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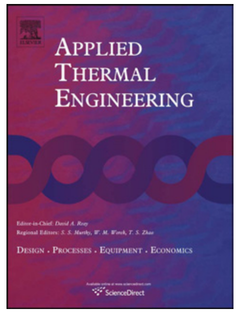

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Expanders for micro-CHP systems with organic Rankine cycle

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ABSTRACT: The continual increases in global energy demand and greenhouse gas emissions call for more and more utilisation of sustainable energy sources, such as solar energy, biomass energy, and waste heat. Solar thermal energy, the heat of biomass combustion and waste heat may be used to drive a combined heat and power (CHP) system. In recent years, several micro-CHP systems with organic Rankine cycle (ORC) suitable for domestic applications (1-10kW$_e$) driven by solar thermal, biomass-fired boilers and waste heat resources have been investigated. These ORC-based micro-CHP systems have lower operation pressures and temperatures compared to conventional steam-Rankine cycle CHP systems and hence safer for household applications. However, the lack of commercially available expanders applicable to ORC-based micro-CHP systems has hindered the development of these novel CHP systems. This paper summarizes the findings of the market research for the expanders and discusses the selection and choices of the expanders for ORC-based micro-CHP systems. The working principles and the characteristics of several kinds of expanders, including turbine expanders (i.e., turboexpander), screw expanders, scroll expanders and vane expanders, are introduced and evaluated.

Keywords: micro-scale combined heat and power (micro-CHP); turbine, expander; organic Rankine cycle (ORC); vane expander.

1. Introduction

In recent years, the accelerated consumption of fossil fuels has caused many serious environmental problems such as global warming, ozone layer depletion, acid rain and air pollution. New energy conversion technologies for electricity generation must confront the energy trilemma which influences the investment decisions and asset portfolio, as shown in Fig.1. Security of supply indicates that the new energy is provided continuously and sustainably; affordability of energy means that the cost of electricity is acceptable by consumers; environment protection tends to low emissions of carbon oxides and sulphur oxides, zero ozone depletion potential (ODP) and low global warming potential (GWP). Biomass/solar-driven combined heat and power (CHP) or tri-generation (CHP + waste heat-driven desiccant cooling), shown in Fig.2, is one of solutions to solve the energy trilemma.

The ever-increasing global energy demand, fast depleting fossil fuel reserves and serious global warming require a further increase in biomass energy utilization for distributed electricity generation and domestic heating in both developing and developed countries. Biomass energy has its advantage of continuity over the intermittence of solar energy and wind power. Biomass is a versatile source of energy in that it can be readily transformed into convenient forms of energy and fuels, by means of a variety of biomass conversion technologies, such as combustion, gasification and biochemical approaches [1]. Biomass combustion is the simplest and the most mature technology that has been widely used in both ancient and modern times. Biomass is renewable and biomass combustion produces no net CO_2 emissions to the atmosphere since biomass absorbs CO_2 during growth and emits the same amount of CO_2 during combustion. Although biomass combustion releases some combustion pollutants (CO, NO_x etc.), which need to be controlled, substituting biomass for fossil fuels, particularly coal, can reduce emissions of SO_X and NO_x which are acid rain precursors due to the low sulphur and low nitrogen contents of many biomass materials.

Electricity is a necessity and a sign of modern life. However, at present 1.3 billion people worldwide do not have access to main grid electricity. Biomass-fuelled CHP systems can efficiently convert biomass chemical energy into electricity and heat. Large-scale biomass CHP plants based on biomass combustion, mostly using steam-Rankine turbines to produce electricity, have been in commercial applications for decades. However, micro-scale biomass-fired ORC-based CHP units (<10kW$_e$), having a great potential to meet the energy needs of buildings, have yet to be demonstrated or commercialized [1].

The organic Rankine cycle (ORC), similar to the conventional steam-Rankine cycle in principle, is widely applied in micro-CHP systems. In an ORC system, instead of water, an organic fluid with a lower boiling temperature is used as working fluid of the organic Rankine cycle due to its favourable thermodynamic properties. CHP systems with ORC operate at lower pressures and temperatures compared to those of CHP systems with steam turbines, reducing system cost and complexity and alleviating safety concerns.

The heart of any ORC systems is the expander, which is a critical component limiting the cycle efficiency. In order to improve the cycle efficiency, the selection of expanders is of considerable importance to the development of biomass-fired ORC-based micro-CHP systems. The selection of the expanders strongly depends on both the operating conditions and the magnitude of power output. Two main types of expanders can be distinguished: the dynamic (velocity) type, such as axial turbine expander, and displacement (volume) type, such as screw expander, scroll expanders.

This paper summarizes the findings of the market research for the expanders and discusses the selection and choices of the expanders for ORC-based micro-CHP systems. Four kinds of expanders are introduced and evaluated. The authors had tried to purchase an off-the-shelf expander from the current commercial market, but failed to get an appropriate one. Instead, a retrofitted air motor was applied as an expander in their experimental micro-

CHP system. After the air motor was successfully retrofitted with proper sealing plates, it was able to work as the expander in their ORC-based micro-CHP system without operating problems such as leaking [2].

2. Expander

2.1. Types of turbines and expanders

A turbine is a kind of rotary machine which converts the kinetic energy in a stream of fluid (gas or liquid) into mechanical energy by driving the stream through a set of blades. There are four broad types of turbines categorized according to the fluid that supplies the driving force: steam, gas, water, or wind. Steam, water, and wind turbines are all used to generate electricity, whereas gas turbines can be used to generate both stationary power and propulsion power of aircrafts. With micro-scale Rankine cycle power generation with a low temperature and low pressure heating source, a turbine expander, instead of a steam turbine, is often used, in which the compressed vapor is expanded into lower pressure and lower temperature. This is mainly because the current commercially available steam turbines are usually bulky and expensive, often with capacities for power plants, and cannot be economically used for micro-scale power generation. Currently turbine expanders with kW scales for organic working fluids are still under development and demonstration.

Expanders, in general, can be categorized into two types: one is the velocity type, such as axial turbine expanders; the other is the volume type, such as screw expanders, scroll expanders and reciprocal piston expanders [3].

2.2. Expander evaluations

In a Rankine cycle, the expander can be that of a turbine, screw machine, scroll machine and reciprocal piston engine; correspondingly it is called turbine expander [4, 5], screw expander [6, 7], scroll expander [8-10] and reciprocal piston expander [11]. In the two types of expanders, the volume-type expanders are more appropriate to the ORC-based micro-CHP unit because they are characterized by lower flow rates, higher pressure ratios and much lower rotational speeds compared with the velocity-type expanders[12]. Moreover, the volume-type expanders can tolerate two-phase conditions, which may appear at the end of the expansion in some operating conditions[12]. Although different types of expanders may be selected, micro-scale expanders (<10kW$_e$) are either not commercially available or very expensive in the form of prototype at present. From the responses to the authors' enquiries, it is known that screw expander manufacturers, ORMAT (ormat.com) and ELECTRATHERM (electratherm.com), currently provide commercially screw expanders suitable for ORC-based CHP units with at least 50kW$_e$ power output, whereas Infinity Turbine (infinityturbine.com) provides 1kW$_e$ or 10kW$_e$ modules with 1kW$_e$ module at a price of $10,000 and 10kW$_e$ at a price of $15,000. Eneftech (eneftech.com) provides model of 010GRE-01 CHP unit (5kW$_e$ or 10kW$_e$) which costs ca. €55,000. Freepower (freepower.co.uk) indicates that they will be able to provide 6kW$_e$ expander from the spring of 2011. As a result of these enquiries and market researches, the authors had to use a modified air motor as the expander in the micro-scale biomass-fired ORC-based CHP system they developed over the past few years. Table 1 summarizes the current market scenarios of micro-scale expanders. Further details of every type of expander are examined below.

2.2.1. Turbine expander (also called turboexpander)

Turbine expander is of the velocity type. The high velocity vapour stream can drive the blades and turn the turbine. An radial-axial turbine has many advantages, such as a compact structure with good manufacturability, a simplex-type lightweight construction, high efficiency, and a single-stage expansion rate that indicates a big enthalpy drop [13]. Fig.3 shows the basic working principle of a turbine expander [14]. Infinity turbine LLC currently manufactures 10kWe turbine expanders - Infinity Turbine MODEL IT10 turbine (10kWe)

[14] for experimental purposes. Further details of IT10 are provided in Fig. 4 [14]: two of the four valves are for 80-120^{0}C input waste heat (liquid form) of the evaporator heat exchanger at 83 litres per minute (LPM) and the other two are for cooling water of the condenser at 166 LPM.

Turbine expanders are generally applied in power cycles with power outputs greater than 50kWe because of their relatively high-expansion efficiency at the high power ratings [10]. Below 50kWe, the performance of turbine expanders begins to deteriorate until unacceptable efficiencies are reached at ~10kWe. In addition, smaller turbine expanders are generally very expensive, operate at very high rotational speeds where reliability has yet to be proven, and the turbine efficiency is relatively low [8].

Since a micro-scale turbine expander (<10kWe) is not commercially available, researchers often turn to those of specifically in-house designed and manufactured turbine expanders such as the one shown in Fig. 5 [13], which is currently mounted in a solar-driven micro-scale CHP system with ORC in University of Science and Technology of China. This particular turbine expander is designed to run with the organic fluid of R123 and at a speed up to 60,000 rpm with power output of 3.5 kW_e [13].

2.2.2. Screw expander

Screw expander is comprised of a pair of meshing helical rotors--a male and a female rotor, contained in a casing which surrounds them with clearances in the order of 50 μm (0.002"). As the rotors rotate, the volume trapped between the rotors and the casing changes. If a fluid is admitted into this space at one end of the rotors, its volume will either increase or decrease, depending only on the direction of rotation, until it is finally expelled from the opposite side of the rotors at the other end. Power is transferred between the fluid and the rotor shafts by pressure on the rotors, which changes with the fluid volume, as shown in Figs. 6 [7] and 7. Prof Ian K Smith in City University London and H. Leibowitz from

ElectraTherm Inc have developed and investigated screw machines as expanders for over 20 years [7]. They have developed the systems for cost effective power production at outputs within the range of 20 - 50kWe. The relatively low installation cost in the range of $1500 to £2000/kWe of net output combined with the ORC's low grade heat source specification results in a very favourable value proposition [7]. However, Prof Ian K. Smith from Centre for Positive Displacement Compressor Technology of City University London [15] had stated that micro-scale screw expander (<10kWe) is hard to obtain in the current market. Responses to the authors' enquiries from various manufacturers of screw expanders have confirmed the above statement. These manufacturers include ORMAT and ElectraTherm, which manufacture screw expanders suitable for ORC-based power generation systems with at least 50kWe power output. For instance, recently ElectraTherm has launched a commercial waste heat generator called the Green Machine [16], as shown in Fig. 8. The 50kWe Green Machine with patented twin screw expander employs minimal heat (93^0C liquid) to generate electricity at $0.03 - $0.04 per kWh during a three-year payback period and at $0.01 per kWh after that.

Prof Ma CF's research group [17] developed a micro-scale screw turbine as an engine in a compressed air vehicle but not applied to an ORC-based micro-CHP unit.

There are few reports in the literature where the screw expanders are applied with mechanical power output lower than 10 kW [18]. One of reasons why the micro-scale screw expanders are not widely used may be due to the difficulty in sealing the organic working fluid. To solve sealing problems, significant modifications are needed, and if not done properly, the rotor becomes locked very easily [14].

2.2.3. Scroll expander

Recently, scroll devices have been gaining some interests as the expanders in small-scale power systems because of no valves, low parts count and low cost. An important feature in adapting a scroll compressor to expander is to lubricate scroll wraps and journal bearings.

Lemort & Quoilin et al [12, 19] simulated a scroll expander integrated into an Organic Rankine Cycle with refrigerant R123 and conducted experiments to validate the theoretical results as well. A scroll expander had also been successfully demonstrated with R134a over a wide range of rotational speeds and expansion ratios with efficiencies exceeding 70 percent by Wang et al. [8]. The scroll expander was modified from a compliant scroll compressor with external control of the scroll sealing pressure [8]. The operational cycle of a scroll expander is shown in Fig.9 [3], whereas Fig. 10 [18] shows the cross-sectional scroll expander.

Scroll expander may be applied in a very small-scale power system, such as 0.1 – 1kWe power range by Peterson et al [10] and around 1.0kWe by Aoun [18] as well. Facao and Oliveira [20] reported that they had a 5kWe in-house manufactured micro-turbine from Eneftech (module 05PLU-01) for their experimental ORC-based power generation system, but the ENEFCOGEN^{PLUS} range is still under tests and validation from Eneftech's answer to author's enquiry in December 2010. ENEFCOGEN^{GREEN} range units are available commercially, such as module 010GRE-01 shown in Fig.11 which may work at either 10kWe output or 5kWe output [21] with the quoted unit cost of €55,000.

2.2.4. Air motor as expander

Air motors are rotary vane machines originally designed to use compressed air to drive the rotors. Compared with other expander concepts, the rotary vane expander has simpler structure, easier manufacturing and lower cost [22]. Air motors are not designed to hold organic working fluids and hence leaking of ORC fluids is inevitable if they are used as expanders without proper modifications, because most turbines are designed for only one specific working fluid and a very narrow operating range [14]. An air motor as an expander was successfully applied by authors' research group[2] after the air motor was successfully modified. An air motor converts the energy of compressed air into mechanical energy and it may be used to replace an electric motor in some spark-prohibited environments [23], such as underground mining tunnels, vehicles and/or storages with explosive materials, etc. An air motor when used as an expander can also be called compressed-air-driven vane-type air turbine [24] and is of the volume type. A vane-type air motor-modified expander turbine (vane expander for short) works on the reverse working principle of a vane-type compressor and its working principles are shown in Fig. 12 [25].

Expansion between sliding vanes is a simple concept. The expansion process is obtained, when the chamber spaces between the cylinder wall and the sliding vanes slotted into the rotor increase as the rotor turns clockwise within the eccentric cylinder housing. As shown in Fig.12, the rotor has 4 longitudinal slots in which vanes slide freely and move outwards by centrifugal force against the cylinder wall of the stator. The highly compressed ORC working fluid vapour rushes into the inlet port to form a chamber A (Fig.12 (a)) and rotates the rotor. The vapour which is trapped is expanded as volume of the chamber increases until the leading vane of the chamber passes the outlet port. The vapour volume expansion results in the pressure differences among the chambers, which drive the rotor turning.

Vane expanders have the advantages of simple construction, low cost, reliability, and compactness. The performance of a vane expander can be evaluated with the isentropic efficiency η below:

$$\eta = \frac{h_{in} - h_{out,real}}{h_{in} - h_{out,ideal}} \times 100\% \quad (1)$$

Where η is the isentropic efficiency of vane expander, h_{in} is the inlet enthalpy of the vane expander (kJ/kg), $h_{out,real}$ is the real outlet enthalpy of the vane expander (kJ/kg), $h_{out,ideal}$ is the ideal outlet enthalpy (isentropic process) of the vane expander (kJ/kg).

Aoun [18] summarizes the efficiencies of several vane expander using different working fluids in different working temperatures and pressures, such as max efficiency of 80% at 800RPM using working fluid R-11, and the efficiency of 50% at expander power output of 1.8kW using working fluid R-113 with inlet temperature and pressure of 110^0C and 5.23bars. However, R-11 and R-113 have been phased out by Montreal protocol on substances that deplete the ozone layer. The vane expander investigated by the authors in their biomass-fired

CHP system with ORC achieved acceptable isentropic efficiencies, as shown in Fig. 13. The isentropic efficiency increases with increasing RPM (rotation per minute) of the vane expander. For example, one of study cases achieved the isentropic efficiency of 54.5% on 26 Aug 2010 (real output of mechanical work of 1.552kW and ideal isentropic output of 2.851kW) at rotational speed of 824RPM. The electric power generated by the vane expander via an alternator was 792W_e which made 17 of 50W-rated bulbs bright. The expander inlet temperature and pressure of the HFE7000 vapour were 113^{0}C and 5.38bars, respectively, and the expander's vapour pressure ratio achieved was 2.0.

It needs to be pointed out that the rotational speed of a vane expander is strongly affected by the pressure and flow rate of the inlet compressed vapour. Further, due to the compressibility of the vapour and the mechanical friction, the RPM of the vane expander is actually nonlinear with its inlet pressure and it has hysteretic behaviour [23].

Another distinguishing feature of this type of rotary sliding vane expander is the injection of liberal quantity of lubricating oil directly into the expansion chamber, in order to seal each chamber from its neighbour and to lubricate the contact friction between the vanes and the stator as well. However, there are also non-lubricating air motors which can be used as expanders of micro-scale ORC-based CHP systems. Indeed, one of such a non-lubricating expanders has been tested by the authors with their biomass-fired ORC-based micro-CHP system and proved to be as good as the lubricating vane expander [2].

3. Selection and choices of expanders for ORC-based micro-CHP systems

Micro-CHP units can be widely applied to domestic and institutional buildings (e.g. schools and hospitals), where safe, simple operation and low investment are necessary. The organic Rankine cycle (ORC) can be used in micro-CHP units to achieve lower operation pressures and temperatures to reduce system cost and complexity and alleviate safety concerns. When selecting expanders for this type of micro-CHP units, there are other factors than efficiency and cost that need to be considered:

(1) Working temperatures and pressures: the operating pressures and temperatures of the expanders are likely to be up to 10 bars and 200^0C respectively. The vane expander used by the authors can withstand 7 bars and 120^0C.

(2) Leaking: the loss of organic working fluid due to leaking is unacceptable under any circumstances. The vane expander used by the authors had been properly modified to prevent leaking.

(3) Noise and safety: excessive noises are not acceptable with building applications of micro-scale CHP units. Turboexpanders as velocity-type of expanders are driven by high velocity streams of vapour to rotate the turbine blades and hence makes considerable noise. If a mixture of vapour with liquid droplets pushes the blades, the noise level will be greater and the blades can be deformed to become unsafe to continue the operation. On the other hand, volume-type expanders are quieter than turboexpanders and allow the mixture of vapour and liquid droplets to enter with little harm to the rotor.

The Choices of expanders for ORC-based micro-CHP units within the size range of 1-10kW$_e$ can be summarized as follows:

(1) Scroll expanders and vane expanders are likely to be good choices because they can provide high expansion ratios and acceptable performances over a wide range of operations with simple design and low cost. In addition, they are relatively easy to be scaled down in a wide range of 1-10kW$_e$.

(2) The rotary vane expander can represent a good option when the required turbine power output is lower than 2 kW$_e$ [18].

(3) If Turboexpanders and screw expanders are scaled down to 10kW$_e$ level, their efficiencies are likely to become unacceptable because they are commonly designed for larger units and

high pressure and high temperature operations. Micro-scale turboexpanders and screw expanders (1 -10kWe) are currently under development with the aim of increasing efficiency and reducing costs.

4. Conclusions

This paper examines different types of expanders, i.e., axial turbine expander, screw expander, scroll expander and vane expander, respectively. It summarizes the findings of the market research for the expanders and discusses the selection and choices of the expanders for ORC-based micro-CHP systems.

Micro-scale expanders (<10kWe) suitable for ORC-based micro-CHP systems are not yet available on the commercial market. Many researchers have used in-house designed and manufactured expanders in their experimental systems. The authors have tested the expanders which are modified from vane-type air motors with their micro-scale biomass-fired ORC-based CHP system [2]. Analyses of the working principles and the characteristics of various expanders have led to the conclusion that scroll expanders and vane expanders are likely to be good choices for ORC-based micro-CHP systems within the capacity range of 1-10KW_e.

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Table 1

Scenarios of commercial availabilities of current small/micro-scale expanders

Manufacturer name	Company websites	Product type	Minimum expander	Available time and cost expected
Infinity Turbine LLC USA	www.infinityturbine.com	Turbine expander	Model IT01 ($1kW_e$) Model IT10 ($10kW_e$)	Now. turbine only US$10,000
Green Energy Australasia, Australia	www.geaust.com.au	Turbine expander	Model SG10 ($10kW_e$)	Now.
ORMAT Tech., Inc. USA.	www.ormat.com	Screw expander	$50kW_e$	Now
ELECTRATHERM, USA.	www.electratherm.com	Screw expander	$50kW_e$	Now
ENEFTECH, Switzerland	www.eneftech.com	Scroll expander	010GRE-01 ($5kW_e$ or $10kW_e$)	Now, CHP unit cost €55,000.
Freepower, UK	www.freepower.co.uk	Scroll expander	$6kW_e$	Supply due spring of 2011.

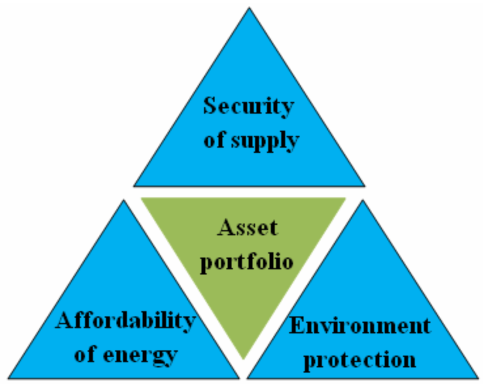


Fig.1. Energy trilemma

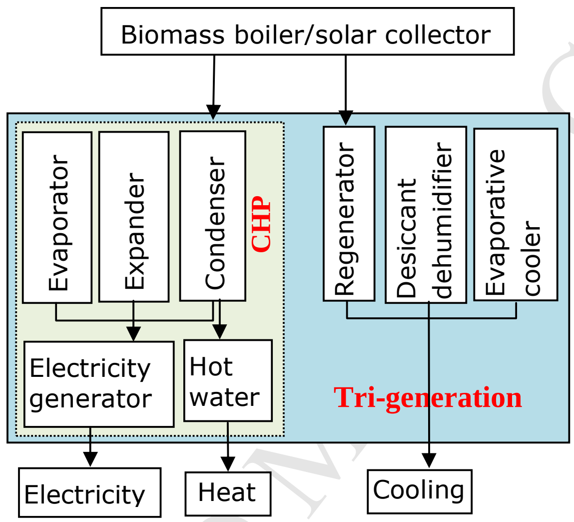


Fig.2. Flow chart of CHP and tri-generation

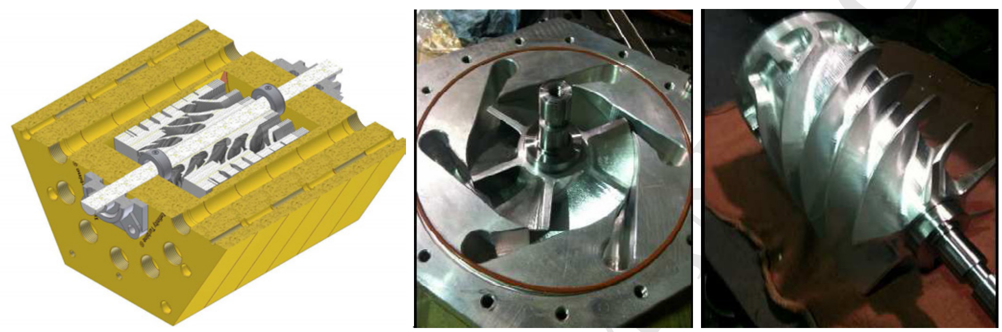
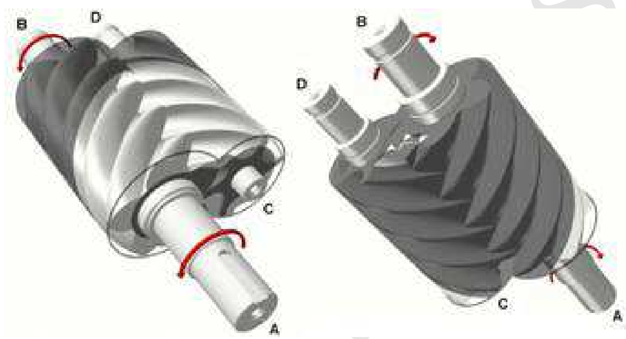


Fig. 3. Working principles of Infinity Turbine MODEL IT10 (10kWe)

Fig. 4. MODEL IT10 turbine (10kWe) with Organic Rankine Cycle (H1220mm×W610mm×D1220mm)

Fig. 5. A high-speed micro turbine for Organic Rankine cycle



a) View from Rear and top   b) View from front and Bottom

Fig. 6. Screw Expander Components

Fig. 7. A twin screw expander from Sprintex of Australia (www.sprintex.com.au)

Fig. 8. ElectraTherm green machine with patented twin screw expander (H1830mm×W1525×D2287mm)

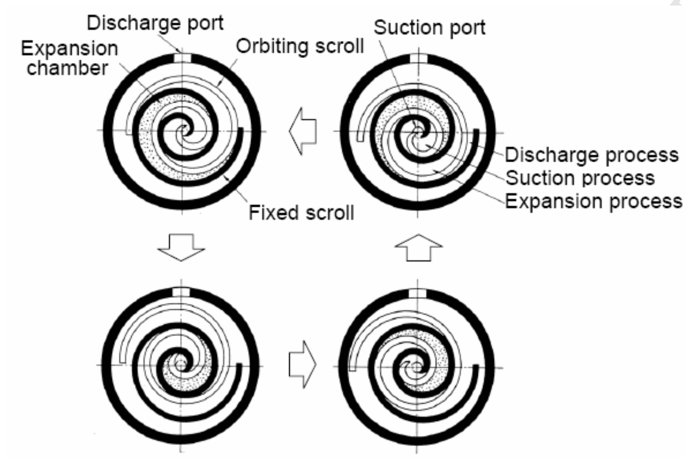
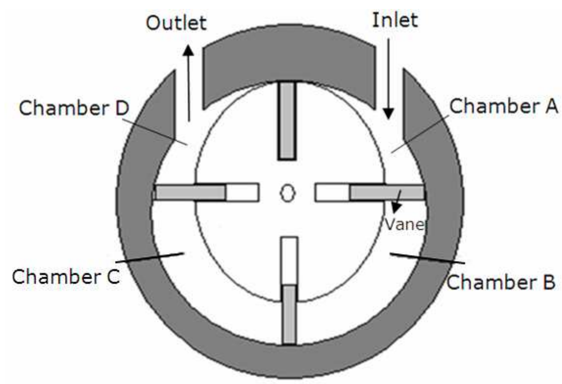


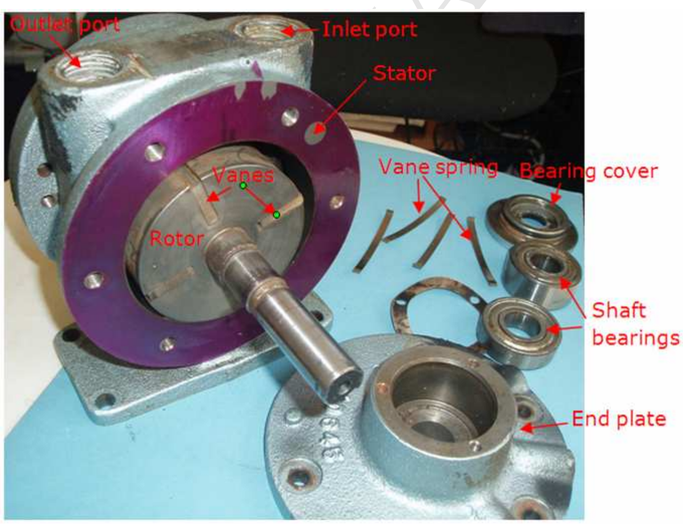
Fig. 9. Operational cycle of scroll expander

Fig. 10. Cross-sectional scroll expander

Fig. 11. ENEFCOGEN^{GREEN} range 010GRE-01 (H1700mm×W1500mm×D750mm)



(a) Diagram of four vanes expander



(b) Rotor and vanes
(Rotor's top edge touches stator's internal surface in the working mode)

Fig. 12. Vane-type air motor as an expander

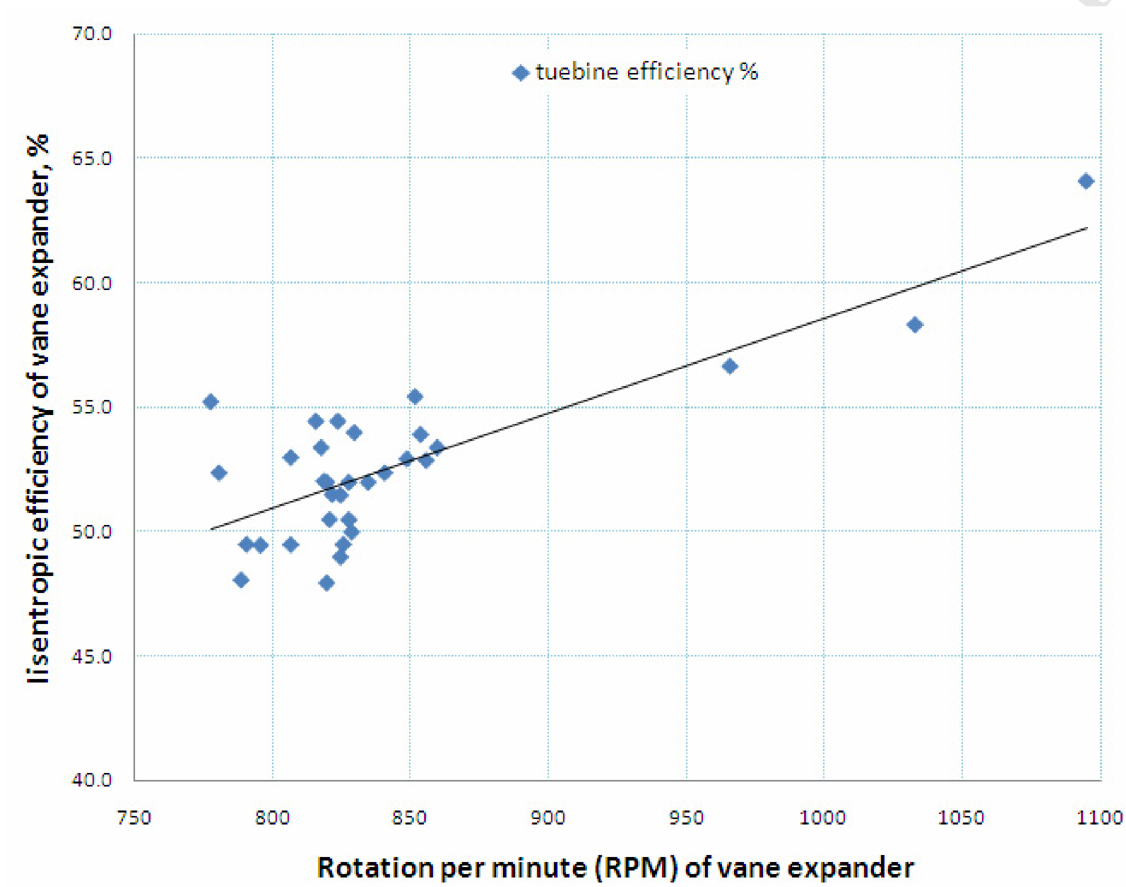


Fig. 13. Variations of isentropic efficiencies vs rotations per minute (RPM) of vane expander