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# Performance analysis and binary working fluid selection of combined flash-binary geothermal cycle

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ABSTRACT

Performance of the combined flash-binary geothermal power cycle for geofluid temperatures between 150 and 250 °C is studied. A thermodynamic model is developed, and the suitable binary working fluids for different geofluid temperatures are identified from a list of thirty working fluid candidates, consisting environmental friendly refrigerants and hydrocarbons. The overall system exergy destruction and Vapor Expansion Ratio across the binary cycle turbine are selected as key performance indicators. The results show that for low-temperature heat sources using refrigerants as binary working fluids result in higher overall cycle efficiency and for medium and high-temperature resources, hydrocarbons are more suitable. For combined flash-binary cycle, secondary working fluids; R-152a, Butane and Cis-butane show the best performances at geofluid temperatures 150, 200 and 250 °C respectively. The overall second law efficiency is calculated as high as 0.48, 0.55 and 0.58 for geofluid temperatures equal 150, 200 and 250 °C respectively. The flash separator pressure found to has important effects on cycle operation and performance. Separator pressure dictates the work production share of steam and binary parts of the system. And there is an optimal separator pressure at which overall exergy destruction of the cycle achieves its minimum value.



## 1. Introduction

The rising energy demand and soaring fossil fuel prices along with awareness of negative environmental impacts of burning fossil fuels to produce power have intensified the urge to use clean and renewable energy sources. Among renewable energy power generation technologies, geothermal power plants have an outstanding position. It is claimed by Chamarro et al. [1] that geothermal power plants have higher capacity factors than other power plants, and by far the highest of all renewable energy systems.

Bertani [2] reported the installed capacity of geothermal power plants worldwide equal 10.9 GW with electrical energy generated equal 67 TWh/year as of 2010. Approximately 1.8 GW (18%) of the installed capacity has been constructed between 2005 and 2010. Also, it is predicted the total installed power generation capacity would reach 19.8 GW (With energy production of 160 TWh/year) by year 2015. Indicating that, power generation from thermal energy stored below the earth surface has been accelerating and is predicted to continue this growth in future years. On the other hand location of hydrothermal fields with high-temperature geofluid, are very limited worldwide, and most of these fields have been already tapped for electricity production [3]. Hence, introducing technologies with higher energy conversion efficiency or improving existing power generation stations are crucial to maintain the increasing trend of geothermal power capacity worldwide. Despite that, like all other renewable power generation systems, geothermal power stations require high capital cost. The costs per kW power can be reduced by improving the performance.

Flash steam cycles are the most common power generation units, used to produce electricity from liquid dominated geothermal fields [4]. Various cycles such as double and triple flash steam cycles, combined flash-binary cycle, integrated flash-binary and combined flash-fossil fuel cycles have been proposed and studied for performance improvement of flash steam geothermal power cycle. Using the combined flash-binary cycle is an effective way to increase the efficiency of existing and planned flash steam geothermal power plants and has been the subject of a number of studies recently. Yari [5] conducted a

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comparative study of different geothermal power plants, based on the exergy analysis. In his study, binary geothermal power plant using a simple ORC (Organic Rankine Cycle), ORC with an IHE (internal heat exchanger), regenerative ORC, regenerative ORC with an IHE, single flash steam cycle, double flash steam cycle and combined flash-binary cycle have been considered. The results showed that the reinjection process is the largest exergy loss in the power cycle, and combined flash-binary cycle has the lowest exergy destruction at the reinjection process among studied cycles. In another study Coskun et al. [6] investigated the optimum power cycle for low temperature geothermal resources (98–162 °C). The cycles considered include double-flash, binary, combined flash-binary, and Kalina cycle. Combined flash-binary cycle was showed to have the highest energy conversion efficiencies and one of the lowest costs of producing a unit amount of electricity.

Selection of the ORC working fluid is an essential parameter in the combined flash-binary cycle design. Design of the binary cycle equipment, operation condition, efficiency and environmental impact are determined to a significant degree by working fluid characteristics. In the recent years, many studies on the effect of different working fluids on the ORC working with various energy resources, are reported in the literature [3,7–14]. By increasing the awareness of the adverse effects of some refrigerants on the environment and putting worldwide limitation on specific substances, the studies are concentrated on more environmentally friendly working fluids at last years. Various studies have been presented on design and analysis of flash steam cycles [4,15–17] and binary cycle [4,18] separately. Although to find the optimum operation conditions and ORC working fluid the whole system should be investigated.

The purpose of present work is to present a procedure to select the ORC working fluid in a flash-binary cycle for geofluid temperatures between 150 and 250 °C. Thirty environmentally friendly substances including; refrigerants and hydrocarbons have been considered as the ORC working fluid candidates. Mass, energy and exergy conservation equations were applied to each cycle component and the whole cycle to find the optimum working conditions. First and second law analysis has been conducted for each case. Exergy destruction and VER (Vapor Expansion Ratio) have been considered as objective criteria.

## 2. Combined flash-binary cycle

Flashing is the process of transforming the pressurized liquid into a mixture of liquid and vapor by lowering the fluid pressure below the saturation pressure corresponding to the fluid temperature. For high-temperature geofluids (higher than 150 °C) flashing is a viable process to reduce the pressure of the flow in order to increase the steam flow rate [1]. In 2010, flash steam cycles counted for 61% of total installed geothermal power capacity [2]. The steam is separated from the liquid in the separator and flows through the turbine to produce mechanical work. In a single flash cycle, the liquid portion of the flow leaving the separator usually with high temperature and flow rate is reinjected into the reservoir to maintain the productivity of the field. In a combined flash-binary cycle an ORC is added to a single flash plant as shown in Fig. 1, to tap into reinjection pipeline. By extracting heat from the high-temperature liquid and reducing its temperature, it is possible to improve the overall efficiency. Also, because there are no additional expenses needed to produce the hot fluid, adding the ORC to a flash steam plant would result to cheap additional electricity production. Table 1 presents some of the existing combined flash-binary plants installed in different locations.

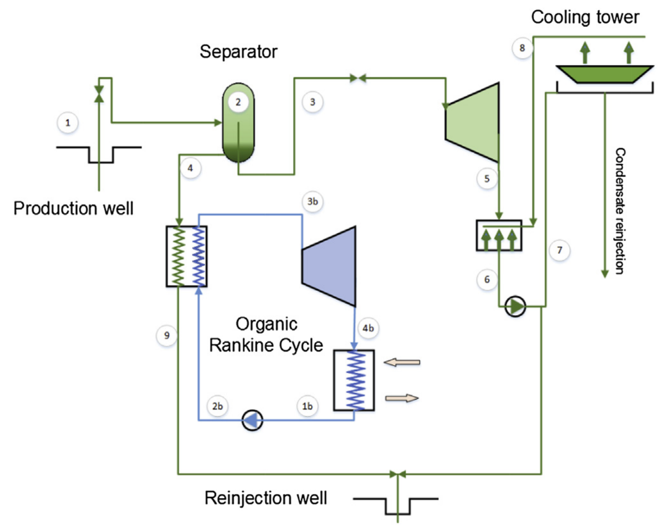


**Fig. 1.** Schematic of a flash – binary combined cycle.

## 3. Modeling and analysis

The combined flash-binary cycle consist of two separate cycles. Although there are no common components in two cycles, operation conditions of the top cycle (flash steam cycle) would affect the performance of the bottoming cycle (binary cycle). Fig. 2 shows the T-s Diagram of a typical flash steam cycle and Fig. 3 depicts the T-s diagrams of typical ORCs using a wet fluid (3a) and a dry fluid (3b) as working medium. In this section, we present the modeling approach to evaluate the cycle performance according to the first and second laws of thermodynamics.

Following assumptions are considered:

- Combined flash-binary cycle operates under steady state conditions.
- Potential and kinetic energy and changes in potential, kinetic and chemical exergies are neglected.
- Heat and pressure losses in all components are neglected.
- Thermophysical properties of geofluid are considered as pure water.
- Geofluid is assumed to be free of any chemical substances and non-condensable gases.
- The dead state temperature and pressure are assumed to be $T_{0b} = T_0 = 25$ °C and $P_{0b} = P_0 = 101$ kPa.

### 3.1. Energy and exergy balances

The first law analysis considers the quantity of energy interactions in different parts of the cycle as well as the whole system, and second law (exergy) analysis allows evaluating each component's quality of energy interaction. Exergy is defined as the maximum amount of work obtained from a certain form of energy or fluid condition, having the environmental parameters as the reference. By exergy analysis of the cycle, it is possible to highlight the processes with highest exergy destruction. Mass, energy and exergy balances for each component of the cycle can be expressed by:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$