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Viscosity Model for Predicting the Power Output from Ocean Salinity and Temperature Energy Conversion System (OSTEC)

Part 1: Theoretical Formulation

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Abstract**—**The mixture between two fluids of different salinity has been proven to capable of producing electricity in an ocean salinity energy conversion system known as hydrocratic generator. The system relies on the difference between the salinity of the incoming fresh water and the surrounding sea water in the generator. In this investigation, additional parameter is introduced which is the temperature difference between the two fluids; hence the system is known as Ocean Salinity and Temperature Energy Conversion System (OSTEC). The investigation is divided into two papers. This first paper of Part 1 presents the theoretical formulation by considering the effect of fluid dynamic viscosity known as Viscosity Model and later compares with the conventional formulation which is Density Model. The dynamic viscosity model is used to predict the dynamic of the fluids in the system which in turns gives the analytical formulation of the potential power output that can be harvested.

Keywords**—**Buoyancy, density, frictional head loss, kinetic power, viscosity.

I. INTRODUCTION

THE exhaustion of conventional energy sources and global environmental issues has implied a major shift from fossil fuels to renewable source. Without contributing to greenhouse gas emissions, renewable energy is a clean source of energy which can be harnessed from natural resources such as wind [1], biomass [2], sea water [3], [4] and ambient vibration [5]-[8]. Huge research funding and giant scientific effort have been spent on studying and investigating the applications of renewable energy, however, it is up to now hardly a single technology could be the panacea to the world energy issue [9].

The ocean, an untapped source of energy, could provide a vast source of potential renewable energy resources [10]. If properly harnessed, this clean energy source may meet the growing global energy demand. To assess the potential, the first generation of commercial ocean energy conversion devices were installed in UK and Portugal respectively in 2008 [11]. Among the ocean energy resources such as wave, tide, current, temperature gradient and salinity gradient, salinity gradient is the one which is still less explored, yet the prospect for electricity generation is huge. There are currently two practical saline power extraction methods which are reverse electrodialysis (RED) and pressure-retarded osmosis, and they rely on osmosis process with ion specific membranes. However to solve the technical and durability issues of membranes, Hydrocratic Generator [12] is later introduced to derive the power from the mixing of sea water and low-saline incoming water without using membranes. It makes use of the upward buoyant force from the mixing of two different saline fluids at the same temperature, with a certain depth beneath ocean surface. With the buoyant force, the lower-density mixtures move upwards to the sea water surface at certain velocity and this movement is later translated into electrical energy using turbine rotor.

Recently, the authors introduced additional parameter into the system that may further excites the upward buoyant force of the rising mixture which is the temperature difference between the two fluids. This new system was named Ocean Salinity and Temperature Energy Conversion System or OSTEC [13]. It was found that the higher fluid velocity can be obtained at the sea water surface when the temperature of the incoming fluid is increased. This is because the density of the fluid reduced as the temperature increased. Theoretically, this means higher electrical energy can be harnessed from the system using the turbine rotor.

Recent literatures study however shows that varying the salinity and temperature difference between the two fluids may affect not only the fluid density but also the fluid dynamic viscosity of the system. Fluid viscosity is a measure of fluid resistance to flow. Therefore, by controlling the variation of salinity and temperature difference, it may help to reduce the frictional drag of flowing water which is due to the incoming fluid viscosity with the pipe wall roughness and viscous dissipation. It is normally in pipe or channel flows, a large part of the energy is lost due to the wall friction, particularly for a turbulent flow. Appropriate handling of the fluid properties may help to reduce the frictional effect of pipe flow. This finding has motivated the authors to refine the theoretical model for better prediction of the electrical energy

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output. The subsequent investigation is separated into two parts. The first paper of Part 1 introduces the new theoretical formulation - Viscosity Model to predict the electrical energy output from the OSTEC system by considering the effect of the fluid dynamic viscosity and further compare with the conventional formulation – Density Model [13].

II. THEORETICAL DERIVATION OF THE VISCOSITY MODEL FOR OSTEC

Ocean Salinity and Temperature Energy Conversion System (OSTEC) consists of an elevated water reservoir and a pair of vertical tubes where the smaller down-tube channels the incoming water from reservoir to the bottom of the vertically submerged bigger up-tube. The naturally heated incoming water from reservoir is injected to the open up-tube (Point 3) and mix with the deeper sea water. Water mixture is produced which in principle lighter than sea water and therefore move upwards due to the buoyant force. Fig. 1 shows the conceptual design of OSTEC system.

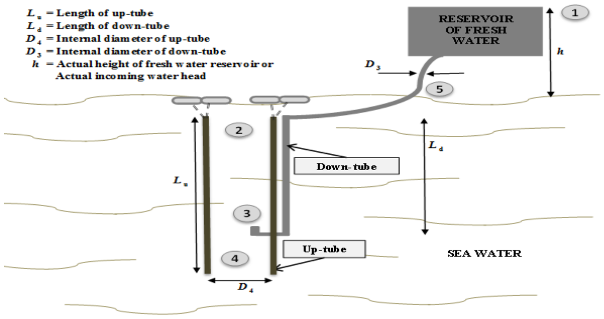

Fig. 1 Conceptual design for OSTEC theoretical experiment

In OSTEC system, the salinity and temperature differences between two fluids are the main parameters in deriving useful energy. It is assumed that the salinity and temperature of sea water remain constant, and there is only the salinity and temperatures of incoming water from reservoir are varied. Salinity and temperature of incoming water are purposely changed for becoming less dense and less viscous to induce the buoyant force so that the water mixture at Point 3 move upwards. Kinetic power may be derived from the upward flow of the rising mixture using turbine rotor at Point 2.

It is in reality that there is a certain amount of energy loss during the mass flows of water from one section to another. In order to derive an analytical formulation by considering the energy loss, Energy Equation is used to derive the Viscosity Model. It is used to predict the behavior of incoming water flow from the reservoir (Point 1) to the mean sea level (Point 5). The actual incoming water head is supposed to be considered from the surface of incoming water in the reservoir (Point 1) to the outlet of down-tube (Point 3) throughout the total displacement of incoming water along the down-tube. It is however well understood that when the incoming water channeling out from down-tube outlet at Point 3, it is required to go through the similar distance (with the incoming water head from Point 5 to Point 3) to rise towards the sea surface. Therefore an assumption is made that the additional water head from Point 5 to Point 3 along the down-tube is cancelled out by the similar distance required to rise upward from down-tube outlet towards the sea surface along the up-tube. As a result, the actual incoming water head, h is just by considered from Point 1 to Point 5. Consequently, the dynamic of the fluid in the system can be written as [14]

$$\frac{p_1}{\gamma}+h_1+\frac{V_1^{\,2}}{2g}=\frac{p_5}{\gamma}+h_5+\frac{V_5^{\,2}}{2g}+h_L \qquad (1)$$

where γ is the specific weight of incoming water per unit volume, g is the gravitational constant, h_L is the frictional head loss experienced by the incoming water flowing from the reservoir to Point 3, while p_1 and p_5, h_1 and h_5, V_1 and V_5 shows the static pressure, the elevation from an arbitrary datum, the fluid velocity, at Point 1 and Point 5 along a streamline, respectively. From (1), the algebraic sum of the pressure head, the elevation head, the velocity head and the frictional head loss accounts for nearly all the energy encompassed in a unit weight of water flowing through a certain section of pipe which obeys the principle of energy conservation.

In view that both the section at Point 1 and Point 5 are exposed to atmospheric pressure, the pressure head at Point 1 and Point 5 are cancelled out by each other in (1). Meanwhile the water velocity in the reservoir (Point 1) is assumed to be very low compared with that in the down-tube, and therefore can be neglected. As a result, velocity of incoming water at Point 5, V_5 can be computed as

$$V_5=\sqrt{2g(h_1-h_5-h_L)} \qquad (2)$$

By referring to the OSTEC diagram in Fig. 1, Point 5 is at the same level with the mean sea level, therefore it is set as the arbitrary datum in which h_5 = 0 m. In addition, an assumption is made previously to cancel out the incoming water head from Point 5 to Point 3, it is therefore the V_3 equals to the incoming water velocity at Point 5 and can be expressed as

$$V_3=\sqrt{2g(h_1-h_L)} \qquad (3)$$

By referring to the velocity of incoming water at Point 3, V_3, in (3), after deducting the head loss from the actual water head of incoming water, the remaining head is termed as the effective head of incoming water, h_e as

$$h_e=h_1-h_L \qquad (4)$$

Head loss is generally classified into major and minor loss. Among the losses, friction head loss is the energy loss caused by pipe wall friction and the viscous dissipation in flowing water. This friction loss is referred as the major loss because of its broad contact along the piping system. All other loses due to pipe fittings such as bends, valves, elbows and joints are referred as minor losses. In the experimental results reported elsewhere [12], it was found that the fresh water channeling system sustains a head loss yet the sources of head loss is unknown. In view that the Viscosity Model in this paper is derived by considering the effect of dynamic viscosity, the head loss due to friction is determined using the Darcy-Weisbach equation of [14]

$$h_L = f \frac{L}{D_3} \frac{{V_T}^2}{2g} \tag{5}$$

where V_T, f, L, and D_3 are the theoretical velocity, Darcy friction factor, pipe length and down-tube diameter, respectively. The theoretical velocity is the velocity of incoming water which assumes the frictional head loss is negligible and therefore its corresponding effective head would be the actual height of reservoir, h_1. The theoretical velocity is given by

$$V_T = \sqrt{2gh_1} \tag{6}$$

The Darcy friction factor is in fact not a constant and depends on the pipe parameter and the velocity of the incoming fluid flow. It is hence necessary to identify the flow regime of a fluid flow before calculating the Darcy friction factor. As a result, Reynolds number N_R is used to characterize different flow regimes which is written as

$$N_R = \frac{D_3 V_T}{v_1} \tag{7}$$

where v_1 is the kinematic viscosity of the incoming water, defined by the ratio of fluid dynamic viscosity, μ to the fluid density ρ. It is expressed as

$$v_1 = \frac{\mu_1}{\rho_1} \tag{8}$$

Dynamic viscosity, μ as a function of fluid salinity and temperature is especially of interest as it can be controlled to minimize Darcy friction factor and hence reducing friction head loss. Due to the low variation of the dynamic viscosity produced and published by various sources of equations at different salinities and temperature, it can be obtained from the reported values through handbooks of fluid mechanics [14]. Meanwhile the fluid density ρ is another key parameter which is a function of fluid salinity and temperature. It is hence can be controlled to produce desired kinetic power output with appropriate structure design. The fluid density ρcan be written as [15]

$$\rho_1(S_1, T_1) = \rho_1(T_1) + S_1 a_1 + {S_1}^{3/2} a_2 + {S_1}^2 a_3 \tag{9}$$

where $\rho_1 a_1$, a_2, and a_3 are coefficients given by

$$\begin{aligned}\rho_1(T_1) = {} & 999.842594 + 6.793952\,\text{x}10^{-2} T_1 \\ & - 9.095290\text{x}1\,0^{-3} {T_1}^2 + 1.001685\text{x}1\,0^{-4} {T_1}^3 \\ & - 1.120083\text{x}1\,0^{-6} {T_1}^4 + 6.536332\text{x}1\,0^{-9} {T_1}^5\end{aligned}$$

$$\begin{aligned}a_1 = {} & 0.824493 - 4.0899\text{x}10^{-3} T_1 + 7.6438\text{x}10^{-5} {T_1}^2 \\ & - 8.2467\text{x}10^{-7} {T_1}^3 + 5.3875\text{x}10^{-9} {T_1}^4\end{aligned}$$

$$a_3 = 4.8314\,\text{x}10^{-4} T_1$$

$$\begin{aligned}a_2 = {} & -5.72466\text{x}10^{-3} + 1.0227\text{x}10^{-4} T_1 \\ & - 1.6546\text{x}10^{-6} {T_1}^2\end{aligned}$$

and S_1 and T_1 are salinity and temperature of incoming water respectively.

From the detailed inspection using theoretical velocity of incoming water, it shows that the Reynolds number of the incoming fluid flowing through down-tube is within the range of transitional zone between laminar and turbulent. As a result, the Darcy friction factor will be a function of both the Reynolds number and the relative roughness (e/D) of the pipe. The attribute e is the measurement of average roughness height of the pipe wall irregular surface whereas D is the pipe internal diameter. It should be noted here that the value for e is normally given for commercial pipe material by the manufacturer. Once N_R and e/D are determined, Swamee-Jain equation can be used to get the Darcy friction factor (refer (5)) which is

$$f = \frac{0.25}{\left[\log\left(\frac{e/D_3}{3.7} + \frac{5.74}{{N_R}^{0.9}}\right)\right]^2} \tag{10}$$

Substituting (10) and (6) into (5) gives the head loss of the system, further substituting into (4) and later into (3) gives the velocity of the incoming water at Point 3, V_3. By having V_3, the flow rate of incoming water from reservoir to the outlet of down-tube (Point 3) can be determined as

$$Q_3 = A_3 V_3 \tag{11}$$

Although in Viscosity Model there is different method to determine velocity of incoming water flow, but the similar equations as reported in [13] are used to determine the following important parameters such as flow rate of sea water entering the bottom of bigger up-tube, flow rate of the rising mixture, density of water mixture and subsequently the predicted power output.

III. RESULTS AND DISCUSSIONS

In view that both Viscosity Model and Density Model [13] have different way of theoretically modeling the velocity of incoming water; the difference is briefly summarized and discussed as:

A. Velocity of Incoming Water in Viscosity Model

The velocity of incoming water at Point 3 is formulated based on the indirect considerations of fluiddynamic viscosity by [14]:

$$V_3 = \sqrt{2g(h_1 - h_L)} \tag{12}$$

where g,$h_1$and h_L are gravity constant, total height of water reservoir from mean sea level, and frictional head loss. Fluid dynamic viscosity is used indirectly (8) in a series of equations from (5) to (10) to determine the $h_{L.}$ This power prediction methodology involves quite a number of equations; however it is a standard norm for proper design of required temperature for fluid injecting or pumping.

B. Velocity of Incoming Water in Density Model

The velocity of incoming water at Point 3 is formulated based on the direct consideration of fluid density as [14]

$$V_3 = \sqrt{\frac{2gh\rho_{PW}}{\rho_3}} \tag{13}$$

where h, ρ_{PW} and ρ_3 are the total height of water reservoir, density of pure water at standard temperature and pressure (STP)and density of incoming water at Point 3, respectively. Rather than using a series of equation from (1) to (10), Density Model requires only the straight forward equation to determine V_3.

Prior to comparison in the kinetic power output from the conceptual setup of Ocean Salinity and Temperature Energy Conversion (OSTEC) system using both models, it is essential to verify the flow rate of incoming water at Point 3 and salinity formed at Point 2 predicted by Viscosity Model, with the experimental measurement reported in [12] using similar setting given in Table I. It is assumed that the pipe material used is polyvinyl chloride (PVC) where its average roughness height is 0.0015 mm. Table II presents the comparisons of the two predicted parameters, which are the flow rate of incoming water at Point 3 and salinity formed at Point 2 with the respective reported experimental values and later further compared with the theoretical prediction from Density Model.

TABLE I
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_T	0.550

It can be noted that the predicted flow rate using Viscosity Model is quite similar with the measured experimental values with maximum deviation of just 0.61%. The predicted salinity is close to the measured salinity as well, with maximum error of 2.7%. These results indicate that the derivation of Viscosity Model is valid with small error, at least when it is compared to reported actual measurements.

TABLE II
COMPARISON BETWEEN THEORETICAL PREDICTION FROM VISCOSITY MODEL AND THE EXPERIMENTAL MEASUREMENT AND FURTHER WITH THE THEORETICAL PREDICTION FROM DENSITY MODEL

		Q_3 ($\times 10^{-4}$ m^3/s)		**S_2**
		Incoming water (S_1= 0.3 psu)	**Incoming water (S_1= 36 psu)**	
Experimental value		2.400	2.300	34.00
Theoretical Prediction	Viscosity Model (11)&(12)	2.400	2.314	33.08
	Density Model (11)&(13)	2.400	2.369	33.08
% of difference with experiment value	Viscosity Model	0%	0.61%	- 2.71%
	Density Model	0%	2.91%	- 2.71%

Besides, comparisons of the deviation percentages produced by Viscosity Model and Density Model suggest that Viscosity Model has higher prediction accuracy compared to Density Model in performing prediction. In predicting flow rate of incoming water through down-tube, the maximum deviation made by Viscosity Model is 0.61% rather than the maximum deviation made by Density Model which is 2.91%. It is however noted that the deviations percentages made by both formulations in performing prediction is less than 5 % and these suggest that both formulations are valid within the range of reliability. As can be seen now the two models perform predictions at the same experimental setting based on two different affecting parameters; the distinction between their corresponding computer simulations would be interested and are presented and discussed in second paper of Part 2.

IV. CONCLUSION

In the present study, a new refined theoretical formulation, known as Viscosity Model is derived where the flow rate of incoming water is computed based on the change of fluid dynamic viscosity. It is later compared with the conventional formulation known as Density Model, where its flow rate of incoming water was determined based on the change of fluid density. Both formulations have different approaches in modeling water injection system especially the velocity of incoming water from the on-land reservoir to down-tube outlet. It is found that for performing predictions, both models are valid within the range of reliability but in particularly Viscosity Model has relatively higher prediction accuracy than the Density Model. They consist of trade-off between the length of governing equations needed in modeling the flow of incoming water and the prediction accuracy.

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