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Research paper

The Effect of Thermal Diffusivity on the System Efficiency of a DOTEC Cycle

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Abstract : In this study, the effect of deep ocean condenser inlet temperature (T_{DOI}), condenser inlet pressure ($P_{cond,in}$), and thermal diffusivity on system efficiency of some selected refrigerants was analyzed using HYSYS. The proposed DOTEC cycle is similar to the reheat Rankine cycle but eliminates irreversibilities by bleeding a fraction of the steam between certain stages of the turbine. The evaporator inlet mass flow rate, inlet temperature of turbine 1, turbine efficiency and inlet and outlet temperature of heat source were imposed. The working fluids considered are sorted in ascending order of their molecular weights as R717, R600a and R152a. Results indicated that a fluid with a lower boiling point temperature like R717 needs a corresponding high heat source and/or evaporator inlet pressure. Also, the response of thermal diffusivity closely follows the change in T_{DOI} as an increase in T_{DOI} increases $P_{cond,in}$ which reduces thermal diffusivity and system efficiency. Furthermore, the fluid with the nominal boiling point temperature has the highest efficiency with efficiency decreasing with an increase in T_{DOI} .

Key Words : Condenser Pressure, DOTEC Cycle, Thermal Conductivity, Thermal Diffusivity, Specific Heat

1. Introduction

Fossil fuels still dominate energy consumption with a market share of 87% whiles renewable energy account for only 2% of energy consumption globally. This has an adverse effect on the environment and recent “peak oil” concerns calls for the exploitation and commercialization of a safe and sustainable source of energy. One such alternative is ocean thermal energy conversion (OTEC) which uses the heat energy stored in the Earth's oceans to generate electricity. OTEC works best when the temperature difference between the warmer, top layer of the ocean and the colder, deep ocean water is about 20℃. To operate, the cold water must be brought to the top through active pumping and desalination with an expensive, large-diameter intake pipe. However, low boiling point fluids can also be pump vaporized into the depth of the cold water in order to reduce pipe cost[1]. OTEC has enormous potential as a clean source of renewable and base-load electricity for tropical countries.

There have been many researches on the

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viability of the OTEC cycle generally focused on the working fluid selection and cycle configuration in order to increase the OTEC efficiency. Some of these studies presented that OTEC efficiency can be increased and equipment cost reduced using refrigerant mixtures and minimizing parasitic power. Also, the thermodynamic efficiency and economic profitability can lead to different optimal working conditions with a lower fluid density leading to bigger component which increase cost. Table 1 summarizes the research works carried out on the selection of working fluids for ORC/OTEC cycles modified from Quoilin et al.

Fluid selection for the OTEC cycle is a major consideration and is very dependent on the target application, working conditions and can affect the overall efficiency. Heat transfer is key to the efficiency of the OTEC cycle as it allows close approaches in the heat exchangers and causes efficiency increase. This paper discusses the effect of deep ocean condenser inlet temperature (T_{DOI}), condenser inlet pressure ($P_{cond,in}$), and thermal diffusivity on system efficiency of some selected refrigerants using a proposed DOTEC cycle.

DOTEC cycle is similar to the Reheat Rankine Cycle but eliminates irreversibilities by bleeding a fraction of the steam. As shown in Fig. 1, a fraction of the steam flow rate is bled in the regenerator at an intermediate pressure between the evaporating and condensing pressures. The steam is directed to a direct contact heat exchanger (regenerator) where it is mixed with pressurized feed liquid from the condenser. This allows the working fluid to be heated to its saturation temperature before entering the evaporator. The addition of static mixer, tank and an expansion valve is to desuperheat the working fluid before entering the condenser. This is aimed at increasing the system's overall efficiency as well as preventing two-phased fluid from entering the turbine. The transport properties of a working fluid are of primary importance for improved efficiency of an OTEC cycle since the cycle involves heat and mass transfer. They are necessary for the

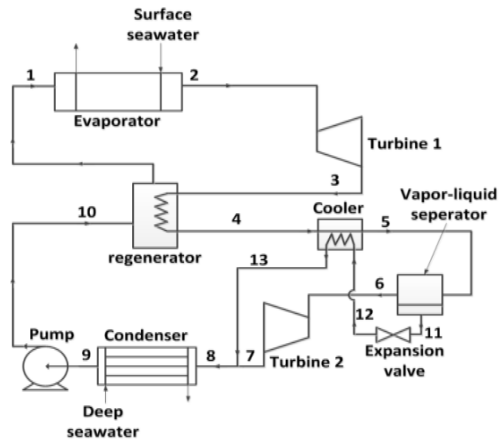

Fig. 1 Schematic diagram of DOTEC cycle[2)]

Table 1 Summary of OTEC studies on different working fluids

Author	Application	Cond. Temp. (℃)	Evap. Temp. (℃)	Considered fluids	Recommended fluids
Gao et al[3)].	Waste Heat Recovery	20 - 24	44 - 185	Organic fluids such as such as CO_2, R125, R143a and so on	R152a, R143a
Gu et al[4)].	Waste Heat Recovery	50	80 - 220	R600a, R245fa, R123, R113	R113, R123
Yoon et al[5)].	OTEC	10	20	Organic fluids such as R236fa, R744 and so on	R744, R717, R152a

evaluation of many transfer coefficients that condition the design and operation of heat exchangers, turbines and pumps and helps in storage and safety operations.

Thermal diffusivity (α) determines how rapidly heat will flow through a substance and increases with the ability of the substance to conduct heat (k) but decreases with the amount of heat needed to change the temperature of the substance (C_P). Known values of thermal conductivity can simultaneously be used to develop data for thermal diffusivity. Thermal diffusivity is related to the steady-state thermal conductivity through the equation

$$\alpha = \frac{k}{\rho C_p} \tag{1}$$

2. System Modeling

2.1 Mathematical Analysis

Evaluations of the aforementioned study parameters are done using the HYSYS software package. The mathematical model is analyzed as follows.

Heat Addition Process :

$$Q_{Evaporator} = m_{re}(h_{evap.exit} - h_{evap.inlet})$$

Expansion Process :

$$W_{Turbine1} = m_{re}(h_{Turb1.inlet} - h_{turb1.outlet})\eta_t$$

$$W_{Total\ Turbine} = W_{Turbine\ 1} + W_{Turbine\ 2}$$

Heat Rejection Process :

$$Q_{Condenser} = m_{re}(h_{Cond.inlet} - h_{Cond.outlet})$$

Pump Work :

$$W_{Feed\,Pump} = m_{re}(h_{Feed.inlet} - h_{Feed.outlet})/\eta_{Pump}$$

$$W_{Total\ Pump} = W_{Deep\,Pump} + W_{Surface\ Pump} + W_{Feed\,Pump}$$

$$\eta_{\dot{E}C} = \frac{W_{Total\,Turbine} - W_{Total}}{Q_{Evaporation}}$$

2.2 Simulation Conditions

The deep ocean condenser inlet temperature (T_{DOI}) was varied (from 4℃ to 6℃) in order to study its relation to efficiency, $P_{cond,in}$ as well as α T_{DOI} is increased steadily at 1℃ in this study since the temperature difference between the warm surface water and deep ocean water should be between 10-25℃ so as to sustain a viable operation of the OTEC cycle. In order to determine the best working fluid, the evaporator inlet mass flow rate, turbine 1 inlet temperature, turbine efficiency and surface water heat source inlet and outlet temperature were imposed. A constant, realistic value of 65% is assumed for the pump efficiency. Also, the evaporator inlet pressure for the individual working fluids was not changed with T_{DOI}. Meanwhile, the hypotheses are as follows:

i. The working fluid at the turbine inlets is saturated vapor.

ii. The turbines and pumps are adiabatic.

The simulation of the double ocean thermal energy conversion (DOTEC) cycle was done using the HYSYS software package.

3. Results and discussion

Table 2 Input parameters of the proposed DOTEC

Parameter	Value
Inlet temperature of warm ocean surface water (℃)	26
Outlet temperature of warm ocean surface water (℃)	23
Evaporator inlet Mass flow rate (kg/s)	2000
Isentropic efficiency of turbines (%)	80
Isentropic efficiency of pumps (%)	65
Inlet temperature of deep ocean water (℃)	4, 5, 6
Turbine 1 inlet temperature (℃)	24
Pressure drop of water in heat exchanges (kPa)	50
Pressure drop of working fluid in heat exchanges (kPa)	10

Table 3 Condenser inlet pressure

Working fluid	Minimum condenser inlet pressure ($P_{cond.in}$), (kPa)		
	4°C	5°C	6°C
R717	639.5	661.5	684.2
R600a	233.2	240.7	248.4
R152a	391.3	404	417.1

From Fig. 2, condenser inlet pressure increased with increase in T_{DOI}. R717 displayed the highest pressure due to its low boiling point temperature. A fluid with a lower boiling point temperature needs a corresponding high heat source and/or evaporator inlet pressure in a DOTEC cycle. And since the heat source temperature is fixed for this study, R717 needed a higher pressure to make up for the low temperature heat source.

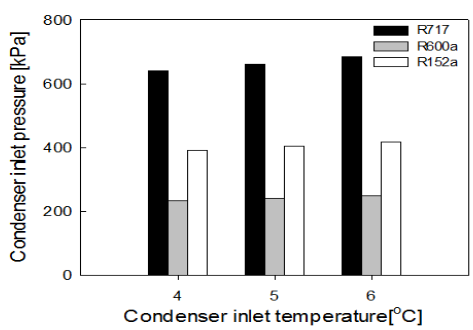

Fig. 2 Comparison of condenser inlet pressures

From Fig. 3, R717 displayed the highest thermal diffusivity with R600a having the least.

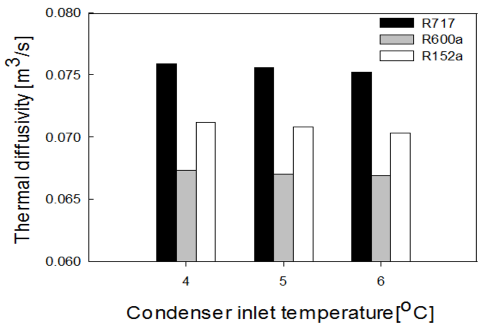

Fig. 3 Comparison of thermal diffusivity at evaporator inlet

This is because R717 had the highest pressure and thermal conductivity from tables 3 and 4, respectively.

More also, it is the wettest fluid thus fostered the rapid movement of heat from the heat source albeit its high Cp values from table 4. Thermal diffusivity values show a strong dependence on $P_{cond,in}$ and T_{DOI} as an increase in $P_{cond,in}$ and T_{DOI} decreases thermal diffusivity

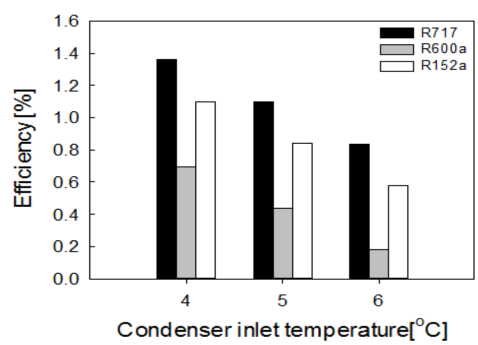

Fig. 4 Comparison of system efficiency

Table 4 Density, specific heat and thermal conductivity values as generated by HYSYS[6)]

Working fluid	ρ (g/m³)			Cp (J/g·C)			k (W/m·C)		
	4°C	5°C	6°C	4°C	5°C	6°C	4°C	5°C	6°C
R717	0.6225	0.6212	0.6199	4.826	4.838	4.851	0.2280	0.2271	0.2262
R600a	0.5604	0.5593	0.5589	2.341	2.348	2.351	8.831e-002	8.802e-002	8.792e-002
R152a	0.9286	0.9262	0.9236	1.752	1.759	1.766	0.1158	0.1153	0.1147

From Fig. 4, R717 which had the highest thermal diffusivity from Fig. 3 had a corresponding high efficiency. R600a being a dry fluid left the evaporator with substantial heat due to the addition of the regenerator and this increased the system load thereby decreasing its efficiency. R717 presented the highest system efficiency because of its low boiling point temperature and high thermal diffusivity. Futhermore, for every 1^{o}C increment in T_{DOI} there is a corresponding reduction in thermal conductivity and thermal diffusivity leading to a decrease in system efficiency. This shows that, system efficiency is dependent on thermal diffusivity, and boiling point temperature.

5. Conclusions

Fluid selection for the DOTEC Cycle is an important issue and is very dependent on the working conditions. In this study, the effect of T_{DOI}, $P_{cond,in}$, and thermal diffusivity on system efficiency of some selected refrigerants was analyzed using HYSYS and discussed. The thermophysical properties led to the selection of working fluid components for the study, sorted by their molecular weight in the order R717, R600a and R152a. $P_{cond,in}$ is an important parameter that affects the thermal diffusivity and efficiency of the cycle and a minimum allowable condenser pressure is ideal for maximum thermal diffusivity and efficiency.

Also, an increase in T_{DOI} corresponds to an increase in $P_{cond,in}$ as well as a decrease in system efficiency. For a DOTEC cycle with fixed heat source temperature, turbine inlet temperature and T_{DOI}, the fluid with the nominal boiling point temperature and highest thermal diffusivity has a corresponding high system efficiency with efficiency decreasing with an increase in T_{DOI}. More also, the DOTEC cycle recorded an increase in efficiency compared to the 0.89% of the basic OTEC cycle and R717 is the most promising fluid except for its toxicity.

Acknowledgement

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