Ocean Thermal Energy Stirling Power Plant (OTE-SPP)

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***Abstract*— This paper outlines the use of thermal energy in sea water to generate electricity. We have replaced the conventional '*Ocean Thermal Energy Conversion System, (OTEC)*' with a suitably designed assembly of multiple stirling engines of alpha type. The novelty in the engine design lies in the use of multiple pistons with a common piston head in a single chamber to reduce dead volume and thereby improve efficiency. The new setup is named as '*Ocean Thermal Energy Stirling Power Plant, (OTE-SPP)*'. It utilizes the temperature difference between the surface sea water and the sea water from bottom layers to run the working fluid in the OTE-SPP. Here Ammonia is selected as the working fluid.**

***Index Terms*— Dead volume, Regenerator, Displacer, Power piston, Working fluid, Multi-piston.**

I. Introduction

THE oil crisis of 1970s and the fast depletion of fossil fuels emphasize the need for finding other solutions to meet the growing global demand for energy. The oceans can be used to provide us with energy to power our homes and businesses. Right now, there are very few ocean energy power plants in operation and most of them are fairly small in size. There are four basic ways to tap the ocean for its energy. We can use the ocean's waves; we can use the ocean's high and low tides; we can harness underwater currents; or we can use temperature differences in the water at different depths.

On an average day, 60 million square kilometers (23 million square miles) of tropical seas absorb an amount of solar radiation equal in heat content to about 250 billion barrels of oil. If less than one tenth of one percent of this stored solar energy could be converted into electric power, it would supply more than 20 times the total amount of electricity consumed in the United States on any given day. Existing systems like 'Ocean thermal energy conversion (OTEC)' systems, extract energy from the difference in temperature between shallow and deep waters by way of a heat engine. The biggest difference in temperature (around 20 degrees Celsius, generally located near the equator or tropics), between a hot and cold source provides the greatest amount of potential energy. The main technical challenge to generate the most amounts of power lies in the small temperature variation. We have suggested a new system christened by us as 'Ocean Thermal Energy Stirling Power Plant (OTE-SPP)' as a viable alternative to OTEC. Figure 1 shows the viable regions for implementations of OTE-SPP around the globe. In general, tropical and sub-tropical regions are preferable as they provide the maximum temperature difference between surface sea water and sea water from bottom layers [7].

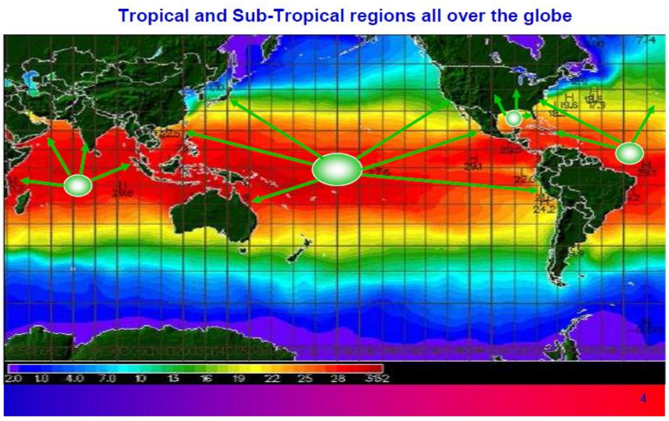

Fig.1. Viable regions for OTE-SPP

II. THEORY

A. Design of Stirling Engine

We utilise the Schmidt theory [3] here. Figure 2 shows the calculation model of alpha type stirling engine. At the outset, the volumes of the expansion- and compression cylinder at a given crank angle are determined. The momental volume is described with a crank angle - x. This crank angle is defined as x = 0 when the expansion piston is located at the top position (top dead point). The momental expansion volume

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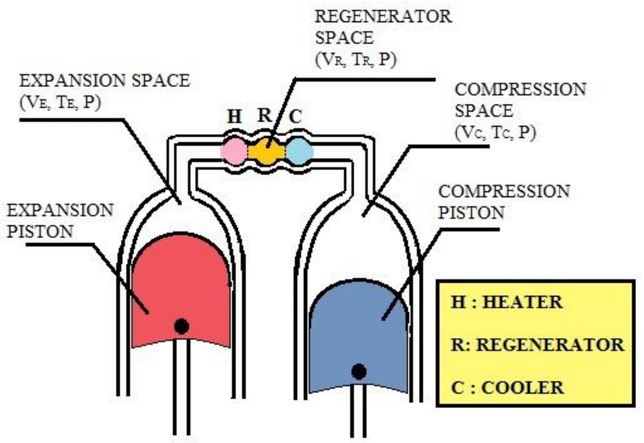
– V_E is described in (1) with a swept volume of the expansion piston - V_{SE}, and an expansion dead volume - V_{DE}.



Alpha - type Stirling Engine

Fig.2 Schematic of Alpha type Stirling engine

$$V_E = \{V_{SE}(1-\text{Cos } x)/2\} + V_{DE} \tag{1}$$

The momental compression volume – V_C is found in (2) with a swept volume of the compression piston - V_{SC}, a compression dead volume - V_{DC} and a phase angle - dx.

$$V_C = [V_{SC}\{1-\text{Cos }(x-dx)\}/2] + V_{DC} \tag{2}$$

The total momental volume is calculated in (3).

$$V = V_E+V_R+V_C \tag{3}$$

The total mass in the engine - m is calculated using the engine pressure - P, each temperature - T, each volume - V and the gas constant - R.

$$m = \frac{PV_E}{RT_E} + \frac{PV_R}{RT_R} + \frac{PV_C}{RT_C} \tag{4}$$

The temperature ratio - t, a swept volume ratio - v and other dead volume ratios are found using the following equations.

$$t = \frac{T_C}{T_E} \tag{5}$$

$$v = \frac{V_{SC}}{V_{SE}} \tag{6}$$

$$X_{DE} = \frac{V_{DE}}{V_{SE}} \tag{7}$$

$$X_{DC} = \frac{V_{DC}}{V_{SE}} \tag{8}$$

$$X_R = \frac{V_R}{V_{SE}} \tag{9}$$

The regenerator temperature - TR is calculated in (10), by using:

$$T_R = \frac{T_E+T_C}{2} \tag{10}$$

When equation (4) is changed using equation (5)-(9), the total gas mass - m is described in the next equation.

$$m = \frac{P}{RT_C}\left(tV_E + \frac{2\tau V_R}{1+t} + V_c\right) \tag{11}$$

Equation (11) is changed in equation (12), using equation (1) and (2).

$$m = \frac{PV_{SE}}{2RT_C}\{S - B\ \text{Cos}(x-a)\} \tag{12}$$

Now,

$$a = \tan^{-1}\frac{v.\text{Sin } dx}{t+\text{Cos } dx} \tag{13}$$

$$S = t+2tX_{DE}+\frac{4tX_R}{1+t}+v+2X_{DC} \tag{14}$$

$$B = \sqrt{t^2+2tv\text{Cos } dx+v^2} \tag{15}$$

The engine pressure - P is defined as the next equation using (12).

$$P = \frac{2mRT_C}{V_{SE}\{S-B\cos(\theta-a)\}} \tag{16}$$

The mean pressure - P_{mean} can be calculated as follows:

$$P = \frac{1}{2\pi}\oint P dx = \frac{2mRT_C}{V_{SE}\sqrt{S^2-B^2}} \tag{17}$$

c is defined in the next equation.

$$c = \frac{B}{S} \tag{18}$$

As a result, the engine pressure - P, based on the mean engine pressure - P_{mean} is calculated in (19).

$$P = \frac{P_{mean}\sqrt{S^2-B^2}}{S-B.\text{Cos}(x-a)} = \frac{P_{mean}\sqrt{1-c^2}}{1-c.\text{Cos}(x-a)} \tag{19}$$

On the other hand, in the case of (16), when cos(x-a) = 1, the engine pressure - P becomes the minimum pressure - P_{min}.

$$P_{min} = \frac{2mRT_C}{V_{SE}(S+B)} \tag{20}$$

The engine pressure - P, based on the minimum pressure - P_{min} is described in (21).

$$P = \frac{P_{min}(S+B)}{S-B\text{Cos}(x-a)} = \frac{P_{min}(1+c)}{1-c.\text{Cos}(x-a)} \tag{21}$$

Similarly, when cos(x-a)=1, the engine pressure - P becomes the maximum pressure - P_{max}. The following equation is introduced.

$$P = \frac{P_{max}(S-B)}{S-B\text{Cos}(x-a)} = \frac{P_{max}(1-c)}{1-c.\text{Cos}(x-a)} \tag{22}$$

B. Indicated Energy, Power and Efficiency

The indicated energy (area of the P-V diagram) in the expansion and compression space can be calculated by an analytical solution with the use of the above coefficients. The indicated energy in the expansion space (indicated expansion energy) - W_E(J), based on the mean pressure - P_{mean}, the minimum pressure – P_{min} and the maximum pressure - P_{max} is described in the following equations.

$$W_E = \oint P dV_E = \frac{P_{mean}V_{SE}\pi c.\text{Sin } a}{1+\sqrt{1-c^2}} = \frac{P_{min}V_{SE}\pi c.\text{Sin } a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1+c}}{\sqrt{1-c}} = \frac{P_{max}V_{SE}\pi c.\text{Sin } a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1-c}}{\sqrt{1+c}} \tag{23}$$

The indicated energy in the compression space, W_c (J) is given by:

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$$W_C = \oint P dV_C = \frac{P_{mean}V_{SE}\pi ct..Sin\ a}{1+\sqrt{1-c^2}} = \frac{P_{min}V_{SE}\pi ct..Sin\ a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1+c}}{\sqrt{1-c}} = \frac{P_{max}V_{SE}\pi ct.Sin\ a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1-c}}{\sqrt{1+c}} \quad (24)$$

The indicated energy per one cycle of this engine – W_i (J) is given by:

$$W_i = W_e + W_c = \frac{P_{mean}V_{SE}\pi c(1-t).Sin\ a}{1+\sqrt{1-c^2}} = \frac{P_{min}V_{SE}\pi c(1-t).Sin\ a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1+c}}{\sqrt{1-c}} = \frac{P_{max}V_{SE}\pi c(1-t).Sin\ a}{1+\sqrt{1-c^2}}.\frac{\sqrt{1-c}}{\sqrt{1+c}} \quad (25)$$

Relations between P_{mean}, P_{min} and P_{max} are determined in the following equations.

$$\frac{P_{min}}{P_{mean}} = \sqrt{\frac{1-c}{1+c}} \quad (26)$$

$$\frac{P_{max}}{P_{mean}} = \sqrt{\frac{1+c}{1-c}} \quad (27)$$

The indicated expansion power - L_E (W), the indicated compression power - L_C (W) and the indicated power of this engine - L_i (W) are defined in the following equations, using the engine speed per one second, n (rps, Hz).

$$L_E = W_E\, n \quad (28)$$
$$L_C = W_C\, n \quad (29)$$
$$L_i = W_i\, n \quad (30)$$

The indicated expansion energy - W_E found equation (23) means an input heat from a heat source to the engine. The indicated compression energy -Wc calculated by equation (24) means a reject heat from the engine to coolant. Then the thermal efficiency of the engine - e is calculated by:

$$e = \frac{W_i}{W_E} = 1-t \quad (31)$$

III. Design and Working of OTE-SPP

The design of the system of which 'Ocean Thermal Energy – Stirling Power Plant' is a proposed part is as shown below.

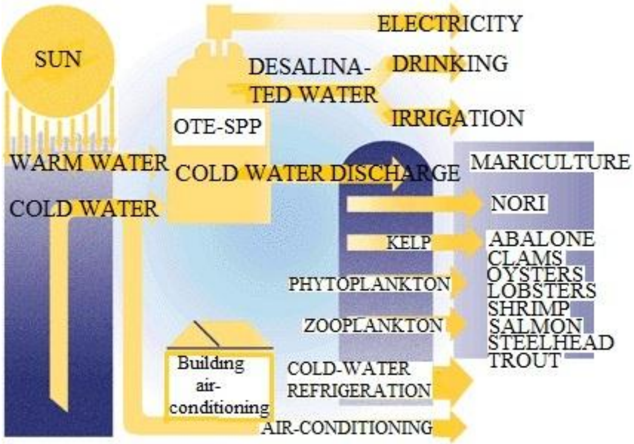

Fig.3 Schematic diagram of OTE-SPP structure

The 'OTE-SPP' is an assembly of modified individual stirling engine modules which uses the thermal energy difference in the ocean to run their working fluid. This setup aims at maximizing the energy tapping from the ocean.

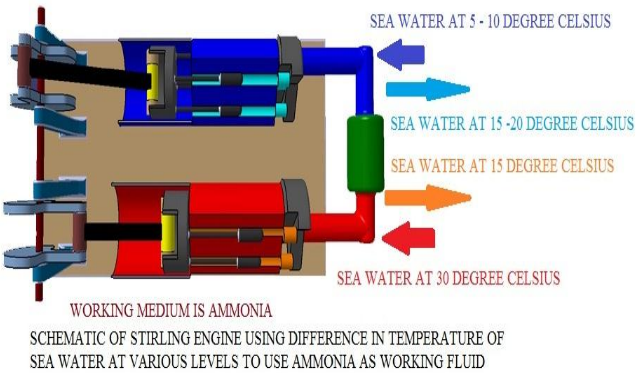

Fig.4 Schematic diagram of a single module in OTE-SPP

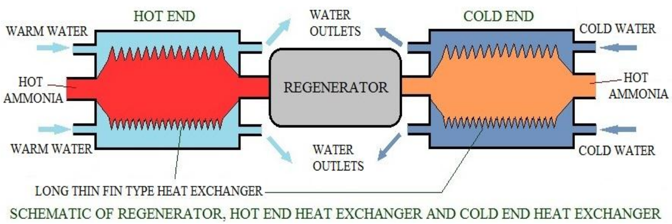

Fig.5 Schematic diagram of Heat exchanger and regenerator assembly in a single module of OTE-SPP

The hot water from the sea surface in the tropical and subtropical regions at 28°-30° C is pumped into the hot end exchanger as shown in fig.5. The hot sea water transfers heat to the working fluid, which is ammonia in this case. The hot ammonia expands and runs the hot end displacer piston. Similarly cooler sea water at 5° – 10° C is pumped from the bottom of the sea and sent to the cold end exchanger as shown in fig.5. This cooler water extracts heat from the hot ammonia and in turn cools it. This leads to contracting of the working fluid, ammonia in the cold end which in turn runs the compression piston. This process repeats continually and this when coupled to a generator can produce electricity. When a large number of such stirling modules are used in tandem to run the

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generator, the resultant energy output is much higher and large amount of electricity can be efficiently generated.

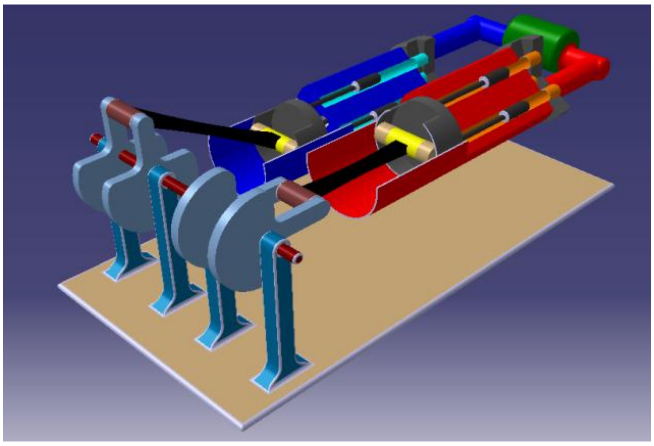

Fig.6 Schematic diagram of a single module in OTE-SPP showing cross sectional view of the modified multi-piston stirling engine

Fig.6 and fig.7 show the modified stirling engine design. We have used multiple piston arrangement in the expansion as well as compression chambers in the stirling engine. Each chamber has 5 pistons with the central piston being smaller in size. These sub-pistons are provided with smaller sub-chambers. This arrangement is conceived to reduce the dead volume in a stirling engine and thus increase the efficiency of the engine. The central piston and the central sub-chamber is smaller in size because the working fluid, ammonia, travels the shortest distance to reach it. Bends are provided along the tubing of the central sub-chamber so as to delay the working fluid. This will allow the working fluid to reach all the sub-pistons at the same time. If the working fluid, ammonia reaches the central sub-chamber earlier then its potential energy gets wasted as it alone cannot move the common piston head as all the sub-pistons are connected to the common piston head in each of the main chambers. The working fluid must reach all the sub-pistons at the same time for the common piston head to move and in turn rotate the cam.

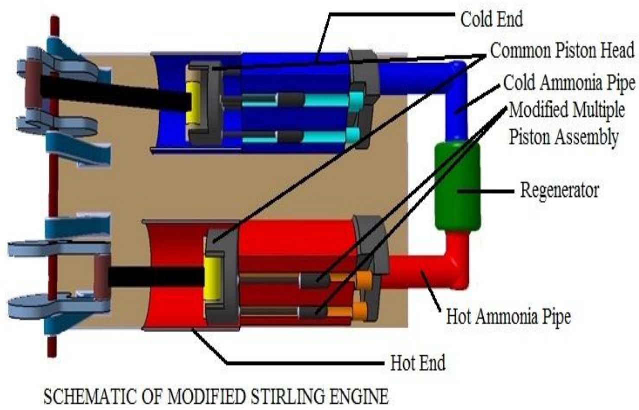

Fig.7 Schematic diagram of a single module of OTE-SPP which shows the modified stirling engine

IV. Heat Flow Equations

$$\text{Compression Ratio } (V_{CR}) = (1+ (\Delta T/1100)) = V_{max}/V_{min} = (V_C+V_E)/V_C \quad (32)$$

$$P_i = B_n p f V_E \quad (33)$$

Where,

B_n = Beale Number = 0.15 (for larger engines)
p = engine pressure in bar = 15 bar
f = cycle frequency of stroke = 40 Hz
P_i = indicated engine power.

Now for transfer of heat from hot water to ammonia in hot end exchanger;

$$m_w C_w \Delta T_{w1} = m_{am} C_{am} \Delta T_{am1} \quad (34)$$

where,

m_w = mass of water in the system in kg
C_w = specific heat capacity of water in J/kg.K at room Temeperature
ΔT_{w1} = drop in temperature of hot surface sea water in Kelvin
ΔT_{am1} = increase in temperature of ammonia at hot end exchanger in Kelvin

Again, for transfer of heat from cold water to ammonia in cold end exchanger;

$$m_w C_w \Delta T_{w2} = m_{am} C_{am} \Delta T_{am2} \quad (35)$$

where,

m_w = mass of water in the system in kg
C_w = specific heat capacity of water in J/kg.K at room Temeperature
ΔT_{w1} = increase in temperature of cold sea water from bottom in Kelvin
ΔT_{am1} = decrease in temperature of ammonia at cold end exchanger in Kelvin

V. Results And Discussion

The following inferences were made as a result of numerical calculations. The swept volume ratio of cold end to hot end was calculated as 0.5105775. The dead volume of expansion space ratio was found to be 0.3185. The subsequent compression dead volume and dead volume of expansion space for a single stirling module were calculated to be 47.775 cm^3 and 95.55 cm^3 respectively. The regenerator volume ratio was found to be 0.3185. The crank angle value was found to be 52.94541 degree. The Indicated expansion power of the stirling module was found as 338.168 kW. Similarly, the indicated compression power was calculated to be 130.367 kW. This gives us the total indicated power of the stirling module as 468.54 kW. The Indicated efficiency was obtained as 61.5% for a single module. Now, for 1000 such stirling modules coupled together, we obtain a total indicated power of 468.54 MW which will require an expansion swept volume of 350 litres. In reality a large OTE-SPP plants can be built with expansion swept volumes as high as 10,000 litres by combining numerous stirling modules. In such large plants, by considering very minimal conversion efficiency of around 20 %, we will still obtain a total indicated power of 2600 MW. Further, we obtain the compression ratio of a single module as 2.75. We have also calculated the estimated temperature change in hot water to be from 30 to 20 degree Celsius and that of the cold water from 10 to 18 degree Celsius approximately. The temperature difference in the

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working medium which is ammonia in this case is calculated as 475 kelvin.

VI. Conclusion

The 'Ocean Thermal Energy - Stirling Power Plant' (OTE-SPP) is a novel approach to solve the serious energy crisis facing the world. It is a zero pollution system which holds great promise for the future. Parallel modules of 'OTE-SPP' can be set up with ease to increase electricity generation in the power plant. Further, the modified multi-piston design enables us to reduce total dead volume which helps us to further increase the efficiency of the system.

Appendix

NAME	SYMBOL WITH UNIT
Engine pressure	P Pa
Swept volume of expansion piston or displacer piston	V_{SE} m^3
Swept volume of compression piston or power piston	$V_{SC}m^3$
Dead volume of expansion space	$V_{DE}m^3$
Regenerator volume	$V_B m^3$
Dead volume of compression space	$V_{DC}m^3$
Expansion space momental volume	$V_E m^3$
Compression space momental volume	$V_C m^3$
Total momental volume	Vm^3
Total mass of working gas	m Kg
Gas constant	R J/KgK
Expansion space gas temperature	T_HK
Compression space gas temperature	T_C K
Regenerator space gas temperature	T_R K
Phase angle	dx (deg)
Temperature ratio	t
Swept volume ratio	v
Dead volume ratio	X
Engine speed	n Hz
Indicated expansion energy	W_EJ
Indicated compression energy	W_CJ
Indicated energy	W_i J
Indicated expansion power	L_E W
Indicated compression power	L_C W
Indicated power	L_i W
Indicated efficiency	e

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