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Analysis and assessment of an advanced hydrogen liquefaction system

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ABSTRACT

In the present work, an advanced hydrogen liquefaction system with catalyst infused heat exchangers is proposed, analyzed and assessed energetically and exergetically. The analysis starts with exergetic considerations on hydrogen liquefaction using different alternatives of pre-cooling including the conversion from normal to parahydrogen. It further explains the fundamentals of a proposed liquefaction process. The goal is then to assess the proposed system, make modifications and improve the system. The present system covers all of these portions of a hydrogen liquefaction system with an ultimate goal of achieving a sustainable and environmentally harmless system. The proposed hydrogen liquefaction system is simulated in the Aspen Plus and the performance of the system is measured through energy and exergy efficiencies. The resulting energy efficiency of the system is calculated to be 15.4%, and the exergy efficiency of the system is found to be 11.5%.

Introduction

As global warming and energy crisis issues arise, new sources of clean and affordable energy options are necessary and investigated accordingly by many researchers. Liquid hydrogen appears to be the ideal scenario for such issues, if produced at low cost as, after use, it is released as water vapor into the environment. High hydrogen liquefaction work requirement represents the most important obstacle to achieving the feasibility of the hydrogen economy. The global hydrogen liquefaction capacity is relatively small at the moment and the liquefier systems are built not for maximum efficiency, but as a compromise between cost and efficiency. Most of these plants are typically based on modification of the well-known Claude cycle, and their exergy efficiencies are typically relatively low: about 20–30%. A hydrogen economy that is the same size as the United States would require about 150 million tons per year of hydrogen for transportation, which would be equal to the consumption of 2–5 billion tons of water, taking into account the current hydrogen production efficiencies. This consumption would be considerably less than the current consumption of water for thermoelectric power generation in the United States in the power plants, which is somewhere around 300 billion tons, while additional 1.2 billion spent in the process of gasoline production. Hence, the most likely scenario is that the hydrogen economy could reduce water consumption in the process of energy generation significantly [1].

Hydrogen energy content per weight is around 125 MJ/kg over two times higher than any other fuel currently in use: fossil fuels have 20–50 MJ kg^{-1}, with diesel fuel at the high end and natural gas at the low end, while batteries have 0.1–0.5 MJ kg^{-1} [2]. This energy outcome makes hydrogen the

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most effective energy carrier and, therefore, a lot of effort has been expended on improving its production and storage. However, energy content per volume of hydrogen is relatively low when not highly compressed or liquefied. Even then, it is significantly lower than that of fossil fuels: 8 MJ L^{-1} for liquid hydrogen, the most efficient form of hydrogen storage, in comparison to 32 MJ L^{-1} for gasoline. In spite of intense research effort devoted to the development of more efficient means of storing hydrogen, hydrogen liquefaction, for all its deficiencies, remains as the most economical method of hydrogen storage to date. When considering the efficiency of hydrogen production, one, therefore, has to take into account the cost of liquefaction accordingly.

Most of the hydrogen produced is today obtained from methane reforming, with carbon dioxide as the side product of the reaction. Since this increases greenhouse gas emissions, a lot of effort has been invested into the exploration of alternative methods of hydrogen production relying on renewable energy. The use of hydrogen produced in this alternative could contribute to the reduction in the level of greenhouse gasses [3]. Hydrogen has shown potential as an important energy carrier for use in transportation vehicles of the future, leading to considerable hydrogen research activities. The biggest challenge today is having relatively low efficiency of the currently used liquefaction plant cycles. Several recent papers have explained methods and ways to overcome the efficiency issues, where some have proposed conceptual plants with efficiencies that can be increased up to 40–60% [4]. Since the efficiencies have always been the main challenge with the conceptual systems, increasing efforts have been exerted to overcome such challenge. In a research by Karsaein *et* al [4] a comparison between multiple system has been shown. The exergy efficiencies ranged from 3% in more realistic systems to 100% in ideal systems. The exergy efficiency of the pre-cooled theoretical Claude system is between 6.2–8.8%.

First successful hydrogen liquefaction was achieved in 1898 by a small device made and invented by Scottish/British scientist James Deware [5,6]. James Dewar's process used a combination of carbolic acid and liquid air to pre-cool the compressed hydrogen gas at 180 bars and Joule-Thompson effect for liquefaction [4]. The amount of work required by a reversible cycle to bring hydrogen from the initial conditions, e.g. 300 K, 100 kPa, and 25% parahydrogen, to the final liquid state at 100 kPa and equilibrium parahydrogen content is referred to as the ideal work of hydrogen liquefaction.

Most current hydrogen liquefier systems utilize steady flow processes like the pre-cooled Linde-Hampson cycle, the Claude cycle and the helium hydrogen condensing cycle [7]. The choice of a particular thermodynamic cycle depends on the projected size of the plant, the available level of technology, equipment cost and, more than anything, the cycle efficiency. Most large-scale hydrogen liquefaction processes are based on the Claude cycle, where hydrogen is both the product and the working fluid [8,9].

Economies of scale mean that centralized hydrogen production is more cost and energy efficient than distributed production. In fact, hydrogen liquefaction plants tend to be more efficient with increase in size [10] and tend to be limited by the financial rather than technical constraints, with capital cost accounting for about 63% of the total lifetime cost of hydrogen liquefaction plant. The main cost of operation of hydrogen liquefaction represents input power, 12–15 kW h/kg, accounting for about 32% of the total lifetime cost of hydrogen liquefaction plant [11,12]. Capacities of hydrogen liquefaction plants vary from 5 tons per day for Air Products plant in Sacramento to 66 tons per day for Air Products plant in New Orleans. An economic analysis of three hydrogen liquefaction systems [13] showed that, while power consumption costs remain relatively constant, fixed charges and operation and maintenance costs decrease rapidly with increased production rate. The cost of production decreased to about 0.7$ and 0.8$ per kg LH_2 for the production rate of 29700 kg per hour, for an optimized large-scale hydrogen liquefier and a two-stage Claude hydrogen liquefier, respectively.

Various designs have been introduced and efficiencies have been calculated. But, when covering all aspects of the system, from the design to the economies of scale to the environmental effect, cost of getting higher efficiency increases and hence, optimization comes to a greater use.

Quack [14] has worked on study in which design is based on modern helium liquefiers that are built with up to ten expansion turbines placed strategically in a cycle to obtain optimal overall efficiency. Efficiencies obtainable by this concept are up to 60% and a specific energy consumption is 5–7 kW h/kg LH2.

Another study by Kuz'menko et al. [15] proposed a helium refrigeration cycle which showed somehow higher efficiency than the Ingolstadt plant.

Valenti and Macchi [16] found an innovative, efficient and large hydrogen liquefier. It is a large-scale plant since the production rate is 10 kg/s of LH_2. The system utilizes four cascaded helium Joule–Brayton cycles and reported efficiency is 47.73% [16]. A study by Yuksel et al. [17] reported and liquefaction process of 57.13% for supercritical hydrogen liquefaction. Mirhadi and Mehdi [18] worked on a cryogenic hydrogen liquefaction process with different mixed refrigerants and recorded a 55.47% exergy efficiency.

In a research conducted by Ratlamwala et al. [19] there is a hydrogen liquefaction based on renewable energy (solar photovoltaic/thermal) proposed based on Linde-Hampson cycle.

This study aims to analyze and assess the performance of an advanced hydrogen liquefaction system. This will include energy and exergy analyses. In more detail, these specific objectives can be listed as follows:

- To develop and design a advanced hydrogen liquefaction systems based on the system developed by Praxair in Ref. [20].
- To make an Exergy analyses of the proposed systems which includes:
  - Flow exergy calculation for each stream.
  - Calculate exergy efficiencies and exergy destructions of the system components. Make all exergy efficiency calculation, including exergy parameters such as exergy destruction ratio, waste exergy ratio and exergy destruction factor.
- To evaluate the varying operating conditions on the process energy and exergy efficiencies.