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# An investigation into the differing efficiencies of working fluids used in binary cycle power plants.

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**Abstract:** In this paper the efficiency of three common working fluids in binary cycle geothermal power plants were compared by modeling the properties of the fluid within the working parameters of the Dora-II geothermal power plant. It was concluded that ammonia has the highest efficiency of the fluids and R-134a was the least efficient.

**Keywords:** geothermal power efficiency; R-134a; n-pentane; ammonia; working fluid; Dora-II; geothermal; binary cycle; Rankine; geothermal power plant

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**Nomenclature**

| | | | |
|---|---|---|---|
| R-134a | 1,1,1,2-tetrafluroethane | $\dot{m}_G$ | Mass flow rate of geothermal fluid |
| $\eta_I$ | First Law efficiency | $h_n$ | Specific enthalpy at point n in simple Rankine cycle |
| $\epsilon$ | Cycle efficiency | $T_n$ | Temperature at point n in simple Rankine cycle |
| $\eta_{II}$ | Second law efficiency | $s_n$ | Specific entropy at point n in simple Rankine cycle |
| $\dot{m}_W$ | Mass flow rate of working fluid | | |

## 1. Introduction

Non-renewable power, such as coal fired power plants, are by nature a limited energy resource. They are limited by both the amount of resources available to be used to fuel power generation and the detrimental effects that the by-products of these plants have on the earth. The major renewable sources are wind, solar, hydro-electric, and tidal power. These sources have restrictive properties that limit where and how often they can produce energy. Wind, solar and tidal power are inconsistent in times that they can generate power as they are reliant on favourable conditions to produce power. Renewable power sources such as wind turbine plants require wind that is strong enough to turn the blades but not so fast as to burn out or cause excessive stress on the turbine itself, severely limiting the conditions that they are effective in. (1,2) Solar is in a similar position in that it requires light from the sun to be incident on the panels to be able to produce power. (1) This limits the operation times to during the day and efficiency can be reduced by cloud cover. The energy in the light from the sun, i.e., areas further away from the equator go through periods of large reductions in incident light as well as decreased energy due to the thicker atmosphere. Tidal power is limited to the number of times the tide changes a day to produce the power. Whilst this is both regular and predictable if the flow of tidal water increases above the operational speed of the generator then the system can be damaged if it is not shut down pre-emptively. Whilst these systems can have greater efficiency for power production than geothermal plants, they have lower consistent power generation when compared to fossil fuel, nuclear and geothermal power. Geothermal power stations can maintain a consistent level of power output as they are not reliant on atmospheric conditions, the location of the sun, or the position of the moon to generate power. As long as the location chosen can produce enough hot water then power generation will be consistent day or night all year round.

The performance of a geothermal power plant is limited by the temperature of the geothermal water. A standard geothermal power plant that uses geothermal water as the working fluid requires water temperatures with a minimum reservoir temperature of 180˚C. (2) The minimum temperature for geothermal power is set so that when the water reaches the turbines it has been converted to super-heated steam and expands fast enough to drive the turbine. To increase the spread of geothermal powerplants, binary cycle systems have been developed. These plants use a closed loop with a working fluid that is not water to generate the power. The working fluids used in these systems are chosen because they have lower boiling points and lower specific heat capacity compared to water (5,6). These fluids are used in binary systems as their low boiling points allow the fluids to be in a gaseous state at lower temperatures than water, thus being able to drive a turbine at lower temperatures. This allows binary powerplants to be built in areas with lower reservoir temperatures that currently range from 70˚C to 250˚C. (2) The fluids that are currently being used in current production plants include 1,1,1,2 Tetrafluroethane (R-134a), ammonia and n-pentane. (5,6,7) One property that is present in ammonia that is not in R-134a or n-pentane is that when in significant concentration, as is present in this simulation, is that ammonia is very corrosive. Ammonia is know to corrode copper- and zinc-containing alloys as well as attacking rubber and plastics. (3)

## 2. Methods

The purpose of this research is to determine to what degree the working fluid impacts the efficiency of a binary cycle geothermal power plant.

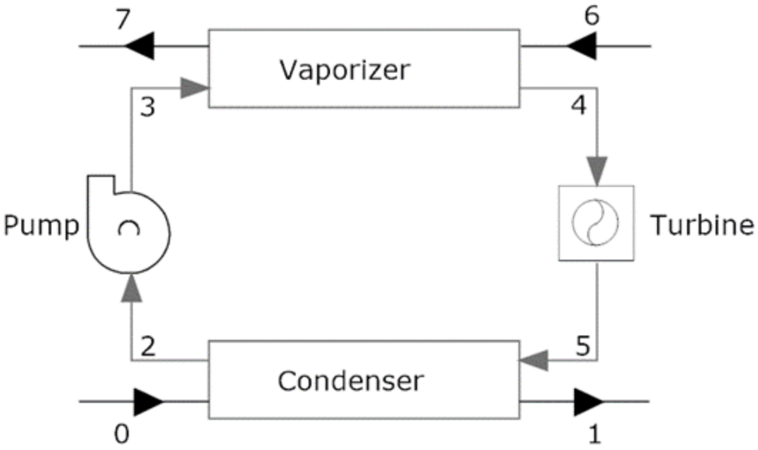
Plant efficiency was modelled using the equations used by Subbiah and Natarajan (4).

$$\eta_I = \frac{(Turbine\ work) - (Pump\ work)}{(Input\ heat)} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7)} \qquad Eqn.[1]$$

$$\epsilon = \frac{Net\ output\ work}{Available\ energy\ input\ to\ rankine\ cycle} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7) - T_0(s_6 - s_7)} \qquad Eqn.[2]$$

$$\eta_{II} = \frac{Net\ output\ work}{Overall\ available\ energy\ between\ T_6\ and\ T_0} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7) - T_0(s_6 - s_0)} \qquad Eqn.[3]$$

Where $\eta_I$ is the first law efficiency, $\epsilon$ is the cycle effectiveness and $\eta_{II}$ is the second law efficiency.



| | | | |
|---|---|---|---|
| 0 | Condenser air inlet | 4 | Turbine inlet |
| 1 | Condenser air outlet | 5 | Turbine out-let |
| 2 | Working fluid pump inlet | 6 | Vaporizer geothermal fluid inlet |
| 3 | Working fluid pup outlet | 7 | Vaporizer geothermal fluid outlet |

***Figure 1.*** *Simple Rankine cycle process*

These equations are matched to a simple binary cycle geothermal power plant (see figure 1). Using these equations and data researched from papers. The effects of the three fluids was compared by using the current working fluid in the production plant then using the same brine and condenser data, and changing the enthalpy and entropy data for each fluid. The enthalpy and entropy was calculated using the Fluid Property Calculator from the International Refrigerant Consortium. (5) The fluid data in table 1 was sourced from Aylward & Findlay's SI Chemical Data 7th edition (6) and from the GESTIS substance database (3) The data in table 2 was taken from the paper by Ganjehsarabi et al. (7) That data was then used as the basis for calculating the efficiencies of R-134a and ammonia. The mass flow rate, temperature and pressure were kept as constants for the plant. The calculated data is shown in table 3 and 4.

The efficiency was also graphed against the price per kg of the fluids. The prices were obtained from Alibaba.com, as it supplies in commercial amounts.

The fluids chosen for this paper were restricted to ones that are currently being used in power plants that are currently supplying power for consumers.

## 3. Results and Discussion

The fluid comparison was based on a combination between the operational specifications of the Dora-II geothermal plant in Turkey and the simplistic Rankine cycle. We can see from the results that ammonia is more efficient than n-pentane and R-134a. The efficiency is noted to be a result of the amount of change in enthalpy between the stages in the Rankine cycle. When the efficiency was graphed against the price per kg of the fluid it was seen that ammonia is again the best option for a working fluid in this plant.

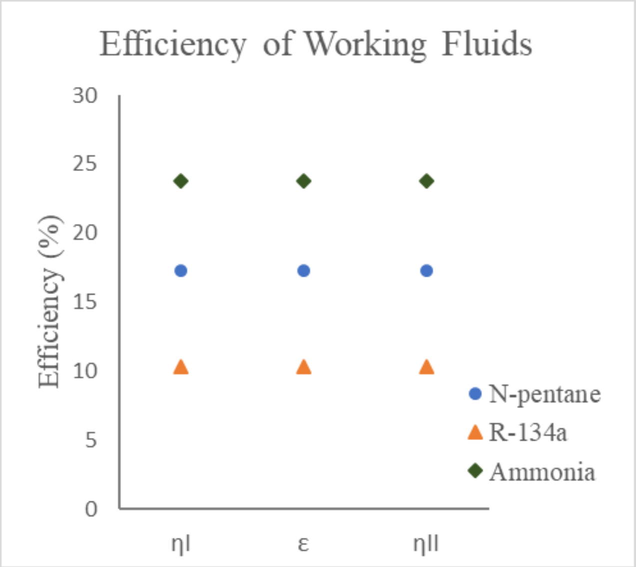


***Figure 2.*** *Comparison of working fluid efficiency.*

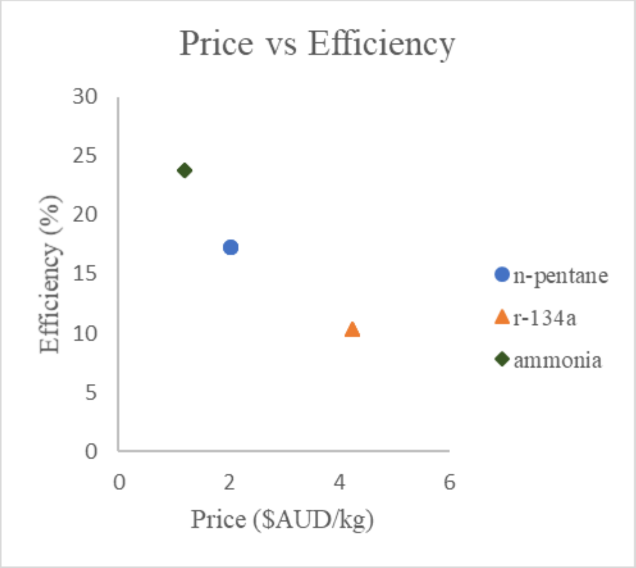


***Figure 3.*** *Graph of price against efficiency of the working fluids*

## 4. Conclusions

A comparison of the fluids show ammonia as the most efficient of the three fluids investigated. This indicates that to achieve a higher level of efficiency at the Dora-II power plant the working fluid of n-pentane should be replaced by ammonia. However, using ammonia will be more expensive in up keep as it is more corrosive then n-pentane and R-134a. This puts the plant at a higher risk of leaks and reduction of efficiency. Leaks will be of great concern when running both ammonia and n-pentane as they are both flammable. From that perspective, R-134a would be a more suitable fluid as it is not corrosive and is not readily flammable. It is not recommended to replace the working fluid with R-134a, as it will greatly reduce the efficiency of the plant. Therefore, n-pentane is the best choice for a long term working fluid. It will reduce the cost of maintenance compared to ammonia and has a higher efficiency than R-134a. It was also concluded that the working fluid can have a theoretical impact on efficiency of 13%.

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## Appendix

| Properties | Fluid | | |
|---|---|---|---|
| | R-134a | N-pentane | Ammonia |
| Mol Mass (g/mol) | 102.03 | 72.1 | 17 |
| Specific heat capacity (gas) (J/(K*mol) | 87 | 120 | 35 |
| Boiling point (Celsius) | -26.3 | 36.1 | -78 |
| melting point (Celsius) | -103.3 | -129.7 | -33 |
| flash point (Celsius) | none | -49 | 630 |

***Table 1.*** *Table of working fluid properties*

| | | Fluid | Phase | Temperature (°C) | Pressure (kPa) | Specific enthalpy (kJ/(kg*K)) | Specific entropy (kJ/kg) | Mass flow rate (kg/s) |
|---|---|---|---|---|---|---|---|---|
| Point in simple rankine cycle | 0 | Air | Gas | 17.1 | 1013 | 290.25 | 1.67 | 4350 |
| | 1 | Air | Gas | 29.1 | 1013 | 302.3 | 1.71 | 4350 |
| | | | | | | | | |
| | 2 | n-pentane | Liquid | 41.87 | 141.85 | 20.66 | 0.065 | 118.61 |
| | 3 | n-pentane | Liquid | 89.3 | 1185.5 | 133.88 | 0.39 | 118.61 |
| | 4 | n-pentane | Vapour | 133.08 | 1185.5 | 510.23 | 1.33 | 118.61 |
| | 5 | n-pentane | Vapour | 83.7 | 141.85 | 444.46 | 1.38 | 118.61 |
| | | | | | | | | |
| | 6 | Brine | Liquid | 169 | 1296.96 | 715.11 | 2.03 | 231.94 |
| | 7 | Brine | Liquid | 124.4 | 1296.96 | 523.15 | 1.57 | 231.94 |

***Table 2.*** *Data for n-pentane at each stage of the simplistic Rankine cycle*

| | | Fluid | Phase | Temperature (°C) | Pressure (kPa) | Specific enthalpy (kJ/(kg*K)) | Specific entropy (kJ/kg) | Mass flow rate (kg/s) |
|---|---|---|---|---|---|---|---|---|
| Point in simple rankine cycle | 0 | Air | Gas | 17.1 | 1013 | 290.25 | 1.67 | 4350 |
| | 1 | Air | Gas | 29.1 | 1013 | 302.3 | 1.71 | 4350 |
| | | | | | | | | |
| | 2 | R-134a | Liquid | 41.87 | 141.85 | 290 | 1.12 | 118.61 |
| | 3 | R-134a | Liquid | 89.3 | 1185.5 | 322 | 1.05 | 118.61 |
| | 4 | R-134a | Vapour | 133.08 | 1185.5 | 368 | 1.18 | 118.61 |
| | 5 | R-134a | Vapour | 83.7 | 141.85 | 329 | 1.24 | 118.61 |
| | | | | | | | | |
| | 6 | Brine | Liquid | 169 | 1296.96 | 715.11 | 2.03 | 231.94 |
| | 7 | Brine | Liquid | 124.4 | 1296.96 | 523.15 | 1.57 | 231.94 |

***Table 3.*** *Data for R-134a at each stage of the simplistic Rankine cycle.*

| | | Fluid | Phase | Temperature (°C) | Pressure (kPa) | Specific enthalpy (kJ/(kg*K)) | Specific entropy (kJ/kg) | Mass flow rate (kg/s) |
|---|---|---|---|---|---|---|---|---|
| Point in simple rankine cycle | 0 | Air | Gas | 17.1 | 1013 | 290.25 | 1.67 | 101.83 |
| | 1 | Air | Gas | 29.1 | 1013 | 302.3 | 1.71 | 101.83 |
| | | | | | | | | |
| | 2 | Ammonia | Liquid | 41.87 | 141.85 | 1560 | 6.27 | 118.61 |
| | 3 | Ammonia | Liquid | 89.3 | 1185.5 | 1630 | 5.47 | 118.61 |
| | 4 | Ammonia | Vapour | 133.08 | 1599.58 | 1740 | 5.75 | 118.61 |
| | 5 | Ammonia | Vapour | 83.7 | 438.5 | 1650 | 6.54 | 118.61 |
| | | | | | | | | |
| | 6 | Brine | Liquid | 169 | 1296.96 | 715.11 | 2.03 | 231.94 |
| | 7 | Brine | Liquid | 124.4 | 1296.96 | 523.15 | 1.57 | 231.94 |

***Table 4.*** *Data for ammonia at each stage of the simplistic Rankine cycle.*