Submersible power-generating unit as an alternative energy sources

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Abstract. There was proposed a compact underwater energy generating device in which energy is produced by underwater currents and tidal phenomena on the Arctic coast for small settlements. These communities will be created to track ships sailing along the Northern Sea Route and to provide operational assistance if necessary. The idea of the technical proposal is structurally distinctive, the device is carried out of a set of conventional pipes of a certain diameter with a fairly wide bell (funnel), horizontally mounted towards the underwater current. This idea is quietly new for Russia, and it’s learned not very well. Calculation was provided in a new way on the basis of Propellers theory. In result there are shown table with calculated efficiency of our turbines with defined quantity of turbines in machine unit.  Also we suppose that our approach is more accurate then results obtained with Betz’s formula as so as Betz’s formula doesn’t consider geometrical option of impeller.

1. Introduction

It is well known that the water masses of the oceans and seas are in constant motion, caused by the Earth's rotation, the lunar attraction, the influence of constantly circulating air masses warmed by the sun. As a consequence of all this, the seas and oceans have quite distinct undercurrents, which are characterized by considerable constancy. The width, depth and length of these currents depend on many factors, such as the heating of the water column by the sun's rays, the temperature of the Earth's bottom surface, the variability of the seabed topography, the roughness of the bottom surface, etc. Sea currents such as the Gulf Stream in Europe or the Kuro-Siwo in Asia are the best known. On the basis of many years of research it can be stated that the intensity of most permanent underwater currents differs only slightly in seasonality [1].

However, if wind activity has been used by mankind since time immemorial, primarily by means of sails at sea and windmills on land, strangely enough marine currents, despite their popularity, have been used by mankind very little, although they have long been known and considered by marine experts only in navigation. The hydrographic and hydrological knowledge of most seas and oceans has already been investigated quite fundamentally; including our permanently frozen Arctic seas. However, the practical application of this knowledge is extremely limited. Our Arctic seas, naturally, are much less well studied overall and, nevertheless, we have some knowledge of the vertical and horizontal (i.e. Along our Euro-Asian continent, there is a certain amount of data on temperature variations, determining underwater current circulation, which mainly takes place from the west to the east along our coastline and vice versa, closer to the north, from the east to the west, i.e. a kind of rotation in horizontal planes (strata) of underwater currents [1]. The general circulation of water in the form of underwater currents is
predominantly wind-driven (the Barents Sea is almost ice-free thanks to the Gulf Stream) while the general movement of surface water is counter-clockwise, complicated by different directions and speeds of currents (about 0.25-1.0 m/s range of speeds). We present all this information in order to justify the possibility of using underwater engines/turbines to generate electricity using underwater currents. It is certainly possible to implement such proposals if such currents are available in specific areas of the seas. The search for these points should be the subject of separate focused hydrographic and hydrological studies of our Arctic seas in order to take advantage of such a gift of perpetual energy in the vast Arctic coastline.

The idea of our technical proposal is not at all new, but nevertheless it is structurally quite original (although similar to the famous Katyusha multiple rocket launcher), quite compact and extremely necessary for long-term security of the entire length of the Northern Sea Route (NSR) and will be very timely.

Our proposal is based on the real possibility of harnessing the near-eternal energy of the almost ubiquitous undercurrents that exist along the vast expanse of our Arctic coastline. In this way, the most suitable locations should be found for the establishment of industrial bases, much needed for the organization of year-round observation/tracking of the condition of vessels travelling along the NSR. No matter how intense global warming may be, dangerous situations are always likely to arise along such an almost lifeless long route and timely operational assistance will always be needed. The proposed industrial bases should be placed "in increments" approximately every 100-150 km of the coastal zone in the most convenient locations for ships as well as for helicopters and seaplanes, and these locations should be chosen with the most intense undercurrents, since the greatest power production is possible where the highest undercurrent velocities are observed or pronounced tidal currents take place. The proposed industrial zones should be equipped with a certain set of technical facilities, which may be necessary for appropriate servicing of vessels passing along the NSR route. It should also be noted that the installation of the proposed power units is slightly above the bottom surface, where the velocity of underwater currents is reduced to almost zero.

It should also be noted that we know about creation of autonomous hybrid electric installation in SRC "Kurchatov Institute" for power supply of small power facilities for communication, etc. in arctic conditions [2]. However, our proposal will be able to meet the needs of creation of greater power, so necessary for the needs of industrial bases with the staff of about 100 people, which will need more energy for their activities, because the range of tasks in such industrial bases is very diverse and may still have to be specified in the future. Below is a possible example of such a simple technical device in the form of a set of ordinary pipes of a certain diameter with a rather wide socket (funnel), horizontally mounted towards the underwater current: the presence of a socket in each pipe will probably increase the speed of water flow in the pipe, inside which several (not more than 3) impellers generating electricity are placed in series (Fig.1); the protection to turbines is provided by setting a quality mesh at the entrance to the socket to avoid ingress of any kind of water into the pipe. In addition, after each impeller in the pipe there is a so called "stabiliser" in the form of a small bundle of hollow tubes (not more than 10 cm long), the presence of which will prevent possible cavitation caused by the rotation of the flow by the impeller. In general, the above-described energy device will make it possible to supply electric power to the entire industrial site located on the deserted space of the Arctic coast.

Below we present the necessary analytical calculations to prove the possible use of the proposed device. We would also like to emphasize that this source of electrical energy has potentially no negative impact on nature, as it does not have any waste, such as that of nuclear power plants. This factor is most relevant offshore, as it is very expensive to eliminate environmental disasters there.
2. The analytical part

To illustrate our idea, let's refer to the conceptual diagram in Figure 1.

![Conceptual diagram of a submarine power unit](image)

Figure 1. Conceptual diagram of a submarine power unit

1- Seabed (soil), 2- Pile, 3- Foundation plate, 4- Rotor plate (rotating part), 5- Generator turbine, 6- Nozzle (socket), 7- Float to optimize the position of the structure towards the current, 8- Carrier pole.

As it was mentioned above, its main idea is to aggregate several dozens of small turbines into a single significantly more powerful structure, taking into account the flow profile.

Let's estimate the produced power, and for this purpose let's consider the case of ideal vane unit in cylindrical tube of arbitrary cross-section. Let's refer to formulas which were obtained by us previously (1) and (2) to calculate power and torque of one turbine [3]:

\[
M = r \rho V t g(\beta); \quad (1)
\]

\[
P = \eta \rho V^3 t g^2(\beta), \quad (2)
\]

Where \( r \) – radius of the blade, \( \rho \) – density of the fluid flowing around the blade; \( V \) – velocity of the incoming flow, \( \beta \) – angle of inclination of the blade to the rotation axis, \( \eta \) – coefficient of efficiency, \( M \) – mechanical moment, \( P \) – power.

The power formula (2) is very similar to Betz’s law (3). In 1919, the German physicist Albert Betz made a discovery. He discovered that a wind turbine can convert only 59.3 % of the kinetic energy of the air into electrical energy. This fact is now known as Betz’s limit or Betz’s law [4]. Thus, the theoretical maximum of any wind turbine is 0.59, a number commonly referred to as Betz’s coefficient.

\[
P = \frac{1}{2} \rho A V^3 C_p, \quad (3)
\]

Where \( \rho \) – is the density of the fluid flowing around the blade; \( V \) – is the speed of the oncoming flow, \( A \) – is the cross-sectional area of the turbine at the impeller location, \( C_p \) – is the Betz coefficient, \( P \) – is the power.

It can be concluded that in our formula (2), the product \( \eta \cdot t g^2(\beta) \) is analogous to the Betz coefficient \( C_p \). Thus, it can be argued that our proposed formulas (1) and (2) do not contradict the generally accepted laws of physics, but, unfortunately, they are not representative from the engineering point of view.

Analyzing them, it is possible to come to conclusion that they are very limited in application as they are connected with geometrical characteristics of impeller through function of tangent, so proceeding from mathematical sense at increase of this angle, both moment and power of turbine should increase, that contradicts with physical sense. Therefore, we decided to consider the energy conversion process on the impeller from the hydrodynamic point of view.

Let's refer to the hydrodynamics of streamlined bodies and use the lifting force coefficient. It is a dimensionless value depending on angle of attack and shape of streamlined body profile. The curve
expressing the lifting force coefficient versus angle of attack is usually obtained experimentally, either in wind tunnels or in a full-scale test. For a more detailed calculation, we refer to the following diagram:

Figure 2. Diagram of lifting force coefficient for an asymmetric profile versus angle of attack.

Figure 2 shows dependence of lifting force coefficient of asymmetric profile on angle of attack $C_y = f(\alpha)$ [5], as the blades in the considered problem have asymmetric profile. Let us consider process of water flow overrun on impeller. For this purpose, let's approximate process of passing of water stream over the blade (Figure 3).

Figure 3. Dynamic processes on the impeller blade element.

$dX$ – drag force, $dY$ – lifting force, $dT$ – tangential force, $V_p$ – oncoming flow velocity, $V_s$ – sliding velocity of fluid on the blade, $V_r$ – circumferential velocity of fluid, $\alpha$ – angle of attack, $\beta$ – inductive angle, $\omega$ – angular velocity.

On a blade element, as on a wing element, as it moves in a fluid or gas medium, there is a lifting force $\vec{Y}$, directed perpendicular to the speed of the incoming flow, in our case speed $V_s$, and a drag force $d\vec{X}$, counteracting the motion of the element. These forces are calculated as follows [6]:

$$dY = C_y \frac{\rho V_s^2}{2} b dr;$$  

(4)

$$dX = C_x \frac{\rho V_s^2}{2} b dr,$$  

(5)
Where $C_y$ – is the lifting force coefficient, $C_x$ – is the drag coefficient, $\rho$ – is the density of the medium in which the flow occurs, $b$ – is the thickness of the blade element at this section, $dr$ – is the elementary radius of the blade element at this section;

If the lifting force $dY$ and the drag force $dX$ are projected onto the circumferential velocity direction, we obtain the tangential force $dT$ highlighted in green in Figure 3.

$$dT = dY \sin \beta (1 + \varepsilon \cot g \beta) z,$$

(6)

Where $\varepsilon = \frac{dx}{dy}$ – the inverse quality coefficient of the element. (*This coefficient describes the profile resistance.*) $z$ – number of blades;

It is evident from these formulas that the stiffness of the element is created solely by the lift force. The profile resistance, on the other hand, causes a reduction of the stop, but at the same time increases the tangential force and therefore increases the torque required to rotate the element:

$$dM = rdT = rdY \sin \beta (1 + \varepsilon \cot g \beta) z$$

(7)

By integrating equation (7) over the entire blade length from $r_c$ to $R$ and making the necessary transformations, the following formulas for determining the moment on the impeller can be obtained:

$$M = \int_{r_c}^{R} r \sin \beta (1 + \varepsilon \cot g \beta) dY = \int_{r_c}^{R} z r \sin \beta (1 + \varepsilon \cot g \beta) C_y \frac{\rho V^2}{2} b \, dr$$

(8)

Let's calculate integral (8), neglecting the dependence of angle $\beta$ on radius, then the cross-sectional area of the blade element will be represented as a thin rectangle and thus we obtain formula (9) to calculate the mechanical moment created by water flow on the turbine impeller:

$$M = z \sin \beta (1 + \varepsilon \cot g \beta) C_y \frac{\rho V^2}{2} \int_{r_c}^{R} r b \, dr = z \sin \beta (1 + \varepsilon \cot g \beta) C_y \frac{\rho V^2}{2} b r^2 \int_{r_c}^{R} \frac{r}{2}$$

(9)

3. Hydromechanical part and energy capacity
In order to determine at what parameters this hydraulic unit will work most optimally and efficiently, consider several scenarios using different hydraulic turbines, varying the impeller diameter and the flow rate of the water flow. Let's look at a few scenarios to determine the parameters of our unit.

**Case №1. "Optimal".**
We will take water stream speed as $V = 4 \, [m/s]$, impeller diameter $D = 2 \, m$, angle will be taken as $\angle \beta = 25^\circ$, efficiency factor $\eta = 0.95$, reverse quality factor of the element will be taken as $\varepsilon = 0.5$; thickness of blade element will be taken as $b = 0.04 \, m$; hub radius $r_c = 0.3 \, m$; number of blades as $z = 3$.

Lift factor is taken equal to 1.1 that corresponds to maximum in Figure 2 ($C_y = 1.1$).

**Case №2. "Optimistic".**
We will perform calculation similarly, varying only water flow speed, impeller diameter $V = 6 \, m/s$, $D = 3 \, m$, the angle is the same.

**Case №3. "Real".**
We will take water flow speed as $2 \, m/s$, impeller diameter as $1.5 \, m$, angle will be left as $25^\circ$.

In order to estimate the industrial effect of this idea, let us calculate how many turbines need to be connected together to supply a small village of 100 people in the North. According to FAS (Federal Antimonopoly Service) [7] in 2017, one Russian citizen used about 85 kilowatt-hours of electricity on average per month. In the southern regions, such as Crimea, for example, the vast majority of families meet the norm of 150 kilowatt-hours. The maximum consumption of the Russian regions has been registered in the Irkutsk region: there, each resident consumes on average 225 kilowatt-hours per month.
On this basis, most experts of the Russian energy sector believe that the norm of 300 kilowatt-hours will cover all the basic needs of a family consisting of two adults and one child.

That is why we propose to take the average monthly consumption of electric energy per person in the Northern region as 250 kilowatt-hours. Then the average monthly consumption of the village will be:

\[ E_{\text{village}} = 100 \cdot 250 = 25000 \text{ kW} \cdot \text{h} \]

\[ 1 \text{ kW} \cdot \text{h} = 1000 \text{ W} \cdot 3600 \text{ s} = 3.6 \text{ MJ} \]

\[ E_{\text{village}} = 25000 \cdot 3.6 = 90000 \text{ MJ} \]

Calculate the electrical energy produced by one turbine in a month:

\[ E = P \cdot i \cdot 24 \cdot 3600 \cdot 30 = 2,592 \cdot P \cdot i, \quad (10) \]

Where \( E \) is the energy supplied in one month, \( P \) is the capacity of one turbine, \( i = 0.9 \) is the water flow rate (a complex factor which corrects for changing water flow rates during the day and other contingencies).

For each of the scenarios we calculate the amount of energy produced by one turbine. To calculate the number of turbines, use the following formula:

\[ N = \frac{E_{\text{village}}}{E_{\text{turbine}}} \quad (11) \]

For case № 1:

\[ E_1 = 2,592 \cdot 940 \cdot 0.9 = 2193 \text{ MJ} \]

Number of turbines in the plant: \( N = \frac{90000}{2193} = 41.04 \rightarrow 42 \text{ turbines} \)

For case № 2:

\[ E_2 = 2,592 \cdot 152000 \cdot 0.9 = 10730.9 \text{ MJ} \]

Number of turbines in the plant: \( N = \frac{90000}{10730.9} = 8.4 \rightarrow 9 \text{ turbines} \)

For case № 3:

\[ E_3 = 2,592 \cdot 11300 \cdot 0.9 = 793.1 \text{ MJ} \]

Number of turbines in the plant: \( N = \frac{90000}{793.1} = 113.4 \rightarrow 114 \text{ turbines} \)

Let’s summaries the results of the analysis in Table 1.

| Scenarios  | n [rpm] | M [kN · m] | P [kW] | N [pcs.] |
|------------|---------|------------|--------|----------|
| Optimal    | 17.8    | 0.53       | 0.94   | 42       |
| Optimistic | 17.8    | 2.61       | 4.6    | 9        |
| Real       | 11.9    | 0.29       | 0.34   | 114      |

From these calculations we can conclude that the lower the flow velocity in a given area and the smaller the impeller blade diameter, the more turbines we need to aggregate. And we can also say that the idea has a full right to exist, because its energy potential can be seen from the mathematical calculations. In our opinion, the main task is to find a zone with high flow velocities and with the help of nozzles try to increase the flow velocity even more, then these power units will be compact and very efficient.

Also we have to say that our approach seems to us more accurate then results obtained with Betz’s formula. But for proving our point of view we have to make computational flow analysis. Betz’s formula doesn’t consider geometrical option of impeller, since that point, we can get same result of generating power for turbines with different blades and impellers. We suppose that it is not correct and offer our own view of that problem.
4. Structural analysis
We feel it is necessary to add that a construction analysis of our facility needs to be carried out as the design does not look simple. The analysis is complicated by the fact that we imply a prefabricated/disassembled design, in other words it will be possible to assemble the unit on the ship with the right number of turbines and install on spot. The structural analysis task then becomes more global. We think we will get into this in our next works.

5. Electrical engineering
The current state of development and manufacture of finished products in the field of conversion and generation of electrical energy is characterized by intensive application of power semiconductor technology: creation of IGBT and MOSFET transistors for switching of power electrical circuits. This made it possible to eliminate the mechanical collector-brush element from electric machines and create a new type of electromechanical converters in which winding currents are switched by electronic switches. This transition was made possible by the rapid development of microprocessor technology, because the control of electronic commutation units is only possible on an algorithmic basis. If in traditional collector machine the rotor position defines physically the switching moments by the position of brushes, in electronic commutation it is necessary to introduce a special rotor position sensor and by it to define the switching moments by algorithmic way of execution by microprocessor or microcontroller of developed program. This means that the complexity of the physical construction of the electrical machine is carried over into the domain of microcontroller technology. The newest developments in this field were brought to realization and output of ready made products [9], from which most interesting is reactive turbine generator (VRD-G) [8], which has better efficiency than traditional asynchronous and synchronous machines, and also valve machines, because it uses reactive torque and does not require availability of rotor position sensors.

The manufacturer [8] offers production and delivery of such devices with power up to 200 kW. The principle of reversible conversion is guaranteed by the control algorithm, so it is stated in the name of the products that it is possible to supply the motor for electric drive and generator mode is also possible. An undoubted advantage of such a choice is the availability of technologies for the creation of VRD-G systems controlled via Internet communication [8]. It will allow uniting separate units in the unified system of power supply of the coastal enterprises and settlements of the northern Russian shelf. The issues of submerged design of the required equipment are provided by the firm to order and the issue is technically worked out. The question of DC power transmission over a distance in coastal conditions is also solved on the basis of products of Russian industrial enterprises [9].

6. Conclusion
Analyzing above presented information it is possible to come to conclusion that underwater currents have big potential both from the power point of view and from the technical point of view as they possess practically constant speed, so we with high reliability can supply consumers with electric power. The technical benefit is that underwater temperatures are almost constant and there are no ice impacts. However, strangely enough, for some reason the problem presented has not yet been taken seriously in Russia, otherwise in other world there are lots of breakthrough achievements in that area [10].

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