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Research Article

Performance of Working Fluids in Ocean Thermal Energy Conversion Technology & Different Applications

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Abstract

Ocean thermal energy conversion system (OTEC) generates electricity indirectly from solar energy, by using temperature difference between warm surface sea water and cold deep sea water by the sun mixed to depths of about 100 m by wave motion. The bottom layer consists of colder water formed at high latitudes. The interface or thermo cline is sometimes marked by an abrupt change in temperature but more often the change is gradual. The temperature difference between the upper (warm) and bottom (cold) layers ranges from 10 °C to 25 °C, with the higher values found in equatorial waters. This implies that there are two enormous reservoirs providing the heat source and the heat sink required for a heat engine. Since OTEC exploits renewable source of energy, recurring cost to generate electric energy is less. There are many applications to this system such as potable water, Hydrogen preparation, nuclear power plant cooling-water purification and electricity generation from the relatively waste and poisonous water.

Keywords: *Ocean thermal energy conversion (OTEC), Renewable energy, Refrigerants Simple Rankine cycle, Uehera cycle.*

1. Introduction

Considering the increasing global temperatures, and also the concern of global climate change, many policymakers worldwide have accepted the importance of reducing greenhouse gas emissions, in particular from the power industries. Energy resource use is one of the most important and contemporary issues of our time. The ocean provides a vast source of potential energy resources. Out of the total solar radiation, oceans are the largest collectors. The most plentiful renewable energy source in our planet by far is solar radiation: 170,000 TW fall on Earth. Harvesting this energy is difficult because of its dilute and erratic nature. Large collecting areas and large storage capacities are needed, two requirements satisfied by the tropical oceans. Oceans cover 71% of Earth's surface. In the tropics, they absorb sunlight, and the top layers heat up to some 25C. Ocean and marine energy refers to various forms of renewable electric energy harnessed from the ocean. There are two primary types of ocean energy: mechanical and thermal. The rotation of the earth and the moon's gravitational pull create mechanical forces. The rotation of the earth creates wind on the ocean surface that forms waves, while the gravitational pull of the moon creates coastal tides and currents. Thermal energy is derived from the sun, which heats the surface of the ocean while the depths remain colder. This temperature difference allows energy to be captured and converted to electric power(A temperature difference of only20°C (36°F) can yield usable energy).With fossil fuel prices increasing and expected to stay high in the future, the search for alternative energy resources is once again on the forefront. The first documented reference to the use of ocean temperature differences to produce electricity is found in Jules Verne's Twenty Thousand Leagues Under the Sea published in 1870.

Eleven years after Jules Verne, D'Arsonval proposed the idea of closed cycle OTEC system. This idea was first implemented by a French Physicist named Jacques Arsene D'Arsonval in 1881. D'Arsonval proposed to use the relatively warm (24 °C to 30 °C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapour to drive a turbine-generator. The cold ocean water transported (up welled) to the surface from 800 m to 1000 m depths, with temperatures ranging from 8 °C to 4 °C, would condense the ammonia vapour through another heat exchanger (i.e., condenser). This concept is based upon the thermodynamic Rankine cycle used to study steam (vapour) power plants. As the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC). D'Arsonval's concept was demonstrated in 1979, when the state of Hawaii and a

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*Corresponding author: **Gaurav Kulkarni** consortium of U.S. companies produced more than 50 kW of gross power, with a net output of up to 18 kW from a small plant mounted on a barge off Hawaii (Mini-OTEC). Since then, the US DOE and Uehara at Saga University in Japan have performed extensive testing of heat exchangers and Kalina (1984) and Uehara (1999) have proposed the use of an ammonia-water mixture as the working fluid.

D’Arsonval’s student, Georges Claude, proposed to use the ocean water as the working fluid. In Claude's cycle the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is also referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system.

However, the major problem in installing OTEC system is its low efficiency. It is known that the deeper the cooling water is pumped from the sea, the more efficient will the OTEC plant work. To achieve higher efficiency a lot of research efforts were directed toward performance improvement of an OTEC plant. Using Freon 22 as a working fluid, Uehara *et al*. (1979) studied the performance of an OTEC plant. Later, Nakaoka and Uehara conducted experiments to test the performance of an OTEC system with shell-and-plate type evaporator and condenser. In addition, Ganic and Moeller (1980) carried out the performance study of an OTEC plant. Owens (1980) investigated the optimization of closed-cycle OTEC plants. Using ammonia as the working fluid, an optimization study by Power method was presented by Uehara and Ikegamia (1990) for a closed-cycle OTEC plant. Both constant and variable turbine efficiencies were considered in their study. Later, Rabas *et al*. (1990) proposed a comprehensive study of the non-condensable gas removal system for a particular 10 MW hybrid power plant. Dividing the power plant into three major subsystems, Tseng *et al*. (1991) utilized an optimal design concept to find the best design for a complex and large-scale OTEC plant. Using the total heat transfer area of heat exchangers per net power as an objective function, an OTEC cycle with plate-type heat exchangers and ammonia as working fluid was investigated numerically (Uehara *et al*., 1996). Recently, based on plate exchangers with surface coating on the ammonia side, Abraham *et al*. (1999) have proposed the design of 1 MW closed-cycle floating OTEC plant.

In this paper, discussion is carried out on close cycle OTEC system and how its efficiency is affected using different working fluids.

List of symbols

A	Average (±)
cp	Specific heat at constant pressure [J/(kg K)]
h	Specific enthalpy (kJ/kg)
DH.Tt;in.	Specific enthalpy difference related to Eq. (1)
Ja(Tt;in.	Jakob number defined as cp, Tt ; in hlv.Tt ; in.
L	Liquid (±)
m	Mass flow rate (kg/s)
M	Molecular weight (g/mol)
OTEC	Ocean thermal energy conversion (±)
P	Pressure (kPa, M Pa)
Q	Heat capacity (kW)
T	Temperature (°C, K)
V	Vapor (±)
VER	Vapor expansion ratio (±)
W	Power, work (kW)
g	Efficiency (±)
D	Difference (±)
Dh	Latent heat (kJ/kg)

Subscripts

bp	Normal boiling point
c	Condenser, condensing
car	Carnot
crit	Critical
ds	Deep seawater
e	Evaporator, evaporating
in	Inlet
lv	Related to latent heat of evaporation
OTEC	Ocean thermal energy conversion
p	Pump
re	Refrigerant
ss	Surface seawater
suc	Subcooling degree
suh	Superheating degree
t	Turbine

2. System modelling

2.1 System prescription

As shown in Fig. 1, the subcritical OTEC power cycle analyzed here is a closed one, which is similar to a basic Rankine cycle consisting of a steam generator, a turbine, a condenser and a refrigerant pump. The only difference is that an evaporator is used instead of a steam generator and volatile fluid instead of steam is used as a working fluid. In this system, heat transfer from the warm surface seawater occurs in the evaporator, producing a saturated vapour from the working fluid. The generated high pressure vapour (state 2) in the evaporator flows into the turbine. Electricity is generated when the vapour expands to lower pressure through the turbine. The low-pressure vapour (state1) is led to the condenser where it is liquefied by the cold deep seawater. The liquid (state 4) available at the con-denser outlet is pumped to a high pressure (state 3), flows into the evaporator, and a new cycle begins. The above described processes are presented in the P-h diagram shown in Figs. 2.Table 1 depicts various working fluids used in this study to compare the performance of the OTEC power cycle. The working fluids using the OTEC power cycle can be divided into three groups: (1) dry fluids have positive slope, (Jung-In Yoon *et al* 2014) wet fluids have negative slope, and (Chengdu Ahmad *et al* 2011) iso-entropic fluids have nearly vertical saturated vapour curves. This categorizations to compare the performance of three fluids. Table 2 lists some properties of the working fluids considered here.

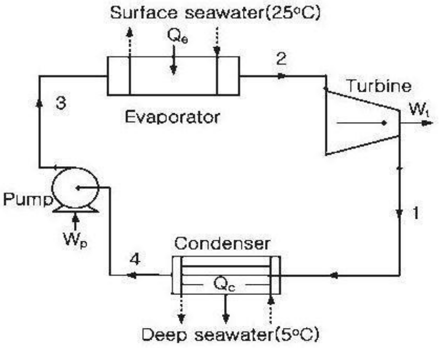


Fig. 1 Schematic diagram of OTEC power cycle

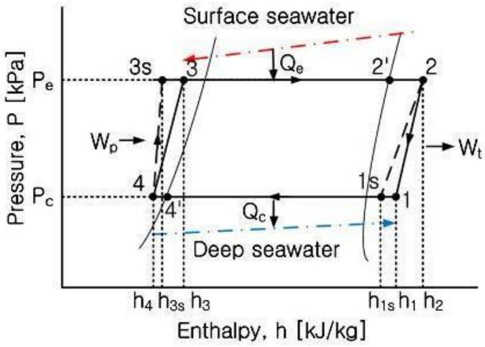


Fig. 2 P-h diagram of OTEC power cycle

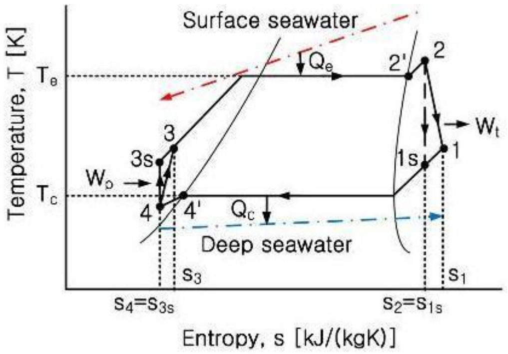


Fig. 3 T-s diagram of OTEC power cycle. a. Wet fluids b. Dry fluids

2.2 Mathematical analysis model

The efficiency comparison of the fluids is evaluated using a software package named as Engineering Equation Solver (EES). The analysis for the efficiency of subcritical OTEC power cycle was performed under the following general assumptions.(J. Yoon *et al*, 2014).

- The internal irreversibility and the pressure drops in the evaporator, condenser, and pipes are ignored when the thermodynamic properties are estimated. (J. Yoon *et al*, 2014)
- Each component is considered as a steady-state steady flow system. (J. Yoon *et al*, 2014)
- The changes in kinetic and potential energy of the components are negligible. (J. Yoon *et al*, 2014)

Taking into account the assumptions previously made, Table 3 gives the calculation of the energy and mass equations of the subcritical OTEC power cycle. Table 4 presents the analysis ranges specified in this paper, which is the most common operation conditions of the OTEC power cycle.

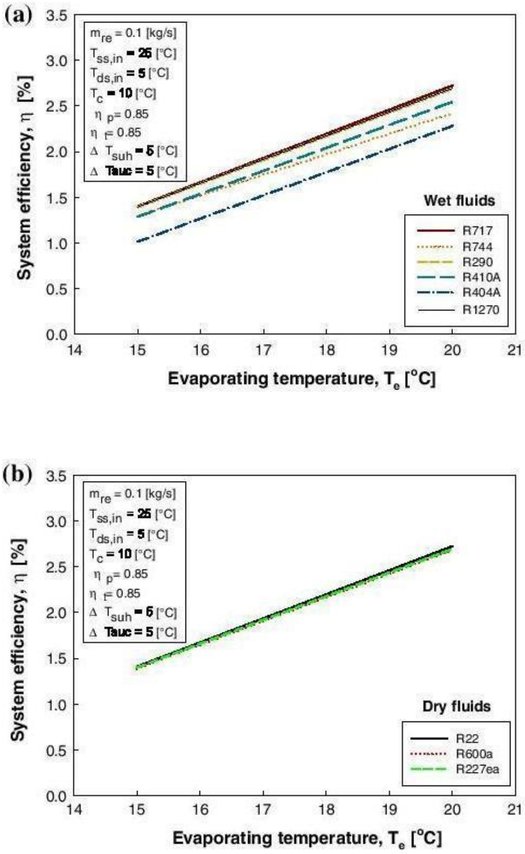
Table 1 Fluid groups of OTEC power cycle used in this study (J. Yoon *et al*, 2014)

Group	Dry Fluids	Wet Fluids	Iso-Entropic Fluids
Refrigerants	R22, R600a, R227ea	R290, R404A, R410A, R717, R744, R1270	R236fa, R245fa, R134a

3. System analysis

3.1 Performance characteristics by each refrigerant

3.1.1 Effect of evaporating temperature



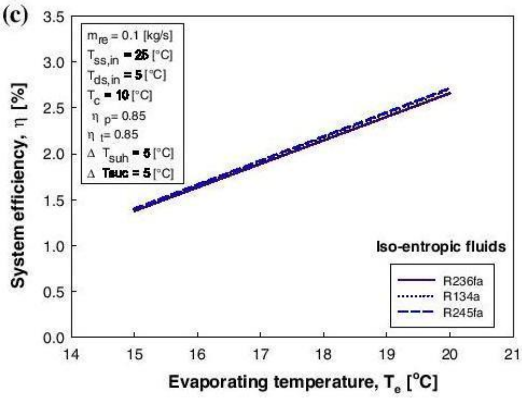


Fig. 4 Effect of evaporating temperature on System Efficiency

In an OTEC power cycle, a suitable choice of the working fluids is an important factor for achieving a high efficiency and a safe operation. Various working fluids used in this study are listed in Table 1. Each working fluid has its own range of applicability according to its thermophysical properties. Table 3 shows the thermodynamic properties of wet fluids, Table 4 shows the thermodynamic properties of dry fluids, and Table7 shows the thermodynamic properties of iso-entropic fluids, respectively. The values were obtained using EES.

Figure 4 presents the variation of thermal efficiency with various evaporating temperatures for the three different groups of fluids. It could be observed that the system efficiency of the three groups increased by about 86±125 %with the evaporating temperatures due to increasing turbine power. Among all the fluids, R404A showed the largest increasing ratio of 125 %.In Fig. 4a, R717 had the highest thermal efficiency among the wet fluid. R404A had the lowest, because of its evaporation latent heat (Dh) as shown in Table 3. High evaporation latent heat yielded a larger thermal efficiency. This means that R717 has a better heat transfer performance than other wet fluid.

As indicated in Fig. 4b, the dry fluids have almost the same efficiencies. Although the evaporation latent heat ofR600a yielded a larger thermal efficiency than that of R22, R600a showed a lower thermal efficiency because of its low density in vapor and liquid phase. Thus, the working fluid with high density presents high turbine power, resulting in high efficiency.

As observed from Fig. 4c, all the fluid had similar efficiencies, but R245fa provided the highest thermal efficiency due to its high evaporation latent heat, as presented in Table 5.

3.1.2 Effect of condensing temperature

Figure 5 displays the performance characteristics of the subcritical OTEC power cycle with condensing temperatures for the three different groups of fluid. As indicated in Fig. 5, the thermal efficiency decreased with the rise of condensing temperature and it varied in the range of 48±56 %. This is because of the decreasing turbine power and increasing evaporation heat as a result of the increase of condensing temperature. Also, R404 provided the highest decreasing ratio of 56 %. R744 yielded the lowest decreasing ratio of about 48 %.

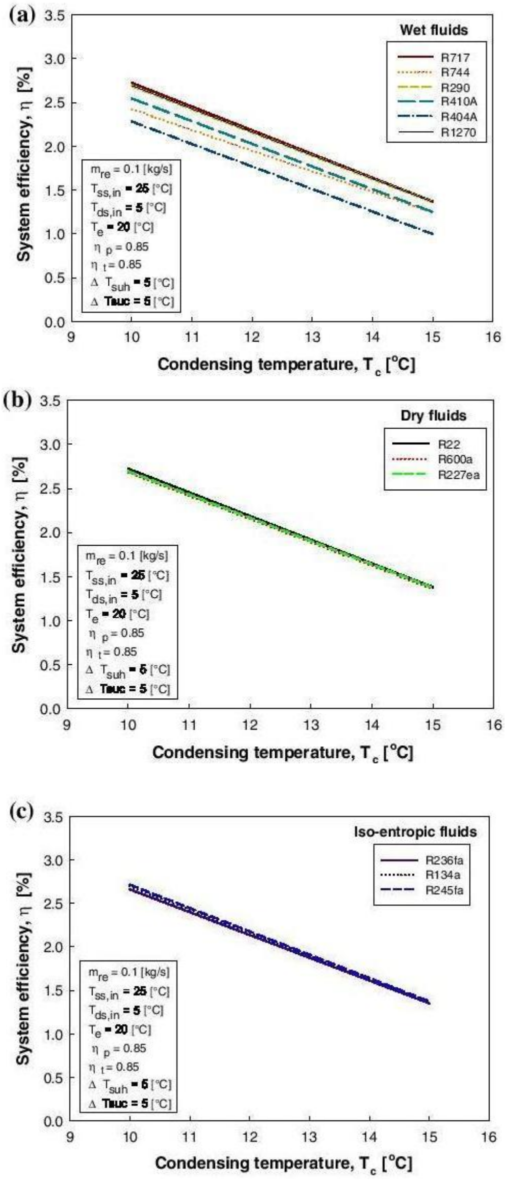


Fig. 5 Effect of condensing temperature on System Efficiency

In Fig. 5a, R717 and R404A had the highest and lowest thermal efficiencies, respectively, which is the same result on the effect of evaporating temperature in Fig. 4. There as on is its latent heat as mentioned in Sect. 3.1.1. As a conclusion, latent heat is a major factor to be considered in selecting proper working fluids in addition to examining other thermophysical properties.

It could be observed from Fig. 5b that the dry fluid presented similar efficiency values, but the highest and lowest thermal efficiencies were yielded by R227ea andR600a respectively. As shown in Table 4, these results are due to their high densities, leading to large turbine powers. As a result, the fluid with higher densities yields larger thermal efficiencies.

As shown in Fig. 5c, the iso-entropic fluid also showed the similar results. These results are related to their properties such as specific heat, thermal conductivity and density, as presented in Table5. Namely, the similar properties provide approximate efficiency values.

3.1.3 Effect of sub cooling degree

Figure 6 depicts the performance characteristics of the subcritical OTEC power cycle as a function of the sub-cooling degrees for the three different groups of fluid. As observed in Fig. 6, the efficiencies of the three groups decreased slightly, by about 2.2±2.8 %, when the sub-cooling degree is increased. The three types of fluid in Fig. 6showed similar sub-cooling degree dependence. This is because the evaporation heat capacity increases with the sub-cooling degree at the condenser outlet, but the turbine power is nearly constant as presented in the P-h diagram of Figs. 2. Thus, the efficiency diminishes due to the increasing evaporation heat and decreasing turbine power(J. Yoon *et al*, 2014).

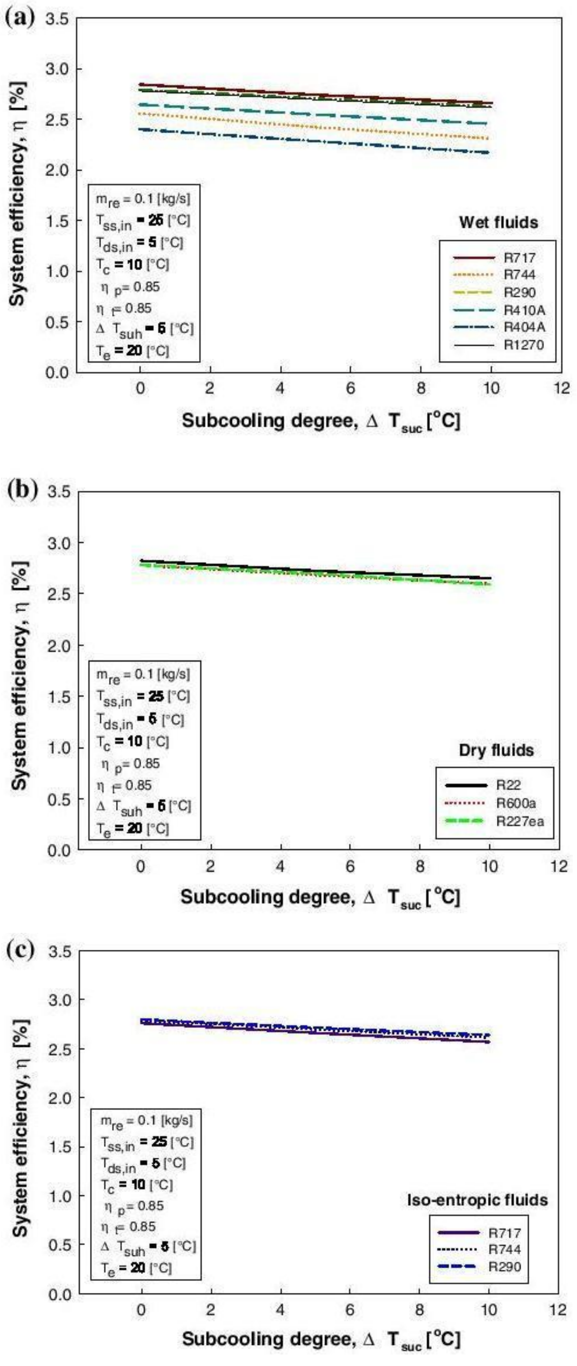


Fig. 6 Effect of subcooling degree on System Efficiency

From Fig. 6a, R717 and R404A had the highest and lowest thermal efficiencies, respectively. As mentioned earlier, these results are because of the dependence on their evaporation latent heats. Also, R744 had a lower efficiency because of its low boiling and critical temperature. The fluids with lower boiling point have the higher vapor pressures. Thus, the area which represents a net work of the cycle in the T-s diagram of Fig. 3 is inevitably reduced, along with the system efficiency. For the dry fluid in Fig. 6b, R600a has a higher latent heat and a lower thermal conductivity than the other dry fluid. However, R600a presented a lower thermal efficiency due to lower density of the vapor and liquid phases. Therefore, the property like the density is a crucial factor which must be taken into consideration in selecting the working fluids under different working temperatures. In Fig. 6b, R22 yielded the highest thermal efficiency (J. Yoon *et al*, 2014).It could be observed in Fig. 6c, that R245fa provides the highest efficiency because of its high latent heat as shown in Table 5.

Table 2 Thermodynamic properties of wet fluids (J. Yoon *et al*, 2014)

Fluids	T_{sat}(°C)	Specific heat(kJ/kg K)			Thermal conductivity (W/mk)			Density (kg/m³)			Enthalpy (kJ/kg)		
		L	V	A	L	V	A	L	V	A	L	V	Δh
R717	10	4.673	2.831	3.752	0.5294	0.0243	0.2768	624.8	4.885	314.8	246.4	1,472.00	1,225.60
	15	4.705	2.92	3.813	0.5147	0.0249	0.2698	617.6	5.744	311.7	269.9	1,476.00	1,206.10
	20	4.741	3.016	3.879	0.5001	0.0255	0.2628	610.3	6.719	308.5	293.6	1,480.00	1,186.40
R744	10	2.997	2.457	2.727	0.0987	0.0232	0.0609	861.1	135.2	498.2	-281	-83.9	197.1
	15	3.432	3.047	3.24	0.0919	0.0255	0.0587	821.2	160.7	491	-266.8	-90.1	176.7
	20	4.236	4.11	4.173	0.0875	0.0285	0.0565	773.4	194.2	483.8	-250.9	-98.9	152
R290	10	2.591	1.883	2.237	0.1026	0.0169	0.0597	514.5	13.78	264.1	225.7	585.6	359.9
	15	2.636	1.939	2.288	0.0999	0.0175	0.0587	507.2	15.81	261.5	238.7	590.8	352.1
	20	2.684	1.999	2.342	0.0097	0.0182	0.014	499.8	18.08	258.9	252	595.9	343.9
R410A	10	1.575	1.227	1.401	0.0981	0.0136	0.0558	1,133.00	41.94	587.5	74.2	283.9	209.7
	15	1.604	1.292	1.448	0.0949	0.0142	0.0545	1,111.00	48.84	579.9	82.3	284.9	202.6
	20	1.637	1.365	1.501	0.0916	0.0148	0.0532	1,087.00	56.75	571.9	90.5	285.7	195.2
R404A	10	1.422	1.034	1.228	0.0731	0.0136	0.0433	1,109.00	41.6	575.3	67.2	223.2	156
	15	1.446	1.072	1.259	0.0714	0.0142	0.0428	1,088.00	48.36	568.2	74.5	225.4	150.9
	20	1.472	1.115	1.294	0.0698	0.0148	0.0423	1,066.00	56.08	561	81.9	227.5	145.6
R1270	10	2.52	1.473	2.132	0.123	0.0158	0.068	529.3	16.41	272.9	-411	-49.3	361.7
	15	2.563	1.799	2.181	0.1177	0.0649	0.0913	521.3	18.8	270.1	-398.3	-45.1	353.2
	20	2.61	1.86	2.235	0.1151	0.0171	0.0661	513.1	21.47	267.3	-385.4	-41.2	344.2

Table 3 Thermodynamic properties of dry fluids (J. Yoon *et al*, 2014)

		Specific heat(kJ/kg K)			Thermal conductivity (W/mk)			Density (kg/m³)			Enthalpy (kJ/kg)		
		L	V	A	L	V	A	L	V	A	L	V	Δh
R22	10	1.204	0.791	0.997	0.0902	0.0107	0.0504	1,238.00	28.63	633.3	213.2	408.8	195.6
	15	1.221	0.816	1.018	0.088	0.0111	0.0495	1,220.00	33.14	626.6	219.3	410.4	191.1
	20	1.267	0.843	1.041	0.0858	0.0115	0.0486	1,201.00	38.22	619.6	225.4	411.9	186.5
R600a	10	2.486	1.714	2.1	0.112	0.0151	0.0635	569.1	5.939	287.5	350.4	690.6	340.2
	15	2.504	1.751	2.128	0.1144	0.0156	0.065	563.2	6.912	285.1	362.9	697.2	334.3
	20	2.52	1.79	2.155	0.1088	0.0161	0.0625	557.1	8.003	282.6	375.6	703.9	328.3
R227ea	10	1.103	0.847	0.975	0.0641	0.0124	0.0383	1,453.00	22.27	737.6	29.3	150.5	121.2
	15	1.118	0.865	0.991	0.0632	0.0128	0.038	1,443.00	26.21	734.6	35.1	153.7	118.6
	20	1.134	0.883	1.008	0.0619	0.0132	0.0375	1,413.00	30.65	721.8	40.9	156.9	116

Table 4 Thermodynamic properties of iso-entropic fluids (J. Yoon *et al*, 2014)

		Specific heat(kJ/kg K)			Thermal conductivity (W/mk)			Density (kg/m³)			Enthalpy (kJ/kg)		
		L	V	A	L	V	A	L	V	A	L	V	Δh
R236fa	10	1.245	0.812	1.029	0.0779	0.0116	0.0447	1,409.00	10.94	710	58.6	213.8	155.2
	15	1.256	0.823	1.04	0.0767	0.012	0.0443	1,393.00	13.06	703	64.9	217.3	152.5
	20	1.267	0.835	1.051	0.0743	0.0124	0.0433	1,376.00	15.49	695.7	71.2	220.8	149.6
R134a	10	1.369	0.943	1.156	0.0903	0.0131	0.0517	1,261.00	20.22	640.6	65.4	256.2	190.8
	15	1.385	0.969	1.177	0.088	0.0136	0.0508	1,244.00	23.75	633.9	72.3	259	186.7
	20	1.403	0.998	1.2	0.0857	0.0141	0.0499	1,226.00	27.77	626.9	79.3	261.6	182.3
R245fa	10	1.29	0.856	1.073	0.0857	0.0128	0.0492	1,378.00	4.882	691.4	212.7	412.6	199.9
	15	1.31	0.871	1.09	0.0842	0.0132	0.0487	1,365.00	5.918	685.5	219.2	416.5	197.3
	20	1.33	0.886	1.108	0.0827	0.0136	0.0481	1,352.00	7.121	679.6	225.9	420.4	194.5

3.1.4 Effect of superheating degree

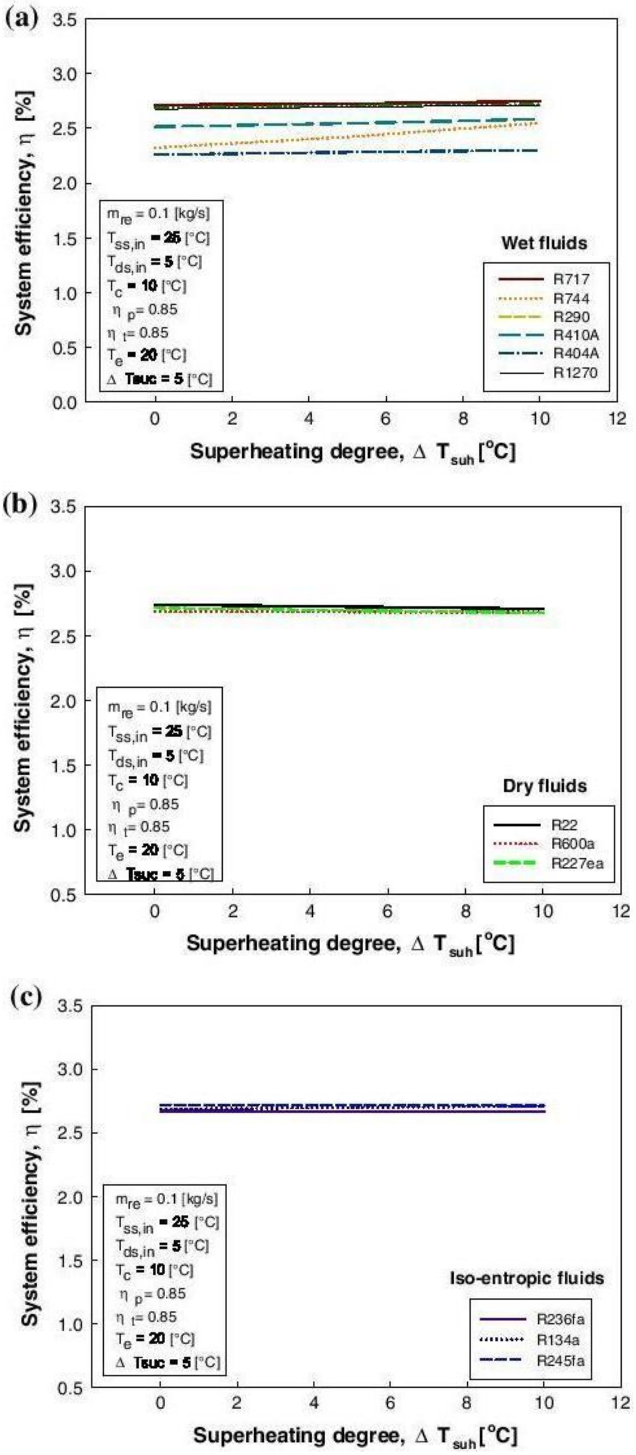


Fig. 7 Effect of superheating degree on System Efficiency

A higher superheating degree at the evaporator outlet is used in a traditional OTEC power cycle to improve the thermal efficiency (R. Yeh *et al*, 2005). However, a higher superheating degree does not always lead to a higher efficiency for all working fluid. If the fluids is too dry, the expanded vapor will leave the turbine with substantial superheat, which is a waste and adds to the cooling load in the condenser. The cycle efficiency can be increased using this superheat to preheat the liquid after it leaves the feed pump and before it enters the evaporator (R. Yeh *et al*, 2005).

Figure 7 shows the dependence of the system efficiency on the superheating degree under fixed operation conditions. As for the wet fluid in Fig. 7a, the efficiencies increased by 0.85±9.7 % with the superheating degree.R744 gave the largest increasing ratio of 9.7 % when the superheating degree varied from 0 to 10 °C. Thus, forR744, the superheating degree is positively necessary for improvement of the cycle efficiency (J. Yoon *et al*, 2014).As presented in Fig. 7b, the dry fluid in general decreased by approximately 0.18±1.4 %. R227ea yielded the highest decreasing ratio of about 1.4 %. This is related to the degree of the positive slope of the saturated vapor line. From Fig. 7c, the iso-entropic fluid showed almost constant values since the value of dT/ds leads to infinity for this group of fluid. Based on the analysis stated above, in order for the cycle efficiency to increase with the degree of superheat, the incremental efficiency must be greater than the efficiency at the reference state (here it is the saturated vapor state)(J. Yoon *et al*, 2014).

For operation between two isobaric curves, the system efficiency increases for wet fluid while it decreases for dry fluid. The iso-entropic fluids achieve an approximately constant value for fixed turbine inlet temperatures. Based on that, superheat contributes negatively to the cycle efficiency for dry fluid, and is not recommended. For wet fluid, superheat is mostly necessary for turbine expansion safety and improvement of the cycle efficiency.

4. Applications of OTEC system

4.1 Electricity generation by Ocean Thermal Energy

4.1.1 Electricity generation by Open-Cycle OTEC

(Chengdu Ahmad *et al* 2011)In an open-cycle plant, warm seawater from the surface is pumped into a vacuum chamber where it is flash evaporated, and the resulting steam drives the turbine. Cold seawater is then brought to the surface and used to condense the steam into water. The open cycle consists of the following steps:

- Flash evaporation of a fraction of the warm seawater by reduction of pressure below the saturation pressure which will reduce the boiling temperature of water creating phase change.
- Expansion of the vapour through a turbine to generate electricity.
- Heat transfer to the cold seawater resulting in condensation of the working fluid.
- Remove air released from the seawater streams at the low operating pressure.

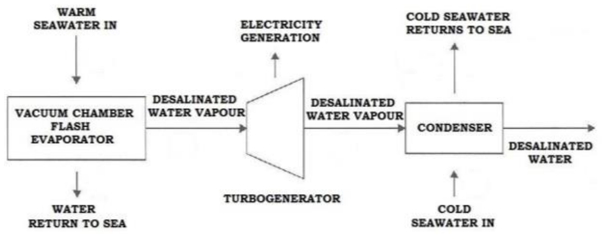


Fig. 10 Open Cycle OTEC

(Chengdu Ahmad *et al* 2011)This Claude cycle as explained above as well as shown in Fig 11 has certain benefits from the selection of water as the working fluid. Water, unlike ammonia, is non-toxic and environmentally benign. Moreover, since the evaporator produces desalinated steam, the condenser can be designed to yield fresh water. In many potential sites in the tropics, potable water is a highly desired commodity that can be marketed to offset the price of OTEC-generated electricity. Although there are some complications while using Claude's cycle:

In the case of a surface condenser the condensate (desalinated water) must be compressed to pressures required to discharge it from the power generating system. (Jung-In Yoon *et al* 2014) The evaporator, turbine, and condenser operate in partial vacuum ranging from 3 percent to 1 percent atmospheric pressure. This poses a number of practical concerns that must be addressed. First, the system must be carefully sealed to prevent in-leakage of atmospheric air that can severely degrade or shut down operation. (Chengdu Ahmad *et al* 2011) The specific volume of the low-pressure steam is very large compared to that of the pressurized working fluid used in closed cycle OTEC. This means that components must have large flow areas to ensure that steam velocities do not attain excessively high values. (Ayub kazim *et al* 2005). Finally, gases such as oxygen, nitrogen and carbon dioxide that are dissolved in sea water come out of solution in a vacuum. These gases are un-condensable and must be exhausted from the system.

From the working cycle explained above Flash evaporation is a distinguishing feature of open cycle OTEC. Flash evaporation involves complex heat and mass transfer processes. In the configuration tested by a team lead by the author, warm seawater was pumped into a chamber through spouts designed to maximize the heat-and-mass- transfer surface area by producing a spray of the liquid. The pressure in the chamber (2.6 percent of atmospheric) was less than the saturation pressure of the warm seawater. Exposed to this low-pressure environment, water in the spray began to boil. As in thermal desalination plants, the vapour produced was relatively pure steam. As steam is generated, it carries away(Chengdu Ahmad *et al* 2011) with it its heat of vaporization. This energy comes from the liquid phase and results in a lowering of the liquid temperature and the cessation of boiling. Thus, as mentioned above, flash evaporation may be seen as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized to become the working fluid. Approximately 0.5 percent of the mass of warm seawater entering the evaporator is converted into steam.(Chengdu Ahmad *et al* 2011) A large turbine is required to accommodate the huge volumetric flow rates of low-pressure steam needed to generate any practical amount of electrical power. Although existing technology limits the power generation by a single turbine module, comprising a pair of rotors, to about 2.5 MW. Unless significant effort is invested to develop new, specialized turbines (which may employ fiber-reinforced plastic blades in rotors having diameters in excess of 100 m), increasing the gross power generating capacity of a Claude cycle plant above 2.5 MW. After producing power the steam proceeds for Condensation, the condensation of low-pressure working fluid leaving the turbine occurs by heat transfer to the cold seawater. This heat transfer may occur in a DCC, in which the seawater is sprayed directly over the vapour, or in a surface condenser that does not allow contact between the coolant and the condensate.(Chengdu Ahmad *et al* 2011) This is how the power is produced in the open cycle OTEC system.

4.1.2 Closed-Cycle OTEC

(Chengdu Ahmad *et al* 2011)In closed-cycle OTEC, warm seawater heats a working fluid with a low boiling point, such as mentioned in Table 1, and those vapours turns a turbine, which drives a generator .The vapour is then condensed by the cold water and cycles back in the system.

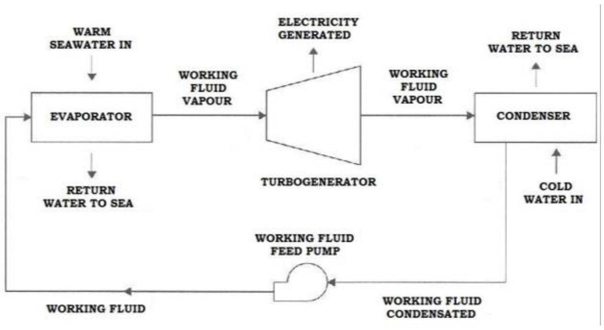


Fig. 11 Closed-Cycle OTEC

This cycle uses a working fluid with a low-boiling point, in a closed flow path (Takahashi and Trenka, 1996). The working fluid is pumped into the evaporator where it is vaporized and in turn moves a turbine. Closed-cycle plants operate on a Rankine cycle. The first stage of this cycle is referred to as isentropic expansion, which occurs in the steam turbine. Isobaric heat rejection in the condenser follows. This stage the water vapour becomes a liquid and therefore the entropy is decreased. The next stage is the isentropic compression in the pump. During this step, the temperature increases due to the higher pressure. The surface water then supplies isobaric heat causing the working fluid to vaporize. In an OTEC system the warm sea water is pumped into the evaporator where the refrigerant (fluid with low boiling point) would be pressurized. This pressure causes the refrigerant to boil or become vapour. This works due to the ideal gas law that states that the temperature is directly proportional to the pressure; therefore if the pressure increases then temperature increases too. The vaporised refrigerant then expands by travelling through a turbine. This turns the turbine making electricity.(Chengdu Ahmad *et al* 2011) The vapour pressure at the outlet of the turbine is higher than the cold seawater temperature, therefore the cold seawater is brought up from the depths where heat exchange occurs and the refrigerant vapour is changed back into a liquid. The liquid phase is then pressurized by a pump starting the cycle once again. Rankine cycles, in theory, are able to produce non-zero net power due to the fact that less energy is required to increase the pressure of a liquid phase than, when the same fluid is in vapour phase. It is for this reason that phase changes are essential when producing energy this way. This is how power is produced in closed-cycle OTEC system.(Chengdu Ahmad *et al* 2011)

4.2 Hydrogen production

(Ayub kazim *et al* 2005)To provide power produced in OTEC plant which are off-shore, situated in remote places, or we can say that to provide power from tropical oceans (i.e. where effective thermocline is available) to the regions which do not share their boundaries with sea, or the ocean body do not have effective thermocline to produce power (Ayub kazim *et al* 2005). Several means of energy transfer and delivery from the plants throughout the tropical oceans have been considered. OTEC energy can be transported by electrical, thermal, chemical and electrochemical carriers. The technical evaluation of non-electrical carriers leads to the consideration of Hydrogen, produced from electricity and desalinate water by electrolysis with OTEC technology. Unfortunately, the production cost of liquid hydrogen delivered to the harbour is very high. Presently the only energy carrier that is cost effective is submarine power cable. (Ayub kazim *et al* 2005)

Conclusion

The main conclusions can be summarized as follows:

1) Lower the temperature of cold seawater is, the higher the maximum net power is obtained.(Jung-In Yoon *et al* 2014)
2) It could be shown that the thermal efficiencies of the subcritical OTEC power cycle depend strongly on the evaporating and condensing temperatures, and turbine efficiencies.(Jung-In Yoon *et al* 2014)
3) Thermal efficiencies of the subcritical OTEC power cycle does not depend on superheating degrees and pump efficiencies. It is necessary to design the OTEC plant considering these effects. R717had the highest thermal efficiency among the wet fluid, and R22 showed the largest efficiency among the dry fluid. As for the iso-entropic fluid, R245fa provided the highest thermal efficiency.(Jung-In Yoon *et al* 2014)
4) For all of the fluid, R717 yielded the highest thermal efficiency. Although it is toxic, it is the most preferable for the subcritical OTEC power cycle. Despite the low thermal efficiency, R744 would provide fewer turbine production problems, because R744 offered the lowest vapor expansion ratio (VER) and suction specific volume ($v_{t,in}$). The fluid with high VER and $v_{t,in}$would result in supersonic flow problems, higher turbine size or greater number of stages. In addition,R744 is one of the most promising fluid for subcritical OTEC power cycle because it is environmentally friendly.(J. Yoon *et al*, 2014)
5) The regenerative Rankine cycle had the highest efficiency of all the cycles examined in this study. In addition, superheating and subcooling have little influence on the system performance and a temperature difference of at least 15 °C between the surface sea water and deep sea water is needed to generate generating electric power.(Jung-In Yoon *et al* 2014)
6) Superheating and sub-cooling have little influence on the system performance and a temperature difference of at least 15 °C between the surface sea water and deep sea water is needed to generate generating electric power.
7) In applications of OTEC system. Unfortunately, the production cost of liquid hydrogen delivered to the harbour is very high. Presently the only energy carrier that is cost effective is submarine power cable.
8) The technologies for OTEC still fairly new. Further research is needed on the environmental effects as well as economic feasibility of renewable ocean energy projects.

References

Rong-Hua Yeh, Tar- Zen Su, Min-Shong Yang(2005),Maximum output of an OTEC power plant *Ocean Engineering 32*.

Jung-In Yoon, Chang-Hyo Son,Seung-Moon Baek,Hyeon-Ju Kim, Ho-Saeng Lee (2014)Efficiency comparison of subcritical OTEC power cycle using various working fluids, *Heat Mass Transfer*

Chengdu,Ahmad Etemadi, ArashEmdadi, Orang Asef Afshar, YunusEmami (2011) Electricity Generation by the Ocean Thermal Energy,*Procedia 12*.

Ayub Kazim (2005) Hydrogen production through an ocean thermal energy conversion system operating at an optimum temperature drop*. Applied Thermal Engineering 25*.