Journal of
Marine Science and Technology

Volume 31 | Issue 4 Article 3

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Recommended Citation

Liang, Nai Kuang and Peng, Hai Kuan (2023) "A PRELIMINARY STUDY ON FLOATING FLEXIBLE OTEC COLD WATER PIPE," *Journal of Marine Science and Technology*: Vol. 31: Iss. 4, Article 3.
DOI: 10.51400/2709-6998.2710
Available at: https://jmstt.ntou.edu.tw/journal/vol31/iss4/3

RESEARCH ARTICLE

A Preliminary Study on Floating Flexible OTEC Cold Water Pipe

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Abstract

Ocean Thermal Energy Conversion (OTEC) requires a large amount of cold seawater. The traditional rigid pipe, semi-rigidly fixed onto the ship bottom is not easy to install and disassemble, so the Floating Flexible Cold Water Pipe (FFCWP) flexibly connected to the ship is proposed. A small FFCWP was designed, fabricated, and successfully installed and recovered in the sea. The flexible pipe adopts commercially available fire ventilation snake pipe. The pipe wall material strength must be improved in the future. Assuming that the drag coefficient Cd value is 1.5, a numerical calculation is employed to simulate the FFCWP attitude from the action of ocean currents. Ocean currents cause the lower pipe inlet to rise. The main influencing factors on pipe design are pipe radius, ocean current speed and pipe weight per unit pipe length. Because the FFCWP ascension quite large as the ocean current becomes greater than 0.5 knots, it is recommended that the grazing OTEC plant ship allow pipe drifting when generating electricity.

Keywords: Grazing OTEC, Floating flexible cold water pipe, Sea test, Lower inlet depth

1. Introduction

The sea surface temperature of tropical oceans is about 27−29 °C. The sea temperature 900 m is always about 5 °C. The French physicist D'Arsonval proposed the idea of an open cycle in 1881. He put warm seawater in container A, which was close to vacuum. The seawater was then evaporated into water vapor. That water vapor was directed into a tube in which a turbine drove a generator to produce electricity. To maintain the water vapor flow, the water vapor through the turbine is introduced into container B containing cold seawater. The water vapor condenses into water so that the air pressure in container B is lower than that of container A. In 1962 American mechanical engineer Anderson proposed a closed cycle, using ammonia as a medium in a closed tube. The warm seawater on the sea surface is passed through a heat exchanger to turn liquid ammonia into vapor, while the deep cold seawater condenses the ammonia vapor into liquid. This causes a pressure difference between containers before and after the turbine. This pressure difference allows the turbine to rotate to generate electricity. This is the principle of ocean temperature difference power generation. The English name is Ocean Thermal Energy Conversion (OTEC).

Due to the world energy crisis in 1973, the U.S. government began to invest in OTEC research. From 1975 to 1980 the Department of Energy allocated $35 to $38 million annually for research and development and held international conferences every year. In 1979 the Mini-OTEC study was completed in Hawaii to test a closed-cycle 50 KW unit that generated 10 KW of net electricity, the first time for mankind. In 1981 the OTEC-1 offshore trial was completed, testing the function of a 1 MW closed-cycle heat exchanger to produce high-pressure ammonia steam. The end of the OTEC-1 program also ended the US government's heavy

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Received 23 April 2023; revised 19 September 2023; accepted 19 September 2023.

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https://doi.org/10.51400/2709-6998.2710

investment in OTEC research. Avery & Wu in 1994 advocated that the United States should develop grazing OTEC in the Gulf of Mexico, without anchorage and transmission to the shore and electrolyzing the water to obtain hydrogen, which is then synthesized with nitrogen to produce ammonia [1]. Liquid ammonia is easy to transport. A 160 MW grazing OTEC vessel produces 1750 tons of ammonia per day. A scale of 10 ships would be profitable.

The ocean seawater temperature decreases as the depth increases. Seaborn nutrients, i.e., nitrate, phosphate and silicate, are essential to phytoplankton growth. It is a well-known fact that the natural upwelling area in the ocean is a high biological productivity area. The famous "Takumi" Experiment on artificial upwelling pumped 1 ton/sec from 200 m depth using a 1 m diameter steel pipe for 7 years in Sagami Bay in Japan [2]. Liang suggested that a grazing OTEC vessel can create an artificial upwelling sea area by mixing cold and warm seawater after power generation and discharging it from the stern. Liang estimated that a 100 MW OTEC vessel can create 18 square kilometers of artificial upwelling sea area [3].

Since OTEC requires a lot of deep seawater, the first idea is offshore type floating bodies in which the cold water pipe length is the shortest. However, floating bodies should avoid typhoons because typhoon waves easily cause damage to the floating bodies and cold water pipe joint and can even damage the entire structure. Nevertheless, for a land-based OTEC plant, the submarine pipe length depends on how far the 1000-m isobaths are offshore. The best location in Taiwan is about 4 km. For a 5 MW power plant, the submarine cold water pipe diameter needs to be 3 m. The current technology has advanced but it is still difficult, so that the current land-based demonstration power plant is only 50-100 KW. The existing cold water pipe technology with floating body or ship, mostly from offshore oil production technology, still uses a rigid pipe [4]. The current cold water pipe floating offshore OTEC power plant is the traditional rigid pipe, of which installation, operation, maintenance and recovery are extremely inconvenient. At present, there is no pilot OTEC plant larger than 2 MW. Hence it is extremely necessary to make a breakthrough. This paper proposes a Floating Flexible Cold Water Pipe (FFCWP) that can be separated from the ship to overcome the above-mentioned difficulties. The original concept is the Republic of China Patent I589775, as shown in Fig. 1. The floating marine deep seawater well consists of a buoyancy part (4), multiple connecting pipes (5) and a counterweight (6). The buoyancy part must bear the weight of the entire deep seawater well so that the system floats on the sea surface.

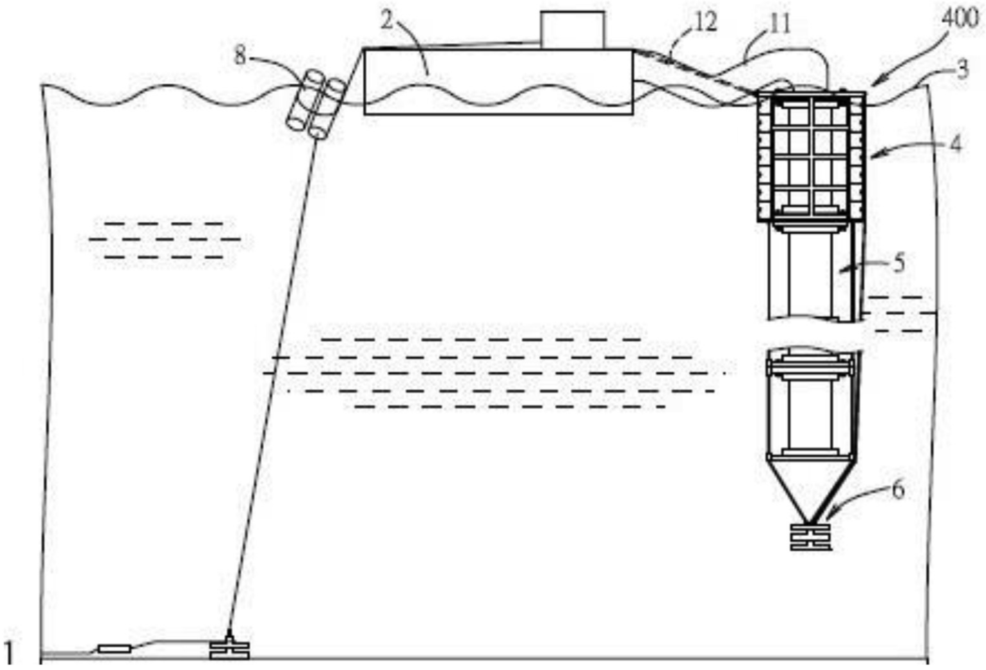

Fig. 1. Schematic diagram of a floating marine deep seawater well (2:OTEC plant ship, 3:sea surface, 8: buoy, 11: pumping pipe, 12: cable, 400: floating marine deep seawater well).

2. Theoretical analysis

According a paper from the 37th Taiwan Ocean Engineering Conference (Peng and Liang, 2015), to analyze the flexible pipe attitude under the action of ocean currents, it is assumed that the floating flexible pipe is simplified into a rope hanging in the sea [5]. Taking a small pipe section, its force balance is shown in Fig. 2. Assume that the wave effect is ignored because the grazing OTEC plant ship always sails in calm seas and the wave effect is limited to the upper pipe end. The buoyancy part is tied to the ship flexibly to resist the ocean current drag force. The force balance equation is established as follows:

$$\Delta x_i = \Delta L \cdot \sin \theta_i \tag{1}$$

$$\Delta y_i = \Delta L \cdot \cos \theta_i \tag{2}$$

$$\Delta A_i = 2 \cdot a \cdot \Delta y_i \tag{3}$$

$$\Delta D_i = \frac{1}{2} \cdot \rho \cdot C_d \cdot \Delta A_i \cdot \mathbf{ui} \cdot \mathbf{ui} \tag{4}$$

$$T_{i+1} \cdot \cos(\theta_{i+1}) = T_i \cdot \cos(\theta_i) - \Delta W \tag{5}$$

$$T_{i+1} \cdot \sin(\theta_{i+1}) = T_i \cdot \sin(\theta_i) - \Delta D_i \tag{6}$$

$$\tan(\theta_{i+1}) = \frac{T_i \cdot \sin(\theta_i) - \Delta D_i}{T_i \cdot \cos(\theta_i) - \Delta W} \tag{7}$$

$$X = \sum \Delta x_i, Y = \sum \Delta y_i \tag{8}$$

Y: Flexible pipe inlet depth

ΔL: Flexible pipe segment unit length

Δx_i: Flexible pipe segment length projected horizontally

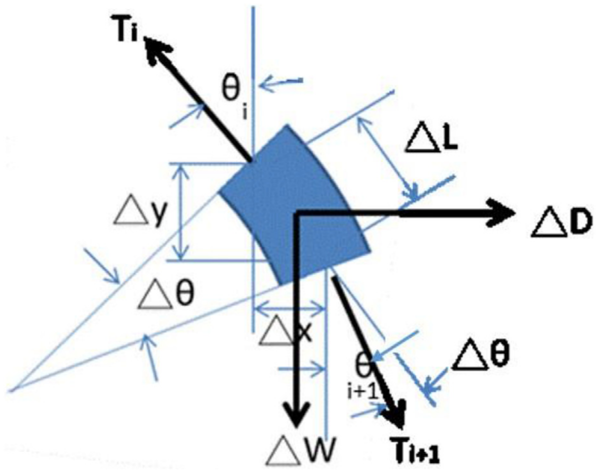

Fig. 2. Schematic diagram of forces on the flexible pipe section.

a: Radius of the flexible pipe section

Δy_i: Flexible pipe segment elements projected vertically

ΔA_i: The projection area of flexible pipe section unit perpendicular to the current

ΔD_i: The horizontal drag force on flexible pipe section unit by current, in Newtons.

C_D: Drag force coefficient

ui: The speed of ocean currents at different depths (y).

T_i, T_{i+1}: The tension at the upper and lower ends of the flexible pipe section

θ_i, θ_{i+1}: The angle between the tension at the upper and lower ends of the flexible pipe segment and the perpendicular

ΔW: The flexible pipe segment weight in water, in Newtons.

The boundary conditions at the upper end of the flexible tube are as follows:

$$T_1 = \sqrt{W^{2+}D^2} \tag{9}$$

$$\theta_1 = \tan^{-1}\left(\frac{D}{W}\right) \tag{10}$$

T_1: The tension between the buoyancy part and the flexible pipe

W: The weight of flexible pipe and counterweight in water, in Newtons.

D: The total horizontal drag force of the flexible pipe by current (the drag force of counterweight is ignored)

The trial and error method is used to calculate the flexible pipe attitude under ocean current effect. The pipe section length, radius, and weight, counterweight and current profile are selected. A lower inlet depth for the flexible pipe is chosen, which can be calculated as the drag force due to the ocean current. The cable tension and inclination angle at the flexible pipe upper end, which is the boundary condition for the upper pipe inlet, can be obtained. The horizontal drift (x) and depth drift (y) of each flexible pipe section caused by the ocean current can then be deduced. The flexible pipe lower inlet depth can then be calculated. We checked whether the lower inlet depth Y error and that previously assumed is within an allowable range. If not, another lower inlet depth is assumed until the error is within the allowable range.

3. Model making and sea testing

To test the operation feasibility of the FFCWP concept a set of small models was designed and produced. The design drawings are shown in Fig. 3. The drawing and manufacturing were

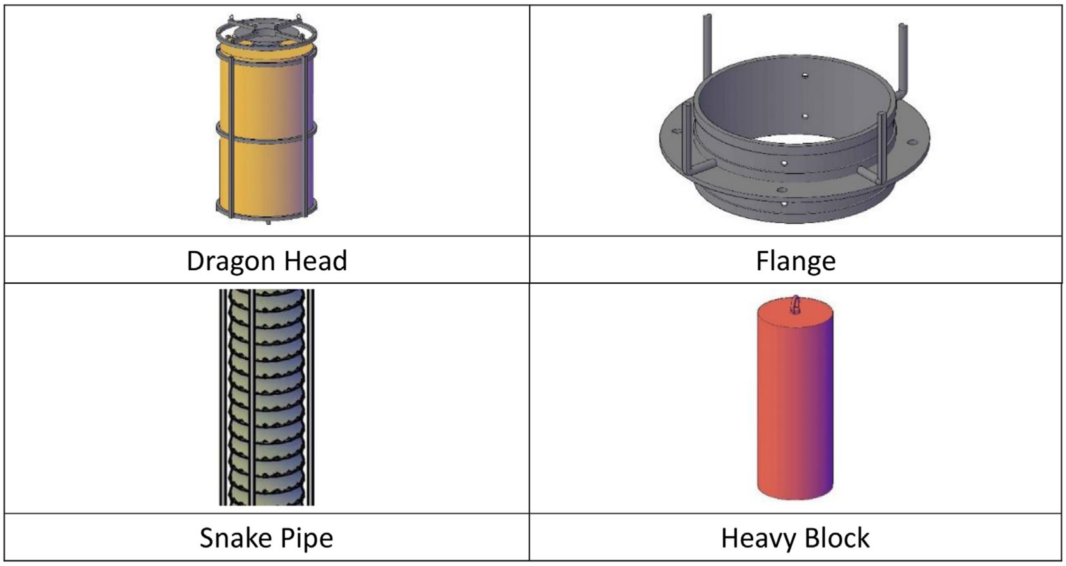

Fig. 3. Floating Flexible Cold Water Pipe (FFCWP) model design.

commissioned to the Zhenyi Company. Among the production designs, Dragon Head is the buoyancy part. The flexible pipe is a commercially available fire supply snake pipe, i.e., the former mentioned connecting pipe. The heavy block is the counterweight and the SBE39 temperature-depth meter tied to the heavy block is used to measure the depth for the flexible pipe lower inlet. The adapter ring is a flange connecting the adjacent snake pipes. The snake pipe and flange are locked to each other with a steel bundle ring. The flange is also welded with 4 L-shaped iron rods, with which the steel cables and flange are fixed together with steel cable clamps. The steel cable length is slightly shorter than that of the fully extended snake pipe, so that the snake pipe is not subject to longitudinal tension. The four steel cables are under tension, limiting the space enclosed by the snake pipe in steel cables.

A sea test was conducted by the New Ocean Researcher 2 (CR0074 voyage) in Keelung Shenao Bay on July 17, 2022. New Ocean Researcher 2 had two other tests underway at the same time. The ship was kept still using dynamic positioning. We first assembled the models on the aft deck, as shown in photo 1. The earrings on the dragon head were hooked with a four-claw hook. A rope was tied to the dragon head to hold it. The flexible pipe was slowly floated onto the sea surface, while the dragon head slowly floated away from the stern. When the whole flexible pipe had been launched, a rope was tied to the heavy block and it was slowly launched into the water. This allowed the air in the pipe to be discharged. and the pipe then sank. At the same time, the rope tied to the dragon head was used to pull it closer to the stern. When the rope tied to the heavy block was slack, it meant that the entire weight was carried by the dragon head buoyancy. The rope was then temporarily tied to the side of the vessel. The ring of the four-jaw hook was then hooked onto the stern A-frame heavy winch hook. The deployment is now completed, as shown in photo 2. When recovering, the heavy block and instrument are first pulled up and removed. The pipe tail is then returned to the sea, while the dragon head and flexible pipe are returned to the ship.

Photo 1. Model on the aft deck of New Ocean Researcher 2.

Photo 2. The model after launching.

4. Experimental and numerical simulation results

When the model is launched, the most critical thing is that the heavy block must be slowly lowered so that the air in the pipe is completely discharged. The pressure in the pipe is then balanced, so that the pipe wall is not subject to water pressure. If only one test is performed the ship can be moved and the installation will be more convenient. Due to the small current, a boat must be used to pull the dragon head in the early stage so that the flexible pipes floating on the sea surface are not twisted together. The same effect can be achieved if the ship can move. Because the ADCP data on board was questionable during the 2-h test, the current bridge speed was 0.4–0.6 knots. The middle 0.5 knots was used for the calculation, which was equivalent to 0.25 m/s. The heavy block weight was 24.9 kg in water, the pipe section was 1 m, the pipe radius 0.1 m, the current speed 0.25 m/s, the number of segments 16. The weight of each meter of pipe section in water was 1.36 kg. The distance between the instrument sensor and the pipe end was 1.28 m. The floating body sank 0.44 m; hence, the correction value is 1.72 m. The average instrument depth was 16.72. The pipe lower end was 15 m from the upper end, and the Cd value was calculated as 2.6. Because the current speed during the test was uncertain, the calculated Cd value may be too large. The Cd value then becomes smaller in theory when the size of the flexible pipe is enlarged. Therefore, when the flexible pipe is estimated in practical application, the Cd value can be assumed to be 1.5.

For simplicity, a constant current profile is adopted for a conservative lower inlet depth and the Dragon Head sinking depth is neglected. Assuming the unit pipe length weight (kg/m): 10, pipe length (m): 1000, current speed (m/s): 0.25, Cd: 1.5, the other nine lower inlet depth Y(m) situations for different heavy block weights (kg): 100, 200, 300 and pipe radius (m): 0.5, 1.0, 1.5 are calculated as shown in Table 1.

Table 1. The heavy block weight and pipe radius influence for lower inlet depth Y(m).

Heavy block weight kg	Pipe radius m		
	0.5	1	1.5
100	919.6	801.1	709.3
200	−922.8	806.2	714.5
300	925.8	811.0	719.6

Taking the pipe radius of 0.5 m to compare the pipe attitude when the heavy block weight changes (Fig. 4), although the heavy block weight can reduce the inlet rise, it only has a minor effect. However, a constant current profile is not real, the simulated pipe attitude is a simplified result.

The pipe attitude, as the pipe radius changes, is shown in Fig. 5 for 100 kg block weight. The pipe radius is an influential factor for the drift effect.

Assuming the heavy block (kg): 100, pipe length (m): 1000, current speed (m/s): 0.25, Cd: 1.5, the lower inlet depth Y(m) in nine situations for different pipe radii (m): 0.5, 1.0, 1.5, and unit pipe length weights (kg/m): 5, 10, 15, are calculated as shown in Table 2.

The pipe attitude of 0.5 m radius is calculated for different unit length weight as shown in Fig. 6, an increase in unit pipe length weight will increase the vertical load, which can reduce the drift effect.

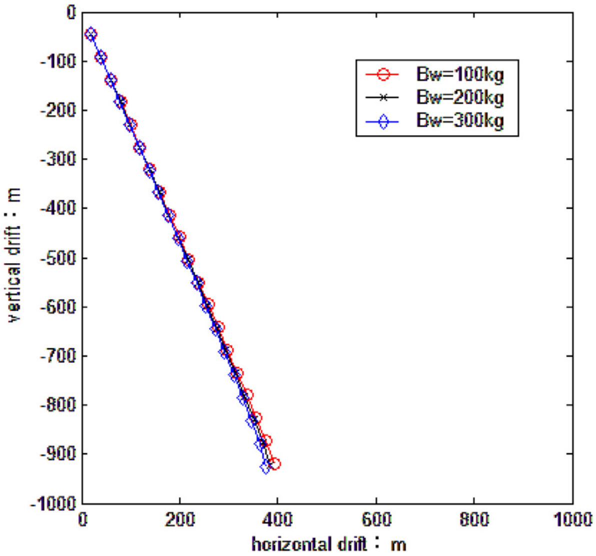

Fig. 4. The pipe attitude (0.5 m radius) for different block weights.

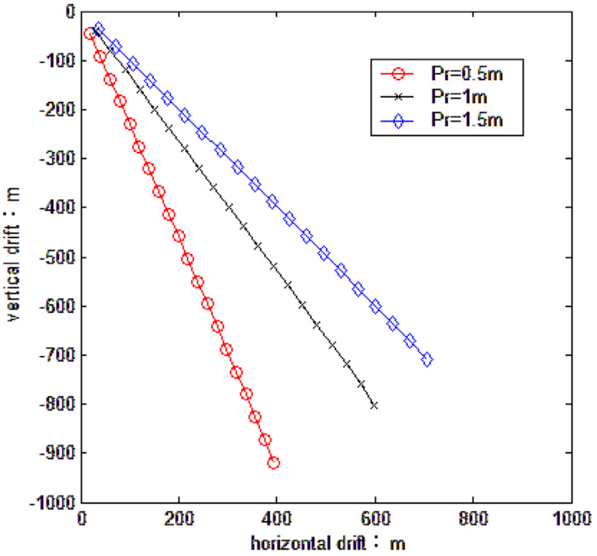

Fig. 5. The pipe attitude (100 kg block weight) for different pipe radii.

Table 2. Pipe radius and unit pipe length weight influence.

Pipe radius m	Unit pipe length weight kg/m		
	5	10	15
0.5	**806.2**	**919.6**	**958.0**
1.0	645.8	801.1	876.7
1.5	550.8	709.3	799.3

Assuming the heavy block weight (kg): 100, the pipe length (m): 1000, the unit pipe length weight (kg/m): 10, Cd: 1.5. The lower inlet depth Y(m) in nine situations for different current speeds (m/s): 0.25, 0.5, 0.75, and pipe radii (m): 0.5, 1.0, 1.5 are calculated as shown in Table 3.

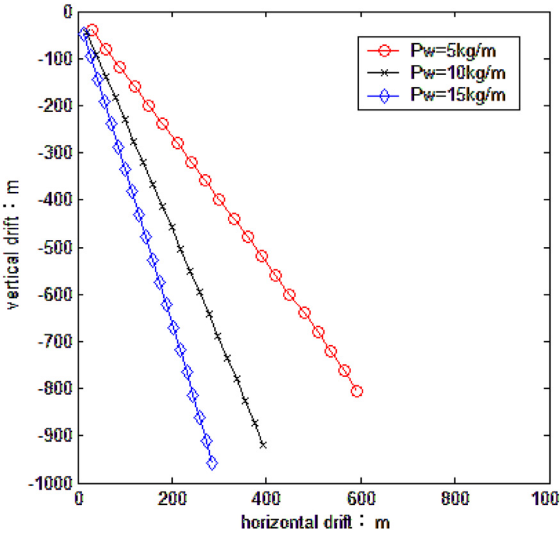

Fig. 6. The pipe attitude (0.5 m pipe radius) for different unit pipe length weights.

Table 3. The current speed and pipe radius effects.

Pipe radius m	Current speed m/s		
	0.25	0.5	0.75
0.5	**919.6**	**640.6**	**459.0**
1.0	801.1	483.3	334.1
1.5	709.3	403.3	275.5

The pipe attitude of 0.5 m radius is calculated for different current speeds (m/s) as shown in Fig. 7. It is obvious that the increase in current speed will significantly increase the drift.

In the real ocean the current speeds are larger in the upper layer and smaller at deeper depths. In order to imagine a pipe attitude example in the real ocean, a two-layer current is assumed. The speed in the upper 300 m is 0.5 m/s and 0.1 m/s at lower depths. The result in the 1 m radius condition, 100 kg heavy block weight, 10 kg/m unit pipe length weight and 1000 m pipe length is shown in Fig. 8. The pipe section length is 1 m in the numerical simulation.

5. Discussion and conclusion

A sea test proved that the installation and recovery method for the designed Floating Flexible Cold Water Pipe (FFCWP) is feasible. The FFCWP discussed in this paper was composed of a floating body, fire supply snake pipes, flanges, 4 steel cables and a heavy block. The flexible material of the fire supply snake pipe needs to be strengthened. The maximum snake pipe product diameter currently on the market is only 12 inches. Only the technical

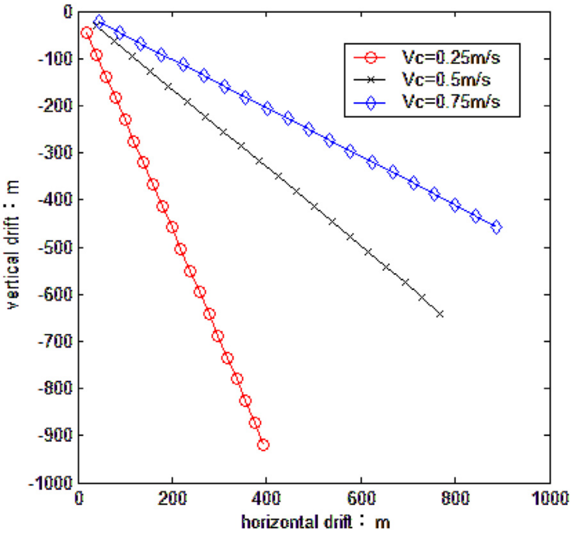

Fig. 7. The pipe attitude (0.5 m pipe radius) for different ocean current speeds.

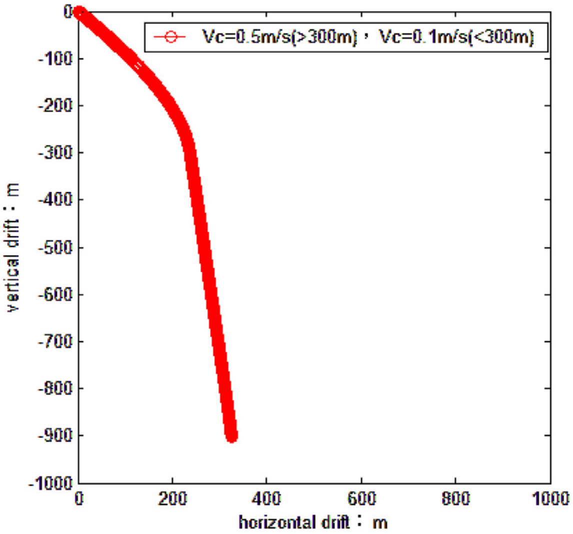

Fig. 8. A two-layer current pipe attitude example.

problems of making a large-diameter snake pipe or other concept designs and materials need to be studied in the future.

According to the numerical analysis, the relative current speed, pipe radius and unit pipe length weight are the main factors affecting FFCWP. The heavy block should not be too heavy under the operational consideration. This study was conducted for a grazing OTEC power generation vessel. The aforementioned FFCWP analysis affected by ocean currents suggests that the power generation vessel naturally drifts with the current, so that the relative current speed with the ocean is low. It is better to let the grazing OTEC power generation ship spin in the ocean vortex. As the power generation ship deviates from the higher water temperature area, let it sail back to the original place. Of course, during a voyage the ship may not pump enough cold water, and the power generation will become smaller. Another way to use FFCWP is to anchor it and tie the power generation ship to a floating body. The pipe inlet depth is then fixed and the electricity can be transmitted to the shore. In addition, it can also be used to arbitrarily extract deep seawater from different areas and depths in the sea for resource utilization. FFCWP has a wide range of applications, so this research direction is worth continuing.

Conflict of interest

No conflict of interest.

Acknowledgment

This study was a subsidy of the National Science and Technology Council. The project title is “The key offshore deep seawater resource utilization technology: small floating flexible deep seawater well sea test”, No. 110-2221-E-002-063. We would like to express our gratitude.

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