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ORGANIC RANKINE CYCLE NUMERICAL SIMULATION BASED ON FLUID PROPERTIES FOR A POTENTIAL GEOTHERMAL POWER PLANT IN INDONESIA

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Abstract

Indonesia has big geothermal power plant potential but is not yet fully utilized. This study focuses on the thermodynamic modelling of the ORC system, with a specific emphasis on working fluid selection and exergy, power production, and heat rejection analysis. The ORC may operate at lower temperatures and pressures by employing organic fluids instead of water, allowing for more efficient geothermal power generation. The simulation findings illustrate the effect of different working fluids on the system's power output and heat rejection. The findings highlight the need for more study to enhance the ORC system's heating and cooling cycles, improving its overall performance and efficiency, this study shows simulation result that the suitable working fluid for potential power plant in Indonesia with heat source of 225 ℃ is working fluid R601 based on highest exergy and heat rejection.

Keywords: Fluid properties, Galunggung, Indonesia, Numerical simulation, Organic Rankine Cycle (ORC).

1. Introduction

According to the projections of the World Energy Agency, energy demand will increase from 2006 to 2030 energy demand will increase by 45% or an average of 1.6% per year, and this is due to human behaviour that is dependent on energy. For example, in Indonesia alone the total energy consumption will reach 909.24 million barrels of oil equivalent (BOE) in 2021, based on data from the Ministry of Energy and Mineral Resources (ESDM), energy consumption in Indonesia edged up 0.4% compared to the previous year which amounted to 905.6 million BOE.

Generally, energy sources known as renewable energy and non-renewable energy [1-4]. One of the renewable energies available in this century is the organic Rankine cycle, known as ORC. The heat source needed by the ORC can use a low-temperature heat source and comes from unlimited energy sources. Different from the conventional Rankine cycle, which requires an external heat source to produce heat energy, such as burning fossil fuels (natural gas, oil, or coal). At the same time, ORC utilizes low- and medium-temperature energy such as geothermal energy, waste heat, wind, fuel cell, and solar energy [5-8]. Indonesia's potential geothermal power plant as shown in Fig. 1.

Fig. 1. Indonesia's potential geothermal power plant [9].

The organic Rankine cycle has been the subject of intense research in the last 10 years. Due to the increasing need for key technologies to convert low-temperature heat energy sources into the system. ORC uses organic fluids such as R134a, R245fa, or isobutane instead of water. Kumar and Shukla [10] and Feng et al. [11] investigating the characteristic of R123 working fluid depending on working fluid mass flow rate and heat source temperature, the result shown that the tested thermal efficiency presents a slight decrease trend with mass flow rate. Wang et al. [12] concluded that 10 kW Organic Rankine Cycle using R245fa working fluid are generating 7.16 kW thermal efficiency. With lower boiling points than water, organic liquids can operate at lower temperatures and pressures [13].

Fluid selection is also necessary to decide which is suitable for the system depending on the heat source temperature [14, 15]. For example, Bao and Zhao [16] and Pang et al. [17] studied that if the heat source is around 150 °C, the suitable working fluids are R32 or R152a. Zoder et al. [18] conducted a comparison study between different working fluid for recovering waste heat and concluded that higher evaporator pressure resulting higher thermal efficiency. Drescher and Brüggemann et al. [19] conducted a performance study between transcritical and supercritical Organic Rankine Cycle with ejector and rank them which one has better thermal efficiency.

Because of its straightforward design and increased efficiency compared to the traditional Rankine cycle at the same operating temperature, ORC shows to be a potential method to produce energy. The organic Rankine cycle (ORC) has been the subject of extensive research in many areas, including the choice of working fluids, experimental tests, parameter optimization [20]. Liu and Karimi [21] states that the creation of simulation models is one of the methods used to create the Organic Rankine Cycle (ORC) system. Wang et al. [22] in their studies Organic Rankine Cycle simulation model are accurate enough to represent the real system.

In this process, Maalouf et al. [23] and Gunawan et al. [24] both scholars discuss that numerical calculations solve by a computer to obtain results that are close to real conditions by considering certain conditions that occur in real situations, such as flow parameters (velocity, viscosity, and liquid content), and temperature. Pambudi [25] uses an opensource framework to simulate gas-turbine model and has been validated.

This study uses a numerical simulation based on fluid properties of the standard Organic Rankine Cycle to find a suitable working fluid for a potential geothermal power plant in Indonesia since the entire geothermal potential in Indonesia is 28,910 GW, Pambudi [25] and Thamrin et al. [26] studied that derived from 312 fields spread over various islands. Unfortunately, while it has the greatest geothermal potential, it only uses 5%. West Java's projected geothermal energy is only 1.164 MW from its potential of 5.294 MW [27]. The main objective is to find the best performance of working fluid that has been selected and used in the simulation.

2. A Thermodynamic Model for ORC

As the fundamental element of the Organic Rankine Cycle, which uses hydrocarbon or refrigerants instead of water as a working fluid to generate mechanical energy [28], there are four primary parts [29]. In a boiler, heat is given to the working fluid to make the cycle begins entering a turbine, the vapor expands and generates power then vapor leaves the turbine and is condensed back into liquid in the condenser after the work produced by the turbine to the generator to generate power. The cycle then restarts when the liquid is pumped back into the boiler [30]. There are deviations in the Organic Rankine Cycle system due to the irreversibility of the pump and turbine.

2.1. Energy analysis of ORC

The thermodynamic equations for components in the ORC as follow [9, 31].

2.1.1. Primary part 1: Pump

Using a set volume around the pump and assuming there is no heat transfer around it, the mass and energy rate balance is given in Eq. (1) for liquid condensate, leaving the condenser in condition 1 as a saturated liquid is pumped from the condenser into the boiler, increasing pressure [9, 31].

$$(q - w) = (h_1 - h_2) + ((v_1{}^2 - v_2{}^2) / 2)) + g (z_1 - z_2) \tag{1}$$

or

$$wp = h_2 - h_1 \tag{2}$$

where wp stands for the input power per mass that the pump is pumping.

2.1.2. Primary part 2: Boiler

The working fluid will enter the boiler as a compressed liquid after being pumped and discharged in condition 2 and compressed to attain the boiler pressure. It will be heated to a saturation point and evaporated in the boiler. The mass and energy rate balance goes through the pump by employing the control volume surrounding, which will shift from condition 2 to condition 3 (superheated vapor). Mass rate balance and yield energy are following Eq. (3).

$$Q_{in} = h_3 - h_2 \tag{3}$$

where Q_{in} is the rate of heat transfer from the energy source into the working fluid per unit mass passing through the boiler.

2.1.3. Primary part 3: Expander

Superheated vapor from the boiler in condition [32], expands in the expander through the turbine to produce work and is then discharged to the condenser in condition 4 with relatively low pressure, ignoring heat transfer with the surroundings, energy, and mass rate balance for set volume around the turbine.

$$w_1 = h_3 - h_4 \tag{4}$$

Where w_1 is the rate of work generated per unit mass of vapor passing through the turbine.

2.1.4. Primary part 4: Condenser

Heat transfer happens in the condenser from the vapor phase to the cooling liquid [33], which runs in distinct streams. As the vapor condenses, the temperature of the cooling liquid rises. The mass and energy rate balance for the control volume that surrounds the condenser and heat exchanger components under steady-state circumstances follows Eq. (5).

$$q_{out} = h_4 - h_1 \tag{5}$$

Where is the rate of energy transfer from the working fluid to the cooling water per unit mass of the working fluid through the condenser. is the rate of energy transfer from the working fluid to the cooling water per unit mass of the working fluid through the condenser.

2.2. Irreversibility in pump and turbine

This deviation occurs because of the irreversibility that occurs in the pump and turbine so that the pump requires more work (W_{in}) and the turbine produces more work (W_{out}), pump and turbine efficiency calculated follows Eqs. (6) and (7) respectively [17].

$$\eta_p = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \tag{6}$$

$$\eta_t = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \tag{7}$$

3. Simulation Parameters and Fluid Selection

According to Li et al. [32], geothermal power plants have several potentials in Indonesia, especially in West Java province. In the Galunggung region, the reservoir temperature is 225 °C, whereas, in this study, the reservoir temperature is a heat source parameter for the numerical simulation. The working fluid temperature inlet is 30 °C with a mass flow rate of 1 kg/s.

The pressure considered that the working fluid phase must be in liquid form, pumping rate at 10 bar with pressure drop in heater and cooler is 0.5 bar. Pump efficiency is 75%, heater and cooler efficiency set as 90% with an assumption of heat loss occurs in piping and heater instrument as 5 °C.

The schematic diagram of ORC as shown in Fig. 2, the schematic diagram of ORC consists of four main components (pump, heater as boiler, expander, and cooler as condenser). In the simulation, the heating and cooling cycle are not simulated, using the heat source parameters is 225 °C according to Galunggung geothermal reservoir temperature.

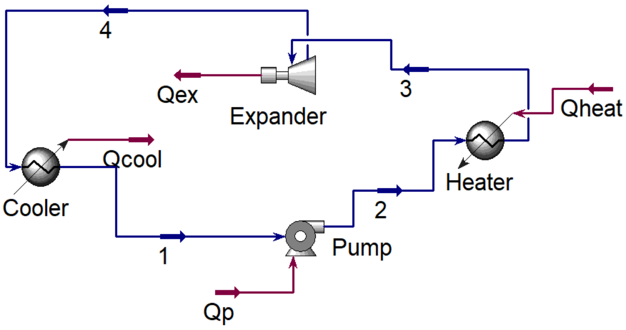

Fig. 2. ORC flow diagram.

Working fluid simulated in this study is R22, R32, R123, R134a, R143a, R227ea, R245fa, R290 (propane), R365mfc, R600 (n-butane), R601 (n-pentane), R601a (isopentane), and Neopentane. The software used for numerical simulation based on fluid properties is an open-source process simulator with complete simulation properties, as shown in Fig. 3. This study is only limited to carrying out numerical simulations with the aim of finding the best working fluid from the 13 working fluids used.

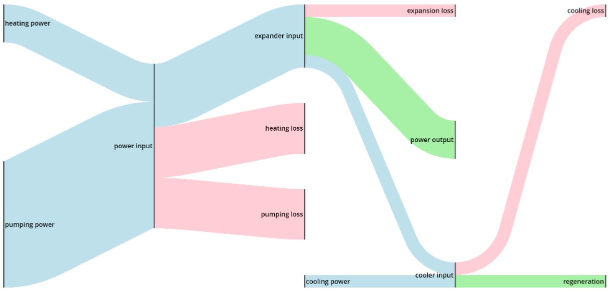

Fig. 3. Sankey diagram of the simulation.

4. Results and Discussions

The choice of working fluid is a crucial aspect of the Organic Rankine Cycle (ORC) as it can significantly influence the system's performance and efficiency. The decision to simulate using 13 different fluids is a comprehensive approach to understanding how each fluid behaves under specific conditions, as outlined in point 3 regarding simulation parameters and fluid selection. This kind of detailed analysis aids in identifying the most suitable fluid for a particular application, optimizing both the performance and potential economic benefits of the ORC system.

When simulating the ORC cycle, it's essential to understand each component's role and the interplay of energies involved. For instance, the pump and the heater are typically where energy is input into the system. The pump requires energy to raise the pressure of the working fluid, prepping it for heat addition in the heater. This heat addition not only elevates the fluid's temperature but also often transforms its phase, turning it into a high-energy vapor ready for expansion.

On the other hand, the expander and cooler are where the system yields its outputs. The expander, as the primary work-producing component, releases exergy, converting the energy-rich vapor's thermal and pressure energy into mechanical energy, usually turning a turbine connected to a generator. Following this, the cooler, or condenser, plays the crucial role of rejecting heat, returning the working fluid to its initial state, ready to be pumped and heated again.

Given these dynamics, it's evident that the selection of the working fluid can have a profound impact on each stage of the process. Different fluids will require varying amounts of pumping power, absorb distinct levels of heat in the heater, yield different amounts of work in the expander, and reject diverse heat quantities in the cooler. Therefore, this simulation not only provides insight into the most efficient working fluid but also furnishes a comprehensive understanding of how different fluids can influence the overall ORC cycle's design and operational strategy.

4.1. Pumping power

The pressure inlet for each working fluid is given a different value according to the minimum pressure required for each working fluid in liquid form. Working fluid inlet pressure follows the parameter in Table 1.

Table 1. Pump pressure inlet.

Working Fluid	R123	R245fa	R143a	R32	R22	R290	R134a	R227ea	R600	R245fa	Neopentane	R365mfc	R601a	R601	R141b
Pressure (bar)	2	2	14	18	12	11	8	6	3	3	2	1	2	1	1

Analysing Fig. 4, the emergence of negative results for R143a and R32 in the context of the ORC cycle is intriguing. Such outcomes, while mathematically possible, may not be physically meaningful in real-world applications. The fact that h_1 is higher than h_2, as stated by Eq. (2), leads to these negative results, and emphasizes the need for careful consideration when selecting working fluids. It's essential to choose fluids that align with the thermodynamic characteristics of the ORC cycle and the specific conditions of the Galunggung region's 225 °C reservoir temperature.

R227 stands out with its low pumping power requirement, making it a potential candidate for a more efficient and economical operation. Lower pumping power usually translates to reduced operational costs and lower wear on equipment, which in turn can lead to longer system lifespans and lower maintenance costs. On the other hand, the higher power requirement of R290 suggests that, while it might be suitable under certain conditions, it might not be the most efficient choice for this specific scenario.

It is also essential to understand that while simulations provide valuable insights, real-world factors such as fluid availability, cost, environmental impact, and compatibility with system materials should also be considered when selecting a working fluid. Thus, a holistic approach, integrating both simulation results and practical considerations, will yield the best decision for the ORC cycle in the Galunggung region.

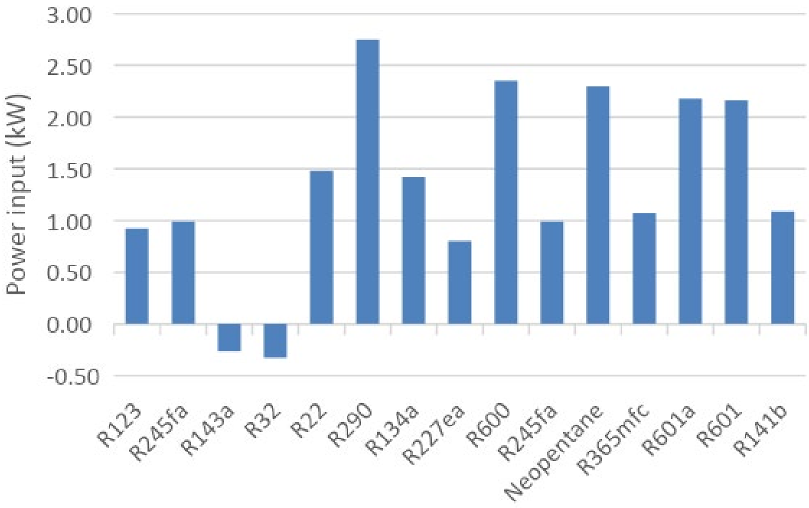

Fig. 4. Pumping power input.

4.2. Heat input

By examining Fig. 5, it is evident that there is a significant difference in the power requirements for the different working fluids to achieve the desired temperature of 220 °C. The disparity in power demand, especially between R600 and R227ea, underscores the importance of choosing the appropriate working fluid for efficiency and power savings. The higher power requirement for R600 suggests that it has a higher heat capacity or could be less efficient in heat transfer when compared to R227ea. Conversely, the lower power needed for R227ea signifies its potential as a more energy-efficient fluid in this heating application.

Furthermore, the significance of achieving a vapor state for the working fluid post-heating cannot be overstated. This ensures that the fluid is in the optimal phase for expansion in the expander, guaranteeing maximum work output. A deviation from the vapor state could lead to inefficiencies in the expansion process, potentially causing damage to the expander or a reduction in power output.

Moreover, it's crucial to account for the 5 °C-heat loss in the heater. This parameter should be factored into the design and operation of the heating system to ensure that the working fluid consistently reaches the desired temperature. Implementing insulation or optimizing the heater design might be strategies worth considering minimizing this heat loss and enhance the overall efficiency of the system.

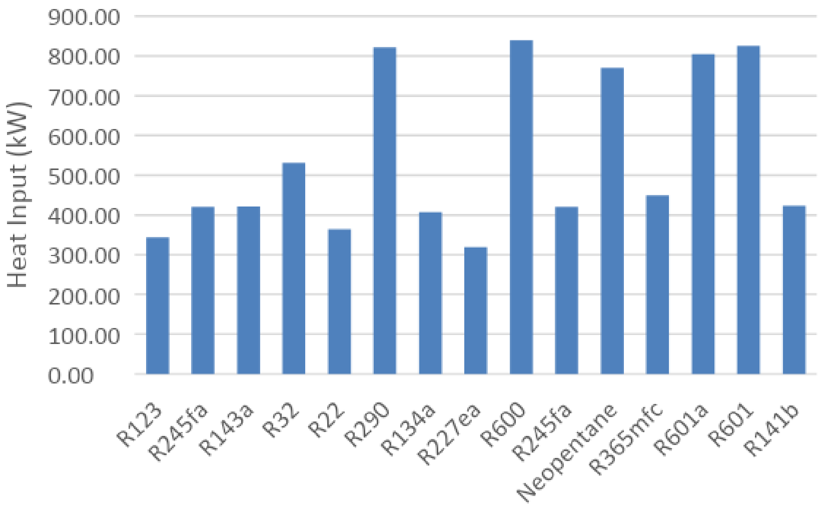

Fig. 5. Heater heat input.

4.3. The results of exergy

Exergy essentially quantifies the maximum theoretical work that can be derived from a process, accounting for the energy that is irreversibly lost. This understanding is crucial in applications like expanders where the goal is to harness as much work or power as possible from the given input. Conducting an exergy analysis allows engineers and researchers to pinpoint inefficiencies, potentially guiding optimizations to enhance the power generation process.

The choice of working fluid in any energy conversion system is pivotal [29, 30]. Different fluids have distinct thermophysical properties, such as latent heat, boiling point, and thermal conductivity. These properties influence how much energy the fluid can absorb and convert into work during expansion. Thus, even subtle differences in fluid properties can lead to significant disparities in power output, as observed in the results presented in Fig. 6. The pronounced difference in exergy between R601 and R227ea reinforces the importance of meticulous working fluid selection. While R601 seems to be more adept at harnessing energy in this context, R227ea might have other benefits, like lower environmental impact, better safety profile, or economic advantages.

Therefore, when selecting a working fluid, a holistic view that weighs both performance and practical constraints is essential. Furthermore, it's crucial to remember that real-world operations might present additional challenges or variations that aren't always captured in numerical simulations, making hands-on testing and iterative refinement equally important in system design.

Pressure changes consideration in the expander from the first step of the cycle, which is in the pump with a pumping rate of 10 bar and after the calculations with the assumption of pressure drop set at 0.5 bar. Figure 7 shows that the highest pressure is R32 at 27.5 bar, and this happens due to the minimum pressure for R32 working fluid to stay in liquid form before entering the pump is around 18 bar after exiting the pump and affected by the pressure drop; the pressure of R32 after pumping process is 27.5 bar. This phenomenon also occurs in every working fluid.

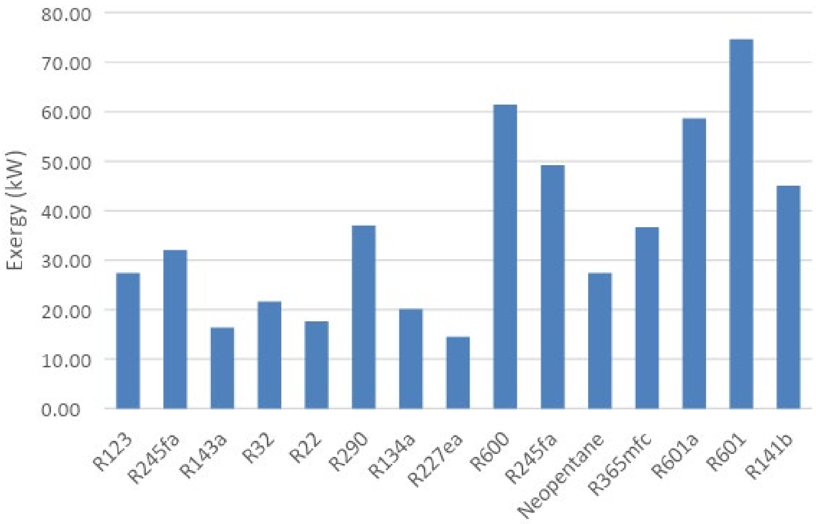

Fig. 6. The results of exergy.

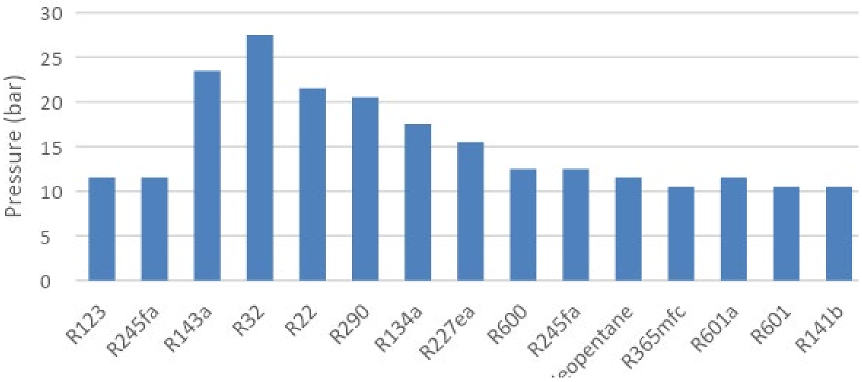

Fig. 7. Working fluid pressure condition as expander pressure input.

4.4. Heat rejection

The condensation process is vital for regenerating the working fluid and ensuring the continuity of the cycle. By condensing the vapor back to a liquid, energy is released, often referred to as 'latent heat of condensation'. This heat rejection is not only significant for the thermodynamics of the system but also from an operational and design perspective. A condenser must be designed to efficiently handle this heat, dissipating it to the surroundings or another medium, to prevent overheating and ensure smooth operation.

Figure 8 provides a valuable insight into the heat rejection characteristics of different working fluids. The disparity between R290 and R227ea indicates how varying fluid properties can influence the overall heat management requirements of a system. A higher heat rejection, as observed with R290, might necessitate a more robust cooling system or a larger heat sink, which can impact both the system's design and operational costs. On the other hand, a fluid like R227ea, with its lower heat rejection, might be suitable for applications where the cooling resources are limited or where a more compact or less energy-intensive cooling system is desired.

It's also worth noting that the heat rejected in the condenser can, in some applications, be harnessed for other purposes, like pre-heating or other cogeneration tasks, offering an opportunity to improve the overall energy efficiency of the system. Finally, the efficiency of the condensation process can also influence the fluid's quality as it returns to the pump, ensuring a consistent and efficient cycle performance. The heat rejection can be used or reapplied for a heat source using a waste heat recovery cycle (WHR) to maximize net power and work produced by the Organic Rankine Cycle [30].

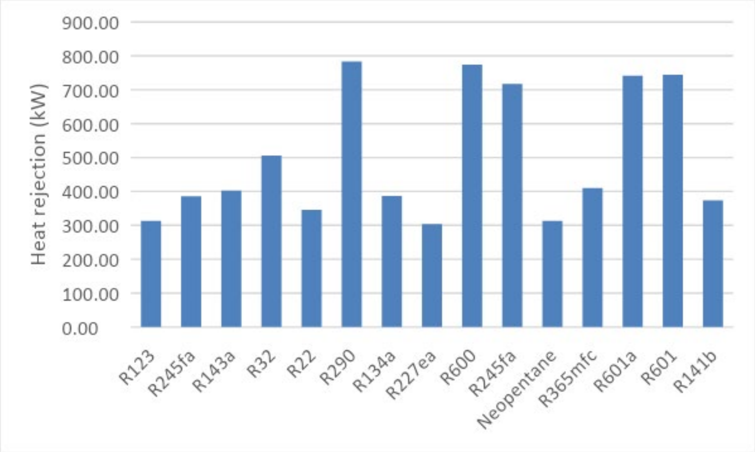

Fig. 8. Heat rejection.

5. Conclusions

The numerical simulation of the Organic Rankine Cycle based on fluid properties uses opensource simulation software using parameters according to experimental data, the heat source parameter using potential geothermal power plant points that have not been explored or installed a system to produce electricity. The simulation studies pump power input, heater heat input, exergy, and heat rejection.

However, this study’s heating and cooling cycles assume heat input and rejection. Simulation results of pumping power and heat input requirements are shown that the lowest value is R227ea working fluid, with values of 0.8 kW and 318.72 kW, respectively. But the R227ea exergy is showing not satisfactory result where it only 14.53 kW, the highest exergy value is R601 with 74.61 kW exergy generated. In addition, heat rejection can be applied for another cycle that can produce exergy, where from the simulation result shown that R290 produce highest value of heat rejection with 782.96 kW.

Overall, the ideal working fluid based on simulation results is R601 which produce high exergy value and high heat rejection value that can re-applied for another power generating cycle. The results obtained are the result of numerical calculations carried out by the software, of course there are differences in the results with real conditions considering that we ignored the calculations for the height and length of pipes and other materials. However, the results of this research can be used to choose which working fluid is suitable for the geothermal potential of Mount Galunggung.

Abbreviations

BOE	Barrel of Oil Equivalent
ESDM	Energy dan Sumber Daya Mineral (Indonesian Ministry of Energy and Mineral Resource)
ORC	Organic Rankine Cycle
WHR	Waste Heat Recovery

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