The Application of Helical Screw Expanding Technology for Geothermal Power Generation

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ABSTRACT

The Helical Screw Expander (HSE) is a unique reciprocating positive displacement machine used to compress air, nitrogen, hydrocarbons and a variety of refrigerants. As expanders, these machines are used as prime movers, accessory power drives and for temperature reduction in gas cycle refrigeration systems. They have been demonstrated to have adiabatic efficiencies in excess of 70-75% over a wide operating range. Widely deployed in China for waste heat recovery, current installed capacity is estimated at approximately 500MW in industries such as; iron and steel, petroleum, chemicals, non-ferrous metal smelting and waste incineration.

Its application for geothermal power production is however relatively recent, with much of the development in this field occurring within China. In this paper we describe Chinese experience; from the early stages of technical development as a waste heat recovery unit through to deployment of the 1st HSE geothermal power generation unit in 2007 in Yangbajing, Tibet. Commercial development of the technology continues with currently 6 operating units generating 6.8MW installed in the Tibet area, further capacity under way in Yunnan province and a first enhanced geothermal system (EGS) project commencing in Zhengzhou.

In New Zealand, an unsuccessful trial of an early-stage version of the HSE technology by the MWD at the Broadlands in 1982 has tended to colour industry attitude in respect of the technology in this country. Chinese experience, however, has demonstrated the potential of HSE technology to extract more power than competing technologies from strongly mineralized low enthalpy geothermal fluids.

To this end, Demeter New Energy Technology Ltd. has proposed a first demonstration project within the Te Mihi geothermal field. If approvals are given the project will initially involve a 2MW single stage, containerized wellhead unit to evaluate mechanical and thermodynamic performance of the technology and its reliability in a NZ geothermal field condition.

1. TECHNOLOGY DESCRIPTION

1.1 Overview

The potential of waste and other low-grade heat sources for power production has been known and investigated for decades, but hitherto the high cost of the equipment needed to generate power from such sources has made it economically unattractive for all but a very limited number of applications. Screw expanders whilst known for a long time have largely been ignored as an alternative option to the Carnot Cycle configuration conventionally used for energy recovery.

The Helical Screw Expander (HSE), the subject of this paper, is essentially a reciprocating positive displacement machine. Positive displacement machines effect pressure changes by admitting a fixed mass of fluid into a working chamber where it is confined and then compressed or expanded, to produce the work required to drive a shaft for an electrical generator. A typical configuration of a Screw Expander machine is as below:

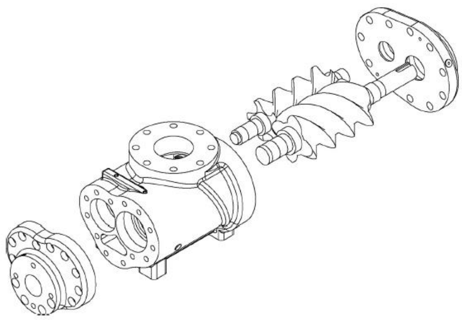
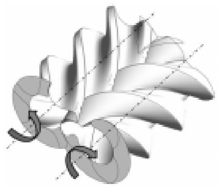


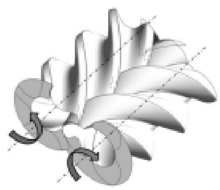
Figure 1: Expanded view screw expander from Smith *et al* [1]

The use of twin-screw expanders instead of turbines as a mechanical drive offers a number of potential advantages in that they can be manufactured relatively cheaply, can operate intermittently and can accept two-phase liquid-vapour mixtures, or even pure liquids. Essentially, screw expanders operate over a slower speed range and without the high radial loads and balance problems that are characteristic of turbines. Volumetric changes within the machine are effectively three-dimensional rather than the constrained two-dimensional flow that occurs in a turbine; with the fluid flow transferring from having a strong axial flow component at the high-pressure inlet end to largely radial flow at the low-pressure discharge end of the machine [1]. This effect is shown diagrammatically in Figure 2 below.

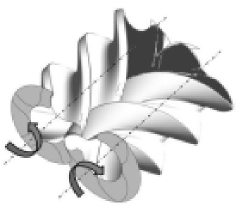
Fluid velocities within the machine are an order of magnitude less than those seen in turbine machines and therefore there is little risk of damage resulting from the admission of liquid/vapour mixtures. An expander machine can admit fluids of any composition from pure liquid to dry vapour, while maintaining thermodynamic equilibrium between the phases; thus achieving an improved thermodynamic cycle efficiency for power recovery [1]. In thermodynamic terms, the process approximates an isentropic expansion from the saturated liquid line for the total amount of flow to the point of lowest expansion pressure.



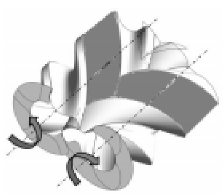
1. Twin Screw Rotor Pair



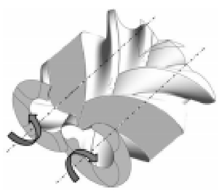
2. High Pressure Filling-Start of Expansion Cycle



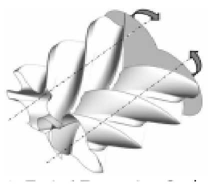
3. High Pressure Port Close



4. Expansion in Progress



5. Low Pressure Port Open



6. End of Expansion

Figure 2: Principle of operation of a screw expander from Smith *et al* [1].

Both adiabatic and volumetric efficiencies are highly dependent on rotor profile, rotor speed, working fluid temperatures and the built-in volume ratios between each stage. Design of these machines and optimisation of the power output per unit flow of the fluid medium is thus strongly reliant on both thermodynamic and fluid dynamic modelling with a significant literature in the public domain describing mathematical modelling and numerical methods for machine design, although much is proprietary [2] [3] [4].

Leakage losses during the expansion process and pressure drop losses are the main influences affecting internal efficiency. The main leakage paths in twin-screw expanders are leakage through inter-lobe clearance and the rotor tip-housing clearance [3]. High inlet pressures provide a greater power output but result in increased throttling losses, leakage losses, and pressure drop in the suction process.

Managing these influences through good design has been the determining factors in their achieving reliable performance and subsequent industrial uptake. Nowadays the machines are routinely used to compress air, nitrogen, hydrocarbons a variety of refrigerant as well as an expander to recover energy from low-grade heat sources.

1.2 Typical Applications

As stated above positive displacement machines have a wide range of application in refrigeration, and compressed air production, and hydrocarbon industries. Their total world production rate is in excess of 200 million units per annum [2]. However, whilst commonly in use as a compressor, it was not until the 80s that there was any extensive commercial application for waste heat recovery as a process expander in closed cycle systems for the recovery of power from low-grade heat sources.

Typically, these applications involve the capture of available energy when a process stream (such as steam or a gas) is reduced in pressure through a pressure reduction valve. The schematic below shows a typical process configuration with the screw expander operated in parallel with the pressure reduction valve. The shaft power, thus extracted, can be used to drive a generator to produce electricity and thereby reduce electricity consumption within the plant.

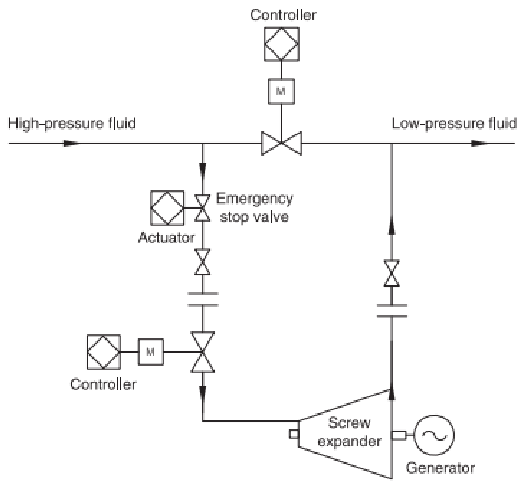


Figure 3: General layout of an expander generator within a larger system. From Smith *et al* [1].

Application of the technology has continued to grow to the present date with installation totalling over 500MW currently in operation in China in various industries; such as iron and steel, petroleum and chemical, coal chemical manufacture, natural gas transport, non-ferrous metal smelting, waste incineration, and in thermal power plant including hybrid ORC systems [5]. In these applications packaged screw-expander machine (as is shown in the figure below) have been demonstrated to have adiabatic efficiencies in excess of 70-75% over a wide operating range.

Figure 4: Sinopec Maoming Petrochemical Complex

A particular application is for small offshore oil rigs, where gas expanders of this type can be used to generate an uninterrupted power supply (UPS) to meet critical rig electrical power requirements in the case of a shutdown or process upset condition.

Since this industrial wave within China the concept of using these-type machines in geothermal applications has become well established [4], although technically still relatively immature. Screw expanders have a growing history of successful operations in China in liquid dominated geothermal environments where it has been shown that the HSE can accept untreated strongly mineralized water from a geothermal well with potential to generate more power per unit mass flow rate of geothermal fluid than a conventional steam separator generator unit.

A typical configuration for geothermal application is shown in Figure 5. Actual field experience to date indicates an efficiency advantage for the screw expander operating on high enthalpy brines gat more than 6 percentage-points over conventional approaches

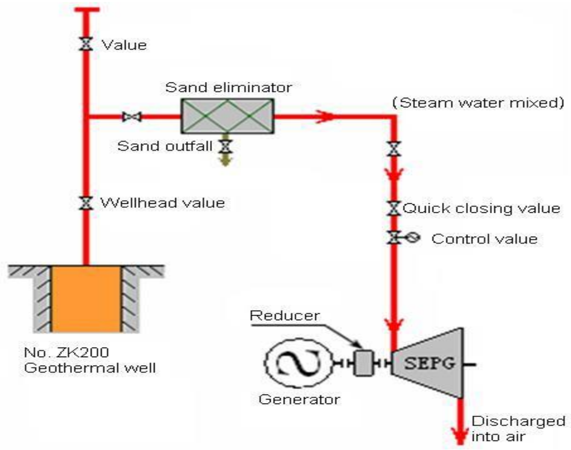


Figure 5: General arrangement HSE well-head generation machine. *Courtesy Demeter New Energy Ltd.*

The reminder of this paper discusses experience with utilizing the screw expander technology in geothermal applications, and aims to draw general conclusions on application in the NZ context. Typical applications envisaged for NZ include energy recovery from low-grade waste process heat, exhaust gases heat recovery, and power generation from low-pressure geothermal and potentially hydrothermal systems.

2. GEOTHERMAL DEVELOPMENT HISTORY

2.1 Historical Work

Amongst the earliest work reported describing the use of screw expanders for geothermal application is work undertaken by the US Jet Propulsion Laboratory (JPL), Pasadena, California around 1974 [6]. This work tested a 62.5 kVA prototype geothermal wellhead system developed by Hydrothermal Power Co., Ltd. (HPC) operating on hot untreated brine or brine and steam mixtures. JPL concluded that these machines were well suited to wet steam geothermal fields and could be a major stimulant to the development of new geothermal energy resources.

A subsequent research and development programme conducted by the International Energy Agency (IEA) completed a range of field trials in Mexico, Italy and New Zealand using a 1MW portable HPC screw expander wellhead generator. This machine type had been previously field-tested in Utah, USA, in 1978 and 1979, with the IEA programme aimed at further testing both performance and reliability of the screw expander in different field settings. The U.S. Department of Energy (DOE) participated in the tests with the assistance of HPC as manufacturer of the power plant, and JPL. [7]

In New Zealand the testing programme were performed by the Ministry of Works & Development at the Broadlands Geothermal Field between September 1982 and June 1983 [8]. The tests undertaken demonstrated that the screw expander had potential to extract more power from a low enthalpy geothermal fluid than the alternative atmospheric exhaust steam turbine generator set, but that life of the shaft seal and issues of plant reliability significantly impacted on overall performance.

As a wellhead generating unit, these plants must be capable of running untended and thus their reliability was seen as a major deterrent for any further deployment. Interestingly, whilst these early units did not offer the efficiency levels that are achievable nowadays, the results of 1632 hours of endurance testing indicated that the growth of a very thin layer of scale on the rotors during the operating period resulted in a 3.5 percentage-point improvement in generation efficiency. At the end of the test the measured efficiency was 46.5% and evidently still increasing.

Based on the operating results from all three countries and a cost/benefit analysis against conventional turbine generators, the IEA rated the screw expander power plant as suitable for non-condensing service in some liquid-dominated fields. Improvements to the shaft seal flush water system and the speed control system were identified as important, and closing of the rotor clearances, either through manufacturing changes or operating changes, were deemed necessary for best performance. It appears, however, that because of these problems the approach was largely abandoned.

Ignored, also was the potential for replacing the pressure reducing valve by a screw expander in existing flash steam plant. We suggest that this has been a lost opportunity, and that this opportunity still exists as a means of augmenting current generation capacity. (see reference [3])

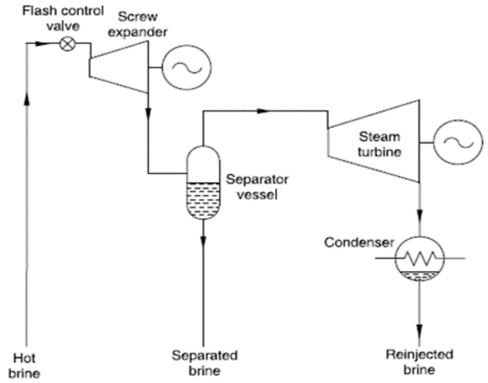


Figure 6: A simplified hybrid geothermal power application from Smith *et al* [1]

Of course, there remains the problems that a geothermal brine will contain significant amounts of silicates and salts, which will come out of solution as the pressure is dropped and temperature reduced but, as described below, modern machines such as those deployed in China have a demonstrated performance with highly mineralised fluids. More important is the ability to match the maximum scale of current machines with the fluid volumes (relatively low pressures and thus associated high volumes) typically seen in a conventional power plant. This is an area deserving of more attention and probably would requires a split flow arrangement that essentially runs the screw expander in a by-pass mode.

2.2 Improvement and Subsequent Commercial Use in China

In China original work on the design and application of the screw expander begin in the mid 50s under the guidance of Prof Hu Liangguang ex Moscow University. Then followed some 30 years of theoretical research from around the 1980s, including the development of 5kw experimental unit tested in Tibet [5]. This work was further extended and support under the auspices of the Chinese 8th 5-Year Scientific and Technology development plan with a number of industrial scale demonstration of the technology undertaken.

Later in the 2000s, the technology was further developed for application as a prime mover operating on geothermal power generation. The first helical screw expander geothermal power generation unit was installed in Yangbajing, Tibet, China in 2007 and was connected to the grid in Sep 2008. Equipment details (from Demeter New Energy Ltd.) are given below.

		Unit	1MW units (1st phase)		1MW units (2nd phase)		Remark
			Design (32t/h)	Actual (28t/h)	Design (28t/h)	Actual (22t/h)	
1	Parameters	–	Inlet / Outlet P 0.68/0.25MPa	Inlet / Outlet P 0.36/0.09MPa	Inlet / Outlet P 0.8/0.25MPa	Inlet / Outlet P 0.39/0.09MPa	problem-free operation for over 2 years.
2	Power	KW	1000	940	1000	800	

A more general arrangement for the Yangi geothermal development is shown in Figures 7& 8. As can be seen these are full well-head arrangements based on a modular containerised design. The screw expander design allows for the full flow of the geothermal fluids, including steam, associated water, dissolved gases and minerals. Reported experience is good with no significant effects from the geothermal parameters on efficacy and flexibility.

Wellhead pressure at the field is 0.32Mpa with flows of 95t/h. Inlet pressure to the expander is 0.25MPa at an outlet pressure (discharged to atmosphere at 4,500m elevation) of 0.055Mpa. Silica content of the geothermal fluid is reported as around 150 g/m^{3}as SiO_2, with a pH of 8.3. The modular design also provides for easier shipping and assembling, faster installation, and higher plant reliability and operational flexibility than conventional plant.

Figures 7 & 8: General Arrangement 500KW HSEPG unit, Yangyi Geothermal Project Stage 2, Tibet (grid connected 2012*). Courtesy Demeter New Energy Ltd.*

The commercial development of the technology has continued to the present day with a total of 6 commercial units generating 6.8 MW now installed in the Tibet area, and with further capacity under commissioning in the Yunnan province and a first enhanced geothermal system (EGS) project commencing in Zhengzhou. The Yunnan development anticipates an eventual 500MW installed capacity at a project cost approximately $NZ 3 billion, although this investment includes significant ancillary works. It would thus seem from the development currently occurring that the bulk of the technical and cost problems associated with commercial development of such devices have been solved.

Figures 9 & 10: Modern 4th Generation Plant Arrangement 1 MW Unit; *Courtesy Demeter New Energy Ltd.*

There remain some areas of uncertainty regards aspects of performance estimation based on computer simulations, but general efficiency predictions based on such models have been substantially confirmed. The key to current technical understandings has been the laboratory tests, design simulations and field trials undertaken. Compared with steam turbine generator units in the same area, the economics and conversion efficiencies are much greater than those achieved by conventional technologies (flash and binary cycles). The current issue for the screw expander is in fact size limitations (2MW maximum single stage) which means that a large geothermal plant would need multiple units. However, as previously indicated, hybrid configurations would allow better utilization of the available geothermal resource.

Shorter payback times, remote control, no requirement for specialist operating skills, and a demonstrated good maintenance record makes these units eminently suitable for geothermal application. A comparison of the screw expander performance against competing technologies is shown below:

Wellhead data / Technology	Temperature （150 C）		
	Dryness		
	0%	5%	10%
	Water Only	Mixed Fluid	Mixed Fluid
1 stage flash steam	6.3 kWh/t	9.3 kWh/t	12.9 kWh/t
2 stage flash steam	7.8 kWh/t	11.6 kWh/t	15.8 kWh/t
ORC	6.8 kWh/t	11.5 kWh/t	18.8 kWh/t
HSEPG	11.3 kWh/t	16.2 kWh/t	20.9 kWh/t

Power generation under different dryness options; outlet temperature (41.5℃), flow (100 tonne/hr). Source; in-house data *Demeter New Energy Ltd.*

3. APPLICATION TO NEW ZEALAND

With geothermal systems occurring across many parts of New Zealand, including both high temperature geothermal fields as well as moderate to low and very low temperature systems there is a significant opportunity to expand the use of geothermal energy in this country. Whilst much of the investment in the past has been looking at large-scale generation, in more recently times there has been a push for better utilisation and more structured development of low enthalpy geothermal resource. The screw expander is well suited for this purpose. Typical applications, apart from the obvious energy recovery from low-grade waste process heat, is power generation from low-pressure geothermal and potentially hydrothermal systems.

An important aspect of power plant design, which becomes more significant at lower temperatures, is the connection between thermal efficiency and cost. This is particularly so in the case of a geothermal power plant. With a brine temperature of 120 °C, the maximum temperature difference between the heat source and the coolant is only of the order of 100C. Thus, the efficiency of a conventional geothermal plant may only be in the region of 10-15 % whereas, for example, it will be much higher in screw expander, which essentially offers an engineered solution to the problems of scale and corrosion whilst also offering an efficient thermodynamic cycle able to maximise heat recovery from the geothermal fluid.

To this end, Demeter New Energy Technology Ltd. has proposed a first demonstration project within the Te Mihi geothermal field, near Taupo. It is currently seeking regulatory approvals from the Overseas Investment Office to proceed with a project will initially involve a 2MW single stage, containerized wellhead unit based on HSE technology. Initial aims are to evaluate mechanical and thermodynamic performance and reliability of the machine in a NZ geothermal field condition. Even at this small scale, economics are expected to be attractive due to the lower installed cost for this system versus larger plant previously planned for the site.

The project is located near the intersections of Tukairangi Road and Poihipi Road, Taupo on private freehold land. Engineering work is well advanced for the screw expander plant. The existing GGL-1 production well was retested by Demeter and MB Century in September 2016, all data has been assessed and evaluated for the project purchase and will be used for the stage one generating unit main design parameters. An indicative site plane is shown below:

Figure 11: Site Plan Proposed NZ Facility

The unit to be installed is designed specifically as a wellhead-generating unit. It is intended that the plant will be capable of running unattended with minimum operator supervision. Ultimately, should the demonstration project prove successful it is intended that the project deploy up to 80 MW of power generating capability to be built in four stages. This will be dependent on reservoir performance and overall efficiencies achieved. The project timeline goes out to the year 2025 for the full-scale project. Initial site works and commissioning of the first unit is expected to be completed within 9 months of the OIO approval and financial commitment. All resource consents for the project are in existence.

4. CONCLUSION

This review describes advances in the industrial application of screw expanders over the recent history. Widely deployed in China for waste heat recovery, Chinese experience with the technology has led to its successful deployment in geothermal applications for wellhead power generation. Based on this success the HSE machine's application in low enthalpy geothermal systems can be regarded as proven. There is also opportunity for the machine's deployment in hybrid systems within conventional geothermal power plant; both for flash/steam turbine and ORC configurations.

As a wellhead unit, the screw expander displays the following outstanding features:

- There is no problem of a thermo-chemical nature occurring inside the machine, such as scaling and precipitation which are major problems in Organic Rankine Cycle Plants;
- Almost all of the available enthalpy of the geothermal fluid is recovered;
- Thermo-mechanical efficiency is of the order of 70% with an internal efficiency between 65%-90%;
- Unit sizes range from 400 KW to 2 MW electricity rated; delivered either prepacked or as a containerized factory unit. This significantly reduces investment costs (pipeline and road infrastructure and associated works) and dramatically shortens construction times;
- Units can be used both for condensing and backpressure application;
- Long life cycle & long major maintenance periods have been demonstrated;
- A Real Time Remote Monitoring & Control System provides for safe and reliable operation, and requires no specific technical expertise under normal operation;
- The optimum power output at the maximum stable operating pressure is stable under various wellhead mass flow rates and wellhead pressures;
- Shorter payback periods over other options.

Successful deployment of the technology in NZ will be do much to broaden NZ's understanding of this technology; creating opportunities for long term investment in New Zealand and enabling further development of this country's medium- to low-enthalpy geothermal resources and, thus, creating an overall economic benefit to New Zealand.

ACKNOWLEDGEMENTS

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