Perspective of membrane distillation applied to ocean thermal energy conversion

A. S. Kim[1], W. Oh[2], H.-S. Lee[2], S. Cha[2] and H.-J. Kim*[2]

Authors investigated the potential application of vacuum membrane distillation (VMD) to the conventional ocean thermal energy conversion (OTEC). Open, closed, and hybrid cycles of OTEC are reviewed, and strategies to enhance performance of open cycle (OC) using VMD are discussed. The advantages of using VMD modular sets include reducing system sizes and enhancing power production rates. Our rough estimation indicates that VMD uses only about 10 per cent of the system volume required by OC-OTEC. Tasks to actualize the promising VMD technology are discussed for the next generation OC-OTEC.

Keywords: Ocean thermal energy conversion (OTEC), Open cycle, Rankin cycle, Flash evaporation, Membrane distillation, Vacuum membrane distillation

Introduction

The twenty-first century can be characterized by depletion of basic resources such as food, energy, and water (FEW). Since the 1950s, as available amounts of these vital resources have either increased slightly or remain fixed, the world's population has disproportionately increased. Proper distribution of FEW is critical for human beings to live unstressful lives without (extreme) scarcity of the vital resources. An extensive, unbalanced use of natural resources by ever-increasing human population ascribe to the resource poverty. A report of the United Nations (UN) in 2013 (United Nations 2013) indicated that the present world population of 7.2bn is projected to increase by 1bn over the next 12 years (by 2025), and that China and India will have equal populations of 1.45bn around 2028. By 2050, Nigeria's population is expected to surpass that of the USA, India's population will be the largest, and the world's population will reach 9.6bn. In the next three or four decades, enormous amounts of FEW need to be properly secured in order to meet the demands by the projected population increase. This paper reviews the current status of energy and water availabilities, explains the necessity for inexpensive renewable energy sources such as ocean thermal energy, and discusses potential methods to enhance renewable energy production rates.

Global energy status

The 2010 World Energy Outlook [International Energy Agency (IEA) 2010] predicts that world demand of primary energy will increase by 36% between 2008 and 2035, and that the need for oil will increase from 2000 to 17 000 mtoe (million tons of oil equivalent) by 2035. In 2009, the UN Development Program (UNDP) and World Health Organization (WHO) estimated that $\sim$3bn people lack access to modern fuels for cooking and heating, $\sim$1.5bn have no access to electricity, and up to 1bn more have only unreliable electricity networks. The World Bank's study indicates that countries with underperforming energy systems may lose up to 1–2% of annual growth potential as a result of (i) electric power outages, (ii) over-investment in backup electricity generators, (iii) energy subsidies and losses, and (iv) inefficient use of scarce energy resources. The fact remains that fossil fuels will continuously dominate the world energy use for the foreseeable future. Only if reliable, cost-effective and efficient alternative energy forms can be developed and utilized, the situation can change and improve (BP 2014). Carbon dioxide emissions of Organization for Economic Co-operation and Development (OECD) countries should be 10% lower, but global carbon dioxide emission is expected to be 27% higher in 2030 than the present.

Renewable energy

Renewable energy technologies became more competitive with other energy sources as their costs were reduced through environmental and energy policies. In 2035, renewable energy sources will grow to 15–26% of all energy sources [International Energy Agency (IEA) 2010], which is the net result of two opposing trends: a dramatic rise in demand for modern renewable energy (albeit from fairly low levels) and a shift away from the use of traditional biomass (mostly fuel wood, charcoal, animal dung, and agricultural residues used for heating and cooking) in favor of modern forms, such as gas, electricity, and liquified petroleum gas. The share of traditional biomass in the global energy demand depends on the reduced use of biomass in Asia versus the population-driven increase in Africa.

Thermal renewable energies include geo, solar, and ocean resources. As of 2011, 4482 TWh of electricity

[1]Civil and Environmental Engineering, University of Hawaii at Manoa, 2540 Dole Street Holmes 383, Honolulu, Hawaii 96822, USA
[2]Sea water Utilization Plant Research Center, Korea Research Institute of Ships & Ocean Engineering, Goseong-gun, Gangwon-do 219-822, Korea

*Corresponding author, email hyeonju@kriso.re.kr

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has been generated worldwide, of which ocean (marine) thermal, solar (including solar photovoltaic [PV] and concentrating solar power), and geothermal energy productions are 1, 63, and 69 TWh, respectively. Solar PV power generation is expected to be more than three times that of geothermal generation by 2035, and ocean thermal energy production is expected to increase 40–60 times. All three renewable forms are, however, still in the lowest ranks of global electricity generation using renewable energy. Ocean thermal energy production may have much larger potential in terms of sea water availability in comparison to other forms of renewable energy.

Water

Water scarcity already affects every continent. Around 1.2bn people (almost one-fifth of the world's population) live in areas of physical scarcity of water, and 500m people are currently approaching this situation. Another 1.6bn people face a water shortage because countries lack the necessary infrastructure to pump water from rivers and aquifers (UNDP 2006, United Nations (UN) Water, 2007). As of October 2014, ~700m people in 43 countries suffer from water scarcity. By 2025, 1.8bn people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population (~5.5bn people) could be living under water-stressed conditions. By 2030, almost half the world's population will regionally face high water deprivation, including as many as 250m people in Africa. This water scarcity in some arid and semi-arid places will displace between 24 and 700m people in the next decades [United Nations Educational Scientific and Cultural Organization (UNESCO) 2012]. In addition, food production will be affected by the water scarcity because each calorie consumed as food requires ~1 L of water to produce. In this paper, however, the authors restricted themselves to issues related to water and energy only.

Desalination

In just 45 years, the desalination industry has grown from virtually 0 to ~60m tons of treated water per day (Desalination.com). Desalination uses either thermal or membrane technologies, and historically its market has been led by brackish water plants in the USA and sea water plants in the Gulf states. The USA has led the membrane market, while Saudi Arabia and the United Arab Emirates (UAE) have led the thermal market. Membrane technologies include reverse osmosis (RO), electrodeionization, and electrodialysis; and (advanced) thermal technologies include multiple-effect distillation and multi-stage flash evaporation (MSF). Desalination programs in Spain, UAE, Algeria, Australia, and Spain have now peaked, and future growth is expected to come from countries such as China, South Africa, and Chile. Membrane desalination has grown rapidly since 2003, and despite expectations of decline, thermal desalination also continues to grow (Borsani 2009). Since 2003, the demand for large sea water desalination plants has grown significantly, and sea water now accounts for almost two-thirds of all feed water for desalination. Ras Azzour (recently renamed Ras Al Khair) in Saudi Arabia has world's largest desalting capacity using MSF-RO hybrid technologies, and the Sorek plant (located ~15 km south of Tel Aviv, Israel) uses RO technology for sea water desalting with capacity of 624 000 m^3/day (currently the world's largest plant using membrane technology).

Ocean thermal energy conversion (OTEC)

As implied in the previous sections, depletion and scarcity of FEW are primarily ascribed to the increase in world population and intense energy demand over the gradual increase in the natural resources. The specific heat of water ($4{\cdot}18\ kJ\ kg^{-1}$°C) is about three times higher than that of soil ($1{\cdot}48\ kJ\ kg^{-1}$°C), and two-thirds of the earth's surface is covered by the ocean. The heat capacity of the entire ocean is, therefore, almost one order higher than that of the land. Most solar energy is absorbed by a thin layer of the ocean surface because sunlight cannot penetrate sea water below 200 m. As a consequence, the deep sea water temperature is maintained at 4–8°C at 600–1000 m depth. When warm surface and cold deep sea water have at least a 20°C temperature difference, electric power and fresh water can be produced using the thermal energy gradient. This technique is called ocean thermal energy conversion (OTEC), having open, closed, and hybrid thermal cycles (Yeh *et al.* 2005). Open cycle (OC)-OTEC maintains the flash evaporator at a very low (close to vacuum) pressure to evaporate warm surface sea water. The steam rotates the turbine, generates electric power, and finally condenses at the same rate of evaporation (Nakamura *et al.* 2009). The condensation generates desalinated water, which is ~0.5–0.6% by volume of the incoming warm surface sea water (Mutair and Ikegami 2014). Closed cycle (CC)-OTEC uses surface and deep sea water for heating and cooling of (organic) working fluids, respectively, during the cycle of periodic phase transformations (Faizal and Ahmed 2013; Aydin *et al.* 2014; Yang and Yeh 2014). Hybrid cycle (HC)-OTEC is a sequential link of CC- and OC-OTEC to use advantages of high power production and desalting capability, respectively (Magesh 2010). Because the desalination of HC-OTEC uses the leftover thermal energy after power generation of (front) CC-OTEC unit, the fresh water production rate is not as high as that of standard OC-OTEC. Historically, most research was conducted on CC-OTEC for power generation only. This is because of the lower power generation rate of OC-OTEC than that of CC-OTEC and inferior desalination capacity of HC-OTEC to that of OC-OTEC (Yoon *et al.* 2014a).

OC-OTEC

The OTEC history in fact originated from Jules Verne's science fiction, '20,000 Leagues under the Sea' published in 1870. In the novel, short dialogs between Captain Nemo and his servant Conseil are as follows:

> Servant Conseil: I was determined to seek from the sea alone the means of producing my electricity.
>
> Captain Nemo: From the sea?
>
> Servant Conseil: Yes, Professor, and I was at no loss to find these means. It would have been possible, by establishing a circuit between two wires plunged to different depths, to obtain electricity by the difference of temperature to which they would have been exposed.In reality, OC-OTEC was invented by French physicist Dr d'Arsonval (D'Arsonal 1881)

and further developed by his former student, Dr Claude, whose technical work is chronologically summarized as follows.

In 1881, Dr d'Arsonval proposed the fundamental idea of OTEC (D'Arsonal 1881), but in the same year, the first thermal power plant started in the USA and received more public attention.

- In November 15, 1926, Drs Claude and Boucherat (Dr d'Arsonval's former students) actualized the OTEC idea by performing a public experiment at the French Academy of Sciences.
  - They used one flask filled with ice cubes and the other with 25 L of 28°C warm water. Initial release of air decreased the gas pressure in the flasks and drove the warm water to evaporate and migrate to another flask of ice cubes. This steam flow rotated a turbine of 15 cm diameter at a speed of 5000 rpm, and turned on lights for three electric lamps. This batch experiment ended after 8–10 min.
- In 1926, Claude's first experimental OTEC sites were selected at Matanzas Bay, Cuba.
- In 1929, the first installation of 1.6 m in diameter pipes that were 2 km long failed because of pipe integrity problems, and in 1930 the second failure happened.
- In 1930, Claude did generate 22 kW of electric power for 10 days using a 14°C temperature difference. (In our opinion, this can be regarded as the first successful demonstration of the real-scale OC-OTEC process although the duration is short.)
- In 1933, Claude converted a 10 000 ton cargo ship, called Tunisie, to an OTEC-installed ship and sailed to Brazil for OC-OTEC operation. This ship sank and the units for offshore power generation were lost.
- In 1940, the Abidjan project was proposed by Claude, and the French government set up the 'Energie des Mers' (Energy from the Sea) project.
- In 1955, the Abidjan project was abandoned because large amounts of inexpensive oil became available in the 1950s.
- In 1960, Claude passed away.

  In 1964, Anderson revised Claude's original OC-OTEC design and applied for a US patent on a 'Sea Water Power Plant' (Anderson and Anderson 1967; Takahashi 2000).
  - Anderson proposed to use an organic working fluid (such as ammonia) of low boiling point in a confined loop (Wang *et al.* 2008). This new scheme is called CC-OTEC.
- In 1979, an offshore CC-OTEC barge plant, called Mini-OTEC, was built in Hawaii, USA, and successfully operated for 3 months (Steinbach 1982).

In the early 1990s, Natural Energy Laboratory of Hawaii Authority (NELHA) developed a real OC-OTEC plant of 210 kW that continuously operated for 5 years (1993–1998), which is based on a conceptual design proposed in 1990 (Bharathan *et al.* 1990).

Recently, Energy Island Ltd designed a 1.8-MW OC-OTEC plant (Energy Island Ltd.).

Current research activities at NELHA include efficiency enhancement of condensing heat exchanger of a 5-MW OC-OTEC plant (Vega 2014) and a new conceptual design of OC-OTEC (Bharathan *et al.* 1990) to generate 80 MW of power and 118 400 m^3 day^{-1} of fresh water by using five modules of 16 MW OC-OTEC (Vega 2010a) with economic analysis (Vega 2010b).

CC-OTEC

Anderson specifically pointed out three basic problems of Claude's original ideal (Anderson and Anderson 1967; Takahashi 2000), which are

1. huge scale and big cost
2. release of non-condensible gases from input sea water, and
3. extraordinarily long (high pressure) pipe that takes in cold deep sea water.

Because of the high thermal efficiency of the Rankin cycle, CC-OTEC is preferred over OC-OTEC (Masutani and Takahashi 1993). The working fluid undergoes periodic phase transformations of alternating boiling and condensing phenomena in the closed thermal loop under high pressure. Therefore, CC-OTEC requires much smaller scale than that of OC-OTEC. The non-condensible gas in OC-OTEC may cause unexpected pressure fluctuations in the flash evaporator, which can nevertheless be minimized by using multiple pressure sensors and automatic adjustment of the pressure in the evaporator using a narrow range. The third problem above regarding the long pipe length to take in deep sea water cannot be resolved by switching from OC-OTEC to CC-OTEC. Owing to the low temperature and high density of the discharged cold deep sea water, its influence on the ambient environment and local variations of sea surface temperature and nutrient level may be problematic [Office of Ocean & Coastal Resource Management National Ocean and Atmospherice Administrations (NOAA) 1986; Comfort and Vega 2011]. In CC-OTEC, the organic working fluids having higher boiling points than water are used during steady cycles (if not leaking). Most widely used organic working fluids include ammonia, R22, R134a, and R32 [Yoon *et al.* 2014b; Environmental Protection Agency (EPA)]. Care needs to be taken in handling ammonia because of its flammability and toxicity. R22 and R134a are synthetic organic compounds, which may cause deleterious effects if exposed to the environment. R22 has high global warming potential (GWP) of 1700 (which indicates 1700 times as powerful as carbon dioxide). Its usage will be, therefore, stopped by 2020, as determined in the Montreal Protocol (in 1989) on substances that deplete the ozone layer. R134a also has high GWP of 1300. R32 is widely used because of its low ozone depletion potential, 0.055, among the lowest for chlorine-containing haloalkanes, but is no longer considered acceptable because of its GWP of 650. Because of these potentially serious environmental influences of the organic working fluid (i.e. a trade-off of their high efficiency), developing policies and strategies for leaks requires immediate attention. One can use mixtures of conventional working fluids (Yoon *et al.* 2014c; Lee *et al.* 2014) to resolve the environmental concerns and to increase the efficiency. A composition ratio of the mixed working fluid needs to be kept unchanged during Rankin cycles of the CC-OTEC. Once there is a leak, not only the leakage but also the changed composition ratio require full replacement of the working fluid. Although CC-OTEC generates electricity more efficiently than OC-OTEC, safe operation of the working fluid becomes a critical issue so that immediate attention must be paid to leak prevention methods as well as cleaning strategies if there is a leak.

HC-OTEC

Recently, HC-OTEC was proposed as a sequential link of CC- to OC-OTEC units (Yeh *et al.* 2005). A standard

CC-OTEC system is designed as a stand-alone plant. Discharged warm sea water, after boiling the organic working fluid, still has extra thermal energy, and the cold sea water used for condensing the hot working fluid has a temperature much lower than that of the surface sea water. The temperature difference between these two discharged warm and cold streams is $\sim 10°C$, which is typically higher than the temperature difference between the turbine-exiting steam and the input cold sea water for OC-OTEC (Yeh *et al.* 2005). Therefore, this HC-OTEC can increase the desalination rate per cold deep sea water intake than that of OC-OTEC. However, the absolute temperature difference, 10°C, for HC-OTEC desalination is essentially low so that the desalination rate increases only marginally. Despite the fact that CC- and HC-OTEC can produce more electric power than that of OC-OTEC, both technologies use organic working fluids, which raises the serious environmental concerns as described above.

Membrane distillation (MD)

Membrane distillation is a type of membrane contactor in which the membrane is used as a physical barrier between multiple phases. Physico-chemical characteristics of membrane material include pore size (O (0.1–1) μm), membrane thickness (O (10–100) μm), hydrophobicity, and thermal conductivity. Across the porous membrane (of flat sheet or hollow fiber types), hot feed and cold distillate (permeate) streams provide a transmembrane temperature gradient for evaporation and condensation, respectively.

Direct contact membrane distillation (DCMD)

In direct contact membrane distillation (DCMD), hot feed and cold permeate (distillate) streams flow in parallel, having contact with membrane surfaces. Flow directions are usually opposite (i.e. counter-current) to maintain a pseudo-constant temperature gradient along the longitudinal direction of the membrane. Temperatures of the hot feed and cold distillate range from 40°C to 80°C and from 10°C to 20°C, respectively. The interstitial porous spaces in the membrane region are maintained at 1.0 atm of mixed gas phase. Water evaporates on the feed/membrane interface, migrates through the pore spaces, and condenses at the membrane/distillate interface. Among other MD processes, DCMD is the most used configuration, especially for desalination of sea water and brackish water. The heat transferred by conduction through the membrane – considered as heat lost in MD – is, however, (much) higher than in any other MD configurations (Kim 2013). Applications of DCMD are very wide, which can be found elsewhere (Khayet and Matsuura 2011).

Air gap membrane distillation (AGMD)

Air gap membrane distillation has a similar set-up on the feed-membrane side to that of DCMD, but replaces the distillate flow by a cold solid wall close to (but not in contact with) the membrane surface. Vaporized water molecules diffuse through membrane pores, slowly condense, and form dew on the cold wall surface. No external condenser is necessary, but flux of water vapor, equivalent to the condensation rate, is the lowest among all types of MD types because of the stagnant concentration of vapor molecules between the membrane and the cold wall.

Air in the permeate side between the membrane and the condensing surface induces low conductive heat loss but increases mass transfer resistance leading to lower permeate flux. Moreover, the condensing surface must be placed inside the membrane module, which makes mechanical configuration of AGMD difficult. Air gap membrane distillation can be used for cogeneration (Kullab and Martin 2011) and also be applied to desalination and other processes such as concentration of fruit juices, treatment of aqueous alcohol, break-up of azeotropic mixtures, and isotope separation in aqueous solutions.

Sweep gas membrane distillation (SGMD)

Air flow is applied to the distillate side to enhance the mass transfer rate, which sweeps and carries the evaporated water molecules to an external condenser. This sweeping reduces vapor concentration to a certain level in the distillate side and keeps the concentration gradient high, i.e. the transmembrane driving force. In addition, the vapor-containing sweep gas needs to be compressed and liquified in an external condenser. Sweep gas membrane distillation can be used to treat aqueous solutions containing non-volatile salts such as NaCl and volatile solutes such as ammonia, alcohols (ethanol, isopropanol), and acetone.

Vacuum membrane distillation (VMD)

To further increase the evaporation rate of water at the feed/membrane interface, a pseudo-vacuum phase is applied to the distillate side which is connected to an external condenser. The gas entering the condenser contains mostly evaporated water molecules. This concentration is only a few percentage of that of SGMS and AGMD, of which gas phases are humid air. In other words, the resistance to the vapor flux across the membrane is much lower in VMD than that of any other MD applications under similar operational conditions. The vacuum phase is maintained by the air compressor connected to the external condenser. The driving force is proportional to the hot feed temperature and the saturation temperature in equilibrium with the vacuum pressure (e.g. 3% of the atmospheric pressure). One can easily adjust the distillate flux by changing the vacuum pressure in VMD, which is fundamentally equivalent to varying the cold permeate temperature in DCMD.

Selection of a specific MD type (among the four mentioned above) requires basic cost estimation. In principle, VMD and SGMD provide higher fluxes than those of DCMD and AGMD. However, pressure maintenance of the gas phases of VMD (and SGMD) and external condensation requires more energy consumption than those of DCMD and AGMD. In addition to comparing the performance of distillate flux, cost of the thermal resources must be evaluated with equal importance.

Advantages of VMD include very low resistances to heat and mass transfer. Owing to the insulation against conductive heat loss through the membrane, the thermal boundary layer in the vacuum side is negligible, which implies a decrease in the heat conduction through the membrane and enhancement of the VMD performance. Vacuum membrane distillation can be widely applied to physico-chemical processes such as extraction of volatile organic compounds, treatment of alcohol aqueous solutions, concentration of fruit juices and recovery of aroma compounds, desalination (possibly coupled with a solar energy collector), energy storage system, and the regeneration of liquid desiccant solutions.

Convergence of MD and OTEC

Why OC-OTEC and what to resolve

Membrane distillation, in general, evaporates hot feed solution for (solvent) extraction and OTEC uses working fluids for power generation. The VMD and OC-OTEC have close similarity as their driving force is the difference between vapor pressure of hot feed and vacuum pressure (usually, a few percentage of the atmospheric pressure). As Anderson indicated (Anderson and Anderson 1967), an OC-OTEC plant is an extraordinarily large system, which requires high initial cost for construction and operation. For example, the original design of 207 kW OC-OTEC plant has the system volume of ~ 10 m in diameter and 20 m in height (Bharathan *et al.* 1990). The net volume for evaporation only is about a quarter of the total volume. The recently designed 1.8 MW unit includes a huge evaporator of 9.2 m in diameter and 20 m in height (Energy Island Ltd, London, UK). This enormous size requires very high initial investment and civil engineering scale design, which significantly hampers the feasibility and portability of the technology. Details about correlations between OTEC capacity and costs can be found elsewhere (Vega 2012).

The authors compare the original OC-OTEC design of 207 kW (Bharathan *et al.* 1990) and two recent designs of 1.8 and 50 MW (Energy Island Ltd., Vega 2010b). In the three designs, mass fractions of evaporated water to inputted warm sea water are calculated as $0.55864 \pm 0.00518\%$, the deviation stemming from the (slightly) different vacuum pressures set to be 2.61 kPa for the original and 2.76 kPa for two recent designs. The (almost) constant mass ratio implies the linearity between the power production rate and the evaporator capacity. Steady availability of warm surface and cold deep sea water is a critical factor for practical implementation of OC-OTEC. Rajagopalan and Nihous (2013a, b) used an ocean general circulation model to assess global OTEC resources to calculate that an achievable OTEC net power production is annually ~ 7 TW. As expected, regions of high OTEC potential reside near the equator between latitude 30°S and 30°N. Installation and operation of OTEC plants in these regions require international collaboration between countries having advanced OTEC technology such as USA, Korea, and Japan, and beneficiary countries such as Fiji and Kiribati in the Pacific region. Initial construction of an offshore OTEC site requires enormous efforts for shipping and handling of individual components to be assembled on site. Another possibility to avoid the assembling task is to build an on-ship plant using Claude's original idea, by installing all the components on an OTEC ship and delivering the ship to a site. The mobility of this ship significantly reduces the initial shipping and handling costs because the ship will be built in a technologically advanced country and sent to a specific OTEC site (belonging to beneficiary countries). Reduction of the on-ship OC-OTEC plant size is a critical issue given the design performance and budget for the initial installation and operation. As the OC-OTEC needs a sea surface temperature (possibly) close to 30°C, if the system is prepared on a smaller scale, prompt installation and exporting delivery of the technology can be much more cost-effective with high mobility of the on-ship plant.

Application of VMD to OC-OTEC

The authors propose to replace the huge flash evaporator by a smaller VMD modular set because system size is a critical factor for investment, installation, and operation in the initial design stage. As indicated above, the 1.8-MW scale OC-OTEC plant requires an evaporator volume of $V = \frac{\pi}{4}(9.2\,\mathrm{m})^2 \times 20\,\mathrm{m} = 1330\,\mathrm{m}^3$, which is approximately one-third of the volume of an olympic-sized swimming pool. If one can significantly reduce the system volume and enhance the evaporation performance, then the cost-effectiveness of OC-OTEC will noticeably increase. Wherever the temperature difference is $\geqslant 20$°C between the surface and deep sea water, electric power and fresh water can be produced at less expensive production costs.

The authors estimate the total system volume required for VMD to provide the same amount of steam flowrate, $\dot{m}_{\mathrm{st}}$, of OC-OTEC:

$$\dot{m}_{\mathrm{st}} = A_{\mathrm{m}} J_{\mathrm{VMD}} = \rho_{\mathrm{pack}} V_{\mathrm{VMD}} J_{\mathrm{VMD}} \tag{1}$$

where A_{m} is total membrane surface area, J_{VMD} is the vapor flux of VMD, i.e. the evaporation/condensation rate per membrane surface, ρ_{pack} is the packing density of VMD membranes (membrane surface area per unit volume), and V_{VMD} is the spatial volume required to install a number of VMD vessels. A packing fraction of hollow fiber membranes in a vessel of diameter D_{vsl} and length L is

$$\varphi_{\mathrm{hf}} = N_{\mathrm{f}} \left(\frac{d_{\mathrm{hf}}}{D_{\mathrm{vsl}}} \right)^2 \tag{2}$$

where d_{hf} is the representative (outer) diameter of a hollow fiber, and N_{f} is the number of hollow fibers in a vessel. Then, the packing density, defined as the total membrane surface area per unit vessel volume, is calculated as

$$\rho_{\mathrm{hf,pack}} = \frac{4\varphi_{\mathrm{hf}}}{d_{\mathrm{hf}}} \tag{3}$$

and furthermore

$$\rho_{\mathrm{pack}} = \varphi_{\mathrm{vsl}} \rho_{\mathrm{hf,\,pack}} = \frac{4\varphi_{\mathrm{vsl}}\varphi_{\mathrm{hf}}}{d_{\mathrm{hf}}} \approx \frac{1}{d_{\mathrm{hf}}} \tag{4}$$

where reasonable values of $\varphi_{\mathrm{vsl}} \sim \varphi_{\mathrm{hf}} \sim 0.5$ are assumed. Substituting equation (4) into equation (1) gives a simple relationship:

$$V_{\mathrm{VMD}} \approx \frac{\dot{m}_{\mathrm{st}} d_{\mathrm{hf}}}{J_{\mathrm{VMD}}} \tag{5}$$

In the conventional OC-OTEC, surface sea water is sprayed in the evaporator to provide small water drops that migrate vertically, and water molecules evaporate from the surfaces of moving water drops. For example, the 1.8 MW OC-OTEC plant is designed to generate 33.4 kg s^{-1} of steam flowrate, using an evaporator of volume 1330 m^3. If the authors use hollow fibers of outer diameter $d_{\mathrm{hf}} = 1$ mm and assume a VMD flux of an order of $J_{VMD} = 1.0$ L m^{-2} h, then the volume required to install VMD modules is $V_{VMD} = 120$ m^3, which is <10% of the conventional evaporator volume. This confirms that the steam production rate is linearly proportional to the evaporator volume. In our opinion, the volume reduction down to 10% can make the OC-OTEC technology much more attractive and practical.

Technical tasks

To replace the flash evaporator by a smaller VMD modular set, several problems need to be solved:

1. *Physical* properties of membrane materials need to be specially designed for given conditions of OC-OTEC in terms of pseudo-invariant temperatures and flowrates of the warm and cold sea water.
2. *Modular* geometry should be specifically designed based on the constant operational conditions.
3. *Chemical* properties of the novel membrane, such as hydrophobicity, need to be well adjusted to maintain organic fouling at lower levels.

Physical

The VMD applied to OTEC differs from the standard VMD for solvent extraction in terms of the semi-fixed operational conditions. The feed stream taken in from the ocean surface has a narrow temperature variation ranging from 25°C to 30°C, which is determined by the ambient temperature during operation. In the flash evaporator, the vacuum pressure should be set below the vapor pressure of the feed sea water temperature, e.g. ⩽0.01 atm. (Note that the saturation pressure at 25°C is 0.03 atm.) To maximize the steam generation rate, the microstructure of hollow fiber membranes needs to be optimized in terms of pore size, tortuousity, and thickness as used to treat feed sea water of temperature from 25°C to 30°C. The membrane length is another critical factor because the average thermal driving force decreases with respect to the net distance that the distillate flow travels along the membrane. In DCMD, membrane wetting is a serious problem, which refers to the direct passage of feed solution through membrane pores without evaporation, which can be regarded as a microfluidic Hagen–Poiseuille's flow. Integrity failure of a few fibers in a bundle causes noticeable membrane wetting, which results in rejection ratio decrease. However, in VMD for OC-OTEC, the wetting potential is not deleteriously problematic even if the membrane consists of large pores, susceptible to the microfluidic viscous flow. This is because only evaporated steam enters the turbine and condensers for power generation and sea water desalination. When the wetting occurs in VMD, the sea water that flows through the membrane can undergo secondary evaporation within the vessel or be drained occasionally. To allow for a fractional loss of VMD hollow fibers because of wetting, the membrane material needs to be specially designed for maximum flux when evaporating 25–30°C warm sea water. Moreover, the packing scheme of hollow fibers, either random or supervised, and the geometrical module configuration must be coherently designed with microscopic characteristics of the membrane material.

Modular

High flux may be reached by an optimal combination of microscopic and macroscopic properties of membranes. Two orthogonal length scales are important: one parallel to and another perpendicular to the aligned flow directions (usually counter-current). For example, in the hollow fiber MD module, the lumen and shell flows along a fiber are parallel to each other near the membrane interfaces. When the produced steam is pumped out of the vessel and sent to an external condenser, the vapor gas flows in the transverse direction to a number of aligned, packed fibers. The transverse packing structure determines a macroscopic mass transfer resistance within a vessel, which contributes to additional energy consumption to maintain the vacuum as related to vapor condensation. The same analysis can be applied to flat sheet type VMD, where the average length traveled by the vapor gas (on the distillate side) is proportional to the macroscopic mass and heat transfer resistances.

Chemical

The most challenging task of sea water MD for OTEC is fouling prevention or minimization. Typical fouling types are inorganic/colloidal, organic, and biological, of which recent critical review can be found elsewhere (Tijing *et al.* 2014; Warsinger *et al.* 2015). Advantages of VMD-OTEC include familiarity to feed (sea water) chemical compositions and their invariance to ambient temperature. Inorganic fouling refers to the deposition of precipitated salts and hard minerals onto the active membrane surface. High feed concentration followed by excessive evaporation can form a scale-deposit layer when the concentration products surpass the solubility limit (Alklaibi and Lior 2005; He *et al.* 2008). This inorganic scaling significantly deteriorates the membrane performance of large systems (Gryta *et al.* 2006). In addition, sub-micrometer-sized colloidal particles such as silica, silt, and clays can block and plug membrane pores and form a cake layer covering the membrane surfaces. For DCMD, Song *et al.* (2008) reported that stable vapor flux and high water recovery were obtained when (real and synthesized) sea water of high concentration was used as a feed solution. On the other hand, Hsu *et al.* (2002) emphasized the importance of pretreatment for real sea water feed. For VMD, Mericq *et al.* (2010) indicated that inorganic (and organic) fouling depend on specific feed water composition and concentration, and Mericq *et al.* (2010)showed that scaling minimally influences the distillate flux. The above observations are somewhat incongruous to derive a universal conclusion on inorganic fouling because of sea water chemistry and temperature, but implies some possibility to minimize and possibly prevent inorganic fouling on VMD membrane surfaces. Organic fouling is the adsorption/deposition of dissolved and colloidal organic materials on the membrane surface, which is difficult to remove without the use of chemical cleaning agents (Tijing *et al.* 2006). The degree of organic fouling depends on foulant types and their interactions with the hydrophobic membrane (Naidu *et al.* 2014). In addition, some foulants can penetrate into both virgin and superhydrophobic membranes even without the occurrence of partial pore wetting (Meng *et al.* 2014). The high membrane hydrophobicity to resist wetting may enhance organic fouling by feed sea water. Information of invariant sea water compositions should be used in the design stage of optimal membrane materials for the combined VMD–OTEC process. In addition, biological fouling (or biofouling) is the accumulation biological species followed by their growth on the membrane surface. Its occurrence in MD processes may be limited because of the chemical and hydrodynamic conditions of the feed, which hinder microorganism growth (Krivorot *et al.* 2011; Gryta 2002). The above experimental investigations provide clear insights on MD fouling because of physical, chemical, and biological characteristics of warm surface sea water. It seems that a microfiltration-type prefilter is necessary in front of the VMD unit to remove (large) particulate matter in the feed stream. Systematic research is required to identify specific fouling behaviors of regional sea water on VMD membranes.

Economic perspective

An economic analysis of the VMD–OTEC here is based on our previous technical work for a new conceptual design [Korea Research Institute of Ships and Ocean Engineering (KRISO) 2014]. The platform structure of an on-ship OC-OTEC plant consists of four decks: (1) a winch, crane, and helideck on the top deck; (2) a residential area on the second deck; (3) an OC-OTEC system on the third deck; and (4) an intake pump system on the fourth deck. The equipment installed on the third deck includes a flash evaporator, which takes 33.3% of the deck area. If the evaporator is replaced by a VMD modular set, the required equipment volume would decrease to 10.0%. In this case, the second, third, and fourth decks can be redesigned to decrease the manufacturing cost by 7.9%, which will also reduce the initial investment by 2.5% and the electricity cost for end-users by 2.08%.

In addition, enhanced evaporator efficiency can decrease the flowrates of warm and cold sea water and also reduce costs for the pipe system installation and maintenance. Intake and discharged warm sea water have only minor changes in salinity and temperature. Salt concentration increases only 0.5–0.6% and temperature decreases by 1–2°C. On the other hand, the cold deep sea water enters the OTEC system with a temperature of 5–7°C and leaves with a temperature close to 10°C. This discharged cold sea water has at least a 10°C temperature difference from the ambient surface sea water. In general, water density slightly changes from 997.075 kg m^{-3} at 25°C to 999.999 kg m^{-3} at 4°C, but water viscosity increases 76% from 0.891 N s m^{-2} (at 25°C) to 1.569 N s m^{-2} (at 4°C). Direct discharge of the deep sea water to the ambient ocean can change the physical characteristics of local surface sea water near the on-ship OTEC plant. This may negatively influence OTEC performance because the power production rate is (very) sensitive to the surface sea water temperature. Our conceptual design indicates that as the surface temperature decreases by 0.10°C, $\sim$25 kg s^{-1} less cold deep sea water is required for condensation, but power production decreases by 15.2 kW. To recover the same power generation rate, 6·4 kg s^{-1} of deep sea water should be additionally pumped in. Note that this deep sea water discharge is a precedented issue of OC-OTEC, not caused by VMD application but possibly mitigated by using VMD instead of the conventional flash evaporator. Therefore, unsupervised discharge of the surface and deep sea water may cause performance reduction and pumping cost increases. Environmental monitoring using a sensor network is required to continually check the feed conditions. In contrast, an enhanced evaporation rate (possibly using VMD) can minimize the overall plant size by optimally re-integrating system components and therefore reduce costs for system maintenance and monitoring. Specific calculation of electricity costs requires more detailed system design and operational parameters, but overall electric costs, to the best of our knowledge, can decrease by $>$2.1%.

Concluding remarks

The authors investigated the feasibility of replacing the conventional flash evaporator of an OC-OTEC plant by a smaller VMD modular set. A promising perspective shows that the VMD module requires only $\sim$10% of the volume of a conventional evaporator, which reduces the entire plant size by 30% and the electricity cost by 2.1%. For VMD to be more advantageous for OC-OTEC, three major tasks need to be carried out: (1) development of tailored, optimized functional membranes for sea water VMD; (2) coherent design of MD system from microscopic membrane characteristics to macroscopic modular and system designs; and (3) specific identification and adequate control and prevention of fouling phenomena. Upon completion of the above core tasks, VMD-OTEC can significantly contribute to energy and water supplies with good quality and availability. Regions and nations near the equator can benefit the most because of easy access to warm surface and cold deep sea water, providing generation of electricity and fresh water.

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