Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Applications of the Screw Expander in Geothermal Power Generation in China

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Keywords: geothermal power generation; screw expander; full-flow system; flash steam system; binary cycle (ORC)

ABSTRACT

The screw expander is a kind of full-flow power machine, which can be applied not only to superheated steam and saturated steam, but also to wet steam and even steam-liquid mixtures. The screw expander shows excellent characteristics: anti-contamination, self-cleaning, simple system structure, few spare parts, convenient maintenance, high equipment reliability and long service time. It has been applied in geothermal power generation in China, such as flash steam systems, full-flow two-phase systems and binary cycle systems (ORC). With its unique technical characteristics, the screw expander will find much wider applications in geothermal power generation, including in high-, medium- and low-temperature geothermal fields and for all kinds of geothermal power generation technologies. Finally, two main geothermal power generation systems with screw expanders for YangYi geothermal power plant planning were designed and analyzed.

1. INTRODUCTION

With geothermal power generation increased year by year, geothermal resources have attracted more and more attention. It has become an important trend to explore new geothermal fields with high-, medium- and low-temperature, and improve geothermal power generation technologies. In the early 1970s, as the countries in the world paid more attention to the development of new energy sources, China started booming of geothermal power development. At that time, China not only developed the medium- and low-temperature geothermal power technologies in different places, but also set up a high-temperature geothermal power plant at YangBaJing in Tibet, which is currently still the largest geothermal power plant in China. After 1991, the development of geothermal power generation in China almost fell into the trough and was in stagnation for almost 20 years. Since the advent of second booming of geothermal power development in recent years, the screw expander has found applications in geothermal power generation in China.

1.1 The traditional geothermal power generation technologies

The geothermal power generation technologies can be classified, according to types of geothermal resource, as: dry steam power generation, flash steam power generation and binary cycle power generation (Chamorro et al. 2012).

Dry steam power plants use high temperature, vapor-dominant hydrothermal reservoirs. The saturated or superheated steam from wells passes directly through the turbine-generator unit and produces electricity. The application of dry steam power generation is very limited because of fewer vapor-dominant hydrothermal resources. Flash steam power plants are applied when a liquid-dominant mixture is produced at the wellhead of the hydrothermal reservoir. In single flash steam power plants, the mixture from the wellhead is separated into vapor and liquid phases in the flash vessel and the vapor is sent to turbine-generator unit. The separated liquid-phase fluid can be sent to the secondary level flash vessel to obtain more steam at a lower pressure and the steam enters low pressure turbine to produce more electricity. These systems are called double flash power plants. The binary cycle is an appropriate technology for geothermal power generation when using geothermal fluid from liquid-dominated resources with relatively lower temperature. In the binary cycle plants, a binary working fluid with a low boiling temperature receives heat from the geothermal brine in evaporator and vaporizes, then expands in turbine to produce work output, condenses in condenser and finally is returned to the evaporator by a pump, which is working in the closed cycle. Most binary cycle plants are based on the Rankine cycle.

The geothermal power generation technology used is directly related to the state of geothermal fluid and its temperature. High-temperature geothermal resources above 150°C are most suitable for commercial production of electricity with dry steam or flash steam systems. Moderate-temperature (between 90°C and 150°C) and low-temperature (below 90°C) geothermal resources are by far the most commonly available resource and are highly recommended for using in local district heating. Some novel designs such as binary cycle or binary-flash system are proposed to generate electricity from low-temperature resources economically (Mohanty et al., 1992 and Yuan et al., 1993).

1.2 A review of geothermal power generation in China

China began its development of geothermal power generation in the early 1970s. At that time, seven small-scale testing geothermal power plants with medium- or low-temperature geothermal sources were established in different places in China. The geothermal fluid temperatures are less than 100°C and the lowest temperature is 67°C. All the systems and equipment were designed and manufactured in-house by adopting the flash steam and binary cycle technologies for medium- and low-temperature geothermal power generation and modifying small waste generators as power generation equipment. The testing was successful to produce electricity for local use and some power plants were running for a long time. However, most of the power plants have been closed because of technical or economical problems. Table 1 shows the seven small-scale testing geothermal power plants and their related information (Zheng and Pan, 2009).

Table 1 The testing geothermal power plants and their related information

Power Plants	Location	Geothermal fluid temperature /°C	Output power /kW
DengWu	Fengsun, Guangdong	92	300
HuiTang	Ningxiang, Hunan	98	300
HouHaoYao	Huailai, Hebei	87	200
TangDongQuan	Zhaoyuan, Shandong	98	300
XioingYue	Gaixian, Liaoning	90	200
ReShuiCun	Xiangzhou, Guangxi	79	200
WenTang	Yichun, Jiangxi	67	100

In spite of small power output and not being connected to the grid, these small-scale testing geothermal power plants were a symbol of the first successful testing of geothermal power generation in China.

The high-temperature geothermal power generation in China started in Tibet in the middle of 1970s. Since the first 1000 kW power generating unit was installed in YangBaJing geothermal power plant and successfully produced electricity in September 1977, a total of 9 turbine-generator units with a total capacity of 25.18MW were installed during 15-year's period, until the last 3000kW turbine generating unit was put into operation in 1991. YangBaJing geothermal power plant sustained stable operation continuously for a long time, more than 36 years since the first generating unit was put into operation. It has already become an important power supply for Lhasa's electricity grid with stable annual power generation of 100GWh (Liao, 2011). In addition, Langjiu geothermal power plant was established in 1983, a 2MW geothermal generating unit was put into operation in 1985 in Ali, Tibet, and Naqu geothermal power plant established in 1993 with a 1MW unit put into operation in 1994. However, these two units later stopped running for various reasons (Zheng and Pan, 2009).

1.3 The novel geothermal power generation technology with screw expander

The screw expander is a kind of rotary, volumetric and full-flow power machine capable of turning low-temperature thermal heat into mechanical energy or electricity. It is suitable for uses not only in superheated and saturated steam but also with two-phase mixtures. The screw expander has potential to find wide applications in geothermal power generation with such significant characteristics as suitability for various working fluids, anti-contamination and self-cleaning characteristics, simple system structure and fewer parts, convenient maintenance, and long service time.

Under the support of Chinese government, the first screw expander generating unit with the capacity of 1MW, manufactured by Jiangxi HuaDian Electrical Power CO. Ltd., was put into operation in YaBaJing for geothermal power generation in 2008, and another screw expander unit with the same capacity was followed by putting into operation in 2010. This new technology applied in YangBaJing has demonstrated that the screw expander generating unit is more suitable for high temperature geothermal resources. After that, a prototype of the full-flow screw expander generating unit, which is much more suitable for two-phase geothermal sources, was successfully produced by Jiangxi HuaDian Electrical Power CO. Ltd. in 2011. Two testing units of full-flow screw expander with capacities of 400kW and 500kW respectively were installed in YangYi, another high temperature geothermal field in Tibet, in 2011 and 2012 respectively.

The successful operation of testing units of screw expander proved full-flow technology has higher thermal efficiency than conventional flash steam system for geothermal power generation. The screw expander generating units also found application in medium- and low-temperature geothermal sources by using a binary cycle system (ORC). The screw expander generating unit with ORC has been successfully applied in the Huabei oilfield in China, which evaporated organic working fluid (R123) by recovering heat of 100 °C liquid from a deep oil well and drove the screw expander for electricity generation.

2. SCREW EXPANDER SYSTEMS FOR GEOTHERMAL POWER GENERATION AND THEIR APPLICATIONS

The screw expander has already been applied in different kinds of geothermal power plants such as flash steam system, full-flow system of two-phase mixtures and binary cycle system.

2.1 The application of flash steam system in YangBaJing

In the 1980s and 1990s, the geological prospecting was carried out for the deep reservoir in north part of YangBaJing geothermal field. The well ZK4001 was drilled and completed with the depth of 1459m by October 1996, with total mixture flow rate of 302t/h, temperature of 200°C and corresponding pressure of 1.47 MPa in the well. Since 2006, the geothermal heat from ZK4001 has been connected to the heat supply system in YangBaJing geothermal power plant.

Under the support of Chinese government, the first screw expander generating unit with the capacity of 1MW, manufactured by Jiangxi HuaDian Electrical Power CO. Ltd., was put into operation in YaBaJing for geothermal power generation in September 2008. The screw expander generating unit produces real power of 940kW with actual operation parameters of inlet pressure 0.36MPa, outlet pressure 0.09MPa and the mixture flow rate 28 t/h. Figure 1 shows the running screw expander generating unit with the capacity of 1MW in YangBaJing geothermal power plant.

Figure 1: A 1MW screw expander generating unit in YangBaJing geothermal power plant

The second screw expander generating unit with the same capacity was put into operation in October 2010. This generating unit produces real power of 800kW with operation parameters of inlet pressure 0.39MPa, outlet pressure 0.09MPa and the mixture flow rate 22t/h. Figure 2 shows the second running generating unit in YangBaJing geothermal power plant.

Figure 2: The second screw expander generating unit in YangBaJing geothermal power plant

2.2 The application of full-flow system of two-phase mixtures in YangYi

The Yangyi geothermal field, located in Tibet of China, was prospected in the late 1980s and the early 1990s and estimated to be a medium- and high-temperature reservoir. The well ZK200 was drilled and completed with the depth of 606m twenty years ago, having total mixture flow rate of 95t/h, temperature of 134° C and corresponding pressure of 0.26MPa at the wellhead. In June 2011, a special recovery processing of ZK200 was conducted and a testing full-flow screw expander unit of two-phase mixtures with the capacity of 400kW, which is much more suitable for two-phase geothermal sources, was installed at the wellhead and put into operation in September 2011. Figure 3 shows the running testing unit in YangYi geothermal field.

Figure 3: The testing screw expander generating unit in YangYi

After the successful running of the testing screw expander generating unit in Yangyi, another same kind of generating unit with the capacity of 500kW, which takes the container type with the function of black start, was trial manufactured by Jiangxi HuaDian Electrical Power CO. Ltd. and successfully put into operation in Yangyi in August 2012. It is becoming more convenient for transportation and installation. Figure 4 shows the testing container type of screw expander generating unit in YangYi.

Figure 4: The testing container type of screw expander generating unit in YangYi

2.3 The application of binary cycle system in Huabei Oilfield

The water content in numerous oil wells in Huabei oilfield is very high, with an average percentage of 95% and even higher than 98% after long time exploitation. How to increase the economic benefit of oil recovery in such oil wells is a significant research subject. The use of heat from hot liquid associated with oil production to generate electricity using a binary cycle system is a good candidate to improve the economic performance of oil wells at high water content stage (Li et al., 2012).

The geothermal binary cycle system was designed based on such parameters as: a temperature of produced oil-water mixture from oil well between 100° C and 105° C, average flow rate of 250m^3/h, and a tail water temperature of 85° C in summer and 90° C in winter. The system is a subcritical organic Rankine cycle system (ORC), mainly composed of an evaporator, a screw expander, an electric generator, a condenser and a feed pump. The geothermal water after separation of oil and water, because of its impurity, is first introduced into a plate heat exchanger to heat clean water as a heat carrier to avoid scaling and blocking in evaporator. The organic working fluid (R123) absorbs heat from the heat carrier to produce high pressure vapor in the evaporator, then the vapor flows into the screw expander where its heat is converted into work for electricity production. The low pressure vapor discharged from the screw expander is led to the condenser where it is liquefied by cooling water, and the liquefied working fluid is pressurized by the feed pump and flows into evaporator again for new cycle.

The screw expander, manufactured by Jiangxi HuaDian Electrical Power CO. Ltd., was used in the system for geothermal binary cycle generation. The binary cycle screw expander generating unit in Huabei oilfield has a power generation of 350kW and a power supply of 310kW, with the self power consumption rate of 12.5%. Figure 5 shows the binary cycle screw expander generating unit in Huabei oilfield.

Figure 5: The binary cycle screw expander generating unit in Huabei oilfield

3. THE ANALYSIS OF SCREW EXPANDER SYSTEMS FOR YANGYI GEOTHERMAL POWER PLANT PLANNING

YangYi Geothermal Power Station is under construction with the adoption of twin screw expanders as core power generation equipment, which are manufactured by Jiangxi Huadian Electrical Power Co. Ltd. Based on the evaluation report for YangYi shallow geothermal reservoir released by the National Reserve Commission, the construction consists of two phases, each of which will have a capacity of 16MW for power generation. After construction, the exploitation of geothermal reservoir with depth of 3km underground will be taken into account. According to authoritative expert judgment, there is a magma chamber with depth of about

6km underground in YangYi geothermal field regional center, which supports the expansion of YangYi Geothermal Power Station in the future.

Two main geothermal power generation systems with screw expander for YangYi geothermal power plant planning were designed and analyzed.

3.1 Full-flow system with binary cycle system (FFS-ORC)

Considering the two-phase characteristics of geothermal fluid and the wide adaptability of the screw expander, a full-flow system with a screw expander, which has already been put into practical operation in YangYi geothermal field, was considered for YangYi geothermal power plant planning. As the exhaust fluid temperature in the full-flow system is above 80° C, there is possibility to make full use of geothermal energy. As the specific volume of organic fluid vapor is much smaller than steam, it is possible for organic working fluid to be used in smaller screw expander as the bottom cycle of the system when working temperature and pressure become lower. The whole system (FFS-ORC) is composed by two cycles, as described in Figure 6. In the geothermal fluid cycle, geothermal vapor-liquid mixture (state 1) first flows into the moderate-temperature screw expander and expands to the pressure p_2. Then it (state 2) is cooled in a heat exchanger to evaporate the organic working fluid. After that, the exhaust geothermal fluid temperature becomes T_6, and finally the cooled fluid (state 6) is reinjected underground by a circulation pump.

In the organic working fluid cycle, R245fa is pumped to pressure p_5 (state 5). Then, it is evaporated in the heat exchanger (evaporator) by the geothermal fluid. In the low-temperature expander, the organic fluid (state 3) expands to the condensing pressure (state 4) to generate. The condensing process is conducted using water. The cooled organic fluid (state 5) is then pumped to the evaporator to recycle (Wang et al. 2013).

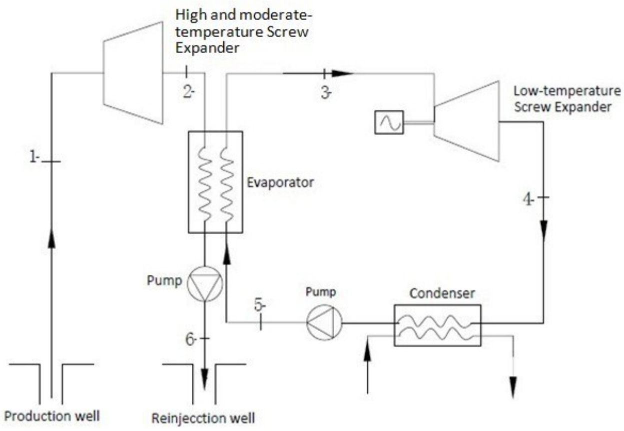

Figure 6: The full-flow system with binary cycle system (FFS-ORC)

3.1.1 Calculation model

The T-s figure for FFS-ORC is shown in Figure7. Each point (1-6) in Figure7 corresponds to the state point in Figure 6. Initial geothermal fluid (state 1 and its position is related to the dryness of the geothermal vapor-liquid mixture) first enters the high- and moderate-temperature screw expander to generate electricity (state 1-2). Then, exhaust fluid (state 2) enters evaporator to transfer heat to organic working fluid. The process of ORC is 5-3-4-5. Initially, the organic working fluid (state 5) is heated into vapor (state 3), and then expands in low-temperature screw expander to generate electricity. Finally, the exhaust vapor (state 4) is cooled in the condenser and pressurized by feed pump to the state of point 5 for recycle. The pinch temperature difference in the evaporator is 10°C.

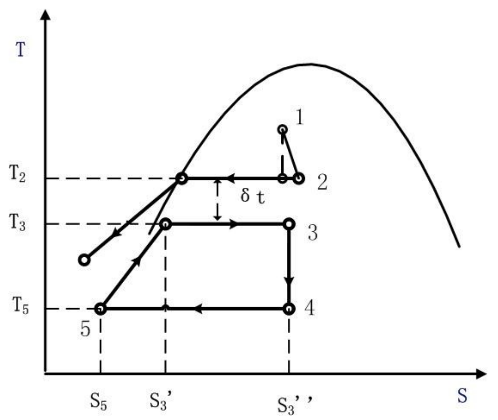

Figure 7: T-s diagram of full-flow system with binary cycle system

The amount of heat released by the geothermal fluid in evaporator can be calculated using Equation 1.

$$Q = m_0 x_2 \gamma + c m_0 \Delta t = m_0 x_2 \gamma + c m_0 (t_2 - t_0) \quad (1)$$

Where γ is latent heat of vaporization and m_0 is the mass flow rate of geothermal fluid. The amount of heat absorbed by organic working fluid is given by Equation 2.

$$Q' = \lambda Q \quad (2)$$

Where λ is heat exchanger efficiency. So, the mass flow rate of organic fluid can be obtained using Equation 3.

$$m' = Q' / (h_3'' - h_5) \quad (3)$$

And the system total power is made up of W_g generated by geothermal fluid and W_o generated by organic fluid. The power efficiency is expressed in Equation 4.

$$W_g = m_0 (h_1 - h_2)$$

$$W_o = m' \cdot (h_3 - h_4)$$

$$\eta = (W_g + W_o) / (m_0 (h_1 - h_0)) \quad (4)$$

3.1.2 Calculation results

The FFS-ORC is a novel design for high- and moderate-temperature geothermal energy utilization. Taking the conditions of geothermal wells in YangYi into consideration, the heat resource is taken as saturated fluid in wells at a temperature of 200°C and the saturated pressure of 1.55MPa with the mass flow rate of 625t/h. The geothermal fluid at the wellhead is a steam-liquid mixture with the temperature of 164.95°C, corresponding saturated pressure of 0.7MPa, and the dryness degree of 7.5%, as the process from the bottom to the wellhead is assumed to be adiabatic and isenthalpic. For convenience, more assumptions of the calculation model used in analyses are:

- The isentropic efficiency of the screw expanders is 75%
- The generator efficiency is 95%
- The mechanical efficiency is 95%
- The pinch temperature difference in evaporator is 10°C
- The difference between the condensing temperature and the outlet temperature of the cooling water in all condensers is 8°C
- The temperature rise of cooling water in condensers is 8°C
- The local cooling water temperature is 18°C

According to above parameters, the power generated by the high and moderate-temperature screw expander is 6.79MW, while the power generated by the low-temperature screw expander is 7.12MW. The total power output of the FFS-ORC system is 13.91MW. The system generation efficiency is 12.7%, which is higher than that of the double flash system for the same parameters.

3.2 The condensing screw expander system

3.2.1 Calculation model

The world's largest screw expanders have been successfully developed and manufactured by Jiangxi Huadian Electrical Power Co. Ltd. in China. These large capacity condensing screw expander generating units are becoming increasingly available. Compared to the FFS-ORC system, the condensing screw expander system is also composed of a high and moderate-temperature screw expander and two low-temperature screw expanders, but the low-temperature screw expander in large size works with normal steam, instead of a small sized screw expander working in a binary cycle system.

Considering the steam-liquid separation for long distance transportation to avoid a water hammer in pipeline, the separation of geothermal mixture carried out at the wellheads leads to the steam and liquid respective transportation to the power plant site. As a result, two types of condensing screw expander systems, the steam type for saturated steam and the mixture type for vapor-liquid two phase (liquid after depressurized), were adopted for YangYi geothermal power generation plant planning.

3.2.2 YangYi geothermal power plant design

The conditions of geothermal wells considered in this design are the same as those in the FFS-ORC, with the temperature of 200°C and the saturation pressure of 1.55MPa in the well and a mass flow rate of 625t/h. The isentropic efficiency of the screw expanders is 75%, while the generator efficiency and the mechanical efficiency are 95%. The local cooling water temperature is 18°C.

Four sets of steam type systems and four sets of mixture type systems were designed with a total installed capacity of 16MW and the total power output of 13.82MW. Table 2 shows the design parameters of the Yangyi geothermal power plant.

Table 2 Design parameters of the Yangyi geothermal power plant

Item	Unit	Steam type system	Mixture type system
Type of screw expander		SEPG600/1000/1000	SEPG800/1000/1000
Inlet pressure	MPa（a）	0.60	0.30
Inlet temperature	° C	158.8	133.5
Inlet dryness degree	%	98.99	5.96
Flow rate	t/h	76	611
Condensing pressure	MPa（a）	0.013	0.019
Condensing temperature	° C	51.1	59
Exhaust dryness degree	%	88.60	17.10
Power output	KW	7,780	6,036

Comparing the FFS-ORC and the condensing screw expander system, the total power output of the two systems is almost the same, but the later has simple system structure, more convenient maintenance, and lower investment cost.

3. CONCLUSIONS

The following conclusions were reached in this study:

(1) The screw expander generating unit is suitable for geothermal power generation and has found wide applications in flash steam , full-flow and binary cycle systems;

(2) The full-flow screw expander has proven to be more thermally efficient than conventional flash steam systems;

(3) The screw expander found successful application in medium- and low-temperature geothermal sources using a binary cycle system (ORC);

(4) The large sized screw expander makes it possible for condensing screw expander systems and it will be applied in the YangYi power generation plant.

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