Applied Thermal Engineering 65 (2014) 564–574

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Thermal performance analysis of intermediate fluid vaporizer for liquefied natural gas

Liang Pu [a], Zhiguo Qu [b,*], Yuheng Bai [b], Di Qi [a], Kun Song [c], Peng Yi [c]

[a] Department of Refrigeration and Cryogenic Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, Xi'an Jiaotong University, Xi'an 710049, PR China
[c] CNOOC Gas & Power Group Research Center, Beijing 100027, PR China

HIGHLIGHTS

- Thermal model was established for an intermediate fluid vaporizer (IFV).
- The mutual coupling and constraints for different parts of IFV were considered.
- Experimental correlations and thermal property were incorporated in the developed codes.
- Effects of inlet operating parameters on the system performance were revealed.

ARTICLE INFO

Article history:
Received 23 July 2013
Accepted 18 January 2014
Available online 25 January 2014

Keywords:
Intermediate fluid vaporizer
LNG
Propane
Thermal model
Heat transfer

ABSTRACT

The intermediate fluid vaporizer (IFV) is a new kind of vaporizer for liquefied natural gas (LNG). A thermal model was established based on the energy balance among the three typical parts of IFV, namely, evaporator, condenser and thermolator, whose mutual coupling and constraints were fully considered. Calculation codes were developed to solve the energy balance equations, in which the formulation of experimental correlations and thermal property codes were incorporated into the iteration. The temperature, pressure and mass flow rate of the inlet LNG and seawater, as well as the heat transfer area of the three parts, were known parameters. The outlet temperature of natural gas (NG) and seawater, the surface and total heat transfer coefficients in the three parts, and the propane saturation temperature were the solution parameters. The effects of the temperature and mass flow of inlet seawater, the pressure, and mass flow rate of inlet LNG on the solution parameters were systematically investigated. The intrinsic link, in terms of the heat transfer performance inside the IFV, was revealed. The outlet temperature of seawater and NG increased with increased temperature and mass flow rate of the inlet seawater and with reduced inlet mass flow rate of LNG. The increased inlet pressure of LNG significantly improved the NG outlet temperature, but this increment has mild influence on the outlet temperature of seawater. The propane saturation temperature also increased with increased temperature and mass flow rate of inlet seawater and with reduced inlet LNG mass flow rate, whereas, it was not sensitive to the inlet LNG pressure.

1. Introduction

Natural gas (NG) owns the advantages of safety and cleanness, and its demand is expected to increase in future energy market considering the global energy crisis and the rapid deterioration of environment worldwide. Liquefied NG (LNG) is a practical approach for large quantity of NG transportation for its mass storage. The LNG must be vaporized to natural gas before it is used as fuel gas in industrial and domestic purposes. Therefore, efficient and reliable vaporizers for LNG receiving terminals are important.

The LNG cold energy can be widely utilized for energy saving and environmental protection [1–3]. A number of studies have focused on the thermodynamic modeling and exergy analysis of the LNG cold energy recovery system during vaporization. Ahmadi et al. [4] conducted thermodynamic modeling and optimization for a polygeneration energy system to gain simultaneous production of heating, cooling, electricity, and hot water from a common energy source. Two objective functions of the total system cost rate and the system exergy efficiency were utilized in the evaluation. Energy and exergy analyses have also been performed for an LNG

* Corresponding author.
E-mail address: zgqu@mail.xjtu.edu.cn (Z.G. Qu).

1359-4311/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2014.01.031

Nomenclature

A	area (m^2)
L	length (m)
D, d	diameter (m)
h	surface heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h^*	enthalpy ($J\ kg^{-1}$)
k	total heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
r	latent heat of vaporization ($J\ kg^{-1}$)
T	temperature (K)
ΔT	logarithmic mean temperature difference (K)
p	pressure ($N\ m^{-2}$)
s	entropy ($J\ kg^{-1}\ K^{-1}$)
q	heat flux ($W\ m^{-2}$)
q_m	mass flow rate ($kg\ s^{-1}$)

Greek symbols

λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
ϕ	heat transfer obtained by energy equation (W)
ϕ^*	heat transfer obtained by heat transfer equation (W)

Subscripts

ev	evaporator
cond	condenser
th	thermolator
pc	pseudo-critical value
cr	critical value
s	saturation condition
b	average value
f, w	based on fluid and tube wall
l, g	based on saturated liquid and vapor
I	based on the inside tube
O	based on the outside tube

re-liquefaction plant [5], in which an exergy economic model based on the total revenue requirement was developed. A comprehensive thermodynamic model of a dual-pressure combined-cycle power plant has been established [6], and the predicted results were verified with the actual data of an Iranian power plant. Sayyaadi and Babaelahi [7] performed an exergetic efficiency optimization for the re-liquefaction cycle of LNG boil-off gas. Ahmadi et al. [8] conducted a thermodynamic modeling and a multi-objective optimization, with an environmental impact assessment, for a new multi-generation energy system. Caprace et al. [9] performed a thermodynamic analysis and proposed a multi-criterion optimization design of LNG carrier. Some studies have also been conducted on the thermal cycle design. Lu et al. [10] analyzed a thermodynamic of Rankine cycle (RC), in which LNG and waste heat were applied as the cold source and low-temperature heat source, respectively. Wang et al. [11] proposed a combined power cycle with propane ORC and natural gas directly expanding cycle to recover the low-temperature exergy and pressure exergy of LNG and low-grade heat source. Liu and Guo [12] studied the efficiency of the power generation by LNG cold energy and recommended the combination of organic RC (ORC) with direct expansion. Liu and You [13] further developed a mathematical model for calculating the low-temperature exergy, pressure exergy, and total cold exergy of LNG. Maizza et al. [14] proposed a calculation method for the working fluids used in ORC recovery systems with small turbines and developed equations to obtain the outflow thermophysical parameter. Other studies have focused on the selection of heat transfer medium and its effect on the efficiency of power generation. Badr et al. [15] compared the performance of RC for three kinds of working fluid with different superior fluorinated hydrocarbons, namely, R-11, R-113, and R-114. The final assessment indicated that R-113 was the most suitable candidate for the application design.

The heat transfer designs for vaporizers have also been proposed. Four types of LNG vaporizers are mainly used in the LNG receiving terminals, namely, open-rack vaporizer (ORV), super ORV, submerged-combustion vaporizer (SCV), and intermediate fluid vaporizer (IFV). The ORV system is mainly composed of panel-shaped heat transfer tubes. The LNG flows inside the tube and seawater is sprayed outside. The seawater tends to freeze on the tube surface because of the very low temperature (−162 °C) of LNG and the huge temperature difference between the two medium. The formed ice layer causes a tremendous thermal resistance that deteriorates the heat transfer efficiency remarkably. Jeong et al. [16] numerically predicted the ice layer thickness and its distribution on the external surface to gain the optimal configuration of heat transfer tubes. The structure of super ORV is similar to that of ORV, except that the lower part of the tube bundles has a double-tube structure. Osaka Gas and Kobe Steel jointly developed the first commercial SUPERORV based on the above conclusions in 1998. The double structure is characterized with the ring gap between the outer and the inner tubes, which can suppress ice formation effectively. ORV and super ORV both have a high standard requirement for the seawater quality [17]. Morimoto et al. [18] compared the heat transfer performances of ORV and super ORV. The results show that the LNG vaporizing capacity per heat transfer tube of super ORV was three to five times higher than that of ORV, and their operating costs and energy consumption were low. Hisada and Sekiguchi [19] established highly endurable structures through a variety of tests or analyses using the finite element method to design a suitable structure and shape of the heat exchanger tubes for the LNG vaporizer. The structure of SCVs was mainly composed of water tank, serpentine coils inside the water tank, and burner. The low-pressure sent-out gas and the extracted heavier gas from the LNG terminals were burned to flue gas as high-temperature heat source. The gas was injected into the water tank to keep the constant temperature of water, and the LNG was vaporized inside the serpentine vaporization coils located inside the water tank. Walle et al. [20] indicates that the major disadvantage of the SCV is that a fraction of 1.2%–1.3% of LNG was consumed in the gasification and the emissions of NO_x and CO_2 largely affected the ambient environment. The IFV is an advanced shell and tube design with propane as the intermediate working medium. Evaporator and condenser are arranged in a tank filled with propane. Seawater flows into the inside tube of evaporator, and propane is heated outside the evaporator. The boiled propane vapor condenses outside the condenser and releases heat to the LNG inside the tube. The LNG is then converted to NG. The advantages of IFV include compact volume, no icing, low requirement for seawater quality, low operation costs, and low carbon emission. Furthermore, the IFVs promote energy saving and low emission and are reliable compared with the other types of LNG vaporizers.

Based on the above review, previous studies have mainly focused on the thermodynamic analysis of LNG cold energy utilization and few studies have reported the thermal design of ORV, super ORV, and SCV. The thermal model and performance