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Analysis of Ocean Thermal Energy Conversion Power Plant using Isobutane as the Working Fluid

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Abstract

The use of organic isobutane will be investigated for a closed-cycle Ocean Thermal Energy Conversion (OTEC) on-shore plant that delivers 110 MW electric powers. This paper will cover concept, process, energy calculations, cost factoids and environmental aspects. In isobutane cycle, hot ocean surface water is used to vaporize and to superheat isobutane in a heat exchanger. Isobutane vapor then expands through a turbine to generate useful power. The exhaust vapor is condensed afterwards, using the cold deeper ocean water, and pumped to a heat exchanger to complete a cycle. Results show the major design characteristics and equipment's of the OTEC plant along with cycle efficiency and cycle improvement techniques.

Keywords: *Ocean Thermal Engineering Conversion (OTEC); isobutene; thermal plant; energy convergence.*

1. Introduction

Due to the sky-rocketing prices of the conventional energy sources (oil, coal and natural gas), along with its increased environmental impacts caused by combustion gases and polluting products; those conventional types are losing interest in the field of energy research and development. On the other hand, the renewable energy sources are gaining more and more interest to improve its utilization methods while minimizing costs and risks. The continuous volatility of petroleum price, the gradual decrease in the reserves of conventional energy resources, and the environmental problems created by the combustion of carbon based fuels, have placed great pressure on energy supplies to find solutions that cuts the energy bill, reduce the environmental impact of burning fossil fuel and improve the burning efficiency of the current combustion systems. Sustainable energy systems for power generation (solar PV and wind power or water free electrical power generation), and new alternative cooling systems for fossil and nuclear power plants are needed to reduce water consumption and CO2 emissions. A large amount of energy is also used and high CO2 emissions are produced to extract, supply, treat and use fresh water and for desalination plants [1].

Oceans cover 70% of the earth surface, forming the world's largest solar energy collector and energy storage system. On an average day, 60 million km^2 of tropical seas absorb an amount of solar radiation equal in heat content to about 250 billion barrels of oil [2]. The oceans are a vast renewable energy resource, with the potential to help produce billions of watts of electric power. The seawater used is also rich in nutrients and it can be used to culture both marine organisms and plant life near the shore or on land. Covering over 70% of the planet's area, the Earth's oceans could potentially be utilized as a source of virtually inexhaustible renewable energy. Ocean Thermal Energy Conversion (OTEC) is a method that employs naturally occurring temperature differences between warm surface water and colder deep ocean water. This technology was originally proposed by the French Engineer Jacques Arsene d'Arsonval in 1881.

As solar radiation strikes the surface of the ocean, it warms the uppermost layers of water. Depending on latitude, weather and time of year, surface temperatures may approach 80°F (26°C). Beneath the surface, at depths greater than about 1500 ft. (457 m), the water temperature approaches 40°F (4°C), since, at that temperature, water has its maximum density. This temperature is also relatively constant all around the year.

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This temperature gradient of about 20°C between warm surface water and deep cold water could be benefitual using an Ocean Thermal Energy Conversion (OTEC) system to produce a significant amount of electrical power. Concerns with efficiency losses due to biofouling, system power requirements and heat exchanging systems have led to exploration through case studies and analysis.

2. Literature Review, OTEC Technology

There are three main types of OTEC cycle designs: open cycle, closed cycle, and hybrid cycle. In an Open Cycle, seawater is the working fluid. Warm seawater is pumped into a flash evaporator where pressure as low as 0.03 bar cause the water to boil at temperatures of 22°C. This steam expands through a low-pressure turbine connected to a generator to create power. The steam then passes through a condenser using cold seawater from the depths of the ocean to condense the steam into desalinized water [3].

In a Closed Cycle, a low boiling point liquid such as ammonia, propane, isobutane or another type of refrigerant is used as the working fluid in a Rankin cycle (common steam cycle). The heat from warm seawater flowing through an evaporator vaporizes the working fluid. The vapor expands through a turbine, and then flows into a condenser where cold seawater condenses it into a liquid.

The closed OTEC cycle will be of interest in this study, and the isobutane working fluid will be analyzed to be used as working fluid. Actual designs of CC (Closed Cycle) OTEC use Ammonia as its working fluid while Isobutane is usually being used along with pentane in geothermal power plants.

A Hybrid Cycle combines the features of both the closed-cycle and open-cycle systems. In a hybrid OTEC system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, which is similar to the open-cycle evaporation process.

The steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer. The vaporized fluid then drives a turbine that produces electricity. The steam condenses within the heat exchanger and provides desalinated water.

OTEC system performance is related to the working fluid properties using good working fluid could generate a more efficient and cheaper plant [4].

Cycle efficiency was investigated by and it was found that higher cycle efficiency could be achieved using isobutane as working fluid. On the other side using isobutene is not recommended in closed-cycle OTEC system because the inlet stable operating turbine pressure is in a very narrow range [6].

In this paper, a case study of design of a 110 MW thermal power plant using isobutane as working fluid showing that the inlet turbine pressure is in the optimum range to reach better cycle efficiency.

2.1. Other Uses for OTEC Technology

OTEC systems not only produce electricity; it can also tackle many other uses in different fields, some of which can be listed as:

A. Fresh water production

The rapid industrial growth and the population explosion all over the world have resulted in the problem of pollution of rivers and lakes by industrial wastes and the large amounts of sewage discharged. On a global scale, man-made pollution of natural sources of water is becoming the single largest cause for fresh water shortage. The only nearly inexhaustible sources of water are the oceans and seas. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water [5].

Desalination is just one of the effective potential products that could be produced via OTEC technology. Fresh water can be produced in open-cycle OTEC plants when the warm water is vaporized to turn the low pressure turbine [7]. Once the electricity is produced the water vapor is condensed to make fresh water. This water has been found to be purer than water offered by most communities as well it is estimated that 1 MW plant could produce 45 m^3 of water per second.

B. Air conditioning and Refrigeration

Once cold water pipes are installed for an OTEC power plant, the cold water being pumped to the surface can be used for other than being the working fluid for the condenser. One of these uses is air conditioning and refrigeration. Cold water can be used to circulate through space heat exchangers or can be used to cool the working fluid within heat exchangers. This technology can be applied for hotel and home air conditioning as well as for refrigeration schemes.

C. Aquaculture and Mari-culture

Another possibility for taking advantage of OTEC plants is the use of the water pipes to harvest marine plants and animals for the purpose of food [8]. This proposition is still under investigation.

D. Coldwater Agriculture

As coastal areas suitable for OTEC are in tropic regions, there is a potential to increase the overall food diversity within an area using the cold water originating from the deep ocean. It has been proposed that burying a network of cold-water pipes underground the temperature of the ground would be ideal for spring type crops like strawberries and other plants restricted to cooler climates.

2.2. Main Characteristics of Isobutane C_4H_{10}

Isobutane C_4H_{10}, also known as methylpropane, is an alkane with four carbons originally called Butane [9]. Alkanes are chains of carbon atoms where each carbon atom has as many hydrogen atoms attached as possible. This means that all of the bonds between carbon atoms are single bonds (no double bonds). Such a molecule is said to be saturated.

Butane has also four carbons, and the form with one carbon in the middle is called isobutane. The iso is short for isomer, which means a molecule with the same atoms, but arranged in a different way.

Isobutane is a Colorless, odorless gas used mainly in lighters and camp stoves as a fuel. It is easily liquefied under pressure, and the liquid becomes a gas immediately when the pressure is released. Isobutane is also used as a propellant in some hair sprays and in spray breath fresheners.

When used as a refrigerant, dry isobutane (also called R-600a, which is a commercial term used to describe isobutane mixtures) has negligible ozone depletion potential and very low Global Warming Potential. It can serve as a good replacement for R-12, R-22, R-134a, and other chloro-fluoro-carbon or hydro-fluoro-carbon refrigerants in most conventional-stationary refrigeration and air conditioning systems. Main properties for isobutene are presented in table 1.

Table 1. Isobutane Properties [9].

Molecular Weight:	58.123 g/mol
Solid phase:	Latent heat of fusion (1,013 bar, at triple point) : 78.115 kJ/kg
Liquid phase:	Liquid density (1.013 bar at boiling point) : 593.4 kg/m^3
	Liquid/gas equivalent (1.013 bar and 15 °C (59 °F)) : 236 vol/vol
	Boiling point (1.013 bar) : -11.7 °C
Critical point:	Critical temperature : 134.9 °C
	Critical pressure : 36.48 bar
Gaseous phase:	Gas density (1.013 bar at boiling point) : 2.82 kg/m^3
	Gas density (1.013 bar and 15 °C (59 °F)) : 2.51 kg/m^3
	Compressibility Factor (z) (1.013 bar and 15 °C (59 °F)) : 0.9675
	Specific gravity (air = 1) (1.013 bar and 21 °C (70 °F)) : 2
	Specific volume (1.013 bar and 21 °C (70 °F)) : 0.406 m^3/kg
	Heat capacity at fixed P (C_p) (1.013 bar and 15 °C (59 °F)) : 0.095 kJ/(mol.K)
	Heat capacity at fixed V (C_v) (1.013 bar and 15 °C (59 °F)) : 0.086 kJ/(mol.K)
	Ratio of specific heats (γ: C_p/C_v) (1.013 bar and 15 °C (59 °F)) : 1.095845
	Viscosity (1.013 bar and 0 °C (32 °F)) : 0.0000689 Poise
	Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 13.97 mW/(m.K)
Miscellaneous:	Solubility in water (1.013 bar and 20 °C (68 °F)) : 0.0325 vol (isobutane)/vol(water)
	Auto-ignition temperature : 460 °C

2.3. Basic Design Assumptions

After going through several OTEC systems and isobutane-operated cycles from different references in the literature review, the following assumptions were made to insure highest power output with lowest heat input. Those assumptions, which were accomplished after intensive isobutane-property reviewing at different pressures and temperatures, started from the turbine-side where the turbine inlet and outlet temperatures and pressures had to be determined, and then remaining conditions were extended by calculations to the condenser, evaporator and pump. The following Fig.1 shows the major cycle components with required data about cycle states and equipment specifications.

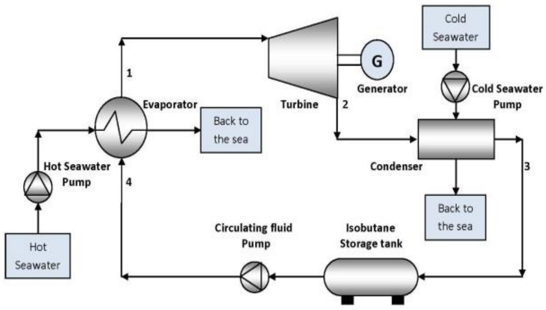

Fig. 1. General Plant Layout

Following are briefed calculations for the design of OTEC plant cycle, those calculations were made for a single sub-plant, and it can be applied for every single sub-plants. The properties of isobutane were taken from its saturation and superheated property tables in [9].

Table 2. Assumptions used in this paper.

General:	110 MW (Net Power Output) OTEC Plant of 24 sub-plants
	Working Fluid: Isobutane C4H10
	Generator Efficiency (η_g): 98%
	Mechanical Efficiency (η_m): 95%
	Isentropic Efficiency (η_s): 97%
Turbine:	Efficiency (η_T): 97%
	Inlet Temperature T_i : 24˚C
	Inlet Pressure P_i : 338.1 kPa (Tables in Appendix at T=24˚C)
	Outlet Pressure P_o : 200 kPa
	Outlet Temperature T_o :18.53˚C (Tables in Appendix at So=Si* η_s)
Shell & Tube Evaporator:	Warm Ocean Water Conditions:
	Depth = 20 m
	Water Inlet Temperature (T_{Win}): 23˚C
	Water Outlet Temperature (T_{Wout}): 20˚C
	Water Specific Heat (C_p) at 25˚C: 4.18 kJ/kg.K
	Heat Transfer Material: Red Brass (85 Cu - 15 Zn) (159 W/m˚C)
	Heat Transfer Thickness: 1 mm
Shell & Tube Condenser:	Cold Ocean Water Conditions:
	Depth = 800 m
	Water Inlet Temperature (T_{Win}): 4˚C
	Water Outlet Temperature (T_{Wout}): 8˚C
	Water Specific Heat (C_p) at 5˚C: 4.18 kJ/kg.K
	Heat Transfer Material: Red Brass (85 Cu - 15 Zn) (159 W/m,˚C)
	Heat Transfer Thickness: 1 mm
Working Fluid Circulating Pump:	Pump Type: Centrifugal
	Pump Efficiency (η_p): 85%
Ocean Water Pump:	Pump Type: Submersible
	Pump Efficiency (η_p): 90%

Assumptions presented in table 2 are based on performance data of vendors and previous experience of the study for geothermal projects that uses isobutane as working fluid [10].

3. Design Calculations and Analysis

3.1.1 Rankin Cycle Analysis:

State1: Saturated Isobutane Gas at Turbine Inlet/Evaporator Outlet

$$T_1 = 24\ ℃ \qquad P_1 = 338.1\ kPa$$

$$h_1 = h_{g@T_1} = 466\ kJ/kg$$

$$s_1 = s_{g@T_1} = 1.623\ kJ/kg.K$$

State2: Superheated Isobutane Gas at Turbine Outlet/Condenser Inlet

$$P_2 = 200\ kPa$$

Table 3. Interpolating table [10].

Pressure 200 kPa	Superheated T(℃)	Superheated T(℃)	Superheated T(℃)
	10	18.53	20
S (kJ/kg.K)	1.631	1.6731	1.689
h (kJ/kg)	448.3	448.99	465.3

$$T_2 = 18.53\ ℃$$

$$s_2 = {}^{s_1}/_{\eta_s} = {}^{1.623}/_{0.97} = 1.6731\ kJ/kg.K$$

$$h_{2@s_2} = 449\ kJ/kg$$

State3: Saturated Isobutane Liquid at Condenser Outlet/Pump Inlet

$$P_3 = P_2 = 200\ kPa$$

Table 4. Interpolating table [10].

Saturation T(℃)	Saturation P (kPa)	h_f (kJ/kg)	S_f (kJ/kg.K)	v_f (m^3/kg)
6	192.2	96.15	0.3746	0.001745
7.18	200	**98.9**	**0.3843**	**0.00175**
8	205.4	100.8	0.391	0.001752

$$T_3 = T_{saturation@P_3} = 7.18\ ℃$$

$$h_3 = h_{f@T_3} = 98.9\ kJ/kg$$

$$s_3 = s_{f@T_3} = 0.3843\ kJ/kg.K$$

$$v_3 = v_{f@T_3} = 0.00175\ m^3/kg$$

State4: Sub cooled Isobutane Liquid at Pump Outlet/Evaporator Inlet

$$P_4 = P_1 = 338.1\ kPa$$

$$v_4 = v_3 = 0.00175\ m^3/kg$$

$$h_4 \approx h_{f@24℃} = 137.5\ kJ/kg$$

3.1.2 Turbine Heat and Work Analysis:

The total plant power must compensate for the mechanical, electrical and turbine losses. Therefore, the total power to be produced and that divided upon the 24 sub-plants' turbines can be calculated as:

$$W_{Total} = \frac{W_{net}}{\eta_m \times \eta_g \times \eta_T} = \frac{110\ MW}{0.95 \times 0.98 \times 0.97} = 121.8\ MW W_{Turbine} = \frac{W_{Total}}{24} = 5.075\ MW$$

To calculate the mass flow rate of Isobutane to be used in each turbine, inlet and outlet states for the turbines can be used as follows:

$$W_{Turbine} = \dot{m}_{isobutane} \times (h_2 - h_1)$$

Then:

$$\dot{m}_{isobutane} = \frac{W_{Turbine}}{(h_1 - h_2)} = \frac{5.075 \times 10^3}{(466 - 449)} = 298.5\ kg/s$$

3.1.3 Evaporator Analysis:

The mass flow of surface-warm ocean water can be calculated by heat-balancing the evaporator knowing the inlet and outlet conditions of Isobutane and water:

$$\dot{m}_{warm\ water} \times C_{P_{warm\ water}} \times \Delta T_{warm\ water} = \dot{m}_{isobutane} \times q_{in}$$

The heat input of Isobutane within is the latent heat of vaporization at T=24˚C represented by:

$$q_{in} = h_{fg@24℃} = 328.5\ kJ/kg$$

Accordingly:

$$\dot{m}_{warm\ water} = \frac{\dot{m}_{isobutane} \times q_{in}}{C_{P_{warm\ water}} \times \Delta T_{warm\ water}} = \frac{298.5 \times 328.5}{4.18 \times (23 - 20)}$$

$$\dot{m}_{warm\ water} = 7819.6\ kg/s$$

Different designs have been proposed for OTEC heat exchangers. The most common type is the shell-and-tube with warm (or cold) ocean water inside the tubes and the evaporating (or condensing) Isobutane on the shell side.

Heat flow rate in the heat exchangers may be decreased due to several factors such as biofouling. Therefore, to maintain the desired quantity of heat transferred, a larger design value of $UA/\dot{m}C_p$ is preferable because biofouling can be countered with a smaller increase in water flow rate [3].

The heat transfer material was selected to be Red Brass alloy that consists of 85% Cu and 15% Zn and has a U-value of 159 W/m.˚C [11]. The red brass has lower relative costs with good heat transfer and antifouling characteristics. Other suggestions for heat transfer material have been proposed later on as an efficiency-improving measure.

The heat transfer area Ah (Assumed to be flat) of the evaporator can be calculated knowing the Log Mean

Temperature Difference (LMTD), heat added to Isobutane, thickness of heat transfers material t_h and the thermal conductivity for the heat transfer material:

$$\Delta T_1 = T_{in,isobutane} - T_{out,water} = 24 - 20 = 4$$

$$\Delta T_2 = T_{out,isobutane} - T_{in,water} = 24 - 23 = 1$$

$$\Delta T_{LM} = \frac{\Delta T_1 + \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} = \frac{4+1}{\ln(\frac{4}{1})} = 3.6$$

$$A_h = \frac{t_h \times Q_{in}}{U_{brass} \times \Delta T_{LM}}$$

$$= \frac{1 \times 10^{-3} \times 328.5 \times 298.5}{159 \times 10^{-3} \times 3.6} \approx 171.3\ m^2\ per\ evaporator$$

3.1.4 Condenser Analysis:

The mass flow of deep-cold ocean water can be calculated by heat-balancing the condenser knowing the inlet and outlet conditions of Isobutane and water:

$$\dot{m}_{cold\ water} \times C_{P_{cold\ water}} \times \Delta T_{cold\ water} = \dot{m}_{isobutane} \times q_{out}$$

The heat output of Isobutane within the condenser is calculated by:

$$q_{out} = h_2 - h_3 = 449 - 98.9 = 400.1\ kJ/kg$$

Accordingly:

$$\dot{m}_{cold\ water} = \frac{\dot{m}_{isobutane} \times q_{out}}{C_{P_{cold\ water}} \times \Delta T_{cold\ water}} = \frac{298.5 \times 400.1}{4.18 \times (8-4)}$$

$$\dot{m}_{cold\ water} = 7142.9\ \ kg/s$$

The heat transfer area Ah of the condenser can be calculated knowing the Log Mean Temperature Difference (LMTD), heat removed from Isobutane, thickness of heat transfer material t_h and the thermal conductivity for the heat transfer material:

$$\Delta T_1 = T_{in,isobutane} - T_{out,water} = 18.53 - 8 = 10.53$$

$$\Delta T_2 = T_{out,isobutane} - T_{in,water} = 7.18 - 4 = 3.18$$

$$\Delta T_{LM} = \frac{\Delta T_1 + \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} = \frac{10.53 + 3.18}{\ln(\frac{10.53}{3.18})} = 5.24$$

$$A_h = \frac{t_h \times Q_{out}}{U_{brass} \times \Delta T_{LM}}$$

$$= \frac{1 \times 10^{-3} \times 400.1 \times 298.5}{159 \times 10^{-3} \times 5.24} \approx 143.4\ \ m^2\ per\ condenser$$

Condenser's heat exchanger is assumed to have the same construction as the evaporator, namely of the shell-and-tube type with Red Brass.

3.1.5 Working Fluid (Isobutane) Pump Analysis

Pump work is the only work input to this cycle, and its theoretical value can be estimated as follows:

$$W_{pump,theo} = \dot{m}_{isobutane} \times v_3 \times \Delta P$$

$$= 298.5 \times 0.00175 \times (338.1 - 200)$$

$$W_{pump,theo} = 72.14\ kW\ per\ pump$$

The actual pump work can be calculated knowing the pump assumed efficiency:

$$W_{pump,act} = \frac{W_{pump,theo}}{\eta_p} = \frac{72.14}{0.85}$$

$$= 84.9\ kW\ rated\ per\ pump$$

The type of working fluid pump more likely to be selected is the centrifugal pump which is a dynamic pump. A centrifugal pump raises the pressure of the liquid by giving it a high kinetic energy and then converting that kinetic energy to work. It normally consists of an impeller (a wheel with blades), and some form of housing with a central inlet and a peripheral outlet. The centrifugal pumps are to be equipped with special seal kits appropriate to the nature of liquid-state isobutane.

3.1.6 Cycle Efficiency:

The maximum cycle efficiency can be calculated using Carnot Efficiency as follows:

$$\eta_{carnot} = \left(1 - \frac{T_{Low}}{T_{High}}\right) \times 100\%$$

$$= \left(1 - \frac{7.18 + 273.15}{24 + 273.15}\right) \times 100\% = 5.7\%$$

The actual cycle efficiency for the whole OTEC plant can be calculated through the following formula:

$$\eta_{cycle} = \left(\frac{W_{net}}{Q_{in}}\right) \times 100\%$$

$$= \left(\frac{5075 - 72.14}{298.5 \times 328.5}\right) \times 100\% = 5.1\%$$

This efficiency seems to be very low but remains inside the normal Rankin Cycle range of Isobutane [12]; therefore, efficiency increase measures should be implemented.

3.1.7 Ocean Warm Water Pump Analysis:

The selection of water pumps depends on the required water flow rate along with the associated manometric head, single pump will be operated for the whole plant with 24 sub-plants, which needs total mass and volume flow rates of warm water.

Density of Ocean Water (ρ_{ocean}) is assumed to be 1.025 g/ml, which is denser than both fresh water and pure water both having density of 1.0 g/ml @ 4 °C. The reason behind that is due to dissolved salts that add mass without contributing significantly to the volume.

The calculated total mass and volume flow rates of warm water are:

$$\dot{m}_{warm\ water} = 4691.7 \times 24 \cong 112600.8\ \ kg/s$$

$$\dot{V}_{warm\ water} = \dot{m}_{warm\ water}/\rho_{ocean\ water}$$

$$= (112600.8/1.025\ ) \times 10^{-3}$$

$$\dot{V}_{warm\ water} \cong\ 112.3\ m^3/s$$

The Associated manometric head of 20 m should be corrected to compensate for miscellaneous pressure losses; an equivalent head of 21 m is to be used for pump selection.

A submersible pump is most appropriate to be selected for this purpose. It has a hermetically sealed motor close-coupled to the pump body. The whole assembly is submerged in the ocean water to be pumped. The main advantage of this type of pump is that it prevents pump cavitation, a problem associated with a high elevation difference between pump and the water surface.

3.1.8 Ocean Cold Water Pump Analysis:

Selecting the deep-cold ocean water pump has the same procedures as warm-water pump, and the variations in ocean water density are to be neglected. Total mass and volume flow rates are:

$$\dot{m}_{cold\ water} = 7142.9 \times 24 \cong 171430\ \ kg/s$$

$$\dot{V}_{cold\ water} = \dot{m}_{cold\ water}/\rho_{ocean\ water}$$

$$= (171430/1.025) \times 10^{-3}$$

$$\dot{V}_{cold\ water} \cong\ 167.2\ m^3/s$$

The Associated manometric head of 800 m should be corrected to compensate for miscellaneous pressure losses; an equivalent head of 850 m is to be used for pump selection. A submersible pump would also be recommended for cold-water pumping.

3.1.9 Heat and Mass Balance:

In this section, mass and heat balance will be conducted separately for each component of the OTEC cycle, the following analysis was conducted for a single sub-plant, and it also applies for all others:

Evaporator:

Mass Balance:

$$\dot{m}_{w\ in} + \dot{m}_{isobutane\ \ in} = \dot{m}_{wout} + \dot{m}_{isobutane\ out}$$

$$(4691.7 + 298.5)\ \mathrm{kg/s} = (4691.7 + 298.5)\ \mathrm{kg/s}$$

Energy Balance:

$$\dot{m}_{w\ in} C_p T_1 + \dot{m}_{isobutane\ in} h_4$$

$$= \dot{m}_{w\ out} C_p T_2 + \dot{m}_{isobutane\ out} h_1 + Q_{loss}$$

$$(4691.7 \times 4.18 \times 296.15 + 298.5 \times 137.5) kW$$

$$= (4691.7 \times 4.18 \times 293.15 + 298.5 \times 466) + Q_{loss}\ kW$$

$$5849\ MW = 5825 + Q_{loss}\ MW$$

$$Q_{loss} = 24\ MW$$

Turbine:

Mass Balance:

$$\dot{m}_{isobutane\ \ in} = \dot{m}_{isobutane\ out}$$

$$298.5\ kg/s = 298.5\ kg/s$$

Energy Balance:

$$\dot{m}_{isobutane\ in} h_1 = \dot{m}_{isobutane\ out} h_2 + W_{out}$$

$$(298.5 \times 466)\ kW = (298.5\ \times 449 + 5075)\ kW$$

$$139.1\ MW = 139.1\ MW$$

Condenser:

Mass Balance:

$$\dot{m}_{w\ in} + \dot{m}_{isobutane\ \ in} = \dot{m}_{wout} + \dot{m}_{isobutane\ out}$$

$$(7142.9 + 298.5)\ kg/s = (7142.9 + 298.5)\ kg/s$$

Energy Balance:

$$\dot{m}_{w\ in} C_p T_1 + \dot{m}_{isobutane\ in} h_2$$

$$= \dot{m}_{w\ out} C_p T_2 + \dot{m}_{isobutane\ out} h_3$$

$$(7142.9 \times 4.18 \times 277.15 + 298.5 \times 449) + Q_{loss}\ kW$$

$$= (7142.9 \times 4.18 \times 281.15 + 298.5 \times 98.9)\ kW$$

$$8409\ MW + Q_{loss}\ = 8424\ MW$$

$$Q_{loss} = 15\ MW$$

Circulating Pump:

Mass Balance:

$$\dot{m}_{isobutane\ \ in} = \dot{m}_{isobutane\ out}$$

$$298.5\ kg/s = 298.5\ kg/s$$

Energy Balance:

$$W_{in} + \dot{m}_{isobutane\ in} h_3 = \dot{m}_{isobutane\ out} h_4$$

$$(72.14 + 298.5 \times 98.9)\ kW =$$

$$\left(298.5\ \times 137.5 + Q_{in\ Sensible\ from\ subcooled\ to\ saturated\ @\ 24℃}\right)\ kW$$

$$92.6\ MW = 41 + Q_{in\ Sensible\ from\ subcooled\ to\ saturated\ @\ 24℃}\ MW$$

$$Q_{in\ Sensible\ from\ subcooled\ to\ saturated\ @\ 24℃} = 51\ MW$$

3.2 The Overall Mass and Energy Balance:

For the whole OTEC sub-plant cycle can be performed as follows:

3.2.1 Overall Mass Balance:

$$\dot{\mathrm{m}}_{\mathrm{cold\ water\ in}} + \dot{\mathrm{m}}_{\mathrm{warm\ water\ in}} = \dot{\mathrm{m}}_{\mathrm{cold\ water\ out}} + \dot{\mathrm{m}}_{\mathrm{warm\ water\ out}}$$

$$(7142.9 + 4691.7)\ kg/s = (7142.9 + 4691.7)\ kg/s$$

3.2.2 Overall Energy Balance:

$$\mathrm{W_{pump}} + \dot{\mathrm{m}}_{\mathrm{cw\,in}}\mathrm{C_p T_{1cw}} + \dot{\mathrm{m}}_{\mathrm{ww\,in}}\mathrm{C_p T_{1ww}}$$

$$= \mathrm{W_{turbine}} + \dot{\mathrm{m}}_{\mathrm{cw\,out}}\mathrm{C_p T_{2cw}} + \dot{\mathrm{m}}_{\mathrm{ww\,out}}\mathrm{C_p T_{2ww}}$$

$$\{72.14 + (7142.9 \times 277.15 + 4691.7 \times 297.15) \times 4.18\}\ kW$$

$$= \{5075 + (7142.9 \times 281.15 + 4691.7 \times 293.15) \times 4.18\}\ kW$$

$$14.1485\ GW = 14.1485\ GW$$

3.3 Efficiency Improving Methods

Following are some suggested measures to improve the cycle efficiency:

3.3.1 The Use of better heat transfer material with higher U-value.

By increasing the U-value would result in decreasing the heat transfer area with improving the heat transfer characteristics through easier and more efficient heat transfer [13].

On the other hand, selection of such material would require additional cost, and the selected material would have less antifouling characteristics, both of which should be carefully studied during selection analysis.

Suggestions for such heat transfer material would be Copper (401 W/m.K) and Aluminum (250 W/m.K) [11].

3.3.2 The Use of Reheat-Regenerative Rankin Cycle.

One of the very common improvements in real power plants on Rankin Cycle is the Reheat-Regenerative Rankin Cycle [13].

For the Reheat process, two turbines work in series. The first accepts isobutane vapor from the evaporator at high pressure. After the vapor has passed through the first turbine, it re-enters the evaporator and is reheated before passing through a second, lower pressure turbine. Among other advantages, this prevents the vapor from condensing during its expansion which can seriously damage the turbine blades, and improves the efficiency of the cycle, as more of the heat flow into the cycle occurs at higher temperature.

The regenerative features here effectively raise the nominal cycle heat input temperature, by reducing the addition of heat from the evaporator at the relatively low feed-water temperatures that would exist without regenerative feed-water heating. This improves the efficiency of the cycle, as more of the heat flow into the cycle occurs at higher temperature.

3.3.3 Decrease Tout of warm water (or Increase Tout of cold water).

Decreasing the warm water discharge temperature (or increasing the cold water discharge temperature) results in a lower warm water (or cold water) flow per unit working fluid flow [13], and hence in lower water pumping provisions.

On the other hand, this would decrease the log mean temperature difference (LMTD) in the evaporator (or condenser) and hence increases the heat exchanger size which will be costly. Therefore, a compromise between water pumping provisions and heat transfer equipment should be performed.

4. Environmental Impacts of OTEC Plants

OTEC technologies have many potential benefits to the environment as it is a source of clean, renewable energy and harnesses the ocean water for electricity generation which is an abundant and is almost unlimited.

The use of OTEC also ensures reliable constant power output that is not dependent on certain climate conditions [14]. OTEC does not discharge any CO_2, and mixing the deep water with the upper layers of the ocean actually helps to grow phytoplankton, algae and coal which may lead to an increase on CO_2 fixation.

Environmental concerns associated with OTEC systems have been brought up. One major concern is with the closed-loop and hybrid systems that depend on a low boiling point working fluid (Isobutane or Ammonia) in heat exchangers [14]. These potentially harmful substances could leak into the ocean if the pipes were ever damaged.

Another problem would be the habitat disruption in the ocean due to the installation of the pipes [15]. Although OTEC does present potential issues that may be negative to the environment, with proper designing, research and care the negative impacts can be reduced or avoided.

5. Conclusions

The basic design considerations were discussed for an OTEC power plant to produce 110 MW of electrical power using isobutane as a working fluid. Detailed calculations for heat flow and material flow rates were performed and actual equipment were suggested for real implementation.

Overall results showed in table 5 represents total values for the whole suggested OTEC plant (consisting of the combined 24 sub-plants each with separate evaporator, turbine, condenser and circulating pump).

Table 5. Results Summary for Isobutane 110 MW OTEC Power Plant.

Perimeter	
Output Work	121.8 MW
Isobutane Mass Flow Rate (Total)	7164 kg/s
Warm Water Volume Flow Rate (Total)	112.3 m^3/s
Cold Water Volume Flow Rate (Total)	167.2 m^3/s
Isobutane Pump Work (24 pumps Total)	1.73 MW
Cycle Efficiency	5.1%

Results presented in this paper agrees with [5] that the use of isobutene as a working fluid in the OTEC power plant help in achieving high cycle efficiency and provide actual equipment suggestion for real implementation to avoid isobutene narrow range of stable inlet pressure to the turbine [5].

Nomenclature

iso	isomer
P	Pressure, kPa, bar
T	Temperature, ˚C, K
C_p	Specific heat at constant pressure, kJ/kg.K
C_v	Specific heat at constant volume, kJ/kg.K
T_i	Inlet temperature, ˚C
T_o	Outlet temperature, ˚C
P_i	Inlet pressure, kPa
P_o	Outlet pressure, kPa
T_{Win}	Water inlet temperature, ˚C
T_{Wout}	Water outlet temperature, ˚C
s	Specific entropy, kJ/kg.K
h	Specific enthalpy, kJ/kg
v	Specific volume, m^3/kg
W_{total}	Total plant power, W
$W_{pump,\ theo}$	Theoretical pump work, W
$W_{pump,\ act}$	Actual pump work, W
W_{net}	Net plant power, W
$\dot{m}_{isobutane}$	Mass flow rate for isobutene, kg/s
$\dot{m}_{warm\ water}$	Mass flow rate of warm ocean water, kg/s
$\dot{m}_{cold\ water}$	Mass flow rate of deep-cold ocean water, kg/s
q_{in}	Heat input of isobutane, kj/kg
q_{out}	Heat output of isobutane, kj/kg
A_h	Heat transfer area, m^2
t_h	Thickness of heat transfer material, mm
U	Overall heat-transfer coefficient, W/m.˚C
$\dot{V}_{warm\ water}$	Volume flow rate of warm water, m^3/s
$\dot{V}_{cold\ water}$	Volume flow rate of cold ocean water, m^3/s
Q_{loss}	Heat loss, W

Greek Symbols

η_g	Generator efficiency, %
η_m	Mechanical efficiency, %
η_s	Isentropic efficiency, %
η_T	Thermal efficiency, %
η_{carnot}	Carnot efficiency, %
η_{cycle}	Actual cycle efficiency, %
η_p	Pump efficiency, %
ρ_{ocean}	Density of ocean water, kg/m^3
γ	Ratio of specific heats

Subscripts

1	Turbine inlet, evaporator outlet
2	Turbine outlet, condenser inlet
3	Condenser outlet, pump inlet
4	Pump outlet, evaporator inlet

Abbreviations

OTEC	Ocean Thermal Energy Conversion
CC	Closed Cycle
LMTD	Log Mean Temperature Difference
O&M	Operations and Maintenance

Non-dimensional Numbers

z	Compressibility Factor

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