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Waste cold energy recovery from liquefied natural gas (LNG) regasification including pressure and thermal energy

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ABSTRACT

The world has been concentrating on waste heat recovery for several decades. The attention has recently been turned to waste energy in cold streams. This work focuses on the recovery of waste cold energy released from the Liquefied Natural Gas (LNG) regasification process, including pressure energy and thermal energy. A direct expansion configuration involving different steps of expansion and mass flow rate extraction at intermediate pressure levels is adopted in the mathematical models for pressure energy recovery. A direct-configuration organic Rankine cycle (ORC) is employed subsequently to recover residual cold energy. An equation of state for methane (the main component of LNG) is used to estimate the thermodynamic properties of LNG in a long-range phase transition of the regasification process. The modified Peng-Robinson (PR) and the Soave-Redlich-Kwong (SRK) equations of state are used to calculate thermodynamic properties of the ORC working fluids. All the models are developed and solved using MATLAB. By adopting propane as the ORC working fluid, the multistage expansion and thermal energy extraction can recover 215 kJ per kilogram of flowing LNG, which can generate 1.7 GWh annually for 1 kg/s LNG, with a payback period less than seven years.

1. Introduction

World energy demand and consumption has been rising rapidly with concern about potential energy crisis, especially for those depending on fossil fuels (i.e. coal, oil and natural gas). These conventional energy sources have been exploited to power the economy in recent centuries. Unfortunately, fossil fuels are not renewable and subject to depletion. World Energy Outlook 2006 [1] expects global energy markets to increase the demands in the next decades. Natural gas (NG) would follow coal as the fastest growing primary energy source. NG infrastructure is built around major reserves across the world for distribution, such as the large-scale pipeline systems in Gulf, Russia-Europe, Northern America, Southern America and the Malaysia-Singapore regions. However, there are still locations out of the connectivity of the global NG pipeline network, so that NG supplies come only by ship. In this case, NG is liquefied with much reduced volume to facilitate storage and transportation to overseas markets. East Asia countries like Japan, Korea, China, India and Taiwan can thus import large amounts of liquefied natural gas (LNG) annually (for example, 260 million tons in total in 2016) from different areas, with the longest voyage being 25,000 km [2].

During the liquefaction process, mechanical energy is required to bring NG to cryogenic temperature $-161.5\,^{\circ}\mathrm{C}$(111.65 K). In operating liquefaction plants, this implies 2900 kJ/kg of energy consumed during the process. However, it is estimated that 2070 kJ/kg of the energy for NG liquefaction is eventually lost and dispatched to the surroundings; only 830 kJ/kg would stay in LNG as so-called “cold energy” [3]. Before arriving at the end-users, regasification is carried out to turn LNG into vaporized natural gas (VNG). Ideally, 830 kJ/kg of the cold energy, equivalent to 0.23 kWh per kg LNG, could be recovered from LNG regasification.

Since the last decade, cold energy recovery from LNG regasification has attracted considerable interest. The recovery of this cold energy is becoming mandatory in view of the environmental issues, for the sake of saving energy resources and reducing environmental impacts. To be convenient and environmental friendly, LNG regasification plants have been operating near the sea. In more detail, at regasification sites, there are two conventional processes used to vaporize the LNG. The majority of the current LNG import terminals use parallel operating vaporizers with spares and seawater to heat

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and vaporize LNG in Open Rack Vaporizers (ORV) [4]. This does not make use of the cold energy stored in LNG during liquefaction processes before LNG is sent to the end-users. Secondly, Submerged Combustion Vaporizers (SCV) use the send-out gas as fuel to provide heat for vaporization [4].

The lost cold energy will be dispatched uneconomically to the environment. A three-staged parallel LNG cold warehouse (LNGCW) system used for energy saving was proposed [5]. An integration of a cryogenic Air Separation Unit (ASU) cycle with LNG as the heat sink has improved the performance of the cycle [6]. On the other hand, there have been significant improvements in the exploitation of cold energy application available in LNG, such as CO_2 capture technology and air separation [7]. Recently, a direct expansion plant with multistage turbines and internal heat exchangers has been analyzed, and the results show high cold energy recovery efficiency [8].

A transcritical CO_2 power cycle, using flat plate solar collectors with storage tanks as the heat source and LNG as the heat sink, was applied for LNG cold energy recovery [9]. Similar thermoeconomic analysis that proposes the use of a regenerative two-stage organic Rankine cycle (ORC) was also presented [10]. Moreover, a promising solution with large potential benefits in terms of primary energy savings compared to both ORV and SCV technologies is multilevel condensation using a modified ORC [11]. A multi-stream cryogenic heat exchanger configured with a five-stage turbine and associated re-heaters, together with three-stage vapor re-condensation processes carried out within direct-contact heaters was considered to be the optimum superstructure, using a stochastic optimization solver and the Aspen Plus-MATLAB interface [12]. Another complicated superstructure consists of a biomass integrated gasifier-gas turbine cycle, a Rankine cycle, a cascade ORC, an absorption refrigeration system and a proton exchange membrane (PEM) to produce hydrogen [13]. Besides enhancing cold energy recovery using ORCs, a cascade Rankine cycle was optimized to recover cold energy by applying a genetic algorithm, highlighting a mixed working fluid composed of ethane and propane [14]. Furthermore, a comparative study of Rankine cycle configurations utilizing LNG cold energy for a wide range of VNG distribution pressures provides new insights into technological combinations of simple well-known cycles, such as the single-stage ORC, the parallel two-stage ORC, and the cascade two-stage ORC with or without the direct expansion cycle employing either propane, propylene, ethane or ethylene as the working fluid [15]. Similarly, previous publication reported that the cascade Rankine cycles operating with argon and methane, followed by a direct expander unit working with regasified LNG, has a high performance index [16].

Concurrently, significant research has focused on energy storage technologies. Energy storage plays an important role in current energy system structures, substituting a rise in energy production. The LNG cryogenic energy seems to be a significant potential for waste cold recovery. The idea appearing here is, yes, actually not either a new concept or a new discovery. However, it can be said that this study bring a new dimension to LNG waste cold recovery with the aim of developing a generic mathematical framework to model the LNG regasification process, and thus to provide further detailed analyses and reliable estimates for LNG cold recovery. Different from the original regasification process, retrofit attempts, as well as technological approaches are suggested in order to provoke an optimal configuration along with the optimal operating conditions, thus maximizing the recovery efficiency of waste cold energy from conventional LNG regasification process. Simultaneously, the maximum amount of generated net power from the novel modification process is also determined regarding to recovered energy meaning.

Furthermore, in this work, a novel approach related to organic Rankine cycle (ORC) application for LNG cold recovery has studied considering treating the problem as a nonlinear programming problem (NLP). ORC is a promising alternative for recovery of LNG cold energy. As been known, LNG is not a pure substance, but a multi-component mixture which is featured by non-isothermal vaporization. Therefore, this study shows attempts to adopt and recover as much as possible the cryogenic cold from a vast cold sink stored under the phase of liquid LNG mixture. Moreover, more suggestions were put forward. Noticeably, a set of double ORCs in series were modeled for the benefit optimization of recovered net power or generated electricity power. It is considerable to show that the amount of cold energy recovered by ORC is as large as a half of those of heat exchanger network modification with pressure manipulation.

The rest of the paper is organized as follows. Section 2 presents the mathematic models for LNG cold energy recovery, involving pressure energy recovery through direct LNG expansion [8] and thermal energy recovery using organic Rankine cycles (ORCs) [17]. Illustrative examples are solved and discussed in Section 3, followed by the economic analysis in Section 4. Finally, conclusion and prospects for future works are given in Section 5.

2. LNG cold energy recovery and mathematic models

2.1. Direction expansion for pressure energy recovery

The LNG regasification process consists of two operations. The first step is pumping LNG at −161.5 °C (111.65 K) atmospheric pressure to distribution pressure 6000–8000 kPa for long distance or 2500–3000 kPa for local distribution. Whereas the second step is heating up to raise LNG temperature to up to the distribution temperature, typically between 0 and 20 °C (273.15–293.15 K), normally using seawater or warm effluent from power plants [18].

Recently, Franco and Casarosa [8] proposed a potential scenario for recovering pressure energy from direct expansion of compressed LNG, such as depicted in Fig. 1 [8]. Therein LNG is first compressed to the highest possible pressure (say, 15,000 kPa) which is higher than the gas-supplying pressure at the distribution stations. The high pressure LNG is heated up and vaporized (VNG) due to the employment of seawater as heat source. A turbine (T1) is employed to generate electricity from the high pressure VNG to bring the pressure down to satisfy the requirement from the distribution station. Noted that pumping directly from 1 atm (101.3 kPa) to the possibly highest pressure, saying 15,000 kPa, is actually a challenge in real. There must be a multistage compression applied for such a dramatic pressure change. Thus, from the storage pressure to the maximum possible pressure, there could be several pumps operating in series to increase the LNG pressure to intermediate levels and finally the highest pressure. In order to enhance electricity generation and at the same time to maintain the output flow rate of the VNG to the distributing station, a split is made to recycle a part of the main VNG stream back a position along the main stream to make a higher flow rate going to drive turbine T1. Furthermore, the second turbine (T2) is installed on the recycle stream for raising electricity generation. This idea is considered for the second recycle stream in case of flow rate of the first recycle stream is sufficient to make the second recycle circle also beneficial. Such as shown in Fig. 1, the third turbine (T3) is then installed on the second recycle stream for capturing more electricity.

The direct expansion scheme proposed by Franco and Casarosa [8] has achieved an impressive results of about 120 kW of cold energy recovered for each kg of LNG. In order to move on next stages to make a contribution toward this topic, this study is decided to depart from the beginning as those of Franco and Casarosa's work. In this way, the authors are able to learn