SINGAPORE STRAIT HYDRODYNAMICS: FROM ANCIENT MYTHS TO RENEWABLE ENERGY

Manasa Ranjan Behera

Physical Oceanography Research Laboratory, Tropical Marine Science Institute,
National University of Singapore, S2S, 18 Kent Ridge Road, Singapore 119227.
Email: manasa.rb@gmail.com, tmsbmr@nus.edu.sg

Xu Haihua

Physical Oceanography Research Laboratory, Tropical Marine Science Institute,
National University of Singapore, S2S, 18 Kent Ridge Road, Singapore 119227.

Pavel Tkalich

Physical Oceanography Research Laboratory, Tropical Marine Science Institute,
National University of Singapore, S2S, 18 Kent Ridge Road, Singapore 119227.

ABSTRACT. — A review is carried out from ancient word of mouth to the present day scientific studies of the hydrodynamics of the Singapore Strait. Various beliefs about whirlpools in and around Singapore Strait are correlated with the present day eddies or vortices observed through hydrodynamic modelling. A semi-implicit Eulerian-Lagrangian finite element (SELFE) model was used for numerical modelling of the hydrodynamics in the Singapore Strait. The vortices and high current streams observed in Singapore Strait are analysed for possible source of clean renewable energy. The vortex-induced vibration (VIV) of eddies or vortices can be converted to renewable energy through available modern technologies. The tidal energy can also be extracted from flood and ebb current of the tidal streams at suitable locations. A review of technologies available for extraction of renewable energy from tidal steam current and VIV was carried out.

KEY WORDS. — Whirlpool, vortices, eddy, vortex-induced vibration, renewable energy, Pulau Hantu, Kusu, Singapore Strait

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INTRODUCTION

The Republic of Singapore is a Southeast Asian city-state off the southern tip of the Malay Peninsula, 137 kilometers north of the equator. An island country consisting of 63 islands, it is separated from Malaysia by the Straits of Johor to its north and from Indonesia's Riau Archipelago by the Singapore Strait to its south. Singapore's past is obscured in myths, starting with the sighting of a lion-like creature on the island, giving the island its name and, much later, the nation's symbol of Merlion (half lion half mermaid).

Having been a fishing village in the past, it is not surprising that many myths in one way or another mention turbid local waters filled with dangerous whirlpools. There was once over 60 offshore islands and patch reefs around Singapore, most of which were situated south of mainland Singapore (Fig. 1). Extensive coastal modification by recent reclamation activity may have altered local flow streams around the islands; however, analysis of ancient myths in the light of modern hydrodynamic theories may provide better understanding of areas of high tidal currents with renewable energy potential.

"HYDRODYNAMIC MYTHS" OF SINGAPORE

In order to get first clues, we review some "hydrodynamical" myths associated with Pulau Hantu, Kusu Island and Sisters' Island (Uma Devi, 2002).

Pulau Hantu. — There were once two great warriors locked in a fierce battle at sea. Many people died and the blue seas slowly became polluted with human blood, upsetting the Jinns at the bottom of the ocean. In anger, one powerful Jinn created a whirlpool and sucked the two warriors into the deep sea to drown them. The warriors continued to battle under the water. Suddenly, the Jinn sprayed water on one of them, and the other warrior seeing his opponent blinded, thrusted his sword into his abdomen. At the same time, the wounded warrior forced his sword into the other man. Both collapsed and died. The gods felt that it was wrong for the seas spirits

to interfere in human affairs; thus, the Jinn transformed the two warriors into islets so that their spirits can continue to live on them. As one of the warriors was smaller than the other, his islet was known as "Pulau Hantu Kecil" while the bigger one was called "Pulau Hantu Besar". However, both the islets together are called Pulau Hantu. It is believed that the whirlpool still exists near Pulau Hantu.

Kusu Island. — Legend has it that a giant sea turtle saved two shipwrecked sailors – one Malay and one Chinese – from the choppy waters in the sea and carried them safely to a nearby island. The two men became good friends and spent their time hunting for animals and fruits in the island. To thank the turtle for saving their lives, the two men built a Chinese temple, a Malay shrine and a huge turtle sculpture, all of which can still be found on Kusu Island, which is also known as Turtle Island. Today, during the ninth month of the lunar calendar, many Chinese go to Kusu Island to pray to Tua Pek Kong, the deity of prosperity, at the Chinese temple. Muslims also visit Kramat Kusu, the Malay shrine. Nowadays visitors to the island may still observe choppy waters and whirlpools from the safety of their large vessels.

Sisters Island. — A long time ago lived a pair of beautiful sisters, Minah and Lina, who shared a bond so strong that nothing can separate them. One day, the notorious chief of the Orang Laut met and fell in love with Lina. Despite the sisters' pleas, the chief took her away and forced her into the sampan. Just then, the sky turned dark and a storm broke out. As Minah made a final attempt to save her sister from leaving the jetty, a large wave came and engulfed her. On seeing this, Lina freed herself from her captors and jumped into the sea to join Minah. The sisters could not be found even after the storm subsided. Instead, two islands emerged from where they had drowned named as, Subar Laut and Subar Darat. These two small islands are now known as Sisters' Islands. It was said that every year on that very day when the sisters turned into islands, there would always be storm and rain. Strong currents off Sisters Island could be observed regularly from cliffs of St. John's Island.
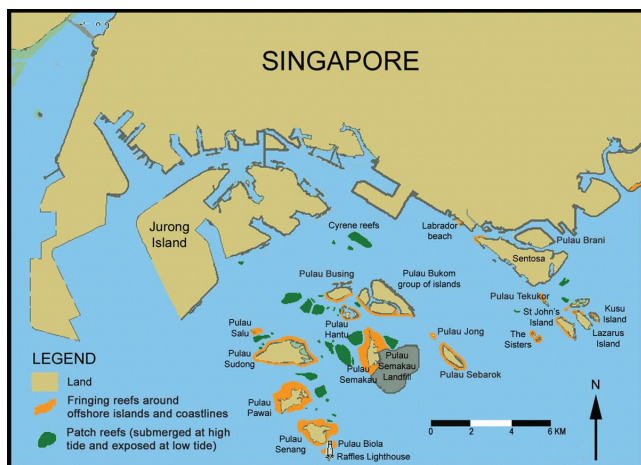
WHIRLPOOLS AND TIDAL ENERGY

Eddies are a circular movement of water that is counter to the main current. They are common in the ocean, ranging in diameter from hundreds of kilometres down to a molecular size. Gradients of velocity have to be significant enough to initiate formation of eddies. There must be a sufficient energy available for cascading from the largest eddies to the smallest ones. In Singapore Strait the preconditions seems to be favourable for the formation of eddies. The tidal range is up to 3m and these may generate water velocities up to 2 m/s. There are many islands obstructing tidal flow that oscillate between the Malacca Strait in the west and South China Sea to the east, thus generating velocity gradients. Due to a small size of Singapore Strait and the islands, the size of eddies are expected to be confined to a few kilometres and smaller.

Eddy. — Pang & Tkalich (2003) have observed the simulated formation of large-scale eddy (~5 km across) in the Singapore Strait at slack phase of the tide (Fig. 3), making the spot another potential area to harness the tidal power.

Karman vortex. — In a case of strong flow around an island, eddies could be shed off the obstacle and propagate downstream in a pattern known as Karman vortex street. A Karman vortex street is generated when fluid passes across a bluff body, generating a swirling pattern on the lee side of the body. The pattern, if observed in a region, may indicate the potential to install tidal power generators in the vicinity. Nesterov & Chan (2010) have shown the presence of Karman vortex streets between Sentosa and St. John's islands in the Singapore Strait (Fig. 2A). At the same time, the surface elevation contours in Fig. 2B shows that the von Karman vortex streets purturb the sea level.

REDISCOVERY OF TIDAL MILLS

The concept to extract tidal energy from the sea was first developed during the first century AD by the Persians. They obtained rotational energy from tidal currents using waterwheels (Charlier & Menanteau, 1997). In the middle

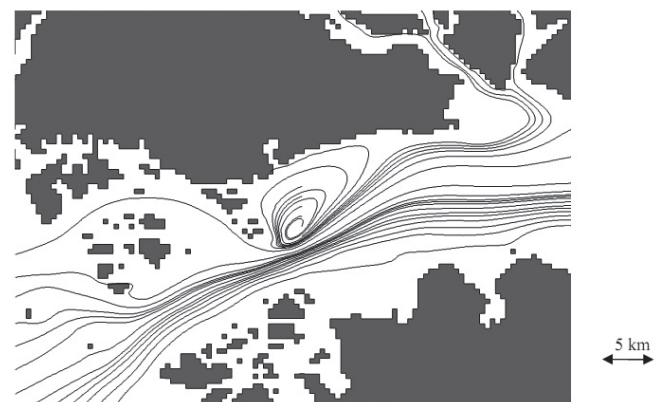Fig. 1. Islands in the south of the main island of Singapore in modern times.

Fig. 2. Large scale eddy (shown by streamlines) located south of Singapore Island typically observed during computation of a slack tide period (Pang and Tkalich, 2003).

ages, the earliest known tide mill was built at the entrance to the port of Dover in southern England between 1066 and 1086, followed by a few more in Europe. The mills at the London Bridge and East Greenwich were the first to use double effect generation. The London Bridge tidal mills, with 6-metre wheels on river Thames, provided part of the city's water supply from 1682 to 1849. The first known drawing of a tide mill first came out in the 16th century by Francisco Lobato and was built at Puerto Real in Spain. In the 17th and 18th centuries, the growth in the number of tide mills along the Atlantic coast was accelerated by the development of grain crops and the colonisation of America. The English engineer William Wilkinson built an iron foundry on an island in the Loire functioning entirely on tidal power from 1778 to 1786. In Spain and Portugal, in the 18th century, there were increased numbers of large tide mills installed for industrial use. There were tide mills in Russia in the 18th century, and in Italy in the 19th century; in Hamburg in 1880, tidal power was used to pump sewage. Figure 4 shows the general working principle of these early tide mills with different phase of tide.

In the early stage of 20th century, steam and later electricity gradually superseded tidal power as they could guarantee an uninterrupted source of energy. As such electricity is mostly produced from thermal power, hydropower or nuclear power, it is limited by the source, dependent on the weather, and/or pose environmental problems. The increasing demand and depletion of natural resources for generation of electricity have refocused the attention of the researchers for other renewable sources of energy. Tidal energy has been rediscovered recently on the support of modern day technologies and advanced hydrodynamic models.

Vertical axis hydro turbine. — The Blue Energy Canada Inc. (BEC), using new insights applied to an old concept that was patented but never built by French hydro engineer Darrieus over 80 years ago, designed the Vertical Axis Hydro Turbine (VAHT). Extensive model testing and field trials have evolved into a new type of low head water turbine whose genesis was the vertical axis catenary type wind turbine proposed by Darrieus in 1931. VAHT can generate electricity from
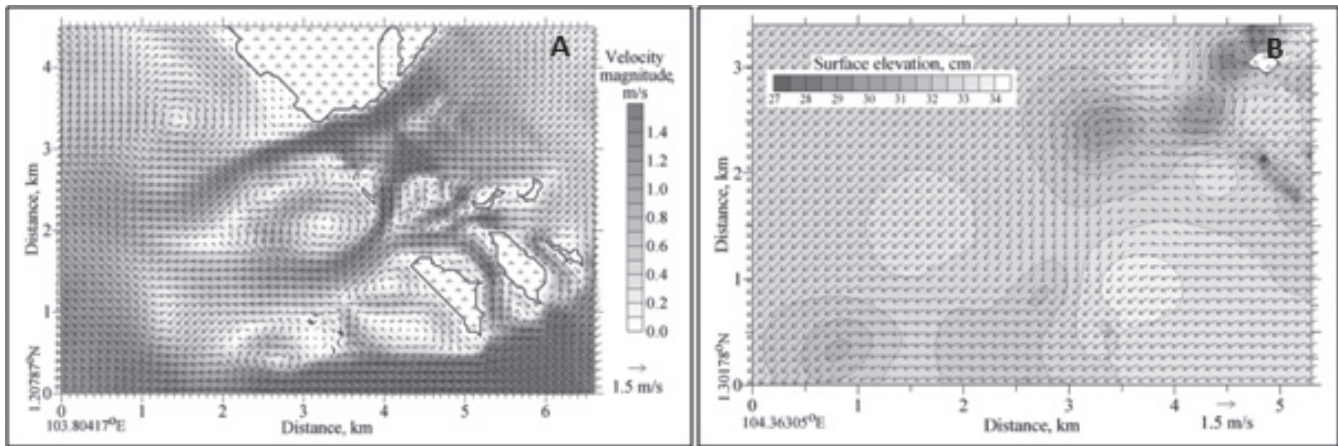

Fig. 3. A. Velocity field (21 Jun 2008, 20:08) shows the formation of von Karman vortex street behind the islands; B. Perturbations of the sea surface elevation (21 June 2008, 22:08) observed due to von Karman vortex streets behind islands. (Nesterov & Chan, 2010)
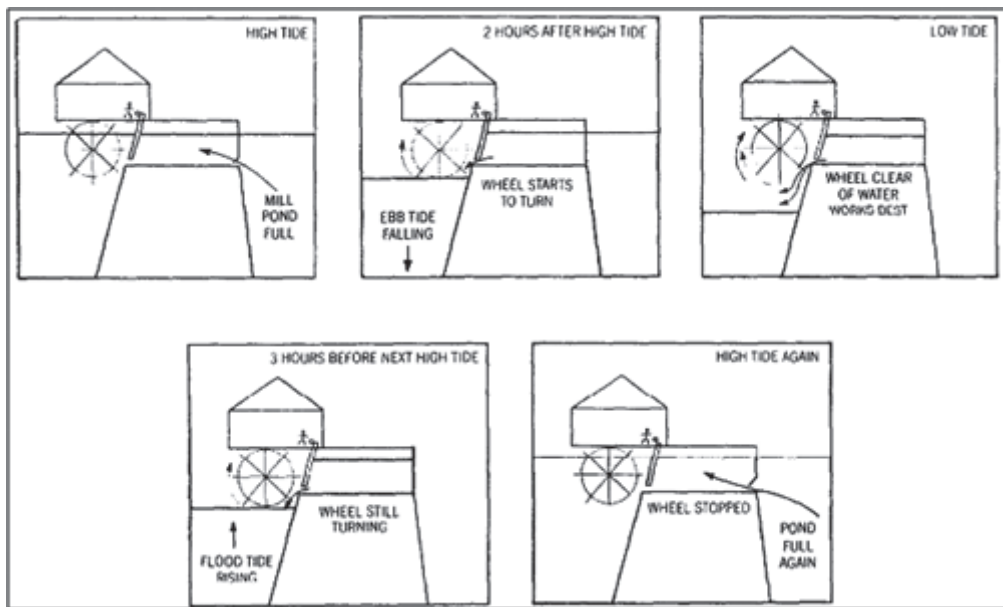

Fig. 4. Schematic diagram of the working principle of the tide mills. (adapted from Charlier and Menanteau, 1997)

the kinetic movement of water in rivers and tidal currents at minimum water velocity of 1 m/s. The schematic horizontal and vertical cross-sections of a VAHT are shown in Fig. 5. Four fixed hydrofoil blades of the turbine are connected to a shaft that drives a generator. The vertical hydrofoil blades employ a hydrodynamic lift principle that causes the turbine foils to move proportionately faster than the speed of the surrounding water. This rotor is mounted in a marine caisson (a watertight chamber that is open at the bottom), which directs the water flow through the turbine, houses the rotor, and supports the generator and electronic controls in a dry climate controlled machinery room above the water line. The cross-flow design is unidirectional, making power during both flood and ebb tide. The vertical axis hydro turbine may be employed at any scale ranging from floating micro turbines that are one or two kilowatts to massive gravity mounted tidal turbines that will form tidal bridges when fully scaled. BEC has also specified the corresponding power output for a 10 meter turbine at different current speed of the stream as given in Table 1.

Horizontal axis tidal turbine. — Horizontal axis tidal turbines (HATTs) are perhaps the most mature and promising technology available in the market and have been developed by several companies (e.g. Marine Current Turbine, Verdant Power, and OpenHydro) (Bir et al., 2011). A HATT works

Table 1. Tidal stream velocity and corresponding power output for a 10-m turbine. (Blue Energy Canada Inc.)

Water Velocity (m/s)	Power Output (MW)
1	0.02
2	0.18
3	0.62
4	1.47
5	2.88

on the simple principle where the rotor blades convert the tidal current kinetic energy into the mechanical energy and a generator converts this mechanical energy into electricity. Figure 6 shows a few examples of HATT configurations with different support structures for various water depths. There are various types of HATT developed in the recent past. Some of the notable turbines are shown in Fig. 7. The Clean Current Turbine, Hammerfest-Strom Tidal Stream Turbine, Rotech Tidal Turbine (RTT), OCGen turbine generator unit and OpenHydro are fully submersible devices (Polagye et al., 2011). The aesthetic view of the sea from the shore and the marine traffic movement will not be disturbed by installation of these turbines. However, in case of SeaGen turbine, although the blades are under the water, the mounting monopile is surface piercing. This will help the rotor and
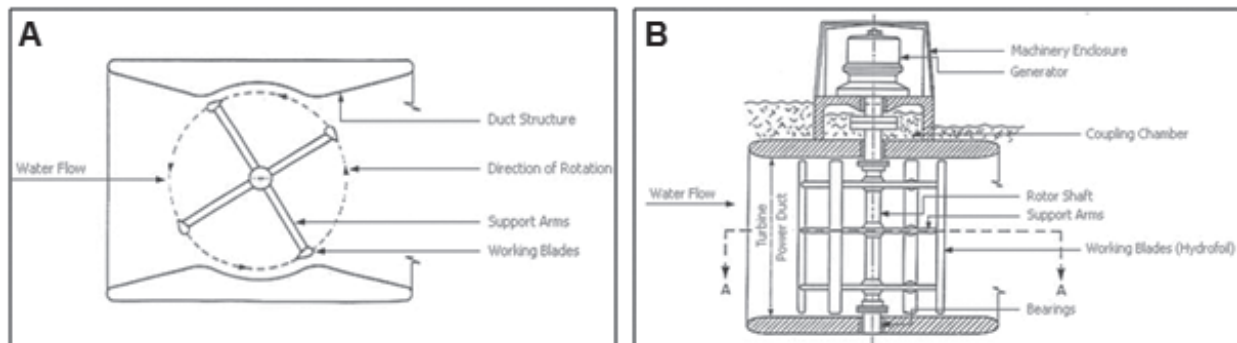

Fig. 5. Schematic of A. horizontal and B. vertical cross-section of a vertical axis hydro turbine. (Blue Energy Canada Inc.)
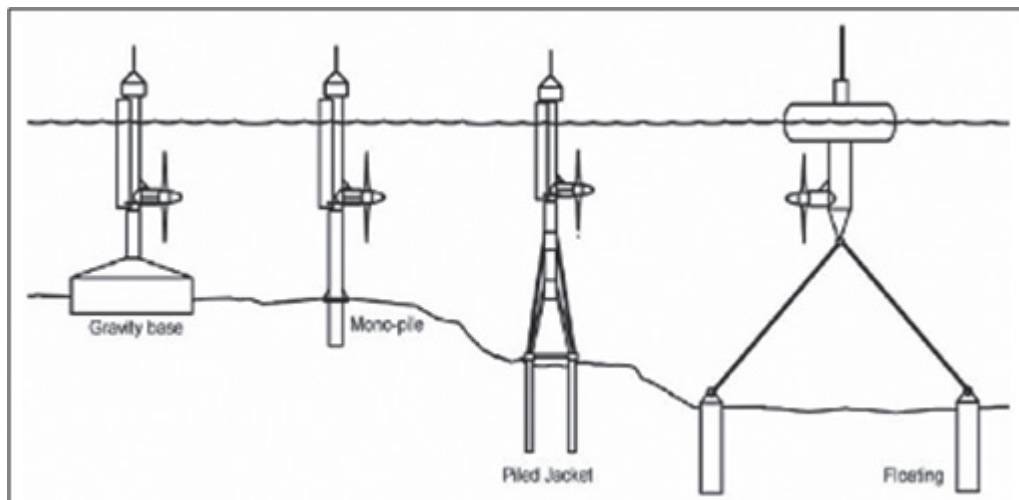

Fig. 6. Typical horizontal axis tidal turbine (HATT) configurations for various water depths. (Bir et al. 2011)
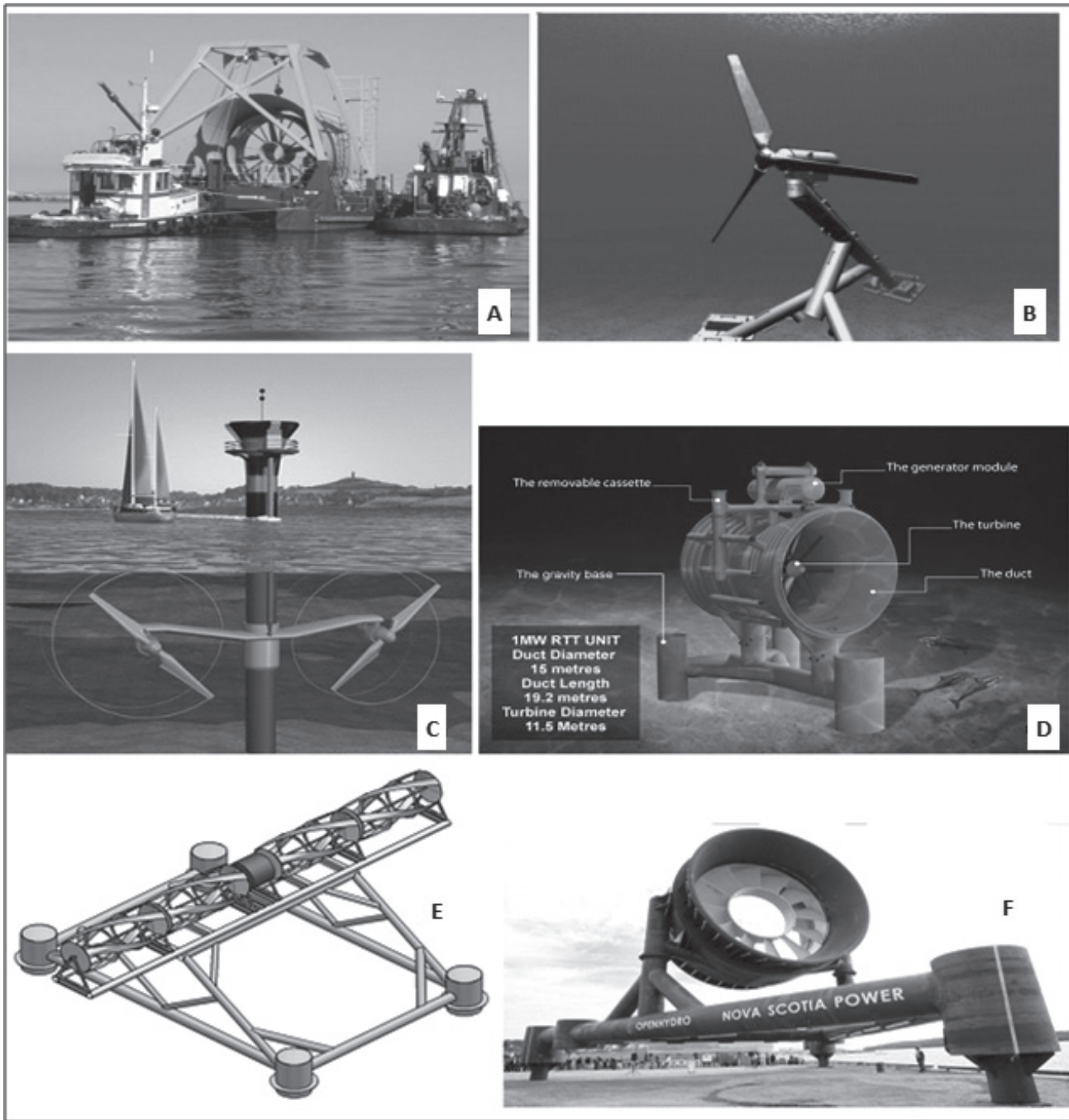
Fig. 7. A. Clean Current Turbine at Race Rocks, British Columbia; B. Hammerfest-Strom Tidal Stream Turbine, UK; C. SeaGen at Stranford Lough, Northern Ireland; D. Rotech Tidal Turbine (RTT) of Lunar Energy Power Limited, UK; E. OCGen turbine generator unit of Ocean Renewable Power Company, Eastport, Maine; and F. OpenHydro, Nova Scotia installed at Bay of Fundy. (Polagye et al., 2011)
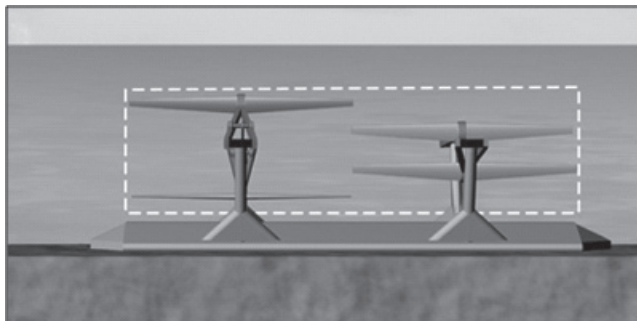

Fig. 8. Schematic view of the oscillating hydrofoil. (Polagye et al., 2011)

the blades to move out of water for maintenance in dry environment. Suitable turbines may be selected based on the site condition and use.

Oscillating hydrofoil. — The oscillating hydrofoil works in the similar principle as an airplane wing but in water. The yaw control system adjusts the angle of the oscillating hydrofoil relative to the water stream, creating lift and drag forces that cause device oscillation. The mechanical energy due to the oscillation is transformed to electricity through a power conversion system (Polagye et al., 2011). A typical view of the oscillating hydrofoil is shown in Fig. 8.

Vortex Induced Vibration Aquatic Clean Energy (VIVACE). — The vortices around the cylinders were considered as destructive energy for a longtime, whereas recently it is been looked at as another potential source of energy by converting the mechanical energy into electricity. The flow around a cylinder generates a vortex on the lee side and alternates between oneside and other in time as shown in Fig. 9A. This vortex propagates downstream, transfers the energy to other cylinders, and vibrates them. The outer water pressures onto the cylinder cause turbulence that transforms into a vortex that is reversed with the next contact to produce energy. Fish actually use vortex-induced vibrations (VIV) to propel forward and to swim in schools. The Vortex Induced Vibration Aquatic Clean Energy (VIVACE) device was first conceptualised by Bernitas et al. (2008), and can extract vortex energy from ocean currents. VIVACE emulates marine life kinematics, which makes it environmentally compatible. The device uses and enhances the vortex shedding to harness renewable energy. It is not obstrusive to navigation, marine life and coastal real estate. An outstanding feature of this device is that it can start generating energy at a current speed of 0.25m/s and can operate at current speed of 2.5m/s or more, extracting more energy. VIVACE's scalability, modularity and design flexibility allow for a broad range of application and site conditions. This device can also be useful in tapping the tidal energy from the small and large scale eddies with low current speeds. This energy converter is unlike any existing technology, as it does not use turbines, propellers, or dams (Fig. 9B).

HYDRODYNAMICS IN SINGAPORE STRAIT

After the available technologies are reviewed, we might better understand what hydrodynamic conditions to search for a site to be recognised as potential for installation of tidal-driven generators. One approach is to go for a massive measurement campaign at various locations in Singapore Strait, but this method could be prohibitively expensive. A cheaper alternative could be usage of a calibrated hydrodynamic model allowing application of automatic searching procedure of required hydrodynamic pattern. To be able to resolve eddies in hydrodynamic models, the domain of interest should be discretised with a fine grid capable of capturing the phenomenon.

The SELFE model (Zhang & Baptista, 2008) is well calibrated to simulate the hydrodynamics in Singapore Strait. The computational domain consists of the central west region (CWR) of Singapore Strait including the West Johor Strait, the islands on south of Singapore and the wetlands connected to the Johor Strait, as shown in Fig. 10A. The domain is forced with tidal elevations from three open boundaries. The domain is discretised using triangular mesh of grid size varying from 20 m near the coastal line to 2000 m at the far region, as shown in Figs. 10B and 10C. Water depths from the southern end of Malacca Strait to the South China Sea are generally less than 50 m, except in small area off the southern coast of St John's Island, where water depths reach more than 100 m. Water depths in the Johor Strait range from few metres along coastal boundaries to about 20 m along the center of the Strait (Chan et al., 2006) as shown in Fig.10D.

Boundary conditions. — Currents in Singapore Strait region are driven by monsoon winds and tides. Although wind driven currents are dominant in the open areas, such as South China Sea, the influence of the wind on the currents in the Singapore Strait is less significant compared to the influence of tidal forcing (Chan et al., 2006). The contribution from river discharges to the currents in the Singapore Strait is also insignificant compared to the peak tidal currents in the Strait. Thus, the SELFE model was forced by the time series of tidal surface elevation prescribed at the open boundaries of the study domain indicated in Fig. 10A. The surface elevations for boundary forcing were obtained using Tropical Marine Hydrodynamic (TMH) model (Pang & Tkalich, 2004; TMH, http://www.porl.nus.edu.sg/main/research/hydro-model), a well-validated coarse grid model developed by Tropical Marine Science Institute, NUS, Singapore.

Simulation. — To capture neap and spring phases of the tide, the simulation was carried out for over a period of 15 days, namely from 02 Jan 2006 to 16 Jan 2006. The model was validated by comparing computed surface elevations as well as currents with measured data at various locations in the domain. Comparisons of computed data with tide gauge
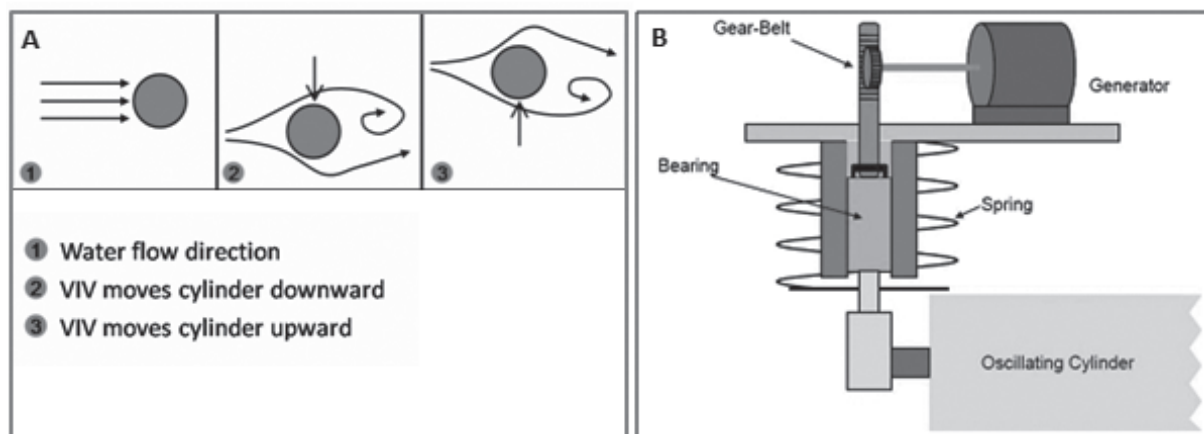

Fig. 9. A. Vortex shedding around a cylinder due to stream flow; B. Schematic diagram for an energy gerator by oscillating cylinder from water current vortices (Bernitas et al., 2008).

data from Tanjong Pagar, Pulau Bukom, and West Tuas are shown in Fig. 11. It is observed that the SELFE results closely follow the measured surface elevations at the tide gauge stations. The flow field in the computational domain was obtained for various time instants during strong and slack tide. The current magnitude and flow patterns were analysed at various locations in the Singapore Strait.

Results and discussion. — The pattern of the tidal flow in the Singapore Strait is shown using streamlines passing across the boundaries. The streamlines during a slack tide in Fig. 12A shows formation of large-scale eddies near and around the islands. Three large eddies of diameter ranging from 5–15 km are observed off the southern coast of Pulau Samakau and Pulau Senang and St John's Island. Two more eddies are also observed, one off the northern coast of Bukom Island and other in the mouth of the basin on the west of Jurong Island. Similarly, small-scale eddies of diameter ranging from 1–3 km are also observed in between Pulau Sudong, Pulau Pawai, Pulau Semakau and Pulau Bukom (see Figs 1 and 12B). However, these eddies exist for short duration only during slack tide when the current between Malacca Strait and South China Sea changes the direction. During strong tidal current local eddies are observed near Pulau Hantu, Kusu and St John's Island those exist for a period of 9 to 10

hours in one tidal cycle of 12.42 hours and are considered for the present analysis. This observation corroborates the myths presented about the Pulau Hantu and Kusu Islands, which might have drowned the sailors into the seawater. The instantaneous streamlines depicting the vortex in the middle of Pulau Hantu islands are seen in Figs. 13A and 13B during strong westard and eastward currents, respectively. Similarly, the instanteneous streamlines depicting the vortex near St John's Island are seen in Figs. 14A and 14B during strong westward and eastward currents, respectively. Eddies near St John's Island have high current magnitude, as they are driven by an adjacent strong current in the centre of the channel. It is also noticed that the current off the west coast of St John's Island is significant enough during the strong tidal flows.

CONCEPTUAL LAYOUT FOR
TIDAL ENERGY DEVICE

The analysis of the tidal current and flow pattern in the Singapore Strait suggests that the available technology for extraction of tidal energy may be feasible to implement at few locations. In particular, tidal energy devices could conceivably be installed near St John's Island, as shown in
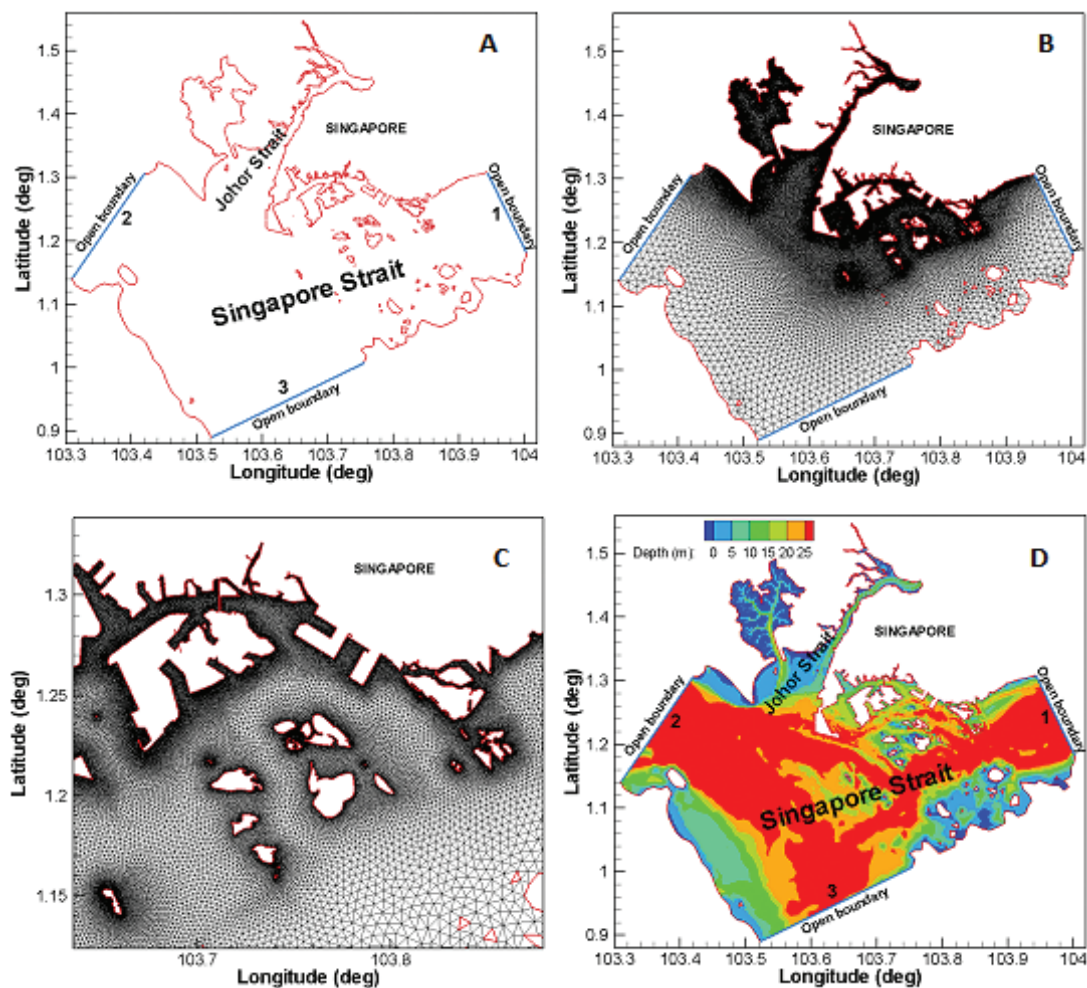

Fig. 10. A. Computational domain layout consisting of west part of Singapore strait and Johor strait encircling all the islands on south of Singapore; B. Discretised Computational domain with fine mesh in the region of interest; C. Typical fine mesh around the islands of interest; and D. bathymetry contours of the central west region of Singapore Strait.

Fig. 15. The device could be centered at the epicentre of the vortex and the blades could be arranged in such a way that it can extract the energy from the main stream current as well as from the vortex as shown in location 1 of Fig.

15. Similarly, a horizontal axis tidal turbine could be placed in the tidal stream along the west coast of St John's Island as shown in location 2 of Fig. 15. The tidal current up to the maximum speed of nearly 2.5 m/s and vortex up to the
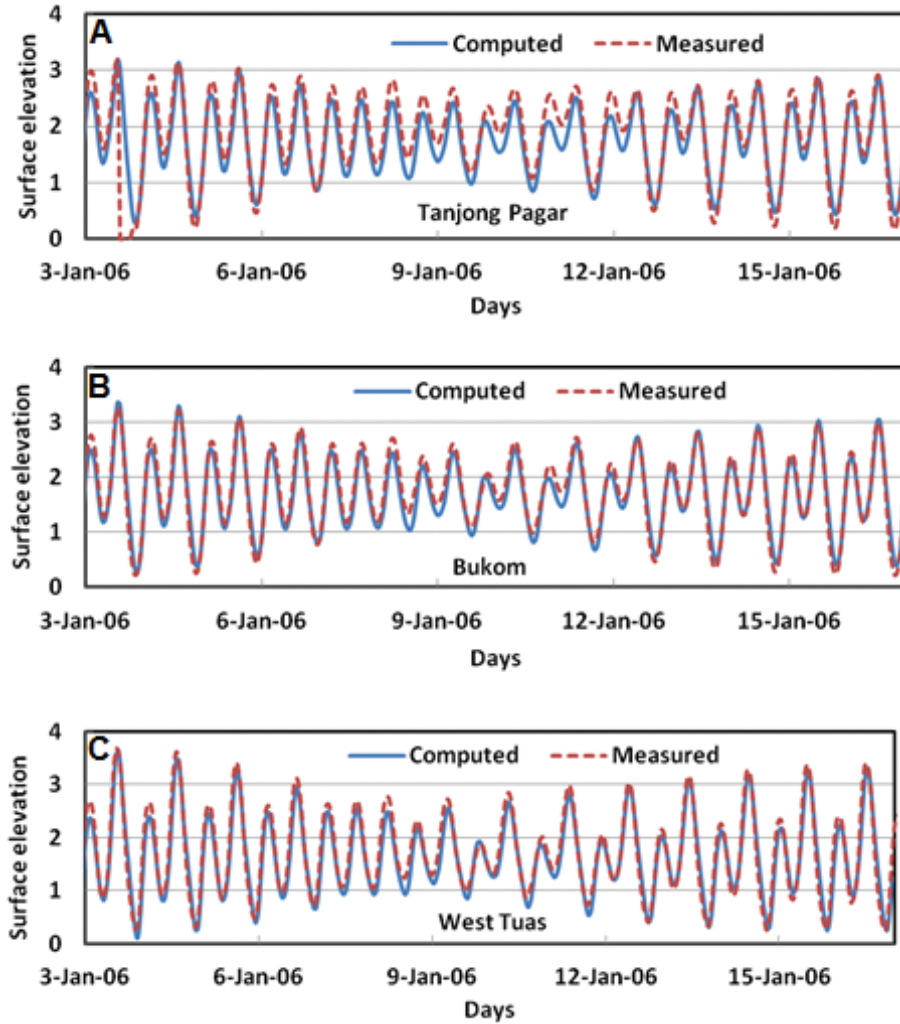

Fig. 11. Comparison between computed and measured surface elevation at: A. Tanjong Pagar; B. Bukom; and C. West Tuas tide gauge stations.
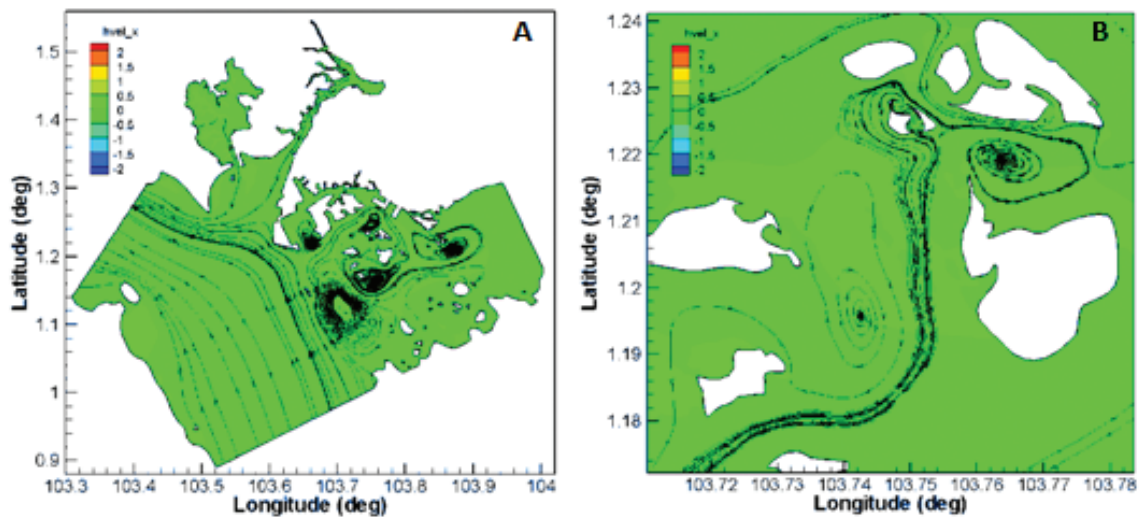

Fig. 12. A. Large-scale vortcies around the southern islands of Singapore during slack tide (4 Jan 2006 22:00hrs); B. Small-scale vortex within islands during slack tide (4 Jan 2006 22:00hrs)
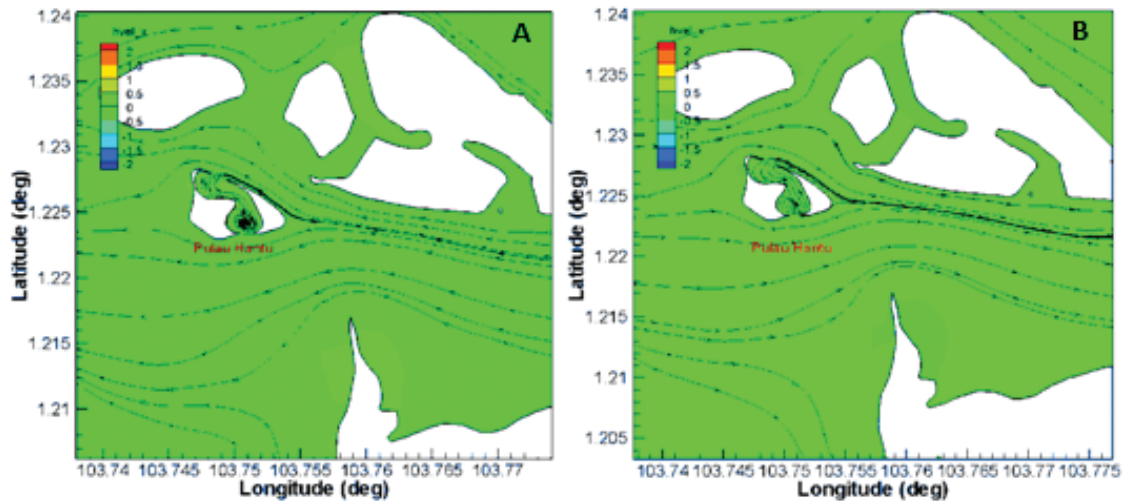
Fig. 13. Vortex near Pulau Hantu islands during strong currents: A. flow from South China Sea to Malacca Strait (7 Jan 2006 02:00hrs); and B. flow from Malacca Strait to South China Sea (8 Jan 2006 07:00hrs)
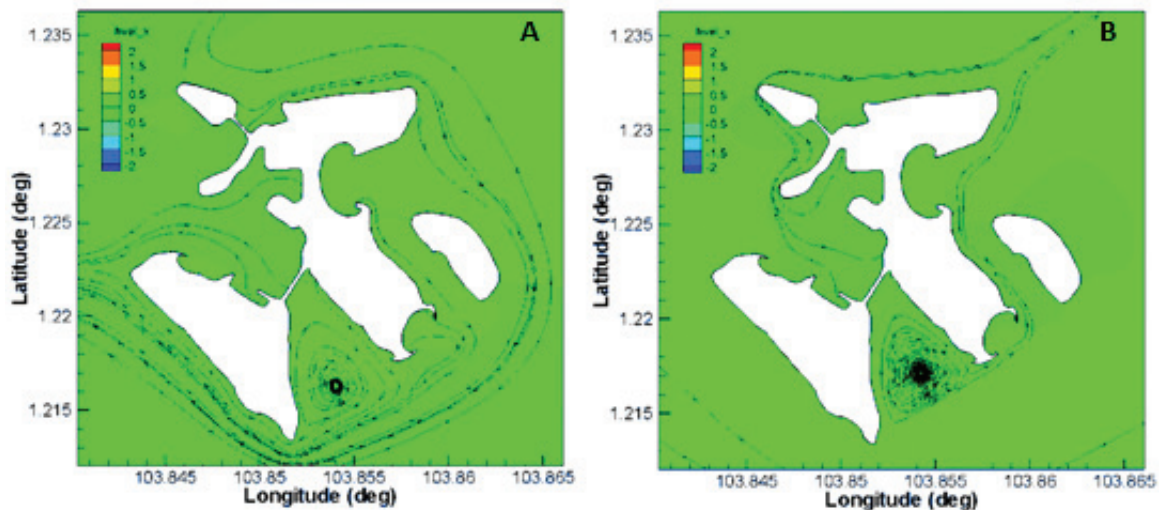

Fig. 14. Vortex near St John's island during strong currents: A. flow from South China Sea to Malacca Strait (7 Jan 2006 06:00hrs); and B. flow from Malacca Strait to South China Sea (8 Jan 2006 08:00hrs)
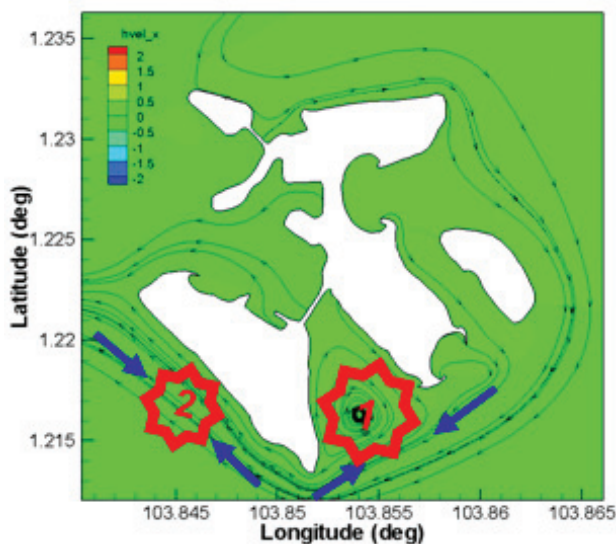

Fig. 15. Possible locations (as indicated by numerals 1 and 2 enclosed in star outline) for installation of tidal energy devices between St John's Island and Lazarus Island, and off the southern coast of St John's Island.

maximum velocity of 1.5 m/s are present at various locations in the considered domain of Singapore waters. However, the model is simulated only for 15 days for part of the Singapore waters and it should be extended for longer duration over the entire Singapore waters to get a complete understanding of the available energy potential.

CONCLUSIONS

We have presented a review of tidal power potential in Singapore Strait for the layman. Ancient myths have revealed the power of tidal currents in the Singapore Strait, including whirlpools near the Pulau Hantu and Kusu Islands. We have also provided a short review of the use of tidal power energy worldwide from historical times to the present. An assessment of the tidal energy potential in Singapore Strait using an advanced hydrodynamic model calibrated for the domain suggested the conceptual possibility of locating tidal energy devices near St John's Island.

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