

Thermodynamic (Energy-exergy) Analysis of Hydrogen Liquefaction System

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Abstract

Hydrogen is rich source of energy but its properties in gaseous state cannot be used efficiently but at the liquid state in can be used in various application but high cost of liquefaction of hydrogen cryogenic system and less efficiency component turned the cryogenic science toward optimization. In this paper First law analysis in terms of coefficient of performance and second law analysis in terms of exergetic efficiency in the system and exergy destruction ratio for finding irreversibility in the system and its components on yield base parameters have been presented for reducing the cost of whole system. A Numerical computational analysis is carried out for hydrogen liquefaction system using ambient condition and compressor pressure at 15 bar as input parameters and second law efficiency (exergetic efficiency) of hydrogen liquefaction system is obtained as 19.82 % along with first law efficiency in terms of coefficient of performance (COP) is 0.9746, It is also observed that both thermodynamic performances start decreasing with further increases of compressor pressure whereas liquefaction mass ratio and total work done in the system is increases with increasing in compressor pressure.

Keywords: Thermodynamic analysis, energy-exergy analysis, Irreversibility analysis, Cryogenic

NOMENCLATURE

m = mass flow rate

m_f = Liquefaction mass

h = Enthalpy

s = Entropy

X = Dryness fraction

T = temperature

P = Pressure

$m_{LN_{evop}}$ = mass of liquid nitrogen

$\eta_{2nd\ law}$ = Second law efficiency

ϵ = Effectiveness of heat exchanger

C = Specific heat capacity fluid or gas

W_{net} = Total Work of compression

W_c = Compressor work

INTRODUCTION

A low temperature environment is termed a cryogenic environment when the temperature range is below the point at which permanent gases begin to liquefy. Permanent gases are elements that normally exist in the gaseous state and were once believed impossible to liquefy. Lack of fossil fuels and increasing need to energy has made us to pay a special attention to replacing fossil fuels with renewable resources. Also the fossil fuels and their combustion products were causing global environment problems. These resources of energy are clean and do not pollute the environment. One these sources are hydrogen energy. Hydrogen derived from renewable energies eventually will contribute to the sustainable development of such countries [1]. Hydrogen combustion produces water vapor that does not make any pollution. Hydrogen is gas form, occupies a large volume and has low density (0.0897 kg/m³) and high pressure [2]. so the demand of dense form of hydrogen increases but liquefaction of hydrogen is a very slow process and it estimated that The fastest flow that a hydrogen liquefaction system can bear in optimum hydrogen flow is 300 lit/hr[3]. Thus we need to liquefy hydrogen for an easier transportation and safety ,it also studied that thermodynamic performance ($\square t$) is low due to existing of nitrogen pre coolers I hydrogen system [4] In hydrogen liquefier the pre-compression of feed gas has generally higher stand-alone exergy efficiency than the cooling and liquefaction sub-process. Decreased feed pressure results in generally higher power consumption but also higher exergy efficiency, and vice versa [5]. Gianluca Valenti et al [6] in research show that the feed, 10 kg s⁻¹, is refrigerated in heat exchangers catalytically promoting the ortho–para conversion down to the low temperature of 20.5 K and at the high pressure of 60 bar with turbo machine expansions show 48% of second law efficiency with low power consumption of hydrogen liquefaction system.

Songwut Krasae-in et al [7] showed effect of multi-refrigerant at the hydrogen liquefaction plant. The MR system can be used to cool feed normal hydrogen gas from 25 °C to the equilibrium temperature of −193 °C with a high efficiency. The overall power consumption of the plant is reduced from 5.35 kWh/kg_{LH2}, to minimum of 2.89 kWh/kg_{LH2}. Gianluca Valenti et al [8] discuss the influence of the thermodynamic modeling of the fluid on the simulation outcomes. Various hydrogen forms (ortho hydrogen and Para hydrogen) and their mixtures (equilibrium-hydrogen and normal-hydrogen) are studied and described in his research. According to viewpoint of David O. Berstad [9] efficiency and cost is to a large extent dependent on the efficiency of the liquefier so high-efficiency hydrogen liquefier based on mixed-refrigerant (MR) pre-cooling has been developed. Based on his models, a reduction in power consumption obtain in the range of 45–48 % . Akihiro Nakano et al [10] proposed a simple estimation method for the liquefaction rate and confirmed that the estimation method well explained the experimental result. A small-scale hydrogen liquefier with a two-stage 10 K Gifford–McMahon cycle (GM) refrigerator is confirmed the estimation method for predicting the liquefaction rate.

2.0 THERMODYNAMIC ANALYSIS OF HYDROGEN LIQUEFACTION SYSTEM:

The design is quite critical at low temperatures due to changes in thermo physical properties of hydrogen gas. Fig 1 showed the block diagram hydrogen liquefaction system in which liquefy nitrogen chamber is introduced to reduce the further temperature up to the critical temperature before J-T which is required to liquefy the hydrogen gas.

“Compressor”

$$Wc_{ideal} = m_2 * R * T_1 * \ln * \left(\frac{P_2}{P_1}\right) \tag{1}$$

$$-Wc = (h_1 - h_2) - T_0 * (s_1 - s_2) \tag{2}$$

"Heat Exchanger A"

$$m_a * h_2 + m_4 * h_{13} = h_3 * m_a + m_4 * h_{14} \tag{3}$$

$$\varepsilon = \frac{m_a * (T_2 - T_3)}{m_a * T_2 - T_{13} * m_{13}} \tag{4}$$

$$P_3 = P_2 \tag{5}$$

"Heat Exchanger B"

$$m_b * h_2 + m_{LN_{evop}} * h_7 = h_4 * m_b + h_8 * m_{LN_{evop}} \tag{6}$$

$$\varepsilon = \frac{m_b * (T_2 - T_4)}{m_b * T_2 - T_7 * m_{LN_{evop}}} \tag{7}$$

"Mixing of two different tem helium"

$$m_3 * c_p * (T_3 - T_5) = m_b * c_p * (T_5 - T_4) \quad (8)$$

"Heat Exchanger C"

$$Q_{LN_{evop}} = m_2 * (h_5 - h_6) \quad (9)$$

$$m_{LN_{evop}} * L_{LN} = Q_{LN_{evop}} \quad (10)$$

$$m_2 * h_5 + m_{LN} * h_{LN} = m_{LN_{evop}} * h_7 + m_2 * h_6 \quad (11)$$

"Heat Exchanger D"

$$m_2 * h_6 + m_4 * h_{12} = h_9 * m_2 + m_4 * h_{13} \quad (12)$$

$$\varepsilon = \frac{m_2 * (T_6 - T_9)}{m_2 * T_6 - T_{12} * m_4} \quad (13)$$

"Expansion Valve"

$$h_9 = h_{10} \quad (14)$$

$$h_{10} = h_{11} + x_{10} * h_{12} \quad (15)$$

Separator"

$$m_2 * h_{10} = h_{11} * m_3 + m_4 * h_{12} \quad (16)$$

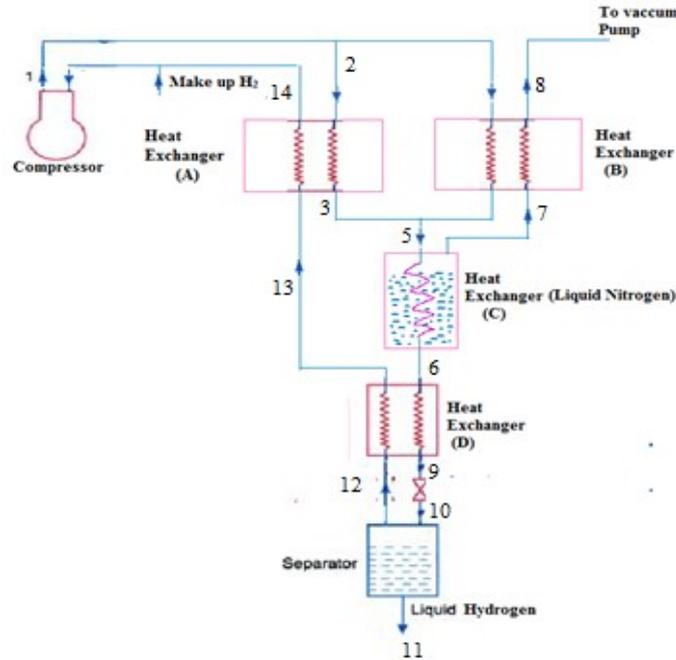


Fig 1: Block diagram of hydrogen liquefaction system

3.0 RESULT AND DISCUSSION

By computational mathematical technique various variable are noticed which are playing high role in hydrogen Liquefaction system and its optimization and to fully understand the effect of these variables on system different values are given and graphs are generated. Fig 1 show the variation of second law efficiency with respect to compressor pressure it show that as increase the compressor pressure after 12 bar the efficiency of system start decreasing whereas Fig 2 show just reverse of this and show increase in liquefaction mass of helium with increase of compressor pressure. Total work is summation of all type of work used in system like compressor work, expander work. Fig 3 shows there not much high fluctuation in variation of total work of system with increase in compressor pressure. At low pressure COP of system is quiet good as comparison with COP at high pressure. Fig 4 show COP of system start decreasing with increase in compressor pressure.

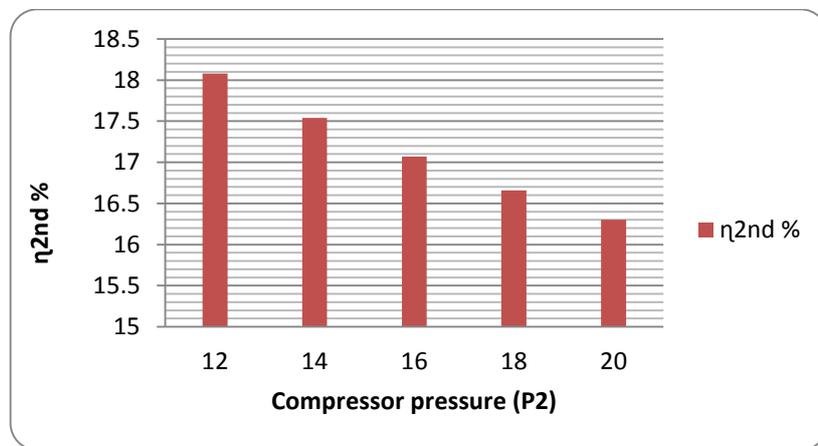


Fig:3 Variation of second law efficiency to Compressor pressure

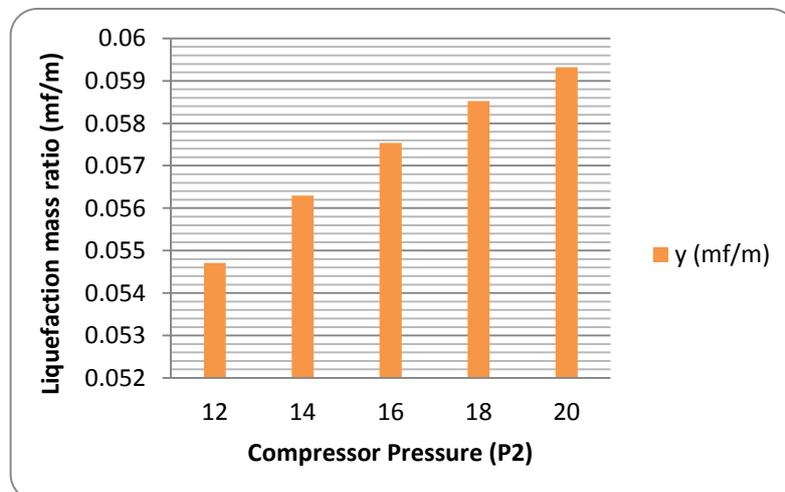


Fig:4 Variation of liquefaction mass ratio to compressor pressure

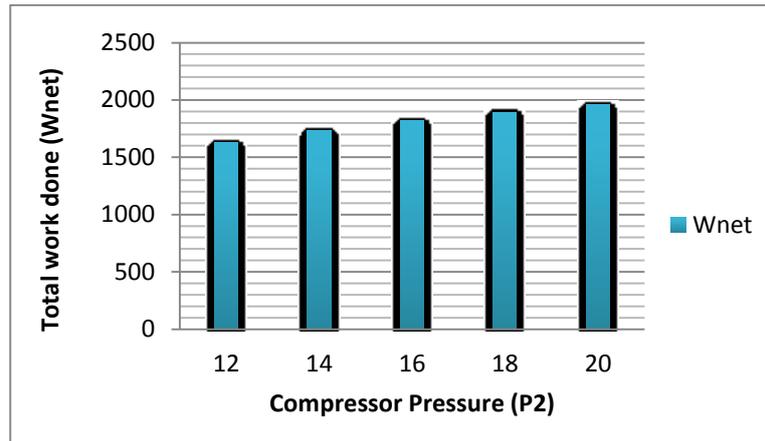


Fig:5 Variation of total work of system to Compressor pressure

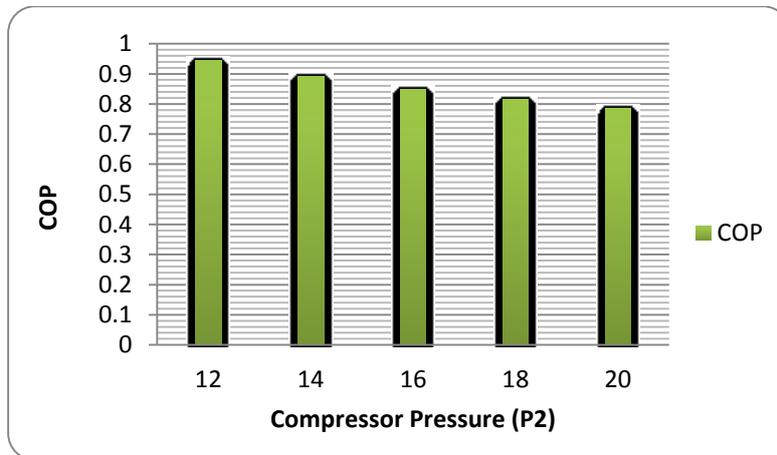


Fig:6 Variation of COP of system to Compressor pressure

CONCLUSION

- 1) Second law efficiency of system is 17.29 % and it start decreasing with further increases of compressor pressure
- 2) COP of the system is 0.8687 when input are at ambient condition and compressor pressure is 15 bar and as like second like efficiency it also start decreasing with increases of compressor pressure.
- 3) Liquefaction mass ratio and Total work done is increases with increase in compressor pressure.

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