Viscosity Model for Predicting the Power Output from Ocean Salinity and Temperature Energy Conversion System (OSTEC) Part 2: Computer Simulation

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Abstract. The paper presents the computer simulation of the improved prediction model in Part 1 and compared with the classical density model. The prediction model in Part 1 is improved by incorporating the effect of fluid dynamic viscosity when there are salinity and temperature differences between two fluids, for better prediction of kinetic power output. The viscosity prediction model takes account of the water head losing causing by frictional effect and viscous dissipation which in turns provides an analytical predicted outcome. Computer simulations are presented in this paper to assess the system as the parameters of system are varied using the Viscosity Model.

1. Introduction

The present study is the continuation of the Part 1 [1] for performing the computer simulations from the improved prediction model. In Part 1, a new refined formulation known as Viscosity Model is developed for predicting the kinetic power output of Ocean Salinity and Temperature Energy Conversion System (OSTEC). Viscosity Model is formulated by considering the effect of fluid dynamic viscosity for specifically determining the flow velocity of incoming water from on-land reservoir. It consists of a series of fluid dynamic equations to estimate the flow velocity. In a different way, Density Model [2] uses one direct equation to determine the respective flow velocity. Despite of the lengthy formulation, Viscosity Model is found relatively accurate than Density Model in Part 1. To gain more insight of the model performance, several important parameters that influencing the overall power output are identified and their corresponding relationships are simulated and compared with classical density model.

The main resources of OSTEC concept for harnessing energy are the salinity and temperature difference between two fluids. The mixing of sea water and incoming water from reservoir at different salinity and temperature in a vertical tube submerged in sea water, produces a rising water mixture due

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to buoyant force. Kinetic power can be derived from the upward motion of the mixture by using appropriate turbine rotor. For clarity, the conceptual design of OSTEC experiment as shown in figure 1 is given which is similar to figure 1 in Part 1.

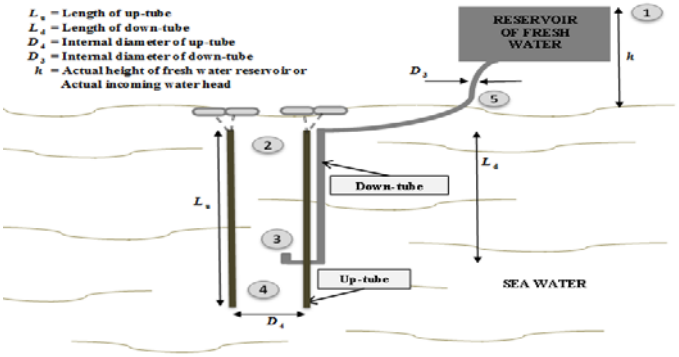


Figure 1. Conceptual design for OSTEC theoretical experiment

To simulate the kinetic power output, several governing equations are summarized. Basically, the maximum kinetic power that can be harvested due to the rising water mixture can be written as

$$P = 8\frac{Q_2^{\,3}\rho_2}{\pi^2 D_4^{\,4}} \tag{1}$$

where Q_2, ρ_2, and D_4 are the volume flow rate of water mixture and density of the water mixture at Point 2, and internal diameter of up-tube, respectively. Volume flow rate at Point 2 is very important in determining the kinetic power. Since the only inlets 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

$$Q_2 = Q_3 + Q_4 \tag{2}$$

Volume flow rate at Point 3 which is the volume flow rate of incoming water from ground elevated reservoir help exciting the amount of sea water going into the bottom of up-tube due to density difference between the two fluids. It relies on the internal cross sectional area of down-tube, A_3 and the velocity of the incoming water at Point 3, V_3 where it is written as

$$Q_3 = A_3 V_3 \tag{3}$$

To quantify the velocity of incoming water at Point 3, two methods which are Density Model [2] and Viscosity Model [1] are used.

1.1. Density Model

As discussed in Part 1, V_3 in Density Model considers the incoming fluid density directly which can be expressed as

$$V_3 = \sqrt{\frac{2gh_1\rho_{PW}}{\rho_3}} \tag{4}$$

where h_1, ρ_{PW}, ρ_3 and g are the total height of water reservoir, density of pure water at standard temperature and pressure (STP), density of incoming water and gravitational constant, respectively. It can be seen that V_3 is affected by the density of incoming water. As the independent parameters of fluid density, both the fluid salinity and temperature are thus varied and simulated to examine the corresponding effects on kinetic power output (Equation (1)).

1.2. Viscosity Model

In Viscosity Model, the dynamic viscosity of the incoming fluid is considered indirectly to determine the frictional head loss, h_L of flowing fluid through down-tube, and therefore the effective water head, h_e and velocity of incoming water which can be written as

$$h_e = h_1 - h_L \tag{5}$$

and

$$V_3 = \sqrt{2g(h_e)} \tag{6}$$

respectively. However, from the formulation of Viscosity Model in Part 1, V_3 is determined based on the dynamic viscosity (Equation (8)) of incoming water in a series of equation (Equation (3) to (10)). It can be noticed that the V_3 is influenced by the dynamic viscosity of incoming water. As the independent parameters of fluid dynamic viscosity, both the fluid salinity and temperature are thus varied and simulated to study their corresponding effects to the kinetic power output. Detail examination of Viscosity Model also shows that fluid dynamic viscosity is used in the early stage to model the frictional head loss of the incoming water flowing through down-tube as shown in equation (5) in Part 1. It can be seen that the frictional head loss is affected by the down-tube diameter and the actual height of reservoir (equation (6) in Part 1). The down-tube diameter and the actual height of reservoir are thus varied and simulated to visualize the corresponding effects to the remaining effective head as shown in equation (5) in this paper.

As the incoming water moves upwards from down-tube outlet to mix with sea water at Point 3, by assuming that there is complete transfer of kinetic power from incoming water to the surrounding sea water to enable continuous flowing of fluid in the up-tube and hence the volume flow rate of sea water at Point 4 can be determined as

$$Q_4^{\ 3} = Q_3^{\ 3}\left(\frac{\rho_3}{\rho_4}\right)\left(\frac{D_4^{\ 4}}{D_3^{\ 4}}\right) \tag{7}$$

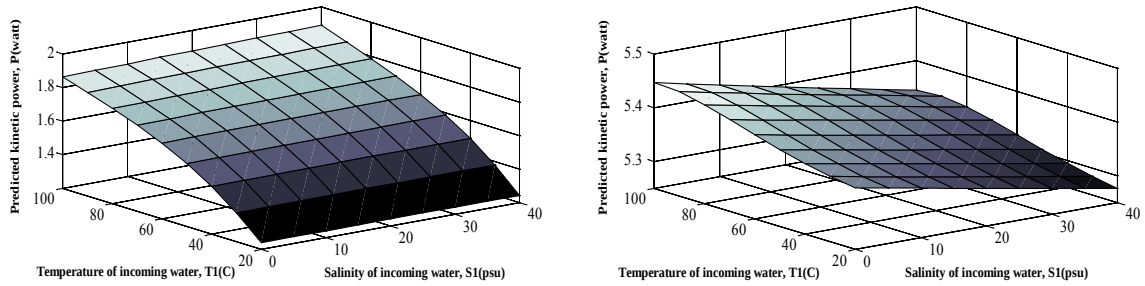
where ρ_4 and D_3 are the density of sea water and internal diameter of down-tube, respectively. It can be seen that Q_4 is influenced by the ratio between fluids density and tube diameter. Due to that the effect of density to the overall kinetic power output is examined, the interest now would be the effects of the diameter ratio and the up-tube diameter to kinetic power output. They are varied correspondingly to examine the impacts to the kinetic power predictions.

2. Computer Simulation Results and Discussions

Computer simulations from Viscosity Model are presented for examining the relationship of important parameters with the potential kinetic power output and further compare with the simulations from Density Model. The main parameters of the Ocean Salinity and Temperature Energy Conversion system (OSTEC) are temperature and salinity difference between sea water and incoming water from reservoir. During the simulation, temperature and salinity of sea water are fixed at 20 °C and 35 psu respectively whereas temperature and salinity of incoming water are varied to increase the kinetic power output possibly. Figure 2(a) and 2(b) show the effects of temperature and salinity to the predicted kinetic power output using Viscosity Model and Density Model respectively, with the setting given in table 1 of Part 1. For clarity, the parametric setting of OSTEC as shown in table 1 is presented here which is similar with table 1 of Part 1.

Table 1. Parametric Dimensions of OSTEC.

Parameter	Value (m)
Internal diameter of up-tube, D_4	0.150
Internal diameter of down-tube, D_3	0.018
Length of up-tube, L_u	1.500
Length of down-tube, L_d	1.000
Height of reservoir from mean sea level, h_1	0.550



(a) Viscosity Model (b) Density Model

Figure 2. Comparison of the temperature and salinity effect to the kinetic power output using different models.

From figure 2(a) and 2(b), It can be observed that by using Viscosity Model, the overall maximum kinetic power output is 1.89 w whereas it is 5.45 w when Density Model is used. The overall power prediction using Viscosity Model is lower if compared to when Density Model is used. This outcome is due to that in Viscosity Model, dissipation of energy (head loss) from frictional effect is considered based on the coefficient of fluid viscosity at specified fluid temperature and salinity, where these are not considered in Density Model.

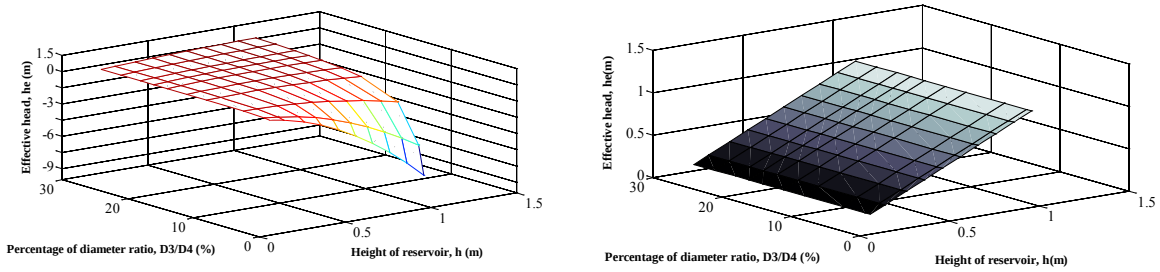
It is nevertheless that in Viscosity Model, the predicted power increases more with higher temperature at a given salinity. Similar ascending trend of power output is observed for other tested salinity as in figure 2(a). When the salinity of incoming water is set at 0 psu, power increases for 50.4 % from temperature of 20 °C to 100 °C using Viscosity Model. It is however at the similar conditions, power increases for only 1.5 % using Density Model. The discrepancy happens due to dynamic viscosity reduces with higher temperature. This results to the reducing of energy loss due to frictional effect when incoming fluid temperature increases, and therefore contributes to higher increment of power output.

The effect of salinity to kinetic power output is not so obvious in Viscosity Model but it is quite apparent in Density Model. Theoretically higher fluid salinity contributes to higher fluid density and fluid viscosity and therefore results to lower kinetic power output of the water mixture. This can be observed in figure 2(b) where kinetic power output increases with lower salinity at a given temperature and similar trend is observed for other tested temperature also. Regarding to the effect of fluid salinity, the different trend in figure 2(a) results from the property of fluid dynamic viscosity also where it is more temperature dependent if compared to salinity. This can be seen from the reduction of fluid salinity from 40 psu to 0 psu at given temperature of 20 °C results to reduction of dynamic viscosity of only 7.8 % whereas changes of fluid temperature from 20 °C to 100 °C at given salinity of

0 psu results to reduction of dynamic viscosity of 71.9 % [3]. This explains the dominancy of temperature in affecting power output prediction using Viscosity Model.

It is specifically can be observed that in figure 2(a), the kinetic power output is strangely having a slight increment with higher salinity of incoming water at a given temperature, and the similar trend is observed for other tested temperature also. This suggests that possibly smaller salinity difference between sea water and incoming water may be used for increasing the kinetic power output slightly. The prediction may be explained by the incoming water requires certain amount of mass to have sufficient momentum for flowing through down-tube, up-tube and towards ocean surface. It is in addition reported by [4] that unpublished experiments show that smaller salinity differences raise the efficiency. However, smaller salinity difference between fluids seemed does not produce significant power increment in figure 2(a) and therefore this finding requires further experimental validation and optimization to be applied in the full-scale experiment. As a result, incoming water with zero salinity or fresh water is preferable at the current stage of investigation.

The percentage of tube diameter ratio (D_3/D_4) at constant up-tube diameter has been found useful to determine the flow rate of incoming water along the down-tube from reservoir as in equation (3). By using the similar setting as the experimental setting [4], the percentage of diameter ratio is varied from 2.4 % to 28 % where up-tube diameter is fixed at 0.15 m. Figure 3(a) and 3(b) present the effective water head of incoming water when percentage of diameter ratio and the height of reservoir are varied using Viscosity Model and Density Model respectively.



(a) Viscosity Model. (b) Density Model.

Figure 3. Comparison of the effective head from incoming water at different percentage of diameter ratio and height of reservoir using different models.

It is presented that in figure 3(a), the percentages of diameter ratio less than 10 % have negative effective head of incoming water and these heads tend to become more negative with higher height of reservoir. This is causing by the increasing of head loss beyond the cutoff water head when down-tube diameter is reduced to less than 10 % of up-tube diameter. The increasing of reservoir height does not help in adding up the effective head but in reverse results to enlarging of head loss. This may due to that the frictional head loss is velocity dependent and proportionate with higher heights. This finding suggests that tube diameter ratio of less than 10% might not work if for the sake of minimizing the input incoming water, neither it worked by elevating the incoming water reservoir at this absolutely lower diameter ratio.

Also, from figure 3(a), effective head increases with higher diameter ratio and tend to become larger with higher elevation of reservoir. This can be explained through equation (5) in Part 1 where head loss reduces with larger down-tube diameter. Due to that the frictional head loss is velocity dependent at various heights, the head loss is in fact increasing with higher heights but its amount is not so significant at larger down-tube diameter and therefore ends up with increasingly positive effective water head with higher heights. Compare to the effective head predicted using Density Model as in figure 3(b), it is always similar with the theoretical height of reservoir h_1 since it has not considered any energy dissipation or water head losing.

Up-tube diameter is proportionate to certain order of sea water flow rate going into the bottom of up-tube as in equation (7). As a result, various percentages of diameter ratio more than 10 % at

different up-tube diameters are used to simulate the corresponding effects to the kinetic power output as presented in figure 4 using Viscosity Model.

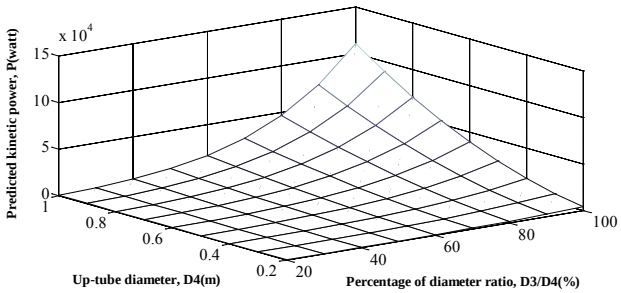


Figure 4. Prediction of kinetic power at different diameter ratio and up-tube diameter using Viscosity Model.

Further examination of figure 4 and figure 4 in [2] for Density Model shows that it is desirable to have diameter ratio as high as possible so that higher power output can be produced. However, there should be a practical ratio constrained by physical argument. From equation (2), the volume flow rate at Point 2 is the summation of the volume flow rate from Point 3 and also Point 4. Thus, adequate space to allow the sea water drift upwards from Point 4 to Point 2 is required. Based on this argument, diameter ratio of 40 % is chosen for further investigation.

Another important point to investigate is on how the height of reservoir (refer figure 1) affects the power output of the system. This is important when the investigation is performed in full-scale experiment at the specific location reported in [2]. In order to have further insight to this, figure 5 is simulated with tube diameter ratio is fixed at 40 % and the temperature of sea water and incoming water (S_1 = 0 psu) from reservoir are set at 25 °C and 32 °C, respectively. This temperature selection is based on the ambient properties where the future full-scale experiment is located. Comparison of figure 5 and figure 6 in [2] for Density Model exhibits that higher kinetic power output can be acquired when the height of reservoir is increased. It is furthermore showing that higher increase rate of power output can be obtained with larger diameter of up-tube.

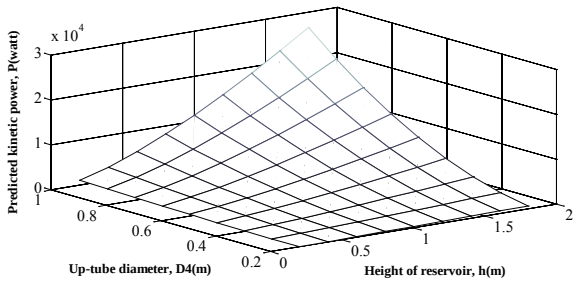


Figure 5. Prediction of kinetic power at different up-tube diameter and height of reservoir using Viscosity Model. The tube diameter ratio (D_3/D_4) is fixed at 40%.

As discussed in Density Model, it is found that up-tube diameter and length of D_4 = 0.6 m and L_u = 7 m are capable to construct a 10kW electrical power generator, at reservoir elevation of h_T = 1.8 m to meet the power demand of a specified amount of households. Meanwhile in Viscosity Model, a slightly larger setting is predicted through figure 5, the required up-tube diameter is 0.7 m with the similar up-tube length and height of reservoir as Density Model for the similar power output. In overall both proposed settings from different model are not differ much except for the up-tube diameter (Viscosity Model: 0.7 m; Density Model: 0.6 m) and down-tube diameter which is 40 % of

up-tube diameter (Viscosity Model: 0.28 m; Density Model: 0.24 m). In view that part of the simulation results using Viscosity Model [1] have relatively closer agreement with reported experimental measurements, it is decided to pursue the actual experiment with the setting from Viscosity Model, with the additional intention that the system is still capable to achieve the expected outcome after undergoing minimum unavoidable energy loss.

Based on the project scale assessment, the expected power output of 10 kW might involve big structure, large volume of incoming water (fresh water) and therefore big project costing. For the purpose of fundamental investigation, it would be desirable to reduce the expected outcome to 1 kW. As mentioned in the system mechanism, the rising of water mixture due to buoyant force is excited by the injection of incoming water at different salinity and temperature. It is therefore expected to have higher normalized power output over the volume flow rate of incoming water. Based on this argument, tube diameter ratio of 15 % is selected for additional investigation. In order to visualize this, and take into account of the previous argument, figure 6 is simulated with tube diameter ratio of 15 % at the respective ambient temperature of sea water and incoming water using Viscosity Model.

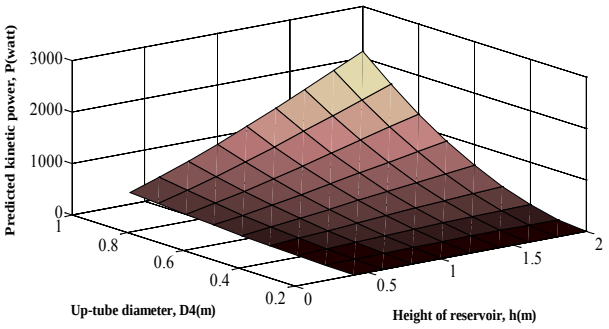


Figure 6. Prediction of kinetic power at different up-tube diameter and height of reservoir using Viscosity Model. The diameter ratio (D_3/D_4) is fixed at 15%.

Detail examination of figure 6 shows that up-tube diameter and down-tube diameter of D_4 = 0.8 m and D_3 = 0.12 m respectively, with reservoir elevation of 1.8 m from the mean sea level are sufficient to meet the new power demand. Compared to the previous expected power outcome and therefore the predicted down-tube diameter (D_3 = 0.24 m) by Viscosity Model, the current predicted down-tube diameter is reduced by half which indicates lesser usage of incoming water in generating useful power. Although for the new power output, the required up-tube diameter is increased by 0.1 m, but in practical the increment of up-tube size does not consume large costing of input resources.

4. Conclusions

The paper of Part 2 presents the computer simulations of Viscosity Model which is derived in Part 1 and later compare with the classical simulations from Density Model. Overall comparison of simulation results reveal that there is power increment with higher temperature as simulated by both models but particularly the increment rate is higher in Viscosity Model. This is due to the reduction of fluid dynamic viscosity where it is relatively temperature dependent. Larger percentage of diameter ratio, bigger up-tube diameter and higher reservoir elevation are found capable to increase the kinetic power output by both models. However in specifically, a limiting boundary is found by Viscosity Model where those tube diameter ratios less than 10 % are unable to produce any useful incoming water flow, neither has it worked by the increasing height of incoming water reservoir at this lower diameter ratio. Parametric setting of the future full-scale experiment predicted by both models to achieve the similar expected outcome are not differ much but Viscosity Model predicts slightly larger setting. It is preferable to pursue the full-scale experiment with the setting from Viscosity Model, with

the additional intention that the system is still capable to achieve the expected outcome after undergoing minimum unavoidable energy loss.

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