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# PERFORMANCE EVALUATION OF OTEC WITH THERMOELECTRIC POWER CONVERTER


*The possibility of using thermoelectric generators in systems of ocean thermal energy conversion (OTEC) is considered. Performance evaluation of such configurations is made, the possibility of creating OTEC with acceptable technical and economic features is shown.*



**Key words:** ocean thermal energy; thermoelectric generator; OTEC.


## Introduction

The world ocean is a natural accumulator of solar energy whose heat content is estimated as 20 to 25 kWh/m$^3$. A small part of energy stored in the ocean would have sufficed to cover all needs of mankind. However, this resource is hard to reach, since currently existing technologies of ocean thermal energy conversion have not reached yet the level sufficient for a large-scale application.

Though a number of implemented pilot projects have confirmed the possibility of obtaining quite acceptable technical and economic features of OTEC [1, 2], this technology has not received any commerical development effort. This is due to the necessity of heavy capital investments in OTEC projects – their sum is estimated as 1 milliard $ for a plant of power 200 to 300 MW, which, naturally, is a serious constraint on the way to using the energy source under study. Nevertheless, research and activities related to OTEC keep up. They are primarily aimed at developing the most capital-intensive system components, namely heat exchangers, turbines, cold and hot water pipelines.

The experience of using modern systems of renewable energy sources conversion (photovoltaic converters, wind-powered engines) shows that their wide application became possible due to commercial use of low-power systems (of order 1 to 100 kW) and introduction of special feed-in tariffs assuring the profitability of running such systems. For ocean thermal energy converters the use of low-power generators is considered to be inacceptable, since economic feasibility of the system is affected considerably by scale factor, i.e. with power reduction below 10 MW, the relative capital investments in OTEC drastically increase (Fig. 1) [1]. It is due to peculiarities of employed energy conversion system based on steam-turbine cycle using a low-boiling heat carrier.

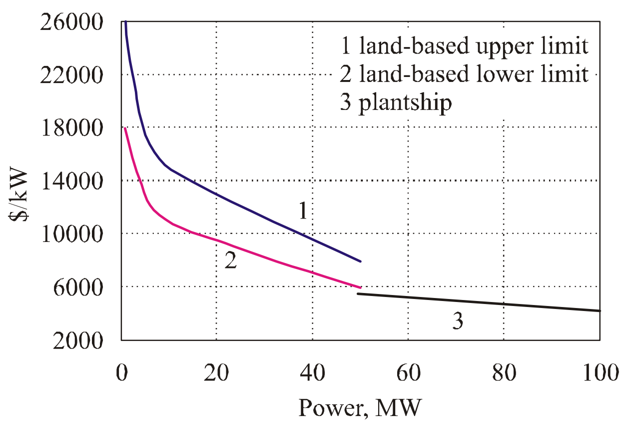


*Fig. 1. Specific cost of OTEC versus power level.*

This paper is concerned with the possibility of using a thermoelectric converter in OTEC and analyzes the possibilities of application of such devices in the power range of order 0.1 MW.

## OTEC configuration with a thermoelectric energy converter

Similar to a classical OTEC system, as a source of thermal energy the configuration under study employs warm water of ocean surface layers and as a heat sink – cold water of deep layers.

The major configuration components:

– thermoelectric generator with systems of supply and removal of heat;

– cold and hot water pipelines;

– pumps;

– OTEC direct current converter into alternating current of industrial parameters (mains inverter).

All configuration components, except for thermoelectric generator, are standard; their characteristics can be determined knowing the source data (power, heat carrier flow rates, hydraulic resistance of the system, etc).

Thermoelectric generator is a thermopile consisting of $n \times m$ standard modules equipped with systems of supply and removal of heat in the form of counter-current heat exchanger. The specific feature of this configuration is essential dependence of generator characteristics on the flow regime of heat carriers. A change in mass flow affects both the available and working temperature difference (i.e. the generator power and efficiency) and the thermal and hydraulic resistance of heat exchangers (i.e. the size and cost of device, as well as auxiliary energy expenditures). Therefore, in the analysis of OTEC characteristics it is necessary to use a mathematical model taking into account the interrelation of said parameters with regard to real design peculiarities.

To determine the generator characteristics, we will use a mathematical model of counter-current TEG in the form [3]:

$$\theta(J,Y) = C_1 + C_2 Y - 0.5 J^2 Y^2 / I_\mathrm{o}, \qquad (1)$$

where

$$C_1 = (a_2 \mathrm{Bi}_c t_c - a_1) / (J - \mathrm{Bi}_h + a_2 (J + \mathrm{Bi}_c)), \qquad (2)$$

$$C_2 = C_1 (J + \mathrm{Bi}_c) - \mathrm{Bi}_c t_c, \qquad (3)$$

$$a_1 = J^2 / I_\mathrm{o} - 0.5\, J^2 (J - \mathrm{Bi}_h) / I_\mathrm{o} + \mathrm{Bi}_h t_h, \qquad (4)$$

$$a_2 = J - \mathrm{Bi}_h - 1. \qquad (5)$$

Here $\theta = T/t_\mathrm{o}$ is dimensionless temperature of thermoelement; $Y$ is dimensionless coordinate; $J = jeh/\lambda$ is dimensionless current density; $e$ is thermoelectric coefficient; $\lambda$ is thermal conductivity; $\alpha$ is heat transfer coefficient; $\mathrm{Bi} = \alpha h/\lambda$ is the Biot criterion; $I_\mathrm{o} = zt_\mathrm{o}$ is the Ioffe criterion; $z = e^2\sigma/\lambda$ is thermoelectric figure of merit of material; $h$ is thermoelement height; $t_\mathrm{o} = t_h$ is defining temperature; $t_c$ is cold water temperature; $t_h$ is hot water temperature.

Indexes "$c$" and "$h$" correspond to the cold and hot thermopile temperatures.

To specify current values of heat carrier temperatures $t_c$, $t_h$, we use a well-known expression for heat carrier temperature difference in a counter-current heat exchanger:

$$\Delta t = A(t_{h\mathrm{o}} - t_{c\mathrm{o}}), \qquad (6)$$

where $t_{h\mathrm{o}}$ and $t_{c\mathrm{o}}$ are initial temperatures of heat carriers;

$$A = 1 / (1 + W / KS), \qquad (7)$$

$W = G_\mathrm{o} \cdot C_p$ is water equivalent of heat, kJ/s; $K = 1/(1/\alpha_h + 1/\alpha_c + h/\lambda)$ is heat transfer coefficient, $\mathrm{W/m^2 \cdot K}$; $S$ is heat exchange surface, $\mathrm{m^2}$.

Considering a change in heat carrier temperatures within one module to be negligibly small, we obtain expressions for heat carrier temperatures:

$$t_c(x) = t_{co} + \mathrm{d}t, \tag{8}$$

$$t_h(x) = t_{ho} - \mathrm{d}t, \tag{9}$$

where $$\mathrm{d}t = \Delta t / n.$$

Solving the system of equations (1 – 9), one can find temperature distribution in a thermopile and, accordingly, thermoelectric generator power.

As mentioned above, parameters of thermoelectric generator are essentially dependent on heat carrier flow rate and the intensity of heat exchange on the surface of modules. A significant influence on the economic feasibility of OTEC is also exercised by heat exchanger's hydraulic resistance which dictates the auxiliary power expenditures. All these parameters are interrelated; the kind of these relations is mainly determined by heat exchanger construction.

For specification of the source data we use characteristics of standard 100 kW plate heat exchanger of the type Funke FP-10 (Fig. 2).

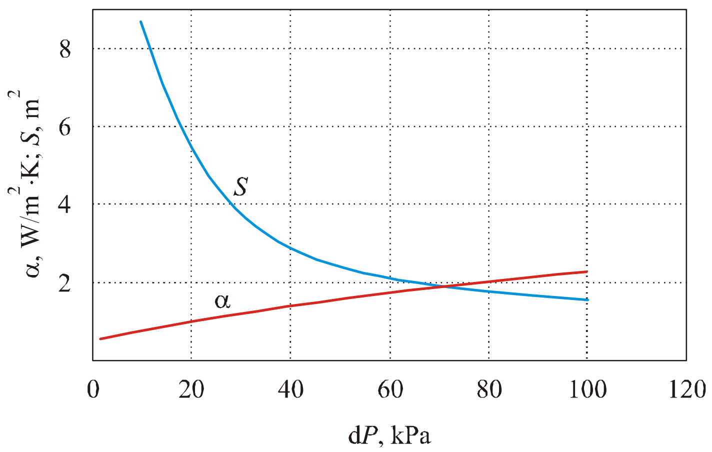


*Fig. 2. The correlation between heat exchange intensity α, heat exchange area S, and hydraulic resistance dP of 100 kW heat exchanger (corresponds to 1 kW OTEC).*

The data given in the figure is approximated by dependences of the type

$$S(G_o, \mathrm{d}P) = (aG_o - b)\ \mathrm{d}P^c, \tag{10}$$

$$\alpha(G_o, \mathrm{d}P) = dG_o \mathrm{d}P^e, \tag{11}$$

where $G_o$ is heat carrier flow rate, kg/s.

As the source data, we also use the following:

– hot water temperature $t_{ho}$ = 27 °C;
– cold water temperature $t_{co}$ = 5 °C;
– thermoelectric module figure of merit $z$ = 0.003;
– thermoelement height $h$ = 0.5 mm;
– module size 40 × 40 mm;
– the cost of one module – 3 $;
– specific cost of heat exchanger – 250 $/m$^2$;
– total length of pipelines 3000 m;
– the cost of pipeline – 10 $/m;
– the cost of pumps – 75 $/(kg/s);
– the cost of invertor – 150 $/kW.

All prices are taken from manufacturers' catalogs [4].

The analysis of a mathematical model of OTEC has shown that in conditions under consideration the governing operating parameter affecting the cost of system in general is a hydraulic resistance of heat exchangers that can be varied over considerably wide limits with a specified heat exchanger power and heat carrier flow rate (in this case, in conformity with hydrothermal analogy concept, the thermal resistance also changes accordingly). The specific cost of a TEC optimized with respect to heat carrier flow rate for different values of heat exchanger hydraulic resistance is illustrated in Fig. 3.

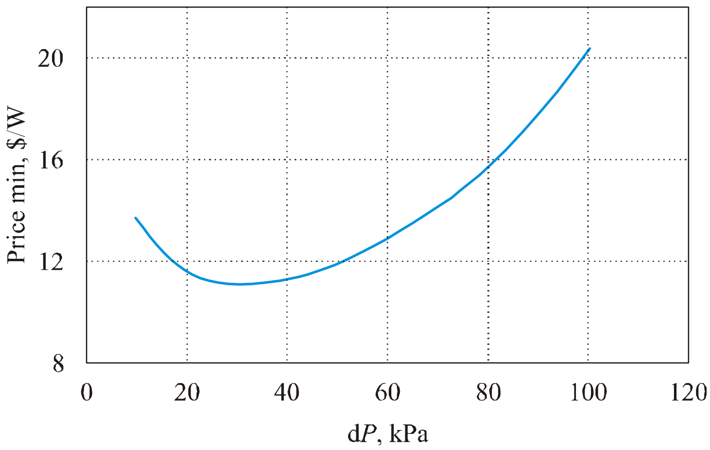


*Fig. 3. Specific cost of TEC ($/W net power) versus heat exchanger hydraulic resistance.*

Fig. 4 represents dependences of relative net power ($N_{net}/N_o$), full power $N_o$, relative power of feed pumps ($N_{pump}/N_o$) and specific cost of OTEC ($/W) on heat carrier flow rate (kg/s) for generator of net power 100 kW.

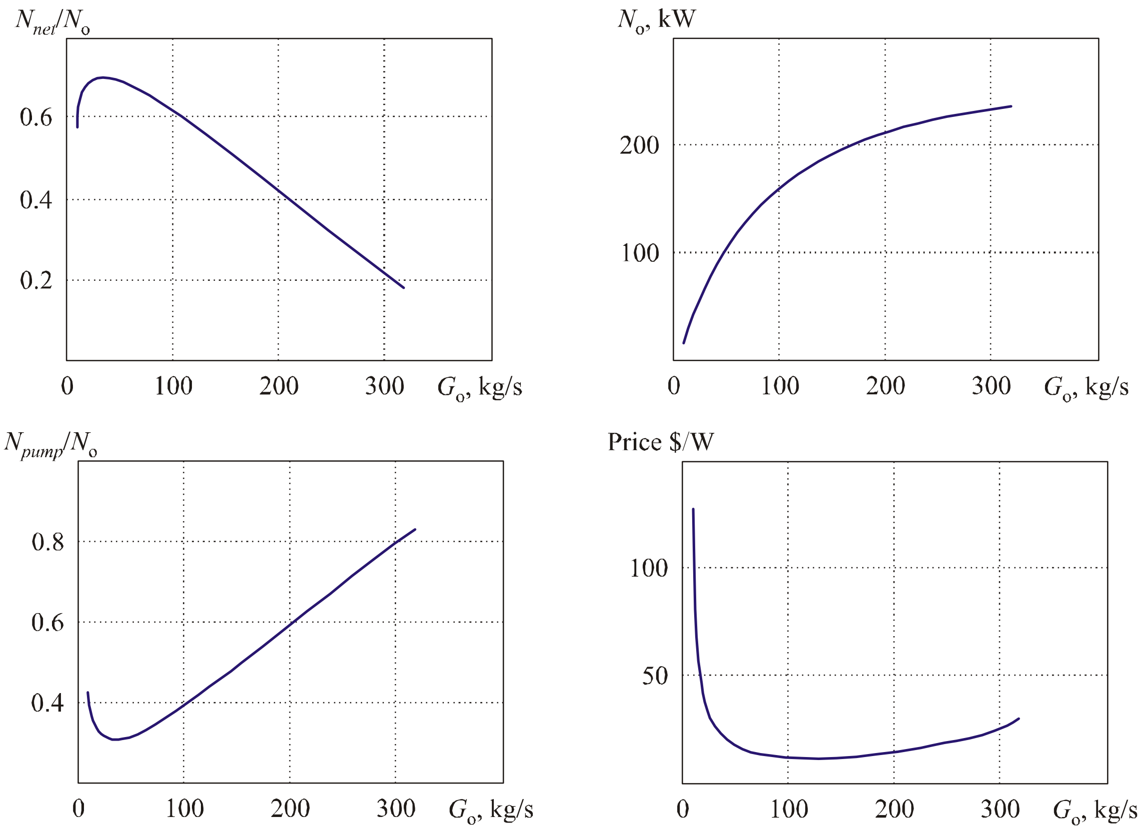


*Fig. 4. Characteristics of 100 kW OTEC versus heat carrier flow rate (kg/s). $N_o$ – full power; $N_{net}/N_o$ – relative net power; $N_{pump}/N_o$ – relative power of feed pumps; Price – specific cost of OTEC, $/kW.*

The resulting data helps to determine the basic technical and economic features of OTEC configuration under study, i.e. the cost of electric energy produced. For a 100 kW generator, with the above source data, the project cost is:

– generating part – 1 million 110 thousand $;
– pipelines – 50 thousand $;
– pumps – 20 thousand $;
– invertor – 15 thousand $;
– other expenditures (50 %) – 600 thousand $;
– Total: 1 million 795 thousand $.

With 100% load of OTEC the electric energy production is about 900 thousand kW·h/year, which for standard appreciation periods of 20 years yields the cost price of electrtic energy of order 0.1 $/kW·h. With regard to maintenance costs, tax deduction and operating organization profit, this figure can increase by another 50% maximum, i.e. to 0.15 $/kW·h.

For comparison, it can be noted that current feed-in tariff for systems of photovolatic conversion of solar energy in power range under study is 0.3...0.6 $/kW·h [4-6]. That is, the existing tariffs exceed by a factor of 2...4 the values obtained for OTEC, which confirms high competitive ability of OTEC configuration analyzed.

## Conclusions

The analysis of thermoelectric system of ocean thermal energy conversion has shown the possibility in principle of creating OTEC in the power range of 100 kW with technical and economic features acceptable for a wide commercial use.

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