Transformation of Waste Heat into Electricity

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Abstract. The aim of this article is to introduce the transformation of waste heat into electricity using conventional Rankine steam cycle. Uncommon part of this cycle is a special designed turbine generator, whose impeller is fitted with rows of steel wires instead of turbine blades. For this reason wet steam can be fed into the turbine. The article describes the principle of connection of research unit together with measured data from the operational measurement and graphical and table outputs.

1 Introduction

Currently, two basic principles of transformation of waste heat into electricity are being used. It is either transformation using the thermoelectric effect, or one of the thermodynamic cycles. Electric generators based on the thermoelectric effect can reach nominal electric power up to tens of watts. The most widely used thermal cycles include Rankine cycle, Organic Rankine cycle, Stirling cycle and Kalina cycle.

To use waste heat at low temperatures (200 °C and lower), the units based on the Organic Rankine cycle or eventually the Kalina cycle can be used effectively. Waste heat with a higher potential can be utilized in the conventional Rankine cycle or Stirling cycle. In this case, the waste heat from flue gas of cogeneration units with a temperature above 400 °C is available, therefore Rankine cycle was chosen.

2 Description of the principle of the research technology

The research technology, a special designed turbine generator, has been installed in an animal and plant farm in Želatovice village. This location was chosen because of large amounts of high-potential waste heat in the form of flue gases from cogeneration units processing biogas from near biogas station. The cogeneration units are operated year-round. Electricity is supplied to the distribution network, while a large part of produced heat is wasted into the atmosphere. The flue gases from the cogeneration units have temperature about 420 °C. A bypass was built at exhaust duct of the cogeneration units in order to divert the flue gases to a steam generator. The steam generator is a classic tube heat exchanger, which transfers flue gases heat into water to generate steam driving the special designed turbine generator. The

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whole technology is placed in a container, steam generator situated on its “roof” (see Figure 1).

Fig. 1. Research technology.

A simplified scheme of the technology depicted in Figure 3. Water as a working fluid is pumped by a high-pressure pump into the steam generator from a feed water tank with a volume of 1.2 m³. By passing through the primary side of the steam generator, the flue gases are cooled to 170 °C. The heat transferred from the flue gases generates saturated steam with temperature about 220 °C by boiling the feed water. The saturated steam is fed into the special designed turbine generator through 9 pressure hoses to 9 nozzles, where it expands to barometric pressure. The outputs of turbine were brought out into atmosphere to simplify the tests. The turbine has 2 outputs – axial and radial. The connection between the generator and the turbine rotor is created with belt clutch equipped by tensioner. The generator operates at nominal parameters at 3 000 rpm. The nominal electric power of the generator is 18.5 kW. The turbine rotor is fitted with rows of steel wires instead of turbine blades and therefore it is not susceptible to steam quality. Individual parts of the turbine generator are described in the Figure 2.

Fig. 2. Turbine generator.

3 Operational measurement

Construction modifications of the turbine generator were carried out during 2017. At the end of the year, several operational measurements were carried out, of which a 26-minute interval was selected for analysis. Data from this interval are evaluated in detail below. In order to evaluate the efficiency of the steam turbine generator, the system was equipped with measuring elements. The inlet mass flow of steam was measured on the water side of the generator by an ultrasonic flowmeter. All measured data are summarized in Table 1. For each parameter there is a mark, which corresponds with the schema in Figure 3. In the last three columns of the table, the minimum, maximum and average values for each parameter in the evaluated interval are determined.

Table 1. Summary of measured values in evaluated time interval.

Parameter	Mark	Unit	Min	Max	Average
Generator Speed	o	rpm	3000.0	3011.3	3006.8
Feed Water Pressure	p ₃	bar (abs)	31.7	43.7	39.3
Feed Water Temperature	t ₃	°C	31.0	56.6	43.8
Steam Temperature	t ₄	°C	209.6	226.6	221.1
Flue Gas Temperature	t ₁	°C	402.8	423.8	421.3
Flue Gas Temperature	t ₂	°C	146.1	189.1	171.3
Electrical Power	P _e	kW	1.1	4.8	3.5
Relative Humidity of Air	Rh	%	30.6	47.3	37.1
Barometric Pressure	p _b	bar (abs)	1.0	1.0	1.0
Water/Steam Mass Flow	m	t.h ⁻¹	0.6	0.8	0.7

It is clear from the previous table that saturated steam parameters are relatively low – mass flow 0.7 t.h⁻¹, temperature 221.1 °C. At these parameters, the turbine achieved average electrical power 3.5 kW.

Summarized data needed for determination of the net efficiency of the turbine generator are presented in Table 2. The calculated value is shown in the last row of the table. In this case, it is very difficult to determine the wet steam enthalpy at the turbine outlet because wet steam quality is not known.

Therefore, the net efficiency of the turbine generator was determined as a ratio of generated electrical power to the theoretical power, which is given by the steam mass flow and the ideal isentropic enthalpy gradient from the inlet pressure to barometric pressure. This efficiency includes all losses, both losses within the turbine itself, and mechanical losses and loss of the generator.

Table 2. Summary of the resulting values in evaluated time interval.

Parameter	Mark	Unit	Min	Max	Average
Feed Water Enthalpy	h_3	kJ.kg^{-1}	132.7	239.9	186.9
Steam Pressure	p_4	bar (abs)	18.9	26.3	23.8
Steam Enthalpy	h_4	kJ.kg^{-1}	2797.2	2802.5	2801.1
Steam Entropy	s_4	$\text{kJ.kg}^{-1}.\text{K}^{-1}$	6.2	6.4	6.3
Steam Enthalpy after Isentropic Exp.	$h_{5 \text{ ise}}$	kJ.kg^{-1}	2256.5	2302.2	2271.2
Enthalpy Drop after Isentropic Exp.	$\Delta h_{\text{ ise}}$	kJ.kg^{-1}	494.9	546.0	529.8
Theoretical Power	$P_{\text{ theor}}$	kW	92.7	119.7	104.0
Turbogenerator Efficiency	η	%	1.2	4.4	3.3

Average measured and calculated values were also plotted for better interpretation in the simplified functional scheme in Figure 3.

Fig. 3. Simplified scheme of the technology.

4 Comparison with traditional turbine generator

In the framework of the project, a company that produces classic single-stage blade steam turbines was addressed in order to compare the achieved efficiency of the presented turbine with that of conventional technology. The same parameters in which the rated turbine was run were sent to this company for evaluation. This manufacturer commonly produces turbines for the same pressure and temperature, but for higher mass flows. Even so, their smallest machine is capable of operating at such reduced conditions and can be compared to the rated turbine. The net efficiency of the competing machine was determined in the same way - as a ratio of produced electrical power to the theoretical power. The comparison results are shown in Table 3.

Table 3. Comparison results with the traditional turbine generator.

Parameter	Unit	Evaluated Turbogen.	Traditional Turbogen.
Mnufacturer	-	GWRD Inc.	G-Team Ltd.
Type	-	NTR	TR 100
Steam Mass Flow	t.h ⁻¹	0.7	0.7
Inlet Steam Temperature	°C	222.0	222.0
Inlet Steam Pressure	MPa (abs)	2.4	2.4
Outlet Steam Pressure	MPa (abs)	0.1	0.1
Theoretical Power	kW	111.0	111.0
Real Power	kW	3.5	14.0
Turbogen. Efficiency	%	3.2	12.6

5 Conclusion

Processes for transformation of waste heat into electricity are very briefly described in the introduction of the article. This is followed by a practical description of one of these principles - conventional Rankine steam cycle with incorporated special designed turbine generator. The turbine is unique in impeller type, which is fitted with rows of steel wires instead of turbine blades. Functionality of this system was proved by series of measurement. At this time, the maximal net efficiency of the presented turbine is about 4.4 %, while classic blades turbine in these low steam parameters achieve about 12.6 %. Despite the lower efficiency compared with classic blades turbine, the analyzed turbine may be suitable for operations that have problems with steam purity, since even small droplets can seriously damage blades of the conventional turbine.

This article was published with the support Student Grant Competition project entitled Technology for Waste Energy Utilization, no. SP2017/179, and project „Innovation for Efficiency and Environment – Growth“, identification code LO1403 with the financial support from the Ministry of Education, Youth and Sports in the framework of the National Sustainability Programme I.

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