



## **Extraction of Thermal Energy from the Ocean Using Gas Hydrates**

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### **Abstract**

The article considers a scheme and cycle for the gas-hydrate energo-technological (GHET) plant to produce electricity, fresh water and cold using ocean thermal energy conversion (OTEC). It is shown that in the cycle of the plant GHET can obtain approximately 3 times more work from 1 kg of working fluid than in the Anderson steam cycle, which is similar to the Rankine cycle. On the basis of the proposed method a comparative analysis of energy indices of these the plants is made using the Anderson cycle and GHET under conditions found in the Black Sea.

**KEYWORDS:** Gas-hydrate energo-technological plant, electric power, fresh water, cold, exergic efficiency.

### **1. INTRODUCTION**

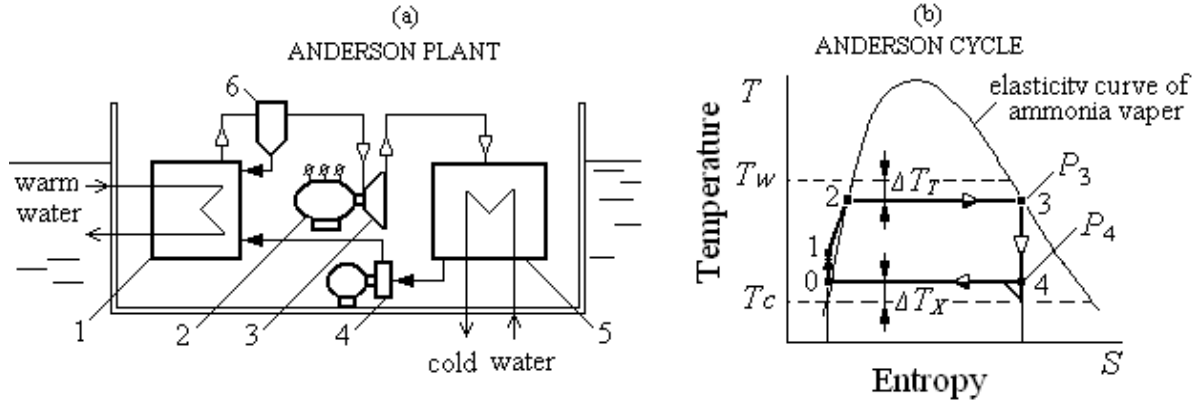
The surface water of the oceans for more than half of the area has a temperature of 20-28 °C, yet the main body of water at a depth of more than 50-100 meters has a temperature of 4-10 °C [18]. There are many proposals for exploiting the thermal energy of the oceans to produce electrical energy, fresh water and cold using ocean thermal energy conversion (OTEC) [1- 4, 5, 9, 14, 15, 18]. However, they have a low thermodynamic efficiency. There are proposals to use OTEC in plant that use gas-hydrates to produce electricity, fresh water, as well as the co-production of fresh water and cold [2, 7, 8, 19, 20] as this has a higher thermodynamic efficiency. The use of gas-hydrates appears to be a promising development. Especially effective is the use GHET can be in the development of subaqueous deposits of gas hydrates using gases that are capable of forming gas hydrates, and use them as working fluids.

### **2. PLANTS WITH CLOSED AND OPEN CYCLES USING OTEC**

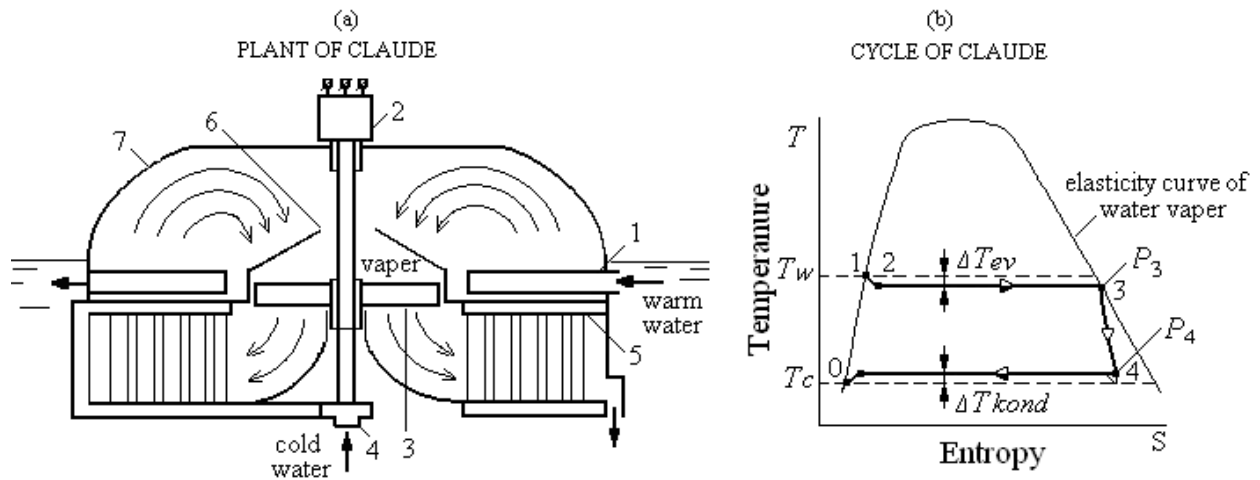
Among the plants using the temperature difference between warm surface and cold deep ocean for electric power generation, prevalent are those that operate a dual circuit with an intermediate working fluid based on the Rankine cycle as shown in Figure 1. (used symbols: a closed cycle, Anderson cycle, Figure 1). Another class of plant operates using a single-circuit in which sea water is used directly as the working fluid [1, 4, 9, 18]. Consider the operation of a

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plant that is based on the Anderson cycle that uses ammonia as the working fluid (see Figure 1,a). Warm surface water, used as a heat source for generating steam, is fed into evaporator 1. The steam enters the turbine 3 and drives an electric generator 2. The steam leaving the turbine is directed into the condenser 5, where it condenses due to the removal of heat condensation by using cold of deep water. A circulation pump, 4, increases the pressure of the condensate and returns it to the evaporator.



**Figure 1.** Scheme of Anderson plant (a) and thermodynamic cycle (b)



**Figure 2.** Scheme of a plant (a) and thermodynamic cycle (Claude cycle) (b) working on a single-circuit

The closed Anderson cycle is based on the Rankine cycle hence it is similar to the conventional steam cycles power plants but the degree of superheating of the working fluid is far less. It consists of the following processes (see Figure 1,b):

- 0-1 Pump 4 is used to force liquid ammonia into the evaporator 1;
- 1-2 Liquid ammonia is heated in the evaporator 1;
- 2-3 Ammonia is boiled in the evaporator;
- 3-4 Ammonia vapor expands in the steam turbine 3;
- 4-0 Ammonia vapor condenses in the condenser 5.

The temperature difference between warm water and the boiling of ammonia is  $\Delta T_w$ :

$$\Delta T_w = \Delta T_{h/e} + \Delta T_{ev} \quad (1)$$

where  $\Delta T_{h/e}$  is the temperature difference between the warm water and the evaporator surface and  $\Delta T_{ev}$  is the temperature difference between the evaporator surface and boiling ammonia. The temperature difference between the cold water and condensed ammonia is  $\Delta T_c$ , i.e.

$$\Delta T_c = \Delta T_{h/e} + \Delta T_{kond}, \quad (2)$$

where  $\Delta T_{h/e}$  is the temperature difference between the cold water and the condenser surface and  $\Delta T_{kond}$  is the temperature difference between the condenser surface and ammonia. Usually  $\Delta T_{h/e} = 2-3$  °C and  $\Delta T_{ev} \approx \Delta T_{kond} \approx 1$  °C, then  $\Delta T_w = \Delta T_c = 3-4$  °C [1, 4].

Heat transfer surfaces are absent in a plant that operates as an open Claude cycle (see Figure 2) and uses seawater directly as the working fluid. The vapor space of the plant is enclosed in a sealed enclosure 7 to avoid air leaks from the environment (a vacuum pump is not shown). Processes that remove heat in the Claude cycle (see Figure 2a) are carried out at a lower temperature than in the Anderson cycle. As a result the thermodynamic efficiency of a plant that operates on an open cycle is higher than that of a plant operating as a closed cycle. A disadvantage of plants that operate on an open cycle is the implementation of the processes under vacuum conditions. This results in a need for the installation to be large, and the steam turbine is large and this leads to high installation costs [1, 4, 5, 9, 14, 18].

Plants that operate on the Anderson cycle require heat exchangers that are optimized for the steam generator and condenser on the level of hydraulic losses during pumping of seawater, since it affects the magnitude of the temperature difference in these devices and, therefore, on the thermodynamic efficiency of plants.

For thermodynamic cycles Claude and Anderson there is a limitation on the range of expansion working fluid in a turbine, due to the small difference between the temperatures of the surface and of the deep of sea water, which determines the low value of the thermal efficiency of plant [1, 5, 9, 14].

### **3. THERMODYNAMIC CYCLES THAT EXPLOIT PROPERTIES OF GAS HYDRATES**

Disadvantages of existing plant that use OTEC stimulate the search for new solutions, the implementation of which will create a more efficient plant. One solution may be to develop plant OTEC, in a cycle which use gases that are capable of forming gas hydrates under certain thermodynamic conditions.

Gas hydrates are crystalline compounds that include clathrates in which a small number of polar or non-polar molecules promote the formation of ice-like structure of water as a result of van der Waals forces [11, 12]. These properties of gas hydrates allow one to create plant OTEC for the combined generation of electricity, fresh water and the cold – GHET.

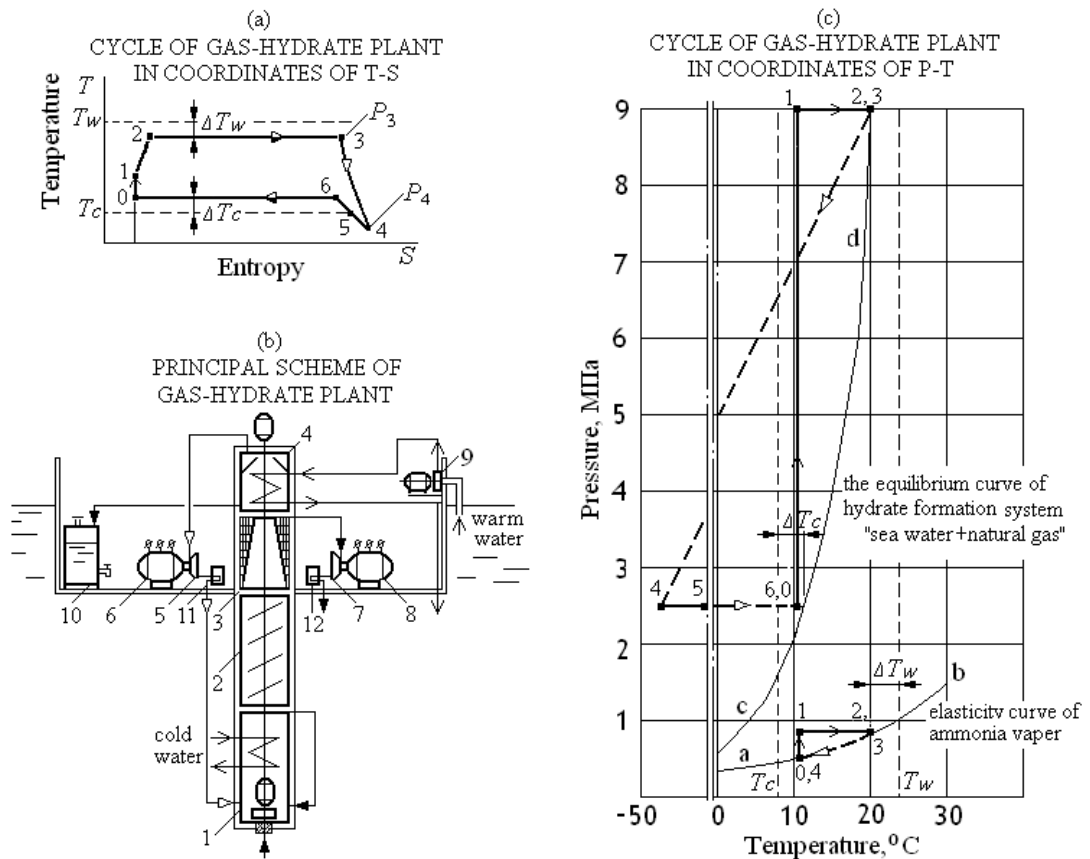
Figure 3 shows a schematic of the scheme (Fig. 3b) and the GHET cycle as T-S and P-T diagrams (see Figures 3a and 3c). Temperatures of  $T_c = 8$  °C and  $T_w = 24$  °C are taken for the Black Sea conditions (see Figure 3,c), ie

Cycle GHET (Figures 3,a and 3,c) consist of the following processes:

- 0-1 – the process of compression slurry of gas-hydrate and water;
- 1-2 – heating gas hydrates;
- 2-3 – the melting of gas hydrates in the melter;
- 3-4 – expansion of natural gas in a gas turbine;
- 4-5 – the heating of the gas in the cooling chamber;

5-6-0 – the formation of gas hydrates in the crystallizer.

The T-S diagram indicates a "qualitative" cycle of the gas-hydrate energo-technological plant in which the working fluid is natural gas without the thermodynamic processes of changing state of gas-hydrate for compound "natural gas +water". The P-T diagram shows the cycles of the gas-hydrate energo-technological plant and of the plant on the cycle Anderson for comparative analysis (see Figer 3,c). The following notation is used: c-d – the equilibrium curve of hydrate formation system "sea water +gas" [13]; a-b – equilibrium saturation curve for ammonia; 0-1-2-3-4 – respectively, the nodal point of the cycle Anderson, shown in Figure 1,b.



**Figure 3.** A GH plant (b) and its thermodynamic cycle: T-C diagram (a) and P-T diagram (c).

From a comparison of the cycles of plants: that harness gas-hydrates and the Anderson cycle using ammonia, it can be seen that the slope of the equilibrium curve of the hydrate is much greater than the saturation curve of ammonia vapour. As a result, for the same temperature difference between the surface of the ocean and the ocean depth, the expansion of the working fluid in the turbine of the gas-hydrate energo-technological plant is substantially greater than in the turbine of plant using the cycle Anderson and thus the GHET produces greater work. Note, that this pattern holds for other working fluids, such as propane and R-22.

A distinctive feature the cycle that employs gas-hydrates is the use phase transitions of formation/of melting of gas-hydrates. The formation of hydrates occurs upon contact of natural gas and seawater, melting – with the release of natural gas and fresh water.

GHET (see Figure 3,b) operates as follows:

Sea water and natural gas are pumped to the crystallizer 1 at  $T_0 = 8\text{ }^{\circ}\text{C}$  and a pressure of  $P_0 = 2.5\text{ MPa}$ . As a result, gas hydrates are formed and heat of formation is removed by means of

cold water which pumped through the heat exchanger of the crystallizer. The mixture of hydrate and brine is fed by screw 2 to the filter chamber 3, where the hydrates are separated from the brine and are washed with a small amount of fresh water in countercurrent operation. Hydrates which are washed from the brine are fed into the melter 4 where they are melted to yield fresh water and natural gas at high pressure ( $P_3 = 9$  MPa). The heat of fusion of the hydrate is transferred to warm water which is pumped through the heat exchanger of melter using the pump 9. The fresh water directed from the melting unit 4 in tank 10 as the useful product. High-pressure gas is supplied to the gas turbine 5, where it expands to the pressure  $P_0 = 2.5$  MPa with the production of work to drive an electric generator 6. From the turbine the gas at a temperature  $T_4 = -45$  °C directly to the cooling chamber 11 as the cold source for the freezing of food products, where this gas is heated to  $T_5 = -20$  °C (process 4-5 in Figure 3,c) and then this is recycled to the crystallizer 1.

The brine from the filter chamber 3 is directed to a hydraulic turbine 7 to drive an electric generator 8 and then at a temperature  $T_0 = 10$  °C it is directed to the heat exchanger 12 where it is used for air conditioning.

#### 4. THERMODYNAMIC ANALYSIS OF POWER PLANTS USING THE THERMAL ENERGY OF OCEAN

To carry out a thermodynamic analysis of reversible cycle power plant using OTEC (see Figures 1a, 2 and 3b) by comparing the thermal efficiency ( $\eta_t$ ) utilizes the corresponding and equivalent Carnot cycles. These are constructed using average the planimetric temperature for the processes: the supply/removal of heat  $T_{mw}$  and  $T_{mc}$  (see Figure 4). For cycles, which operate at the constant temperatures of the warm and cold water, and for the equivalent cycles built for the same temperatures  $T_{mw}$  and  $T_{mc}$ , thermal efficiency will be equal.

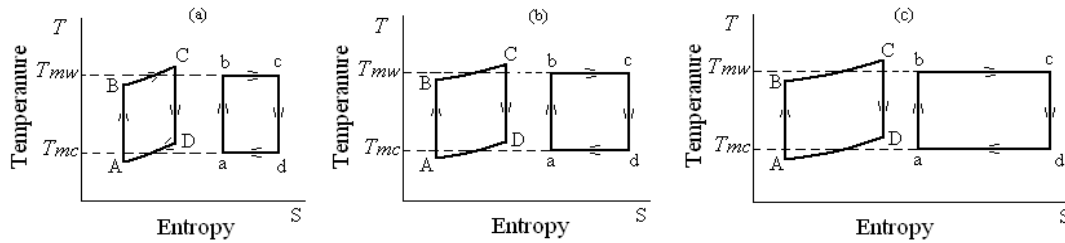


Figure 4. Equivalent Carnot cycles

This follows from the definition of  $\eta_t$  [13] for the reversible corresponding and equivalent Carnot cycle (see Figures 4a, 4b and 4c) for three OTEC systems at the equality of temperatures  $T_C$  and  $T_A$  as well as  $T_{mw}$  and  $T_{mc}$  in these cycles:

$$\eta_t = \frac{T_w - T_c}{T_w}, \quad (3)$$

where:  $T_w = T_C$  and  $T_c = T_A$  – for the respective cycles;

$T_w = T_{mw}$  and  $T_c = T_{mc}$  – for cycles that are equivalent.

In carrying out analyses of the actual (irreversible) cycles of the OTEC plant must take into account the losses arising from external and internal irreversibilities and which are associated with an increase in the entropy of an isolated system, which leads to the degradation of its working performance. These losses can be divided into two parts: the first is related with heat exchange between working fluid and the heat source: the warm surface waters and the cold deep waters; the second defined by internal irreversibility of the processes taking place within the working fluid [13].

The thermal efficiency a Carnot cycle, taking into account losses associated with external irreversibility (due to heat transfer) is by the defined by the expression [9,13]:

$$\eta_T = \frac{(T_w - \Delta T_w) - (T_c + \Delta T_c)}{T_w - \Delta T_w} \quad (4)$$

As a first approximation, losses of efficiency due to internal irreversible processes can be taken into account using adiabatic efficiency ( $\eta_{ad}$ ), which takes into account the deviation of the real process of expansion of the working fluid in the turbine from the process adiabatic expansion [6, 13,16]. Then, the thermal efficiency of a Carnot cycle, taking into account external and internal irreversibilities is defined as:

$$\eta_T = \frac{(T_w - \Delta T_w) - (T_c + \Delta T_c)}{T_w - \Delta T_w} \eta_{ad} \quad (5)$$

The results of the estimated thermal efficiencies of the power plants using OTEC are presented in Table 1.

Table 1 – The estimated thermal efficiencies of real cycles for plants using OTEC.

Type of plant	$\Delta T$	$\eta_t$
Plant using the Anderson cycle	3	0,024
Plant using the Claude cycle	1	0,037
Plant that employs gas-hydrates of technology	3	0,024

Note: in the calculation it is assumed that  $T_w = 295$  K,  $T_c = 281$  K,  $\Delta T_w = \Delta T_c$  and  $\eta_{ad} = 0.9$ .

Table 1 shows that the open cycle Claude has a higher  $\eta_t$ , than the Anderson and GHET cycles. However, as noted above, a significant disadvantage of plants operating on an open cycles, is the need to use a vacuum steam turbines, sizes of which exceed the sizes turbine for plant with a closed cycle by an order or more, leading to a rise of the costs and complexity of such systems. It prompts the initiation of an experimental study of pilot plants with the closed cycle Anderson, despite a lower energy efficiency [1, 4, 9, 18].

The equality the efficiencies of the Anderson and GHET cycles determined according to the above irreversibilities, does not mean that these cycles have the same degree of thermodynamic perfection when taking into a full account the irreversible losses. A comparative analysis of the degree of the perfection of the Anderson and GHET cycles is advisable to perform based on analyze the exergetical effectivity [6, 8,13]:

$$\eta_{ex} = \frac{e_{us}}{e_{sp}}, \quad (6)$$

where  $e_{us}$  – useful exergy (for plant of Anderson  $e_{us} = l_{us}$  and for GHET  $e_{us} = l_{us} + e_{fr} + e_{qo}$ );

$l_{us} = l_t - l_p - l_{s.w.}$  – useful work of the plant;

$e_{fr}$  – useful exergy of fresh water;

$e_{qo}$  – useful exergy of cold;

$l_t$  – the work of expansion of the working fluid in the turbine;

$l_p$  – the work of compression of the working fluid in the pump;

$l_{s.w.}$  – the work of circulation of sea water through heat exchangers of

evaporator/crystallizer and condenser/melter.

$e_{sp} = e_{c.w.} \cdot G_{c.w.}$  – the exergy spent determined with reference consumption cold sea water  $G_{c.w}$  used as a cold source.

The work of expansion of the gas in the turbine of plant  $l_{t,g}$ , kJ/ kg gas [16] is expressed by:

$$l_{t,g} = c_p \cdot T_3 \cdot \left[ 1 - \frac{1}{\left( \frac{P_3}{P_4} \right)^{\frac{k-1}{k}}} \right] \cdot \eta_{ad} , \quad (7)$$

where  $c_p$  – specific heat capacity of the gas (the average for the gas expansion process [10];  
 $k$  – coefficient of adiabatic for the gas (the average for process of expansion gas [10]);  
 $\eta_{ad}$  – adiabatic efficiency for process of expansion of the gas.

Note, the gas-hydrate energo-technological plant uses the work of expansion of the brine in the hydraulic turbine after separation the brine from gas-hydrates in the filter chamber and the work of expansion of fresh water formed by melting of gas hydrates. The work of expansion of the brine in hydraulic turbine  $l_{t,b}$ , kJ/ kg gas:

$$l_{t,b} = \frac{G_b \cdot (P_1 - P_0) \cdot \eta_{ad}}{\rho_b \cdot 1000} , \quad (8)$$

where  $G_b$  – the mass flow rate of the brine;  
 $\eta_{ad}$  – the adiabatic efficiency of the turbine;  
 $\rho_b$  – brine density.

The work of expansion of fresh water in the hydraulic turbine  $l_{t,fr}$ , kJ/ kg gas:

$$l_{t,fr} = \frac{G_{fr} \cdot (P_1 - P_0) \cdot \eta_{ad}}{\rho_{fr} \cdot 1000} , \quad (9)$$

where  $G_{fr}$  – the mass flow rate of fresh water;  
 $\rho_{fr}$  – fresh water density.

Work of feeding sea water into the crystallizer  $l_{p,s.w.}$ , kJ/ kg gas is:

$$l_{p,s.w.} = \frac{G_{s.w.} \cdot (P_1 - P_{s.w.})}{\rho_{s.w.} \cdot 1000 \cdot \eta_{ad}} , \quad (10)$$

where  $G_{s.w.}$  – mass flow sea water, compressed by the pump;  
 $\rho_{s.w.}$  – density of the sea water;  
 $P_1$  and  $P_{s.w.}$  – respectively the working fluid pressure at the pump outlet and in inlet;  
 $\eta_{ad}$  – adiabatic efficiency for process of compression.

Note, that the pump of GHET wich compress the water and the gas hydrates, is spending on work of pump  $l_{p,h.s.}$ , kJ/ kg gas:

$$l_{p,h.s} = \frac{G_{h.s.} \cdot (P_1 - P_{h.s.})}{\rho_{h.s.} \cdot 1000 \cdot \eta_{ad}} . \quad (11)$$

Work of the pump circulation on pumping seawater through the heat exchangers evaporator/crystallizer and condenser/melter  $l_{s.w.}$ , kJ/ kg gas:

$$l_{s.w.} = \frac{G_{s.w..} \cdot \Delta P_{s.w.}}{\rho_{s.w..} \cdot 1000 \cdot \eta_{ad}} , \quad (12)$$

where  $G_{s.w.}$  – the mass flow rate of cold and warm sea water through heat exchangers (accepted these costs is the same);

$G_{s.w.} = G_{s.w.(A)}$  – for the plant Anderson and  $G_{s.w.} = G_{s.w.(G)}$  – for GHET;

$\Delta P_{s.w.}$  – the flow resistance the circulation of sea water in the heat exchanger (the same for both units), Pa.

Work on seawater circulation in heat exchanger of the evaporator/crystallizer and condenser/melter is:

$$l_s = 2 l_{s.w.} \quad (13)$$

### Defining useful exergy for products generated on GHET:

Exergy of fresh water produced during melting of gas hydrates:

$$e_{fw} = W_{min} \cdot n \frac{\mu_w}{\mu_g}, \quad (14)$$

where  $W_{min}$  – minimum work seawater desalination, kJ/ kg gas [19];

$n$  – number of molecules of water that falls on a single molecule of natural gas [12];

$\mu_w$  and  $\mu_g$  – molecular mass of water and gas.

Useful exergy of gas  $e_{q0}$  which used in the refrigeration chamber  $e_{q0(g)}$ :

$$e_{q0(g)} = q_0 / \varepsilon_k \quad (15)$$

where  $q_0$ , kJ/ kg of gas – cold of the gas stream at the outlet of the gas turbine:

$$q_0 = c_p \cdot (T_5 - T_4); \quad (16)$$

$\varepsilon_k$  – the coefficient refrigerating for the reverse Carnot cycle (at average temperature of the gas in the cooling chamber  $T_{av}$  and at environment temperature, equal  $T_{en}$  (for the warm water on surface sea):

$$\varepsilon_k = T_{av} / (T_{en} - T_{av}). \quad (17)$$

Useful exergy of brine for using on conditioning the air  $e_{q0(b)}$ , is defined as in (15).

Then:

$$e_{q0} = e_{q0(g)} + e_{q0(b)} \quad (18)$$

### Exergy spent for the plant:

The exergy spent  $e_{sp} = e_{c.w.} \cdot G_{c.w.}$  determined with reference consumption cold sea water  $G_{c.w.}$  used as a cold source. Here  $e_{c.w.}$  – exergy 1 kg of deep cold seawater:

$$e_{c.w.} = c \cdot [(T_{c.w.} - T_{en.}) - T_{en.} \ln(T_{c.w.} / T_{en.})], \quad (19)$$

where  $c$  – specific heat capacity of the deep cold seawater, kJ/kg;

$T_{c.w.}$  – temperature deep cold seawater;

$T_{en}$  – environment temperature (for the warm water on surface sea).

a) the flow of deep cold seawater for plant Anderson:

$$G_{c.w.(A)} = r_a / (c \cdot \Delta T_k), \quad (20)$$

where  $r_a$  – heat of phase transition for ammonia;

$c$  – the specific heat capacity of sea water;

$\Delta T_k$  – the heating of sea water while cooling the condenser.

b) the flow of deep cold seawater for the GHET:

$$G_{c.w.(G)} = \Delta H_G / (c \cdot \Delta T_{kr}), \quad (21)$$

where  $\Delta H_G$  – heat of formation of gas-hydrates;

$\Delta T_{kr}$  – the heating of sea water while cooling the crystallizer.

The results of the calculation of specific energy indicators (kJ/ kg gas) and exergetical efficiency for cycles of plants which are shown in Figure 3,c are shown in Table 2.



Table 2 – Results of calculation for plants using OTEC

n/n	The plant on cycle of Anderson (working fluid – ammonia)		the gas-hydrate energo-technological plant (working fluid – natural gas)	
	The equation for calculating	Calculation	The equation for calculating	Calculation
1. Work expansion, $l_t$	$l_t = l_{t,g}$	32,5	$l_t = l_{t,g} + l_{t,b} + l_{t,fr}$	252,4
2. Work compression, $l_p$	$l_p = l_p$	0,5	$l_p = l_{p,s.w} + l_{p,h.s}$	156,6
3. Work on seawater circulation, $l_s$	$l_s = 2 \cdot l_{s.w.}$	18	$l_s = 2 \cdot l_{s.w}$	56,5
4. Useful work, $l_{us}$	$l_{us} = l_t - l_p - l_s$	14,0	$l_{us} = l_t - l_p - l_s$	39,3
5. Exergy freshwater, $e_{fr}$	–	–	$e_{fr} = W_{min} \cdot n \cdot \mu_w / \mu_g$	14,1
6. Exergy cold gas, $e_{qo(z)}$	–	–	$e_{qo(g)} = q_0 / \varepsilon_{\kappa}$	12,8
6.1. Cooling capacity, $q_0$	–	–	где $q_0 = c_p (T_5 - T_4)$	126,5
6.2. Refrigeration coefficient, $\varepsilon_{\kappa}$	–	–	$\varepsilon_{\kappa} = T_{a.t.} / (T_{e.t} - T_{a.t.})$	5,8
7. Exergy cold brine, $e_{qo(b)}$	–	–	$e_{qo(b)}$	1,4
8. Exergy spent, $e_s$	$e_s = e_{c.w.} \cdot G_{c.w.}$	173,0	$e_s = e_{c.w.} \cdot G_{c.w.}$	540,0
8.1. Exergy deep cold seawater, $e_{x.e}$	$e_{c.w.} = c \cdot [(T_{c.w.} - T_{en.}) - T_{en.} \cdot \ln(T_{c.w.} / T_{en.})]$	1,195	$e_{c.w.} = c \cdot [(T_{c.w.} - T_{en.}) - T_{en.} \cdot \ln(T_{c.w.} / T_{en.})]$	1,195
8.2. Consumption of deep cold seawater, $G_{c.w.}$ (kg/ kg gas)	$G_{c.w.(A)} = r_a / (c \cdot \Delta T_k)$	145	$G_{c.w.(G)} = \Delta H_g / (c \cdot \Delta T_{kr})$	452
8.3. The heat of the phase transition of the working fluid, $\Delta H$	$\Delta H_a$	1210	$\Delta H_g$	
9. The exergy efficiency of the plant, $\eta_{ex}$	$\eta_{ex} = l_{us} / e_{sp}$	0,08	$\eta_{ex} = (l_{us} + e_{fr} + e_{qo}) / e_{sp}$	3785
				0,12

When calculating the energy performance settings, the following data were used:

1) for equation (8):

$$G_b = G_s - G_g = 15.46 - 7.73 = 7.73 \text{ kg of brine/ kg gas;}$$

$$G_s = G_g / S = 7,73 / 0,5 = 15.46 \text{ kg of suspension/ kg gas;}$$

$$G_g = G_w + 1 = 1 + 6.73 = 7.73 \text{ kg hydrate/ kg gas;}$$

$$G_w = 6.73 \text{ kg water/ kg gas [7.13].}$$

2) for the equation (10):

$$P_{s.w.} = 0.5 \text{ MPa (acceptable for the crystallizer, which is placed on depth equal } H \approx 50 \text{ m).}$$

3) for the equation (12):

$$\Delta P_{s.w.} = 0.5 \cdot 10^5 \text{ Pa – acceptably the same for both plants.}$$

4) for the equation (14):

$$W_{min} = 2.175 \text{ kJ/ kg of fresh water – minimum work seawater desalination [12];}$$

$$n = 5.75 \text{ – number of molecules of water sitting on single molecule the natural gas [12];}$$

$$\mu_w = 18 \text{ and } \mu_g = 16 \text{ – molecular weight of the water and gas.}$$

5) for the equation (16):

$$c_p = 2.2 \text{ kJ/ (kg} \cdot \text{K) – specific heat capacity of the gas in the cooling chamber [10];}$$

$$T_4 = 253 \text{ K – gas temperature at the outlet of the cooling chamber;}$$

$T_5 = 228 \text{ K}$  – gas temperature at the inlet of the cooling chamber.

6) for the equation (17):

$\varepsilon_k = T_{av} / (T_{en} - T_{av}) = 241 / (297 - 241) = 4.3$  – the coefficient refrigerating for the reverse Carnot cycle (at average temperature heat removal in the cooling chamber  $T_{av}$  and at environment temperature, equal  $T_{en}$  (for the warm water on surface sea);

$T_{av} = (T_5 + T_4) / 2 = (253 + 226) / 2 = 241 \text{ K}$ .

7) for (19):

$c = 4.2 \text{ kJ} / (\text{kg} \cdot \text{K})$  – specific heat capacity of the deep cold seawater  $T_0 = 8 \text{ }^\circ\text{C}$ ;

$T_{c.w.} = 291 \text{ K}$  – temperature deep cold seawater;

$T_0 = 297 \text{ K}$  – the temperature for the warm water on surface sea.

8) for equation (20):

$r_a = 1200 \text{ kJ} / \text{kg}$  of ammonia – heat of phase transition of ammonia at  $T_4 = 12 \text{ }^\circ\text{C}$  [17];

$c = 4.2 \text{ kJ} / (\text{kg} \cdot \text{K})$  – specific heat of deep cold water at  $T_0 = 8 \text{ }^\circ\text{C}$ ;

$\Delta T_k = 2 \text{ }^\circ\text{C}$  – heating sea water while cooling the crystallizer.

9) for the equation (21):

$\Delta H_g = 3785 \text{ kJ} / \text{kg}$  gas – heat of formation of gas-hydrates/ melting.

## 5. CONCLUSIONS

We have examined the scheme and the cycle of the gas-hydrate energo-technological plant (GHET) using ocean thermal energy (OTEC) to produce electricity, fresh water and cold. Based on the proposed methodology we have ascertained the efficiencies of plants using the Anderson and GHET cycles.

Assuming the same difference between temperatures at the surface and a depth, the expansion ratio of the gas in turbine of the plant of GHET is several times greater than that of a steam turbine of the plant using the Anderson cycle. It suggests that the useful work obtained from 1 kg of the working fluid in the GHET plant is approximately 3 times higher.

The thermal efficiency of the GHET plant and plants using the Anderson cycle under the same conditions are approximately equal. However for the GHET plant produces two additional products – fresh water and the cold, the exergetic efficiency is greater 1.5 greater than the Anderson cycle.

Further researches on producing energy, fresh water and cold by harnessing gas-hydrates technology using ocean thermal energy (OTEC) are required in the direction of optimization of equipment and simulation of processes occurring in it and a specific use OTEC.

## REFERENCES

- [1] Da Rosa, Aldo Vieira (2009). "Chapter 4: Ocean Thermal Energy Converters". Fundamental of new able energy processes. Academic Press. – 2009. – pp. 139 – 152.
- [2] Denisov Y.P., Klymenko V.V. The use of gas hydrate plants to generate electricity/ Zbirnik tes dopovidey mizhnarodnoï naukovo-praktichnoï konferentsii "The problem the energoeftivnosti and avtomatizatsii in promislovosti and agroprom" Kirovograd National Technical University, 21-22.10.2015. – p. 23-25.
- [3] Denisov Y.P., Klymenko V.V. Plant gas-hydrate for produce electricity and fresh water/ The news of the politechnical institute, Vinnitsa, №3 (126), 2016.- p. 65-72.
- [4] Electronic Resources: [https://en.wikipedia.org/wiki/Ocean\\_thermal\\_energy\\_conversion](https://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion).
- [5] Electronic Resources: Hawaii First to Harness Deep Ocean Temperatures for Power; <http://www.scientificamerican.com/article/hawaii-first-to-harness-deep-ocean-temperatures-for-power>.
- [6] Kirillin V.A. et al. Engineering Thermodynamics / V.A. Kirillin, V.V. Sychev, A.E. Sheyndlin. – M.: Energoatomisdat, 1983. – 416 p.
- [7] Klymenko V.V., Smirnov L.F. (USSR). Seawater desalination plant – A. C. 608767, M. Kl2 C02 B 1/12, № 2425748/ 29-66, st. 29.11.76, publ. 05.30.78. Bul. № 20.
- [8] Klymenko V.V. The use of natural sea water temperature difference to produce fresh water and cold/ V.V. Klymenko // Refrigeration equipment and technology. – 1974, №.19. – p. 75-79.

- [9] Korobkov V.A. Ocean Energy Conversion. – L: Shipbuilding. – 1986. – 280 p.
- [10] Kozachenko A.N. Operation of compressor stations of main gas pipelines. – M.: Oil and Gas. – 1990. – 463 p.
- [11] Makogon Y.F. Hydrates of Natural Gases/ Y.F. Makogon, M.: Nedra, 1974. – 208 p.
- [12] Makogon Y.F. Hydrates of Hydrocarbons. Tulsa: Penn Well, 1997. – 504 p.
- [13] Martynovsky V.S. Analysis of real thermodynamic cycles. – M.: Energia, 1972. – 216 p.
- [14] Mohammed Faizal, M. Rafiuddin Ahmed. Experimental studies on a closed cycle demonstration OTEC plant working on small temperature difference/ Renewable Energy. – Volume 51, March 2013, Pages 234–240.
- [15] Patent US 3312054. Sea water power plant/ Jr. James H. Anderson (USA). April 4, 1967 Filed Sept. 27, 1966.
- [16] Pavlov K.F. Examples and problems at the rate of processes and apparatuses of chemical technology/ K.F. Pavlov, P.G. Romankov, A.A. Noskov. – L.: Chemistry, 1981. – 560 p.
- [17] Problems in heat transfer processes in the food and refrigeration industry/ G.N. Danilova, V.N. Filatkin, M.G. Shcherbov, N.A. Buchko. – M.: Agropromizdat, 1986. – 288 p.
- [18] Renewable Energy From The Ocean: a guide to OTEC/ William H. Avery, Chih Wu. – New York: Oxford University Press, 1994. – P. 446.
- [19] Smirnov L.F. The use of deep sea water to produce fresh water and cold/ L.F. Smirnov, V.V. Klymenko// Refrigeration. – 1975. – № 2. – p. 34-37.
- [20] Smirnov L.F., Klymenko V.V. (USSR). Seawater desalination plant – A. C. 709547, M. Kl. C02 B 1/06. №1865650/ 23-06, st. 01.03.1973, publ. 01.15.80. Bul. № 2.