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RESEARCH ARTICLE

An assessment and thermodynamic analysis of an actual power plant in the frame of a tri-generation concept

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Abstract

In the case of technological developments, energy consumption is rising. Due to this reason, it is essential for more efficient use of limited energy resources all over the world. The waste energy should be recovered for useful applications. Moreover, the improvements in terms of system efficiency and environmental impacts should be utilized for conventional power plants in the frame of co/tri-generation systems as well as waste-to-energy concept. For all these reasons, in coal-fired power plants and other power cycle enhancement studies, supercritical and ultra-supercritical conditions are being designed for more efficient power plants. In this study, a conventional gas power plant was analyzed in terms of thermodynamic aspect and some recommendations were developed in order to increase the system efficiency. As a result of the thermodynamic analyses, the thermal efficiency of the plant was found to be 43.78%. The aim of this paper is to point out the importance of tri-generation systems that can be adapted to existing ones in order to increase system efficiency.

1. Introduction

Nowadays, energy consumption is increasing all over the world and its scarce amount leads to people to find out alternative solutions for efficient usage of energy. With population growth in the world, energy consumption is also increasing. It is possible to increase the efficiency of a system by decreasing the exergetic losses and/or adapting new auxiliary systems to the existing ones. The most important attempt that can be achieved in this respect is energy recovery by utilizing waste energy. In this phenomenon, first of all, the updated portrait of any system should be outlined thermodynamically. There are many studies in which thermodynamic and thermoeconomic analyses were made in this respect in the open literature [1-4]. As a result of these comprehensive analyses on actual systems, in order to increase the system efficiency, optimization studies are also performed [5-8]. An actual system's efficiency can be recovered by using many different systems such as gas turbines, supercritical CO_2 (S-CO_2) cycles, Brayton, organic Rankine and Kalina cycles. Such as; Organic Rankine cycle (ORC) is an alternative solution for low-grade thermal energy recovery technology, which is utilized to all kinds of low-temperature heat sources including geothermal, solar, biomass and especially waste heat energies [9]. A power cycle with ammonia-water mixtures as a working fluid can be used for waste heat in order to improve the efficiency of a power plant. This cycle is named as Kalina cycle which was designed by Alexander Kalina using a bottoming cycle instead of the Rankine cycle in combined cycle power plants in 1989 [10]. A study on the S-CO_2 cycle in the open literature [7] was seen to optimize energy production of actual power plants. Besides this, for thermoeconomic optimization of actual power plants after well-performed thermodynamic analyses, a method named as specific exergy costing (SPECO) method can be utilized [11, 12]. Besides this, the utilized systems can also be considered in the frame of co/tri-generation concept in the purpose of an efficiency increase. Herein a tri-generation is a simultaneous production of electricity and heat as well as cooling from a single energy source.

In the concept of more efficient power plants, a well-known Brayton cycle can be utilized. The Brayton cycle emerged for use in a two-stroke kerosene-fired reciprocating engine was patented by US engineer George Brayton in 1872. The components in gas turbines are; gas compressor, combustion chamber and expansion turbine. Air enters the compressor and pressurized. Compressed air is then burned with fuel and the burned air expands in the turbine stages, providing mechanical energy. Although the thermal efficiency of open cycle gas turbine systems is quite low, they are preferred because of their rapid commissioning and low investment costs compared to other systems. All gas turbine systems are operated by the so-called Brayton Cycle and produce mechanical power.

Moreover, supercritical fluids are of interest to the scientific community with their superior solvent properties, which can be changed easily by temperature and pressure. Among the supercritical fluids, thanks to its low critical temperature and critical pressure values, carbon dioxide solvent is frequently used because of not being toxic to the environment. S-CO_2 is a fluid state of carbon dioxide which is held above the critical pressure and critical temperature point, behaving similar to that of a liquid. This allows a significant reduction in the pumping power needed in a compressor and a

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significant increase in the thermal energy-electric energy conversion efficiency.

In accordance with the information given above, in this paper, by combining the advantages of Brayton and S-CO_2 cycles, a study was carried out in the concept of tri-generation system. Thermodynamic analyses of an actual power plant as well as tri-generation system are presented. As a result, a tri-generation system to increase overall efficiency of the actual systems is suggested herein in general manner.

2. Materials and Methods

In the thermodynamic analyses of the actual power plant as well as the tri-generation system, Engineering Equation Solver (EES) program was used using the actual data of the plant. The actual operating data were taken and under the light of those, the system was analyzed thermodynamically. The schematic layout of the actual power plant with the proposed tri-generation system is given in Fig. 1.

The actual data of the plant are tabulated in Table 1. The operating pressure, temperature and mass flow rate data of the three working fluids such as air, water and S-CO_2 were taken from the system. The inlet and exit states of each device were numbered sequentially and then the thermodynamic analyses were performed in EES program in this manner.

For thermodynamic analyses, the well-known equations which are given below were used. For the mass balance throughout all devices, continuity equation for control volumes was used in the presence of steady state steady flow conditions as:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

where $\dot{m}$ is the mass flow rate and sub-indices i and e represent *inlet* and *exit* states, respectively. The first law of thermodynamics for steady state steady flow processes throughout the related control volumes which are given in Fig. 1 in the absence of the change in both kinetic and potential energies, is given as:

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{2}$$

After analyzing each control volume in the proposed system, the thermal efficiency of the system is evaluated by using the Eq. (3) as:

$$\eta_{th} = \dot{W}_{net} / \dot{Q}_H \tag{3}$$

where η_{th} is the thermal efficiency of the system, $\dot{W}_{net}$ is the net power output, $\dot{Q}_H$ is the heat transfer rate to the system from high temperature reservoir.

3. Results and Discussion

As a result of the thermodynamic analyses, the amount of heat transfer rate to/from system devices and the amount of power produced/consumed by each device were evaluated using the actual operating data and then tabulated in Table 2.

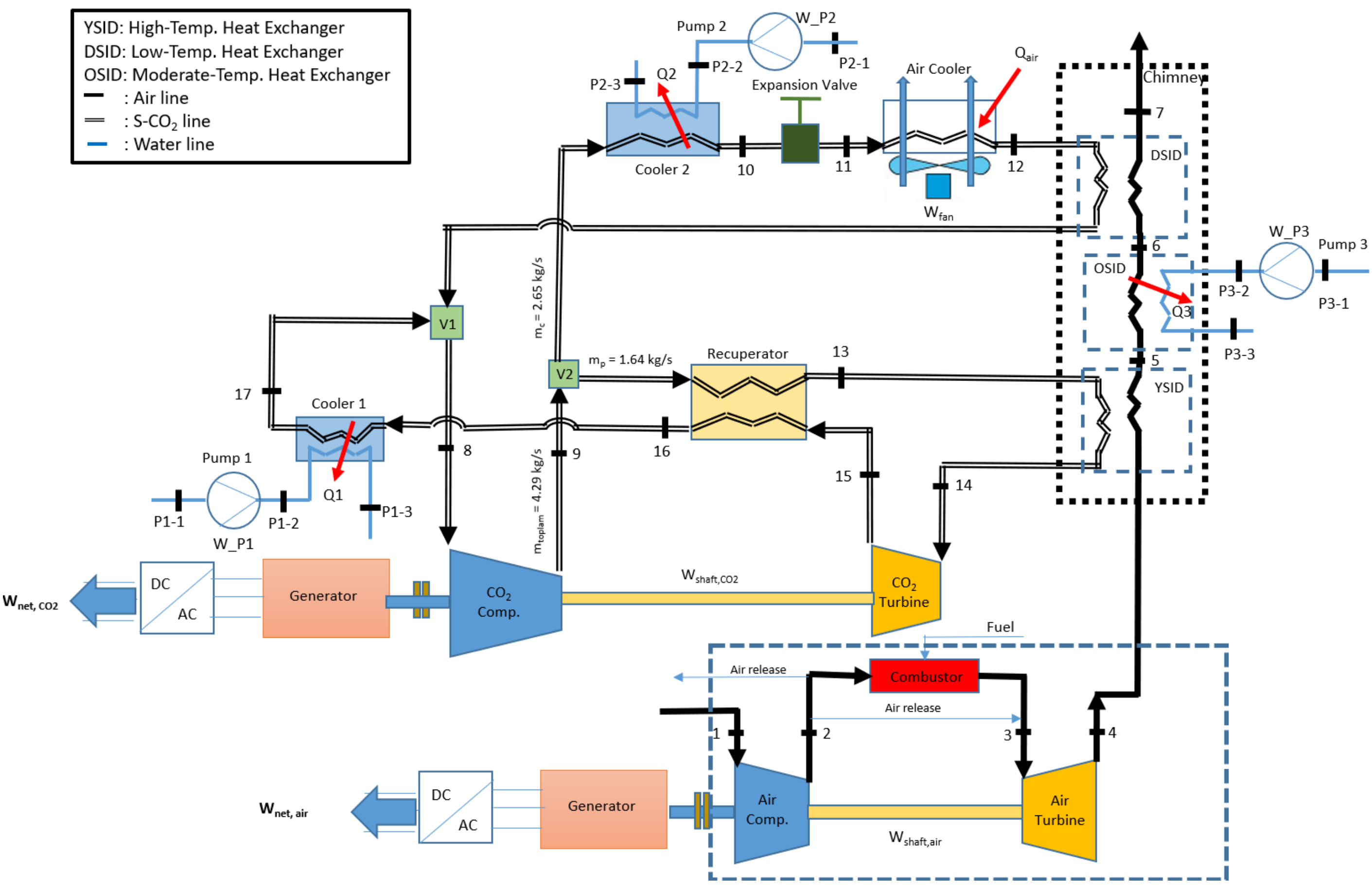

Figure 1. The schematic layout of the system

Table 1. Thermodynamic properties of the states in the plant

State	Fluid	P (bar)	T (ºC)	ṁ (kg/s)
1	air	1.01	20	1.71
2	air	14.2	420	1.71
2 -1	air evacuation (%15)	14.2	420	1.45
3	air	13.5	1250	1.45
3 -1	air evacuation (%5)	13.5	1250	1.62
4	air	1.8	801	1.62
5	air	1.5	460	1.62
6	air	1.3	97	1.62
7	air	1.03	47	1.62
8	S-CO_2	78	32	4.29
8 -v1	S-CO_2	78	32	2.65
9	S-CO_2	230	64	4.29
9-v2-mp	S-CO_2	230	64	1.64
9 -v2-mc	S-CO_2	230	64	2.65
10	S-CO_2	229	23	2.65
11	S-CO_2	17.1	78	2.65
12	S-CO_2	77.8	27	2.65
13	S-CO_2	229	435	1.64
14	S-CO_2	229	721	1.64
15	S-CO_2	78.4	581	1.64
16	S-CO_2	78.2	99	1.64
17	S-CO_2	78	32	1.64
P1-1	water	1.01		1.44
P1-2	water	20	27	1.44
P1-3	water	10	95	1.44
P2-1	water	1.01		1.45
P2-2	water	20	20	1.45
P2-3	water	77.8	27	1.45
P3-1	water	1.01		1.99
P3-2	water	20	25	1.99
P3-3	water	10	95	1.99

The turbine and compressor were considered as isentropic ones. The work produced by the air turbine was found as 864 kW and the work consumed by the compressor was evaluated as 706 kW with their evaluated isentropic efficiencies of 75.86% and 80.06%, respectively. The work produced by the turbine in the S-CO_2 line was 276 kW besides the work consumed by the compressor was 114 kW. It was seen that the network for both air and S-CO_2 line systems was almost 150 kW. As a result of the thermodynamic analyses, the overall thermal efficiency of the system was found as 43.78%.

Table 2. Thermodynamic results

States	Devices	$\dot{Q}$(kW)	$\dot{W}$(kW)
1 -2	Air Compressor	-	706
2 -3	Combustion Chamber	708	-
3 -4	Air Turbine	-	864
4 -5	Air High-Temp. Heat Exch.	626	-
5 -6	Air Moderate-Temp. Heat Exch.	609	-
6 -7	Air Low-Temp. Heat Exch.	83	-
8 -9	S-CO_2 Compressor	-	114
9 -10	Cooler 2	239	-
11-12	Fan	87	-
13 -14	S-CO_2 High-Temp. Heat Exch.	592	-
14-15	S-CO_2 Turbine	-	276
15-16	Recuperator	922	-
9-13	Recuperator	921	-
16-17	Cooler 1	358	-
8 -12	S-CO_2 Low-Temp. Heat Exch.	81	-
P1.1-P1.2	Water Pump 1	-	2.85
P2.1-P2.2	Water Pump 2	-	2.87
P2.2-P2.3	Cooler 2	239	-
P3.1-3.2	Water Pump 3	-	3.94
P3.2-3.3	Water Moderate-Temp. Heat Exch.	581	-

4. Conclusions

In this study, a thermodynamic analysis of a power plant which was constructed as a couple of two cycles, Brayton and S-CO_2 cycles was performed in order to illustrate the positive effect in energetic efficiency of the system. These systems are called as tri-generation ones in which simultaneous production of electricity and heat as well as cooling from a single energy source are carried out. The importance of co/tri-generation systems is emphasized herein. As a result of the thermodynamic analyses, the thermal efficiency of the power plant was found as 43.78% which is a remarkable value for a typical power plant. As a future study, in the frame of increasing of system thermal efficiency, alternative cycles such as Kalina, organic Rankine and other alternative power cycles can be adapted to conventional power plants to compare their existing thermal efficiencies.

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