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Investigation of the hydrokinetic energy extraction from tidal currents in the Hormozgan maritime zone

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ABSTRACT

It has been more than 30 years that marine currents are studied over the Hormozgan maritime zone. In this paper, in addition to discussing results of some previous related studies, simulation results of the hydrodynamic regime of currents are presented. The aim of this study is to investigate feasibility of construction of tidal power plants in the region. We believe that the existing analytical and field data can be used for energy zoning of tidal currents in the Hormozgan region, which can be scrutinized with small convertors. Based on these data, it is found that in most of the time, the maximum speed of the current does not exceed 1.8 m/s. Density of the exploitable power in the hottest point is estimated between 1 and 3 kW/m^2. The extent of zones with the maximum speed of greater than 1.6 m/s is found in the Qeshm Canal, reaching to approximately 22km^2, while in two regions, the depth of the zone reaches to approximately 40m. Although small convertors with the cut-in speed of approximately 0.5m/s contribute to 50% of the energy production during a day, construction of a tidal power plant requires improvements in the technology of these convertors.

1. Introduction

The Persian Gulf in southern Iran encompasses approximately 237473 km^2, making it the third-largest water body in the world after the Hudson Bay and the Gulf of Mexico [1]. Near the Persian Gulf is Hormozgan province, which is located between 52° 40' and 59° 15' N and 25° 26' and 27° 19' E.

The tidal energy technology is a branch of different technologies, including tidal barrages, tidal lagoons, tidal in-stream convertors (TISECs) and dynamical tidal power, which use tides to generate electricity [2]. TISECs use the hydrokinetic energy of water flows originated from horizontal motions of tides. The largest unbounded potential of the tidal energy is coming from a tidal current, whose commercial ones are expected to be in the market in the coming years. For the economic extraction of this energy with the existing technology, the average of maximum speed of tidal currents should be within the range of 1.5 to 2.5m/s. The speed of the current reaches to relatively high values nearly in 10 regions across the world [3], while water currents of the Persian Gulf are relatively calm.

Over the last 30 years, numerous studies related to environmental and coastal engineering have been conducted in the Hormozgan region. Some researchers believe that considering the pattern of currents in this region, the extraction of energy is not economically doable [4, 5]. On the other hand, some believe that the Qeshm Canal is the best place in Iran for extraction of the tidal hydrokinetic energy [6,7]. In this study, the most important results of previous studies are presented, while by conduction of a hydrodynamic simulation of the current, the potential of the region in terms of TISECs are discussed. Although some information in terms of wind speed and direction, temperature, salinity, concentration of sediments and water turbidity need to be analyzed to feasibility study of construction of tidal power plants, in this study to investigate density of the potential energy, only the existing current speed and direction are analyzed.

2. A review of field studies

Equations In the literature, there have been eight reports in terms of field studies in the Hormozgan region. Locations over which measurements were taken are shown in Figure 1, in some of which several physical measurements were conducted. As can be seen, dispersion of the locations nearly covers the entire zone, although there are more sites near the Qeshm Island.

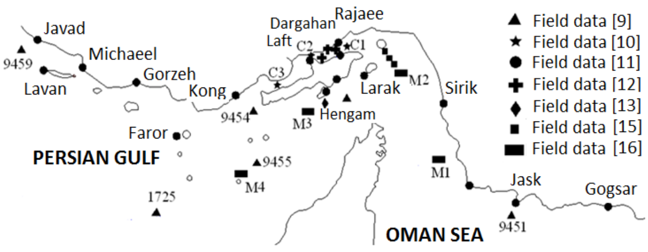


Figure 1. Geographic locations of field study in Hormozgan Province

To investigate how pollutants can be distributed, Reynolds [9] presented a report for activities of the NOAA research vessel in the ROPME region, including the Persian Gulf, Strait of Hormoz and Gulf of Oman. In this field study, which conducted from mid-winter to early summer of 1992, two current meter moorings equipped with 5 RCM and 7 drifters were used. In Figure 1, the locations of measurements and in Table1,theobserved valuesare provided. The maximum average speed of the current was less than 0.3m/s. Based on Reynolds [9] observations, the statistical speed of the current reached to the highest value (drifter 9451) near the Jask Port. The maximum average speed of the current was lower over the Abu Musa Island and Bandar Javadalameh, with a higher reduction of the speed over the Hormoz Strait and over west of the Qeshm Island. The Qeshm Canal was not investigated in this study.

Table 1. Results of Reynolds [9] for the average speed of current over the Hormozgan maritime zone

N0.	TYPE	Lat.	Long.	S (m/s)
1725	CMOD	25 30.2	55 50.1	0.2125
9451	DAVIS	25 23.8	57 23.8	0.3037
9452	DAVIS	26 41.8	56 12.5	0.0859
9454	DAVIS	26 29.4	54 56.1	0.0712
9455	DAVIS	25 57.1	55 08.1	0.2065
9459	DAVIS	27 07.3	52 33.9	0.1443

Using field data, Hadjizadeh et al. [10] analyzed dynamics of currents in the Qeshm Canal. The field measurements were taken in the summer of 2005 for 33 days in three stations named C1, C2 and C3 (Figure 1). In stations C1 and C2, measurements were conducted at the 5-meter depth by moorings equipped with the RCM9. In station C3, an ADCP was mounted on the seabed, but due to malfunction of battery, measurements are only available for 7 days in this station. Direction of the current in Figure 2 indicates that the horizontal component of the velocity is in a way that the resultant current becomes parallel to the coast. Based on observations of Hadjizadeh et al., in the spring tide, the maximum velocities of the current parallel to the coast are reported in stations C1, C2 and C3,with values of 1.16, 1.23 and 1.18 m/s, respectively. These values in the neap tide reach to less than 0.5 m/s. The maximum speed in the ebb is higher than that in the flood and a westerly residual current parallel to the canal with the average speed of 0.056 m/s was observed.

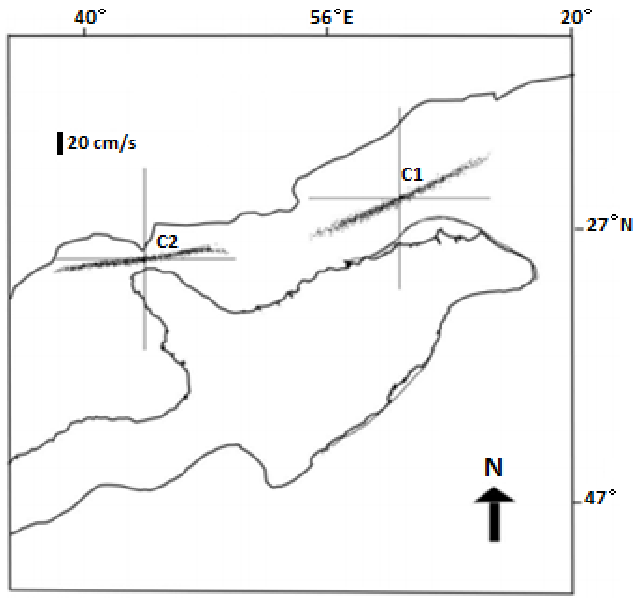


Figure 2. Scatter plots of hourly current data at stations C1 and C2 [10]

In Figure 1, geographic locations of stations of the Ports and Maritime Organization of Iran in the Hormozgan region are shown, over which measurements were taken [11]. In Table 2, maximum and average speeds of the current are reported in 24 stations. In the vertical direction, a number of cells with specific altitudes are defined, while speeds of the current in a specific cell (often the cell number 4) are reported. It can be seen that the average of the speed of the current in the maritime zone of the province is less than 0.45 m/s. It should be noted that in the Laft station over which the average speed reached to 0.6 m/s, the impacts of local winds are considered only in a limited time period in 2010. The triple regions of Laft, Hengam and Dargahan experienced the maximum speed between 1.5 and 1.8 m/s. Although the reported average speeds are slightly higher than those in report [9], both datasets indicate relatively low speed of the current in the region. These datasets also suggests that throughout the coastal line of the region, the Khuran Strait has the highest potential for extraction of energy. Based on results of [11] and further measurements, Hosseini et al. [12] provided analysis for the vertical profileofthecurrent in the Qeshm Canal. Measurement were taken twice in two different seasons, each time for 25 hours over 7 parts of the Canal. Based on these

Table 2. Maximum and average speeds of the current in 24 locations of the coastal regions of Hormozgan [11]

Station Name	Vmean m/s	Vmax m/s	Station Name	Vmean m/s	Vmax m/s
Faror	0.32	1.3	Gorzeh1	0.17	0.5
Lavan	0.30	1.11	Gorzeh2	0.07	0.27
Larak	0.28	0.95	Laft1	0.6	1.8
Larak-Ext.	0.26	0.87	Kong1	0.09	0.32
Jask11	0.17	0.71	Kong2	0.26	0.85
Jask1-Ext.	0.18	0.64	Michaeel1	0.21	0.58
Hengam	0.45	1.5	Michaeel2	0.095	0.4
Dargahan1	0.41	1.56	Javad	0.07	0.27
Rajaee	0.34	1.13	Jask2	0.06	0.25
Dargahan2	0.14	0.67	Jask3	0.11	0.43
Sirik1	0.14	1.1	Gogsar1	0.07	0.39
Sirik2	0.06	0.41	Gogsar2	0.12	0.6

measurements, vertical profiles of the speed of water were analyzed. Figure 1 shows geographic locations of these stations over which measurements were taken, as well as locations of those stations reported in [11]. Water speed and direction were measured by a vessel mounted ADCP. Maximum speed of the current was reported in Pohl station (1.7 m/s).

Yarveisi et al. [13] reported field measurements over one of the triple oil platforms of Hengam. Based on Table 3, maximum speed in this region reached to 1.7 m/s, which was approximately 13% higher than the reference data [11] for Hengam station. The speed of the current at the surface was less than that in the half depth, while opposite of this generally occurs.

Table 3. Water speed (m/s) and direction for the Hengam oil platform [13]

Depth	Direction from							
	NW	*W*	*SW*	*S*	*SE*	*E*	*NE*	*N*
10-year return								
Surface	1.0	0.8	0.7	0.8	1.0	0.8	0.7	0.8
Mid-depth	1.7	1.6	1.5	1.5	1.7	1.6	1.5	1.6
5m above seabed	0.5	0.4	0.3	0.4	0.5	0.4	0.3	0.4
0.5m above seabed	0.4	0.3	0.3	0.3	0.4	0.3	0.3	0.3

Yari and Shahrbaf [14] measured characteristics of the current for 40 days in November and December 2014 in Pohl station. Vertical profile of the speed of the current was measured at altitudes 5, 7, 9 and 11 meters by the ADCP, then averaged on a 10-minute time step to be converted to a 1-hour time step. Maximum speed in this point was measured at the depth of 6 m with the value of 1.5 m/s.

Torabi and Hamzei [15] measured speed and direction of the current at three points of A, B and C shown in Figure 1 at the depth of 25, 30 and 35 m. These measurements were taken for 8 days during January to May 2006. With a further distance from the coast toward the sea, and associated with an increase of the depth of water, the speed of the current was decreased. The speed of the current was higher at the surface, which can be caused by the layered water and the impacts of the seabed effects and wind at the surface. Maximum speed of the surface current was measured at station A, with the value of 1.12 m/s. The speed of the current in response to the impact of wind and the density difference was higher in spring (0.08 m/s) than that in winter (0.05 m/s). After removing tides' frequencies, the speed of the current in the north of the Hormoz Strait in the depth of 5 m was between 0.045 and 0.076 m/s. Inflows to the Hormoz Strait were stronger in summer than those in autumn and winter. Results indicated that wind has a strong impact on the speed of the current in the Hormoz Strait, such that the onset of the monsoon in the region caused an increase in the speed of inflows in spring and summer. Recently, they have reported the results of a similar study in the region [16].

Azizpour et al. [17] conducted measurements at four stations of M1 to M4 (Figure 1) for a 3-month period from November 2012 to February 2013 and analyzed contribution of different components of tides. Measurements were taken by the RCM9 up to the depth of 110 m. Results are shown in Table 4. Among the four stations, the highest speed of the current at the surface layer was at M4 station, with the value of 1.3 m/s. As measurements were taken between the depth of 25 and 35 m for the surface layer during the cold season, a higher speed is expected at the surface.

Table 4. Maximum values of velocity components at four stations [17]

Component	*M1*	*M2*	*M3*	*M4*
Along-shore in surface layer (m/s)	0.64	0.47	0.92	1.02
Along-shore in bottom layer (m/s)	0.61	0.45	0.81	0.87
Cross-shore in surface layer (m/s)	0.29	0.30	0.40	0.81
Cross-shore in bottom layer (m/s)	0.22	0.34	0.29	0.63

By conduction a simulation, Khosravi [18] estimated that maximum current speed at the Khuran Strait is 2 m/s, while it is 1.8 m/s based on field measurements [19]. Vessel-mounted measurements were conducted to describe the transverse structure of the flow between the two headland tips in the Khuran Strait with the highest tidal speed in the spring tide. In Figure 3, the studied region and three transects over which results of the simulation have been evaluated are shown. The length of each transect is 2.2 km and their distance is 5 km, measurements over each of which were repeated 9 times, with the data gathering for 13 hours for each transect. Measurements were taken during a spring tide on 8 October 2014, in which the first day of measurements was started from weaker tides. Data were averaged over the period of 40 seconds. Measurements were taken during the calm conditions when there was no wind. Distribution of the speed of M2 semidiurnal component in the T3 cross section with the highest speed is shown in Figure 4. Maximum speeds are near the surface at upper 10 m, such that speeds of the current decrease in all transects with an increase of the depth of the water. Maximum speed in transects T1 and T2 are 1.3 and 1.5 m/s, respectively. Maximum speed at T3 transect was occurred at the middle and northern transect, with the value of approximately 1.8 m/s. The experimental results of Khosravi et al. are in agreement with previous reports. Their results also introduced a new location in the Qeshm Canal along with the T3 cross section, over which the speed of the current at the surface was higher than those in the monitoring studies [11] and Hadjizadeh Zaker et al. [10].

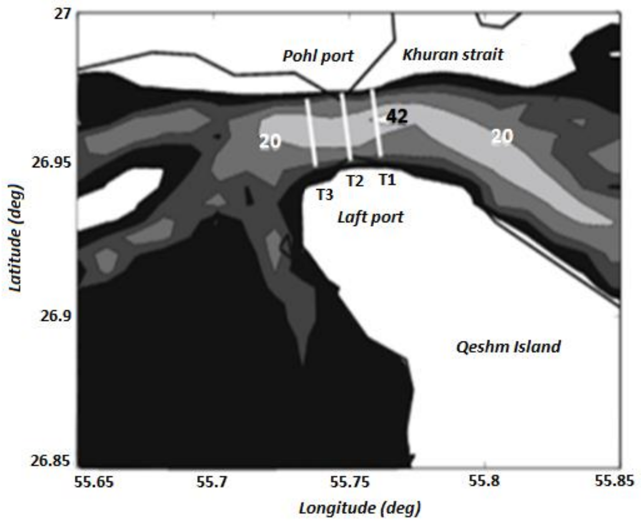


Figure 3. Map of the study and locations of T1, T2 and T3 transects [19]

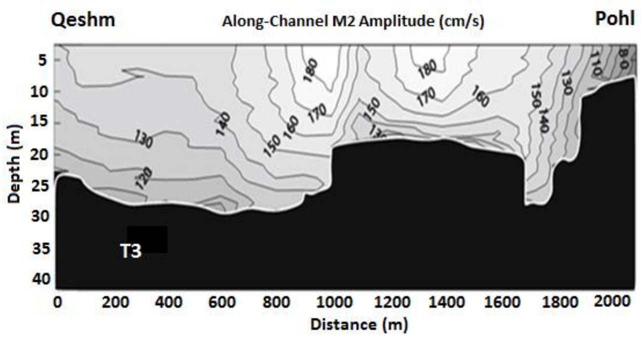


Figure 4. Experimental distribution of the speed due to the M2 component along with the T3 transect [19]

3. A review of analytical studies

Qiasi [20] simulated regime of tidal currents in the Qeshm Canal by the CECAD-FF software. Maximum speed occurred at the tightened places, with values of 1.6 and 1.3 m/s for the flood and the ebb, respectively, while the average speeds at the western and eastern boundaries were between 0.5 and 1 m/s. Due to the low resolution and applied hydrographic maps, results of Qiasi [20], particularly the average speed in the western and eastern boundaries, are higher than those observed. Using the tidal components obtained in ports near the Hormoz Strait, available in the Admiralty tidal table, Vahdat Torbati et al. [21] calculated and corrected components of tides of the Hormoz Strait, and thereby they obtained tidal currents in this region. They reported the speed of currents between 1 and 5 m/s, which based on the results of Torabi and Hamzei [15], these analytical values are higher than those of experimental values.

Shafieifar and Hosseini [22] examined hydraulic and hydrodynamic behavior of waves and the current in the Persian Gulf Bridge. Their analysis was based on two hydrodynamic mathematical models for the current and waves, while validation was based on field data provided by the CESCO consulting company. To more precisely study the current, three points are considered near the bridge. Their analysis was conducted over the stations for a 30-year period, in which the most critical condition in this period was selected as limit points. The CESCO recorded variation of the speed in AB36 station for 24 hours at different depths. Figure 6 shows variation in the speed and direction of the current in the triple points of the Khuran Strait for the long-term period. The speed of the current in this figure is the average speed and the specified direction is relative to the north. The speed of the current shortly before the entrance of the current to the Khuran Strait was higher than that in the middle of the strait because in the latter place the depth of water is greater. Maximum speed of the current in this region was reported approximately 2.5 m/s.

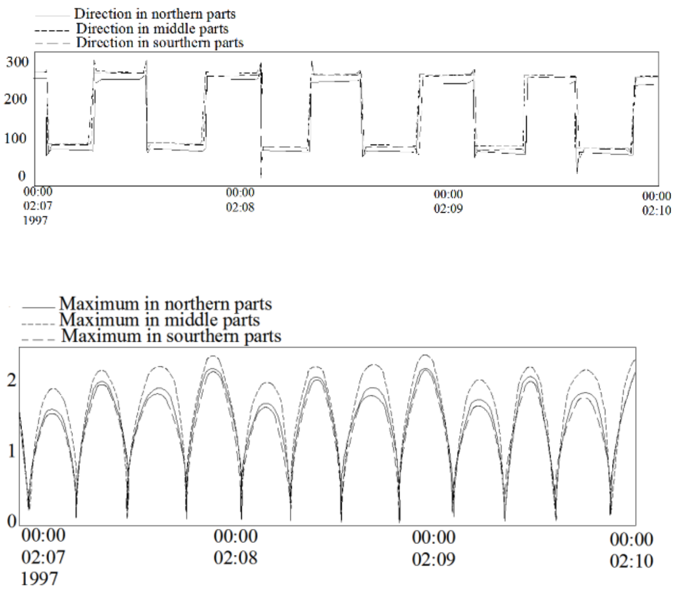


Figure 5. Variation of the direction (top) and speed (bottom) of the current in the triple points under study [22]

Sabagh Yazdi [2] numerically studied the impacts of oscillations of tides, surface evaporation and the perturbation of the flow near the Hormoz Strait. In the Harmonic analysis, components presented in the Admiralty tide table are used. Results were presented as variation in the level of surface water. In another study [23], Sabagh Yazdi introduced a numerical model for simulation of tidal currents in the Qeshm Canal and compared the results with those obtained from field measurements. The small impacts of wind were ignored. In Figure 6, results of the hydrodynamic model and field data of speed for a 48-hour period are shown at Kaveh platform of Qeshm. Based on this figure, maximum speed in this region was 1.23 m/s, which is consistent with observations of the Ports and Maritime Organization of Iran.

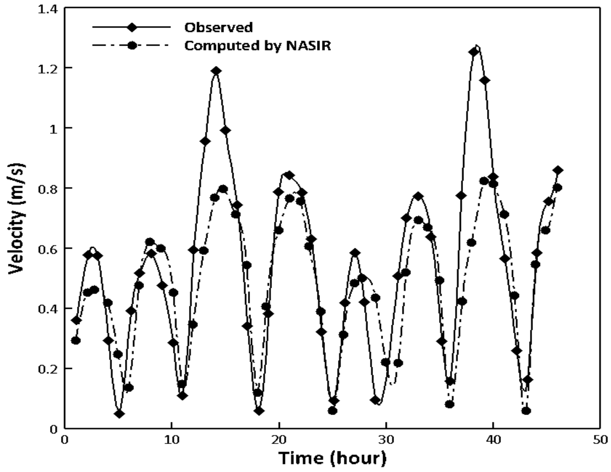


Figure 6. Comparison of the simulated speeds with those obtained from the field measurements (17-18 February 2002) [23]

Rashidi et al. [24] simulated tidal currents in the Persian Gulf using a 3D two-layer numerical model. It can be seen in Figure 7 that maximum coastal speeds in the Persian Gulf mostly occur near the coasts of Hormozgan in the Qeshm Island. Results of this numerical investigation are qualitatively consistent with field measurements of the monitoring project [11]. Maximum speeds of the current in the first and second layers are 1.9 and 1.2 m/s, respectively. The simulated speed in the first layer over the region is consistent with the experimental values.

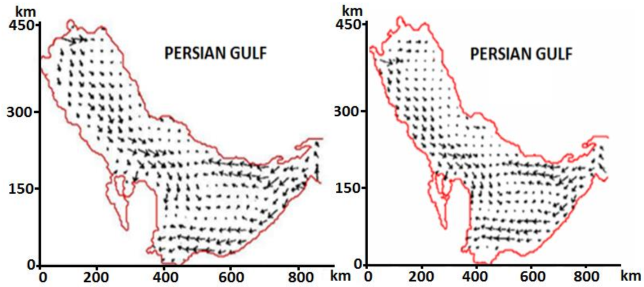


Figure 7. Flow field caused by the tidal force in the eastern border in the (right) first layer and (left) second layer after 64 hours [24]

Arvin et al. [25] numerically simulated tidal currents in the Qeshm Canal using Delft3D, Mike3 and Mike21 models. First, the hydrodynamic model was executed 3 dimensionally, the results of which compared against field data obtained in the eastern, central and western canal. Then, the 2D hydro-dynamic model was used for simulation of tidal currents for the year 2005. The analytical results were calibrated by the reference field data [10]. To examine variation in the speed of the current in the canal, 9 points according to Figure 8 were selected. In Figure 8, results are shown based on a 1-year analysis. In the average depth of the model, the average of the speed at point 6 is larger than other points. Maximum speeds were simulated at points 4 and 6, while the minimum was simulated at point 5. The average annual speed of the water in the canal in all points except 6 was 0.4 m/s, with the maximum speed reaching to 1.4 m/s. Only in point 6, the northern component of the horizontal speed was higher than the eastern component. It is predicted that in this point and its nearby locations, the maximum interfering of currents occur, which perturbs the flow. This perturbation, but with a lower degree was also reported in points 5 and 7. The simulated speed and the level of water were lower than those of experimental values. Based on the monitoring report, it is expected that the speed at point 4 reaches to 1.7m/s. However, based on the simulation results, point 6 is the potential point for field study.

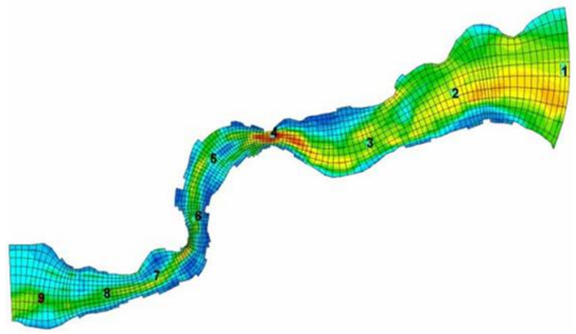


Figure 8. Locations of the selected points for examination of variation of speed in the Qeshm Canal [25]

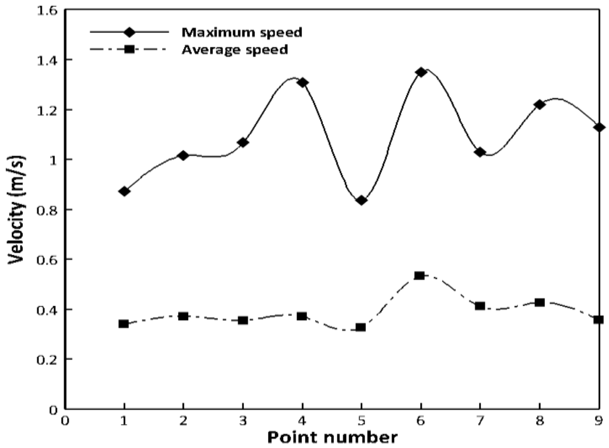


Figure 9. Variation of the annual average and maximum speed at 9 points in the Qeshm Canal [25]

Abaspour and Rahimi [26] used a 2D hydrodynamic model to estimate sources of energy for tidal currents in the Persian Gulf, the results of which were evaluated against tidal altitudes and stream diamonds obtained from the Admiralty charts. In the simulations, raw bathymetry of Iran National Cartographic Center with the resolution of 50 m was used. The impact of wind was ignored. Distribution of maximum speed of the current in the mean spring tide and the neap tide over the Hormozgan maritime zone was simulated (Figure 10). Maximum speeds of the current were predicted near the Hormoz Strait. In most of the places, speeds of the current were less than 1 m/s. A maximum speed of the current with the value of 1.8 m/s occurred in the Khuran Strait. Density of the computing power is shown in Figure 11. In this figure, maximum density of the power in the flood was approximately 2.5 kW/m^2, which was observed over a small area near the Pohl region. This value was considerably decreased in the low tide. It was predicted that density of the power varies between 0 and 3 kW/m^2 during a 14-day period. Zoning of the density of the power in the southern Qeshm Island requires further field investigations.

Figure 10. Maximum analytical speed in mean spring and neap tides [26]

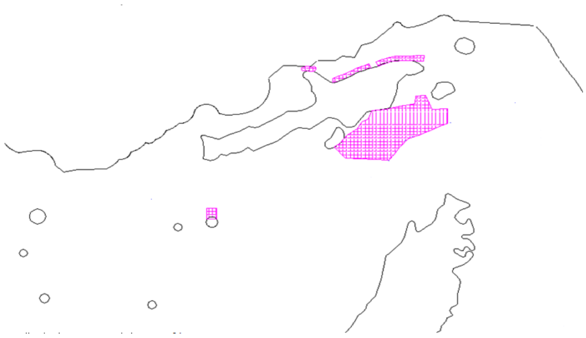


Figure 11. Regions with the maximum density of the computing power in the spring tide near Hormozgan Province [26]

By determining the speed of the current and variation of density, Karimi et al. [27] estimated the energy of tides. They used the 3D hydrodynamic model of Mike3HD for a full cycle of tides. The Qeshm Canal between the territorial coast and the coastal land of Qeshm was studied. Based on their results, middle of the Qeshm Canal is the best place for extraction of energy from the tidal current. Near the Pohl port, the speed of the current at the surface exceeds 2 m/s. This place with the depth of 20 to 30 m is a good location for installation of the convertor. Assuming that the power coefficient is equal to C_p=0.33, exploitable energy of turbines with the rotors' diameter of 12, 14 and 16 were estimated to be 1152, 1580 and 2070 MWH, respectively. Based on this, it was predicted that using 4 turbines with the rotor diameter of 16 m, the annual exploitable energy at this point is 7.5 GWh. To calculate the exploitable power of the farm, the speed of the incoming current was corrected by a speed coefficient.

Using a 3D hydrodynamic model in COHERENCE, Mahmoudof et al. [4] estimated the energy of tidal currents in the Qeshm Canal. They argued that due to the impact of tides on the speed of marine currents in the Qeshm Canal, the impacts of wind and density can be ignored. First, hydrodynamic of the region under the impact of 4 main components of tides was simulated, with the horizontal resolution of 250 m and 8 levels in the vertical. Simulated results were compared against the reference currents [10]. The power of speed components in each cell was calculated and added in columnar. In Figure 12, averaging of the power of the flow in columns of water is shown in Watts. Based on the outputs, maximum power is occurred in a point equivalent to point 6 in [25]. In this point, maximum accumulated power in the upper cell of the water column reaches to more than 12 MW and maximum energy of the surface reaches to more than 2MW. To determine the candidate points for extraction of energy, one-month averages of the energy of the current for each column of water are divided by the corresponding vertical cross section of the column. Two points with the potential power of higher than 1 kW/m^2 were introduced.

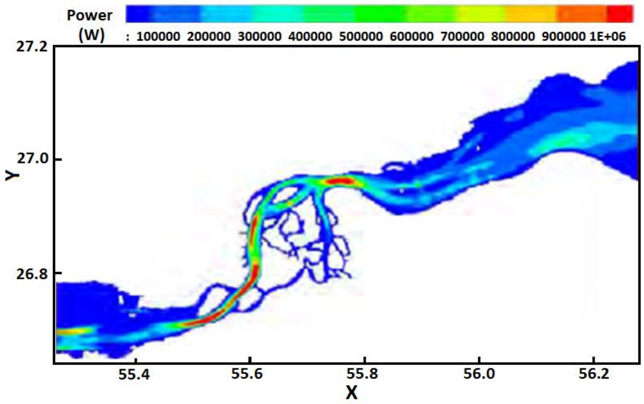


Figure 12. Monthly average of the energy of the current in water columns [4]

Kouchakian et al. [28] estimated maximum speed of the current in the Khuran Strait as 1.65 m/s. Based on the guideline of the EMEC and assuming that 14 rotors are installed and working only with 50 % of their capacity, potential for the power generation in the selected site in the Qeshm Canal is 1850 MW.

Mohamamdi et al. [29] studied the importance of each factor contributing in creation of the marine current in the Persian Gulf. To this end, the 3D COHERENCE model was used. Results indicated that the long-term pattern of the water circulation in the Persian Gulf is mostly determined by density differences and then wind. Maximum speed of the tidal current is in the Khuran Strait was estimated to be equal to 1.65 m/s.

Yari and Shahrbaf [14] estimated the exploitable power from the energy of marine currents in the Khuran Strait. To this end, after conducting field measurements for characteristics of the current in the Pohl station and computing tidal components for the time series, they predicted the speed of the current for a 1-year period. In Figure 13, results of the 1-year prediction are shown. They argued that due to geometry of the canal, currents are mostly oriented easterly-westerly; with the value of the easterly component is 8 to 10 times greater than the northern component. Most of the energy of the current originates from tidal currents. Maximum flux of the total extractable energy on the unite area is estimated to be 248 kW/m^2 for the turbine with the power coefficient of 0.35, which is a high value.

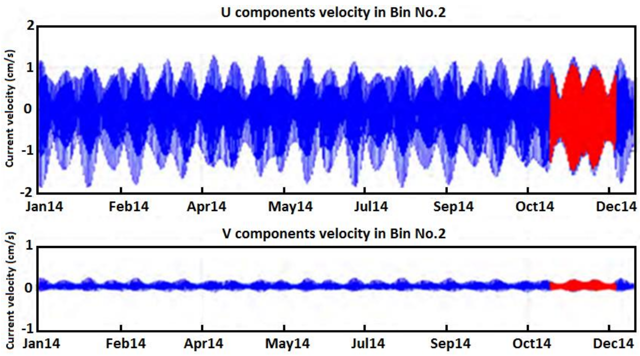
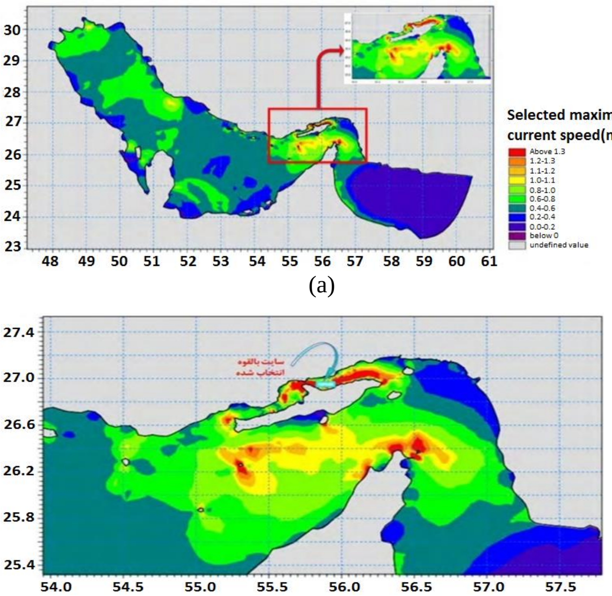


Figure 13. Time intervals of the results of the field measurements and the 1-year prediction [14]

Radfar et al. [30,31] investigated technical and economic feasibility for extraction of energy from tidal currents. The zoning map of the maximum speed of tidal currents is shown in Figure 14a. Three regions, including the Khuran Strait, the Hengam Island and the Greater Tunb are examined in terms of extraction of energy from tidal currents. In Table 5, maximum speed and density of the potential power of the tidal currents in these three regions are provided. Although maximum speed of the current was reported in the Khuran Strait, this region is not an appropriate place for extraction of energy due to the depth of water. In the site shown in Figure 14b,



(a)

(b)

Figure 14. (a) Zoning of maximum speed of the current and (b) distribution of maximum speed of the current and location of the candidate site near the Khuran Strait [31]

based on analytical model of Gert and Kaminz, maximum potential exploitable power was estimated to be 52 MW [30]. The approach and data used by Radfar [30, 31] caused values of the speed and thus the density of the computing power in the Khuran Strait to be 40% higher than experimental values.

Varnaseri and Ketabdari [32] 3-dimensionally simulated hydrodynamic conditions of the Qeshm Canal using the MIKE3HD software. Based on their results, maximum speed of the current occurs in the tightest part of the canal. Average speed of the current in the eastern entrance of the canal is 0.3 m/s, but reaching to 1 m/s in the tightest part. Results introduced the potential of a location in west of the Khuran Strait, which had been previously mentioned by Arvin [25] and Mahmoudof [4].

Table 5. Maximum speed and density of the potential computing power in sites [31]

Location	Max. Speed of current (m/s)	Power density (kW/m^2)
Khuran strait	2.55	11.2
Hengam island	1.45	2.99
Greater tunb	1.65	5.46

4. Hydrodynamic simulation of the current and results

In this study, simulation of the current and variation in the sea level water has been conducted using the MIKE21 Flow-FM numerical model. First, the overall model of tidal currents in the Persian Gulf is implemented. The dimension of the elements of the meshed model varies between 0.001° and 0.17° and contains 44351 computing nodes. To obtain more precise results, smaller elements are created along the coastal regions of Iran and the Hormoz Strait. The time history of the predicted tidal level based on the observed data in Chabahar port is considered to be constant along the considered open border, and the model is executed for 18 months (the second half of the year 2009 and the whole 2010). As a large area is considered in the model simulation, the Coriolis force is activated. The maximum and minimum time steps are 0.01 and 50 s, respectively, the Courant number is 0.8, roughness of the bed varies between Manning's coefficient 55 to 75 m$^{1/3}$ s^{-1}, viscosity coefficient is considered a constant value of 0.28, the dry and wet options are activated and due to the fact that the model is 2D, the impacts of density are not considered (i.e. a barometric model). Results of this model provide boundary conditions for local models of currents including level of the surface water and flux of the flow.

In the next step, local models with higher resolutions (for example, 25 m in the local model compared to 250 m in the general model) are applied. Boundary conditions are obtained from the results of the general model. The roughness coefficient is used as the calibration coefficient to make the best match between the simulated and observed results. For evaluation of local models, models of the local current are executed for the whole 1-year period. The historical speed and direction of the current are compared against the measured data (averaged in depth) at stations, and statistical parameters related to the comparison of the speed of the current are calculated. The obtained statistical parameters indicate that these parameters are in the satisfactory range.

Figure 15 shows a 2D map of the maximum speed of the computed current in January and February 2010. Maximum speed of the current is simulated in the Qeshm Canal and nearby the Greater and Lesser Tunbs islands. Maximum speed of the current occurs in the coastal parts in the Khuran Strait, which is less than 2 m/s. This is consistent with the observed and previous analytical studies. Only in two reports [30,33], maximum speeds were reported to be 2.55 and 3 m/s, respectively, which seems to be higher than the potential of the region.

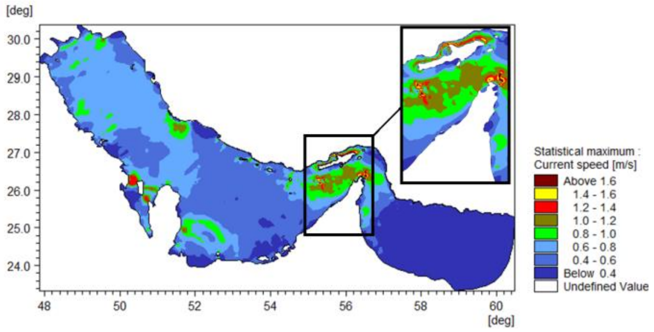


Figure 15. Map of maximum speed of the current obtained from execution of the 2D model in January and February 2010

In the Qeshm Canal, 31 regions with different areas and depths are located within the range of the maximum tidal speed, as shown in Figure 16 and their characteristics are provided in Table 6. The whole area with the maximum tidal speed is approximately 22 km^2, which lies within the range of the maximum density of the potential power of 1-3 kW/m^2. Four regions of 2, 6, 17 and 20 are more appropriate in terms of the depth, conditions of the current and the fact that they are disturbing the port pathways. Among them, region 6, which encompasses more than 1 km^2 and has the average depth of 28 m, is more appropriate and has an appropriate distance from the nearby port.

For a 14-day cycle of tide, the observed data in the Laft station obtained by the Ports and Maritime Organization of Iran are shown in Figure 17. Assuming that the density of the sea water is 1024 kg m^{-3}, density of the power is approximately provided as Figure 18. The area confined under the diagram of Figure 18 indicates the average density of the potential energy during the 14-day period,

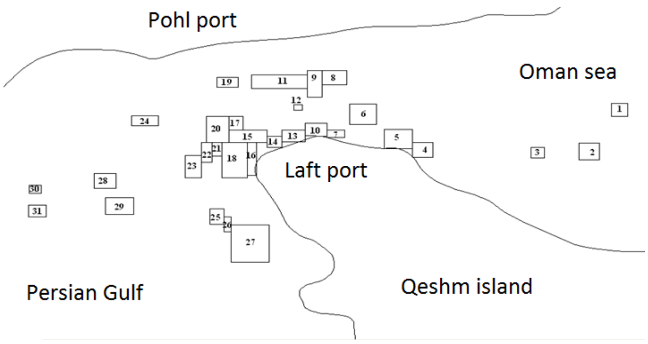


Figure 16. Locations of the selected regions in the Khuran Strait with the maximum speed of the current

Table 6. Characteristics of 31 regions with tidal speeds of more than 1.6 m/s in Figure 16

#	Area ($10^3 m^2$)	Depth (m)		#	Area ($10^3 m^2$)	Depth (m)	
		Lower right	upper left			Lower right	Upper left
1	397.5	4-8	0-4	17	397.5	16-20	12-16
2	883.9	8-12	8-12	18	1811.4	0-4	8-12
3	353.3	0-4	4-8	19	397.4	4-8	>0
4	795.7	8-12	4-8	20	1113.6	8-12	16-20
5	1094.2	0-4	12-16	21	247.1	0-4	8-12
6	1214.3	16-20	36-40	22	371.0	4-8	8-12
7	264.8	0>	8-12	23	743.0	0-4	8-12
8	772.8	12-16	>0	24	582.6	0-4	4-8
9	861.0	24-28	>0	25	504.2	>0	>0
10	619.6	>0	20-24	26	176.6	0-4	>0
11	1069.7	12-16	>0	27	2784.4	4-8	0-4
12	73.0	24-28	24-28	28	716.2	8-12	0-4
13	546.0	>0	16-20	29	928.4	>0	8-12
14	291.6	>0	12-16	30	199.0	0-4	>0
15	958.2	0-4	8-12	31	464.2	0-4	0-4
16	510.8	>0	12-16	-	-	-	-

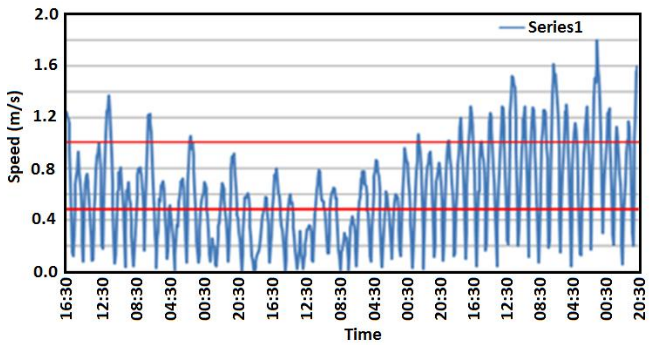


Figure 17. Time series of a full cycle of tide for the Laft station in the depth of 6 m in 2010 [11]

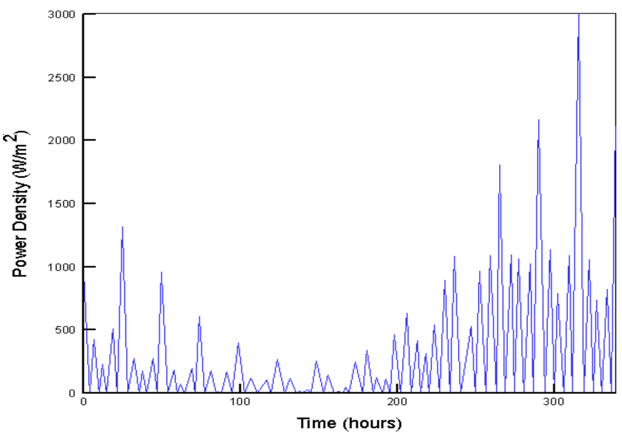


Figure 18. Density of the power corresponding to Figure 17 for a full cycle of tide in the Laft station

whose value reaches to 104.5 kWh/m^2, which is averagely equal to 7.5 kWh/m^2 for a day. Assuming that the power coefficient of the turbine is C_P=0.33, the average density of the exploitable energy reaches to 2.5 kWh m^{-2}, which is close to the value of 2.7 kWh/m^2 reported by Mahmoudof et al. [4], but is less than the values computed by Abbaspour [26] (5.8 kWh/m^2) and Karimi [27] (8.4 kWh/m^2) and more than the report of Soyuf and Emami [34]. It should be noted that when the cut-in speed of the convertor is 0.5 m/s and C_P=0.33, based on the observed data, 12.5 hours of electricity can be generated per a day in the Khuran Strait with the density of 1.6 kWh/m^2. When the lower threshold of the convertor is 1 m/s, only 3 hours of electricity can be generated per day, with the density of 0.6 kWh/m^2. From field studies, it can be concluded that the average of the speed of the current in the whole region is less than 0.5m/s, and the average of maximum speed of the current is less than 1 m/s. Reports of [10, 15] from the remaining currents indicate that contribution of these components is small in the region.

5. Conclusion

Tidal current is one of the promising resources of renewable energy, the importance of which indicates the necessity for further investigations and investments in this branch. Many regions across the globe have similar characteristics to those of the Khuran Strait and different companies are developing the knowhow of the convertor for these regions. In this report, previous data as well as results of previous experimental and analytical studies in the field of the energy of the marine currents in the Hormozgan region are discussed. Then, numerical densitometry of energy in this zone is discussed. Economical extraction of energy in this region requires technological advances and presentation of commercial arrays. Technologies such as BeamRich 6 MW^{TM} (proposed by Tidal Sails AS) with the cut-in speed of 0.5 m/s and a large area which is under the influence of the current can lead to this goal after technology proof.

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6. References

[1] Mahmoudi Karamjavan, Z., (2008), *Determination of marine currents and variation of the mean sea level of the Persian Gulf using satellite radar altimetry*, The Third National Congress of the Civil Engineering. (In Persian)

[2] Sabagh Yazdi, R., (2000), *A 2D model of tidal current in the Persian Gulf by solving equations of the average depth over the discrete mesh of the non-structured triangle,* The Fourth International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[3] Raeisi, A. and Mehrfar, H., (2017), *Study and feasibility of extraction of energy from the Caspian Sea and the Persian Gulf.* The Second National Conference on Novel and Applied Approaches in the Mechanical Engineering, NAAME2017. (In Persian)

[4] Mahmoudof, M., Chegini, V. and Akhyani, M., (2013), *Study and estimation of the renewable energy of the tidal currents in the Qeshm Canal using a numerical model*, The Third Iranian Conference of Renewable Energies and Distributed generation, ICREDG2013. (In Persian)

[5] Bozorgan, N. and Farahat, S., (2015), *Technical and economical examination of the extraction of energy from tides*, The Third National Conference of Mechanical Systems and Industrial Innovations. (In Persian)

[6] Rashid, A., (2012), *Status and potentials of tidal in-stream energy resources in the southern coasts of Iran: A case study,* Renewable and sustainable energy reviews, Vol. 16, pp. 6668-6677.

[7] Soleimani, K. , Ketabdari, M.J. and Khorasani, F., (2015), *Feasibility study on tidal and wave energy conversion in Iranian seas,* Sustainable energy Tecnologies & assessments, Vol. 11, pp77-86.

[8] Zibandeh, H., (2015), *Examination of the clean and renewable energy of tides and its conversion to electricity*, International Conference of the Electrical Engineering and Computer Sciences, ICEECS2015. (In Persian)

[9] Reynolds, R.M., (1993), *Physical Oceanography of the Persian Gulf, Strait of Hormuz, and the Gulf of Oman — Results from the Mt. Mitchell Expedition*, Marine Pollution Bulletin, Pergamon Press.

[10] Hadjizadeh Zaker, N., Ghaffari, P., Jamshidi, S. and Nourian, M., (2011), *Dynamics of the Currents in the Strait of Khuran in the Persian Gulf*, Journal of Shipping and Ocean Engineering, Vol. 1, pp. 109-115.

[11] Hemmati, S.J., (2019), *Feasibility study of Electricity Generation from Marine Energy in the Hormozgan Region*, Project Report No. 96-58, Hormozgan university. (In Persian)

[12] Hosseini Bandar Abadi, M., Allahiari, M., Tavakoli, M. and Madihi, M., (2012), *Analysis of the vertical profile of the water flow in the Pohl port region based on a 25-hour measured project for monitoring and simulating studies of the coastal regions of Iran, Hormozgan Province*, 10th International Conference of the Coasts, Ports and Marine Structures, ICOPMAS2012. (In Persian)

[13] Yarveisi, H., Saberi, J., Bagheri, M. and Ahmadi Livani, M., (2014), *Examination of the energy of tides in the Persian Gulf and its application in generation of electricity considering the Hengam oil platforms,* 16th Marine Industries Conference, MIC2014. (In Persian)

[14] Yari, S. and Shahrbaf, B., (2016), *Estimation of the extractable energy from tidal currents in the Khuran Strait,* 3th International Conference on the Persian Gulf Oceanography. (In Persian)

[15] Torabi, M. and Hamzei, S., (2016), *Field study of flows in the north of Strait Hormoz,* Journal of Environment Science and Technology, Vol. 18, No. 1, pp.64-77. (In Persian)

[16] Fallahi, M., Torabi Azad, M., and Mansoury, D., (2021), *A Hydrodynamic Model of Tidal Current in the Strait of Hormuz*. International Journal of Costal & Offshore Engineering. Vol. 6, N. 1, pp. 37-45.

[17] Azizpour, J., Siadatmousavi, S.M. and Chegini, V., (2016), *Measurement of tidal and residual currents in the Strait of Hormuz*, Estuarine, Coastal and Shelf Science, Vol. 178, pp.101-109.

[18] Khosravi, M., Siadatmousavi, S.M., Chegini, V. and Vennell, R., (2017), *Observation of cross-channel flow in the Khuran Channel*, Persian Gulf, Iran, 1st International Conference on Oceanography for West Asia.

[19] Khosravi, M., Siadatmousavi, S.M., Vennell, R. and Chegini, V., *The transverse dynamics of flow in a tidal channel within a greater strait,* Ocean Dynamics https://doi.org/10.1007/s10236-017-1127-3.

[20] Ghiasi, R., (1996), *Study of tidal currents in the north of the Qeshm Island,* 2nd International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[21] Vahdati Torbati, T., Morovati, H. and Banazadeh Mahani, M., (2000), *Examination and study of vertical profiles of the speed of tidal currents in the Hormoz Strait.* 4th International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[22] Shafieifar, M. and Hosseini, S.H., (2000), *Hydraulic examination of current and wave in the Khuran Strait,* 4th International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[23] Sabagh Yazdi, R. and Sharbati, S., (2007), *Application of the NASIR software in modeling tidal flows of the Qeshm Canal.* 3th National Congress of the Civil Engineering. (In Persian)

[24] Rashidi, A., Hesari, A., Zamanian, M., Azarmsa A. and Izadi, M., (2006), *Modeling flows caused by tides in the Persian Gulf using a 3D numerical model*, 7th International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[25] Arvin, A., Sadeghi, A. and Tajziechi, M., (2010), *Numerical examination of tidal currents in the Qeshm Canal*, 9th International Conference of the Coasts, Ports and Marine Structures, ICOPMAS2010. (In Persian)

[26] Abbaspour, M. and Rahimi, R., (2011), *Iran atlas of offshore renewable energies,* Renewable Energy, Vol. 36, pp. 388-389.

[27] Karimi, M., Mousavizadegan, H. and Saibani, M., (2012), *Computing energy of the tidal current using a numerical hydrodynamic model,* 14th Maritime Industry Conference. (In Persian)

[28] Kouchakian Sabour, S.h., Moeini, M.H. and Kolahdouzan, M., (2014), *Evaluation of extraction of energy of tidal currents in the Qeshm Canal (Khuran Strait),* 11th International Conference of the Coasts, Ports and Marine Structures. (In Persian)

[29] Fayaz Mohammadi, M., Sardnasb, M. and Einali A., (2015), *Comparison of the magnitude of flows caused by wind, density and tides in the Persian Gulf using numerical modeling,* 6th International Offshore Industries Conference. (In Persian)

[30] Radfar, S., Panahi, R. and Mazyaki, A.R., (2015), *Feasibility study and characterization of potential sites for tidal energy extraction in Persian Gulf using zonation in Mike21*, 18th Marine Industries Conference. (In Persian)

[31] Radfar, S., Panahi, R., Javaherchi, T.R., Filom, S. and Mazyaki, A.R., (2017), *A comprehensive insight into tidal stream energy farms in Iran,* Renewable and Sustainable Energy Reviews, Vol. 79, pp. 323–338.

[32] Varnaseri Ghandali, S.h. and Ketabdari, M.J., (2016), *Modeling and analysis of the behavior of tidal flows in the Qeshm Canal,* 18th Marine Industry Conference. (In Persian)

[33] Ketabdari, M.J. and Soleimani, K., (2019), *Study of the feasibility of obtaining energy of tides in the coastal Hormozgan,* A research proposal. (In Persian)

[34] Soyuf Jahromi, M. and Emami, M., (2021), *The role of different positions of tidal turbines for energy extraction in Qeshm channe.* International Journal of Costal & Offshore Engineering. Vol. 6, N. 5, pp. 1-9.