Cascaded Steam and Organic Rankine Cycles with Screw Expenders

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ABSTRACT

Low pressure saturated steam exists in a lot of industries. The recovery of the energy from the low pressure saturated steam can save tremendous power consumption for those industries. Although the Rankine cycle with a steam turbine can be used to generate the power from the low pressure saturated steam, the isentropic efficiency of the steam turbine is low, the reliability is questionable due to the two phase expansion, and the size is typically large due to the low pressure. This paper presents a system in which steam Rankine cycle and organic Rankine cycle are cascaded to achieve the maximum thermal efficiency. In the cascaded steam and organic Rankine cycles, the organic Rankine cycle is used to condense the exhausted wet steam from the steam expander and at the same time to generate the power by use of the latent heat of the steam. An oil free screw expander is used for the saturated steam expansion, as it is more suitable for the application than a steam turbine and its isentropic efficiency is much higher than a steam turbine too. In addition, a lubricated screw expander is used for the refrigerant vapor expansion in the organic Rankine cycle. A real application case is presented together with the measured performance data from the installation site. For the steam with the saturated pressure of only 0.4 MPa (g), the cascaded steam and organic Rankine cycles achieved the thermal efficiency of 15.6%.

1. INTRODUCTION

In various industries, such as steel mills, refineries and chemical plants etc., different working processes can generate the low pressure saturated or wet steam. The steam has the following characteristics:

- The steam is typically generated with softened water through a cooling process.
- The pressure is low, with a typical pressure of 0.8 MPa (g) or lower.
- The steam is saturated or wet, with a typical dryness of 95 to 97 percent.
- The mass flow capacity of the steam typically is not high, and it is fluctuated quite a lot.

In a lot of industries, the steam is believed useless and is vented to the atmosphere directly, which not only wastes the valuable softened water, but also pollutes the environment. If the steam is used to generate the electricity, a tremendous amount of energy can be saved.

The energy the exhausted steam has can be recovered through a steam expander when the pressure exits, or through organic Rankine cycle when the steam is at the atmosphere pressure. In order to achieve the highest thermal efficiency for the wasted steam with a pressure as low as 0.1 MPa (g), the author proposed and applied the cascaded steam and organic Rankine cycles. The author also optimized and developed screw expanders for the steam expansion and refrigerant vapor expansion. The screw expenders used for a steam expansion are oil free, and the screw expanders for organic Rankine cycle is lubricated. The screw expanders for both the applications achieved a very high isentropic efficiency.

The reasons why the screw expanders, instead of turbines, are used for the application are obvious:

- A screw expander can achieve much higher isentropic efficiency for the application. In addition, for the synchronous speed of 50 Hz and 60 Hz generators, the screw expanders are typically running at their optimum tip speed, and can drive generators directly. The gearbox between the expander and the generator, or a variable frequency invertor, is eliminated, which improves the system thermal efficiency and reliability further.

- A screw expander is not sensitive to the droplets in the expansion working fluid. A turbine expander typically is running at high speed, and its impellor is very sensitive to the droplets in the expansion working fluid. Although in these days turbine expanders for the saturated steam is available, its isentropic efficiency for a low mass flow capacity is low, and its discharge dryness of steam is limited. As mentioned above, the wasted steam enters an expander typically with a dryness of 95 – 97%, and the discharge dryness can reach 85% or even lower. Only screw expanders can be used for the application with satisfied reliability.
- The efficiency of a screw expander is not so sensitive to the mass flow capacity and inlet pressure, and at wide range of flow capacity its isentropic efficiency remains high. A properly designed screw expander has a wide sweet range, instead of a sweet spot. The flow capacity of the wasted steam typically fluctuates quite a lot, screw expanders are more suitable for its energy recovery.

Since 2013, the author has directed the installations, site commissioning and site optimizations of many power generation plants of cascade steam and organic Rankine cycles with screw expanders. In this paper, the power plant utilizing the wasted saturated steam of 0.4 MPa (g) at Tianfeng Steel Mill, Tianjing, China, is presented.

2. CASCADED STEAM AND ORGANIC RANKINE CYCLES

Fig. 1 shows the cascaed steam and organic Rankine cycles. The top cycle is a typical steam Rankine cycle. The steam from the boiler enters the expander to drive the expander, and thus the rotational expander drives a generator or a rotational machinery, such as a blower, a pump or a compressor etc. The exhausted steam from the steam expander then enters the steam condenser to be condensed into water. The water is pumped by a water pump back to the boiler. The difference of the cascaded cycles from a typical steam Rankine cycle is the steam condensation process. In a steam Rankine cycle, the exhausted steam from the expander is condensed by a steam condenser, which can be a water-cooled, air-cooled or evaporative style. In the cascaded steam and organic Rankine cycles, the exhausted steam from the steam expander is condensed by an organic Rankine cycle, which is the bottom cycle in Fig. 1. The exhausted steam enters the evaporator and pre-heater of the organic Rankine cycle, and is condensed into water. The latent heat of the steam heats up the refrigerant in the organic Rankine cycle, and turn the refrigerant liquid into vapor. The high pressure and high temperature refrigerant vapor then enters the ORC expander and drives the expander. The low pressure and temperature refrigerant discharged from the ORC expander is condensed back into liquid in the refrigerant condenser, and the refrigerant pump pumps the refrigerant liquid back to the pre-heater and the evaporator.

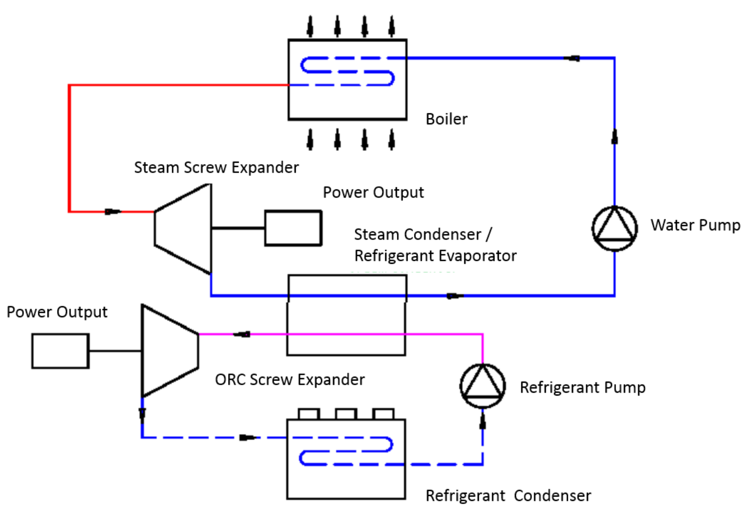

Fig. 1: cascaded steam and organic Rankine cycles

In the cascaded steam and organic Rankine cycles, the steam Rankine cycle recovers the energy of the pressure and the organic Rankine cycle recovers the energy of the latent heat. Most of the thermal energy of the wasted steam is the latent heat. In the cascaded cycles, the organic Rankine cycle is acted as an ORC condenser of the exhausted steam from the steam expander. In a steam condenser, the condensation process consumes the power. However, an ORC steam condenser does not consume any power, but generates the power.

As the cascaded steam and organic Rankine cycles are used to recover the energy from the wasted steam, the thermal efficiency of the cascaded cycles can be defined as the ratio of the net power generated by the cycles over the energy absorbed by the cycles. The net power of the cycles is the power output from the generators minus the power consumed by the cycles. The energy absorbed by the cycles is the mass flow capacity of the steam times the differential enthalpy of the steam entering the steam expander and the water leaving the per-heater of the organic Rankine cycle. As the refrigerant temperature entering the pre-heater is only a few degrees higher than the ambient temperature, the temperature of the returning water can be controlled according to the request of the customer.

3. SCREW EXPANDERS FOR STEAM EXPANSION AND REFRIGERANT VAPOR EXPANSION

For steam expansion, oil free expanders have to be used. Table 1 indicates KSGe series of oil free screw expanders, which can be used for steam expansion. For refrigerant vapor expansion, oil lubricated expanders can be used. Table 2 indicates SKYe series of oil lubricated screw expanders. In the cascaded steam and organic Rankine cycle, the oil free screw expanders are used for steam expansion, and the oil lubricated screw expanders are used for refrigerant vapor expansion.

Both KSGe series and SKYe series of screw expanders are developed for the applications of gas expansion, and they are not modified from screw compressors. Y-5 rotor profile was specially developed for the expanders, and all the geometrical parameters were optimized too for the applications of gas expansion.

Table 1: KSGe series of oil free screw expanders

Rotor profile	Y-5
Lobe configuration	5+6
Male rotor diameter range (mm)	168 - 745
Theoretical discharge volumetric flow capacity (m^3/min)	15.8 - 910.6
Inlet pressure range (MPa (g))	0.8 - 3.0
Design temperature (°C)	200 - 250

Table 2: SKYe series of oil lubricated screw expanders

Rotor profile	Y-5
Lobe configuration	5+6
Male rotor diameter range (mm)	75 - 541
Theoretical discharge volumetric flow capacity (m^3/min)	0.76 - 207.8
Inlet pressure range (MPa (g))	1.6 - 2.5
Design temperature (°C)	135

4. POWER PLANT WITH CASCADED STEAM AND ORGANIC RANKINE CYCLES INSTALLED AT TIANFENG STEEL MILL, TIANJING, CHINA

Since 2013, many power generation plants with the cascaded steam and organic Rankine cycles have been installed. In this section, the performance of the power generation plant No. 1 installed at Tianfeng Steel Mill, Tianjing, China, is presented (Zhejinag Kaishan, 2013). The plant was installed in the summer of 2013, and it has been generating power since September of 2013. Table 3 shows the specifications of total 3 power generation units installed at Tianfeng power plant No. 1. There is one steam expander unit, the exhausted wet steam from which feeds into two ORC units. Fig. 2 shows the steam expander installed at the site, and Fig. 3 shows the installation of ORC units with evaporative condensers. The plant was designed for 0.4 MPa(G) saturated steam and with the flow capacity around 10 ton/hour.

Table 3: power generation units installed at Tianfeng power plant No. 1

Unit model	KES600	KE450-95V-1-50	KE185-95V-1-50
Unit type	Steam expansion	ORC	ORC
Number of units	1	1	1
Working fluid	Steam	R245fa	R245fa
Screw expander model	KSGe469150	SKYe297	SKYe192
Heat source inlet	0.4 MPa (g) sat. steam	0 MPa (g) wet steam	
Heat source outlet	0.008 MPa (g) wet steam	0 MPa (g) saturated water	
Condenser style	ORC	Evaporative	
Designed evaporation temperature (°C)	N/A	95	95
Designed condensing temperature (°C)	N/A	25	25
Generator rated power (kW)	600	450	185
Generator power output at design conditions (kW)	500	424	168
Unit net power output at design conditions (kW)	490	349	138

Fig. 2: steam expander KES600 installed at Tianfeng power plant No. 1

Fig. 3: ORC units installed at Tianfeng power plant No. 1

The performance data of the three units were measured at the site. Table 4 summarizes the performance of steam expander unit KES600, and Table 5 summarizes the performance of the two ORC units. These data were measured in the same day on November 6, 2013. As indicated in Table 4, the performance of the steam expander fluctuated due to the fluctuation of the inlet steam mass flow capacity. During the measurements, the mass flow capacity of exhausted steam from the steam expander was higher than what two ORC units can consume, both the ORC units were running at stable conditions, and the inlet pressure and the steam mass flow capacity to the steam expander did not influence the performance of ORC units. The extra steam between the steam and organic Rankine cycles was vented to the atmosphere. Later in November 2013, one more ORC unit of KE185-95V-1-50 was installed at the same site to consume the extra steam from the steam expander.

Table 4: the measured results of KES600

Inlet pressure (MPa (g))	0.316	0.445	0.406	0.300	0.366	0.411	0.312	0.409	0.352	0.337	0.429
Discharge pressure (MPa (g))	0.023	0.028	0.027	0.023	0.026	0.026	0.023	0.027	0.023	0.023	0.027
Steam mass flow (ton/hour)	8.4	10.8	10.1	8.1	9.3	10.2	8.3	10.1	9.1	8.8	10.5
Net power output (kW)	327.1	537.9	475.2	308.0	397.7	480.2	324.7	479.7	384.9	361.3	510.1
Isentropic effciency (%)	72.4	77.6	76.9	73.1	74.0	76.3	73.8	76.7	73.8	73.9	76.5

Table 5: the measured results of two ORC units

Model of ORC unit	KE450-95V-1-50	KE185-95V-1-50
Model of screw expander	SKYe297	SKYe192
Average evaporation pressure (MPa (g))	1.112	1.037
Average expander discharge pressure (MPa (g))	0.165	0.130
Average unit net power output (kW)	337.4	138.3
Average screw expander isentropic efficiency (%)	88.7	84.7
Average unit thermal efficiency (%)	8.8	8.9

The relationship of the isentropic efficiency of screw expander KSGe469150 and the expansion ratio is shown in Fig. 4. The design expansion ratio of the expander is 4.63, and the expander is running at the expansion ratios, which are lower than the design expansion ratio. Although the isentropic efficiency increases when the expansion ratio increases, the screw expander does not reach its peak performance. Fig. 4 also indicates that in a wide range of the expansion ratios or a wide range of the steam mass flow capacities, the screw expander remains high isentropic efficiencies.

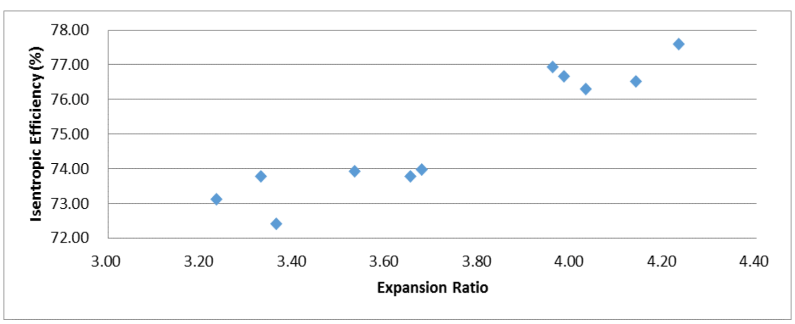

Fig. 4: isentropic efficiency vs expansion ratio of steam expander KSGe469150

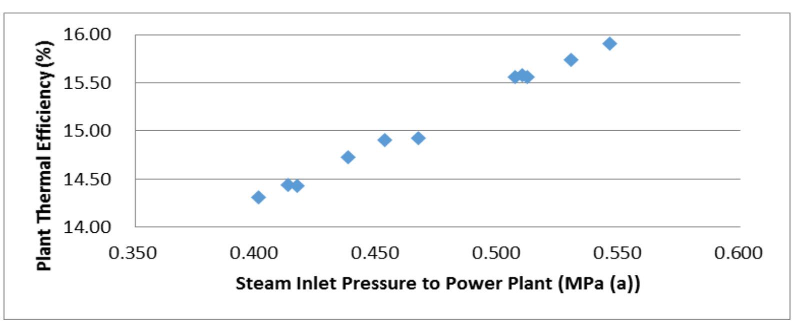

Fig. 5: thermal efficiency of Tianfeng power plant No. 1 vs steam inlet pressure

Fig. 5 shows the relationship of the thermal efficiency of Tianfeng power plant No. 1 and the steam inlet pressure to the plant. As expected, the higher the steam inlet pressure, the higher the thermal efficiency of the power plant. For the saturated steam with 0.4 MPa (g), the cascaded steam and organic Rankine cycles achieved the thermal efficiency of 15.6%.

5. DISCUSSIONS AND CONCLUSIONS

1. In the cascaded steam and organic Rankine cycles, the thermal efficiency of ORC is influenced by the ambient temperature. If the evaporative condenser is used, the thermal efficiency of ORC is influenced by the wet bulb temperature. There exits an optimized steam condensation pressure in the cascaded cycles. Many factors, such as the steam inlet pressure to the power plant, the local ambient conditions, the screw expander efficiencies etc., influence the optimized steam condensation pressure. At Tianfeng power plant No. 1, the optimized steam condensation pressure is lower than the atmosphere pressure, and in order to simplify the system, the steam is condensed at the atmosphere pressure.
2. Screw expanders have their great advantages when they are used for the energy recovery of the wasted steam, which is saturated or wet, and the mass flow capacity of which is small to medium and fluctuates quite a lot. The screw expanders properly designed and optimized can achieve very high isentropic efficiency for the application, and in a wide range of operation conditions, high efficiencies can be maintained. Although this paper does not intend to discuss the design and optimization of screw expanders, it is for sure that the design and optimization of screw expanders have a lot of differences from screw compressors.
3. The cascaded steam and organic Rankine cycles maximize the net power output of wasted steam. However, in reality the payback term of the investment is always the most important factor to be considered. The bottom cycle in the cascaded cycles can be replaced by a steam expander and a steam condenser, which is going to condense the steam at a high vacuum level. As a result, the cascaded cycles become a steam Rankine cycle with two stage screw expanders. In order to save the investment further, the two stage screw steam expanders can be replaced by a single stage screw steam expander too. The wasted steam condition and the price per kWh are two most important factors to define which cycle to be used.

REFERENCES

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