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Modeling of Hydrogen Production through an Ocean Thermal Energy Conversion System

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Abstract*— *OTEC (Ocean Thermal Energy Conversion) is one of the renewable energy technologies that convert solar radiation to electric power through different process. OTEC systems use the ocean's natural thermal gradient to drive a power producing cycle. The oceans are thus a vast renewable resource, with the potential to help us produce billions of watts of electric power. The cold, deep seawater used in the OTEC process is also rich in nutrients, and it can be used to culture both marine organisms and plant life near the shore or on land. The temperature gradient between the depths of ocean surfaces plays a major role in power generation. This power can be used for the production of hydrogen which is stored as fuel cells. In this paper, the OTEC System along with PEM electrolyser has been analyzed. The mathematical modeling of Poly Electrolyte Membrane Electrolyser coupled with OTEC has been carried out. The Ideal Power Input,

Actual Power Input, Ideal Power Output, Actual Power Output, Ideal Conversion Efficiency, Actual Conversion Efficiency, Ideal Rate of Hydrogen Production and Actual Rate of Hydrogen Production outputs for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C) have been reported.

Index Terms*—*OTEC, PEM, Hydrogen Production, Ocean Energy.

I. INTRODUCTION

The ocean thermal energy concept was proposed as early as 1881 by the French physicist Jacques d' Arsonoval. The sun continuously heats the oceans, maintaining the surface water at temperatures significantly higher than those of the deep water. The thermal energy of the warm water is constantly renewed by solar radiation and can be drawn upon day and night. When compared with conventional power plants, the OTEC plant requires considerably larger heat exchangers because the available temperature differences are small. It is an economical potential source and pollution-free electricity is produced with a cycle efficiency of about 2 to 3 percent. The possible work output of the system is proportional to the temperature drop across the turbine.

The two different methods for harnessing Ocean Thermal Energy are.

1. Open cycle or Claude cycle,
2. Closed cycle system or Anderson cycle.

A. Open Cycle OTEC System (Claude Cycle)

The Claude cycle or open cycle utilizes the sea water as the working fluid which is flashed evaporated under a partial vacuum.

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The low pressure steam is passed through a turbine for energy conversion and the spent vapor is sent to the condenser to be cooled. This cycle derives the open cycle as the condensate is flushed instead of being returned to the evaporator, as in the case of the closed cycle. However, the condensate can be utilized to produce desalinated water using a surface condenser or a spray condenser. The condensate is further mixed with cooling water and the mixture is discharged back into the ocean. In the open cycle process, the low energy content of the low pressure steam requires huge turbines or several smaller units operating in parallel mode in order to achieve a sizeable electric power output. Huge quantities of ocean water and high volume flow rates are required in open OTEC systems. In addition, more degasifiers (deaerators) are required to remove the gases dissolved in the sea water.

B. Closed Cycle OTEC System (Anderson Cycle)

The closed cycle was first proposed by Barjot in 1926, but the most recent design was proposed by Anderson in 1960. Hence the modified closed cycle is also called as Anderson cycle. In this cycle normally, propane is chosen as a working fluid. The temperature difference between warm surface and cool surface is maintained around 20°C. The cold water is pumped from oceans deeper than 600 m. Propane is vaporized in the boiler or evaporator at about 10 kg/cm^2 (10 bar) or more and exhausted in the condenser at about 5 bar. In the closed cycle system, a liquid working fluid, such as ammonia or propane, is vaporized in an evaporator (or boiler); the heat required for vaporization is transferred from the warm ocean surface to the liquid by means of a heat exchanger. The high pressure vapor leaving the evaporator drives an expansion turbine. The turbine is connected to an electric generator for power generation. The low pressure exhaust from the turbine is cooled and converted back into liquid using the condenser. The cooling is achieved by passing cold, deep ocean water, from a depth of 700 to 900m or more, through a heat exchanger. The liquid working fluid is then pumped back as high pressure liquid to the evaporator, thus closing the cycle.

C. Polymer Electrolyte Membrane

Electrolyzer converts abundant chemicals into more valuable ones by the passage of electricity, normally by breaking down compounds into elements or simpler products. Electrolysis of liquid water [H_2O] into hydrogen gas [H_2] and oxygen gas [O_2] is the classic example of electrochemistry. The reason for producing H_2 from electricity which of course consumes energy is to create a form of energy storage useful for indefinite or long time-scales. As necessary storage time increases, the more superior economy of chemical storage compensates for this energy expenditure. The PEM electrolyzer efficiency is a function primarily of membrane and electro-catalyst performance.

This becomes crucial under high-current operation, which is necessary for industrial-scale application.

II. LITERATURE SURVEY

Abrahim Law and Gay Heit Lavi [1] carried out a study on social and environmental issues of OTEC and concluded that the economic, social and environmental issues are pertinent to the commercialization of OTEC. Also technical problems in certain locations can be solved by priori assumptions and OTEC can be competitive with conventional base-load power systems. Ayoub Kazim [2] technically analyzed the hydrogen production through OTEC coupled with PEM electrolyser and inferred that hydrogen production increases with temperature difference. Chakwat and Ridgway [3] studied about the implementation Mist-Lift concept for the generation of power from thermal gradients in warm oceans. He concluded that the concept uses open cycle to operate on the ambient sea-water using state-of-the-art hydraulic turbines. Chih Wu [4] carried out a study on performance bound for real OTEC heat engines and concluded that the evaluation of existing OTEC systems or influence design of future OTEC heat engines can be guided by that bound. Chih Wu [5] carried out a study on power optimization of OTEC systems and concluded that the bound on specific power output provides the basis for a practical engineering effort towards maximizing the per unit time and per unit total heat exchanger area production. Chih Wu [6] studied on specific power analysis of thermoelectric OTEC plants, by treating thermoelectric OTEC as an external and internal irreversible heat limited to the factors of heat transfers and Joulean loss and thus compared with Carnot OTEC, endo- reversible OTEC and external reversible thermoelectric OTEC. Curto .P.A [7] studied on an update of OTEC baseline design costs. The circumstances that lead to specific opportunities for OTEC for island complexes were discussed by him and concluded that the technical as well as economic uncertainties have to be for OTEC to acquire a substantial share of energy markets. Damy and Marvaldi [8] carried out some investigations for seawater desalination by using ocean thermal gradient (OTG) and he reported some technical solutions for desalination modules and a brief description of cold water pipe and preliminary economical evaluations. Dugger et al [9] studied on technical and economic feasibility of OTEC, various OTEC plant-ship concepts, their economics, onboard production plants, and said that ammonia produced by grazing tropical OTEC plants could also be used as a hydrogen carrier for production of electricity by fuel cells, production of other chemicals and metals (aluminum, magnesium). Ganic and Wu [10] studied about the selection of working fluids for OTEC plants, inferred that ammonia as the best fluid among ammonia, propane and Freon 114 because of its lowest value of the ratio of heat transfer area (A) to net work (Wnet) and high thermal conductivity. Gay Heit Lavi [11] carried out a study in OTEC commercialization issues and analyzed on various incentives required for OTEC establishment their impact on manufacturers of, investors in, and users of OTEC technology. He concluded that OTEC is technically and economically ready to enter the electric utility market in tropical islands. Griffin [12] studied on OTEC cold water pipe design because of the problems caused by vortex-excited oscillations. His study is limited in scope to the problems of vortex shedding from bluff, flexible structures in steady currents, the resulting vortex-excited oscillations and designed OTEC cold water pipeline accordingly. Lennard D.E. [13] studied on viability and best location for OTEC systems around the world. He studied on the design and performance of small unit's up to 1 MW systems and the design requirements of 5-10 MW OTEC systems. Mark S Olsson [14] studied on salinity-gradient vapor-pressure power conversion, examined that the energy conversion approach uses only the differences in vapor pressure between solutions and concluded that salinity-gradient, vapor-pressure power generation is within reach of current technology. Raghavan et al [15] studied about the fin profile of plate-fin evaporators using ammonia as a working fluid and inferred that the plate-fin heat exchanger depends on minimum exchanger volume, minimum pumping power requirement and low ammonia side pressure drop. Rey and Lauro [16] studied on ocean thermal energy and desalination; the combined distillation and OTEC scheme is compared with conventional desalination plant producing both potable water and electricity and concluded that the OTEC scheme has highly flexible and showed considerable economic promise. Rong-Hua Yeh [17] carried out a study of maximum output of an OTEC power plant. They considered parameters like pipe length, pipe diameter, seawater depth, and the flow rate of seawater and concluded that large maximum net output can be obtained by employing a higher temperature of the surface warm seawater. Uehera et. al [18] carried out a conceptual design on OTEC power plant of 5MW on-land type and concluded that electricity can be produced at a cost of 5.33 to 7.57 cents / kWh and at a rate of 14.71 to 18.09 cents / kWh for a 25 MW floating type. Wu and Burke [19] studied on intelligent computer aided optimization on specific power of an OTEC Rankine power plant, through manipulation of the boiler pressure and condenser pressure the specific power of the OTEC plant was calculated and the upper bound was determined.

III. MATHEMATICAL MODELLING OF OTEC COUPLED WITH PEM ELECTROLYSER

OTEC power is simple in principle. The sun continuously heats the oceans, maintaining the surface water at temperatures significantly higher than those of the deep water. The resulting surface-to-depth temperature difference (ΔT) can be as high 10 - 27°C, depending on the particular site and depth; this provides a good potential for a closed Rankine cycle power plant. The thermal energy of the warm water is constantly renewed by solar radiation and can be drawn upon day and night. When compared with conventional power plants, the OTEC plant requires considerably larger heat exchangers because the available temperature differences are small. Although its cycle efficiency is less, it is a potential source of economical and pollution-free electricity.

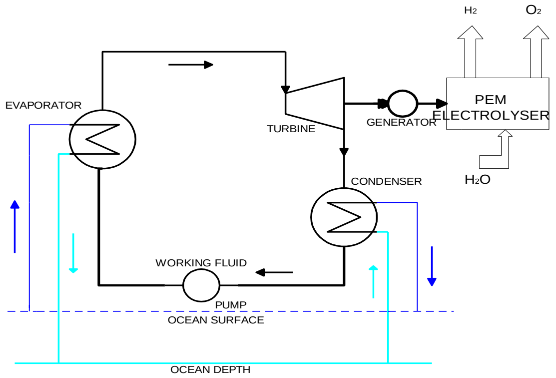

Figure 1. Schematic representation of OTEC plant

This OTEC system consists of simple Rankine cycle. It has turbine, condenser, pump, evaporator and generator.

A. *Mathematical Modeling Of OTEC System*

The thermo-physical properties used in the current analysis are taken from published works and the operating conditions of the OTEC system as well as the electrolyser in Table 1 [2]. The analysis of OTEC plant is carried out by varying the surface water temperature from 32 to 26 °C and varying the cold water temperature from 5 to 25 °C. A sample calculation based on the equations published by [2] is presented below.

Table 1. Fluid properties (Sea Water)

Property	Symbol	Value	Units
Density	ρ	1000	kg/m^3
Specific heat	c	4.200	kJ/kgK
Volume flow rate	$\dot{q}$	0.12	$m^3/\sec$
Required power input to electrolyser	$\dot{W}_{elec}$	4.532	kW h/N m^3 H_2
Thermal resistance between water and fluid	R_{wf}	1x10-6	K/W
Water required for electrolysis process	$Q_{H2O\ elec}$	0.8	l / N m^3 H_2

1. Temperature Difference between Surface Sea Water and cold seawater at the ocean depth

T_C = 25 °C

T_H = 32 °C

$$\Delta T = T_H - T_C$$

= 32-25

= 7 °C

2. Carnot Efficiency

$$\eta_{carnot} = \frac{\Delta T}{T_H} = 1 - \frac{T_C}{T_H}$$

= 7/32

= 0.2188 %

3. Ideal Power Input

$$P_{ideal,\,in} = \rho c \dot{q} \Delta T$$

=1000 x 4200 x 0.12 x 7x10^{-3}

= 3528 W

4. Ideal Power Output

$$P_{ideal,\,out} = \frac{\rho c \dot{q} \Delta T^2}{T_H}$$

= (1000 x 4200 x 0.12 x 49 x 10^{-3}) / (32+273)

= 80.9749 W

5. Actual Power Input

$$P_{act,\,in} = \frac{\delta T_{op}}{R_{wf}} = \frac{\Delta T}{4R_{wf}}$$

= 7 / (4 x 1 x 10^{-6})

= 1750 W

6. Actual Power Output

$$P_{act,\,out} = \frac{\Delta T^2}{8 T_H R_{wf}}$$

= (7 x 7) / (8 x (32 + 273) x 1 x 10^{-6})

= 20.0817 W

7. Actual Conversion Efficiency

$$\eta_{act} = \frac{\Delta T}{2T_H}$$

= (7 + 273) / (2 x (31+273))

= 1.147541

8. Carnot Efficiency

$$\eta_{carnot} = 2\eta_{act}$$

= 2 x 1.147541

=2.295082

9. Volume Flow Rate Of Working Fluid

$$\dot{q} = \frac{2P_{act,\,in}}{\rho c \Delta T}$$

= (2 X 1750) / (1000 X 4200 X (7 + 273))

= 2.976 X 10^{-6} m/sec

10. Ideal Rate of Hydrogen Production

$$\dot{q}_{H2,\,elec} = \frac{P_{out}}{\dot{W}_{elec}}$$

= 80.9740 / 4.3

=18.83035 N m^3/h

11 Actual Rate of Hydrogen Production

$$\dot{q}_{H2,\,elec} = \frac{P_{out}}{\dot{W}_{elec}}$$

=20.08197 / 4.3

= 4.670225 N m^3/h

12. Ideal Rate of Oxygen Production

$$\dot{q}_{O2,\,elec} = \frac{P_{out}}{2\dot{W}_{elec}}$$

= 80.97059 / (2 X 4.3)

= 9.415173 N m^3/h

13. Actual Rate of Oxygen Production

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$$\dot{q}_{O_2,\,elec} = \frac{P_{out}}{2\dot{W}_{elec}}$$

$= 20.08197 / (2 \times 4.3)$
$= 2.335112\ N\ m^3/h$

14. Ideal Rate of Water Production

$$\dot{q}_{H_2O,\,elec} = \frac{P_{out}}{\dot{W}_{elec}} * q_{H_2O}, elec$$

$= 18.830 \times 0.81$
$= 15.25258\ l/N\ m^3\ H2$

15. Actual Rate of Water Production

$$\dot{q}_{H_2O,\,elec} = \frac{P_{out}}{\dot{W}_{elec}} * q_{H_2O}, elec$$

$= 4.670 \times 0.81$
$= 3.782882\ l/N\ m^3\ H2$

16. The actual ratio of the working fluid's flow rate in the OTEC system operating at an optimum temperature drop over rate of water consumption in the electrolysis process

$$\left(\frac{\dot{q}}{\dot{q}_{H_2O,\,elec}}\right)_{actual} = \frac{\left(\dfrac{2P_{act,\,in}}{\rho c \Delta T}\right)}{\dfrac{P_{act,\,out}}{\dot{W}_{elec}} * q_{H_2O}, elec}$$

$= 3.1470 \times 10^{-5}$

17. The ideal ratio of the working fluid's flow rate in the OTEC system operating at an optimum temperature drop over rate of water consumption in the electrolysis process

$$\left(\frac{\dot{q}}{\dot{q}_{H_2O,\,elec}}\right)_{actual} = \frac{\left(\dfrac{2P_{act,\,in}}{\rho c \Delta T}\right)}{\dfrac{P_{act,\,out}}{\dot{W}_{elec}} * q_{H_2O}, elec}$$

$= 1.5735 \times 10^{-5}$

B. Mathematical Modeling of PE:

This mathematical modeling of polymer electrolyte membrane gives the amount of hydrogen being produced by this electrolysis process.

$H_2O = 2+16=18$ grams
Hydrogen = (2/18)*100 =11.11%
Oxygen = (16/18)*100 =88.89%

1000 grams of water contains 11.11% of H_2 and 88.89% of O_2
Hydrogen = (11.11/100)*1000
= 111.1 grams of H_2 / 1000 gms
Oxygen = (88.89/100)*1000
= 888.9 grams of O_2/ 1000 gms
1 liter of H_2 = 0.098 gms
1 liter of O_2 = 1.478 gms
H_2 = (111.1/ 0.098) = 1133.68 liters of H_2 / 1 liter of H_2O
O_2= (888.9/1.478) = 601.42 liters of O_2 / 1 liter of H_2O
1 gm of H_2O contains = (1133.3/ 1000)
= 1.133 lts of hydrogen
1 gm of H_2O contains = (601.42/ 1000)
= 0.60142 lts of Oxygen
Energy consumed for production of 1000 liters = 4kWh
For 1.133 liter = 4.532 Wh

IV. RESULTS AND DISCUSSION

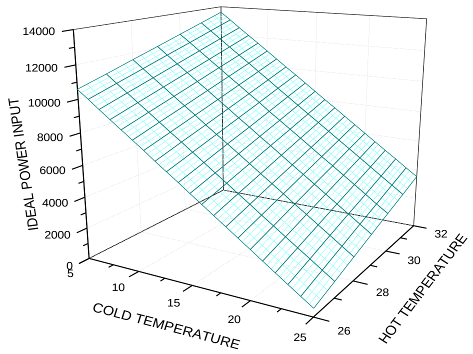

Figure 2. Cold Temperature (°C), Hot Temperature (°C) vs. Ideal Power Input (kW)

Figure 2 represents the change in ideal power input for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum ideal power input of 13600 kW is obtained.

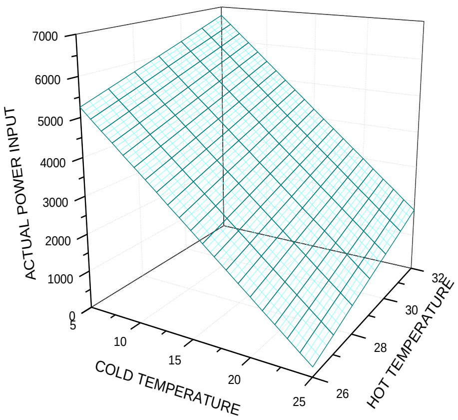

Figure 3. Cold Temperature (°C), Hot Temperature (°C) vs. Actual Power Input (kW)

Figure 3 represents the change in actual power input for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum actual power input of 6750 kW is obtained.

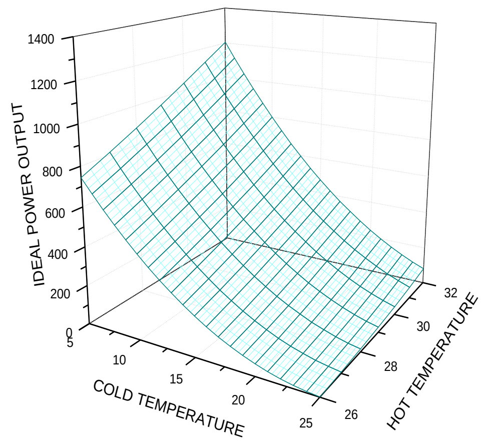

Figure 4. Cold Temperature (°C), Hot Temperature (°C) vs. Ideal Power Output (kW)

Figure 4 represents the change in ideal power output for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum ideal power output of 1204 kW is obtained.

Figure 5 represents the change in actual power output for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum actual power output of 298 kW is obtained.

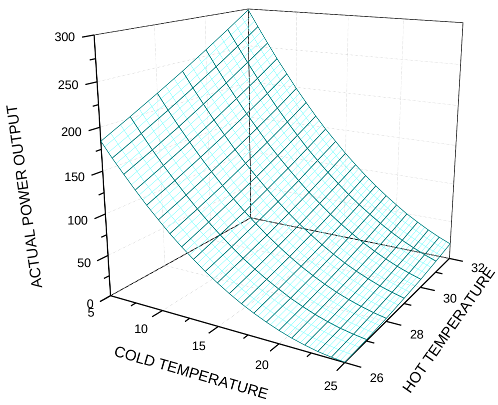

Figure 5. Cold Temperature (°C), Hot Temperature (°C) vs. Actual Power Output (kW)

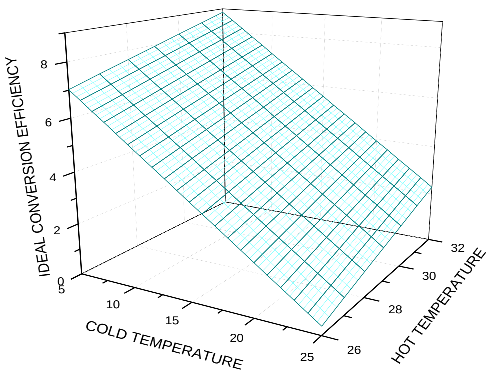

Figure 6. Cold Temperature (°C), Hot Temperature (°C) vs. Ideal Conversion Efficiency (%)

Figure 6 represents the change in ideal conversion efficiency for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum ideal conversion efficiency of 8.8 % is obtained.

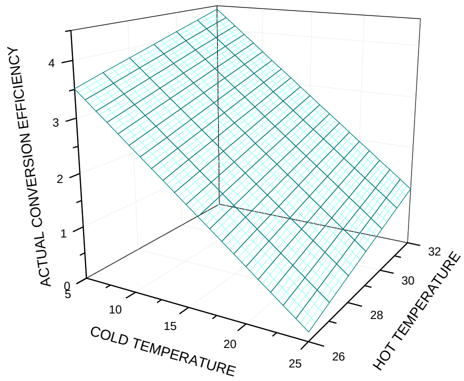

Figure 7. Cold Temperature (°C), Hot Temperature (°C) vs. Actual Conversion Efficiency (%)

Figure 7 represents the change in actual conversion efficiency for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum actual conversion efficiency of 4.4 % is obtained.

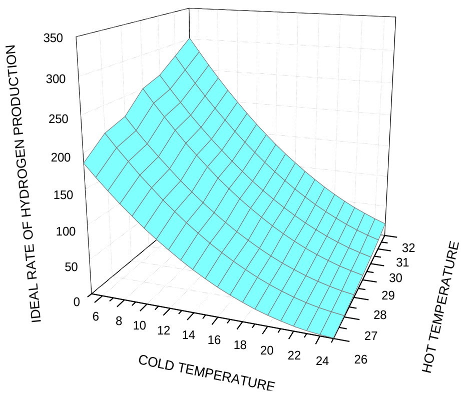

Figure 8. Cold Temperature (°C), Hot Temperature (°C) vs. Ideal Rate of Hydrogen Production (l/hr)

Figure 8 represents the change in ideal rate of hydrogen production for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature (5 °C to 25 °C). For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum ideal rate of hydrogen production of 301.6 l/hr is obtained.

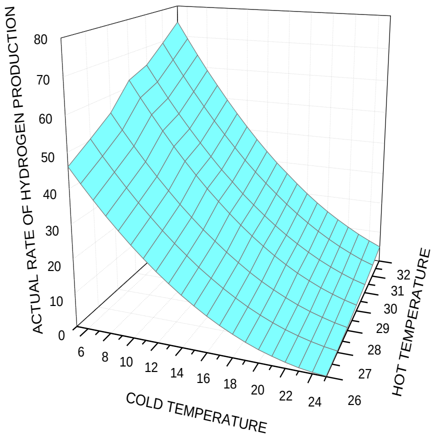

Figure 9. Cold Temperature (°C), Hot Temperature (°C) vs. Actual Rate of Hydrogen Production (l/hr)

Figure 9 represents the change in actual rate of hydrogen production for various combinations of warm water temperature (26 °C to 32 °C) and cold water temperature 5 °C to 25 °C. For a warm water temperature of 32°C and cold water temperature of 5°C, the maximum actual rate of hydrogen production of 74.69 l/hr is obtained.

V. CONCLUSIONS

The energy analysis of hydrogen production through an OTEC system coupled with PEM Electrolyser for various combinations of warm water and cold water was conducted. The outputs for a warm water temperature of 32 °C and cold water temperature of 5 °C are as follows:

Ideal Power Input	= 13600 kW
Actual Power Input	= 6750 kW
Ideal Power Output	= 1204 kW
Actual Power Output	= 298 kW
Ideal Conversion Efficiency	= 8.8 %
Actual Conversion Efficiency	= 4.4 %
Ideal Rate of Hydrogen Production	= 301.6 l/hr
Actual Rate of Hydrogen Production	= 74.69 l/hr

The above mentioned results have been obtained for a maximum temperature drop for the range of temperatures considered for warm and cold water. However, the simulated results in the graphical form can be utilized to find out the power input, power output, conversion efficiency and hydrogen production for a realistic warm water and cold water temperature pertaining to various temperature gradient actually existing in the ocean site under investigation.

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