TIME-EVOLUTION PROCESS OF TEMPERATURE FOR GEOTHERMAL BINARY CYCLE POWER PLANT FROM LOW-TEMPERATURE GEOTHERMAL RESOURCE

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ABSTRACT

The purpose in this research was to predict tendency of increase Carnot efficiency of the geothermal binary cycle power plant from low-temperature geothermal resource. Low-temperature geothermal resources are usually exploited by means of binary-type energy conversion systems. For this reason, the analysis of maximum efficiency for electricity production of the geothermal binary cycle power plant from low-temperature geothermal resource was important. The methodology of this research used model of the heat exchanger equivalent to a power plant together with the calculation of the combined heat and power (CHP) generation. The CHP was solved in detail of the development from previous research. Such development was the time-evolution process of temperature for source fluid inlet-outlet and cooling fluid supply. The Carnot efficiency from the CHP calculation was divided in two cases. The first was condition of time-evolution process of increase temperature for source fluid inlet-outlet. The second was condition of time-evolution process of decrease temperature for cooling fluid supply. Result in this research show that the Carnot efficiency for the geothermal binary cycle power plant from low-temperature geothermal resource has tendency increase in condition of time-evolution process of decrease temperature for cooling fluid supply.

Keywords: geothermal binary cycle power plant, combined heat and power (CHP), Carnot efficiency, Low-temperature geothermal resources, cooling fluid supply

1. INTRODUCTION

In recent years, accelerated consumption of fossil fuels has caused lots of serious environment problems. In this context, using renewable like geothermal for electricity production becomes important. Generally, the high-temperature reservoirs (> 220 ^{o}C) are the ones most suitable for commercial production of electricity with dry stream and flash stream systems. The low- and medium-temperature geothermal resources with temperatures of typically below 220 ^{o}C are by far the most commonly available resource and are highly recommended for using in local district heating (Hettiarachchi H et al, 2007). Low-temperature geothermal resources, typically 150 ◦C (300 ◦F) or less, are usually exploited by means of binary-type energy conversion systems (Liebowitz H M., 1999, Mlcak H A, 2002, Mlcak H A., 2002). A binary cycle geothermal power plants, pumps are used to pump hot water from a geothermal well, through a heat exchanger, and the cooled water is returned to the underground reservoir (Abdeen M O.,2008, Madhawa Hettiarachchia H D, 2007, Alessandro F and Marco V., 2009). A second working or binary fluid with a low boiling point, typically a butane or pentane hydrocarbon, is pumped at fairly high pressure through the heat exchanger, where it is vaporized and then directed through a turbine

(Geothermal Technologies Program, Hydrothermal Power Systems. Geothermal Technologies Program, 2010, Scott W., 2010, Cengel Y A and Michael A B., 2002). Production of electricity from heat requires a heat engine working between two heat reservoirs, a heat source and a heat sink. The Carnot efficiency is defined for the reversible heat engine working between two reservoirs of infinite heat capacity and constant temperature (Izumida Y and Okuda K., 2014, Shihong L., 2014). Geothermal heat source is a stream of water, either in the liquid phase or as liquid-steam mixture of any quality. The streams in and out of the system have four flow properties: mass, heat capacity, enthalpy and exergy. The mass conservation is obvious, no mixing of the source and cooling streams is assumed. The heat capacity is important for the characteristics of the heat conversion, and will be treated here as a heat capacity flow, the product of fluid heat capacity and flow rate. The product of the enthalpy relative to the environmental temperature and the flow rate defines the heat flow in and out of the system. The exergy will give information on the work producing potential of the system, and is calculated in the same way as the enthalpy. Reference textbooks such as (Cengel B., 2002) give basic information on exergy and its definition, but here the analysis is as well based on (Kotas T J 1985) and (Szargut J.,1988). (Porolfsson G., 2002) and (Valdimarsson P., 2002) apply these methods on specific geothermal applications. The hypothesis in this research is electricity production depend on the Carnot efficiency. This efficiency is defined for the reversible heat engine working between two reservoirs based on heat and exergy flow (Soundararajan K.,2014, Mohamad R B.,2017). This research analyzes when the heat source and the heat sink do not have a constant temperature and focus on calculation of the combined heat and power (CHP) generation (Florian H and Dieter B.,2010, Casisia M, Pinamontia P and Reinib M.,2009, Tim S Ing, Ingo S and Ing H 2016). The maximum efficiency is analyzed for geothermal application of the binary plant generating power from low-temperature geothermal resource. The result in this research show that the Carnot efficiency for binary plant generating power from low-temperature geothermal resource has tendency increase by decrease temperature of cooling fluid supply.

2. THEORETICAL OVERVIEW OF THERMODYNAMICS

The general Second Law formulation for open systems (Ronald D.,2004), is given as

$$\dot{\varphi}_p = \frac{dS}{d\tau} - \sum_{i=1}^{n} \dot{m}\, s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T} \frac{\delta Q}{\delta \tau}. \qquad (1)$$

We will deal here only with steady systems therefore, all time derivatives of thermodynamic properties will vanish, leading to our working equation

$$\dot{\varphi}_p = -\sum_{i=1}^{n} \dot{m}\, s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T} \frac{\delta Q}{\delta \tau}. \qquad (2)$$

In analyzing any system it will always be necessary to augment equation (1) and (2) with equations expressing conservation of both energy and mass. Applying the First Law of thermodynamics for open systems operating in steady state yields the working equation

$$\dot{Q} - \dot{W}_{ss} = -\sum_{i=1}^{n} \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right). \qquad (3)$$

We often refer to the state of the surroundings as the *dead state* because when fluids are in thermodynamic equilibrium with the surroundings there is no potential for doing work and the fluid may be considered dead. A consequence of the first condition is that $\dot{\varphi}_p$ in equation (2) vanishes

$$-\sum_{i=1}^{n} \dot{m}\, s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T} \frac{\delta Q}{\delta \tau} = 0. \qquad (4)$$

Let us consider a simplified system with only two channels one inlet (state 1) and one outlet (state 2). Also, let us for the moment ignore the effects of kinetic and potential energy. Then, Eq. (3) becomes

$$\dot{Q} - \dot{W} = \dot{m}_i \left(h_2 - h_1 \right). \qquad (5)$$

where the subscript *ss* on the power in equation (3) has been dropped for clarity. Since the only heat transfer is between the system and the dead state, Eq. (5) and (4) can be rewritten, respectively, as:

$$\dot{Q}_0 - \dot{W} = \dot{m}_i \left(h_2 - h_1 \right). \qquad (6)$$

and

$$-\dot{m}_i \left(s_2 - s_1 \right) - \frac{\dot{Q}_0}{T_0} = 0. \qquad (7)$$

Eliminating $\dot{Q}_0$, one obtains

$$\dot{W} = \dot{m}_i \left[h_1 - h_2 - T_0 \left(s_1 - s_2 \right) \right]. \qquad (8)$$

Finally, we use the exit state be identical to the dead state, and so obtain the maximum power output:

$$\dot{W}_{\max} = \dot{m}_i \left[h_1 - h_0 - T_0 \left(s_1 - s_0 \right) \right]. \qquad (9)$$

The expression in brackets is given a distinctive name, the specific exergy, e_{x1}:

$$e_{x1} \equiv h_1 - h_0 - T_0 \left(s_1 - s_0 \right). \qquad (10)$$

The equation (10) may be used to find the specific exergy of any fluid stream at a temperature T_1 and pressure P_1, relative to a given set of ambient conditions T_o and P_o.

For a fluid flowing at a certain mass flow rate, multiplying the specific exergy by the mass flow rate results in the maximum power output theoretically obtainable from the given fluid for the given surroundings; we will call this the exergetic power. Instead of using the symbol $\dot{W}_{\max}$ as in equation (9), we will henceforth use a new symbol, $\dot{E}$, for this important quantity. If kinetic or potential energy effects are important, the enthalpy h_1 should be augmented by $1/2 v_1^2$ or gz_1, respectively. Since state 1 is really arbitrary, we can drop the subscript 1 and obtain a general expression:

$$e_x = h - h_0 - T_0 \left(s - s_0 \right). \tag{11}$$

where the properties at the dead state are evaluated at T_o and P_o. The power plant as a whole, the overall exergetic efficiency reduces to a very simple formula, namely, the ratio of the net power output to the exergy of the motive fluid serving as the energy source for the plant (DiPippo R 1984).

3. THE COMBINED HEAT AND POWER (CHP) GENERATION

In figure 1, the temperature of the entering cooling fluid is taken to be the environmental temperature, the lowest temperature which can be obtained, as well as defining the thermal sink temperature for the Carnot engine efficiency.

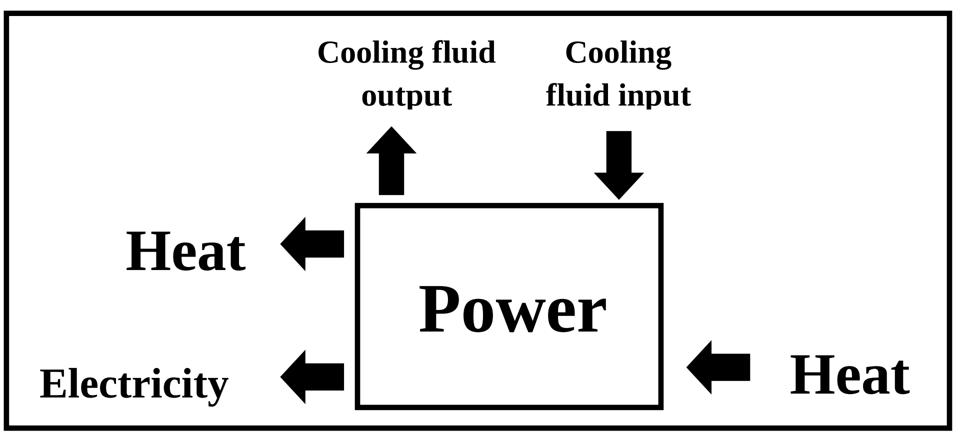

Fig. 1. The generic power plant.

In the following this system will be analysed in order to gain a better understanding of the conversion of low temperature heat into electricity (Pall V and Scient I.,2003), from figure 2.

c_h = Source fluid heat capacity, T_h = Source fluid inlet temperature

$\dot{m}_h$ = Flow rate of source fluid, T_s = Source fluid outlet temperature

c_c = Cooling fluid heat capacity, T_c = Cooling fluid outlet temperature

$\dot{m}_c$ = Cooling fluid flow rate, T_0 = Cooling fluid inlet temperature (Environmental temperature)

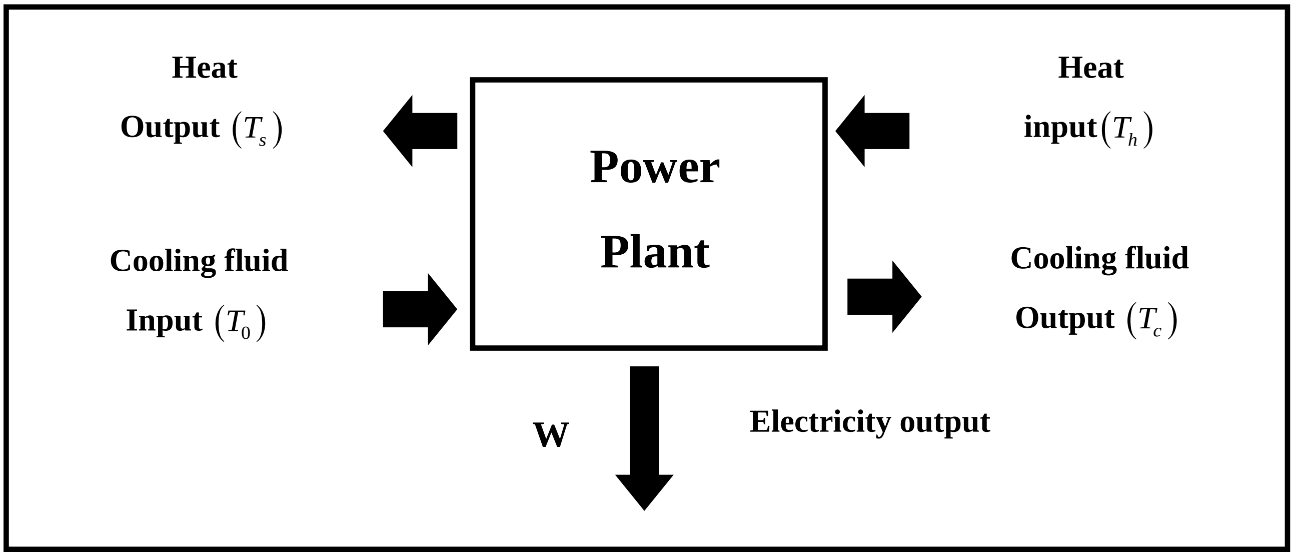

Fig. 2. Model of a heat exchanger equivalent to a power plant.

The heat flow of geothermal source fluid $\left(\dot{Q}_h\right)$, geothermal outflow $\left(\dot{Q}_s\right)$ and cooling fluid supply $\left(\dot{Q}_c\right)$, respectively, are given by

$$\dot{Q}_h = \dot{m}_h c_h \left(T_h - T_0\right). \tag{12}$$

$$\dot{Q}_s = \dot{m}_h c_h \left(T_s - T_0\right). \tag{13}$$

$$\dot{Q}_c = \dot{m}_c c_c \left(T_c - T_0\right). \tag{14}$$

The exergy flow $\left(\dot{\psi} = \dot{m}e_x\right)$ of geothermal source fluid $\left(\dot{\psi}_h\right)$, geothermal outflow $\left(\dot{\psi}_s\right)$ and cooling fluid supply $\left(\dot{\psi}_c\right)$, respectively, are given by

$$\dot{\psi}_h = \dot{m}_h c_h \left[\left(T_h - T_0\right) - T_0 \ln\left(\frac{T_h}{T_0}\right)\right] = \dot{Q}_h - \dot{m}_h c_h T_0 \ln\left(\frac{T_h}{T_0}\right). \tag{15}$$

$$\dot{\psi}_s = \dot{m}_h c_h \left[\left(T_s - T_0 \right) - T_0 \ln\left(\frac{T_s}{T_0} \right) \right] = \dot{Q}_s - \dot{m}_h c_h T_0 \ln\left(\frac{T_h}{T_0} \right). \quad (16)$$

$$\dot{\psi}_c = \dot{m}_c c_c \left[\left(T_c - T_0 \right) - T_0 \ln\left(\frac{T_c}{T_0} \right) \right] = \dot{Q}_c - \dot{m}_c c_c T_0 \ln\left(\frac{T_h}{T_0} \right). \quad (17)$$

The energy (1. law) and exergy (2. law) balances are:

$$\dot{W}_{rev} = \dot{Q}_h - \dot{Q}_s - \dot{Q}_c - c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s} \right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0} \right), \quad (18)$$

where, $\dot{W}_{rev} = \dot{\psi}_h - \dot{\psi}_s - \dot{\psi}_c$ and $\dot{W} = \dot{Q}_h - \dot{Q}_s - \dot{Q}_c$.

The energy balance is valid for all processes, ideal and real. The exergy balance gives only information on the reversible work or the largest amount of work that can be obtained from the power plant. If the power plant ideal is $\dot{W}_{rev} - \dot{W} = 0$, then the energy (1. law) and exergy (2. law) balances in the equation (18), become

$$-c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s} \right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0} \right) = 0. \quad (19)$$

Then the heat capacity flow ratio for a reversible power plant is

$$C_{rev} = \left. \frac{c_c \dot{m}_c}{c_h \dot{m}_h} \right|_{rev} = \frac{\ln\left(\frac{T_h}{T_s} \right)}{\ln\left(\frac{T_c}{T_0} \right)}. \quad (20)$$

4. THE EFFICIENCIES OF THE COMBINED HEAT AND POWER FROM TIME-EVOLUTION PROCESS

The efficiencies for the combined heat and power production process are thus electrical power generation efficiencies. All the heat contained in the stream flow rate of source fluid outlet, $\dot{m}_s$ is considered a by-product, and does not enter the efficiency calculation. Product are $\dot{W}$ and $\dot{Q}_s$. Input is $\dot{Q}_h - \dot{Q}_s$. Rejected is $\dot{Q}_c$. The first law maximum efficiency as

$$\eta_{I,\max,CHP} = \frac{\dot{W}_{rev}}{\dot{Q}_h - \dot{Q}_s} = \frac{\dot{\psi}_h - \dot{\psi}_s - \dot{\psi}_c}{\dot{Q}_h - \dot{Q}_s}$$

$$= \frac{\dot{Q}_h - \dot{Q}_s - \dot{Q}_c - c_h \dot{m}_h T_0 \left(\ln\left(\frac{T_h}{T_0}\right) - \ln\left(\frac{T_s}{T_0}\right)\right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right)}{\dot{Q}_h - \dot{Q}_s}$$

$$= \frac{c_h \dot{m}_h (T_h - T_s) - \left\{ c_c \dot{m}_c (T_c - T_0) + c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s}\right) - c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right)\right\}}{c_h \dot{m}_h (T_h - T_s)} \tag{21}$$

By using the heat capacity flow ratio for a reversible power plant in the equation (20), $\eta_{I,\max,CHP}$ in the equation (21) can be rewrite as

$$\eta_{I,\max,CHP} = 1 - \frac{\ln\left(\frac{T_h}{T_s}\right)}{\ln\left(\frac{T_c}{T_0}\right)} \frac{(T_c - T_0)}{(T_h - T_s)}. \tag{22}$$

where, $(T_c - T_0)$ is temperature difference between the cooling fluid supply inlet-outlet as α

$(T_h - T_s)$ is temperature difference between the heat source inlet-outlet as β

so that, $\alpha < \beta$ in unit of temperature. By using Newton's Law of Cooling to develop change the total temperature into time-evolution process. This step is so-called Time-Evolution Process of Temperature.

$$\int_{T_i=\beta}^{T_f=\alpha} \frac{1}{(T - T_{Env})}\, dT = -k \int_{t_i}^{t_f} dt. \tag{23}$$

Let α and β are more than T_{Env} so that, $T_{Env} \approx 0$ and $\frac{(T_c - T_0)}{(T_h - T_s)} = \frac{\alpha}{\beta} = \exp\left[-k(t_f - t_i)\right]$,

thus

$$\eta_{I,\max,CHP} = 1 - \left(\ln\left(\frac{T_H}{T_S}\right)\right)\left(\ln\left(\frac{T_C}{T_O}\right)\right)^{-1} \exp\left[-k(t_f - t_i)\right] \tag{24}$$

5. ANALYSIS CARNOT EFFICIENCY FOR BINARY PLANT GENERATING POWER

From Eq. (24) to investigate the Carnot efficiency for binary plant generating power from low-temperature geothermal resource, we can rewrite Eq. (24) as

$$\eta_{I,\max,CHP} = 1 - (\ln(a))(\ln(b))^{-1} \ \exp\ [-\ k\ t]. \tag{25}$$

where a, b and k are the factor of source fluid inlet temperature, cooling fluid inlet temperature and radiation, respectively. So that from Eq. (24) and Eq. (25), thus

$$\frac{T_h}{T_s} = a \ \rightarrow\ T_h = aT_s \qquad a \in \Re \ and\ a > 1 \qquad \text{so that,} \qquad T_h\ \alpha\ a$$

If increase <u>"a"</u> means source fluid inlet temperature T_h is <u>"increased"</u>

$$\frac{T_c}{T_0} = b \ \rightarrow\ T_0 = \frac{T_c}{b} \qquad b \in \Re\ \ and\ \ b\ >\ 0 \qquad \text{so that,} \qquad T_0\ \alpha\ b^{-1}$$

If increase <u>"b"</u> means cooling fluid inlet temperature T_0 is <u>"decreased"</u>

$$-k = \frac{4R_C A T_{Evn}^3}{mc} \qquad \text{so that,} \qquad -k\ \alpha\ R_C A$$

If increase <u>"k"</u> means multiplied result of Radiation constant and area $R_C A$ is <u>"decreased"</u>

5.1) The comparison of $\eta_{I,\max,CHP}$ between "increase T_h" and "decrease T_0"

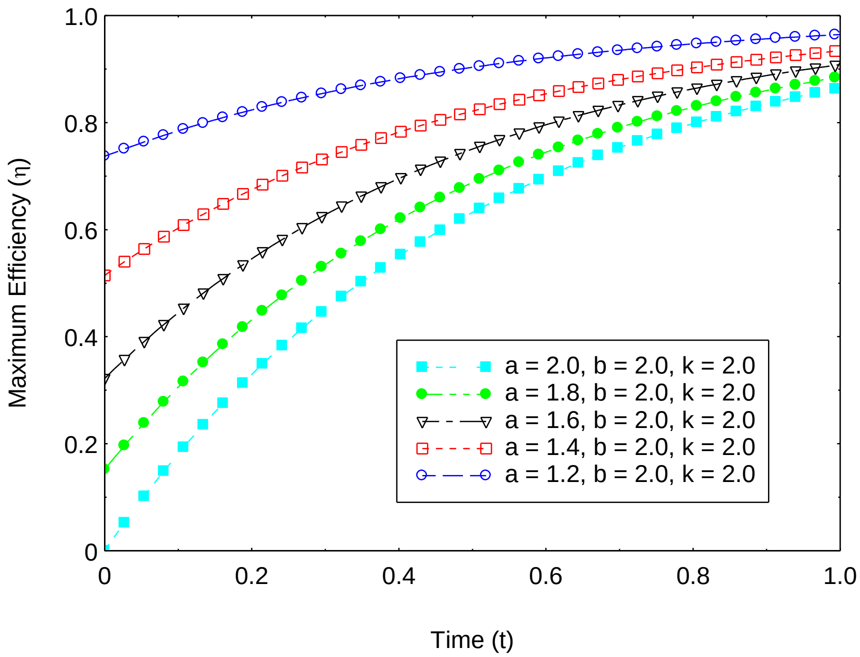

Fig. 3. 1st case :"increase" source fluid inlet temperature (T_h) by increase value of "a" $\left(T_h \;\alpha\; a\right)$

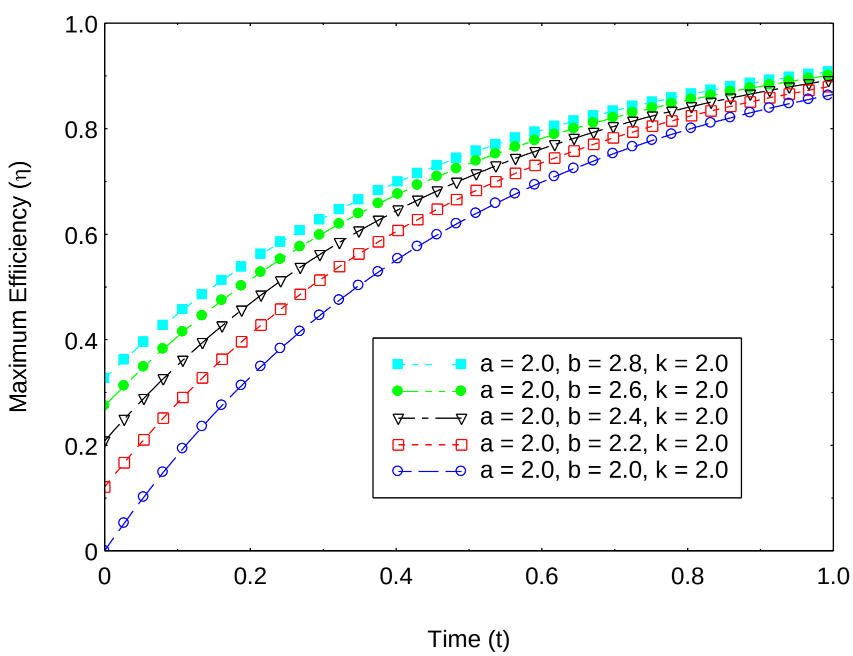

Fig. 4. 2nd case : "decrease" cooling fluid inlet temperature (T_0) by increase value of "b" $\left(T_0 \;\alpha\; b^{-1}\right)$

5.2) The comparison of $\eta_{I,\max,CHP}$ between "decrease $R_C A$ " and "increase $R_C A$ "

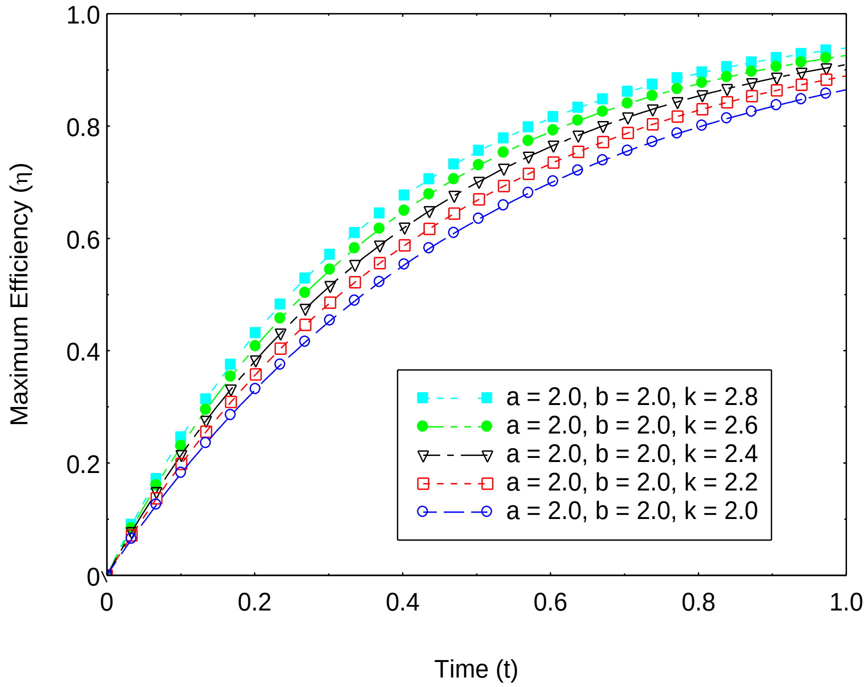

Fig. 5. 1st case : "decrease" the multiplied result of $R_C A$ by increase value of "k" $(-k \; \alpha \; R_C A)$

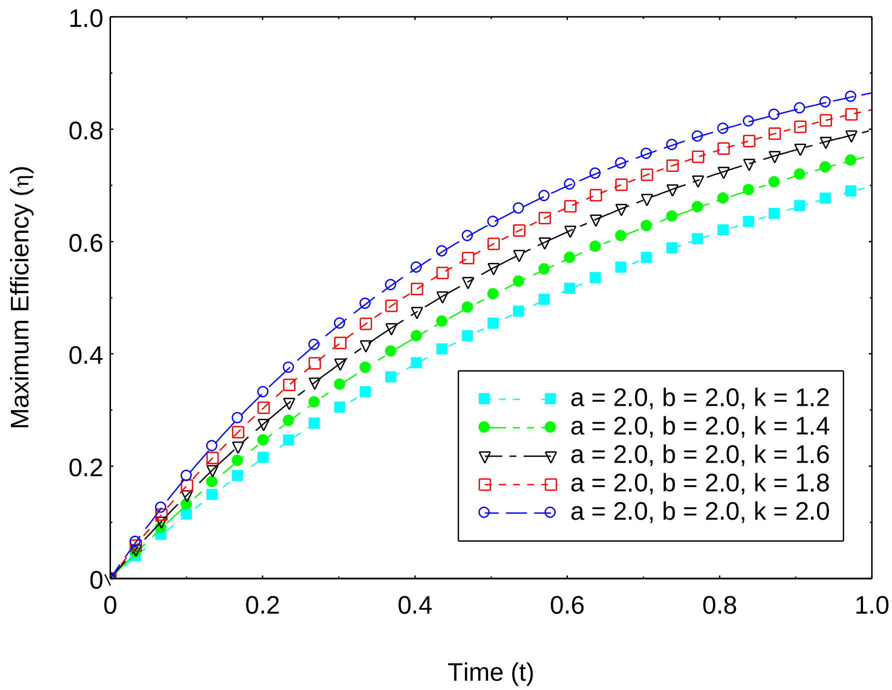

Fig. 6. 2nd case :"increase" the multiplied result of $R_C A$ by decrease value of "k" $(-k \; \alpha \; R_C A)$

5.3) The comparison of ***the best case*** for $\eta_{I,\max,CHP}$ between "decrease $R_C A$ " and "increase $R_C A$ "

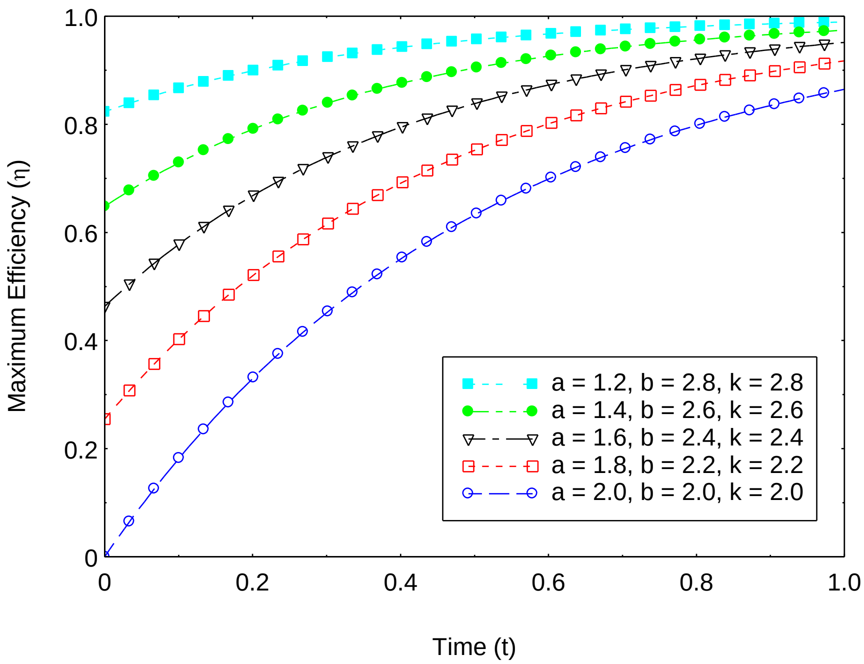

Fig. 7. 1st case : "decrease" the multiplied result of $R_C A$ by increase value of "k" $(-k\,\alpha\,R_C A)$

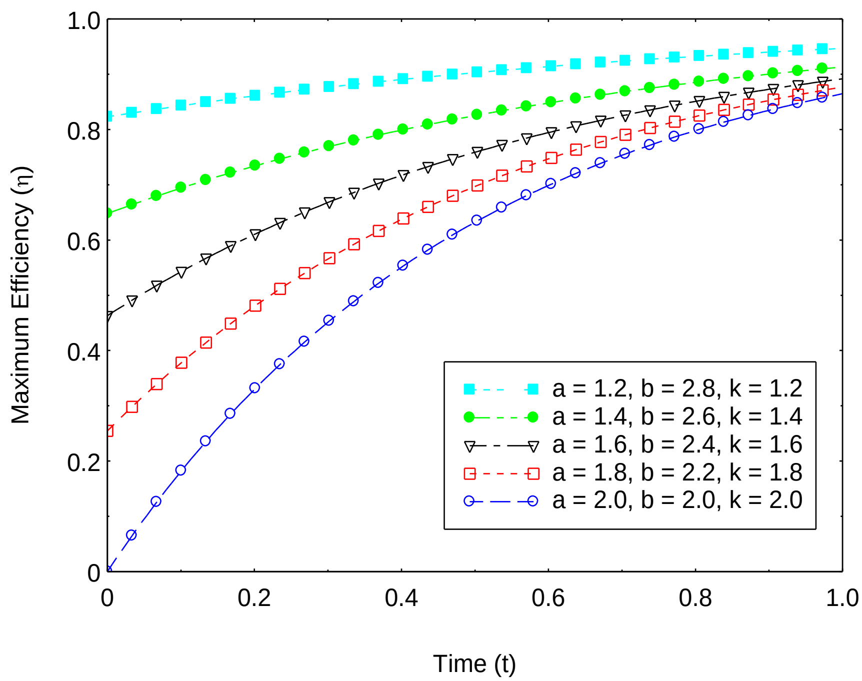

Fig. 8. 2nd case :"increase" the multiplied result of $R_C A$ by decrease value of "k" $(-k\,\alpha\,R_C A)$

6. CONCLUSIONS

By following methodology in the section 3-5, to investigate the Carnot efficiency for binary plant generating power from low-temperature geothermal resource. The CHP calculation was compared between condition of increase temperature of source fluid inlet-outlet in case 1 and decrease temperature of cooling fluid supply in case 2. Tendency was demonstrated by the last term in the equation 24 and equation 25. In 5.1) By comparing between condition of increase temperature of source fluid inlet-outlet in case 1 and decrease temperature of cooling fluid supply in case 2. Maximum efficiency has tendency increase by decrease temperature of cooling fluid supply (T_0). In 5.2) & 5.3) By comparing between condition of decrease $R_C A$ in case 1 and increase $R_C A$ in case 2. Maximum efficiency has tendency increase by decrease value of $R_C A$. Result in this research shown that the Carnot efficiency $\eta_{I,\max,CHP}$ has tendency increase by decrease temperature of cooling fluid supply for binary plant generating power from low-temperature geothermal resource.

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