

HEAT RECOVERY IN HYBRID FLASH/ORC POWER PLANTS

Andriy Redko¹, Adam Ujma², Anna Pavlovska¹, Yurii Burda¹, Volodymyr Andoniev¹

¹Kharkiv National University of Construction and Architecture, Ukraine;

²Czestochowa University of Technology, Poland

andrey.ua-mail@ukr.net, adam.ujma@pcz.pl, anuta0067@gmail.com,

burda.yurii.1991@gmail.com, andoniev.volodymyr@gmail.com

Abstract. The usage of exhaust gas heat in WHR (Waste Heat Recovery) systems and its conversion into electrical energy using ORC technologies is limited by the thermal stability of working bodies at a temperature of exhaust gases above 270-300 °C. Therefore, thermal schemes of hybrid power plants, in which water vapor and organic heat carriers are used as working fluids, are being developed. Numerous studies indicate that the efficiency of the thermal scheme of energy conversion is significantly influenced by the properties of working bodies and their parameters. Due to the large number of working bodies, the problem of their thermodynamic parameter effect has not been sufficiently studied. This paper [13] presents a review on hybrid renewable energy power generation systems focusing on energy sustainability.

Keywords: energy efficiency, biofuel, hybrid installation, hybrid power plant.

Problem state

Increasing the energy efficiency of agricultural enterprises, including greenhouses, is possible by using cogeneration units of heat pumps of various types of biofuels. The usage of solid biofuels (pellets, briquettes, chips), liquid biofuels (ethanol, methanol, biodiesel), biogas and biohydrogen increases the economic efficiency of agricultural enterprises from 20% to 25%, as well as improves environmental performance. Many European countries widely use wood waste (Denmark, Sweden, Great Britain, the Netherlands and Germany) for heat supply of enterprises. The largest biofuel producers are the USA (40 million tons) and Brazil (20 million tons).

Biofuel consumption in Poland reaches 10% [1-4]. The country is dominated by the production of biodiesel from rapeseed oil and ethanol from corn. In Ukraine, biofuel production is 1.923 million tons of oil equivalent, and in Poland it is 518 thousand tons of oil equivalent. Increasing the efficiency of fuel-using units is achieved by using waste gas heat recovery systems and converting it into electrical energy [4; 5]. The report presents the results of a numerical study of a hybrid power plant in which heat recovery of exhaust gases from internal combustion engines of boiler units and other fuel-using units is provided. The use of the heat of exhaust gases with a temperature from 250 °C to 350 °C ensures the generation of electricity, which increases the efficiency of energy supply systems for agricultural enterprises. The hybrid power system consists of three circuits, including an evaporator boiler, a steam separator, a steam turbine and two organic working fluid turbines [6-13].

The energy system (Waste Heat Recovery Systems) works as follows (Fig. 1).

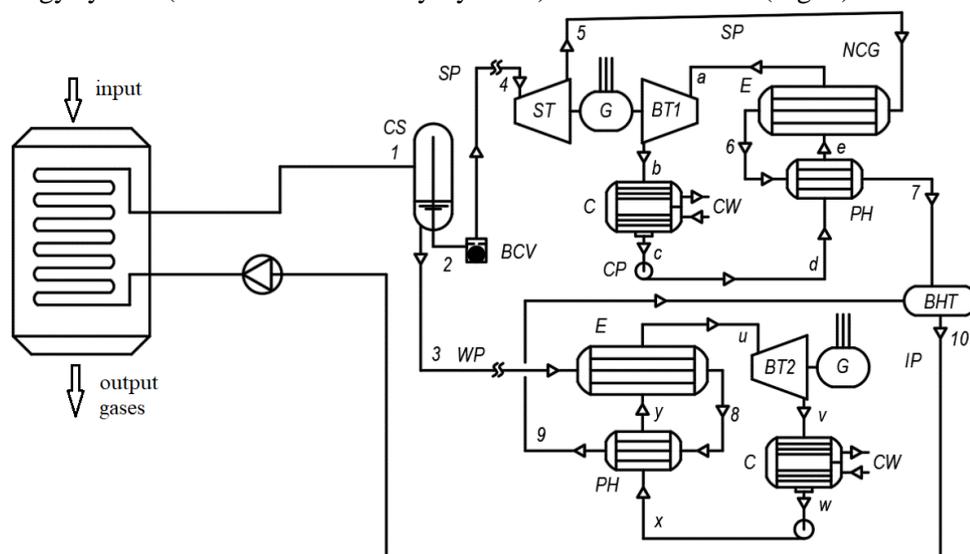


Fig. 1. Schematic diagram of hybrid installation

Waste gases of the fuel-using unit (boiler, industrial furnace, internal combustion engine) enter the heat recovery boiler, where heat is removed from the gases and transferred to water. The boiler produces wet steam with varying degrees of dryness. Steam enters the separator where saturated steam is generated, and water is separated. Saturated steam is fed to the ST steam turbine, and then to the E evaporator and the PH recuperator, where it gives off heat to the organic working heat-carrier (Wf) of the second (a-b-c-d-e) circuit. [1-2] The generated steam is fed to the second circuit turbines. The liquid after the separator enters the evaporator E of the third circuit with organic Wf (u-v-w-x-y). The organic steam Wf is fed to the third circuit turbine BT2. Thus, the steam turbine ST and the turbines of the organic circuits VT1 and VT2 generate electric power.

Research results and their analysis

The calculations of thermal circuits have been carried out with the following initial data: efficiency of a steam turbine is 0.85, efficiency of freon turbines is 0.85, efficiency of pumps is 0.75, ambient temperature is 25 °C, under recovery temperature difference is 5 K [1-2].

Case A

The research results show that the total generated specific electric power is 511 kW. At the same time, the power of the steam turbine is 286 kW, and the power generated in the second and third circuits, implementing the organic Rankine cycle (ORC), is 253 kW. The efficiency of the hybrid plant is 23.4%. The parameters of the working bodies at the control points of the thermal scheme of the installation are given in Table 1.

Table 1

Parameters of working bodies at control points of the thermal scheme (Case A)

No.	P , kPa	t , °C	x	s , kJ·(kg·K) ⁻¹	h , kJ·kg ⁻¹	m , kg·s ⁻¹
1	3 976	250.0	0.0	2.794	-14 840	1.30
2	3 976	250.0	0.5	4.433	-13 980	1.30
3	3 976	250.0	0.0	2.794	-14 840	0.65
4	3 976	250.0	1.0	6.073	-13 120	0.65
5	150	11.40	0.8504	6.359	-13 560	0.65
6	150	111.40	0.2906	3.117	-14 810	0.65
7	150	81.06	0.0	2.266	-15 140	0.65
8	3 976	132.20	0.0	1.654	-15 370	0.65
9	3 976	39.63	0.0	0.5658	-15 760	0.65
10	150	60.78	0.0	0.8409	-15 670	1.30
a	2 700	106.20	1.0	2.727	-7 175	4.00
b	675	41.34	1.0	2.750	-7 216	4.00
c	675	29.32	0.0	1.788	-7 507	4.00
d	2 700	31.00	0.0	1.790	-7 504	4.00
e	2 700	87.49	0.0	2.167	-7 378	4.00
u	2 700	144.9	1.0	2.702	-2 327	1.49
v	355	76.45	1.0	2.733	-2 388	1.49
w	355	32.70	0.0	1.637	-2 731	1.49
x	2 700	34.66	0.0	1.642	-2 727	1.49
y	2 700	111.90	0.0	2.130	-2 557	1.49

Note: P – pressure; t – temperature; x – degree of dryness; s – specific heat capacity; h – entropy; m – mass flow.

Case B

The calculations of the thermal circuit of the hybrid power plant have been performed with the same parameters as for CASE A, but the mass flow rate of water vapor is reduced to $m = 0.5 \text{ kg}\cdot\text{s}^{-1}$. The calculation results are shown in Table 2. Analysis of the results shows that at a mass flow rate of $0.5 \text{ kg}\cdot\text{s}^{-1}$, a steam temperature is 250 °C and a steam pressure is 3976 kPa, the generated electric power is reduced to 220 kW, and the power of the turbine using R152a is 121.4 kW, and the power of the turbine with R600a/R141b is 69.4 kW. The total generated power is reduced to 391.1 kW, and the efficiency of the thermal circuit is 23.6%.

The generated electrical power decreases with a decrease in the heat load in the steam generator and a decrease in the mass flow rate of water vapor.

The **Case C** variant, in which the steam parameters are changed, namely, the steam mass flow rate is $0.35 \text{ kg} \cdot \text{s}^{-1}$, the steam temperature is $250 \text{ }^\circ\text{C}$, and the steam pressure is 3976 kPa , is considered as well. The working fluids in the power plant have been changed: in the circuit (a-b-c-d-e), a mixture of R600a/R141b is used, and in the circuit (u-v-w-x-y), R152a is used. The calculation results are shown in Table 3. The steam turbine power is 156.8 kW , the R600a/R141b turbine power is 36 kW , and the R152a turbine power is 74.4 kW . The total generated power is reduced to 256.1 kW , and the efficiency of the power plant is 19.3% .

Table 2

Parameters of working bodies at control points of the thermal scheme (Case B)

No.	$P, \text{ kPa}$	$t, \text{ }^\circ\text{C}$	x	$s, \text{ kJ} \cdot (\text{kg} \cdot \text{K})^{-1}$	$h, \text{ kJ} \cdot \text{kg}^{-1}$	$m, \text{ kg} \cdot \text{s}^{-1}$
1	3 976	250.0	0.0	5.561	-14 790	1.00
2	3 976	250.0	0.5	7.224	-13 920	1.00
3	3 976	250.0	0.0	5.561	-14 790	0.50
4	3 976	250.0	1.0	8.887	-13 050	0.50
5	150	111.4	0.8504	9.184	-13 510	0.50
6	150	111.4	0.3046	8.713	-13 690	0.50
7	150	108.8	0.0	4.058	-15 480	0.50
8	3 976	173.8	0.0	4.763	-15 180	0.50
9	3 976	67.10	0.0	3.548	-15 660	0.50
10	150	88.50	0.0	3.817	-15 570	1.00
a	2 700	106.20	1.0	2.727	-7 175	3.00
b	675	41.34	1.0	2.75	-7 216	3.00
c	675	29.32	0.0	1.788	-7 507	3.00
d	2 700	31.00	0.0	1.79	-7 504	3.00
e	2 700	88.56	0.0	2.645	-7 205	3.00
u	2 700	144.90	1.0	2.702	-2 327	1.08
v	355	76.45	1.0	2.733	-2 388	1.08
w	355	32.70	0.0	1.637	-2 731	1.08
x	2 700	34.66	0.0	1.642	-2 727	1.08
y	2 700	128.80	0.0.	2.259	-2 506	1.08

Table 3

Parameters of working bodies at control points of thermal scheme (Case C)

No.	$P, \text{ kPa}$	$t, \text{ }^\circ\text{C}$	x	$s, \text{ kJ} \cdot (\text{kg} \cdot \text{K})^{-1}$	$h, \text{ kJ} \cdot \text{kg}^{-1}$	$m, \text{ kg} \cdot \text{s}^{-1}$
1	3 976	250.0	0.0	2.794	-14 840	1.00
2	3 976	250.0	0.35	3.942	-14 240	1.00
3	3 976	250.0	0.0	2.794	-14 840	0.65
4	3 976	250.0	1.0	6.073	-13 120	0.35
5	140	109.30	0.8487	6.365	-13 570	0.35
6	140	109.30	0.261	2.935	-14 880	0.35
7	140	109.30	0.1116	2.063	-15 220	0.35
8	3 976	92.00	0.0	1.213	-15 540	0.65
9	3 976	37.21	0.0	0.5335	-15 770	0.65
10	140	83.87	0.0	1.121	-15 570	1.00
a	1 148	99.71	1.0	2.448	-2 466	2.00
b	580	77.74	1.0	2.457	-2 484	2.00
c	580	57.37	0.0	1.653	-2 755	2.00
d	1 148	57.90	0.0	1.654	-2 754	2.00

Table 3 (continued)

No.	P , kPa	t , °C	x	s , $\text{kJ}\cdot(\text{kg}\cdot\text{K})^{-1}$	h , $\text{kJ}\cdot\text{kg}^{-1}$	m , $\text{kg}\cdot\text{s}^{-1}$
e	1 148	88.56	0.0	1.823	-2 695	2.00
u	2 700	219.00	1.0	3.127	-7 002	1.206
v	700	163.00	1.0	3.152	-7 063	1.206
w	700	30.61	0.0	1.796	-7 504	1.206
x	2 700	32.31	0.0	1.798	-7 501	1.206
y	2 700	87.49	0.0	2.167	-7 378	1.206

Conclusions

As a result of the study, it has been found that the generated electrical power significantly depends on the operating mode of the heat source. Variable modes and loads of hot water supply lead to a decrease in the generated power in the hybrid power plant due to the fact that steam with varying degrees of dryness (from 0.1 to 0.5) is generated in the waste heat boiler. At the same time, the generated power varies from 250 kW to 511 kW.

The influence of the parameters of water vapor in front of the turbine has been established. Changing the steam temperature from 165 °C to 250 °C, leads to a change in the generated power from 295 kW to 500 kW. The increase in steam consumption provides an increase in the generated electric power from 15% to 25%.

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