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Performance of Ocean Thermal Energy Conversion Closed Rankine Cycle Using Different Working Fluids

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Abstract. Ocean Thermal Energy Conversion (OTEC) is a foundation for an appealing renewable energy technology regarding its vast and inexhaustible resources of energy, renewability, stability, and sustainable output. The principle of an OTEC power plant is to exploit the energy accumulated in between the top layer of warm surface seawater (heat source), and the cold layer of deep seawater (heat sink). The plant operates based on a Rankine cycle to produce electricity between the source and the sink at the smallest temperature difference of approximately 20 K. In an OTEC power plant, a commonly utilized working fluid is ammonia since its qualities are suitable for the OTEC cycle. Nevertheless, ammonia poses certain potentially lethal health risks and hazardous fluid. Hence, the effect of the working fluid types, and the subsequent operation conditions may be critical and therefore become the subject of this study. The analysed working fluids, including that of ammonia, are ammonia-water mixture (0.9), propane, and refrigerants (R22, R32, R134a, R143a, and R410a). The results revealed that ammonia-water mixture showed the highest network performance and reliability. Even so, it is essential to continue seeking the suitable working fluids which are safe and economically effective to replace ammonia.

Keywords: ocean, thermal energy, rankine cycle, power plant

1. Introduction

Ocean Thermal Energy Conversion (OTEC) has tremendous prospective in deep ocean water area, in which a sufficiently high temperature difference between the surface water and a specific depth is required to effectively run an OTEC power plant. In 1881, Arsonval's initial concept specified that the optimum temperature difference needed for the installation of an OTEC plant is larger than 20 K [1]. The system will work between the surface seawater at 30°C (known as heat source), and seawater at 1000 m depth with temperature of 4°C (known as heat sink) [2-4]. OTEC power plant technology is developed on a basis of open (OC-OTEC) and closed Rankine cycles (CC-OTEC). Previous research reported that the process has to be founded upon the Uehara cycle for optimal power plant output, implementing ammonia-water mixture as the working fluid with smaller than 20 K of temperature difference, and at 5-6% thermal efficiency [5].

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Additionally, the selection of suitable working fluids has a significant impact on the entire system viability and efficiency. Ammonia has been considered as the best working fluid because it has a suitable boiling temperature (28°C - 32°C) for the OTEC purpose [6]. However, it is toxic and therefore can be hazardous to the environment. Recent development of working fluids shows that ammonia can be replaced by other working fluids with zero Ozone Depletion Potential (ODP) and zero Global Warming Potential (GWP). Finding other suitable substitutes is a big challenge to this study. Several studies have been done which have shown better results with the use of other working fluids such as hydrocarbon (HC) and hydrofluorocarbons (HFCs) [7-10]. The other findings reported that R123 displayed the best performance, but the fluid contributes to the ODP and GWP. Therefore, isopentane is suggested as it showed the second-best performance and regarded as environmentally friendly working fluid for the system. However, the applications of their research are for waste heat systems but can still be operated at low temperature.

A paper that reviews about 35 working fluids and analyzes the effect of fluid properties on the cycle efficiency is written by Chen at al. (2010) [11]. They have categorized the working fluids under three characteristics which are dry, isotropic, or wet fluid according to the T-s diagram. Understanding the characteristic of the working fluids eases the process of selecting the appropriate working fluid for the cycle. Calm and Hourahan (2007) [12] have interpreted the data of working fluids into a table with ODP and GWP of selected refrigerant. Figure 1 shows the numbers of OTEC previous research focusing on different working fluids from 1979 to 2016.

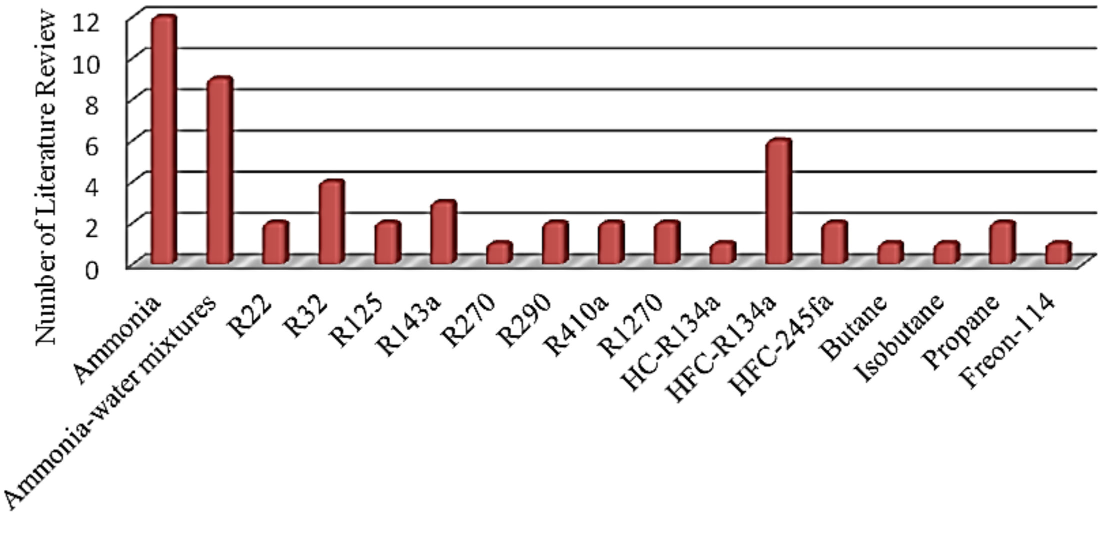


Figure 1. The numbers of OTEC previous research focusing on different working fluids from 1979 to 2016

Therefore, the objective of this paper is to examine the efficiency of the OTEC basic closed Rankine cycle using varying working fluids. At the initial stage of the study, preliminary simulation was conducted to confirm the simulation model with the reference from past OTEC studies. The similar developed model was implemented to analyze the efficiency of the OTEC basic closed Rankine cycle using eight varying working fluids.

2. Methodology

2.1. Introduction

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a platform design framework created by National Instruments that is employed as languages of visual programming. Its implementation in numerous fields of engineering (e.g., aeronautical, mechanical, electrical, etc.) has led to the advancement of the world's largest and most complex applications to fulfill future demands. LabVIEW offers the users with flexibility through intuitive graphical programming which helps to reduce the time needed for test development. The thermodynamic model has been created in LabVIEW and linked to the working fluid data base in National Institute of Standards and Technologies (NIST) RefProp 9 and PROPATH. The thermodynamic model of OTEC cycle is created in LabVIEW to run numerical calculation, simulations and compare the working fluids from a thermophysical perspective.

2.2. Analytical Techniques of Thermodynamics

The simulation was based upon the thermodynamic analysis of the OTEC Rankine cycle performance. The Rankine cycle comprises of four major components, which are condenser, coolant pump, turbine, and evaporator. Several assumptions were included to facilitate the simulation analysis and assessment [13,14], which are described as follows:

- Every component is in steady state.
- Any heat loss and pressure drop are disregarded.
- The system is completely insulated.
- All pumps and turbines are given isentropic efficiency.

For the steady state energy balance equation, the total energy entering a system is equal to the total energy exiting the system, as expressed in equation (1)

$$E_{in} = E_{out} \tag{1}$$

or it can be elaborated as in equation (2)

$$W_{in} + Q_{in} + \sum \dot{m}_{in} = W_{out} + Q_{out} + \sum \dot{m}_{out} \tag{2}$$

where $\dot{Q}$ represents heat transfer rate; $\dot{m}_{in}$ and $\dot{m}_{out}$ is inlet and outlet mass flow rate; whereas W_{in} and W_{out} is work inlet and outlet, respectively. By assuming the system is completely insulated and any heat losses are neglected; $Q_{in} = 0$, $Q_{out} = 0$ and $W_{out} = 0$; the energy balance in the pump is expressed as in equation (3)

$$W_{in} + \sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

From equation (3), the work supplied is given as in equation (4)

$$W_{in} = \sum \dot{m}_{out} - \sum \dot{m}_{in} \tag{4}$$

Rate of heat supplied to the cycle (evaporator), $\dot{Q}_e$ is expressed as in equation (5)

$$\dot{Q}_e = \dot{m}_{wf} \, \Delta h_e \tag{5}$$

Rate of heat rejected from the cycle (condenser), $\dot{Q}_c$ is indicated as in equation (6)

$$\dot{Q}_c = \dot{m}_{wf}\, \Delta h_c \tag{6}$$

Rate of heat absorbed from the warm seawater, $\dot{Q}_{e,ws}$ is expressed as in equation (7)

$$\dot{Q}_{e,ws} = \dot{m}_{ws}\, c_p \Delta T_{ws} \tag{7}$$

Rate of heat rejected into the cold seawater, $\dot{Q}_{c,cw}$ is indicated as in equation (8)

$$\dot{Q}_{c,cw} = \dot{m}_{cs}\, c_p \Delta T_{cs} \tag{8}$$

where $\dot{m}_{ws}$ and $\dot{m}_{cs}$ are the mass flow rate of warm and cold seawater, respectively. c_p is the seawater specific heat capacity at constant pressure.

The working fluid pump, $W_{P_{wf}}$ and the turbine work, W_T is written as in equation (9) and equation (10)

$$W_{P_{wf}} = \dot{m}_{wf}\, v(P_2 - P_1) \tag{9}$$

$$W_T = \dot{m}_{wf}\, \Delta h \tag{10}$$

where Δh represents the enthalpy difference in the turbine system.

Referring to Uehara and Ikegami (1990) [14], the working fluid pumping power, P_{Pwf} is given as in equation (11). The pumping power of warm seawater, P_{ws} is indicated as in equation (12); whereas the pumping power of cold seawater, P_{cs} is expressed as in equation (13)

$$P_{Pwf} = \frac{\dot{m}_{wf}\, \Delta H_{wf}\, g}{\eta_{wf,p}} \tag{11}$$

$$P_{ws} = \frac{\dot{m}_{ws}\, \Delta H_{ws}\, g}{\eta_{ws,p}} \tag{12}$$

$$P_{cs} = \frac{\dot{m}_{cs}\,\Delta H_{cs}\, g}{\eta_{cs,p}} \tag{13}$$

where ΔH refers to the difference in pressure.

The net power output, P_n is indicated as in equation (14)

$$P_n = P_G - P_{ws} - P_{cs} - P_{p_{wf}} \tag{14}$$

2.3. *Selection of Working Fluid*

An ideal working fluid should have the relevant thermophysical properties corresponding with its application, besides sustaining its chemical stability within the specified range of temperature. Working fluid selection plays a major part on the system in terms of its performance, operating conditions, effects on the environment and economic feasibility. In this section, the parameters for identifying a suitable working fluid for the cycle system are described. Sami (2012) [15] has listed the main factors affecting the properties of thermodynamic and thermophysical of the system, among which are thermal conductivity, chemical stability, specific heat, boiling temperature, latent heat, toxicity, as well as flash point, as outlined in Figure 2.

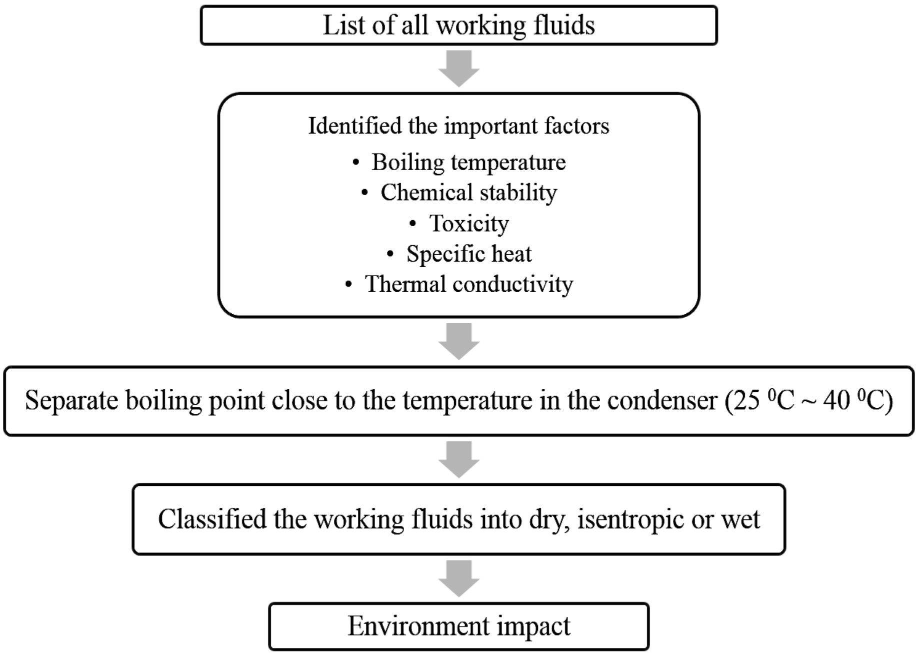


Figure 2 Steps in selecting the working fluids [15]

The OTEC closed Rankine cycle in this study utilized the boiling point of the working fluid near the evaporator operating temperature, that is about 25°C to 40°C [16]. In addition, the fluids were classified as dry, isentropic, or wet relative to the saturation curve (dT/ds). A dry or isentropic fluid is appropriate to be implemented in OTEC closed Rankine cycle [17]. The purpose of separating the type of fluids is to make sure that the fluids are totally superheated after isentropic expansion, intended to avoid the appearance of liquid drops on the blades of the turbine.

2.4. Types of Working Fluids

There are dual kinds of working fluid, namely pure fluid (pure compound) and pseudo-pure fluid (a mix of several pure compounds of fluid). Ammonia, propane, R22, R134a, and R143a, are marked as pure fluid, and are not combined with some other compounds. Meanwhile, ammonia-water mixture, R404a, R410a, R470c, and R507a are a pseudo-pure fluid. Figure 3 and Figure 4 show that the highest enthalpy difference can be discovered in ammonia-water mixture, followed by ammonia, propane and R32.

According to Figure 4, in contrast with other working fluids, ammonia-water mixture has the highest quantity of heat applied. This situation is caused by its greater latent heat value, also can be defined as the amount of heat that a liquid absorbs to stay at a constant pressure or temperature throughout the process of vaporization.

2.5. Preliminary Simulation

A preliminary design model for simulation of a 1 MWe OTEC closed Rankine cycle was conducted using ammonia as working fluid. This preliminary simulation is to validate the model developed by Yeh et al., (2014) [18]. Apart from that, the preliminary design model allows the estimation for 5 MWe and 10 MWe OTEC closed Rankine cycle.

Table 1. Parameters for three OTEC cycles to be investigated

Parameter	Symbol	Unit	Value
Evaporating temperature	T_E	°C	28
Condensing temperature	T_C	°C	8
Warm seawater inlet temperature	T_{wsw}	°C	30
Cold deep seawater inlet temperature	T_{csw}	°C	5
Working fluid pump efficiency	η_{wf}	%	0.75
Turbine efficiency	η_T	%	0.82
Generator efficiency	η_G	%	0.95
Warm seawater pump efficiency	$\eta_{pump,wsw}$	%	0.80
Cold deep seawater pump efficiency	$\eta_{pump,csw}$	%	0.80

The OTEC closed Rankine cycle simulation based on Uehara and Ikegami (1990) [14] was conducted according to the fixed condition parameters as tabulated in Table 1, in which the ammonia is in a steady state. The graph that represents the simulated model is shown in Figure 5 (b). When comparing the reference case with the preliminary analysis, it was found that ammonia generated the maximum total work output. Such results are reinforced by the point that ammonia possessed the maximum as well as the most appropriate value of latent heat for the OTEC cycle system.

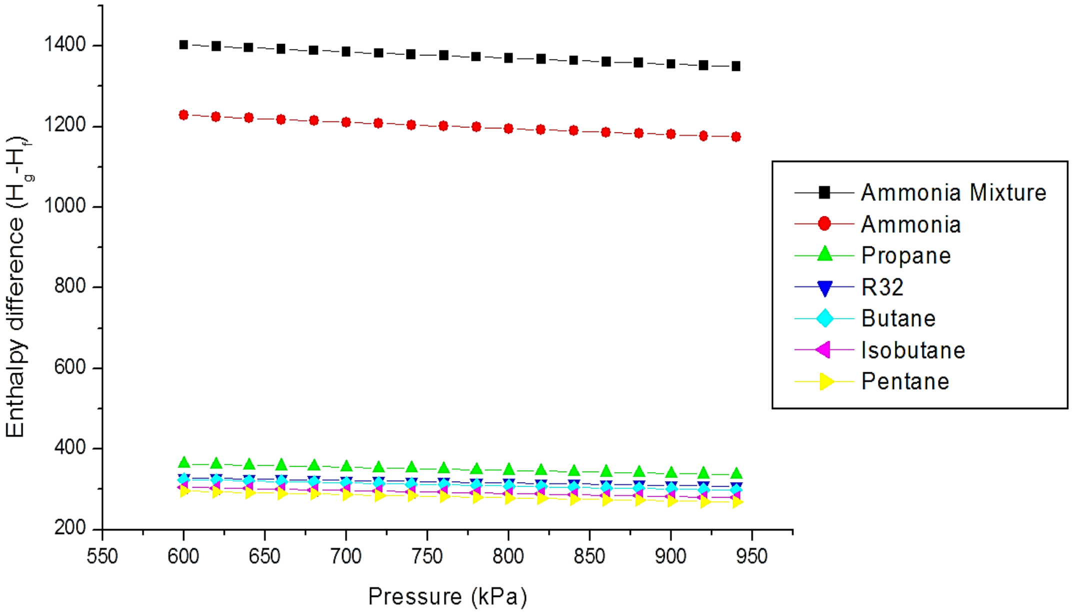


Figure 3 Latent heat-pressure diagram of pure fluid and pseudo-pure fluid

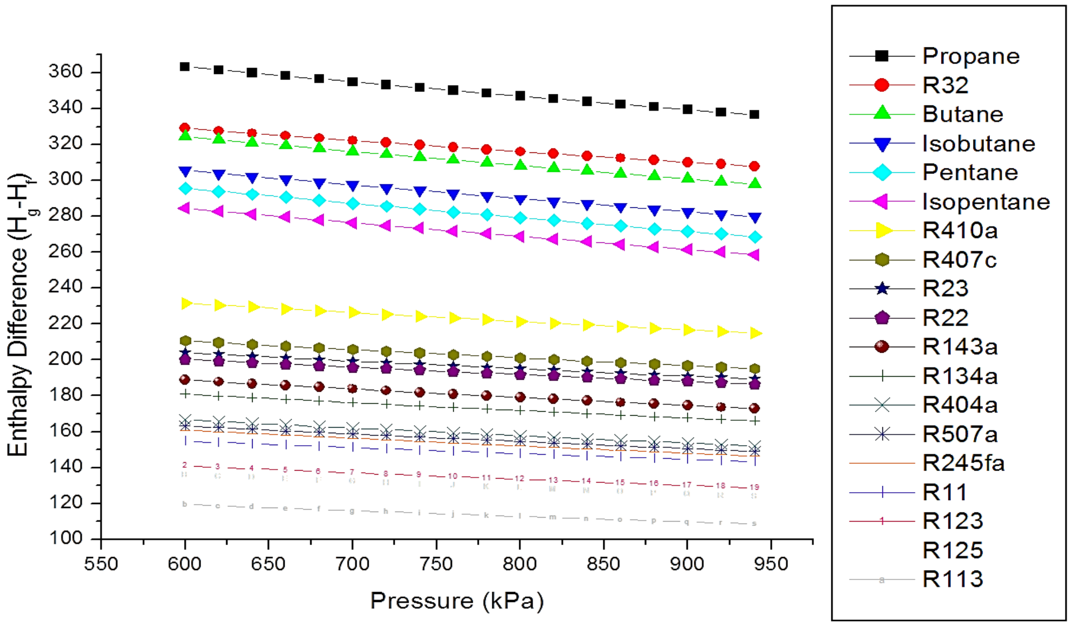
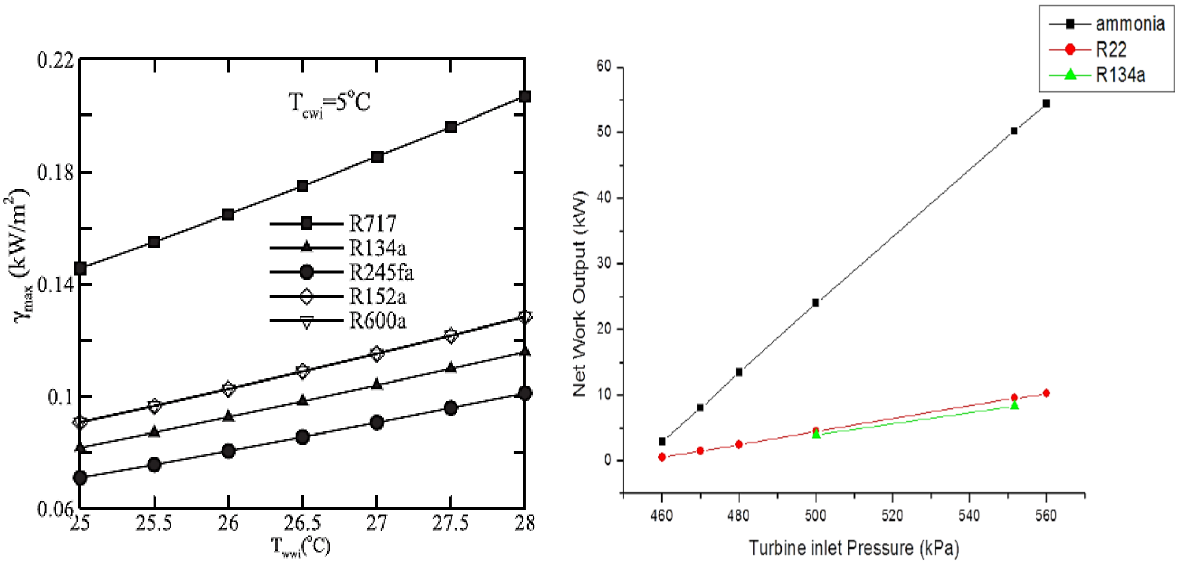


Figure 4 Close up of latent heat-pressure diagram of pure fluid and pseudo-pure fluid



(a) (b)

Figure 5 The network output of closed Rankine cycle using several working fluids; (a) reported by Yeh et al., (2014) [18]; (b) simulation model using LabVIEW and RefProp

As can be seen from Table 2, the net power output increased significantly when the system was scaled up [19]. The preliminary study acts as an initiation to the visualization procedure used in the subsequent assessment in Section 3. On the other hand, the preliminary simulation is shown to explain the sufficiency of the parameters used in this study.

Table 2 Analysis of OTEC Closed Rankine cycle using ammonia as working fluid

	Unit	1MWe	5MWe	10MWe
Q_{in}	kW	19724.40	81375.50	162751.00
Q_{out}	kW	18685.00	76166.90	152334.00
$W_{p(wf)}$	kW	13.22	54.53	109.06
$W_{p(wsw)}$	kW	96.74	399.12	798.24
$W_{p(cws)}$	kW	118.76	484.11	968.21
$\dot{m}_{wf}$	kg/s	15.82	65.25	130.50
$\dot{m}_{wsw}$	kg/s	1793.01	7397.29	14794.60
$\dot{m}_{csw}$	kg/s	1587.67	6471.91	12943.80
W_T	kW	905.00	4525.00	9050.00
W_{net}	kW	676.28	3587.24	7174.48

3. Results and Discussion

The simulated net power output of eight varying working fluids produced by a work pump of deep seawater is shown in Figure 6. It was noticeable that the net power output for ammonia-water mixture was the maximum with 740 kW, and that the power needed for the cooling system to pump deep seawater was also small. A feature which is widely recognized in the OTEC power cycle is the point that ammonia resulted in the second highest net power output value. The third highest net power output was R134a followed by R22 and propane. R134a was the possible candidate to replace the ammonia as it possessed the highest net power output among the other five working fluids; however, it has the biggest value of work pump for deep seawater. Therefore, it required a big pipe to pump from the deep seawater to condense R134a. R22 has the higher net power output but lower pumping power for deep seawater compared to propane. R32 was the fourth possible candidate to replace ammonia. As the graph shown, R32 gaves the lowest pumping power than the other working fluids including pure ammonia. The graph also indicated that R410a and R143a have low pumping power compared to pure ammonia, but it has the lowest net power output. Even so, a substitute working fluid must be introduced to replace ammonia which is detrimental to the ecosystem and needs a special substance to be preserved.

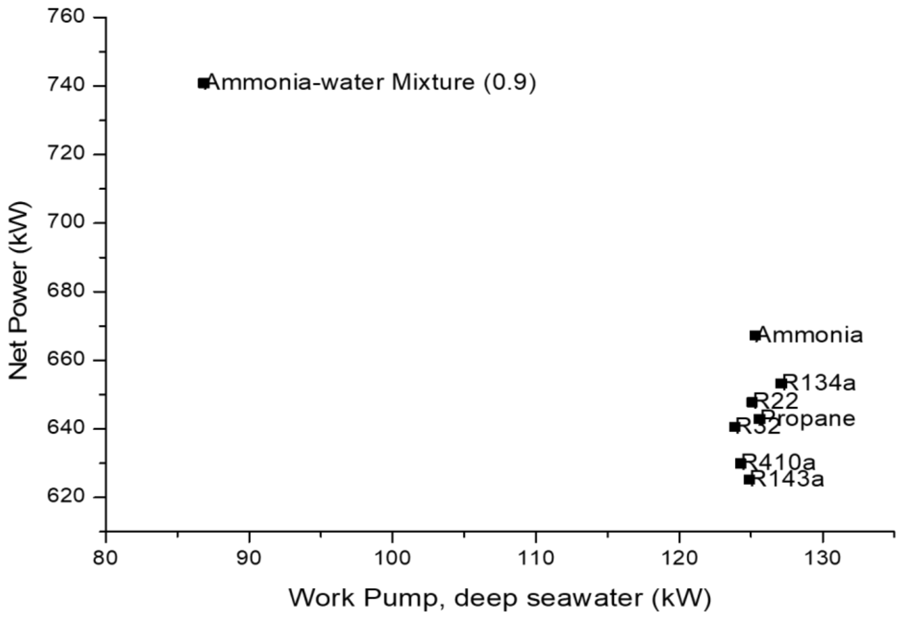


Figure 6. The simulated net power output of eight varying working fluids produced by a work pump of deep seawater

The relationship between the network output and efficiency is shown in Figure 7. Although both ammonia and ammonia-water mixture have greater network output and efficiency in contrast to the other working fluids, they need a separator to make sure that water vapor from the fluid (particularly for ammonia-water mixture) does not affect the blade of the turbine. When propane and R32 were implemented as working fluids, the resulting performance was poorer. However, in comparison with R22, R134a, R143a, and R410a, both propane and R32 have a comparatively broader range of working pressure as well as a more stable working range.

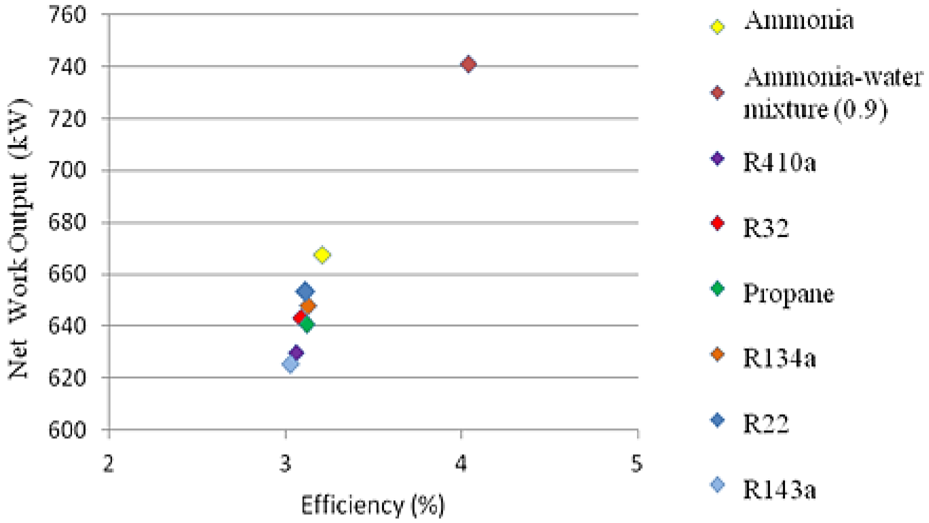


Figure 7 The relationship between the network output and efficiency of eight varying working fluids

4. Conclusion

In conclusion, a model which incorporated LabVIEW and Refprop software's was successfully developed and deployed for a preliminary assessment of the OTEC cycle efficiency. The preliminary analysis of a test run at a net power output of 1 MW showed a close agreement with that of exiting data. The similar developed model was implemented to analyse the efficiency of the OTEC basic closed Rankine cycle using eight varying working fluids. The analysed working fluids, including that of ammonia, are ammonia-water mixture (0.9), propane, and refrigerants (R22, R32, R134a, R143a, and R410a). The results revealed that ammonia-water mixture showed the highest network performance and reliability. Even so, it is essential to continue seeking the suitable working fluids which are safe and economically effective to replace ammonia.

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