Thermodynamics Analysis of Binary Plant Generating Power 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 binary plant generating power from low-temperature geothermal resource. Low-temperature geothermal resources or less, are usually exploited by means of binary-type energy conversion systems. The maximum efficiency is analyzed for electricity production of the binary plant generating power from low-temperature geothermal resource becomes important. By using 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 with appropriate boundary originating an idea from the effect of temperature of source fluid inlet-outlet and cooling fluid supply. The Carnot efficiency from the CHP calculation was compared between condition of increase temperature of source fluid inlet-outlet and decrease temperature of cooling fluid supply. 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.

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 °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 °C are by far the most commonly available resource and are highly recommended for using in local district heating [1]. Low-temperature geothermal resources, typically 150 ◦C (300 ◦F) or less, are usually exploited by means of binary-type energy conversion systems [2]-[4]. 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 [5]-[7]. 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 [8]-[10].

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 [11], [12]. 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 [13] give basic information on exergy
and its definition, but here the analysis is as well based on Kotas [14] and Szargut [15]. Porolfsson [16]
and Valdimarsson [17] 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 [18], [19]. 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 [20]-
[22]. 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. Fundamental of thermodynamics

The general Second Law formulation for open systems [23], is given as

$$\dot{\phi}_p = \frac{dS}{dT} - \sum_{i=1}^{n} m_i s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T} \frac{\delta Q}{\delta \tau}. \quad (1)$$

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

$$\dot{\phi}_p = -\sum_{i=1}^{n} m_i s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T} \frac{\delta Q}{\delta \tau}. \quad (2)$$

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 equat

$$Q - W_{ss} = -\sum_{i=1}^{n} m_i \left( h_i + \frac{v_i^2}{2} + g z_i \right). \quad (3)$$

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 $\dot{\phi}_p$ in equation (2) vanishes

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

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

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

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:

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

and

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

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

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

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

$$\dot{W} = \dot{m}_i \left[ h_1 - h_2 - T_0 \left( s_1 - s_2 \right) \right]. \quad (8)$$
\[
\dot{W}_{\text{max}} = \dot{m}_i \left[ h_i - h_0 - T_0 ( s_i - s_0 ) \right].
\]

(9)

The expression in brackets is given a distinctive name, the specific exergy, \( e_{xi} \):

\[
e_{xi} = h_i - h_0 - T_0 ( s_i - s_0 ).
\]

(10)

The equation (10) may be used to find the specific exergy of any fluid stream at a temperature \( T_i \) and pressure \( P_i \), 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 \( \dot{W}_{\text{max}} \) 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 \( h_i \) should be augmented by \( 1/2 v_i^2 \) or \( gz_i \), respectively. Since state 1 is really arbitrary, we can drop the subscript 1 and obtain a general expression:

\[
e_s = h - h_0 - T_0 ( s - s_0 ).
\]

(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 [24].

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.

\[\begin{array}{c}
\text{Cooling fluid output} \\
\text{Cooling fluid input}
\end{array}\]

Heat

\[\begin{array}{c}
\text{Heat} \\
\text{Electricity}
\end{array}\]

Power

Figure 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 [25], from Figure 2.

\[
c_h = \text{Source fluid heat capacity}, \quad T_h = \text{Source fluid inlet temperature}
\]

\[
\dot{m}_h = \text{Flow rate of source fluid}, \quad T_i = \text{Source fluid outlet temperature}
\]

\[
c_c = \text{Cooling fluid heat capacity}, \quad T_c = \text{Cooling fluid outlet temperature}
\]

\[
\dot{m}_c = \text{Cooling fluid flow rate}, \quad T_0 = \text{Cooling fluid inlet temperature (Environmental temperature)}
\]
Figure 2. Model of a heat exchanger equivalent to a power plant.

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

\[
\dot{Q}_h = \dot{m}_h c_h (T_h - T_0),
\]
\[
\dot{Q}_s = \dot{m}_s c_s (T_s - T_0),
\]
\[
\dot{Q}_c = \dot{m}_c c_c (T_c - T_0).
\]

The exergy flow \( \psi = \dot{m} e \), of geothermal source fluid \( \psi_h \), geothermal outflow \( \psi_s \) and cooling fluid supply \( \psi_c \), respectively, are given by

\[
\psi_h = \dot{m}_h c_h \left[ (T_h - T_0) - T_0 \ln \left( \frac{T_h}{T_0} \right) \right] = \dot{Q}_h - \dot{m}_h c_h T_0 \ln \left( \frac{T_h}{T_0} \right).
\]
\[
\psi_s = \dot{m}_s c_s \left[ (T_s - T_0) - T_0 \ln \left( \frac{T_s}{T_0} \right) \right] = \dot{Q}_s - \dot{m}_s c_s T_0 \ln \left( \frac{T_s}{T_0} \right).
\]
\[
\psi_c = \dot{m}_c c_c \left[ (T_c - T_0) - T_0 \ln \left( \frac{T_c}{T_0} \right) \right] = \dot{Q}_c - \dot{m}_c c_c T_0 \ln \left( \frac{T_c}{T_0} \right).
\]

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

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

where, \( \dot{W}_{rev} = \psi_h - \psi_s - \psi_c \) 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

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

Then the heat capacity flow ratio for a reversible power plant is
\[ C_{rev} = \frac{c_r \dot{m}_r}{c_h \dot{m}_h} = \ln \left( \frac{T_h}{T_s} \right) \]. 

(20)

4. The efficiencies for the combined heat and power production 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, \( \dot{m}_h \) is considered a by-product, and does not enter the efficiency calculation. Product are \( \dot{W} \) and \( \dot{Q}_c \). Input is \( \dot{Q}_h - \dot{Q}_s \). Rejected is \( \dot{Q}_c \). The first law maximum efficiency as

\[ \eta_{I, max,CHP} = \frac{\dot{W}_{rev}}{\dot{Q}_h - \dot{Q}_s} = \frac{\dot{Q}_h - \dot{Q}_s - c_r \dot{m}_h T_0 \left( \ln \left( \frac{T_h}{T_0} \right) - \ln \left( \frac{T_c}{T_0} \right) \right) + c_r \dot{m}_h T_0 \ln \left( \frac{T_c}{T_0} \right)}{\dot{Q}_h - \dot{Q}_s} \]

\[ = \frac{c_r \dot{m}_h (T_h - T_s) - \left( c_r \dot{m}_h (T_c - T_0) + c_r \dot{m}_h T_0 \ln \left( \frac{T_c}{T_0} \right) - c_r \dot{m}_h T_0 \ln \left( \frac{T_c}{T_0} \right) \right)}{c_h \dot{m}_h (T_h - T_s)} \]

(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

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

(22)

5. The analysis efficiencies for low-temperature geothermal power plant

From the first law maximum efficiency in the equation (22), thus

\[ \eta_{I, max,CHP} = 1 - C_{rev} \left( \frac{T_c - T_0}{T_h - T_s} \right). \]

(23)

Let \((T_h - T_s) = a(T_s - T_c), a \in \mathbb{R} \) and \( a > 1 \), so that \((T_h - T_s) > (T_c - T_0)\). Let \(+\Delta T \) and \(-\Delta T \) are the increase and decrease of temperature, respectively and \( \Delta T / (T_c - T_0) \equiv \delta \). The situation are divided in 2 cases

Case1: If increase the temperature of source fluid inlet-outlet \((T_h - T_s)\) as \((T_h - T_s) + \Delta T\) , let temperature of cooling fluid supply \((T_c - T_0)\) and the heat capacity flow ratio for a reversible power plant \( C_{rev} \) are constant then

\[ \eta_{I, max,CHP(i)} = 1 - C_{rev} \left( \frac{T_c - T_0}{T_h - T_s + \Delta T} \right). \]
\begin{equation}
= 1 - C_{rev} \frac{(T_c - T_0)}{a(T_c - T_0) + \Delta T},
\end{equation}

\begin{equation}
= 1 - C_{rev} \frac{1}{a + \frac{\Delta T}{T_c - T_0}} = 1 - C_{rev} \frac{1}{a + \delta} = 1 - C_{rev} \frac{1}{a(1 + \frac{\delta}{a})},
\end{equation}

\begin{equation}
= 1 - C_{rev} \frac{1}{a(1 + \frac{\delta}{a})} = 1 - C_{rev} \frac{1}{a} \left(1 - \frac{\delta}{a}\right),
\end{equation}

\begin{equation}
= 1 - C_{rev} \left(1 - \frac{\delta}{a}\right). \tag{24}
\end{equation}

So that, the first law maximum efficiency in case 1, can be rewrite as

\begin{equation}
\eta_{I, \text{max}, CHP(1)} = 1 - C_{rev} \left(1 - \frac{\delta}{a}\right) + C_{rev} \delta \left(\frac{1}{a^2}\right). \tag{24}
\end{equation}

Case 2: If decrease the temperature of cooling fluid supply \((T_c - T_0)\) as \((T_c - T_0) - \Delta T\), let temperature of source fluid inlet-outlet \((T_h - T_s)\) and the heat capacity flow ratio for a reversible power plant \(C_{rev}\) are constant then

\begin{equation}
\eta_{I, \text{max}, CHP(2)} = 1 - C_{rev} \frac{(T_c - T_0) - \Delta T}{(T_h - T_s)},
\end{equation}

\begin{equation}
= 1 - C_{rev} \left(1 - \frac{\Delta T}{T_h - T_s}\right),
\end{equation}

\begin{equation}
= 1 - C_{rev} \frac{(T_c - T_0)}{a(T_c - T_0)}(1 - \delta),
\end{equation}

So that, the first law maximum efficiency in case 2, can be rewrite as

\begin{equation}
\eta_{I, \text{max}, CHP(2)} = 1 - C_{rev} \left(1 - \frac{\delta}{a}\right) + C_{rev} \delta \left(\frac{1}{a}\right). \tag{25}
\end{equation}

6. **Summary**

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. The last term in both equations were demonstrated by factor \(a^{-2}\) in case 1 and by factor \(a^{-1}\) in case 2, so that \(\eta_{I, \text{max}, CHP(2)} > \eta_{I, \text{max}, CHP(1)}\). Result in this research shown that the Carnot efficiency \(\eta_{I, \text{max}, CHP}\) has tendency increase by decrease temperature of cooling fluid supply for binary plant generating power from low-temperature geothermal resource.

7. **Acknowledgments**

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8. **References**

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