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# A novel conceptual design of hydrate based desalination (HyDesal) process by utilizing LNG cold energy

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## HIGHLIGHTS

- A novel hydrate based desalination process by utilizing LNG cold energy is proposed.
- The optimal heat exchanger network is obtained by using a mathematical model.
- The specific energy consumption of the proposed process is 0.84 kWh/$m^3$ of potable water.
- 1000 kg/h of LNG can produce 1.29 $m^3$/h of potable water with 40% of water recovery rate.
- The process can desalinate high concentration brines with low specific energy consumption.

## ARTICLE INFO

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## ABSTRACT

Liquefied Natural Gas (LNG) is the best mode to transport natural gas from producing locations to importing countries when pipeline transport is not feasible. LNG industry has seen a phenomenal growth due to the widespread adoption of natural gas as a clean fuel. There is an ongoing effort to develop new technologies that can utilize LNG cold energy which is mostly being wasted at the LNG regasification terminals around the world. This work presents a novel conceptual design for a clathrate hydrate based desalination (HyDesal) process by utilizing LNG cold energy (ColdEn-HyDesal). This ColdEn-HyDesal process overcomes the high energy consumption of the traditional HyDesal process by using the cold energy of LNG to replace the external refrigeration cycle. An optimal heat exchanger network for the ColdEn-HyDesal process is obtained by employing mathematical programming based heat integration methodology for the LNG flow rate of 1000 kg/h in an LNG regasification terminal. The results indicate that the specific energy consumption (SEC) of the HyDesal process is 65.29 kWh/$m^3$ of potable water, while that of the ColdEn-HyDesal process is only 0.60 kWh/$m^3$ when the hydrate former is not recycled. When the hydrate former is recycled, then the specific energy consumption of the HyDesal process is 65.13 kWh/$m^3$, while that of the ColdEn-HyDesal process is only 0.84 kWh/$m^3$. In addition, the effects of recovery pressure, water recovery rate, and NaCl concentration in seawater on SEC and the volumetric rate of potable water are also analyzed and discussed. The results show that the SEC decreases substantially (27.42%) with the increase of water recovery from 40% to 70% in one hour. Further, the NaCl concentration in the feed has a small impact on the SEC, which only increases by 2.81% when the NaCl concentration increases from 3.5 wt% to 7.0 wt%. Thus, the ColdEn-HyDesal process is an energy efficient desalination process and can be a potential technology to desalinate seawater, and high concentration brines in an LNG regasification terminal.

## 1. Introduction

Due to the global population rise and industrial development, one of the most pervasive problems afflicting the human being is inadequate access to clean and fresh water [1]. More than 1.1 billion people are living in countries without access to clean drinking water [2], and the even larger population is suffering from the water-stressed situation. Water affects many aspects of our society, especially in health, energy, food production, agriculture and national safety. The ocean covers around 70.8% of the total surface area of our planet. However, 97% of the earth's total water resource is saline, and only around 3% is fresh water which is accessible to the human being and animals. Thus, in the last few decades, people are paying more attention to obtain fresh water from seawater. Desalination is a process to remove the mineral

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**Nomenclature**

*Symbols*

| | |
|---|---|
| *V* | volumetric flow rate [$m^3$/h] |
| *W* | energy consumption [kW] |

*Acronyms*

| | |
|---|---|
| B | brine |
| C | coolant/compressor |
| H | hydrate |
| HEX | heat exchanger |
| HF | hydrate former |
| IFV | intermediate fluid vaporizer |
| LNG | liquefied natural gas |
| ORV | open rack vaporizer |
| P | pump |
| PW | pure water |
| R | refrigerant |
| SCV | submerged combustion vaporizer |
| SEC | specific energy consumption |
| SW | seawater |
| V | valve |
| WR | water recovery |

components from seawater and is considered to be one of the most promising technologies to solve the freshwater scarcity. Several technologies of desalination have been proposed and developed in the past decades [1].

Desalination technologies are mainly classified into distillation, ion exchange, membrane process, freezing process and clathrate hydrate based process [3]. The commercial desalination plants are primarily based on multi-stage flash (MSF) distillation and reverse osmosis (RO) processes due to their reliability. Multi-stage flash (MSF) distillation desalination is a low water recovery process with high energy consumption. It is widely used in the Middle-East due to the lack of fresh water and local abundance of oil and gas. The water recovery of the MSF process is up to 20% [4], and the specific energy consumption is 13.5–25.5 kWh/$m^3$ depending on the operating conditions [5]. Its overall cost is 0.56–1.75 $/ton [6,7]. The reverse osmosis (RO) desalination process is a type of membrane process operating at very high pressure (50–80 bar). It is energy intensive and sensitive to impurities. Its water recovery is up to 55% [1] which is much higher than the MSF process. The specific energy consumption for the RO process varies between1.85–36.3 kWh/ $m^3$, and the overall cost is in the range of 0.45–0.66 $/ton [6,8].

The clathrate hydrate-based desalination (HyDesal) process was first proposed for seawater desalination in 1942 [9]. The HyDesal process is similar to the freeze desalination approach [10]. In the HyDesal process, water molecules create a structured cage (host lattice) around a guest gas/liquid atom at the appropriate temperature and pressure [11]. The hydrate formation excludes the dissolved ions and salts from the hydrate crystals [12]. Then the hydrate crystals can be easily separated from the brine solution using a solid-liquid separator. The hydrate crystals are then dissociated into fresh water and guest component by heat stimulation or pressure reduction. The majority of research on clathrate hydrate based desalination process was conducted in the 1960s and 1970s [13–18]. The performance of different hydrate formers such as propane [19,20], carbon dioxide [21–27], refrigerant [28–30], methane [31,32] and cyclopentane [33–35] for seawater desalination at the lab-scale was studied from the 1990s to present. Two pilot desalination plants based on the HyDesal process were built in Hawai and San Diego by Thermal energy systems [36–39]. They adopted R141b as the hydrate former with a formation temperature around 5.6 °C. The overall cost of produced water was around 0.46–0.52 $/ton. An optimal design approach of the gas hydrate and reverse osmosis hybrid desalination system was proposed by Lee et al. [40]. They used the gas hydrate desalination process as a pre-treatment of reverse osmosis process to reduce the specific energy consumption of the hybrid system, to make it comparable to seawater reverse osmosis. The results indicated that the specific energy consumption of the hybrid system was 2.1 kWh/$m^3$ with 1.5 kWh/$m^3$ of the gas hydrate specific energy consumption and 90% of gas hydrate salt rejection [40].

With some particular guest components, the hydrate formation temperature could be higher than the freezing point of water. However, it should be pointed out that the HyDesal process is still energy intensive due to its low-temperature operation and exothermic nature of the hydrate formation. The HyDesal process requires an external refrigeration cycle to cool the feed streams, i.e., seawater and hydrate former to a low temperature. In addition, the heat generated during the hydrate formation needs to be removed. The need for this refrigeration cycle makes the energy consumption of the HyDesal process fairly high. To reduce this energy consumption and improve the economic performance of the HyDesal process, utilizing waste cold energy is an innovative option. This approach will be suitable for countries that import a lot of natural gas in the form of LNG like Singapore, China, India, Japan, South Korea, etc.

Natural gas as one of the cleanest fossil fuel has been the fastest growing fossil fuels in the recent decades [41]. Liquefied natural gas contributes most of the global remote natural gas trade, which is obtained by cooling natural gas below −162 °C at the atmosphere pressure [42]. During the liquefaction, a considerable amount of cold energy has been stored in LNG. The cold energy in LNG is around 837 kJ/kg, which needs to be removed by supplying heat at the receiving end of the supply chain (markets) to convert liquid (−162 °C) to gas phase (15 °C). In LNG regasification terminals, LNG is usually heated in a vaporizer (open rack vaporizer (ORV), submerged combustion vaporizer (SCV), and intermediate fluid vaporizer (IFV)) using massive amounts of seawater [43,44]. In Singapore, about 40 tonnes of seawater is used to re-gasify 1 tonne of LNG, and this results in about 36% of the energy costs attributed to the seawater pumps in the process. This valuable cold energy is ejected into the ocean without utilization [45]. How to utilize LNG cold energy has become a significant problem both from environmental and economic aspects. The traditional ways of LNG cold energy recovery include electric power generation [46–50], carbon dioxide capture [51,52], air separation [53] and ice production, etc. [54,55].

In this paper, a novel conceptual design of a clathrate hydrate based desalination process by utilizing LNG cold energy (ColdEn-HyDesal) is first proposed. In the ColdEn-HyDesal process, the energy consumption could be reduced significantly making it a sustainable approach to strengthen the energy-water nexus as it is possible to use waste energy to produce industrial grade or potable grade water. Firstly, the ColdEn-HyDesal process is described in detail. Then, process integration and heat integration technologies are adopted to obtain the optimal process configuration. Later, the ColdEn-HyDesal process is compared with the traditional HyDesal process with external refrigeration cycle. Finally, three sensitivity analyses are conducted on the ColdEn-HyDesal process.

## 2. Process design basis

### 2.1. Hydrate based desalination technology

In this section, the clathrate hydrate based desalination technology