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Large-scale liquid hydrogen production methods and approaches: A review

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HIGHLIGHTS

- Large-scale hydrogen liquefaction (LHL) methods are chronicled.
- A novel classification of hydrogen liquefaction systems is introduced.
- Hybrid conceptual hydrogen liquefaction plants are reviewed.
- Specific energy consumption (SEC) of hydrogen liquefiers is discussed.

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ABSTRACT

Large-scale hydrogen liquefaction (LHL) methods and different approaches of the configuration of hydrogen liquefaction cycles are chronicled. History landmarks of permanent gases liquefaction are quick reviewed and the basic hydrogen liquefaction cycles, the existing in-service LHL plants around the world, and LHL conceptual proposed plants, including the state of the art plants, are recorded and categorized based on the systems' main parameters. In addition, a novel classification of hydrogen liquefaction systems in terms of heat exchange and expansion process method is introduced. As well as, the authors infer that renewable energy technologies section should be added to the old sectioning of the hydrogen liquefaction plants. In addition, hybrid conceptual hydrogen liquefaction plants, combining with renewable power cycles are reviewed and the increasing contribution of this new approach is demonstrated. Finally, the operational costs of the plants considering the systems' efficiency are examined, and a trend in specific energy consumption (SEC) and exergy efficiency of hydrogen liquefiers is discussed. Accordingly, considering the existing technologies, SEC reduction of hydrogen liquefaction will not be abrupt in near future and it will remain within the range of 5–8 $\mathrm{kWh/kg_{LH_2}}$. Moreover, exploiting of isentropic expansion processes instead of isenthalpic one, cascading of refrigerating cycles, using of new mixed refrigerants as working fluid of refrigeration cycles, and hybridization of renewable energy power cycles to refrigeration cycles are the main four growing approaches in the hydrogen liquefaction context.

1. Introduction

Hydrogen is an abundant and accessible element, which is also known as the final optimum fuel [1,2]. In addition, liquid hydrogen has unique characteristics such as lower weight and volume and higher energy content than the gaseous hydrogen. Therefore, hydrogen is the most promising energy carrier for storage in chemical form within the large energy storage systems [3–5].

Large energy storage systems can eliminate the problem of energy demand fluctuations of renewable energy grids [6–8] by storing excess produced energy and compensating energy demand deficit [9–11]. Therefore, the development of hydrogen energy storage systems will facilitate the evolution of renewable energy sources utilizing. These privileged energy sources will mitigate concerns arising from damage to the environment [12–14].

Moreover, hydrogen liquefaction provides higher storage densities. Therefore, it is a suitable solution making possible large-scale hydrogen storage and long distance transportation [15–20]. Finally, demand for liquid hydrogen, driven by environmental friendly applications and numerous other uses [21] will increase in the near future. As the result, LHL plants will play an important role within clean energy supply chain [22,23].

Hydrogen liquefaction is an energy-intensive process and low efficiency of equipment and processes are the obstacles to the realization of a hydrogen economy. Patterns and trends of LHL systems' SEC and exergy efficiency changes are investigated. Opportunities for

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Nomenclature

Symbols

$\mathbf{e_x}$	specific exergy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
P	pressure
s	specific entropy, kJ/kg−K
T	temperature
W	power, kW
w	specific work/energy requirement, kJ/kg$_{LH_2}$ or kWh/kg$_{LH_2}$
$\dot{Q}$	heat flow, kW
$\dot{W}$	Work transfer rate, kW

Abbreviations

MR	mixed refrigerant
C	compressor
Comp	compressors
JB	Joule-Brayton
LH_2	liquid hydrogen
GH_2	gaseous hydrogen
LN_2	liquid nitrogen
LNG	liquid natural gas
NGL	natural gas liquids
WE-NET	world energy network system
EX	expander
J-B	Joule-Brayton
Sys	system
L-H	Linde-Hampson
H_2	hydrogen molecule
o-p	ortho-para
Min	minimum
Max	maximum
Config	configuration
LH	Linde-Hampson
Sp	liquid separator
BFD	block flow diagram
Eff.	efficiency
ARS	absorption refrigeration system
ALSRC	auto-cascade solar Rankine cycle
HX	heat exchanger
SEC	specific energy consumption
Sat	saturated
n-	normal
p-	para
o-	ortho
PV/T	photovoltaic/Thermal
Ref.	reference
i or in	inlet
o	out or outlet
US	United States
SLH	simple Linde-Hampson
SC	simple Claude
PFD	process flow diagram
TPD	tons per day
N_2	nitrogen molecule

Subscripts

Comp	of the compressors
in	of the inlet stream
geo	of the geothermal system
a, b, … to f	of a, b, … to f
1, 2, … to n	of the numbers: 1, 2, … to n/of stream numbers: 1, 2, … to n/ of equipment numbers: 1, 2, … to n

improvements in the LHL plant's performance are identified through this way. As well as, an overview of status of the renewable energy technologies, as a growing section, in the processes of liquid hydrogen production is obtained. Finally, review of the historical development of the large-scale hydrogen liquefaction cycles clarifies the new area of investigations for LHL plants improvement. Large-scale hydrogen liquefaction methods and different approaches in liquefiers' configuration are reviewed.

2. Initial preparations prior to hydrogen liquefaction

The feeling that some things are warmer than others and some are cooler dates back to the dawn of the human history. However, it may be argued that the thermometers were invented to quantify this difference. The emerging of the thermometer is reviewed [24]. Results introduce Galileo as one of the possible inventors of the thermometer in 1592. This invention can be considered as the beginning of the thermodynamics science and emerging of the question whether there is a lower limit for the temperature. The existence of the absolute zero is predicted in 1704 [25,26]. Gases liquefaction is one of the main and important sections of the history of the quest to achieve absolute zero temperature.

The story commences almost from the beginning of the 21 century, when experiments with the gases that had been discovered a few decades earlier, were great interest to the researchers [27]. Accordingly, liquefaction of gases by cooling and compressing was a challenge that is attempted by Sir Humphry Davy at the royal institute in London [28,29]. However, in 1812, he employed Michael Faraday [30,31], the founder of the development of industrial gases, who carried out many experiments to liquefy gases. In 1823, Faraday presented a method of gas liquefying using a bent glass tube [32]. Accordingly, he filled the thick-walled tube shown in Fig. 1 with chlorine gas while heating one end and cooling the other end. However, the heated gas is expanded, and it pressurized the gas in the cold end [33]. Therefore, chlorine is liquefied combining the pressure and the cooling effect. Faraday liquefied ammonia and carbon dioxide using the same method [34], however, was unable to liquefy oxygen, hydrogen, and nitrogen in this way. Moreover, in 1844, the experiments are repeated on a large scale by Thilorier [35] using a mechanical compressor [36,37]. As the results, compressors are developed to produce greater quantities.

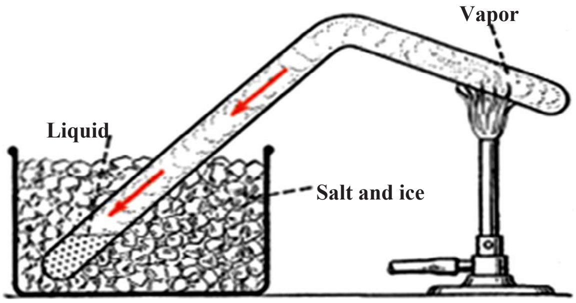

Fig. 1. Faraday bent glass tube [33]. The compression pressure is generated by the gas production in the closed vessel.

In 1845, a hydraulic pump is used to make larger quantities of liquid and solid carbon dioxide by Faraday [38]. According to the Faraday, compressing of some gases is lead to liquefaction and six known gases including oxygen, nitrogen, carbon monoxide, nitrous oxide, methane,