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Numerical Study into the Effect of Working Environment on Energy Extraction Performance of Tandem Arranged Flapping Foils

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Abstract- More recently, the oscillating foil hydrokinetics turbines, as a new method to extract energy from incoming flow field, have been studied significantly. However, the focus of previous investigations is directed towered the fundamental parameters which affect the performance of the system. In this work, the impact of working environment on the efficiency of flapping foil hydrokinetic turbine is investigated. The system is placed in proximity the floor sea and the mean distance between the foil pitching axis and the seabed, h_0, are changed as h_0=6c, 3c and 1.5c. The results show that the total energy extraction efficiency of shallow water condition has decreased considerably to compare with deep water case because of interaction between the boundary layer of the seabed and the flapping foils. In addition, the upstream foil losses more energy than downstream foil.

Keywords- Energy extraction; Flapping foil; Tandem configuration; Renewable energy

Nomenclature

α: angle of attack
C_P : power coefficient
$C_L(t)$: instantaneous lift coefficient
$C_M(t)$: instantaneous momentum
c: blade chord length (m)
d: swept area
f: oscillating frequency
f^*: reduced frequency of flapping foil
h_0: heave amplitude
$h(t)$: instantaneous heave of foil
P: instantaneous power of the system
Re: Reynolds number
t: time
U_∞: free stream velocity
V_{eff} : effective upstream velocity
x_P: pivot point locates
θ_0: pitching amplitude
ϕ: phase difference between the pitch and heave motions
η: system energy-extraction efficiency
ρ: density
M: pitching moment
Lx: gap between the upstream and downstream foil

1. Introduction

In recent years, due to the rise of fossil fuel prices and their harmful effect on the environment such as air pollution, global warming, and climate change [1,2]; there is a growing intention to find new methods to extracts sustainable renewable energy sources. While wind and solar have both received significant attention, ocean energy, and more specifically tidal energy, has also emerged as important players in energy space. Recently, a new type of mechanism to extract energy, the flapping foil power generation system has been investigated [3]. The research about the concept of flapping foil energy extraction began in 1981 by the experimental work of MaKinney and DeLaurier [4].

Following these pioneering studies, many researchers carried out several numerical, experimental and prototype-based investigations on the flapping foil system for power extraction [5-11]. Kinsey and Dumas [12-14] performed a serious of numerical and experimental simulation and identified that the motion characteristic has stronger effects on foil performances than geometry and viscous parameters. Xiao and Zhu [15] identified the connection between energy extraction efficiency and kinematic parameters such as frequency, the effective angle of attack and the amplitudes of pitch and heave. Lemann [16], Ashraf [17] and Kinsey and Dumas [18] have studied numerically the two foils in the tandem arrangement. The results indicated that the amount of harnessed power of tandem foils is more than single foil. Since the downstream foil observed energy from the wake of the upstream foil. To achieve the more power output, the downstream foil should be located at an optimal place in the wake to the upstream foil [16-18].

The significant focus of pervious investigations about oscillating foil hydrokinetics turbine is directed towards the study of geometrical and kinematical parameters of flapping foil system to achieve the highest efficiency. However, the effect of working environment on the flapping foil device sill receives very limited attention. Few studies have been conducted in regard to the sea floor effect on a flapping foil. The present investigation studies two flapping foils in the tandem arrangement which operates in shallow water. The system is assumed to be placed in proximity the floor sea and the level of sea water is considered as ten-time chord length. The mean distance between the foil pitching axis and the seabed, h_0, are changed as h_0=6c, 3c and 1.5c. To make a comparative analysis, another simulation in which the flapping foil system oscillates under deep-water conditions is also performed. The results include two important concerns. One is to precisely capture vortex structure under working conditions and the other is to accurately compute the aerodynamic forces on the foil and total performance of the system.

2. Problem Description

2.1. Model description

"Fig. 1" show a 2D schematic diagram of the tandem configured, flapping foils energy harvesting device. The kinetic motion of each foil is a combination of heaving and pitching motion at their pitching axis. Two NACA0015 foils with a gap separation L_x and a chord length of c are flapping in a uniform, viscous water flows with a velocity of U_∞. The Reynolds number is 500,000, which measured according to the foil chord length. The pitching center of the foil located at x_p = c/3 from the leading edge. Two different water depths, ten times foil chord length, and deep water, are considered. The mean distance between the foil pitching axis and seabed are changed; three cases h_0=1.5c, h_0 =3c, h_0=5c are simulated (see "Fig. 2").

The equations for the foil motions are defined as [19]:

$$\theta(t) = \theta_m \sin(\omega t) \tag{1}$$

$$h(t) = h_0 + h_m \sin(\omega t + \pi/2) \tag{2}$$

Where θ(t) is the instantaneous pitching angle and θm is the pitching amplitude, h(t) is the instantaneous distance between the foil pitching axis and the ground, h0 and hm are the mean distance and the plunging amplitude respectively, ω is the angular frequency.

According to the velocity U_∞ and the foil chord c, the dimensionless reduced frequency f* is expressed as:

$$f^* = \frac{fc}{U_\infty} \tag{3}$$

Following the previous investigations are done by Kinsey and Dumas [22], the pitching and heaving amplitudes are set at θ_0=75°, h_0=c, respectively; the phase difference between the upstream foil and downstream foil, ψ, is fixed at 180°; the gap distance between two foils L_x equals to 5.4c and the reduced frequency f* equals to 0.14 for all cases in the present study. This choice in the parametric range is a good starting point to investigate the

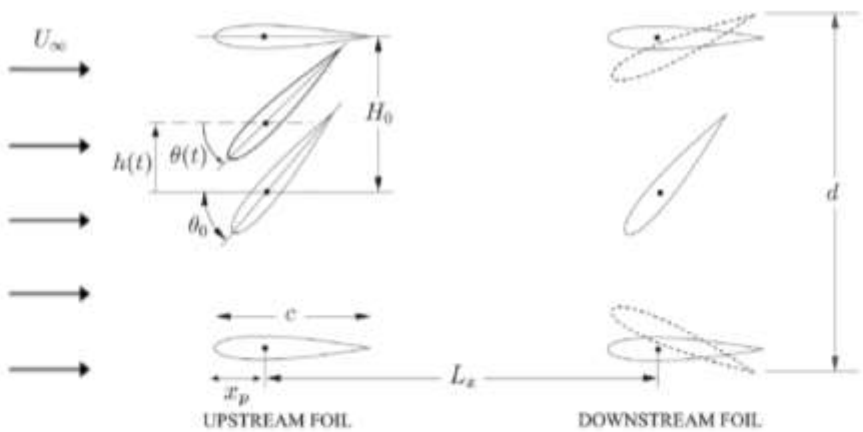


Fig 1. 2D schematic diagram of the tandem configured, flapping foils energy harvesting system

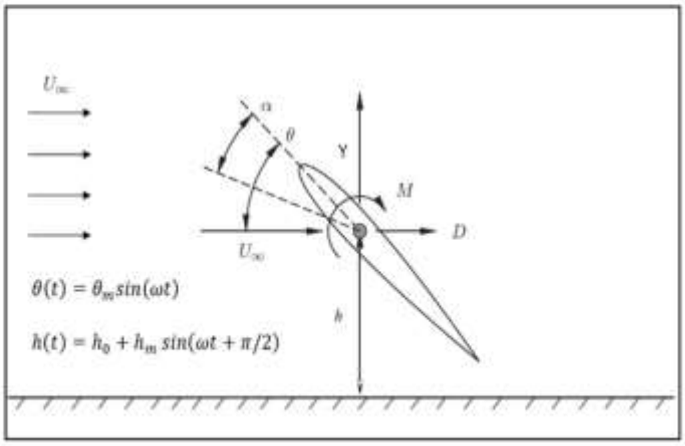


Fig 3. Sketch of flows over a flapping foil is placed in near of the seafloor [19]

effect of working environment on the system at present stage. The parameters used in this simulation are shown in Table 1.

Table 1 Parametric details

Foil profile	NACA0014
Chord length (c)	0.24
Pitching amplitude (*hm*)	c
Heaving amplitude (θ_m)	75°
Phase angle (φ)	90°
Motion phase lag (ψ)	180°
Gap distance (L_x)	5.4c
Reduced frequency f^*	0.14

2.2 Energy harvesting performance

Based on the decomposition of motion, the amount of power extracted from the flow field to the foil through the heaving and the pitching motion can be defined as

$$P_y(t) = Y(t)\, dh/dt \tag{4}$$

$$P_\theta(t) = M(t)\, d\theta/dt \tag{5}$$

Where $Y(t)$ the vertical is a force on the foil, dh/dt is the instantaneous heaving velocity, $M(t)$ is pitching moment, $d\theta/dt$ is the instantaneous pitching velocity. The overall power extraction is

$$P(t) = P_y(t) + P_\theta(t) = Y(t)\, dh/dt + M(t)\, d\theta/dt \tag{6}$$

The non-dimensional power coefficient C_p is expressed by

$$C_P = \frac{P}{1/_2 \rho U_\infty^3 c} = \frac{1}{U_\infty}\left[C_L(t)\frac{dh}{dt} + C_M(t)\frac{d\theta}{dt}\right] \tag{7}$$

Where $C_L(t)$ is the lift coefficient and $C_M(t)$ is the momentum is defined as:

$$C_L(t) = Y(t) \Big/ \tfrac{1}{2}\rho U_\infty^2 c \tag{8}$$

$$C_M(t) = M(t) \Big/ \tfrac{1}{2}\rho U_\infty^2 c \tag{9}$$

The total energy harvesting efficiency η is determined as the ratio between the total extracted power and the total incoming flow energy flux within the swept area, A, [13]

$$\eta = \frac{\bar{P}}{\frac{1}{2}\rho U_\infty^3 A} \tag{10}$$

2.3. Computational approach and validations

In the present work, all cases are simulated two-dimensionally by using the commercial CFD package, Open FOAM, which is based on solving unsteady Reynolds-averaged Navier-Stokes equations (URANS). To model turbulence, a URANS approach with the one equation Spalart-Allmaras model is utilized. This model was found to give good predictions of the hydrodynamic performance of flapping foil compered to experimental data [13,14].

For shallow water cases, the size of the computational domain is 75c × 21c. A uniform constant velocity in the X axis direction is imposed at the inlet. The incoming flow is considered as calm water than means no wave is produced from the inlet boundary. The outlet of a domain is set as pressure outlet with $\partial p / \partial n = 0$. The bottom boundary is considered as a non-slip wall to reflect the sea floor. The top boundary is set symmetry and free surface is located at D=10c between the top and bottom boundaries. For reducing the effect of boundary conditions on the results under deep water case, the computational domain is extended 85c away from the flapping foil device. The oscillating of rigid body is used, and the body-fitted a grid moves with the motion of the foils simultaneously. The selected mesh is C-type with structured mesh around the foil. The grid is built with approximately 50,000 cells with close to 400 points on the foil and Y^+ is almost lower than 1 during modeling. For the setting of the moving grid, refer to [20-23].

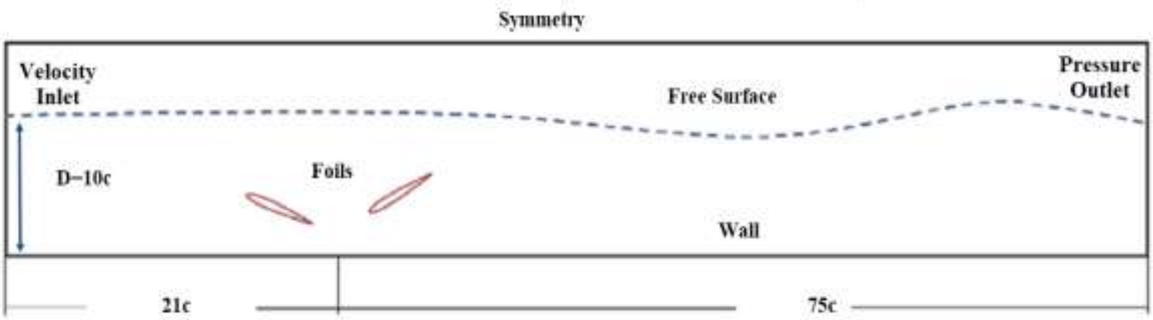


Fig 2. Boundary conditions

Prior to conducting a detailed computation, the validity and accuracy of the numerical methods should be corroborated. The validation is the comparison of the lift and power coefficients of one cycle with results of Kinsey and Dumas [13]. In this case, the tandem configured flapping foils system which operates in $Re=5\times10^5$ is simulated.

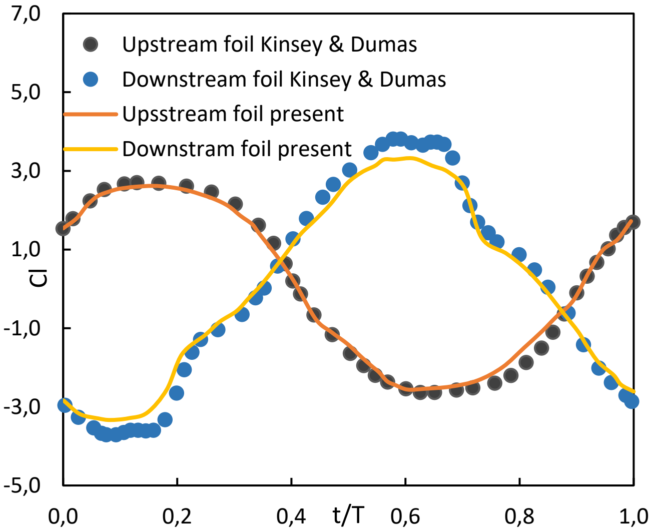


Fig 4 (a). Lift coefficient

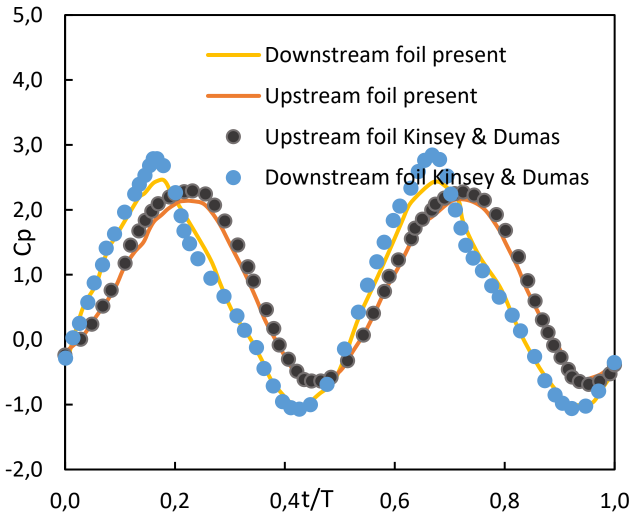


Fig 4 (b). Power coefficient

Two NACA0015 foils flap with a reduced frequency, $f^*=0.14$ and a pitching amplitudes$\theta_0=70°$, a heaving amplitude $h_0=c$ and a pitching center at the third chord ($x_p = c/3$). The gap distance between the upstream foil and downstream foil L_x, is 5.4c. The phase difference in between two foils, ψ, is 180°. According to "Figs. 4a and 4b", the results of the present computational model compare well with the work of Kinsey et al. [14].

3. Result

The main concept of this work is on the impact on the working environment on the energy extraction performance of the tandem foils power generator. For this purpose, the numerical simulations are performed and the mean distance between the foils and the seabed, h_0, are changed and power extraction performance of such a flapping foil system in a shallow water are investigated.

3.1. The effect of mean distance on power extraction performance

In this section, three mean distances h_0=6c, 3c and 1.5c are considered. The value of the power extraction efficiency of the system η, the maximum value of lift coefficient C_L, for four operation condition are reported in table 2. When the effect of working environment is considered in simulation, the performance of the total system has experienced a decrease. The total power extraction efficiency for h_0=6c, h_0=3c and h_0=1.5c decline 7.24%, 8.5% and 10.14% respectively to compare with deep water case. This amount of energy loss is due to the seabed effect and water surface level. It is interesting to note that the downstream foil lost less energy than the upstream foil.

Table 2. The value of power extraction efficiency and the maximum value of lift coefficient for four operation conditions

		η	$\widehat{C_l}$
Deep water	*Foil 1*	*62.1*	*2.67*
	Foil 2	*35.2*	*3.51*
	Total	*26.9*	
h_0 =6c	*Foil 1*	*57.6*	*2.50*
	Foil 2	*32.6*	*3.21*
	Total	*25*	
h_0 =3c	*Foil 1*	*56.5*	*2.37*
	Foil 2	*31.8*	*3.05*
	Total	*24.7*	
h_0=1.5c	*Foil 1*	*55.8*	*2.18*
	Foil 2	*31.2*	*2.85*
	Total	*24.6*	

As demonstrated in "Fig. 5" and table 2, when the effect of working environment is considered, the peak of lift coefficient reduces monotonically. In h_0=1.5c condition, the peak of lift coefficient is the lower than other conditions. As reported in [27,28], the contribution of lift force towards power extraction is positive (i.e. energy transferred from the flow to the foil) when it has the same sign as the heaving velocity, and vice versa. As can be seen in Fig. 5(a), although the curve of lift coefficient for deep water case has higher peak values, the portion of time that the contribution of lift force is positive is shorter than other cases. In the periods of $0 < t/T < 0.4$ and $0.5 < t/T < 0.65$, the working environment conditions reduce the absolute value of the lift coefficient of the upstream foil when both the lift forces and the heaving velocity have the same sign. Therefore, the instantaneous power coefficient of the upstream foils is less than that of the deep water case during the same portions of time, which it can be observed in Fig.6 (a). In the period

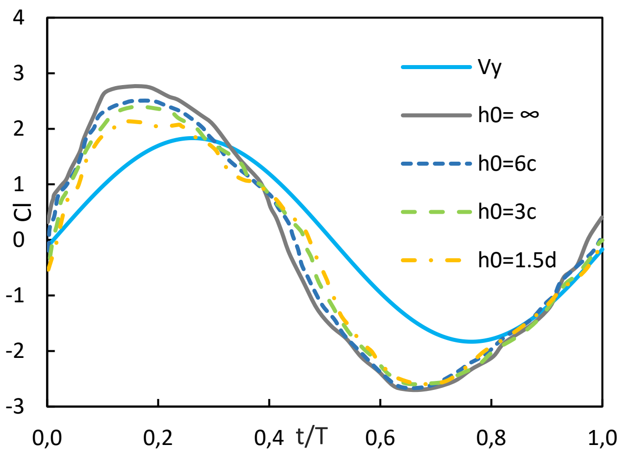


Fig 5 (a). Lift coefficient for upstream foil

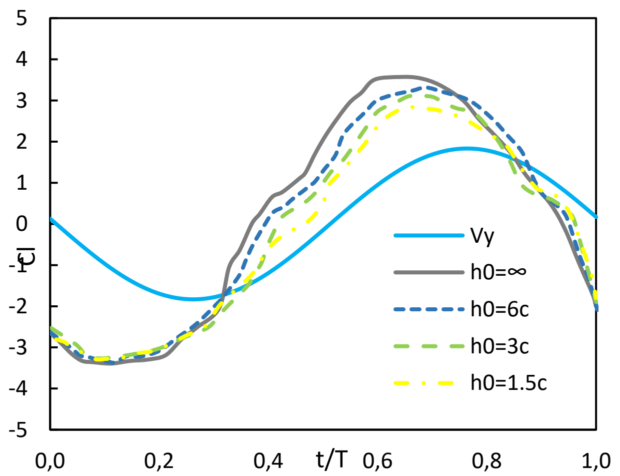
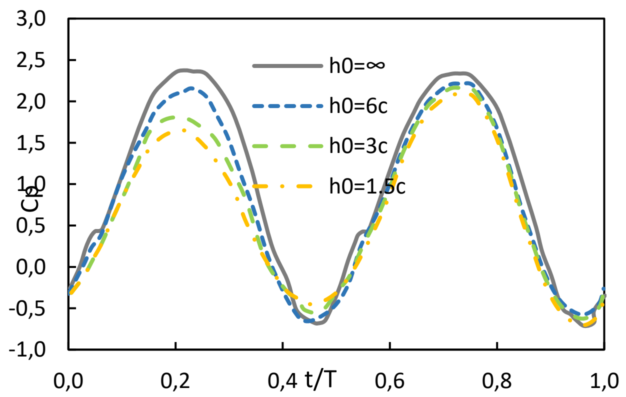


Fig. 5 (b). Lift coefficient for downstream foil



of 0.4< t/T < 0.5, the sign of lift coefficients changes to a

Fig. 6 (a) Power coefficient for upstream foil

negative value and the instantaneous power coefficient of deep water case is lower than other cases.

In Fig. 5(b), lift coefficient and heaving velocity of downstream foils have the same sign during two portion of time (0.25 < t/T < 0.35 and 0.5 < t/T <0.85). In the first period of time, the curve of lift coefficient for the shallow water conditions is larger than deep water case. However, the working environment conditions cause that the value of lift for shallow water downstream foils becomes smaller than that for deep water case during 0.4 < t/T < 0.65. For the

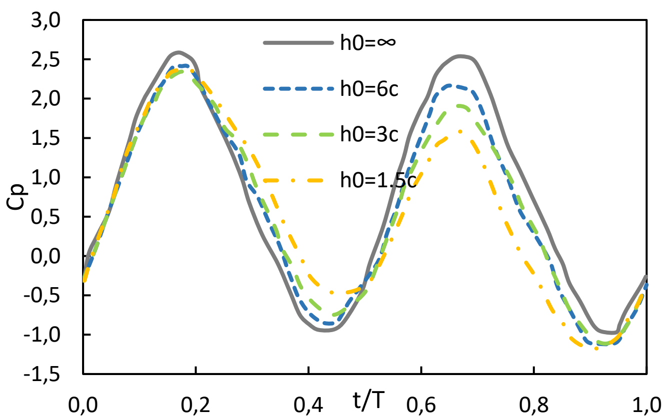


Fig. 6 (b) Power coefficient for downstream foil

period of 0.2 < t/T < 0.4 the working environment condition has a positive effect on the performance of the downstream foil. From 0.5 < t/T < 1, this condition has a negative effect on the power extraction capacity of the downstream foil. These observations coincide with that shown in Fig. 6(b).

3.2. The effect of vortex structure on energy extraction performance

In this section, the vortex structure impact on energy harvesting performance of foils is evaluated. By flapping the upstream foil, two types of vorticities are formed and shed, which one of them is in a counter-clockwise direction, while other is in the clockwise direction. Similarly, the motion of downstream foil generates two reverse rotating vortices.

Figs. 7 and 8 give the snapshots of near-field vorticity distributions at t=1/4T and t= 3/4T, respectively. At t=1/4T, the upstream foil is at the middle point of the upstroke near the bottom and the heaving velocity of foil reaches its maximum value. At this time, the leading edge vortex is growing and is attached to the foil. The working environment has a significant effect on the vortex structure and sheading. In shallow water condition, when h_0 equals 1.5c the vorticity which generated from the upstream foil has a strong interaction in the sea floor and a vortex generated from the seabed with the counter-clockwise direction. The vortex of seabed gets some part of the dynamic energy of upstream foil which causes to reduce the lift force generation of the upstream foil at t=1/4T, as confirmed in Fig. 5(a). In h_0=3c and h_0=6c conditions, the effect of the interaction between vorticity generated from the upstream foil and seabed on energy extraction system is less than h_0=1.5c. As the mean distance between the foil and the seabed increases, the value of lift force generated by the upstream foil also rises smoothly (Fig. 5(a)).

At t= 3/4T, the upstream foil is at the down stroke point in an oscillating cycle and another vorticity is attached to the upstream foil. At this time, the position of upstream foil causes the effect of sea floor on the vorticity structure reduces but the sea surface impact increases, especially for h_0=6c condition. However, there is very little difference between the boundary layer structures of the upstream foil in the shallow water conditions and deep water case. For this reason, the lift force generated by the upstream foil has approximately same value in all conditions (Fig. 5(a)). It demonstrates that the effect of the seabed on the power extraction performance of the flapping foil energy harvesting system is stronger than the free surface at the present working condition.

The downstream foil benefits from interacting with the shed vortices from the upstream foil. The shape a position of the vortices experienced by the downstream foil play important role in the energy harvesting capacity of this foil [18]. The downstream foil generates two types of vortices, in a counter-clockwise direction and clockwise direction, respectively. The downstream foil is at its down stroke position at t=1/4T and at the up stroke position at t=3/4T, which has a 180° phase difference with the upstream foil. The vortices generated by upstream foil affect the downstream foil at t=1/4T and t=3/4T, respectively and raise the local dynamic pressure to improve the energy harvesting efficiency at these times [17]. However, at t=3/4T, the downstream foil of the shallow water condition interacts with weaker vortices of the upstream foil due to the seabed effect (Fig. 7). Therefore, comparison with the deep water case, the performance of the system decreases monotonically, especially in h_0=1.5c condition. Similar to the upstream foil, when the downstream foil is at the middle point of the down stroke at t=1/4T, the vortex patterns of the

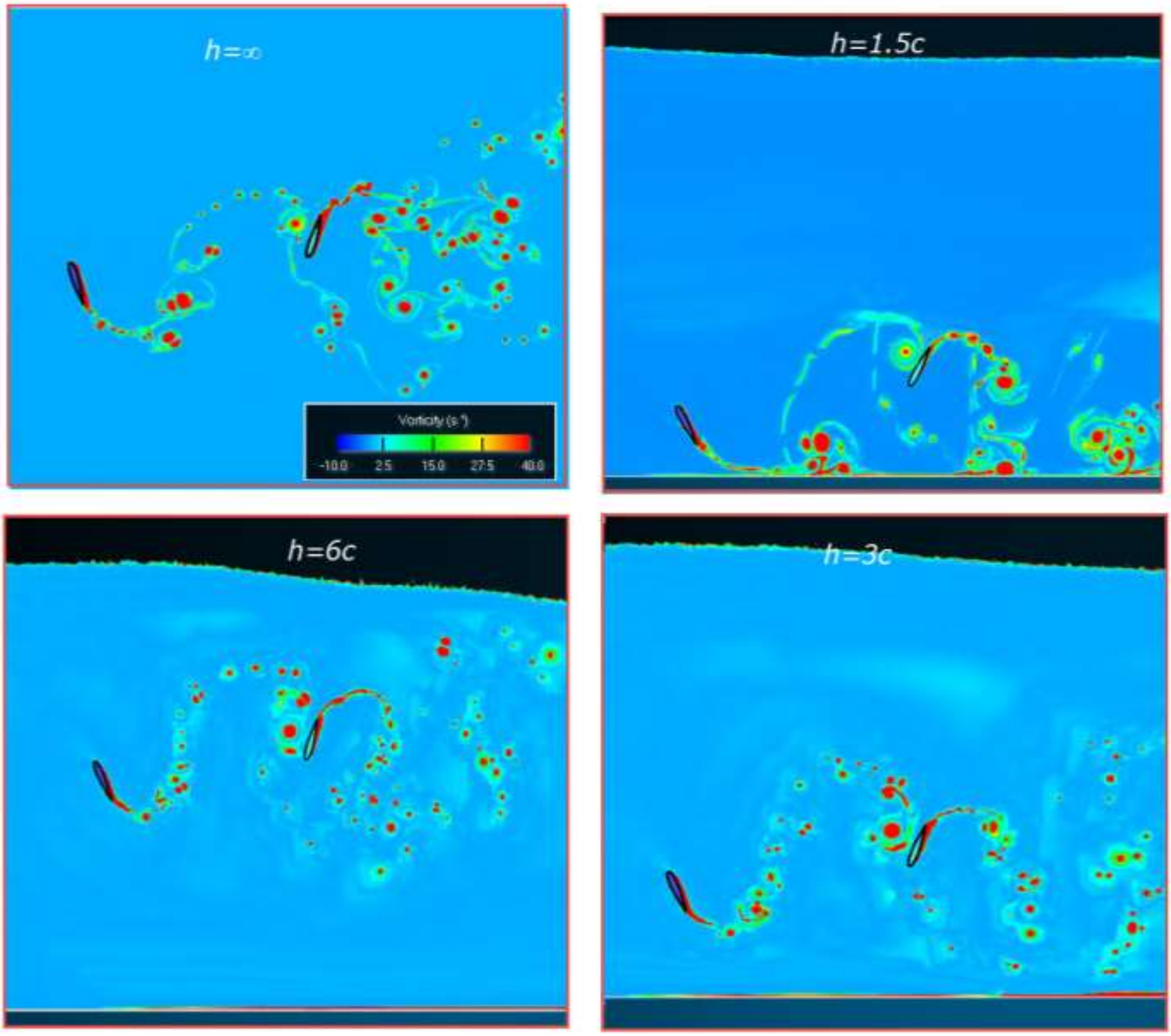


Fig.7. The vorticities contour with different h_0 at t=1/4T

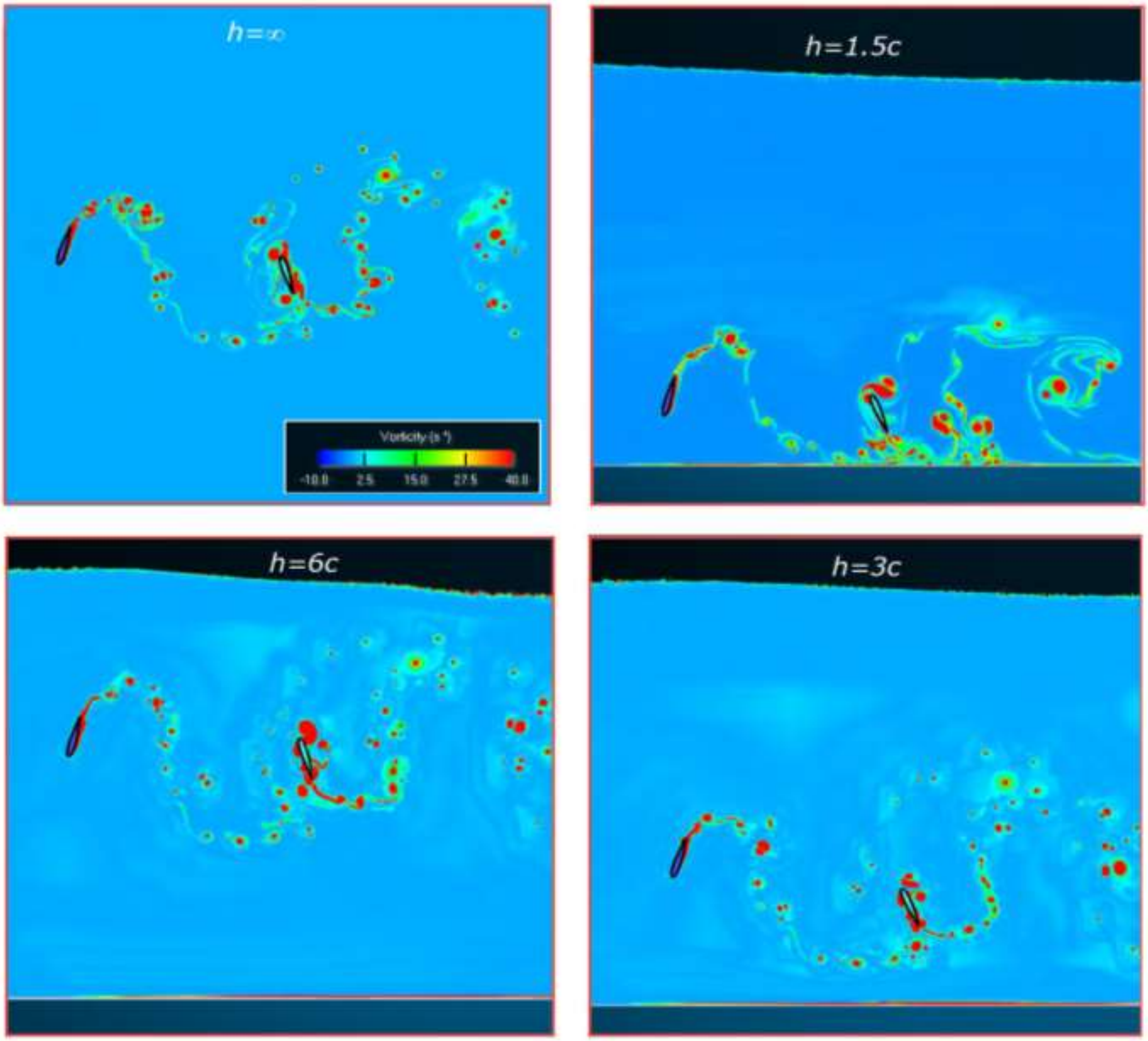


Fig. 8. The vorticities contour with different h0 at t=3/4T

downstream foil is like to that the deep water condition so the performance of the system is approximately similar in all conditions.

4. Conclusion

The present investigation focused on the effect of the sea floor on the energy extraction performance of oscillating foils hydrokinetic turbine. The level of sea water is considered as ten-time chord length. The mean distance between the foil pitching axis and the seabed is varied as h_0=6c, 3c and 1.5c. It has been concluded that the energy extraction efficiency and vortices structures of flapping foils are affected by the shallow water conditions. The upstream foil losses more energy than the downstream foil when the system is assumed near the sea floor. Therefore, the total efficiency of system has decreased considerably to compare with deep water condition. The results show the strong interaction between the boundary layer of the sea floor and the upstream foil is the reason for the reduce of performance.

Present simulations are simplified the sea floor as a non-slip wall. But, in real condition, the seabed is covered with the underwater plates and sediment. In addition, the effect of changing the water density due to more or less concentration of the sand, mud or other dirt in the water should be considered. These topics will be studied in the follow up investigations in near future.

References

[1] Sharad P., "Solar Thermal Desalination: Sustainable Alternative for Sultanate of Oman.", International Journal of Renewable Energy Research., Vol 8, No 2, pp. 733-751, 2018

[2] Kolisetty D., Jose B., "Indian Progress in the Renewable Technologies: A Review on Present Status, Policies, and Barriers.", International Journal of Renewable Energy Research., Vol 8, No 2, pp. 805-819, 2018

[3] Young, J. Lai J., Platzer, M.F., "A review of progress and challenges in flapping foil power generation", Progress in Aerospace Sciences, vol. 67, pp. 2-28, 2014

[4] McKinney W, DeLauier J. The Wingmill, "An oscillating-wing windmill. Journal of energy", vol. 5(2), pp: 109-115, 1981

[5] Lu k., Xie Y., Zhang D., "Nonsinusoidal motion effects on energy extraction performance of a flapping foil", Renew Energy, vol.64, pp. 283-93, 2014

[6] Xiao Q, Liao W., "Numerical investigation of angle of attack profiles in flapping foil propulsion", Journal of Fluid Structure, vol.39 pp.1366-80, 2010

[7] Longo M., Roscia M., Lazaroiu M., Pagano M., "Analysis of sustainable and competitive energy system.", proceeding of 3rd International Conference on Renewable Energy Research and Application, Milwaukee, WI, USA, 19-22 Oct. 2014

[8] Zhu Q, Peng Z. "Mode coupling and flow energy harvesting by a flapping foil", Physics of Fluid, vol. 21, No. 033601, 2009

[9] Young J, Ashraf M, Lia J, Platzer M. "Numerical simulation of fully passive flapping foil power generation", AIAA J, vol.1(11), pp. 2722-2739, 2011

[10] Simpson BJ. Experimental studies of flapping foils for energy extraction, M.Sc. thesis, Massachusetts Institute of Technology, Cambridge, 2009

[11] Lu k., Xie Y., Zhang D. "Nonsinusoidal motion effects on energy extraction performance of a flapping foil". Renew Energy, vol.64, pp. 283-93, 2011

[12] Kinsey T, Dumas G. "Parametric study of an oscillating airfoil in a power-extraction regime.", AIAA J, vol.46, pp.1318-30, 2008

[13] Kinsey T, Dumas G, Lalnde G, Ruel J, Mehut A, Viarouge P, Lemay J, Jean Y. "Prototype testing of a hydrokinetic turbine based on oscillating hydrofoils". Renewable Energy., vol. 36(6), pp. 1710-1718, 2011

[14] Kinsey T, Dumas G. "Optimal operating parameters for an oscillating foil at Reynolds number 500,000", AIAA Paper. Vol. 52(9), pp.1885-1895,2014

[15] Xiao Q, Zhu Q. "A review of flow energy harvesters based on flapping foils", Journal of Fluid and Structures, vol.46, pp.174-191, 2014

[16] Lehmann F-O. "Wing- wake interaction reduces power consumption insect tandem wings", Exp Fluids vol.46, pp.765-75, 2009

[17] Ashraf M, Young J, Lai J, Platzer M., "Numerical analysis of an oscillating-wing wind and hydropower generator". AIAA J.vol.49, pp.1374-1386, 2011

[18] Kinsey T, Dumas G., "Optimal tandem configuration for oscillating-foils hydrokinetic turbine". J. Fluid Eng, Vol. 134,No. 021104.2012

[19] Wu,J., Y.L. Qiu, C. Shu, "An adaptive immersed boundary-lattice Boltzmann method for simulating a flapping foil in ground effect", Computer& Fluid, 2015

[20] OpenFOAM, the Source CFD Tool box. User's Guide, Version 2.11. 2012

[21] OpenFOAM, the Source CFD Tool box. Programmer's Guide, Version 2.11. 2012

[22] Zhu Q, Peng Z., "Mode coupling and flow energy harvesting by a flapping foil", Physics of Fluid, vol. 21No. 033601, 2009

[23] José Vitale A., Genchi A, Rossi P., Aerodynamic Performance of Straight-Bladed Vertical Axis Wind Turbines: A Practical Open Source Implementation., International Journal of Renewable Energy Research., Vol 8, No 2, pp. 1025-1037, 2018

[24] Connell K., Cashman A., "Mathematical & CFD Analysis of Free Floating Heave-Only Body", proceeding of 4th International Conference on Renewable Energy Research and Applications, 22-25 Nov. 2015

[25] Ayaz M., Colak I., Boran K., "CFD Based Wind Assessment in West of Turkey". proceeding of 4th International Conference on Renewable Energy Research and Applications, 22-25 Nov. 2015

[26] Koiwa K., Takahashi R., Tamura J., "A study of hydrogen production in stand-alone wind farm", Published in: International Conference on Renewable Energy Research and Applications, Nagasaki, Japan, 11-14 Nov. 2012

[27] Kinsey T, Dumas G., "Optimal tandem configuration for oscillating-foils hydrokinetic turbine." J. Fluid Eng., vol. 134, No. 021104, 2012

[28] Yasa Y., Mese E., Design and analysis of generator and converters for outer rotor direct drive gearless small-scale wind turbines", proceeding of 4th International Conference on Renewable Energy Research and Applications, 22-25 Nov. 2015