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Thermo-economic optimization of low-grade waste heat recovery in Yazd combined-cycle power plant (Iran) by a CO_2 transcritical Rankine cycle

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A B S T R A C T

A transcritical CO_2 Rankine cycle is proposed for recovering low-grade waste heat of Yazd combined-cycle power plant in Iran. Each power generation module of this plant consists of two 159 MW Siemens SGT-5-2000E gas turbines and one 132 MW steam turbine. Reducing exhaust gas temperature from 150 °C to 70 °C, the plant can generate excessive power. From thermodynamics approach, it is demonstrated that by fixing the maximum temperature at 145 °C and varying the maximum pressure, the efficiency and the net power output are maximized at P_{max} = 185 bar. In the aforementioned operating point, about 6.3 MW is retained for the selected power plant with a nominal 450 MW of power generation. A more actual case considering thermodynamic losses and economic considerations is then investigated. Genetic algorithm is implanted to conduct a parametric optimization to maximize the benefit-cost ratio which is defined on the basis of total bare module cost and net power output. The results indicate that the cycle costs are more influenced by the maximum pressure rather than the maximum temperature. Through this parametric optimization, the CO_2 cycle can produce about 4.04 MW. This is about 0.9% of the plant capacity and increases the total efficiency about 0.4%.

1. Introduction

In recent years, industrial and residential demands for electricity have seriously increased. On the other hand, the environmental effects of consumption of fossil fuels to generate power have threatened the globe through different manners, e.g. the atmospheric pollution, the global warming and the ozone layer depletion [1]. To avoid such damages there are two possible ways to follow; first to use alternative sources such as solar and wind energies to generate electricity, and second to develop and optimize the existing power plant technologies in order to reach higher efficiencies.

The former solution which is also known as using renewable or green energy sources, has been widely on the talk in recent decades, simply because such sources never finish, they are natural and non-pollutant, and with low running costs [2], but the biggest problem about the renewable sources is that they are not sustainable enough to respond to power demand at any time [3]. For example, the solar energy is only available during the day, the amount of which also depends on the season of the year [4]. Thus at least for now, even if the renewable energy sources are considered as the main power suppliers, it seems necessary to complete the supply network with conventional fossil fuel power plants to guarantee the demand peaks at any occasion [5]. Here comes the turn for the latter solution mentioned above, i.e. improving the existing methods of power generation to achieve more efficient thermodynamic cycles. A characteristic of fossil fuel power plants is the high operating temperature of such cycles, which is due to the combustion process involved. One knows the higher the temperature, the higher the efficiency, but these relatively high efficiencies are still too low in comparison to the ideal Carnot cycle. In order to approach to the highest possible efficiency, so many efforts have already been put into this domain of technology. For instance, one can mention adding feed-water heaters, reheaters, regenerators, and etc. to simple Rankine cycle to improve its conditions [6]. All of

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these methods have been helpful, but there is another problem left. In all these conventional power plants, there are huge amounts of heat rejection, which is low-grade waste heat at temperature levels between 100 °C and 200 °C. In fact the temperatures at which this heat is rejected to the environment are too low to run another downstream steam cycle. Therefore, consideration of an efficient system that can effectively utilize the waste exhaust heat at low temperature is crucial for the improvement of overall plant efficiency [1], and as Schuster et al. state [7], the fact that such techniques are free of fuel cost makes them even more attractive. It is clear that the economics of a Rankine cycle is demonstrated by the thermodynamic properties of the working fluid, which affect the system efficiency, operation, and environmental impact. For instance, Liu et al. [8] found that the hydrogen bond in molecules like water, which results in higher evaporating enthalpies, is an inappropriate characteristic for ORC (organic Rankine cycles) systems working with low temperatures. Also, Carcasci et al. [9] have shown that different properties of working fluids make each of them suitable for a specific maximum temperature and a specific cycle configuration.

By choosing an appropriate working fluid with a relatively low critical temperature, the temperature of the waste heat discussed above will be high enough to run a downstream cycle. This relative behavior is due to the nature and characteristics of different working fluids, which make them attractive for usage in low-grade waste heat recovery for power generation. So many studies have already been performed in search of proper fluids to run such cycles. The results presented by Dai et al. [10] show that the cycles with organic working fluids convert low grade waste heat to useful work more efficiently. Also, Drescher and Bruggemann [11] demonstrated that the family of Alkylbenzenes represents the highest efficiency in biomass power plants.

Choice of appropriate organic working fluid, which depends on the application, waste heat temperature level, thermodynamic fluid properties, and the cycle parameters, leads to higher efficiencies [8,12]. ORC's (organic Rankine cycles) are usually more efficient when the working fluid is run in the supercritical region [13], and studies have shown that fluids with low critical properties are to be preferred [14]. Small specific volume, low viscosity, high thermal conductivity and stability, being non-corrosive, non-toxic and compatible with engine material and lubricating oil are other favorable properties of a working fluid, which have been proposed by V. Maizza and A. Maizza [15]. Carbon dioxide (CO_2) benefits from most of the mentioned characteristics, besides it is non-combustible and abundant in the nature and thus, relatively inexpensive. In addition, sufficient knowledge of its thermodynamic properties is available [16].

Also an experimental study has shown that CO_2 is efficiently converted into high-temperature supercritical state, and works stably in transcritical region [17]. Therefore CO_2 has been chosen as the working fluid of the downstream cycle. Although it has been proved that some man-made substances may give higher efficiencies in Rankine cycle, this choice is more logical compromising with all the mentioned characteristics of CO_2. Yamaguchi et al. [18] have shown that the transcritical CO_2 Rankine cycle has a better economic performance than the refrigerant-run cycle in terms of cost per net power output; however, its first-law efficiency is lower.

In another study, Chen et al. [16] showed that the CO_2 transcritical cycle leads to higher power outputs than the R123 subcritical cycle. Furthermore this system is more compact, according to higher pressures, and more environmental friendly rather than cycles run by artificial substances like R123.

Most of the efforts in the literature include ways of maximizing the efficiency of the low-temperature cycle for better waste heat recovery [7]. But efficiency may not tell the whole story and the power output is the other important parameter of the cycle, which has to be considered. Therefore in this study, more attention has been paid to power generation of the cycle in addition to efficiency.

In this study, the low-grade waste heat recovery for a 450 MW combined-cycle power plant located in Yazd (Iran) with final exhaust gas temperature of 150 °C is studied. The general features and design parameters of this power plant are summarized in Table 1. On the basis of the benefits mentioned above, a CO_2 transcritical Rankine cycle is chosen to recover the waste heat available in Yazd power plant. The amount of waste heat that can be used for a final stack temperature of 70 °C is about 80,000 kW.

The primary goal of this work is to investigate the thermodynamic behavior of the suggested cycle, i.e. the efficiency and the net power output, under different scenarios, and detect any probable optimal conditions in which the efficiency or the net power output, or both, reach a maximum value. Then, the economic factors and losses associated with the CO_2 cycle are considered. In this approach, thermo-economic aspects of an actual plant are investigated. Economic factors impose serious constraints on the design of such power plants. Therefore, plant optimization using Genetic Algorithm is proposed with respect to total bare module cost and net power output.

2. Thermodynamic analysis of the cycle

On the basis of the discussion of the previous section, carbon dioxide has been chosen as the working fluid of the downstream transcritical ORC for Yazd combined Power Plant in Iran. Similar to a simple Rankine cycle, a CO_2 transcritical cycle is based on four basic processes [19] which are depicted in Fig. 1, right after the steam turbine module. These processes include increasing the pressure of the working fluid through a pump, heat addition to the cycle in a boiler, for which in this study the source is a heat recovery exhaust, expansion of the high-pressure and high-temperature gas through a turbine, and finally the low temperature heat rejection in a condenser.

As stated in section one, the heat recovery process is performed on Yazd combined-cycle power plant. To achieve this goal, a heat exchanger should be installed in the combined cycle stack. The heat exchanger is considered to be installed in a completely insulated stack so that all the heat rejected from the flue gases will be added to the carbon dioxide in the ORC. Also at this stage, the pressure drop over this heat exchanger is assumed to be negligible.

The nominal mass flow rate of the Siemens SGT-5 2000E (V94.2) gas turbine [20] is 500 kg/s. In a typical arrangement in combined cycles, as in Yazd power plant, the exhaust of two identical gas turbines heats up the water in HRSG (heat recovery steam generator). The mentioned mass flow rate is for one gas turbine which is considered for all further calculations in this work. The general

Table 1
Yazd power plant design parameters, for each power generation module.

Gas turbine model	Gas power	Steam power	Total power	HRSG inlet temperature	HRSG outlet temperature	Average ambient temperature	Exhaust mass flow rate
Siemens SGT-5-2000E	2 × 159 MW	132 MW	450 MW	540 °C	150 °C	19 °C	1000 kg/s