years are discussed and presented. These innovations include piezo compressor [1-4], rotaprocating compressor [5-6], sliding cam compressor [7], revolving vane compressor and its variants [8-28], twin-plate rotary compressor [29], revolving vane expander [30-40] and cross-vane mechanism for expander-compressor unit [41-43]. The revolving vane compressor had won the World Best Technology Showcase, in Arlington, Texas, USA in 2009 and it has licensed to a Japanese compressor manufacturer for air-conditioning applications in automobile and private boats sectors, while the invention of the piezo compressor was sold to another Japanese compressor manufacturer. In this paper the working principles of each of these innovations, their uniqueness, advantages and challenges in applications will be shown and discussed.

## 1. INTRODUCTION

Positive displacement compressors have been used in cooling/heating systems for many years. Amongst them, the more commonly used compressors today are the reciprocating compressors which are mostly used in refrigerators and some room air-conditioners; rolling piston compressors which are mostly employed in room air-conditioners and some refrigerators; screw compressors which are generally used in systems with cooling capacity more than 50 kW and the scroll compressors which are mostly used in refrigeration systems with cooling capacity above 15 kW. The same compressors are also used in heat pump systems.

Over the years, research carried out in the research centres, universities and companies have led to significant improvement in all aspects of these compressors. Today, further improvement in these existing compressors can only be incremental. To provide possible venues for a more significant improvement, a new compressor may be introduced. This paper presents the compressor innovations for the past two decades which were carried out in School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU), Singapore.

The principles in coming up with a new compressor design are guided by some or all of the following principles. As compared to the existing compressors, the new design or invention should be:

i. more economical and simpler to manufacture,
ii. higher energy efficiency in operation,
iii. use less materials, and
iv. more compact.

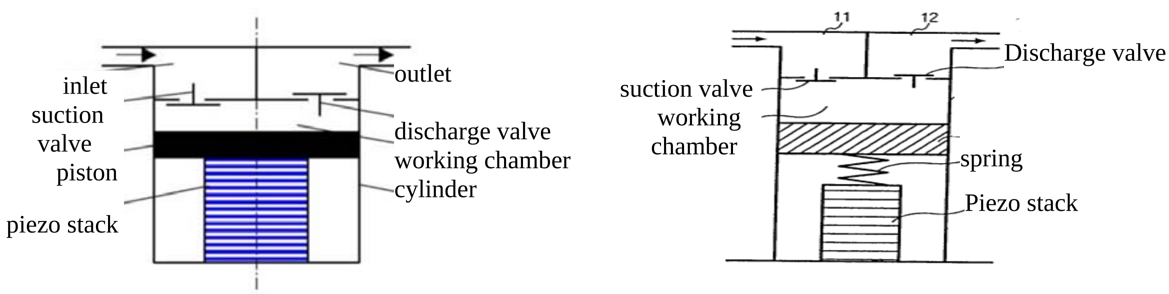
The following sub-sections illustrate each of the new compressors which were conceptualized in NTU in chronological order in the past 20 years.

## 2. INNOVTIONS INSPIRED BY RECIPROCATING COMPRESSOR

Reciprocating compressor is the oldest positive displacement compressor which is still widely used today. It has a long working history with a very mature technology and it is very reliable. Notwithstanding that, due to its working principle, which is “reciprocating” in nature, as compared to rotary machines, it has certain negative inherent operational characteristics such as vibrations, noise and thus is less suitable to operate at high operational speeds. Because of this “reciprocating” nature of this compressor, the motor is mounted "perpendicular" to the centerline of the piston, causing the design to be less compact as compared to its rotary counterpart. Piezo-electric compressor [1-4] and rotaprocating compressor [5-6] are introduced in attempts to negate these negative characteristics of the reciprocating compressor.

### 2.1 Piezo-electric compressor [1-2]

In this compressor [1-2], the bulky and heavy electric motor is replaced by a small piezo-actuator, see Fig. 1. The figure shows the schematic of the simple piezo compressor. In its basic form, it consists of few major parts: a cylinder 'h', a piezo-actuator 'd' and a piston 'c', a working chamber 'g', valves 'b' and 'f' and plenum 'a' and 'e'. A spring can also be added to enhance the operational frequency of the compressor, as shown in Fig, 1(b). Since the piezo actuator gives only a very small displacement, but with a very high force, a linear displacement amplifier similar to that of the hydraulic ramp is used to increase the displacement [3,4], as shown in Fig.2. A mathematical model has also been formulated to study the performance of the compressor [1]. Prototype machine has also been fabricated and performance has been measured. Fig. 3 [1] shows the comparison between the measured and the predicted P-V history.




(a) Basic unit [1]

(b) Spring is added to enhance the operational frequency [2]

**Figure1** Schematic of the piezo-compressor [1,2]

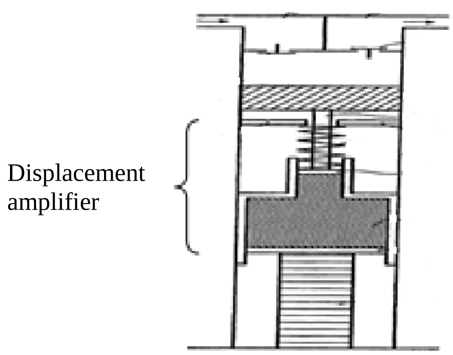



**Figure 2** A piezo compressor with a displacement amplifier [3,4]

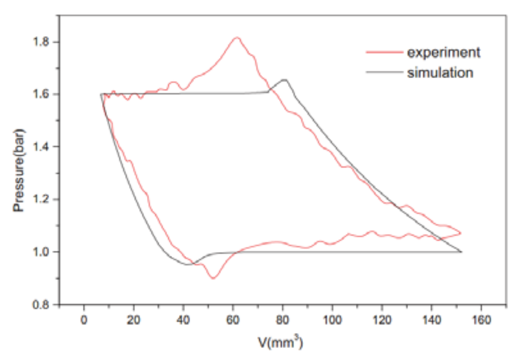



**Figure 3** Comparison of the measured and the predicted P-V histories [1]

The invention was sold and patents [2,3,4] were filed by a compressor manufacturer.

### 2.2 Rotaprocating compressor [5,6]

In another attempt to make the reciprocating compressor more compact, a compressor design [5,6] is developed that dispenses with the bulky crank-connecting rod mechanism of the reciprocating compressor and replaces it with a new mechanism which directly couples the piston to the motor. This new compressor is called rotaprocating compressor. The name rotaprocating comes from the words "**rota**ry" and "reci**procating"**. With this new concept, the reciprocating compressor now behaves like a rotary compressor in the way that it is directly coupled to the motor and the piston and motor are both mounted on one common axis without being connected through the crank-connecting rod mechanism, and it does away with the "perpendicular mounting" between the axes of the piston and the motor.

This latter design results in a more compact and simpler machine with fewer parts. However, preliminary analysis showed that the main disadvantage in this design is the significant variation of the driving torque as shown in Figure 4(b). It is noted that for a given major dimensions of a compressor, the magnitude of the torque variations is somewhat proportional to the stroke length of the piston. It also means that the magnitude of the torque variations can be reduced by reducing the stroke length, while increasing the piston diameter to keep the volumetric displacement the same.

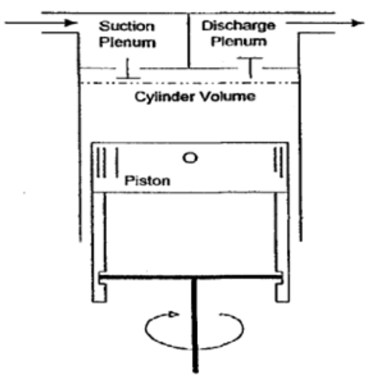



**Figure 4(a)** Schematic of a rotaprocating

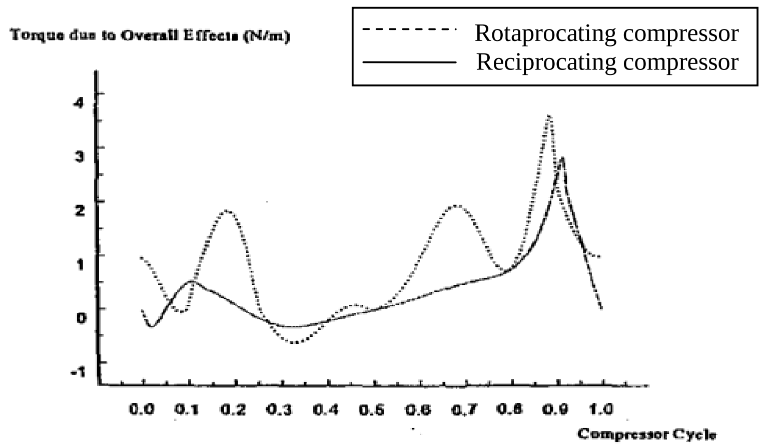



**Figure 4(b)** Torque variation for reciprocating and rotaprocating compressors [5].

## 3. INNOVTIONS INSPIRED BY ROTARY COMPRESSOR

Positive displacement rotary compressors are rotating machines in which the processes in the compressor are achieved by rotating components which cause an increase or a decrease in the working chamber volume. As compared to their reciprocating counterpart, these rotary are machines generally have fewer parts, more compact, lower vibration, lower noise and operating at higher operating speeds. Because of these inherent characteristics, they are getting more popular and over the years, have been employed in many application areas which were previously dominated by only the reciprocating machines. Some of such areas include compressors for room air-conditioners and refrigerators.

One of the most widely used rotary compressors is rolling piston compressor. It is simple, and in its basic form, it consists of five major parts: a cylinder, a roller piston, an eccentric, a vane and a discharge valve. Recently, the application areas of this rotary compressor have been widened. They are also being employed in applications which required higher cooling capacities, those above 10 kW or even 15 kW.
Though inherently, it has many advantages over its reciprocating counterpart, it also exhibits many weaknesses. Among these include high friction loss, critical operating area at the vane tip, big volumetric space occupied by the rotor, etc. The following innovations are attempts to overcome some or all of these weaknesses inherent in this type of compressor.

### 3.1 Sliding cam rotary compressor [7]

In this design, attempt has been made to increase the displacement volume of the existing rolling piston compressor while keeping the overall dimensions and the operational conditions the same. Fig. 5 shows one such design. The circular roller in the rolling piston compressor has been replaced by a non-circular roller (called it cam), the latter gives more flexibility in compressor design, in particular, in determining the design dimensions and it also comes with a smaller volumetric size. While this new design increases the working volume of the compressor, and hence increase it compactness, it also increases the mechanical losses as it requires a higher torque to operate. Further work is needed to further improve the performance of the compressor. Many other possible variants of the rotor are shown in reference [7].

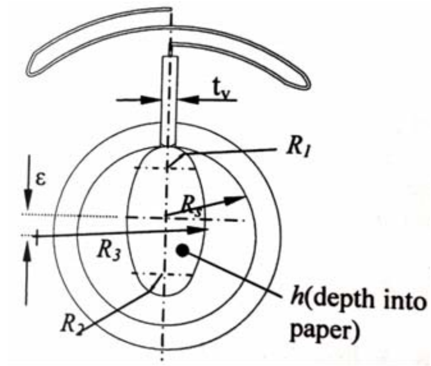



**Figure 5** Schematic of one version of the sliding cam compressors [7]

### 3.2 Revolving Vane Compressor [8-28]

This a new compressor that is designed to overcomes almost all the problems and disadvantages which are inherent in the existing rolling piston compressor and the sliding vane compressor. The unique feature of this new compressor is that its rubbing components are all moving together and hence this design reduces friction caused by moving components rubbing against stationary components as seen in other rotary compressors. The new compressor is called revolving vane compressor. Its schematic is shown in Fig. 6. In its basic form, it consists of a cylinder, a rotor, a vane and two plain bearings. It reduces energy losses of the existing rolling piston compressor from friction by 80% which resulted in overall energy saving of 14%. This invention has won the Silver prize in World's Best Technology Showcase in USA in 2009.

Figure 7 shows the snapshots operation of the revolving vane compressor. It is noted that when the compressor operates, the discharge valve is also rotating. The rotating discharge valve provides the positive effects of the valve opening and hence reduces the valve discharge loss [20]. Figure 8 shows the oil film design information for the plain journal bearing of a revolving vane compressor [17]. This invention is currently exclusively licensed to a Japanese compressor manufacturer solely for automobile and private boat applications only. Figure 9 shows the sectional view of the automobile compressor [27] designed by this manufacturer employing the revolving vane concept.

The performance of the existing rolling piston compressor reduces significantly when the compressor operates at high differential pressure between suction and discharge conditions. This is due to large pressure differential force acting on the vane, resulting in very high friction losses at the rubbing surfaces of the vane and the slot. However, this problem can be overcome by physically fixing the vane on to the rotating cylinder [12]. After fixing the vane, the dependency of the vane side-slot frictional loss on the pressure differential force across the vane, is completely removed. This feature has a very significant advantage in allowing the compressor to function at very high pressure differential such as those in $CO_2$ compressors. The revolving vane compressor should therefore be designed with a fixed vane.

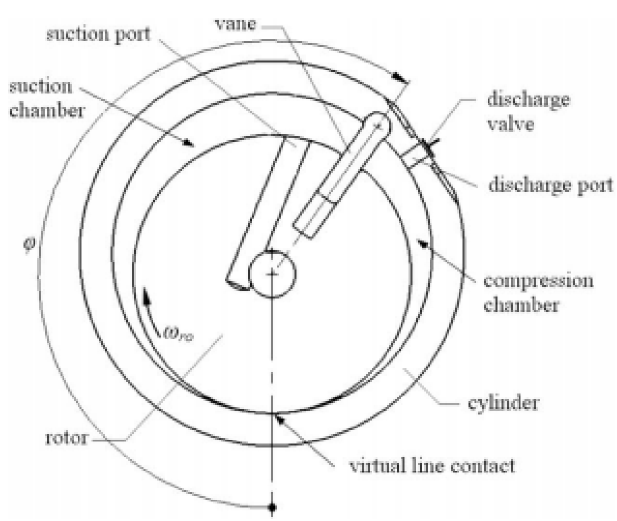



**Figure 6** Basic concept of revolving vane compressor [8]

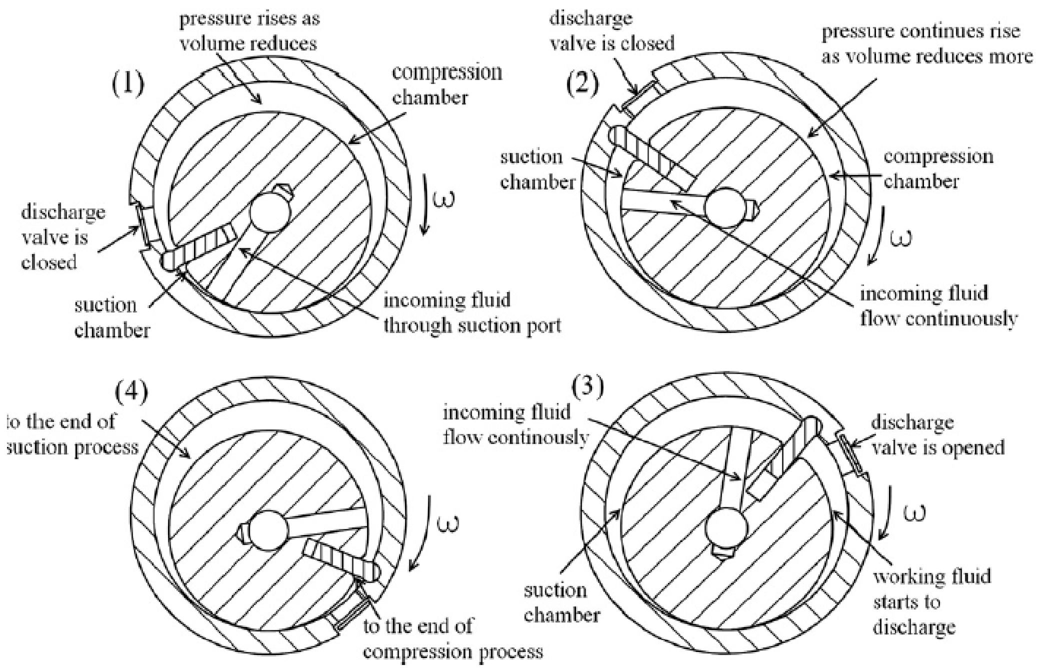



**Figure 7** Snapshots of the operation of the revolving vane compressor [16]

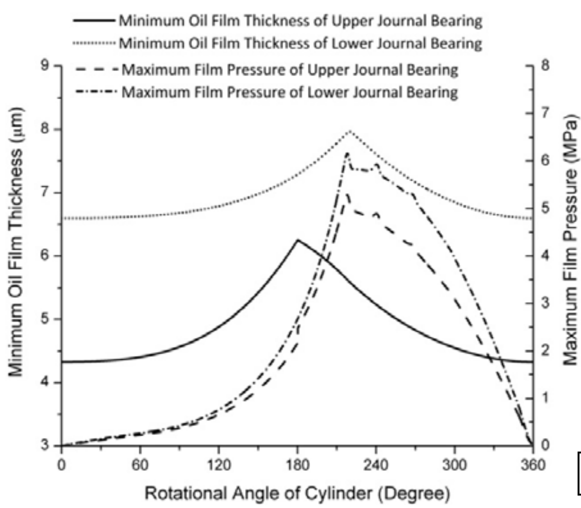



**Figure 8** Oil film bearing design information for RV compressor [17]

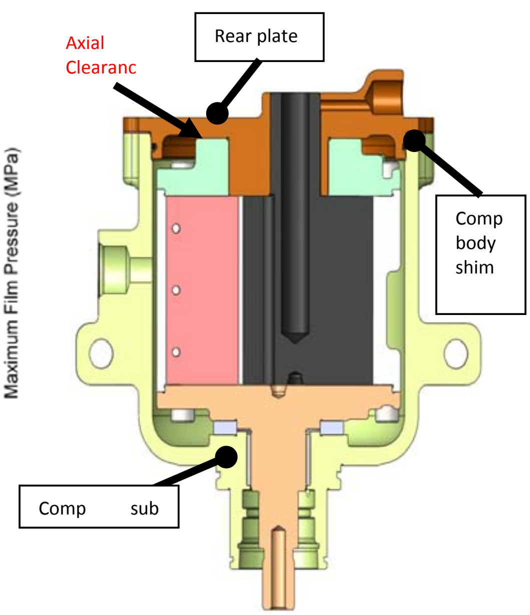



**Figure 9** Revolving vane compressor for automobile applications [27]

### 3.3 Twin-Plate Rotary Compressor [29]

A new compressor design, see Fig. 10 was introduced which was based on a revolutionary idea of two rotating spheres. The unique feature of this compressor is that it has low friction between the rotating components. It was awarded a US patent, US 7726960B2, on 1 June 2010 [29]. This is the precursor to the Revolving Compressor. The accuracy required by the conical plates posed some challenges in using conventional manufacturing method.

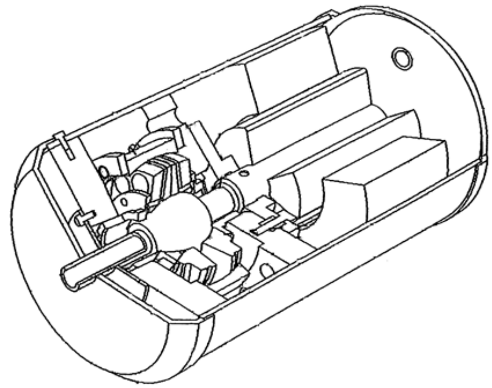


**Figure 10** Twin plate rotary compressor

### 3.4 Revolving Vane Expander [30]

This system uses and applies the energy efficient revolving vane mechanism in an expander. This invention introduces a new valve system [30] which works with high energy efficiency concept as inherited from the basic mechanism of the revolving vane. Fig.11 shows the sectional views of the expander, while Fig. 12 shows the power production from the expander when working with $CO_2$ as the working fluid. For medium scale air conditioners assuming that additional cost needed for a refrigeration system with an expander installed is assumed to be US$100, the payback periods are less than 5 years. For $CO_2$ and R404A systems, the payback period is even shorter at less than 1 and 3 years, respectively [44].

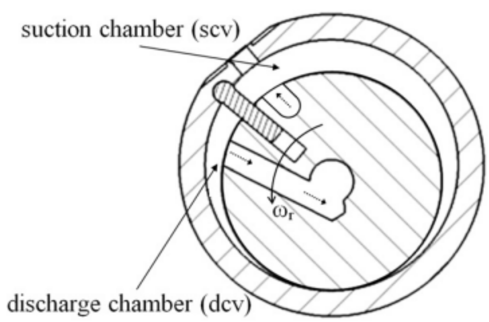



**Figure 11** Revolving vane expander [30]

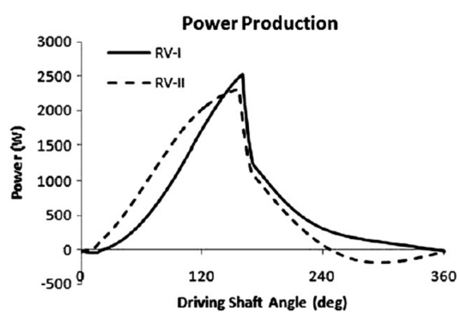



**Figure 12** Power production of a Revolving vane expander [34]

### 3.5 Cross Vane Expander-Compressor unit (CVEC) [41]

This invention of cross vane expander-compressor unit (CVEC) [41] incorporates the expander (to recover energy during the expansion process of the refrigerant) and compressor into one single simple mechanism. This mechanism would replace the expansion valve and the compressor in existing refrigeration/air-conditioning/heat pump systems. The mechanism is expected to reduce the power needed to run existing refrigeration/air-conditioning systems by 14%-40%, depending on the refrigerant used. These energy savings can be achieved without additional costs because the new mechanism uses fewer parts than most existing compressors. Fig. 13 shows the construction of the CVEC [42], while Fig. 14 shows the operational cycle of the CVEC [42]. Fig. 15 shows the predicted variations of the instantaneous power of the system with and without the CVEC. It shows how the employment of the CVEC reduces the peak torque and overall power input [43].

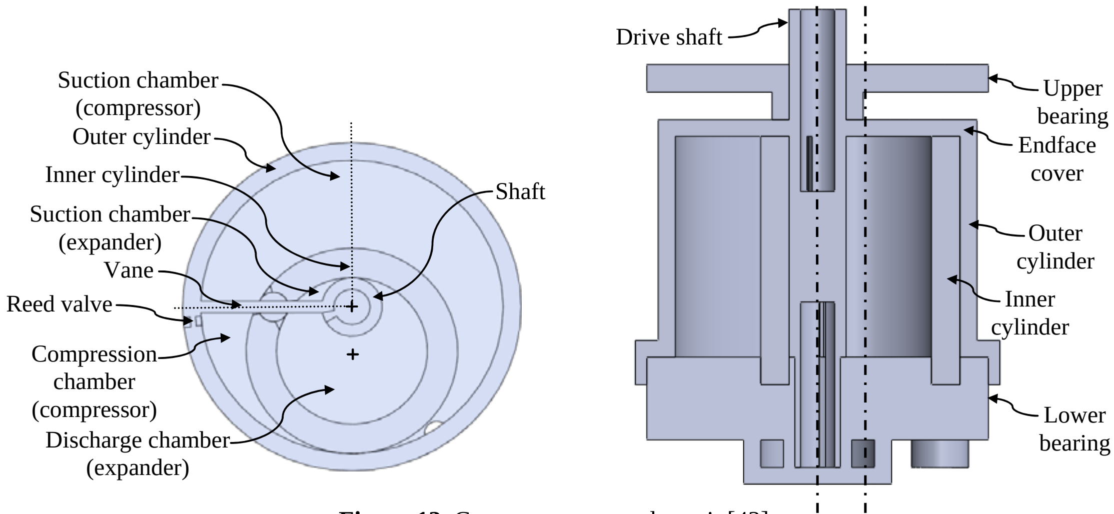



**Figure 13** Compressor-expander unit [43]

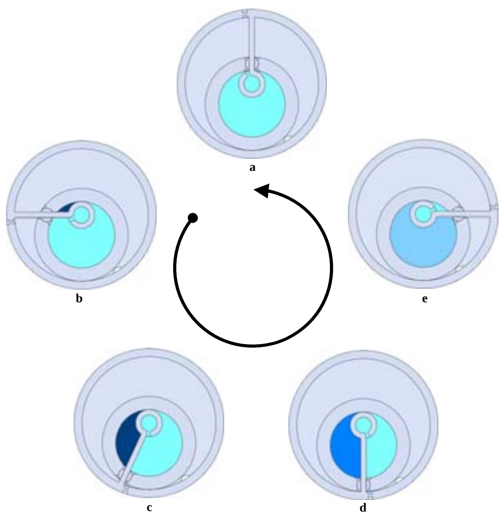



**Figure 14** Operational cycle of the CVEC [42].

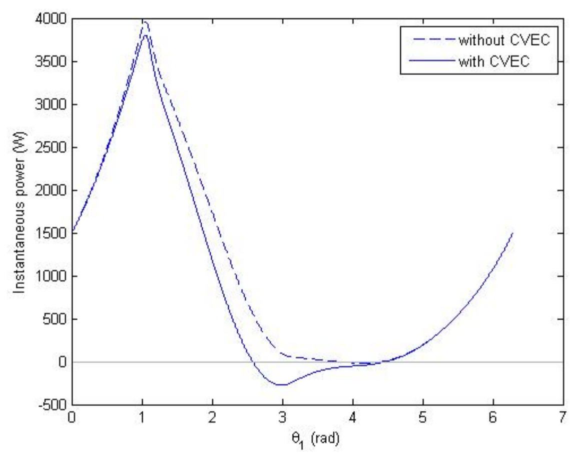



**Figure 15** Variation of instantaneous power for a CVEC [43].

## 4. CONCLUSIONS

New compressors have been invented and introduced in this paper. These compressor innovations have their roots in either reciprocating or the rotary compressors. The following conclusions can be made:

i. Piezo compressor can be made very small, it can be a pen-sized compressor due to its construction which replaces the entire electric motor with a piezo stack. It can operate at very high frequency, limits only by the maximum frequency of the valves. It has been acquired by a Japanese compressor manufacturer.

ii. Rotaprocating compressor removes the entire crank-connecting rod mechanism of a reciprocating compressor and replaces it with the rotaprocating mechanism. While it simplifies the construction of the reciprocating compressor, its torque characteristics is found to be less desirable than the former.

iii. Sliding cam compressor replaces the circular roller of the rolling vane compressor to the non-circular roller. While it provides flexibility in the choice of the roller geometry and makes the compressor more compact, it also increases the friction and torque required.

iv. Revolving vane compressor removes the many disadvantages found in rolling piston and vane compressor in general and it results in a more efficient, more compact and relatively easier to produce compressor. Preliminary measurement shows that this compressor has great potential in meeting the demand of today's ever increasing energy efficiency demand. It has been licensed to a Japanese compressor manufacturer for automobile and private boat applications. It is believes that this compressor will find its applications in room air-conditioners, automobile, refrigerators and many others in the near future.

v. The revolving vane expander which uses the basic mechanism of the revolving vane compressor is expected to improve the efficiency of the vapour compression refrigeration systems by recovering the expansion energy and feed it back to the compressor to reduce the overall energy required.

vi. The cross-vane expander-compressor unit which takes its inspiration from the revolving vane compressor and revolving vane expander, cleverly adapting the concepts of rotating cylinder to come out with a single unique mechanism which has the simplicity of a normal rotary compressor geometrically but it allows the waste energy at the expansion side of the vapour compression refrigeration cycle to be recovered and hence improves the energy efficiency of the cooling and heating systems significantly. The prototype machine is currently being developed. More research has to be done to fully recover the advantages of this new mechanism.

## REFERENCES

1. Ooi, K.T., Simulation of a piezo-compressor, Applied Thermal Engineering, v 24, n 4, p 549-62, March 2004.
2. Piezo electric compressor. WO 2004/022/973 A1. International Intellectual Properties organisation (WIPO), international application published under Patent Corporation Treaty (PCT).
3. Piezo electric compressor with displacement amplifier. US 2006/0051232 A1. United State patent application publication, March 9, 2006.
4. Piezo electric compressor with displacement amplifier , European patent, EP1534955
5. Ooi, K. T. and Wan, T. T., "A Rotaprocating Compressor" (2000). International Compressor Engineering Conference. Paper 1461.http://docs.lib.purdue.edu/icec/1461
6. Ooi, K. T. and Ng, S. K., " Optimization Of A Rotaprocating Compressor " (2002). International Compressor Engineering Conference. Paper 1524. http://docs.lib.purdue.edu/icec/1524
7. Ooi K.T. (2003). A study of a sliding cam compressor. International conference on compressors and their systems IMechE, U.K.
8. Revolving vane compressor, WO2008/004983 A1, Patent Corporation treaty, 10 Jan 2008
9. Revolving vane compressor, US8206140 B2, awarded United State patent, 26 Jun 2012
10. Revolving vane compressor and its method of manufacture, WIPO, PCT, WO2011087457A1, 27 Aug 2009.
11. Revolving vane compressor and its method of manufacture, US patent, 20100310401 A1, 9 Dec 2010.
12. Fixed vane assembly, WIPO, PCT, WO2011087457A1, 21 Jul 2011.
13. Revolving vane compressor, WIPO, PCT, WO2013036203A1, 14 March 2013 (Automotive and private boat applications)
14. Tan KM, Ooi, K T. (2014). Experimental study of fixed-vane revolving vane compressor. Applied Thermal Engineering, 62(1), 207-214.
15. Tan KM, Ooi K.T. (2011). A novel revolving vane compressor with a fixed-vane. International Journal of Refrigeration, 34(8), 1980-1988.
16. Tan K M, Ooi K T. (2011). Heat transfer in compression chamber of a revolving vane (RV) compressor. Applied Thermal Engineering, 31(8-9), 1519-1526.
17. Tan K.M., Ooi K.T. (2011). Journal bearings design for a novel revolving vane compressor. International Journal of Refrigeration, 34(1), 94-104.
18. Teh Y. L., Ooi, K. T. (2009). Experimental Study of the Revolving Vane Compressor. Applied Thermal Engineering, 29, 3235-3245.

19. Teh Y. L., Ooi K. T. (2009). Theoretical Study of a Novel Refrigeration Compressor - Part I: Design of the Revolving Vane Compressor and its Frictional Losses. International Journal of Refrigeration, 32(5), 1092-1102.
20. Teh Y. L., Ooi K.T., Wibowo Djamari D. (2009). Theoretical Study of a Novel Refrigeration Compressor - Part II: Performance of a Rotating Discharge Valve in the Revolving Vane Compressor. International Journal of Refrigeration, 32(5), 1103-1111.
21. Teh Y. L., Ooi K. T. (2009). Theoretical Study of a Novel Refrigeration Compressor - Part III: Leakage Loss of the Revolving Vane Compressor and a Comparison with that of the Rolling Piston Type. International Journal of Refrigeration, 32(5), 945-952.
22. Ooi KT, Teh YL. (2009). International Conference on Compressors and Their Systems: Revolving Vane Compressor: Design of Mechanism. (pp. 269-277) UK.
23. TAN K M, OOI K T. (2009). 7th International Conference on compressor and Coolants: Compressor 2009: A Theoretical study of a revolving vane compressor. (pp. 228-234)Casta Papiernicka, Slovakia Republic: Slovak Association for cooling and air conditioning technology, Slovakia
24. Ooi KT, Tan KM. (2013). Compressors 2013 - 8th International Conference on Compressors and Coolants: LUBRICATION SYSTEM OF REVOLVING VANE COMPRESSOR. Compressors 2013 - 8th International Conference on Compressors and Coolants. Proceedings of- 8th International Conference on Compressors and Coolants, Slovakia.
25. A. Subiantoro, Ooi K.T. (2011). Design limitations and flexibilities of the revolving vane compressor. International Conference on Compressors and their Systems 2011, UK.
26. A, Subiantoro, K T Ooi. (2011). Analytical Study of the Endface Friction of the Revolving Vane Mechanism. International Journal of Refrigeration, 34(5), 1276-1285
27. Tan, Kok Ming; Choo, Wei Chong; Chee, Michael; Law, Ken; Iswan, Ismail; Ooi, Kim Tiow, Performance Measurement of Revolving Vane Compressor. A paper submitted to be published at 2014 Purdue Compressor technology conference, USA, Purdue University.
28. Aw, Kuan Thai; Ooi, Kim Tiow, Theoretical Analysis of Revolving Vane Compressor Vibrations. A paper submitted to be published at 2014 Purdue Compressor technology conference, USA, Purdue University.
29. Ooi K.T., Teh Y. L., Twin-Plate Rotary Compressor. (Name on patent document appears as Kim Tiow Oui, Yung Liang Teh, SG). US 7726960B2.
30. Subiantoro A., Yap K.S., Ooi K.T. (2013) Revolving vane expander, US 20130045124A1.
31. Subiantoro A., Ooi K.T. (2013). Experimental Investigation of the Revolving Vane (RV-I) Expander. Applied Thermal Engineering, 50(1), 393-400.
32. A. Subiantoro, Ooi, K.T., (2012). Analysis of the revolving vane (RV-0) expander, part 2: Verifications of theoretical models. International Journal of Refrigeration, 35(6), 1744-1756.
33. A. Subiantoro, Ooi K.T. (2012). Analysis of the revolving vane (RV-0) expander, part 1: Experimental investigations. International Journal of Refrigeration, 35(6), 1734-1743.
34. A. Subiantoro, K.T. Ooi. (2010). Design analysis of the novel Revolving Vane expander in a transcritical carbon dioxide refrigeration system. International Journal of Refrigeration, 33(4), 675-685.
35. Alison S., Ooi K. T. (2009). Introduction of the Revolving Vane Expander. ASHRAE International Journal of Heating, Ventilating, Air-conditioning and Refrigeration Research, 15(4), 801-816.
36. Subiantoro A., Ooi K.T. (2012). Investigation of the Centrifugal Force Effect to a Revolving Vane (RV) Machine. 21st International Compressor Engineering Conference at Purdue.
37. A Subiantoro, Ooi K T. (2013). Proceedings of International Conference on Compressors and their Systems 2013: A comprehensive simulation model of the dynamics of the revolving vane machine. International Conference on Compressors and their Systems 2013London, UK: IMechE.
38. A Subiantoro, Ooi KT. (2010). 20th International Compressor Engineering Conference at Purdue: Analysis of the Vane Contact Force and the Vane Side Friction Loss of the Various Revolving Vane Expander Designs. International Compressor Engineering Conference at Purdue, July 12-15, 2010 (pp. paper no. 1132 (page 1-8)) Purdue University, USA.
39. A Subiantoro, Ooi KT. (2010). 20th International Compressor Engineering Conference at Purdue: Study of the Endface Friction of the Revolving Vane Mechanism. International Compressor Engineering Conference at Purdue, July 12-15, 2010 (pp. paper no. 1134 (page 1-8))Purdue University, USA: Purdue University, USA
40. A Subiantoro, OOI KT. (2009). 7th International Conference on Compressors and Coolants: Compressor 2009: Comparison between the rotor-driven revolving vane expander and the cylinder-driven revolving vane expander. (pp. 404-411) Casta Perpiernika, Slovakia Republic: Slovak Association for cooling and air conditioning technology, Slovakia.

41. A vane mechanism, WIPO, PCT, WO/2013/162477A1, 21 July 2011.
42. Yap, Ken Shaun; Ooi, Kim Tiow; Chakraborty, Anutosh, Introduction of the Novel Cross Vane Expander-Compressor Unit for Vapour Compression Cycle. A paper submitted to be published at 2014 Purdue Compressor technology conference, USA, Purdue University
43. Yap, Ken Shaun; Ooi, Kim Tiow; Chakraborty, Anutosh, Modelling and Simulation of the Dynamics of Cross Vane Expander-Compressor Unit for Vapour Compression Cycle. A paper submitted to be published at 2014 Purdue Compressor technology conference, USA, Purdue University
44. Subiantoro, A., Ooi KT, Economic analysis of the application of expanders in medium scale air-conditioners with conventional refrigerants, R1234yf and CO, International Journal of Refrigeration, v 36, n 5, p 1472-82, Aug. 2013