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Study of Various Models of Combined Flash Binary Cycles

H. Shokouhmand[1], A. Jafar Yazdi[2]
[1,2]Department of Mechanical Engineering, University of Tehran, Tehran, Iran
([1]hshokoh@ut.ac.ir, [2]Ariayazdi@yahoo.com)

Abstract- With the progress of technologies, it is necessary to evaluate new and applicable ways to get high possible amount of energy from renewable resources. One of the newest technologies is combining different types of geothermal cycles to decrease wastage of the energy and environmental pollution. This paper presents an investigation on the flashing pressure optimization and performance comparison of the different flash-binary geothermal power plants. The cycles studied in this paper are the combination of single and double flash power plants with two different ORC cycles as basic Organic Rankine Cycle (ORC), ORC with IHE, regenerative ORC and regenerative ORC with an IHE. The main gain due to using combined flash-binary power plants with various types of ORCs is to achieve optimum and efficient energy utilization for Sabalan geothermal power plants.

Keywords- *Flash binary cycles, Renewable energy, Geothermal power plants, Organic Rankine Cycle, Internal heat exchanger (IHE)*

I. INTRODUCTION

Utilization of geothermal energy resources has a wide range from direct heating of domestic stuffs and newest green houses to the electricity production in power plants. Indeed, low to medium temperature water provides a good potential for industrial and commercial exploitations whereas, high-temperature geothermal resources are generally used for power generation. Type selection and establishing of geothermal power plant, which has three main concepts of dry steam, flash and binary is dependent to the reservoirs temperature. Dry steam power plants use high temperature vapor-dominant reservoirs while, flash steam power plants are applied when a liquid-dominant geofluid is produced at the wellhead of the geothermal reservoir. Binary power plants are the best energy conversion systems to exploit medium and low temperature resources.

In the recent years, much effort has been done to improve the efficiency of flash and binary power plants, distinctively and also there have been some attempts to explain criteria for the optimal design of flash and binary cycle power plants: Cerci [1] evaluated the performance of an existing single-flash geothermal power plant using exergy analysis. It was shown that the second law efficiency of the power plant is 20.8 %. Also, an examination of the exergy destruction throughout the power plant reveals that the largest exergy destruction occurs from the brine discharge to the river. According to that, two alternative designs were proposed improving the efficiency of the existing power plant: double-flash design and a binary design added to the single flash cycle. Borsukiewicz-Gozdur and Nowak [2]have presented a different method of increasing the power output of the binary geothermal cycle without an additional input of external energy. The method is based on increasing the flow of the geothermal water by returning the stream of geothermal energy medium from the outlet of the evaporator to the upstream input line of the evaporator. Gu and Sato [3] studied utilization of the supercritical cycles to raise the thermal efficiency and power output by optimizing cyclic parameters. Amiri et al. [4]have determined optimum flashing pressure of single and double flash geothermal power plants to get maximum efficiency of flash-steam plants using first- and second-laws of thermodynamic. Their results indicate that both views anticipate very close optimum flashing pressure. Second law analyses of binary geothermal power plants using different organic Rankine cycles were performed by Yari [5] .The analysis shows that the Dry steam power plants are the most efficient for the high enthalpy, vapor dominant hydrothermal reservoirs. In addition, it is presented that double flash technology raises the net power more than twice than that of single-flash plant, and the CO_2 reduction is also twice as large. Pasek et al. [6]evaluated the performance of a flash-binary cycle and investigated the limitation factor to get maximum net power such as: pinch temperature, flashing pressure and thermal design of heat exchanger. Franco [7] presented an optimization procedure for the design of binary power plant under the various operating condition. The results show that, for each combination of geothermal fluid and working fluids, there is a particular recovery cycle that permits maximization of the thermodynamic performance of the system.

Literature review shows that there has not been any performance analysis for different cycles of combined flash-binary geothermal power plants yet. In this paper, parallel flash-binary models with different types of ORC cycles are studied gaining optimum operating pressure for the separator and surveying the effect of different ORC cycles on the efficiency of the geothermal power plant. Also, the effect of binary cycle working fluid on the performance of the different combined flash-binary power plants is investigated.

II. FORMULATION OF GEOTHERMAL POWER PLANT SYSTEM

Flash steam plants are the most common type of geothermal power plants. Single flash steam technology is used where the hydrothermal resources are liquid. In flash power plants, high-pressure hot water rushes from the production wells into a separator, where a pressure reduction process vaporizes some of the fluid, rapidly. The double flash steam power plant is an improvement of single flash plant which can produce 15 to 25 % more power output from a same inlet condition of geofluid. Binary power plants are used when the hydrothermal resources are not hot enough to produce steam for a single flash power plant or where the resource contains many chemical impurities. The hot liquid of the separator of a flash cycle can be utilized as the inlet of a binary cycle as well as the directional injection of the geofluid into the binary power plant. Hence, the combination of a flash power plant with a binary cycle can be suitable to decrease the wastage of the energy and produce more energy and electricity. One of the combinations of flash cycles with binary power plants is parallel flash-binary power plants, in which binary power plant works with the liquid that extracted from the flash cycle separator. In this study, the considered binary cycles are basic Organic Rankine Cycle (ORC), ORC with an IHE, regenerative ORC and regenerative ORC with an IHE.

Fig. 1 shows the schematic diagram of two combined flash-binary power plant. Fig .1 (b) has been selected as a sample to explain the procedures that happen in the power plant. As can be observed from Fig. 1(b) the geofluid goes into the separator, causing some of it to vaporize rapidly. After the flashing process, produced steam passes through the flash cycle turbine, and also the remained liquid from flashing process goes through the evaporator to exchange the water heat to the working fluid of the binary cycle and then the geothermal fluid would injected to the injection well. Some complicate processes would be accomplished on the working fluid at evaporator which contains preheating, evaporating and superheating of the organic working fluid. The superheated vapor generates mechanical work by passing through an expander. The expanded vapor is pre-cooled in an IHE. The precooled vapor is condensed in a condenser then, the pump pumps it to the IHE. After that, the vapor extracted from the turbine mixes with the feed-water exiting from IHE, and also the saturated liquid leaves open feed-organic heater at the heater pressure, and it goes to the evaporator again.

III. ANALYSIS

The performance evaluation of the four flash-binary systems is considered by determining the first- and second-law efficiency of the power plant. For each component, the first and second-laws of thermodynamic are applied to find the work output and the system irreversibility. The mass and energy balance equation can be expressed as:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{1}$$

$$\sum_{in} \dot{m}_{in} h_{in} + \dot{Q} - \sum_{out} \dot{m}_{out} h_{out} - \dot{W} = 0 \tag{2}$$

The irreversibility rate for power plant components with steady state condition without chemical reaction is:

$$\dot{I} = T_0 \left[\left(\sum \dot{m}_e s_e - \sum \dot{m}_i s_i \right) - \frac{\dot{Q}_{c.v}}{T_j} \right] \tag{3}$$

IV. ANALYSIS OF COMPONENTS

As discussed before a combination of flash cycle with the binary system of regenerative ORC with an IHE has been chosen to describe the different components of the power plant. The reason for this selection is that this combination has all the necessary components of the other cycles.

A. *Separator*

As the name of this component implies, its duty is separation of the steam from the liquid phase of the brine. The geofluid, which goes to the separator, comes out as two distinct parts of steam and liquid because only steam should enter the turbine. Separators always work with a pressure decrement process. Increasing the pressure drop in separator increases mass flow of vapor, but decreases its enthalpy. Therefore, there is an optimum pressure getting the maximum possible efficiency in combined flash-binary geothermal power plants. The flashing process is modeled as an isenthalpic process, because it occurs steadily, adiabatically with no work involvement, so mass and energy equations in flashing chamber can be expressed by:

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_4 \tag{4}$$

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_4 h_4 \tag{5}$$

where the subscripts refer to state points in Fig. 1(d).

The temperature and the pressure loss of the separator unit have been considered to zero. Regarding this issue, the temperature and the pressure of the steam and liquid extracted from the separator are the same as the temperature and pressure of the geothermal fluid that comes into the separator:

$$T_2 = T_3 = T_4 = T_{sat}(P_{flash}) \tag{6}$$

$$P_{flash} = P_2 = P_3 = P_4 \tag{7}$$

The enthalpies of the steam, h2, and the enthalpy of the brine, h3, are determined as saturated steam enthalpy and saturated liquid enthalpy at the flashing pressure. The entropy of the steam and the brine can be calculated from pressure and enthalpy.

B. *Turbine*

The turbine has an isentropic efficiency. The isentropic efficiency of the turbine is considered 80% and defined as:

$$\eta_t = \frac{h_3 - h_5}{h_3 - h_{5s}} \tag{8}$$

Where h_{5s} is the turbine outlet enthalpy in ideal condition, which is a function of a condenser pressure. Using Eq. (9), the actual enthalpy of the geofluid at the turbine outlet is calculated.

The flash-turbine power is given by:

$$\dot{W}_{flash-turbine} = \dot{m}_3 (h_3 - h_5) \quad (9)$$

C. Flash Cycle Condenser

The condenser is considered as an air-cooled type [8]. The heat transfer in condenser is calculated by:

$$\dot{Q}_{flash-condesnser} = \dot{m}_3 \left(h_5 - h_6\right) = \dot{m}_{air1} \left(h_{air,out} - h_{air,in}\right) \quad (10)$$

where the $h_{air,out}$ and $h_{air,in}$ are the enthalpies of cooling air in the air cooled condenser at T=35ºC and T=25ºC respectively. $\dot{m}_{air,1}$ is the mass flow rate of the air flows in the condenser to cool the fluid.

D. Evaporator of the binary cycle

The evaporator heats the working fluid to the turbine inlet condition, which is saturated vapor. An energy balance in the evaporator between geofluid and working fluid can be written as:

$$\dot{m}_4 \left(h_4 - h_{pp}\right) = \dot{m}_9 \left(h_9 - h_{f,binary}\right) \quad (11)$$

$$\dot{m}_4 \left(h_{pp} - h_7\right) = \dot{m}_9 \left(h_{f,binary} - h_{17}\right) \quad (12)$$

where $h_{f,binary}$ is the saturated liquid enthalpy of the working fluid at the vaporization temperature and h_{pp} is the enthalpy of the geofluid at the pinch-point temperature of the geothermal fluid. The pinch-point difference is considered as 10 °C in this paper. Solving these equations the enthalpy of geofluid reinjected to the wellhead is calculated.

E. Open feed organic heater (OFOH)

In OFOH heat is transferred from the extracted vapor to the feed organic fluid, and ideally, the working fluid leaves the heater as a saturated liquid at the heater pressure.

The fraction of the working fluid that goes into the open feed-organic heater is achieved by applying energy balance in the feed-organic heater:

$$y = \frac{h_{16} - h_{15}}{h_{10} - h_{15}} \quad (13)$$

where h_{16} is the enthalpy of saturated liquid of working fluid at the extraction pressure.

F. Internal heat exchanger (IHE)

The IHE heats the working fluid from the pump outlet to the open feed organic heater inlet condition and cools the saturated vapor of working fluid from outlet condition of the turbine to the condenser inlet condition.

The IHE effectiveness can be expressed as:

$$\varepsilon = \frac{T_{11} - T_{12}}{T_{11} - T_{14}} \quad (14)$$

G. Binary cycle turbine

Ideally, the entropy of the working fluid after the turbine is the same as the entropy of the working fluid before the turbine. In this paper, isentropic efficiency is considered for turbines. The isentropic efficiency of the binary cycle turbine is considered as 85% [20] and defined as:

$$\eta_t = \frac{h_9 - h_{10}}{h_9 - h_{10s}} = \frac{h_{10} - h_{11}}{h_{10} - h_{11s}} \quad (15)$$

where h_{10s} and h_{11s} are the enthalpies of the working fluid at the exit of the turbine for the ideal case.

The saturated vapor of working fluid passes through the turbine to generate mechanical work. The turbine power is:

$$\dot{W}_{binary-turbine} = \dot{m}_9 \left[y\,(h_9 - h_{10}) + \left(1 - y\right)\left(h_9 - h_{11}\right)\right] \quad (16)$$

H. Condenser in the binary cycle

The working fluid leaving the IHE goes through a condenser and saturated liquid is exited.

The heat transfer rate for the condenser is shown in Eq. (17):

$$\begin{aligned} \dot{Q}_{binary-condesnser} &= \dot{m}_9 (1 - y)\left(h_{13} - h_{12}\right) \\ &= \dot{m}_{air2} \left(h_{air,out} - h_{air,in}\right) \end{aligned} \quad (17)$$

I. Pumps

Isentropic condition is considered for the pump. The isentropic efficiencies of the pumps are considered 90%and it can be expressed as:

$$\eta_{pump} = \frac{v_{13}\left(P_{14} - P_{13}\right)}{h_{14} - h_{13}} = \frac{v_{16}\left(P_{17} - P_{16}\right)}{h_{17} - h_{16}} \quad (18)$$

The pumps power can be determined as:

$$\dot{W}_{pump,1} = \dot{m}_9 (1 - y)(h_{13} - h_{14}) \quad (19)$$

$$\dot{W}_{pump,2} = \dot{m}_9 \left(h_{16} - h_{17}\right) \quad (20)$$

An understanding analysis of a geothermal power plant includes both energy and exergy analysis in order to obtain a more complete picture of the system behavior. Exergy analysis is a powerful tool like an energy analysis, because it helps identify the causes of losses to improve the overall system and its components [9, 10].

For a combined flash-binary cycle, the thermal and exergy efficiency can be expressed as:

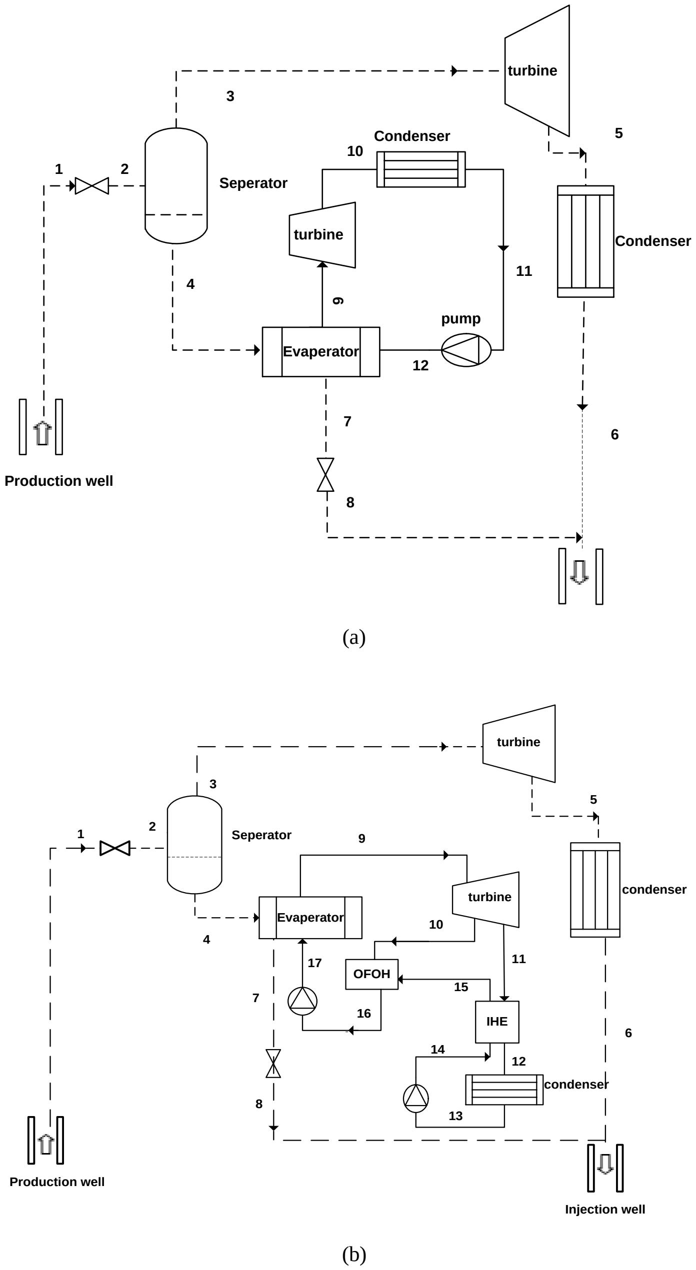
$$\eta_{thermal} = \frac{\dot{W}_{net}}{(\dot{m}_2 h_2 - \dot{m}_4 h_4) + (\dot{m}_4 h_4 - \dot{m}_7 h_7)} \quad (21)$$

$$\eta_{exergy} = \frac{\dot{W}_{net}}{(\dot{m}_2 ex_2 - \dot{m}_4 ex_4) + (\dot{m}_4 ex_4 - \dot{m}_7 ex_7)} \quad (22)$$

where ex is the specific flow exergy of the fluid and calculated with Eq. (32):

$$ex_i = (h_i - h_0) - T_0(s_i - s_0) \quad (23)$$

The dead state condition is represented by subscript 0.



(a)

(b)

Figure 1. Simplified scheme of parallel flash-binary geothermal power plants (a) basic ORC, (b) regenerative ORC with IHE.

V. RESULTS AND DISCUSSIONS

In this article performance evaluation of different flash-binary geothermal power plants using various organic Rankine cycles as a binary cycle is considered and compared based on the first and second laws of thermodynamics. Also, the influence of the some key parameters such as flashing pressure, working fluid selection, extraction pressure on the flash-binary geothermal power plants is investigated.

In the first step of evaluation, various types of flash-binary cycles will be evaluated using R123 as working fluid and then in the second stage of optimization, different working fluids would be used to study the effects of common working fluids on the efficiency of combined geothermal power plants.

Figure 2 shows the variation of the thermal efficiency with the flashing pressure of the flash-binary power plants. The evaporator temperature and condensers temperature were kept constant at 120 ℃ and 40 ℃, respectively. As shown in this figure, thermal efficiency has a maximum value in the optimum flashing pressure for each cycle of flash-binary power plant. Also, it can be observed that the regenerative ORC with an IHE shows the best thermal efficiency amongst the others. The optimum thermal efficiency of the flash-binary power plants of regenerative ORC with IHE , regenerative ORC and ORC with IHE is 1.22%, 0.97% and 0.55%, respectively, more than combined flash-binary of the basic ORC.

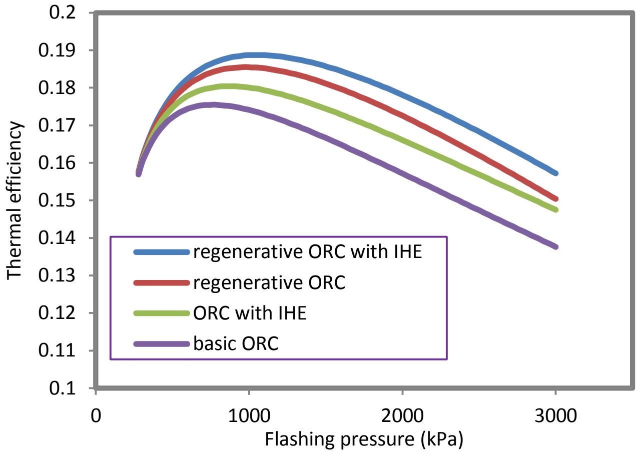


Figure 2. Thermal efficiency of different parallel flash-binary geothermal power plants

Figure 3 shows the variation of total exergy destruction with the flashing pressure. It can be observed that the total system irreversibility also has optimum flashing pressure for four configurations. The trend observed in this figure is consistent with the result shown in Figure 3, where the regenerative ORC with an IHE has the minimum exergy destruction and maximum thermal efficiency.

The remarkable thing is that both views of thermodynamic lows approximately show almost the same optimum flashing pressure for various configurations. The optimum flashing pressure for the flash-binary power plant using basic ORC based on the first- and second-laws of thermodynamic is 763.9 and 775.7 kPa, respectively. The optimum flashing pressure for the ORC with IHE based on the first- and second-laws of thermodynamic is 870 and 857.2 kPa, respectively.

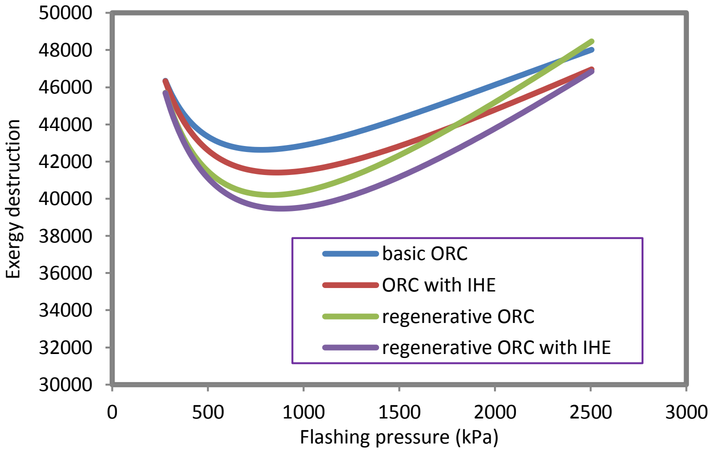


Figure 3. Total exergy destruction of different parallel flash-binary geothermal power plants ORC

Figure 4 illustrates the exergy destruction at major components of regenerative ORC with an IHE. As it is observed, the turbine makes the highest contribution to the total exergy destruction, 9.8 % of the total exergy. Other exergy destruction and locations are: 1.35% for the transmission of the geofluid from the reservoir to the wellhead, 6.17 % for the evaporator, 6.14% for the condensers, 1.36% for the OFOH, 0.1 % for the IHE, 0.04% for the pumps and 7.01% for the waste fluid re-injected to the wellhead. It can be seen that the rate of the exergy destruction during turbine losses, condenser losses and flashing process decrease significantly compared with the basic ORC and other configurations. The utilization of OFOH and IHE cause the decrease of exergy destruction of these components as explained before but it increases the exergy destruction of the waste water during reinjection processes. Also the diagram shows that the remaining 66.36% of the total exergy is converted to power which is higher than other configurations.

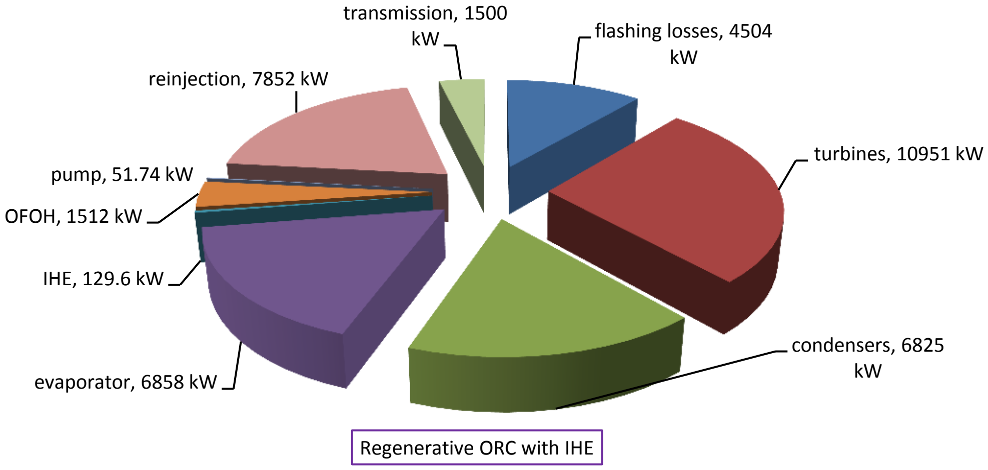


Figure 4. The exergy destruction of component of parallel flash-binary geothermal power plant using regenerative ORC with IHE

Table 1 shows the efficiency performance of the single and double flash combined with the four configurations in parallel condition based on the first and second-law analysis. It can be seen that adding the second separator the maximum thermal efficiency increased in all of four configurations. For the basic ORC, the increment of 1.48% thermal efficiency is achieved by adding a second separator. For the ORC with IHE, 1.95% more efficiency is achieved. And for regenerative ORC and regenerative ORC with IHE 0.83% and 1.81% more thermal efficiency is achieved by adding the second separator.

TABLE I. THE EFFICIENCY PERFORMANCE OF SINGLE AND DOUBLE FLASH-BINARY GEOTHERMAL POWER PLANTS USING DIFFERENT ORCS COMPARED WITH THE FLASH STEAM CYCLES IN THE REFERENCE [24]

Type plant		Net power output (MW)	Thermal efficiency (%)	Exergy efficiency
Flash-binary using Basic ORC	Single flash	55.86	17.55	63.43
	Double flash	56.04	19.03	68.48
Flash-binary using ORC with IHE	Single flash	56.72	18.04	64
	Double flash	56.56	19.99	73.52
Flash-binary using Regenerative ORC	Single flash	52.41	18.55	63.7
	Double flash	54.69	19.38	69.39
Flash-binary using Regenerative ORC with IHE	Single flash	53.6	18.87	64.25
	Double flash	58.16	20.68	74
Flash steam [26]	Single flash	31.105	7.32	32.73
	Double flash	49.78	9.96	43.35

VI. CONCLUSION

In the present study the thermodynamic performance of different combined flash-binary geothermal power plants are investigated. Flashing pressure and extraction pressure optimization of these cycles was performed. The conceptual models of different flash-binary geothermal power plants are studied for a geothermal project on the western slopes of Mt. Sabalan in northwest Iran in order to validate the models. According to this study the cycle which gives maximum thermal efficiency to a parallel combined flash-binary power plant is regenerative ORC with IHE which is on average 1.22 % higher than basic ORC. Also, the efficient working fluid for the binary cycle has been studied and R123 is selected. Finally, the effect of some operating parameters on the performance of different cycles is investigated.

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