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A review on the development of tidal current energy in China

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ABSTRACT

Nowadays and in the coming years, increased attention is being given to the tidal current energy development all over the world. China is a country endowed with abundant tidal current energy resources. In this paper, the distribution of tidal current energy in China was presented. Policies and current status of usage and technology development of tidal current power generation in China were introduced. Meanwhile, special focus was given to the research programs being carried out and the achievements made. Finally, existing challenges were addressed and the future perspectives of tidal current energy development in China were provided.

Contents

1. Introduction

With economic development and industrialization in developing countries, their demands for energy resources increase rapidly in nowadays. However, environment pollution and depletion of traditional fossil fuels caused by excessive consumption seem to be influencing their development trend. How to achieve the harmonious development of economy society and environment is an emergent issue. Acknowledging the looming energy crisis and global climate warming, more and more countries around the world start to invest much time and money on the clean and renewable energy [1–3], such as wind, ocean and solar energy, etc. China participated the procession of developing the renewable energy, and Chinese government and energy departments accelerated the renovating process. In the past five years, several energy laws have been passed in order to promote the use of renewable energy sources, in which the tidal current energy was put in the first position.

In China, from a very early period, public interest in utilization of renewable energy sources emerged, for example, the wind energy application appeared in the 1950s. However, the absence of government support and encouragement considerably slowed down the development of renewable energy technology. Until 1980s, the wind energy once again was put back on the political agenda. In recent years, great achievements have been made in the application of wind energy. The total installed wind power capacity has amounted to 5906 MW in 2007 in China, which was 127% higher than that achieved in 2006, and has reached 12,170 MW in 2008. Thus, China's goal of bringing its total installed wind power capacity up to 10,000 MW by 2010 in the "Eleventh Five years" had been completed ahead of schedule [4]. Meanwhile, as enthusiasm for renewable energy is on the rise in China, the government also invests heavily in other clean energy sources including solar energy, wave energy and tidal energy, etc. The research and development of wave energy in China started in the late 1970s, which was performed mainly at the Guangzhou Institute of Energy Conversion [5]. The tidal energy research started in 1980s by the Harbin Engineer-

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Table 1
Tidal current energy distribution in China, 1989 [8].

Area	Velocity distribution (m/s)			Theory Power ($\times 10^4$ kW)
	$V_m \geq 3.06$	$2.04 \leq V_m < 3.06$	$1.28 \leq V_m < 2.04$	
Liaoning Province	North of the Laotieshan channel		Changshan east channel, Guapi channel, Sanshan and Xiaosanshan channel	113.05
Shandong Province		North of Beihuangcheng island	Channels in temple archipelago and eastern coast	117.79
Estuary of Yangtze River		North harbor and south trough	Hengsha harbor and North trough	30.49
Zhejiang Province	Jintang, Guishan and Xihou channels, etc. North of Hangzhou Bay	Some channels in Zhoushan and estuary of Jiaojiang	Some channels in Zhoushan, Xiangshan harbor, Sanmen bay, Taizhou and Leqing bay	709.03
Fujian Province	Northwest of Sandu cape in Sanduao	East of Sandu island, Estuary of Mingjiang, south of Haitan straint and Dazuo channel	Shacheng harbor, Xinghua bay, and some channels in Haitan straint	128.05
Taiwan Province		North and south of Penghu, North of Taiwan, North of Linshanbi	Penghu island, West of Taiwan, Northeast of Sandiaojiao	228.25
Guangdong Province		East mouth of Qiongzhou strait, and Wailuo channel	Pearl River estuary, channels in western coast of Guangdong	37.66
Hainan Province		South channel of East mouth of Qiongzhou strait	Chengmai estuary, Yinggehai	28.24
Total				1394.85

ing University (HER), and its research was primarily focused on the vertical axis tidal turbine. The study of horizontal axis tidal turbine only was carried out in the last decade by scholars at Zhejiang University and followed by Ocean University of China and Northeast Normal University, so China is currently lagging behind many other countries, such as UK and USA, in the development of tidal current technology. The purpose of this paper is to give an overview of the distribution of tidal current and the present stage of development of tidal current turbine technology in China.

2. Tidal current energy and relevant policy in China

Ocean current is caused by the gravitational pull of the moon and the sun (for the tidal current), the temperature difference of ocean water (for the tropical circulation), the monsoon wind and the salinity difference, etc. Marine currents carry enormous amounts of energy, which is sustainable, widely distributed, and highly predictable. China, as a big maritime country, has over 18,000 km shorelines and thousands of islands, and China is rich in tidal current resource [6].

In order to boost the development of renewable energy, improve the energy consumption structure and protect the environment, the Chinese government has passed a landmark renewable energy law and also made several plans in past five years, such as the National Guideline on Medium- and Long-Term Program for Science and Technology Development drawn in 2005, the Renewable Energy Law which was enacted on January 1st, 2006, in which enhancing energy diversity and security has been emphasized. In the coming years, it can be expected that more renewable energy policies would be made.

2.1. Distribution of tidal currents in China

The exploitation of tidal energy in China was started in 1958 and numerous tidal barrage power plants were then constructed over the following years [7]. It is estimated that the average power available from tidal currents in China exceeds 13,940 MW without considering the uninvestigated sea area that may experience strong currents [6]. According to the Coastal and Rural Ocean Energy Resource Investigation which has assessed over 130 water channels at national level in 1989, it was found that tidal current energy resource is distributed unevenly across China. Most of the tidal energy is concentrated in three coastal regions which are north of Yellow sea, East Sea and South Sea respectively. Zhejiang province has the richest tidal energy resource in China. It owns about 37 channels and approximate 7090 MW of tidal current energy capacity, which accounts for half of the total tidal current resource in China. The distribution of tidal energy for other regions is shown in Table 1.

From Table 1, it can be seen that Liaoning province, Shandong province, Zhejiang province, Fujian province and Taiwan province all have large tidal current resources. The power density in most of their water channels is 15–30 kW/m^2, especially Jintang channel, Guishan channel and Xihou channel in the Zhoushan archipelago, Zhejiang province, whose average power density is above the 20 kW/m^2 and thus it is very suitable for tidal current energy exploitation, as illustrated in Fig. 1.

Except the Taiwan and South China Sea, the current flows around the mainland of China are less affected by the global circulation as they are mainly caused by the tides of the ocean. In the South China Sea, the current is thought to be driven by the monsoon blowing from the southwest in summer and from the northeast in winter. Moreover, it is partly influenced by the North Equatorial Current circulation. Compared with the above coastal regions, the current around Taiwan is relatively stable. The shortest distance from the Kuroshio Current center to the eastern land is 60–66 km. The average velocity of the Kuroshio Current is 0.9 m/s and it is estimated that the water flux amounts to 1700–2000 m^3/s. If the Kuroshio Current could be exploited, it would promise a broad prospect.

2.2. Renewable energy policy in China

Policies and targets have been established to promote the development of the renewable energy in the last decade. The *Notification of Recent Priority Task in Constructing Economical Society by the State Council* published in 2005 stated that the ocean energy should be greatly promoted, especially in the eastern coastal areas and some islands. The *Renewable Energy Law* went into effect on 1st January 2006. Soon after, the *middle and long term development program of the renewable energy* was published in 2007, in which a specific goal was put forward that renewable energy will account for 10% of the overall energy consumption before 2010 and gradually reach 15% by 2020 [9]. In these programs and laws, the development and exploitation of the renewable energy in China has been planed in detail, covering resource survey, technology support, financial

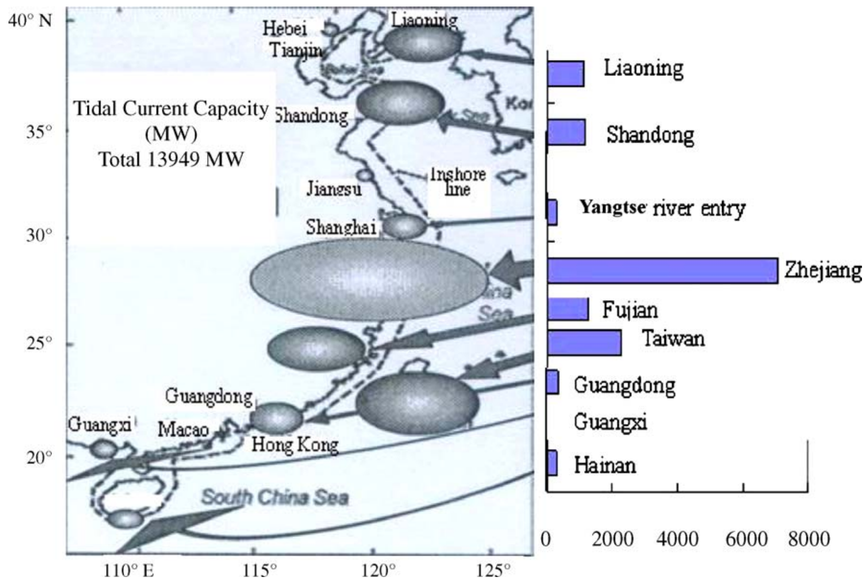

Fig. 1. Tidal current energy distribution in China.

incentives and supervisory measures, etc. Besides, in the *layout compendium of the national middle and long term target of science and technology development (2006–2020)*, the renewable energy has been put in the first position [10]. Research programmes related to renewable energy are also funded by *National High Technology Research and Development Program 863*, the *National Natural Science Foundation of China* and the State Oceanic Administration P.R.C.

Encouraged and guided by the national renewable energy policy, the first academic symposium for the foundation of the Ocean Energy Professional Committee of China Renewable Energy Association was held in 2008, followed by the International Ocean Energy Symposium and the second academic symposium of the ocean energy in September 2009. At these symposiums, the current status of the ocean energy research in China was described and the future perspectives were discussed.

In order to encourage enterprises in China to develop renewable energy sources, the *Renewable Energy Law* was revised in December 16, 2009. As a result, China National Offshore Oil Corporation, Eastern Electric Corporation, etc. have expressed great interest in the exploitation of wind energy and ocean energy.

3. Development of tidal current turbine in China

Compared with wind and wave energy which are intermittent and variable, tidal current energy has some distinct advantages, such as high predictability and regularity, which make the exploitation of tidal current energy more attractive. On the other hand, tidal current energy is compatible with the environment. Therefore, many countries began to carry out research into various aspects of tidal current power in the latter part of the last century, including UK, Canada, Italy, Japan, China and USA, etc. and nowadays more and more researchers engage in this field of research.

On the basis of the structure for a power take-off unit, tidal current energy converters can be categorized into two main types: horizontal axis and vertical axis. From the earlier parachute system and "Coriolis" system (USA) in 1976 to the 1.2 MW *Seagen* system in 2008 which is the largest ocean current power unit in the world [11], many novel tidal current energy conversion prototypes have been built and tested, such as the 300 kW *seaflow* system (Marine Current Turbine Ltd UK) in 2003 [12], the 150 kW Stingray deployed in Yell Sound off the Shetland Islands in the autumn of 2002 [3,13], the TidEl tidal stream generator by the SMD Hydrovision, and so on [14]. The DeltaStream turbine device by Tidal Energy Ltd. (UK) and the Evopod Tidal Turbine by Ocean Flow Energy Ltd. (in England) have also been developed and tested [15]. The Verdant Power (USA) initiated Roosevelt Island Tidal Energy (RITE) Project which developed *Free Flow* System and completed the Phase II demonstration in 2008 [16]. In addition, the Clean Current Power Systems Incorporated (in Canada) [17], the Openhydro Corporation [18] in Ireland, the Hammerfest Strom in Norway (300 kW Tidal Stream Turbine) [19], the Lunar Energy Ltd. based in the UK [20], the Atlantis Resource Corporation Ltd. in Singapore and London UK (400 kW Nereus and Solon Tidal Turbines and 500 kW Solon Tidal Turbine have been tested in 2008 [21]), all carried out research works on the horizontal axis tidal current turbine (HATCT). Additionally, professor A.S. Bahaj et al. (University of Southampton, UK) has is engaging in the research on marine current turbine (MCT) for several years [22–28]. The Wales Swansea University (in UK) has developed a direct-driven marine current turbine [29]. Except the horizontal axis type, Blue Energy Ltd. (Canada) has developed Darrieus-type vertical axis turbines. Ponte di Archimede developed and tested the vertical axis variable-pitch blade KOBOLD turbine (in Messina Strait, Italy) in spring 2003 [30]. GCK Technology Inc. (in USA) tested the Gorlov Helical Turbine [31]. Nihon University (in Japan), the Reggio Calabria University (in Italy) and University College London (in England) investigated on the pitch-control mechanism of vertical axis marine current turbine (VAMCT) [32–34].

Compared with those industrialized countries mentioned above, the development of tidal current energy in China is relatively slow. China began using tidal power at the mid-1950s and more than 76 plants were thereby built between 1950s and 1980s, all of which were barrage tidal plants. However, only three of those tidal power plants are still in operation now. Few institutions or universities conducted research on novel tidal current turbines, for instance *open* structure tidal turbine. At 1970 s, due to the environment pollution and also the impact of global oil shocks, the utilization of diversified energy supply and renewable energy has been recognized by the Chinese government as an effective way to tackle those problems. Hence, ocean current energy exploitation has also become a focal point in the research of renewable energy sources.

The earliest tidal current turbine (see Fig. 2) in China was developed and tested in 1970s. The prototype adopted hydraulic system for power transmission and generated 5.8 kW at the current veloc-

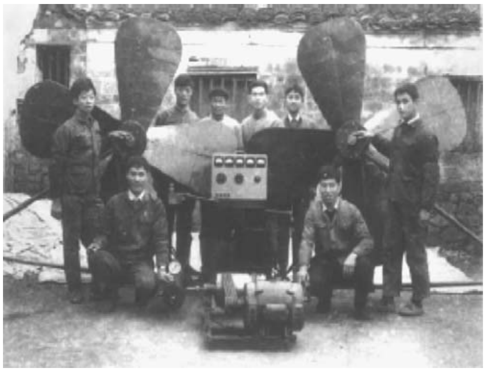

Fig. 2. The first MCT in China in 1970s.

Fig. 3. 70 kW tidal current energy plant.

ity of 3 m/s [35]. The turbine was similar to a ship propeller and further researches into the components of the unit were not able to be carried out at the same time. At 1980s, the Harbin Engineering University (HEU) in China began the study of a vertical axis tidal turbine. Their vertical axis turbine can work in bidirectional water flows without using the pitch adjustment or yaw system, but the efficiency is lower than that of the horizontal axis turbine. With the aim of improving the turbine efficiency, some additional pitch adjustment mechanisms had to be installed on the device, which would make the entire structure become more complex [33,36]. In 1984, HEU tested a 60 W prototype, followed by another kW-scale unit in 1989. A 70 kW floating tidal energy plant (*Wanxiang I*) was built between 1996 and 2002 and tested in Daishan, Zhejiang province, as shown in Fig. 3. The 40 kW *Wanxiang II* with a gravity based support structure was tested in 2005, as shown in Fig. 4. In 2006, supported by the United Nations Industrial Development Organization, the Ponte di Archimede International Company in Italy signed a joint venture with HEU to develop a Kobold vertical axis turbine prototype in China [37].

Fig. 4. 40 kW tidal turbine by HEU.

Fig. 5. 5 kW tidal turbine by OUC.

Besides HEU, Ocean University of China (OUC) also conducts research on the vertical tidal turbine, and Fig. 5 displays its 5 kW prototype, which has been tested twice during two periods from October 31 to November 11 and from December 12 to December 19, 2008. Different from the HEU's prototype, the OUC's turbine used the flexible blades [38].

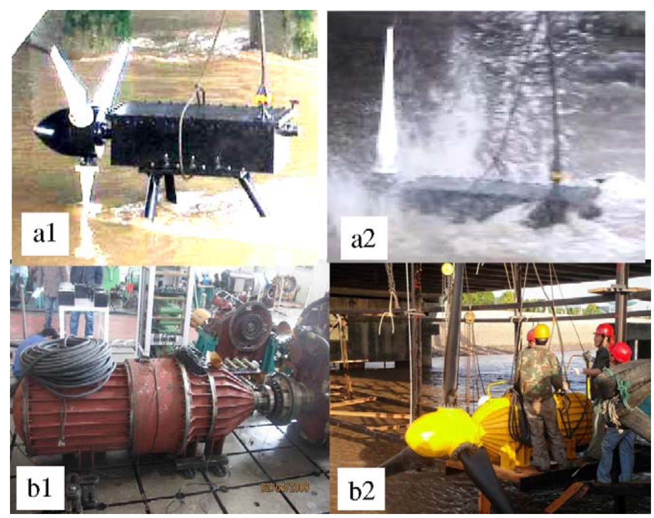

Fig. 6. Test of the MCT prototype.

Fig. 7. 2 kW MCT prototype by NNU.

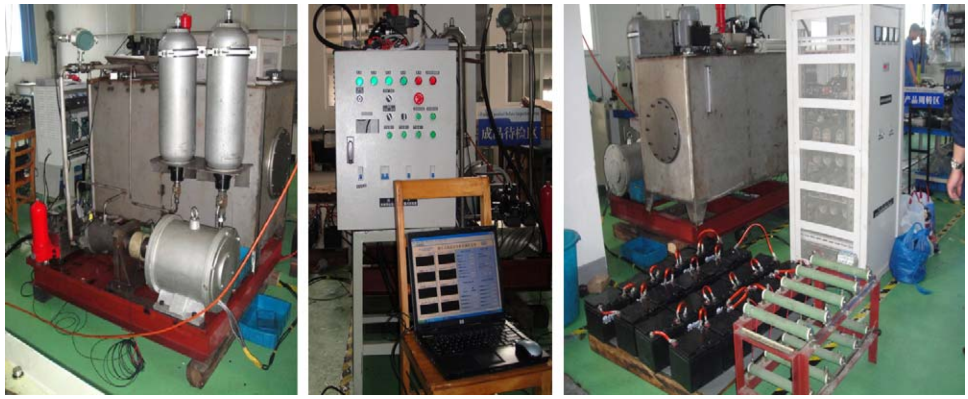

Fig. 8. Hydraulic power transmission system for HAMCT.

Zhejiang University (ZJU) began investigating the horizontal axis tidal current turbine under the vigorous support of the *National Nature Science Foundation of China* in 2005 and has tested a 5 kW prototype in May 2006 [39], as shown in Fig. 6a(1) and a(2). The prototype can generate 2 kW power at a water speed of around 1.8 m/s. Northeast Normal University (NNU) developed a multiple-blade turbine running in the low speed current (lower than 1 m/s) and a 2 kW prototype was tested in December 2005 (Fig. 7).

In order to measure the total efficiency of the units with different power transmission structure, the gearbox transmission and the hydraulic power transmission were studied by ZJU. The Fig. 6b(1) and b(2) showed the assembly and sea trial of the 25 kW horizontal-axis tidal turbine that was tested by ZJU in April 2009, generating a peak power of 30 kW at a water speed of 2.4 m/s. The test results suggest that the total system efficiency is around 25% [40]. In fact, if the power loss at the rotating seal could be reduced, the efficiency can be further improved. The direct drive transmission has been adopted in the NNU's turbine prototype, by which the blades were coupled directly to the rotor of the generator. Because of the low speed and direct drive, the unit features a low rotational speed and large-size turbine generator.

The stability of the output power, voltage and frequency etc. is another key issue for tidal current turbine. The researchers employed the hydraulic transmission in tidal current turbine to help stabilize the output. Fig. 8 showed the hydraulic system designed by ZJU, and a field test of those components will be implemented soon [40]. In addition, it was considered that a variable-speed tidal turbine could be designed to maintain the optimum power production with the aid of a variable-displacement pump or hydraulic motor.

For a horizontal axis turbine, the pitch-controlled mechanism is essential to ensure the turbine produce electricity from bidirectional fluid flow. Hitherto, three measures are being studied, consisting of the hydraulic, electronical and self-adjusting pitch control mechanism. Among them, the hydraulic one is preferred as it can create large driving force easily and has been adopted in the design of a horizontal axis tidal turbine prototype by ZJU. The electronical one is thought to have a complex structure, while the self-adjusting one is uncontrollable and vulnerable to disturbance of water currents.

4. Challenges in utilizing tidal current energy in China

China is a huge emerging market for tidal current energy which can be harnessed to provide enormous power to the remote rural areas which cannot access to a reliable electric network or are lack of conventional fossil fuel energy resources. Moreover, exploitation of tidal current energy will substantially benefit the coastal areas.

So far, although some progress in China has been made, more research and development (R&D) on tidal current energy technology is still urgently needed. (1) The tidal current resource is dispersed and remote from the land. In some places like Zhejiang province where the amount of tidal energy available is vast, but the marine environment is harsh, how to greatly improve the reliability of tidal current energy converter is crucial for its commercialization. (2) More than twenty years have passed since the previous country-wide survey of the ocean energy resource was conducted in 1989, therefore, new assessment of the tidal energy resources in China should be carried out. (3) Technically, in order to capture more energy from the flow, novel blade or airfoil should be developed and tested, in the mean time, advanced control strategies such as variable speed running mode of the tidal turbine should be investigated, through which the optimal blade tip speed ratio λ_p can be obtained. (4) International co-operation will be of paramount importance for the development of tidal current turbine in China. It is hoped that more and more domestic and foreign institutions or enterprises can share their experience on the tidal current energy exploitation. (5) Policies are needed to be set up to encourage more corporations to join the R&D of the ocean energy.

Besides all mentioned above, there are still many other challenges needed to be solved for the commercialization of tidal current energy. One of them is the mounting of tidal turbine, in the current tests, the installation had the drawbacks of high cost (e.g. pole foundation), and uncertainty (e.g. floating structure). Other problems include the cost effectiveness, environmental impact analysis, so more researches and data from full-scale experiments are needed before any definite conclusions can be drawn.

5. Conclusion and perspectives

Nowadays, as more and more people have recognized the importance of renewable energy, the enormous energy contained in ocean has gained more attentions recently and consequently have developed considerably, such as the tidal current energy and wave energy, etc. In this paper, the distribution and current development of tidal current energy in China is presented.

The tidal current energy is estimated to be about 61.3 TWh/yr in China, and it has several competitive advantages over other renewable energy sources, such as predictability, regularity and low environmental impact, thus it ought to be an effective option for solving energy shortage and environmental pollution. At present, many institutions or universities and corporations have started doing more research into the tidal current turbine, and it can be expected that more achievements would be obtained in near future.

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References

[1] Robin Pelc, Rod M Fujita. Renewable energy from the ocean. Marine Policy 2002;26:471–9.
[2] Ting Mazharul Islam, Amir Fartaj, David S-K. Current utilization and future prospects of emerging renewable energy applications in Canada. Renewable and sustainable Energy Reviews 2004;8:493–519.
[3] Tidal/current stream. The World Offshore Renewable Energy Report 2004–2008 [chapter 5].
[4] He Dexin. China becomes one of the important markets of wind energy in the world. China Wind Energy 2008;5.
[5] Zhang Dahai, Li Wei, Lin Yonggang. Wave energy in China: current status and perspectives. Renewable Energy 2009;34:2089–92.
[6] Wang Chuankun, Shi Weiyong. The ocean energy resource reserves and evaluation in China. In: 1st academic symposium for the foundation of the Ocean Energy Professional Committee of China Renewable Energy Association, Hangzhou; 2008. p. 169–79.
[7] Liang Liang Ni Yongqiang. Tidal energy exploration and application research in Zhejiang Province. In: 1st academic symposium for the foundation of the Ocean Energy Professional Committee of China Renewable Energy Association, Hang Zhou, China; 2008. p. 180–4.
[8] Wang Chuankun, Lu Wei. Analysis method of ocean energy resource and storage estimation. Beijing: Ocean Publisher; 2009.
[9] Energy situation and policy in China. P.R.C.; 2007.
[10] http://www.most.gov.cn/kjgh/.
[11] http://www.marineturbines.com/.
[12] Baddour Emile. Ocean energy: an update. St Andrews; 2005.
[13] Trapp Tony. The stingray tidal stream generator – 150 kW demonstrator completes on-site testing. Energy World 2002;304:14.
[14] George Marsh. Energy from the sea. Refocus, 2005;6 (6):30–2.
[15] Rourke FO, Boyle F, Reynolds A. Tidal energy update 2009. Applied Energy 2010;87(2):398–409.
[16] http://www.verdantpower.com.
[17] http://www.cleancurrent.com/.
[18] http://www.openhydro.com.
[19] Richard Stone. Norway goes with the flow to light up its nights. Science 2003;299:339.
[20] http://www.lunarenergy.co.uk.
[21] http://www.atlantisresourcescorporation.com/.
[22] Molland AF, Bahaj AS, Chaplin JR, Batten WMJ. Measurements and predictions of forces, pressures and cavitation on 2-D sections suitable for marine current turbines. Proceedings of the Institution of Mechanical Engineers 2004:218.
[23] Bahaj AS, Molland AF, Chaplin JR, Batten WMJ. Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank. Renewable Energy 2007;32(3):407–26.
[24] Bahaj AS, Myers LE. Fundamentals applicable to the utilisation of marine current turbines for energy production. Renewable Energy 2003;28:2205–11.
[25] Myers L, Bahaj AS. Power output performance characteristics of a horizontal axis marine current turbine. Renewable Energy 2006;(21):197–208.
[26] Myers Luke, Bahaj AS. Wake studies of a 1/30 scale horizontal axis marine current turbine. Ocean Engineering 2006.
[27] Batten WMJ, Bahaj AS, Molland AF, Chaplin JR. Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines. Ocean Engineering 2006.
[28] Batten WMJ, Bahaj AS, Molland AF, Chaplin JR. Hydrodynamics of marine current turbines. Renewable Energy 2006;31:249–56.
[29] http://home.clara.net/darvill/altenerg/tidal.htm.
[30] Richard Boud. Status and research and development priorities, 2003 wave and marine current energy; 2003.
[31] Jahangir Khan, Gouri S Bhuyan. Ocean Energy: Global Technology Development Status 2009:63.
[32] Kiho S, Shiono M, Suzuki K. The power generation from tidal currents by darrieus turbine. Renewable Energy 1996;9(1–4):1242–5.
[33] Alessandro Schönborn, Matthew Chantzidakis. Development of a hydraulic control mechanism for cyclic pitch marine current turbines. Renewable Energy 2007:32:662–79.
[34] Camporeale Sergio M, Magi Vinicio. Streamtube model for analysis of vertical axis variable pitch turbine for marine currents energy conversion. Energy Conversion & Management 2000;41:1811–27.
[35] Gao Xiangfan. Tidal current power generation. 1979.
[36] Wang Lubing, Zhang Liang, Zeng Niandong. An optimization method for improving hydrodynamic performance of the vertical-axis turbine for tidal streams energy conversion. Journal of Harbin Engineering University 2004;25 (4):417–22.
[37] Company Ponte di Archimede International. http://www.pontediarchimede.it/language_us/comunicati.mvd.
[38] Wang Shujie. Research on the tidal current energy equipment with flexible blades. 2009.
[39] Liu Hongwei, Li Wei, Lin Yonggang, Ma Shun. Model analysis and test research of horizontal-axial marine current turbine. Acta Energiae Solaris Sinica, 2009;30 (5):633–8.
[40] Ma Shun, li Wei, Liu Hongwei, et al. Experimental investigation of a horizontal axial tidal current energy conversion system. In: International Ocean Energy Symposium 2009, Harbing China; 2009. p. 64–71.