A new fresh water generation system under high vacuum degrees intensified by LNG cryogenic energy

Liu, M.; Wu, D.

DOI:
10.1016/j.egypro.2019.01.194

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 726–732

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

A new fresh water generation system under high vacuum degrees intensified by LNG cryogenic energy

Meixi Liu[a]*, Dawei Wu[a]

[a]*School of Engineering, Newcastle University, Armstrong Building, Newcastle upon Tyne, NE1 7RU, United Kingdom*

Abstract

With the widely-used for industry and the benefits for the environment, liquefied natural gas (LNG) has become a substitute marine fuel of oil. During LNG vaporization process, about 830kJ/kg cryogenic energy is released which can be utilized for domestic purposes on LNG powered vessels. This paper investigated a multi-stage condensers system which utilizes the low temperature and large amount of LNG cryogenic energy to condense the water steam. The simulation model is conducted in Siemens LMS Imagine. Lab AMESim in order to investigate the performance of the system in different conditions under higher vacuum degrees such as different temperature, different relative humidity, and different stages of condenser and so on. In addition, the spare part of cryogenic energy can be stored as cooling energy rather than wasting. The results show that the multi-stage condensers system can be used for any water steam under any conditions, increase the mass of fresh water and decrease the requirement capacity of LNG cryogenic energy.

Keywords: LNG; cryogenic energy; fresh water; multi-stage condenser;

1. Introduction

With the population growth and greenhouse gas emissions significant effects by fossil fuels combustion, liquefied natural gas (LNG) is becoming widely-used as a marine fuel because of its less volume under liquid phase and less emissions[1-3]. As recorded, there are 103 LNG fueled ships in service and 97 on order until April 2017 while there were 74 such vessels in service and 88 on order a year ago [4]. Until 2025, between 13 and 1963 LNG fueled ships

* Corresponding author. Tel.: +44(0)738 0500 075.
E-mail address: m.liu24@newcastle.ac.uk

10.1016/j.egypro.2019.01.194

will be built for deep sea shipping as Lloyd's Register (2012) predicted [5, 6]. When LNG is converted to NG in a LNG vaporizer for the marine engine, the required heat for LNG phase changing which is called cryogenic energy [1, 7, 8], around 830 kJ/kg, should be recovered for other applications such as separation process, seawater desalination, cold storage systems and power generation rather than wasting [1].

Either for ocean-going shipping line or coastal shipping line, fresh water is the most important source for domestic use and equipment, which makes the fresh water generator being one of the most necessary facilities on board. It has supplied large amounts of fresh water for cooking, drinking, showers, laundry and machines, produced at least 200 liters per day per person [9]. Nowadays, there are two kinds of fresh water generator on board: RO and thermal distillation. Because of RO's higher sensitivity to the inlet water quality, lower water purity, higher energy consumption, higher chemicals consumption, more skilled personnel requirement and higher costs, the most commonly used method on board is still evaporative distillation. In order to achieve the higher standard drinking water and consume less energy, more companies have paid attention on how to promote the fresh water generator by installing new heat exchangers as evaporator and condenser on board such as Alfa Laval and Wartsila. Also, much more research has focused on improving the system by utilizing sustainable energy sources such as solar power and recoverable energy such as waste heat and waste cryogenic energy.

During the evaporative distillation process, the seawater or the condenser has been the most widely-used technology for condensation. Zhi-jiang Jin et al. [10] introduced a siphon flash evaporation desalination system using ocean thermal energy to supplement the condenser. However, limited studies have been conducted on how to utilize the same low temperature LNG cryogenic energy which has been utilized as cooling fluid for other applications for evaporation distillation process on board. In addition, it is hard for water steam to be condensed completely in the condenser in a few seconds because of the water steam conditions and the condenser characteristics. Therefore, this paper investigates a multi-stage condensers system as shown in Fig. 1 which utilizes the low temperature and large amount of LNG cryogenic energy to condense the water steam rather than wasting in counter flow. The simulation model is conducted in Siemens LMS Imagine. Lab AMESim in order to explore the performance of the system in different conditions under higher vacuum degrees such as different temperature, different relative humidity, and different stages of condenser and so on.

Nomenclature

ah_{in}	The moist air inlet absolute humidity, kg_{vapour}/kg_{dry}
ah_{out}	The moist air outlet absolute humidity, kg_{vapour}/kg_{dry}
ah_{pipe}	The moist air absolute humidity at pipe temperature, kg_{vapour}/kg_{dry}
A	The moist air cross sectional area, m^2
C_a	The convective heat exchange area, m^2
h	The heat transfer, W
h_{conv}	The heat transfer coefficient, $W/m^2/K$
h_{max}	The maximum heat transfer, W
hv	The latent vaporization heat of water, J/kg
m_{cond}	The fresh water production, kg/s
m_{dry}	The dry air mass flow rate, kg/s
$m_{s,in}$	The inlet moist air mass flow rate per unit of surface, kg/s
$m_{s,out}$	The outlet moist air mass flow rate per unit of surface, kg/s
T_{pipe}	The pipe temperature, $degC$
T_{in}	The inlet moist air temperature, $degC$

2. Analysis

Based on the calculation results shown in the Fig. 2(a) and (b), more water steam exists under higher temperature and higher vacuum degrees. The reason is that the water steam partial pressure covers the most of the air parcel pressure with low pressure and higher temperature. Therefore, the water steam with higher temperature and higher vacuum degrees will promote the fresh water production. Even under lower pressure conditions, some air still exists in the chamber which will affect the pressure of the water steam, the water steam and the air in the condenser is assumed as moist air. The condensing temperature of the moist air is increased with the increasing of the relative humidity as shown in the Fig. 2(c). And when the relative humidity is below 45%, the condensing temperature is below 0 ℃ even under -50 ℃ which means that the lower temperature LNG cryogenic energy is feasible for condensing rather than conventional 10 ℃ cooling water even under only 0.01% relative humidity. In addition, limited capability of the one stage condenser in limited time narrows the fresh water production. And the counter flow between water steam and LNG will promote the heat exchange efficiency. Therefore, the system shown in Fig. 1 is proposed to overcome these problems and promote the fresh water production. It consists of a few stages to condense the moist air by LNG cryogenic energy in a counter flow under higher vacuum degrees after the seawater evaporated in the flash chamber.

This new system is modelled and analyzed with Siemens LMS Imagine. Lab AMESim for calculating the fresh water production. The moist air is considered as the water steam in the condenser, and the methane (CH_4) is considered as low temperature LNG. In addition, a few assumptions are made. Firstly, the entire system is sealed completely, and there is no gas leaking in any stage. Secondly, there is no non-condensable gas existing in the condenser. Thirdly, this model has neglected the initial unsteady-state influence. Although these are idealized conditions compared with the actual production, the model turns simplified based on these assumptions. The fresh water production is given by:

$$m_{cond} = m_{dry}(ah_{in} - ah_{out}) \quad (1)$$

$$m_{dry} = \frac{m_{s,in}A}{1+ah_{in}} \quad (2)$$

$$m_{s,out} = \frac{1+ah_{out}}{1+ah_{in}} m_{s,in} \quad (3)$$

$$ah_{out} = ah_{in} + \frac{h}{h_{max}}(ah_{pipe} - ah_{in}) \quad (4)$$

$$h = h_{conv}C_a\left(T_{pipe} - T_{in}\right) + m_{cond} \cdot hv \quad (5)$$

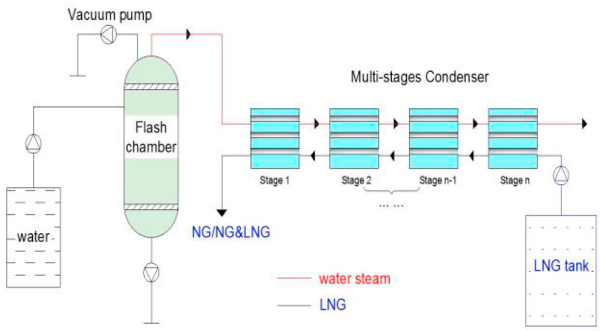


Fig. 1. The new system diagram

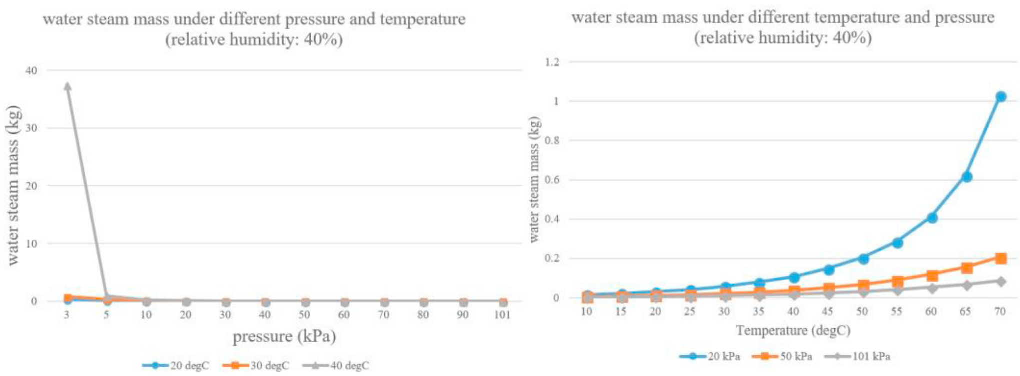
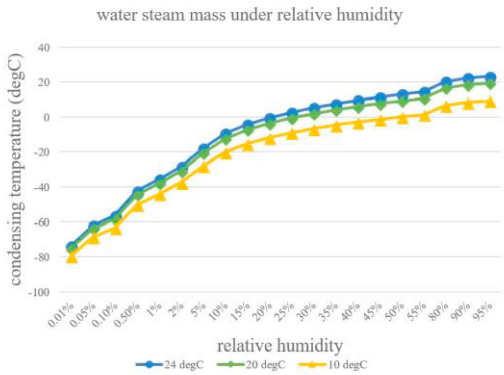


Fig. 2. (a) Water steam mass under different pressure Fig. 2. (b) Water steam mass under different temperature



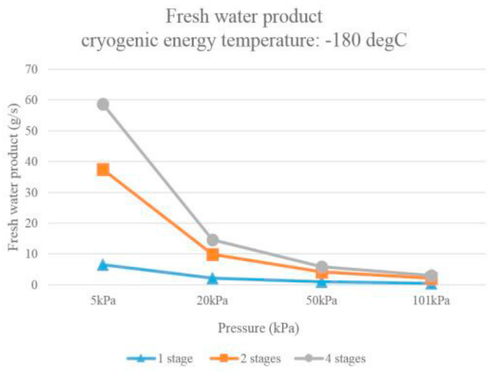


Fig. 2. (c) Condensing temperature under different relative humidity Fig. 3. Fresh water product under different stages

Table 1 presents the simulation operating parameters. The temperature range has been selected regarding the saturation temperature of the moist air. Therefore, there is only 10 ℃ existing under 5kPa, the reason is that when the pressure is 5kPa, the saturation temperature of the air parcel is less than 20℃. The saturation conditions under every operating condition is shown in Table 2. In order to explore the influencing factors, the LNG temperature is selected as -180℃. The temperature, the pressure of water steam and the water mass in the air parcel are main parameters on the fresh water product which are meaningful to explore the influence in the model. In addition, the capacity of LNG cryogenic energy is also required to be compared by investigating the LNG temperature range.

Table 1. Operating parameters.

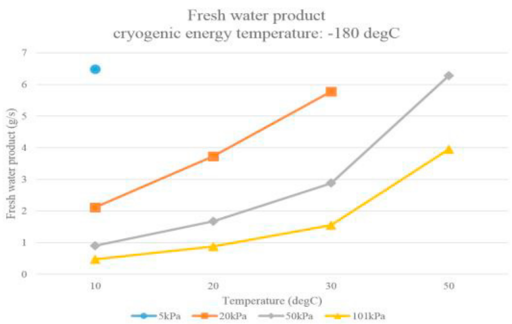
Figure	Number of stage	Pressure (kPa)	Temperature range (degC)	Relative humidity (%)	LNG mass flow rate (kg/s)	Simulation time (s)
Fig. 4.	1	5, 20, 50, 101	10, 20, 30, 50	40	0.2	10
Fig. 5.	2	5, 20, 50, 101	10, 20, 30, 50	40		
Fig. 6.	4	5, 20, 50, 101	10, 20, 30, 50	40		
Fig. 7.	1	5, 20, 50, 101	10	40, 80, 90		
Fig. 8.	2	5, 20, 50, 101	10	40, 80, 90		
Fig. 9.	4	5, 20, 50, 101	10	40, 80, 90		

Table 2. Saturation conditions of water steam.

Pressure (kPa)	Temperature (degC)	Saturation temperature (degC)	Saturation pressure (kPa)
5	10	32.9	1.227
5	20	32.9	2.337
5	30	32.9	4.243
20	10	60.0	1.227
20	20	60.0	2.337
20	30	60.0	4.243
20	50	60.0	12.340
50	10	81.3	1.227
50	20	81.3	2.337
50	30	81.3	4.243
50	50	81.3	12.340
101	10	100.0	1.227
101	20	100.0	2.337
101	30	100.0	4.243
101	50	100.0	12.340

3. Results

The multi-stage condensers system is evaluated by Siemens LMS Imagine. Lab AMESim to compare the presented simulation results with the previous moist air calculations. As been illustrated in the Fig. 3, compared with the 1 stage condenser and 2 stages condenser, the condenser with 4 stages under the same pressure creates more condensate. The multi-stage system creates different inlet and outlet heat exchange temperature between the LNG and the air parcel in every stage. And especially in the higher vacuum degrees, the 4 stages condenser will produce about 10 times than 1 stage. The reason could be found in the Fig. 2, under higher vacuum degrees, more water steam exists in the same mass of air parcel. Fig. 4-Fig. 6 presents that under the same temperature of LNG cryogenic energy, the water is produced more under higher water steam temperature. The reason is that as shown in Table 2 the temperature of the moist air is approaching to the saturation temperature. As is shown in Fig. 7-Fig. 9, the water is generated more under higher relative humidity. The results obtained from these figures present a good agreement with the previous calculations.



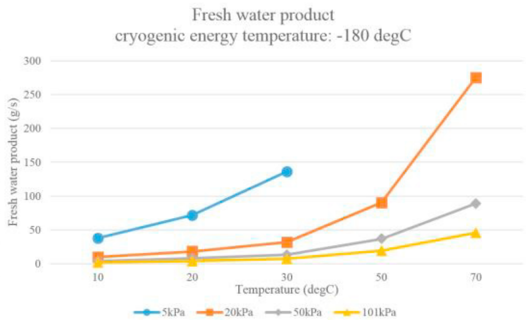
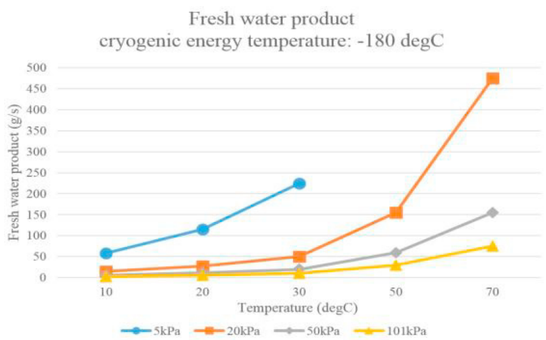


Fig. 4. Fresh water product under different temperature in 1 stage Fig. 5. Fresh water product under different temperature in 2 stages



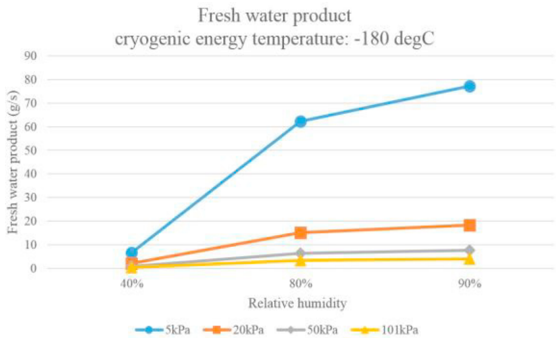
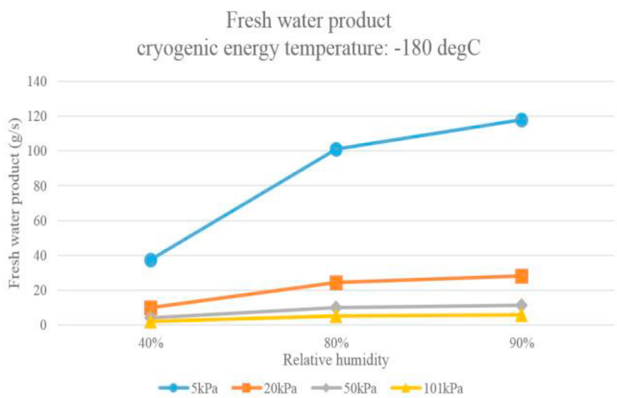


Fig. 6. Fresh water product under different temperature in 4 stages Fig. 7. Fresh water product under different relative humidity in 1 stage



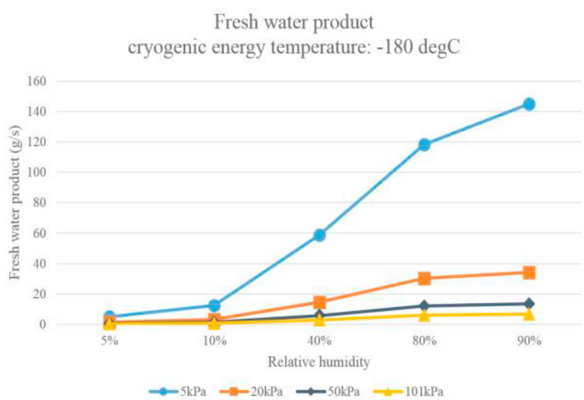


Fig. 8. Fresh water product under different relative humidity in 2 stages Fig. 9. Fresh water product under different relative humidity in 4 stages

In order to calculate the different capacity of LNG cryogenic energy required in the different stages, the range of LNG temperature for condensing is simulated to compare among the 1 stage condenser and 4 stages condensers. It can be seen from the Table 3- Table 7 below, under the same condition, the range of the LNG temperature in 1 stage condenser is smaller than in 4 stages condenser which is a restriction of the cooling fluid temperature. The reason is that the relative humidity of the moist air will be increased with the counter flow LNG condensation process, and the condensing temperature of the moist air in the last stage requires higher temperature cooling resource. These results show that the required temperature of LNG cryogenic energy is easier to achieve for condensation in multi-stage condenser system.

In addition, as portion of LNG cryogenic energy is applied for condensing the water steam among its large capacity, the spare of the cryogenic energy can be utilized for cooling storage for other uses.

Table 3. The required LNG cryogenic energy under 5Kpa, 40% relative humidity condition.

	4 stages			1 stage		
Water steam temperature (degC)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)
10	-180	-60	0.2	-180	-174	0.2
20	-180	-52	0.2	-180	-180	>0.2
30	-180	-43	0.2	-180	-180	>0.2

Table 4. The required LNG cryogenic energy under 20Kpa, 40% relative humidity condition.

	4 stages			1 stage		
Water steam temperature (degC)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)
10	-180	-60	0.2	-180	-174	0.2
20	-180	-51	0.2	-180	-168	0.2
30	-180	-42	0.2	-180	-173	0.2
50	-180	-28	0.2	-180	-180	>0.2
70	-180	-13	0.2	-180	-180	>0.2

Table 5. The required LNG cryogenic energy under 50Kpa, 40% relative humidity condition.

	4 stages			1 stage		
Water steam temperature (degC)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)
10	-180	-60	0.2	-180	-174	0.2
20	-180	-50	0.2	-180	-165	0.2
30	-180	-41	0.2	-180	-166	0.2
50	-180	-25	0.2	-180	-176	0.2
70	-180	-11	0.2	-180	-180	>0.2

Table 6. The required LNG cryogenic energy under 101Kpa, 40% relative humidity condition.

	4 stages			1 stage		
Water steam temperature (degC)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)
10	-180	-60	0.2	-180	-174	0.2
20	-180	-50	0.2	-180	-163	0.2
30	-180	-41	0.2	-180	-164	0.2
50	-180	-24	0.2	-180	-168	0.2
70	-180	-8	0.2	-180	-180	>0.2

Table 7. The required LNG cryogenic energy under different relative humidity condition.

	4 stages			1 stage		
Relative humidity (%)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)	LNG Minimum temperature (degC)	LNG Maximum temperature (degC)	LNG mass flow rate (kg/s)
5%	-180	-162	0.2	<-180	<-180	-
10%	-180	-151	0.2	<-180	<-180	-
40%	-180	-60	0.2	-180	-174	0.2
80%	-180	-2	0.2	-180	-50	0.2
90%	-180	8	0.2	-180	-21	>0.2

4. Conclusions

In order to improve the fresh water production, exploit waste energy, promote the fresh water generator efficiency, this paper investigates a multi-stage condensers system which utilizes the waste cooling fluid: low temperature and large amount of LNG cryogenic energy to condense the water steam on board. Based on the simple calculations about the moist air property under different conditions, the relative humidity, temperature and pressure are the main influencing factors. The simulation model is conducted by Siemens LMS Imagine. Lab AMESim to explore the fresh water production and the capacity of LNG cryogenic energy. The conclusions could be drawn:

(1) The low temperature LNG cryogenic energy can be utilized as cooling fluid for condensation in any conditions.

(2) The multi-stage condensers system performs better than one stage condenser in the fresh water production, the temperature range of required LNG cryogenic energy under any conditions especially under higher vacuum degrees.

(3) The current models present that the assumption of the water steam as moist air is a promising method to simulate the complicated process in the condenser.

(4) The spare low temperature LNG cryogenic energy can be stored for cold storage system for other uses.

In the future, the research will develop experiments to verify the simulation results and focus on investigating the most optimized fresh water generation process.

References

[1] B. B. Kanbur, L. Xiang, S. Dubey, F. H. Choo, and F. Duan, "Cold utilization systems of LNG: A review," *Renewable and Sustainable Energy Reviews,* vol. 79, pp. 1171-1188, 2017.

[2] IGU, "World LNG report 2017," IGU2017.

[3] H. Thomson, J. J. Corbett, and J. J. Winebrake, "Natural gas as a marine fuel," *Energy Policy,* vol. 87, pp. 153-167, 2015.

[4] M. Corkhill. (2017, 24 Apr). *The world's LNG-fuelled ships on order, 2017*. Available: http://www.lngworldshipping.com/news/view,the-worlds-lngfuelled-ships-on-order-2017_47089.htm

[5] C. W. Graugaard, "LNG for Shipping – Current status," 2013.

[6] L. Register, "LNG-fuelled deep sea shipping," *Lloyds Register, August,* 2012.

[7] E. S. Jeong, "Optimization of power generating thermoelectric modules utilizing LNG cold energy," *Cryogenics,* vol. 88, pp. 29-35, 2017.

[8] W. Sun, P. Hu, Z. Chen, and L. Jia, "Performance of cryogenic thermoelectric generators in LNG cold energy utilization," *Energy Conversion and Management,* vol. 46, pp. 789-796, 2005.

[9] B. E. L. Eyvind Andersen, "Water Report 129; Safe, Sufficient and Good Potable Water Offshore; A guideline to design and operation of offshore potable water systems," 2017.

[10] Z.-j. Jin, H. Ye, H. Wang, H. Li, and J.-y. Qian, "Thermodynamic analysis of siphon flash evaporation desalination system using ocean thermal energy," *Energy Conversion and Management,* vol. 136, pp. 66-77, 2017.