A Theoretical Investigation on the Potential Application of Ocean Salinity and Temperature Energy Conversion (OSTEC)

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Received: 20.03.2012 Accepted:10.05.2012

Abstract- This paper discusses the theoretical investigation on the effect of salinity and temperature differences between ocean sea water and the incoming fresh water from surrounding area, as main parameters, to the generation of electrical power. A theoretical formulation is first derived to predict the water flow rate at the sea water surface when fresh water is funnelled at the bottom of an up-tube, immersed in the sea water, using smaller down-tube. The flow rate is then converted into corresponding kinetic power that may be translated into electrical energy using water turbine. The paper ends with computer simulations when the temperature and salinity differences between incoming fluid and the sea water, and also when the diameter of the up-tube and down-tube, are varied, at various elevation of the reservoir of the incoming fluids.

Keywords Kinetic power output, ocean energy conversion system, buoyant force, total kinetic power transfer, heat energy transfer.

1. Introduction

Energy is an essential input for social and economic development. The world energy consumption often follows ascending trend and the demand is projected to rise to 1000 EJ (EJ = 1018 J) or more by 2050 if economic growth continues its path of recent decades [1]. Numerous studies have predicted that if the consumption of non-renewable energy sources continues at the current rate, some of these energy sources will be depleted within a century or otherwise a few decades [2]. Moreover, both reserve depletion and greenhouse gas emissions impose a major shift from fossil fuels as the dominant energy source. In addition, the fact that burning of fossil fuels directly contributes to climate change has amplified public interest to environmental protection [3]. These latest and ongoing predicaments facing the world especially the limited usage duration of fossil fuels that meet a giant portion of the world energy demand, the destruction upon the environment and energy needs of future generations have amplified the significance of renewable energy sources [4]. Since nuclear power is now unlikely to raise its present modest share, renewable energy from wind [5], biomass [6] and piezoelectric [7], will have to provide most energy requirement in the future. However, even though large research funding and huge scientific effort have been spent, it is up to now hardly a single technology could be the panacea to the world energy challenge [8].

The ocean, which covers more than 70% of the planet surface, is a huge source of renewable energy. If properly explored, this environmental friendly energy resource will contribute towards meeting the increasing global energy demand. The ocean holds such vast amount of energy that it is hard to quantify the potential [9]. To underline this potential, a number of initiatives are being pursued by several governments such as New Zealand, United Kingdom, Australia, European Union, the United States, and Japan [2]. As a result, in 2008, the first generation of commercial ocean energy conversion devices known as SeaGen and the Pelamis, were constructed and installed in the UK and Portugal, respectively [10]. While salinity gradient is one of the ocean energy conversion principles which are not fully explored, the prospect for electricity generation is enormous. Since the driving force of this energy conversion principle is the osmotic potential between fluids, the effect of temperature difference between fluids which may help to excite the osmotic potentials combined with the effect of salinity difference are explored and investigated as a new renewable and clean energy source.

2. Theoretical Derivation

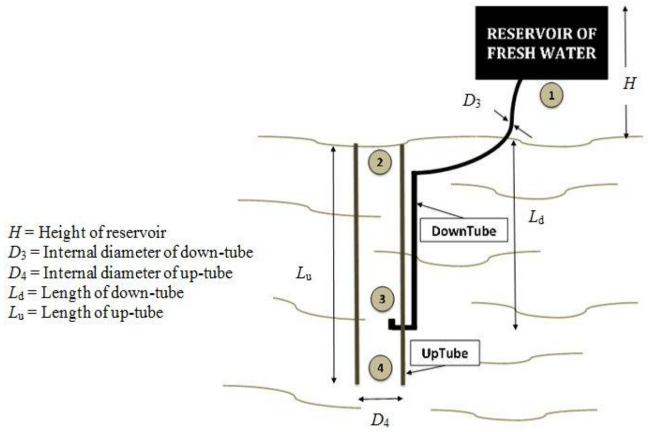


Fig. 1. Conceptual design for the theoretical experiment of the Ocean Salinity and Temperature Energy Conversion (OSTEC)

Consider fresh water from its reservoir at certain height of H, is being funneled, using down-tube with internal diameter of D_3 into the bottom of an up-tube that immersed in sea water with certain depth of L_d and with internal diameter of D_4. Fig. 1 shows the conceptual design of the above system used for theoretical experiment in this paper.

The fresh water from the reservoir flows downward at point 3 due to gravitational force and mix up with the salt water. This will form brackish water that moves upward towards point 2 because of the momentum its gains during the downward flow and also because of buoyant force. The buoyant force is contributed from the density difference between the sea and incoming fresh water which is resulted from the differences in salinity and temperature. The aim is to derive the kinetic power of the brackish water movement at point 2 due to the salinity and also temperature differences between the fluids, that later may be converted into electrical power if water turbine is used.

The maximum kinetic power that can be harvested due to the brackish water movement at point 2 can be written as

$$P_2 = \frac{1}{2} M_2 V_2^{\ 2} \tag{1}$$

where M_2 and V_2 are the total mass movement and the velocity of the water at this point, respectively. If there is Q_2 of volume flow rate of brackish water at point 2, then

$$M_2 = \rho_2 Q_2 \tag{2a}$$

$$V_2 = \frac{Q_2}{A_4} = \frac{4Q_2}{(\pi D_4)^2} \tag{2b}$$

where ρ_2, A_4 and D_4 are the density of the brackish water at point 2, the internal cross sectional area of the up-tube and the internal diameter of the up-tube, respectively. Therefore, Eq. (1) can be rewritten as

$$P_2 = 8\frac{Q_2^{\ 3}\rho_2}{\pi^2 D_4^{\ 4}} \tag{3}$$

It can be seen from this equation that there are two unknown parameters which are the volume flow rate of the brackish water at point 2 (Q_2) and its density (ρ_2). Since the only paths to point 2 are from point 3 and point 4, the volume flow rate at point 2 is the summation of the flow rate from point 3 and point 4 or

$$Q_2 = Q_3 + Q_4 \tag{4}$$

The density of the brackish water at point 2 is particularly of interest because it can be manipulated to get the desired kinetic power output with appropriate design. It is influenced by two parameters - its salinity and temperature, and hence the system is called Ocean Salinity and Temperature Energy Conversion syatem, OSTEC. The density of a fluid as a function of its salinity and temperature can be expressed as [11]

$$\rho_2 = \rho_{fw} + S_2 a_1 + S_2^{\ 3/2} a_2 + S_2^{\ 2} a_3 \tag{5}$$

where

$$a_1 = 0.824493 - 4.0899\text{x}10^{-3} T_2 + 7.6438\text{x}10^{-5} T_2^{\ 2}$$
$$- 8.2467\text{x}10^{-7} T_2^{\ 3} + 5.3875\text{x}10^{-9} T_2^{\ 4}$$
$$a_2 = -5.72466\text{x}10^{-3} + 1.0227\text{x}10^{-4} T_2 - 1.6546\text{x}10^{-6} T_2^{\ 2}$$
$$a_3 = 4.8314\text{x}10^{-4} T_2 \,,$$

and S_2, T_2 and ρ_{fw} are the salinity of the brackish water at point 2, temperature of the brackish water at point 2 and the density of fresh water, respectively. The density of the fresh water as a function of its temperature alone is written as [11]

$$\rho_{fw} = 999.842594 + 6.793952\text{x}10^{-2} T_{fw} - 9.095290\text{x}10^{-3} T_{fw}^{\ 2}$$
$$+ 1.001685\text{x}10^{-4} T_{fw}^{\ 3} - 1.120083\text{x}10^{-6} T_{fw}^{\ 4} + 6.536332\text{x}10^{-9} T_{fw}^{\ 5} \tag{6}$$

where T_{fw} is the temperature of the fresh water. This equation shows that the density of the fresh water decreases as the temperature increases.

As previously discussed, it is desirable that the temperature of the fresh water is higher than the salt water to produce higher buoyant force. As the fresh water of temperature T_3 flows into the up-tube at point 3, it will transfer part of its heat energy into the sea water from point 4 (with temperature of T_4) in which they move up-wards together to point 2 to settle at their equilibrium temperature of T_2. The initial temperature of the fresh water at point 3 (T_3) can be higher or the same with T_2, and the temperature at point 4 (T_4) can be lower or the same with T_2. If it is assumed that the total heat energy of the system remain in the column of the up-tube, the heat energy gained by the salt water from point 4 will be the same with the heat energy loss from the fresh water. Mathematically, this can be expressed as [12]

$$m_4C_4(T_4 - T_2) = m_3C_3(T_2 - T_3) \tag{7}$$

where m_3 and m_4 are the mass flow rate of fresh water at point 3 and the mass flow rate of salt water at point 4, whereas C_3 and C_4 are the specific heat of the fresh water from point 3 and the specific heat of the salt water from point 4, respectively. This equation can be rearranged to get the equilibrium temperature at point 2 as

$$T_2 = \frac{m_4C_4T_4 + m_3C_3T_3}{m_4C_4 + m_3C_3} \tag{8}$$

As previously mentioned, the salinity difference between the salt and fresh water (or simply the incoming fluid when the salinity is varied) also affect the buoyant force of the system. Higher salinity difference is expected to produce high power output at point 2. In general, the salinity of any fluid is defined as the ratio between the weight of salt in the solution and the total weight of the solution. Therefore, the salinity of the fluid at a point *i* in Figure 1 can be written as

$$S_\mathrm{i} = W_{S\mathrm{i}} / W_{T\mathrm{i}} \tag{9}$$

where W_{Si} and W_{Ti} are the weight of salt in the solution and the total weight of the solution at the point of interest, respectively. Since the brackish mixture at point 2 comes from the fresh water from point 3 and the salt water from point 4 (see Eq. (4)), the salinity of the brackish can be written as

$$S_2 = (W_{S3} + W_{S4})/(W_{T3} + W_{T4}) \tag{10}$$

where W_{T3} and W_{T4} are the total weight of the fresh water transported from point 3 and point 4, respectively, and W_{S3} and W_{S4} are their respective salinity. Using Eq. (9), Eq. (10) can be rewritten as

$$S_2 = (S_3W_{T3} + S_4W_{T4})/(W_{T3} + W_{T4}) \tag{11}$$

The total weight of fluids transported from a particular point is given by the flow rate at that point, multiply with the density of the fluid. Therefore, Eq. (11) can be expressed as

$$S_2 = (S_3Q_3\rho_3 + S_4Q_4\rho_4)/(Q_3\rho_3 + Q_4\rho_4) \tag{12}$$

At this point, assuming that the salinity of the fresh water funneled from the reservoir is very low and can be neglected (or $S_3 = 0$), Eq. (12) reduces to

$$S_2 = (S_4Q_4\rho_4)/(Q_3\rho_3 + Q_4\rho_4) \tag{13}$$

S_4, ρ_4 and ρ_3 are parameters that can be predetermined by measurement, whereas the flow rate of fresh water at point 3 (Q_3) can be calculated using equation

$$Q_3 = A_3V_3 \tag{14}$$

A_3 and V_3 are the cross-sectional area of the down-tube and the velocity of the fresh water at point 3, respectively. Velocity V_3 can be determined using the well-known formula [13].

$$V_3 = \sqrt{\frac{2gH\rho_w}{\rho_3}} \tag{15}$$

where g is the gravity constant.

At this point, there is one left unknown parameter in Eq. (13) which is Q_4. This parameter can be derived as follow. As the fresh water move upwards at point 3, there is complete transfer of kinetic power to the salt water at point 4 to ensure continuous flow of fluid in the up-tube. Referring to Eq. (3), this can only be true when

$$\frac{{Q_3}^3\rho_3}{{D_3}^4} = \frac{{Q_4}^3\rho_4}{{D_4}^4} \tag{16}$$

Therefore,

$${Q_4}^3 = {Q_3}^3\left(\frac{\rho_3}{\rho_4}\right)\left(\frac{D_4}{D_3}\right)^4 \tag{17}$$

It can be seen that the volume flow rate of the salt water at point 4 is influences by the ratio between their salinity and the tube diameter.

Now that the flow rate at point 4 is known, salinity of the brackish water at point 2 in Eq. (13) can be calculated. Substituting the salinity (Eq. (13)) and the temperature at point 2 (Eq. (8)) into Eq. (5) gives the density of the brackish water at point 2, and further substitution of the resultant equation together with Eq. (4) into Eq. (3) gives the maximum kinetic power that can be harvested from the system.

3. Computer Simulation Results and Discussions

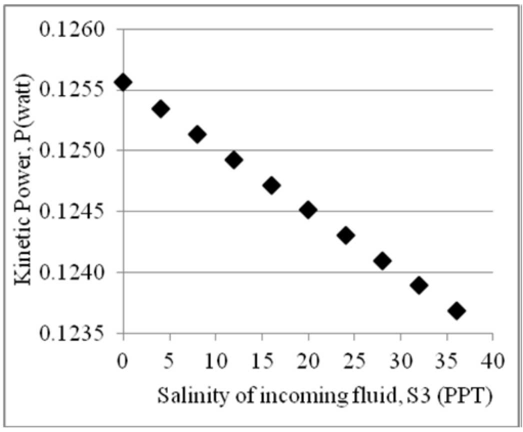
Table 1. Comparison between theoretical prediction and the experimental measurement reported in [14] of the volume flow rate at point 3 and the salinity at point 2.

	Volume flow rate of fluid at point 3(x 10^{-4} m^3/s)		Salinity at point 2
	Incoming fluid with salinity of 0.3PPT	Incoming fluids with salinity of 36PPT	
Experimental value	2.4	2.3	34
Theoretical prediction (Eq. 15)	2.39	2.36	33.08
% of difference [a]	-0.4%	2.6%	-2.7%

Before it is proceed to computer simulation to predict the possible power output from the conceptual experimental setup, it would be interesting to cross check two of the important parameters derived in this paper with the experimental result reported in [14] which are the volume flow rate at point 3 and the salinity of the fluid mixture at point 2. Table 1 shows how the predicated parameters value in comparison with the reported experimental data of similar experimental setting (see Table 2 for the setting). It can be seen that the volume flow rate predicted using Eq. (15) is quite similar with measured rate with maximum deviation of 2.6%. Similarly, the predicted salinity at point 2 is very close to the measured data with maximum error of 2.7%. This result shows that the theoretical formulation derived in this paper is valid with small error, at least when compared to the reported actual measurement.

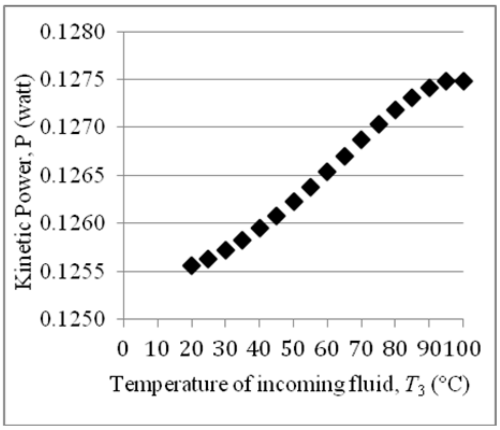
As previously mentioned, the purpose of this paper is to theoretically predict the potential kinetic power produced when fresh water (or incoming fluids in general) is funneled and mixed with sea water using experimental setting shown in Figure 1. As a result, the fresh water will gain buoyant force that makes the mixture move upwards to the sea water surface with certain velocity that may be converted into electricity using water turbine.

From physical point of view, it is well known that the buoyant force of a fluid is affected by the salinity and temperature differences between the incoming fluids, from its reservoir, and sea water. It is however interesting to investigate how much each of the parameter affects the kinetic power output of the system. Figure 2(a) shows the predicted kinetic power of the system as the temperature of the incoming fresh water is increased from 20^{o}C to 100^{o}C with the setting given in Table 2. Similarly, Figure 2(b) shows how the salinity of the incoming water from the reservoir affects the power output from the same system. It can be seen that the kinetic power output is equally affected by the temperature and the salinity of the incoming fluids within the range of interest.



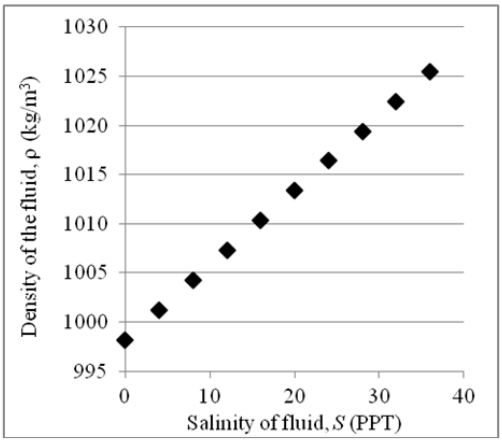
(a). Effects of salinity change.

The source of the power production in the system is the density difference between the incoming fluid at down-tube and the existing fluid at up-tube (Figure 1). Theoretically, fluid with higher temperature with lower salinity will have higher buoyant force, and therefore produce higher kinetic power. Consequently, the effect of the salinity and temperature of the incoming fluid at point 3 to the fluid density is investigated and is shown in Figure 3 (refer Table 2 for experimental setting). Again, similar to Figure 2, the rate of change in the fluid density is equally affected by the salinity and the temperature of the incoming fluid within the range of interest.

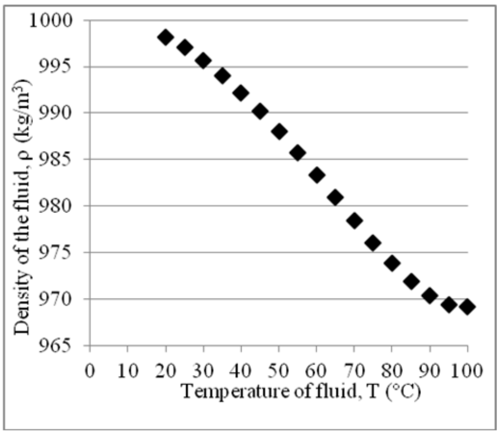


(b). Effect of temperature change

Fig. 2. Effect of the salinity and temperature of the incoming water from the reservoir, to the power output of the system



(a).Effects of salinity change.



(b). Effect of temperature change

Fig. 3. Effect of the salinity and temperature to the density of a fluid. (a).

Table 2. Experimental setting used for comparison with experimental data reported in [14].

Parameter	Value
Diameter of up-tube, D_4	0.150 m
Diameter of down-tube, D_3	0.018 m
Length of up-tube, L_u	1.500 m
Length of down-tube, L_d	1.000 m
Height of reservoir from sea water surface, H	0.550 m

From Equation (17), it is noted that the volume flow rate of the salt water at point 4 is also influenced by the diameter ratio between the up tube and the down tube. Therefore, it would also be interesting to investigate how the diameter ratio affects the power output of the system. Figure 4 shows the effect of the diameter ratio of the tubes at different up-tube diameter. It can be seen that lager size of up-tube produces higher power output. It can also be seen that higher diameter ratio produces higher power output. In this simulation, temperature of sea water and the incoming fluid from the reservoir are fixed at 20^{o}C with the same experimental setting shown in Table 2 (similar to temperature setting in [14]).

Further examination of Figure 4 shows that it is desirable to have down-tube of the same diameter with the up-tube (which is $D_4 = D_3$). However, this size is not advisable to proceed from physical ground. From Equation (4), the volume flow rate at point 2 is the summation of the flow rate from point 3 and also point 4. Therefore, sufficient space to make the sea water moves upwards from point 4 to point 2 is required. Based on this argument, maximum diameter ratio of 40% is selected for further investigation.

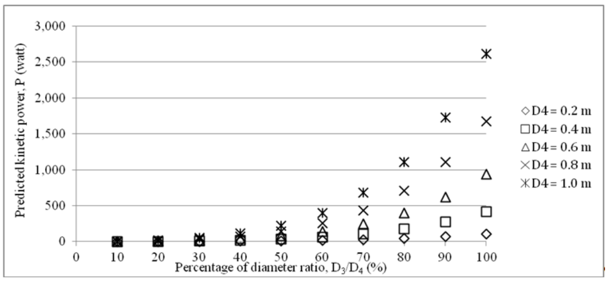
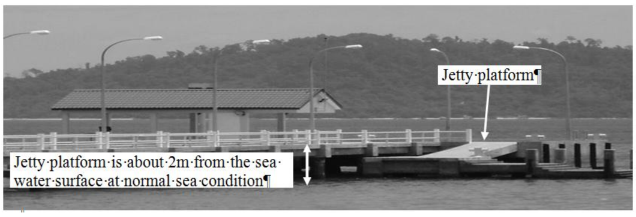


Fig. 4. Change in kinetic power output of the system as the diameter ratio increases.

Another interesting point to investigate is on how the height of the resevoir (refer Figure 1) affects the power output of the system. This is important when the investigation is carried out in an actual experiment. A specific location has been indentified to perform this experiment at the jetty in the Universiti Malaysia Sabah main campus compound near Kota Kinabalu. The jetty is streched out about 500m from the beach with 9m heignt from the bottom of the sea and its platform has about 2m height from the sea water surface during the normal sea condition as shown in Figure 5.

(a). The jetty is streched out about 500m from the beach.



(b). Closed up of the jetty. The water resevoir is to be constructed at the jetty platform.

Fig. 5. The jetty at the main campus of University Malaysia Sabah near Kota Kinabalu.

In order to visualize this, and considering the previous argument, Figure 6 is simulated with tube diameter ratio is fixed at 40% and the temperature of sea water and incoming fluid from the reservoir are fixed at 25^{o}C and 32^{o}C, respectively. This temperature selection is considered to predict the power output of an actual system that is intended to be built at the jetty. Figure 6 implies that higher kinetic power can be obtained if the height of the reservoir is increased. Higher increase rate can also be obtained with lager diameter of up-tube.

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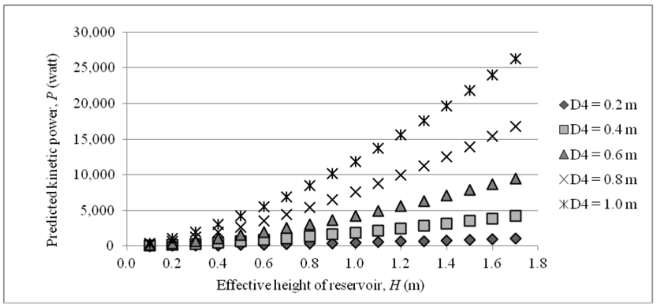

Fig. 6. Effect on the kinetic power output of the system as the height of the reservoir is increased. The diameter ratio between the down-tube and up-tube is fixed at 40%.

In Kuala Lumpur, it was reported that the averaged electrical energy consumption of a typical household is about 366kW-h monthly [15]. This is equivalent to about 12.2kW-h a day of electrical usage. If this electrical energy consumption is used as a general reference for power demand in Malaysia, then it is desirable to build a 10kW electrical power generator to be used by 10 households for 12 hours of operation, with adequate storage capacity. Detail examination of Figure 6 shows that up-tube diameter and length of D_4 = 0.6m and 7m, respectively, are sufficient to meet this power demand with reservoir elevation of 1.8 m from the sea water surface.

4. Conclusion

In this paper, a theoretical investigation on how to use the salinity and temperature differences between ocean sea water and the incoming fresh water from surrounding area, to generate electricity was discussed. A conceptual experimental setup was used in this investigation where incoming fluid with different salinity and temperature is assumed to be funneled at the bottom of an up-tube immersed in the sea water using smaller down-tube. Higher temperature and lower salinity of the incoming fluid make it lighter compared to the sea water and therefore moves upwards to the sea surface at certain velocity because of the buoyant force. It was found that the salinity and temperature difference between the fluids equally affecting the buoyant force of the incoming fluid. Additional kinetic power could be obtained when the reservoir of the incoming fluid is elevated higher from the sea water surface and when the diameter of down-tube is increased. An elevation of 1.8m of the reservoir with 40% of diameter ratio between the down-tube to the up-tube are sufficient to produce 10kW of electricity for up-tube diameter of 0.6m and up-tube length of 7m when the sea water and the fresh water temperature are fixed at 25^{o}C and 32^{o}C, respectively. The actual experimental investigation will be carried out in the near future at the jetty inside the main campus of Universiti Malaysia Sabah near Kota Kinabalu.

Acknowledgements

This research was supported by SIRIM Berhad under research grant number GL0066, and is greatly acknowledge.

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