Estimation for heat loss to the working fluid in the heat exchanger of an Organic Rankine Cycle for a given concentration of gases

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ABSTRACT

Geothermal Energy is the thermal energy derived from the earth's subsurface, often extracted from steam or hot water. It is a clean, reliable, and promising source of renewable energy. However, geothermal fluids brought to the surface through production wells contain non-condensable gases and minerals. These gases can reduce the heat transfer efficiency process in the surface plant, impacting the turbine's efficiency when used to generate electricity. The gases mainly constitute CO_2.

The paper demonstrates two process models one calculating the output from the turbine for similar input conditions as in one of the geothermal powerplant in New Zealand and the second calculating the change in heat transfer efficiency of the heat exchanger for a given concentration of gases in the geothermal fluid. The second process model is a cut-down model of the heat exchanger from the complete process model developed, which helps understand the loss of efficiency in heat transfer when geothermal fluid with different concentrations of gases passes through it. The heat exchanger is run for a range of values of the concentration of gases. The primary focus is on evaluating the change in heat transfer efficiency in the heat exchanger.

1. INTRODUCTION

Geothermal Energy can be utilized in different ways. Power can be generated from a geothermal energy source using different technologies (Enthalpy et al., 2011), (GNS Science, 2005), such as dry, flash turbines, and binary systems. Binary geothermal power plants use a secondary working fluid, which flows through the Organic Rankine Cycle(ORC) and gets heated by the geothermal fluid after passing them through a heat exchanger. The binary cycle geothermal power plants are the focus of this study. The Organic Rankine Cycle allows us to utilize lower-temperature geothermal fluid to produce electricity using the organic working fluid (Shengjun et al., 2011), (Tchanche et al., 2011), (McLean & Richardson, 2016). Comprehensive literature is available on the variety of ORC applications (Proctor et al., 2013).

The geothermal fluid bought to the surface for the electricity generation process may contain gases that are non-condensable and can impact the efficiency of a geothermal power plant. The amount of gases in the geothermal fluid varies across different geothermal sites(McLean & Richardson, 2016),(Mclean & Richardson, 2021),(Mclean et al., 2020). Current research on the reinjection of gases back into the geothermal field indicates that it could be beneficial to the reservoir, and more mass flow rate from the production wells could be achieved (Kaya et al., 2011),(Kaya & Zarrouk, 2017a).

This paper is organized as follows. First, in section 2, the geothermal energy system and different components of a binary geothermal powerplant are discussed individually in subsections. Next, the methodology used for developing the process model and calculating the change in the heat transfer efficiency in the heat exchanger is discussed in section 3. Finally, section 4 consists of this work's results, discussions, and conclusion.

2. COMPONENTS OF A BINARY GEOTHERMAL POWERPLANT

Geothermal fluids in New Zealand contain non-condensable gases, particularly CO_2, which are believed to come from magmatic sources. Discharging of this CO_2 has become a particular concern in the industry in New Zealand. In the natural state, the gases come to the surface naturally in the form of fumaroles, flux through the soil, and from hot pools. When a geothermal power station is developed, most of the CO_2 emissions are then discharged through the power station (see Figure 1).

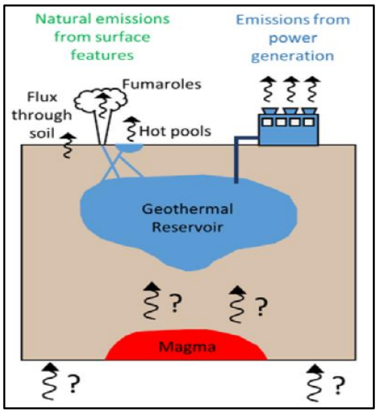

Figure 1: Schematic diagram of a geothermal reservoir showing different forms of greenhouse gas emission (McLean & Richardson, 2016).

In a binary geothermal powerplant, the energy present in the geothermal fluid in the form of heat is transferred to a secondary working fluid (Sadeghi et al., 2016), (Yari, 2010). The secondary working fluid flows in the Organic Rankine Cycle. A binary geothermal powerplant consists of different parts such as:

1) The geothermal reservoir
2) The Production Wells
3) Fluid Collection System

4) Heat Exchangers
5) The Organic Rankine Cycle
6) Fluid Disposal System
7) The Reinjection Wells

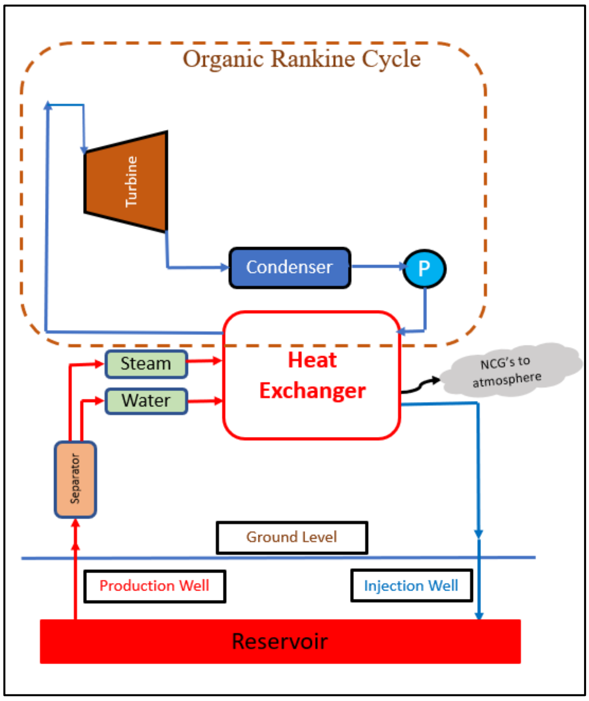

Figure 2: Schematic diagram of a binary cycle powerplant including all the components of the binary type geothermal powerplant.

2.1 Separator

A separator is a component used in the geothermal system to separate steam from the brine. The separated steam is passed through the vaporizer, transferring energy to the secondary fluid (Organic fluid). It returns to the reinjection wells after passing through the fluid preheater, where the organic fluid entering the vaporizer gets preheated. Separators are designed and optimized according to the requirement of the system (Zarrouk & Purnanto, 2015),(Rivas-Cruz et al., 2015),(Lazalde-Crabtree, 1984),(Sihombing et al., 2018).

2.2 Organic Rankine Cycle

Organic Rankine Cycles use a working fluid for electricity generation. The working fluid, also called secondary fluid (cold fluid), is heated by the primary fluid (hot fluid) while passing through the heat exchangers. The Organic Rankine Cycle has broad applicability for geothermal systems as it gives the flexibility to work with low-temperature resources and provides an option for reinjecting all the fluid back to the geothermal reservoir through the reinjection wells (Lee et al., 2019),(Clarke & McLeskey, 2015),(Coskun et al., 2014). The components of an Organic Rankine Cycle are an evaporator, a pump, a turbine or expander, and a condenser. First, the primary fluid is transferred to the heat exchanger, where the transfer of energy from the primary fluid vaporizes the working. Next, the vapor is used to run the turbine to transform the energy into electricity. Finally, the working fluid is passed through the condenser for cooling. The pump then pressurizes the liquid from the condenser, and the cycle repeats.

2.3 Heat Exchangers

Heat exchangers play a vital role in binary geothermal power plants transferring the energy of geothermal fluid into energy in the working fluid used in an Organic Rankine Cycle. Therefore, the type and size of heat exchangers are essential aspects to be considered while designing a binary geothermal powerplant (Bull et al., 2020),(Whalley & Ebrahimi, 2018),(Laskowski, 2015). Figure 3 shows a shell and tube heat exchanger with hot geothermal fluid passing through the shell and cold working fluid passing through the tubes.

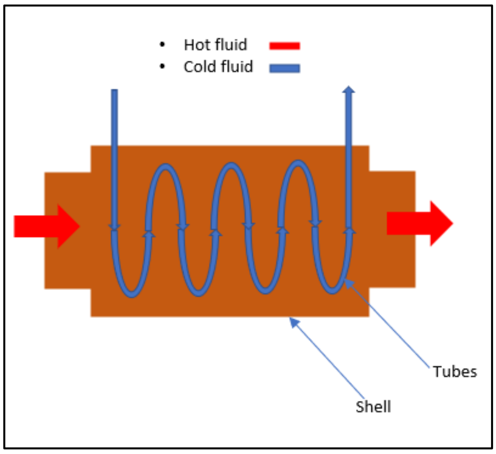

Figure 3: Schematic diagram of a shell and tube type heat exchanger.

2.4 Reinjection

The geothermal fluid passed through the heat exchangers is then reinjected to the reservoir, and the separated NCGs are typically discharged into the atmosphere. This is the issue of concern about the operations of these systems, as releasing the gases into the atmosphere is no longer seen as an acceptable practice, and effective solutions to avoid releasing the gases into the atmosphere are being explored in the geothermal field. Reinjection of gases could be one of those solutions(Bonafin et al., 2019),(Niknam et al., 2020),(Kaya et al., 2018),(Callos et al., 2015),(Kaya & Zarrouk, 2017b),(Choudhary, Burnell, Rayudu, et al., 2021a),(Choudhary, Burnell, Hinkley, et al., 2021), (Choudhary, Burnell, Rayudu, et al., 2021b).

3. METHODOLOGY

The methodology of this work is divided into three parts. The first section defines the objective of this work, followed by section 2, which introduces the software package used for this analysis, and section 3, which demonstrates the process model developed and used for this analysis.

3.1 Objective

The main objective of this work is to estimate the effect of various levels of CO_2 on a heat exchanger's efficiency in an Organic Rankine unit attached to a geothermal powerplant. We will consider temperature ranges typical of the produced fluid at the Ngawha geothermal reservoir (Burnell et al., 2016), and we will consider CO_2 concentration in the range of 0 to 2%. These are typically concentrations that have been observed at Ngawha geothermal field (Glover & Scott, 2005).

The reason for undertaking this study is that typical operations of geothermal binary plants see concentrations of produced CO_2 decreasing with time as a result of reinjecting a degassed fluid. As reinjection of CO_2 is being considered by field operators in New Zealand, which have been seen through a talk on "CO2 reductions Industry collaboration project" presented by Katie McLean at the NZGA 2022 Winter Seminar (*NZGA 2022 Winter Seminar*, n.d.). We are considering the effect this could have on the efficiency of the power plant.

3.2 Software Package

DWSIM, an open-source chemical process simulator with the functionality of working on the steady-state mass and energy balances, was used in this study to generate a process flow diagram and a process model.

3.3 Process model

The input parameters for the process models were the pressure, enthalpy, mass flow rate, and concentration of gases in the geothermal fluid.

Figure 4 shows a process model in which the primary fluid is the geothermal fluid, while the secondary fluid is taken as n-pentane (KAHRAMAN et al., 2019), (Nurhilal et al., 2016). The temperature of the geothermal fluid is set to a saturation temperature at the wellhead of 199.167º C and a wellhead pressure of 16 bar. The flow rate of 100kg/s was used, which is chosen to be typical of a single production at Ngawha geothermal powerplant, and the enthalpy of 990 kJ/kg was used. The input parameters for the geothermal fluid are the properties at the surface. This process model (figure 4) ran for the geothermal fluid composition having 1 % of gases (mainly CO_2).

For the heat exchanger, the cold and hot fluid pressure drop was considered as 0 bar, the global heat transfer coefficient of 3000W/m^2k, and the heat exchange area of 1000m^2 were chosen by adjusting until the correct amount of heat transfer was achieved. For the turbine, the outlet pressure was set to 1bar and the adiabatic efficiency to 50%. When pentane comes out of the turbine, its pressure drops to 1 bar, and the temperature drops as it passes through the cooler to bring it to liquid conditions. Then, a pump is placed to repressurize the fluid before it enters the heat exchanger and gets vaporized, and the cycle repeats.

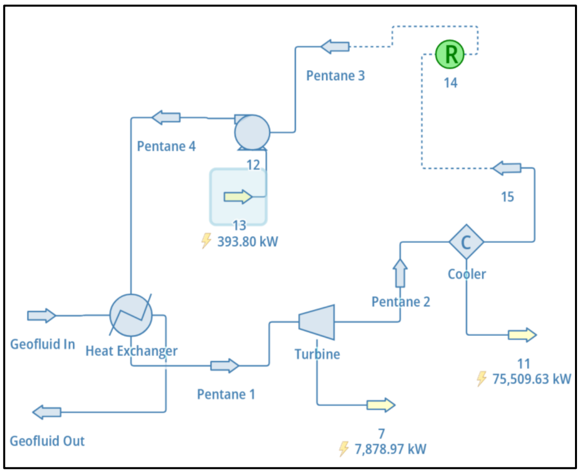

Figure 4: Process model diagram of a binary Geothermal powerplant.

The process model gives approximately similar values to what is seen at Ngawha geothermal power plant. A flow rate of 100kg/s is generating about 8MWe. Tables 1 and 2 show the input parameters for the geothermal fluid and n-pentane at the inlet of the heat exchanger. Tables 3 and 4 show the input value of the heat exchanger and the turbine.

Table 1: Input parameters for geothermal fluid into the heat exchanger.

Temperature at the inlet (º C)	Wellhead Pressure (bar)	Flow rate (kg/s)	Concentration of gases in brine
199.167	16	100	1% by mass

Table 2: Input parameters for n-pentane into the heat exchanger.

Temperature at the inlet (º C)	Inlet Pressure (bar)	Flow rate(kg/s)
35.8014	14	138.88

Table 3: Input parameters for the heat exchanger.

Cold fluid pressure drop	0	bar
Hot fluid pressure drop	0	bar
Global heat transfer coefficient	3000	W/m^2k
Thermal efficiency	89.3	%
Heat load	82.994	MW

Table 4: Input parameters for the turbine.

Outlet Pressure	1	bar
Adiabatic efficiency	50	%

3.3.1 Heat Exchanger Model

Another model developed for this study is a process model of a heat exchanger, which is a cut-down version of the complete process model, as shown in figure 5. The purpose of this model was to test the effect of CO_2 gas concentration in the geothermal fluid on the heat load (MW).

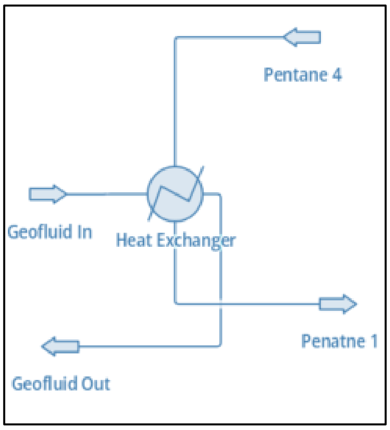

Figure 5: Process model of a heat exchanger.

4. RESULTS AND CONCLUSION

The results of the process models are as follows :

4.1 Complete Process Model

The complete process model gives an output of about 8 MWe from the turbine, with a flow rate of 100kg/s of geothermal fluid. The temperature and pressure conditions are similar to the Ngawha geothermal field. The Output of the model is consistent with output from the Ngawha geothermal power plants, with 25MWe being produced from approximately 300kg/s of geothermal fluid flow.

4.2 Heat Exchanger Model

The heat exchanger model was developed using conditions related to the heat exchanger from the Complete Process Model. Namely :

- Pressure and enthalpy of the geothermal fluid
- Flow rate of the geothermal fluid
- Flow rate of n-pentane
- Inlet temperature of n-pentane

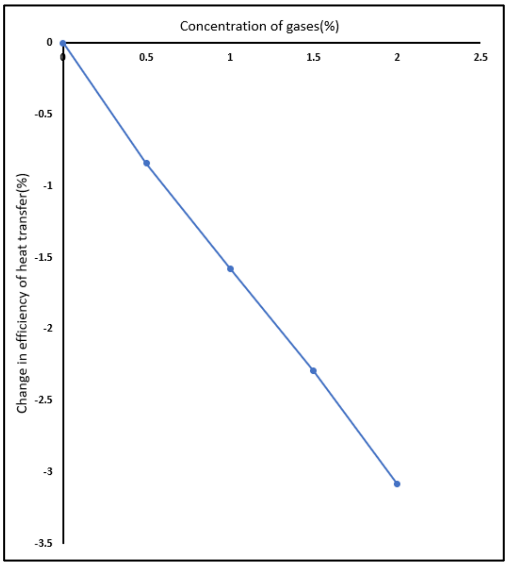

Figure 6: Heat transfer efficiency changes with increasing gas concentration in the geothermal fluid.

Figure 6 shows how the output of the heat exchanger changes with the concentration of NCGs. The decline curve shows that as the concentration of NCGs increases from 0-2%, the reduction in heat exchanger output reaches about 3.2%.

For the process model of a heat exchanger, shown in figure 5, the enthalpy of the geofluid stream was assumed to be constant when the concentration of CO_2 was changed. This condition was chosen as at the reservoir conditions at Ngawha; the enthalpy will be approximately constant as the gas concentration changes. The reason being that fluids in the Ngawha reservoir are in liquid conditions.

We conjecture that the reason for these results in Figure 6 is that increasing the NCG concentration in the geothermal fluid reduces the temperature as the flash pressure has increased. Note that the geothermal fluid that enters the heat exchanger is at saturation conditions due to the operating wellhead pressure. With a lower fluid temperature, the temperature difference between the geothermal fluid and the organic fluid reduces and hence reduces the heat transfer.

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REFERENCES

Bonafin, J., Pietra, C., Bonzanini, A., & Bombarda, P. (2019). CO2 emissions from geothermal power plants: evaluation of technical solutions for CO2 reinjection. *European Geothermal Congress 2019, Den Haag, The Netherlands, 11-14 June 2019, June*, 9.

Bull, J., Buick, J. M., & Radulovic, J. (2020). Heat exchanger sizing for organic rankine cycle. *Energies*, *13*(14). https://doi.org/10.3390/en13143615

Burnell, J., Weir, G., & Kissling, W. (2016). Modelling the Ngawha geothermal field. *Proceedings: 38th New Zealand Geothermal Workshop*, *November*. http://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2016/108_Burnell_Final.pdf

Callos, V., Kaya, E., Zarrouk, S. J., Mannington, W., Burnell, J., Zealand, N., Limited, C. E., Zealand, N., & Zealand, N. (2015). Injection of Co 2 Into Liquid Dominated Two-Phase Geothermal Reservoirs. *Proceedings 37th New Zealand Geothermal Workshop*, *November*, 9.

Choudhary, A., Burnell, J., Hinkley, J., Elias, A., & Rayudu, R. (2021). Reinjection as a solution to greenhouse gas emissions from high emitting geothermal powerplants in New Zealand. *Eea2021*, *figure 3*, 6.

Choudhary, A., Burnell, J., Rayudu, R., & Hinkley, J. (2021a). Analysis of the impact of the reinjection of gases on the mass flow rate from production wells at varying reservoir conditions. *New Zealand Geothermal Workshop Proceedings*, *November*.

Choudhary, A., Burnell, J., Rayudu, R., & Hinkley, J.

(2021b). Greenhouse gas emissions from geothermal powerplants in New Zealand: Is reinjection of gases a solution? *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, *2021-Decem*, 811–815. https://doi.org/10.1109/TENCON54134.2021.9707393

Clarke, J., & McLeskey, J. T. (2015). Multi-objective particle swarm optimization of binary geothermal power plants. *Applied Energy*, *138*, 302–314. https://doi.org/10.1016/j.apenergy.2014.10.072

Coskun, A., Bolatturk, A., & Kanoglu, M. (2014). Thermodynamic and economic analysis and optimization of power cycles for a medium temperature geothermal resource. *Energy Conversion and Management*, *78*, 39–49. https://doi.org/10.1016/j.enconman.2013.10.045

Enthalpy, L., Energy, G., & Planning, N. Z. (2011). *Low Enthalpy Geothermal Energy New Zealand Planning and Regulatory Assessment : Resource Management Act 1991 and Building Act 2004 Prepared for : Table of Contents*.

Glover, R. B., & Scott, T. M. (2005). Geochemical Monitoring Before and During Six Years of Power Generation at Ngawha , New Zealand. *Proceedings World Geothermal Congress 2005*, *April*, 24–29.

GNS Science. (2005). *Geothermal Energy Using Low Temperature Geothermal Resources*.

KAHRAMAN, A., ŞAHİN, R., & ATA, S. (2019). Thermal efficiency evaluation of an organic Rankine cycle with n-pentane as working fluid. *International Journal of Energy Applications and Technologies*, *6*(2), 31–38. https://doi.org/10.31593/ijeat.444464

Kaya, E., Callos, V., & Mannington, W. (2018). CO2 –water mixture reinjection into two-phase liquid dominated geothermal reservoirs. *Renewable Energy*, *126*, 652–667. https://doi.org/10.1016/j.renene.2018.03.067

Kaya, E., & Zarrouk, S. J. (2017a). Reinjection of greenhouse gases into geothermal reservoirs. *International Journal of Greenhouse Gas Control*, *67*(November), 111–129. https://doi.org/10.1016/j.ijggc.2017.10.015

Kaya, E., & Zarrouk, S. J. (2017b). Simulation of Reinjection of Non-Condensable Gas-Water Mixture into Geothermal Reservoirs. *PROCEEDINGS the 42 Stanford Geothermal Reservoir Engineering*, 1–14.

Kaya, E., Zarrouk, S. J., & O'Sullivan, M. J. (2011). Reinjection in geothermal fields: A review of worldwide experience. *Renewable and Sustainable Energy Reviews*, *15*(1), 47–68. https://doi.org/10.1016/j.rser.2010.07.032

Laskowski, R. (2015). The black box model of a double-tube counter-flow heat exchanger. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *51*(8), 1111–1119. https://doi.org/10.1007/s00231-014-1482-2

Lazalde-Crabtree, H. (1984). Design approach of steam-water separators and steam dryers dor geothermal applications. *Geothermal Resources Council Bulletin*, 11–20. papers3://publication/uuid/C44B5C53-E615-40D0-8D54-4883EFC61386

Lee, I., Tester, J. W., & You, F. (2019). Systems analysis, design, and optimization of geothermal energy systems for power production and polygeneration: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, *109*(April), 551–577. https://doi.org/10.1016/j.rser.2019.04.058

Mclean, K., & Richardson, I. (2021). *Geothermal Greenhouse Gas Emissions in New Zealand in 2020 : Lifecycle and Operational Emissions*. *November*, 1–8.

McLean, K., & Richardson, I. (2016). Greenhouse Gas Emissions from New Zealand Geothermal Power Generation in Context. *New Zealand Geothermal Workshop*, *23*, 1–9. https://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2019/101.pdf

Mclean, K., Richardson, I., Quinao, J., Clark, T., Owens, L., Zealand, N., Tuwharetoa, N., & Assets, G. (2020). *Greenhouse Gas Emissions From New Zealand Geothermal : Power Generation and Industrial Direct Use*. *November*.

Niknam, P. H., Talluri, L., Fiaschi, D., & Manfrida, G. (2020). Gas purification process in a geothermal power plant with total reinjection designed for the Larderello area. *Geothermics*, *88*(January), 101882. https://doi.org/10.1016/j.geothermics.2020.101882

Nurhilal, O., Mulyana, C., Suhendi, N., & Sapdiana, D. (2016). The simulation of organic rankine cycle power plant with n-pentane working fluid. *AIP Conference Proceedings*, *1712*(February 2016). https://doi.org/10.1063/1.4941880

NZGA 2022 Winter Seminar. (n.d.). https://www.nzgeothermal.org.nz/news--events/recap-geothermal-week-2022/

Proctor, M. J., Yu, W., & Young, B. R. (2013). Validation of an Organic Rankine Cycle Model of a Geothermal. *Nzgw 2013*, *November*.

Rivas-Cruz, F., Garcfa-Gutiérrez, A., Martínez-Estrella, J. I., & Ortiz-Bolaños, Á. A. (2015). Design and evaluation of geothermal steam separators: A review of the state of art. *Transactions - Geothermal Resources Council*, *39*, 881–886.

Sadeghi, M., Nemati, A., ghavimi, A., & Yari, M. (2016). Thermodynamic analysis and multi-objective optimization of various ORC (organic Rankine cycle) configurations using zeotropic mixtures. *Energy*, *109*, 791–802. https://doi.org/10.1016/j.energy.2016.05.022

Shengjun, Z., Huaixin, W., & Tao, G. (2011). Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. *Applied Energy*, *88*(8), 2740–2754. https://doi.org/10.1016/j.apenergy.2011.02.034

Sihombing, C., Kurniawan, H. A., Wirakusumah, A. D., Fanani, A. F., & Yani, A. (2018). *Production Test Analysis Using Separator Method with Respect to Separator Efficiency*. 1–7.

Tchanche, B. F., Lambrinos, G., Frangoudakis, A., & Papadakis, G. (2011). Low-grade heat conversion into power using organic Rankine cycles - A review of various applications. *Renewable and Sustainable Energy Reviews*, *15*(8), 3963–3979. https://doi.org/10.1016/j.rser.2011.07.024

Whalley, R., & Ebrahimi, K. M. (2018). Heat exchanger dynamic analysis. *Applied Mathematical Modelling*, *62*, 38–50. https://doi.org/10.1016/j.apm.2018.04.024

Yari, M. (2010). Exergetic analysis of various types of geothermal power plants. *Renewable Energy*, *35*(1), 112–121. https://doi.org/10.1016/j.renene.2009.07.023

Zarrouk, S. J., & Purnanto, M. H. (2015). Geothermal steam-water separators: Design overview. *Geothermics*, *53*, 236–254. https://doi.org/10.1016/j.geothermics.2014.05.009