Pumping Power Dependence of OTEC Systems

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Abstract: - Ocean Thermal Energy Conversion (OTEC) systems use seawater pipes to harness the natural temperature difference between the surface water and the deep seawater mainly for electricity generation; they also have the potential tof generate by-products. The temperature of seawater fluctuates according to the geographical location but also depends on factors such as ocean depth and proximity to the coastline. This paper examines several scenarios for the pumping power affected by various factors related to the cold-water pipe and the warm-water pipe. A parametric analysis is performed on factors such as the size of the cold-water pipe, the mass flow rate, and the distance from shore. The results could potentially be used to identify the positioning of an OTEC systems, in terms of onshore or offshore placement.

Key-Words: - Ocean Thermal Energy Conversion, Cold Water Pipe, OTEC offshore, OTEC onshore, pumping power, seawater.

Received: May 26, 2024. Revised: September 9, 2024. Accepted: November 12, 2024. Published: December 31, 2024.

1 Introduction

Ocean Thermal Energy Conversion (OTEC) systems take advantage of the natural temperature difference (ΔT) of the cold deep seawater and the surface sea water to run a thermodynamic cycle and generate power in terms of electricity and/ or by-products such as fresh water.

This temperature difference however is location-dependent (i.e., see distance from the Equator), with ΔTs of 20°C (with 25°C surface seawater and 5°C deep seawater) or higher being recommended (which would lead to a Carnot efficiency of 6.7%). As OTEC systems aim at the highest possible ΔT, for a sufficiently high system efficiency, it is suggested that they be ideally placed in the tropical regions (or regions within ±20° from the Equator, including the Caribbean) where such high ΔTs are recorded.

Another important feature of OTEC systems is itheir actual positioning in relation to the shore. For example, the OTEC system can be positioned either onshore or offshore as presented in Figure 1. Onshore systems are built on land, based on land availability and approximability, whereas offshore systems can be positioned on fixed or floating sea platforms.

Fig. 1: OTEC positioning, from left to right: onshore (land-based) systems, offshore fixed platform, offshore floating and semi-submersible platform, offshore spare platform, offshore FPSO (Floating Production Storage and Offloading), [1]

This selection and availability play a crucial role in the length of the required piping for both the cold-water pipe (CWP) and the warm-water pipe (WWP).

The pumping power required on the other hand for the OTEC pipes, namely for CWP and WWP, is of importance for the net output of the system, as these values could be in the range of 20-30% of the net generated OTEC system power, [2].

Onshore OTEC systems, are situated on land, and therefore eliminate the need for a lashing system for stability. Furthermore, the system's maintenance may be conducted with greater ease and, as a result, at a reduced expense compared to offshore systems. Additionally, the system is fortified against severe weather conditions, as it may be designed to endure storms. The generated power can be efficiently disseminated in all scenarios, including situations where desalinated water can also be produced and transferred to the pre-existing network, [3]. Conversely, the coastline land possesses a significant high value, which can offset the decreased expenses associated with installation and upkeep. Another disadvantage is that transporting seawater onto land increases the cost, as it necessitates the installation of long-distance pipes, with the pipes exposed to tides and storms, [4].

Offshore systems, in contrast, effectively address certain drawbacks associated with onshore systems by being situated in closer proximity to the necessary sea depth for cold seawater. However, these systems are susceptible to the marine environment. Offshore systems can be placed on a platform at a maximum seawater depth of approximately 100m, [5]. Alternatively, when floating structures are used, they can be positioned at the appropriate sea bed depth of over 1km, which allows them to avoid the impact of breaking waves and the associated nonlinear stresses. To ensure a steady position, offshore systems are constructed as either fixed platforms or floating ones that utilize mooring lines for station keeping, [6].

Table 1 summarises the main benefits and drawbacks between onshore and offshore systems.

As for every system, there are several other factors that can characterize the performance of the system; a review of the aspects related to the energy, environment, and economy can be found in [1].

The current paper examines the factors affecting the pumping power for the OTEC pipes, through a small parametric analysis. The main equations related to the pumping power are described in Section 2 and the initial findings are presented in Section 3. Note that the methodology is verified with similar cases in the literature, due to the lack of experimental data available.

Table 1. Comparison between onshore and offshore OTEC systems

Onshore OTEC Systems	**Offshore OTEC Systems**
Installation	
No lashing system needed to secure in place	Minimal pipe distance, reducing construction and material costs
The system can be designed to withstand strong weather conditions, like storms	Constant sea movement (waves, currents) necessitates sophisticated, costly design for pipes and components
The generated electricity can be distributed easily, with the potential for integration into existing networks	Requires subsea cables or additional infrastructure to connect to land-based distribution systems
Coastal land often has a high value, potentially increasing land acquisition costs	Generally higher installation costs due to structural needs to withstand sea movement and anchoring requirements
Higher initial investment due to the need for long seawater transfer pipes that are secure against tides and storms	Anchoring a floating platform in the deep sea is complex and costly
Environmental Impact	
Coastal impact is higher due to land use and possible effects on coastal ecosystems	Lower impact on coastal land but may disturb deep-sea ecosystems
Maintenance Complexity	
Easier and more accessible on land, reducing overall maintenance costs and complexity	Maintenance is challenging and expensive due to the exposed environment
Energy Distribution	
Easier integration into existing grids and water distribution networks	Requires subsea cables or additional infrastructure to connect to land-based distribution systems

2 Methodology

The pumping power of the pipes is of high importance to the overall efficiency of the system, and for either the CWP or the WWP, it is estimated using the following equation, [7], [8]:

$$\dot{W}_{p,P} = \frac{m_P \Delta H_T g}{\eta_p} \tag{1}$$

where m_P is the pipe mass flowrate [kg s^{-1}], g is the gravitational acceleration [m s^{-2}], η_p is the pump efficiency, and ΔH_T the total head difference of the pipe [m], [9]. The main difference between the CWP and the WWP lies in the estimation of the total head difference of the pipe, which is essentially the sum of the pump head difference, the friction losses (of the pipe), the friction loss of the heat exchangers, the bending/ minor losses, and the density difference losses. The total head difference is expressed as:

$$\Delta H_T = \Delta H_{PH} + \Delta H_d + \Delta H_{HE} \tag{2}$$

where ΔH_{PH} is the pump head difference, which is the sum of the head loss due to friction (Equation 3), and the minor losses of the pipes (Equation 5). The head loss due to friction can be described by the Darcy's friction factor as shown in Equation (3), and the fluid velocity of the pipe is described by Equation (4). Both of the pipes (CWP and WWP), being placed in the seawater, are subject to biofouling, which in turn can have an effect on the friction factor as well as the velocity profile in the pipe [10]. In fact,

$$\Delta H_{CWP,f} = f_D \frac{L_P}{D_{P,i}} \frac{u_P^2}{2g} \tag{3}$$

$$u_{CWP} = \frac{m_P}{A_P \rho} = \frac{m_P \times 4}{\rho_P \times \pi \times D_P^2} \tag{4}$$

$$\Delta H_b = \sum f_m \times \frac{u_P^2}{2g} \tag{5}$$

where L_P is the pipe's length [m], $D_{P,i}$ is the inner diameter of the pipe [m], f_D is the Darcy's friction factor [unitless], A_P is the cross-sectional area of the pipe, ρ is the seawater density, and $\sum f_m$ is the sum of all of the bending and minor loss coefficients. The bending and minor losses are due to fittings, pipe bends, valves, etc. These losses are theoretically added to the pipe length, where the pipe is considered as frictionless and straight.

The head difference due to the density differences in the seawater (as density changes with depth), is only applicable to the CWP (due to discharging at shallower depths from the pumping depth), and it is described by:

$$\Delta H_{CWP,d} = L_P - \frac{1}{\rho_{cs}} \left(\frac{L_P}{2}\right) (\rho_{ws} + \rho_{cs}) \tag{6}$$

where ρ_{cs} is the density of the cold seawater and ρ_{ws} is the density of the warm seawater [kg m^{-3}]. Finally, the head difference due to the heat exchanger mainly depends on system capacity and hence the size. Therefore, these values will vary depending on the size of the heat exchangers, either the condenser or the evaporator, and they can be neglected in the estimations here, to avoid any miscalculations of the system.

3 Initial Results and Discussion

The initial results regarding different head losses are presented in Figure 2 and Figure 3. The fluid velocity and the pipe length were varied, as shown in Figure 2(a) and Figure 2(b). Both variables are presented against the head difference due to friction and bending and minor losses. The ranges of the pipe are based on the distance from shore and were assumed to vary between 1km to 10km in length. On the other hand, the CWP diameter values as well as flowrate values are based on the literature, for either computational or experimental set-ups.

In Figure 2(a) and Figure 2(b), it is observed that with a reduction in velocity, the head differences both due to friction and due to bending & minor losses are increased. However, the velocities are generally kept at high values in the OTEC systems due to the high amount of heat exchange required. In Figure 2(c) the length of the pipe was varied, and the head difference due to density is presented, for a fixed mass flow rate at 45 kg s^{-1} and an inner diameter of 1.9022 m.

Increasing the value of the inner diameter does not have a significant effect on the head differences (all ΔH values observed are well below 1 m); note that the contribution on the total head difference change due to the inner diameter change is of the order of 5% (not shown here). As expected, increasing the pipe's length has the highest impact on ΔH, with the head difference due to density rapidly increasing. Note that ΔH due to density has a contribution to the total head difference change of the order of 95% (for high L_P values), although it is only 25% for an inner diameter of 0.2m (with the head difference due to friction at 67%). Also, the smaller the L_P the smaller the ΔH_d contribution.

By observing Equation (1), the above reported head differences, have a direct impact on the required pumping power. Hence, the pumping power of CWP versus the head difference due to friction (see Equation 3) is plotted in Figure 3. By varying the friction factor, the length of the pipe, the velocity of the fluid, and the inner diameter of the pipe, one can obtain linear relations for each parameter; the corresponding slopes are shown in Table 2.

Figure 3 and Table 2 demonstrate that L_{CWP} exhibits the highest slope, and consequently the highest change in head difference and in pumping power. It should be noted here, that the sum is used for the total pumping power (Equation 2) and not the individual values projected in Figure 3.

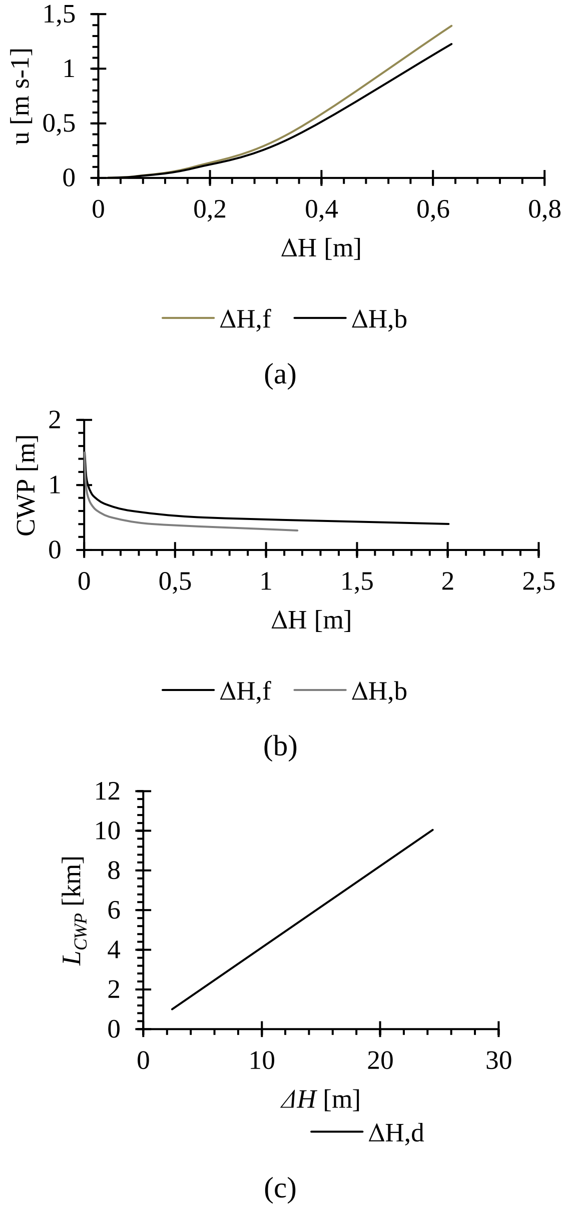

Fig. 2: Head difference due to: (a) friction (ΔH,f) and minor/ bending losses (ΔH,b), at various fluid velocities; (b) friction (ΔH,f) and minor/ bending losses (ΔH,b), at various inner pipe diameters; (c) density difference between deep seawater and surface seawater, at various pipe lengths

Pumping power change due to friction factor and due to inner pipe diameter exhibit a lower impact as observed with lower projected slopes. Note that, even the presence of biofouling, which will in turn affect the friction factor and the pipe diameter, will not contribute to rapid changes in pumping power (not shown here). The fouling factor can be represented as an extra pipe wall resistance (thermal), which will theoretically overestimate the heat exchanger's performance; as fouling develops over time, it will be reduced until the cleaning threshold is achieved.

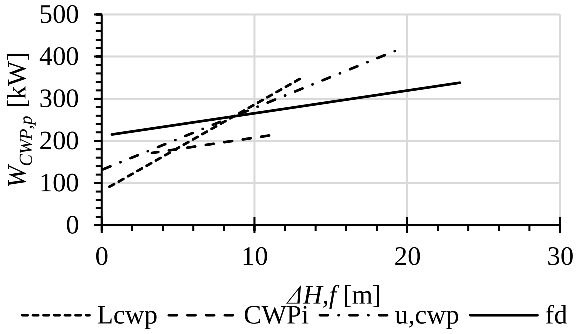

Fig. 3: Head difference due to friction with different varying parameters, namely the length of the pipe, the inner diameter of the pipe, the fluid velocity and the friction factor.

Table 2. Projected slope for the Head difference due to friction with different varying parameters

Head difference	Parameter	Slope
ΔH,f	L_{CWP}	20.553
	u_{CWP}	14.698
	$D_{CWP,i}$	6.854
	f_D	5.394

The parameters of fluid velocity and pipe length are also presented in Figure 3 against CWP pumping power. The higher impact can be observed with the change in the length of the pipe. However noticeable impact is also observed in the fluid velocity. Although the length can be adjusted due to the location, the velocity of the fluid is directly related to the heat exchange required for the thermodynamic cycle and the net power produced.

Consequently, the latter's effect can be computed in relation to the overall system power, where a system could be characterized by the optimum point of the pumping power and the net power, in terms of the electricity output of the system; this however requires further details into the selection of thermodynamic cycles, the circulation fluid selection, as well as on the characteristics of the generator, the pumps, and the heat exchangers.

Unfortunately, the lack of data from real case studies or pilot projects is a major issue surrounding OTEC systems, and, hence, theoretical or computational research cannot yet be validated. In future funded systems and with the inclusion of EU's open access science, it is expected that data will become available either for validation purposes or to effectively assist engineers to design and characterise such systems.

4 Conclusion

The current research aimed to investigate the different parameters affecting pumping power for offshore and onshore OTEC systems. The net power of an OTEC system highly depends on the required pumping power, as the OTEC systems are highly location-dependent. The current study has reported on different variables, highlighting the factors with the higher impacts on the pumping power.

The obtained results have indicated that the highest impact on pumping power is due to the change in the length of the pipe. The noticeable impact is also observed by the fluid velocity or mass flow rate of the CWP. Minimum impact on the other hand is observed by head difference due to bending (or minor losses) as well on the head difference due to the friction effect.

The results reported and discussed in Section 3 could be used to determine whether an OTEC system would have a higher performance when placed onshore or offshore.

A further parametric analysis, in addition to head difference by factors such as the CWP length and diameter, and the mass flow rate, can be performed in relation to temperature difference between deep seawater and inlet to the condenser.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The research presented in this paper has received co-funding from the European Union CETPatnership and the Research and Innovation Foundation of Cyprus under Grant agreement EP/CETP/0922/0055.

Conflict of Interest

The authors have no conflicts of interest to declare.