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Validation of various cryogenics systems using exergy analysis

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Abstract

The exergy analysis (second law analysis) is used for providing information about the losses qualitatively as well as quantitatively along with their locations. Exergetic (thermodynamic) optimization improves the performance of a system. This paper present, the validation of Linde,Dual compressor Linde system , Pre-cooled Linde system, simple Claude Katiza Claude Haylent Claude, Collin system Hydrogen liquefaction system, Modified Helium liquefaction systemin terms of system performances.

Key words: Cryogenicsystems, Thermodynamic Analysis, Energy-exergy Optimization, Low temperature system Validation

1. Introduction

Cryogenics has been an important area of refrigeration because of its application in industrial and commercial utilization, and many scientific and engineering researches are going on by using low temperature liquefied gases. Cryogenics isa branch of physics which deals with the achieving very low temperatures (below the 173 K.) and study their effects on matter .Cryogenic study presents broad goals for cryogenic support for various gas liquefaction systems. Due to industrial revolution, various issues like cost, efficiency and reliability are the challenges factors in employment of cryogenic support technology. In field of mechanical engineering we try to refine or improve the ability or quality of material to get in maximum use at maximum level at a reduce cost. In past many fantasticclaimhave been made as to the degree of improve performance achieved by employing cryogenics technology.

2. Literature Review

Second law efficiency are very low in all above said cryogenic systems like hydrogen ,helium liquefaction etc. and its value ranging from 3% to 23 % for most of systems. Effect of different input gas also studies carefully and behavior of different gases in different system is concluded i.e. first law efficiency (COP) and second law efficiency (exergetic efficiency) of Claude system decrease with increase in pressure ratio. For Methane gas COP decreases [1].
It was observed that in all gases methane gas show highest performance in most of systems while argon show lowest thermodynamic performance. Improved Collin system show high efficiency as compared to Collin system, the nitrogen chamber and extra expander gives extra refrigerant effect which enhance liquefaction rate in the system and increasing the performance parameters of systems. (xii) The improved Collin system at PR 11 bars show highest exergtic efficiency of 54.19% keeping the expander ratio of all three expander is 70%,10%,10% respectively while simple Collin helium liquefaction system show 3.54% exergtic efficiency keeping the both expander flow ratio 35% and 50% respectively [2].
Argon has the highest value of second law efficiency (i.e. exergetic efficiency = 41.32%) and fluorine has the maximum value of first law efficiency (i.e. COP=0.9595) among the other gases. Methane has the highest value of liquefaction value of mass flow rate, which is around 0.3167 at cycle pressure ratio of 40. Fluorine has the highest value of exergy destruction rate in separator and it first decreasing up to 400K and then it starts increasing order [3]. It was observed that the outlet temperature of compressor affect the performance parameters of system. The second law efficiency decreasing with increasing compressor outlet temperature Similarly liquefaction rate is decreasing with increase outlet temperature of compressor and optimum expander flow fraction 0.55 flow ratio and optimum second law efficiency is 3.5 %, while first heat exchanger (HX1) shows highest rate of exergy destruction ranging from 36 % to 24 % with increase in temperature from 200 K to 400 K [4-5]. COP and second law efficiency decrease with increase

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in pressure ratio. For Methane gas COP decreases. Second law efficiency of system is highest for fluorine gas followed by nitrogen, air oxygen respectively which has 80-83% and methane gas shows lowest second law efficiency is which continuously decreases [6].

3. Result and Discussion

3.1 Validation of Linde system

Linde system and its T-S diagram in current study is shown in fig-1(a)-1(b) respectively.

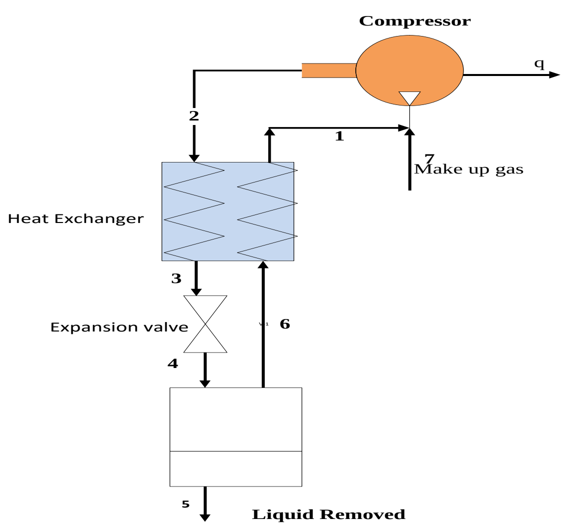

Fig: 1(a) Schematics Linde Hampson System [7]

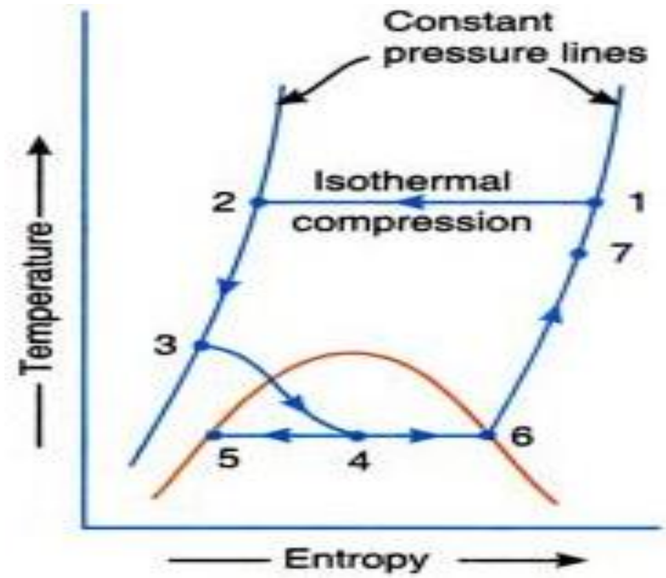

Fig: 1(b) Schematics Linde Hampson System T-S diagram [7]

The results of Linde system in current study has been validated with previous model, i.e. The COP and second law efficiency of the Linde cycle matched with the results of Kanoglu et al. [7] as shown in Fig.1(c). It has been observed that results related to efficiency and COP of the current model properly follows the results of COP and efficiency was concluded by Kanoglu et al [7]

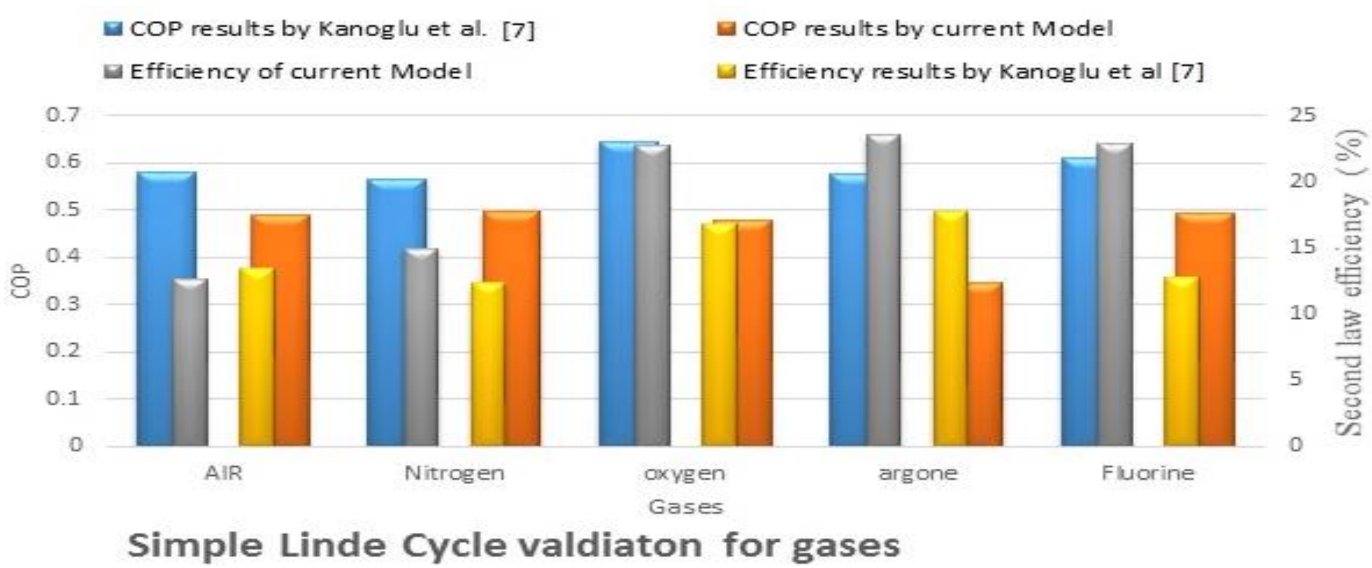

Fig-1.(c) Validation results of COP and second law efficiency in current model and literature Kanoglu et al. [7]

It has been also concluded that both the model shows the highest value of second law efficiency in case of argon gas, i.e. 23.49% for current model and 17.8% for the previous model results. Moreover, the results of work done of simple Linde cycle in the current study has been validated with the results of previous model results, (i.e. Kanoglu et al. [7] as illustrated in Fig.1.(d).

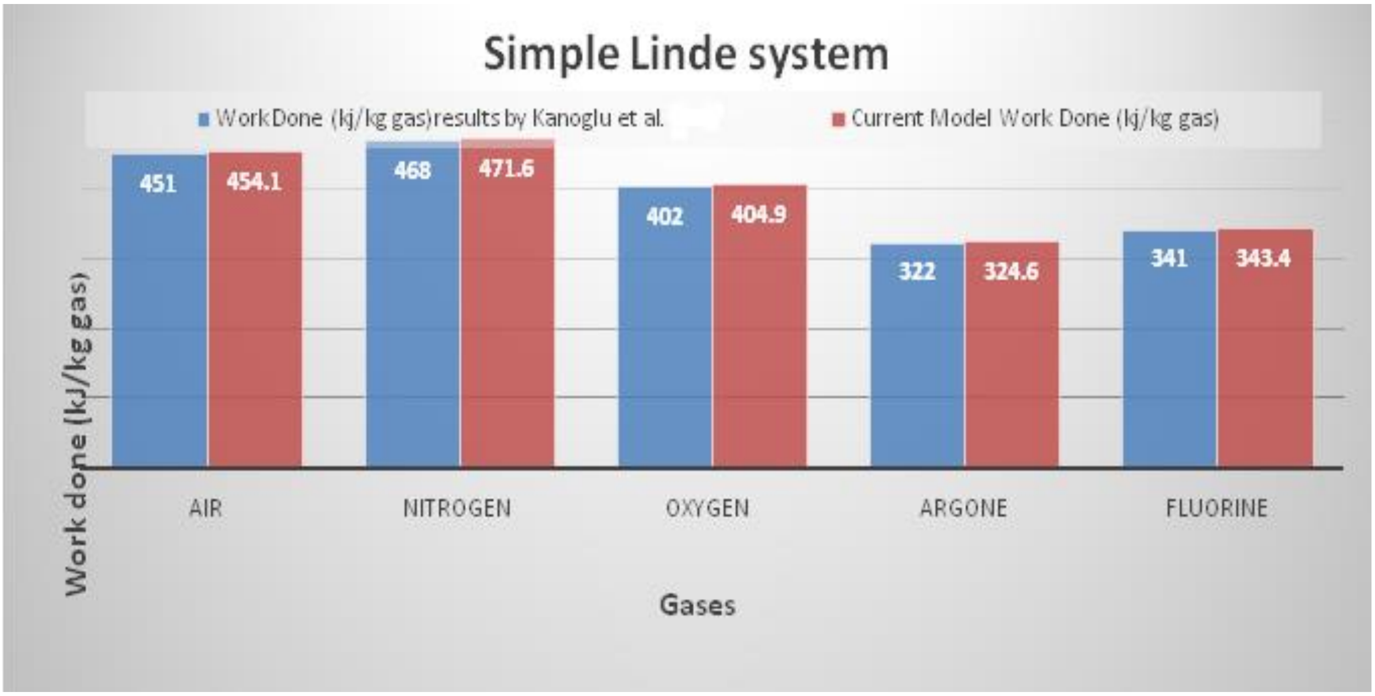

Fig. 1(d) Validation results of work done in current model and literature[7]

It has been concluded that work done by all gases follows the same trend of work done concluded in past research work. It has been found that nitrogen has the highest value of work done, i.e. 471.6kJ/kg. While in case of previous research, the work done by nitrogen is found to be 468kJ/kg. On the other hand, work done concluded by Linde, Dual compressor Linde, Pre-cooled Linde in the current model has been validated with previous results of Kanoglu et al. [7] .It has been concluded that all the systems in the current study shows good results and in the order as compared to previous model result. Lastly, it has been observed that pre-cooled Linde model has the highest work done, i.e. 784.7kJ/kg among the other listed systems as shown in Fig.2

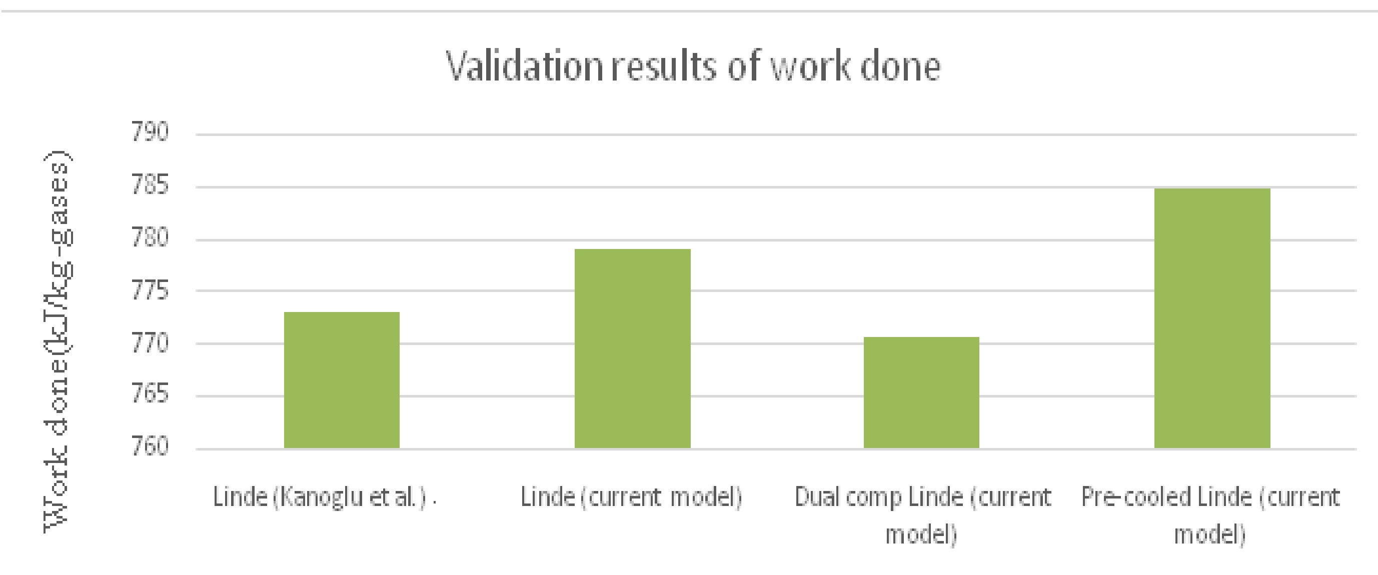

Fig.2. Validation results of work done in current model and literature for different systems

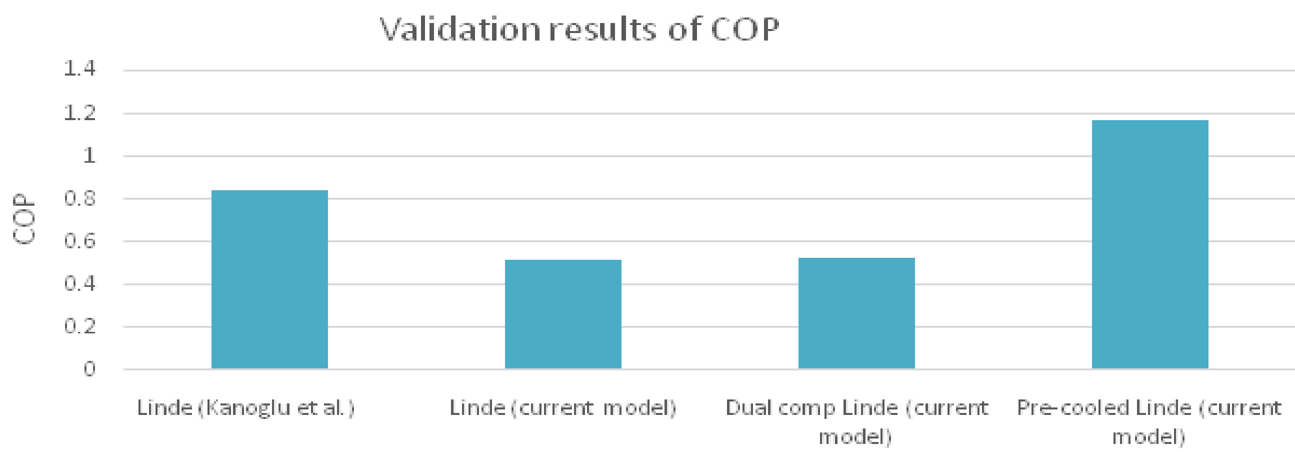

Fig.3. Validation results of COP in current model and literature for different systems

In addition, the second law efficiency results of Linde, Dual compressor Linde, and pre-cooled Linde system has been validated with the literature. Table 1

Simple Claude (AirLiquefaction)	P2	r _Exp ratio (%)	EHX effectiveness (%)	Compressor_ Efficiency _ (%)	Liquid yield y-m/mf	Work done (Btu/lb)	Work done kJ/kg gas
Timmerhaus[9]	40	0.7	100	100	0.260	382	-
Timmerhaus [9]	40	0.7	95	70	0.189	867	-
Ruhemann et al.	-	-	-	-	-	1540	-
Simple Claude	40	0.7	0.85	100	0.2828	-	396
Katizaclaude	40	0.7	0.85	100	0.1409	-	486.8
Haylentclaude	40	0.7	0.85	100	0.00599	-	309.8

Validation of simple Claude (air liquefaction) system It has been found that pre-cooled Linde has the highest second law efficiency, i.e. 46.73% among the other considered system as well as previous model as shown in Fig4

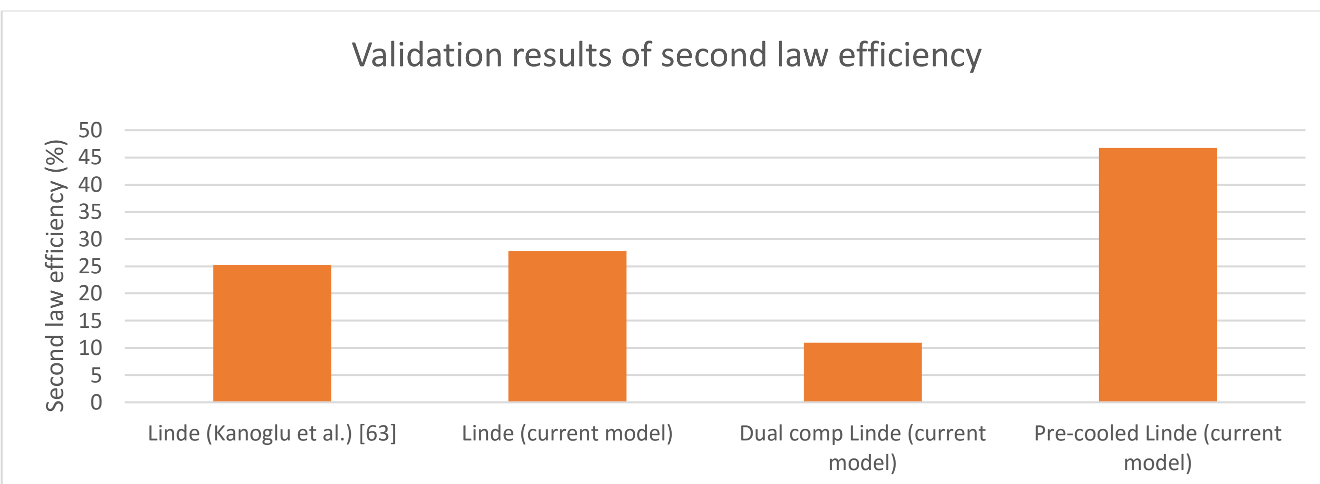

Fig.4: Validation results of second law efficiency in current mode and literature of differentLinde,Dual compressor Linde, Pre-cooled Linde system

3.2 Validation of Claude systems

Table 1 validation results of current study as well as previous model. It has been observed that at the same simulated conditions, i.e. pressure (P2), expander flow ratio, and effectiveness, the efficiency, liquid yields and work done of the current model are in good order with the previous study of Timmerhaus [9]. In this study, the concluded results of liquid yield ofsimple Claude, Katizaclaude, and Haylentclaude system is found to be0.2828, 0.1409, and 0.00599 y-m/mf, respectively. On the other hand, the concluded results of work done by these systems in current study is found to be 396, 486.8, and 309.8kJ/kg.

3.3 Validation of Hydrogen system

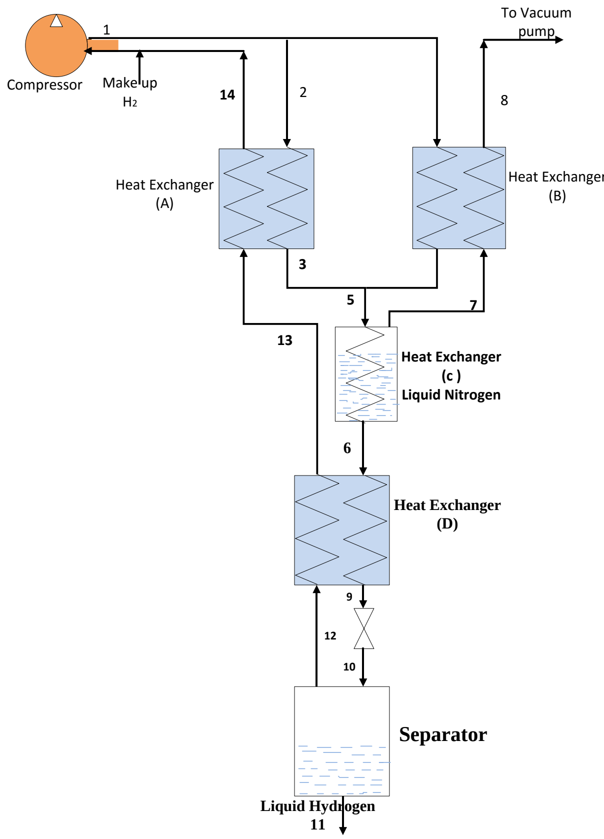

Fig: 5. Block diagram of hydrogen liquefaction system

The results of current model of hydrogen liquefaction system has been validated with the results concluded by Sargolzaei et al. [10]. The results of work done and mass flow of liquid nitrogen has been compared with the previous study results as shown in fig.3**.** It has been observed that current model shows better results relative to the results concluded in past results. It has been found that work done and mass flow of liquid nitrogen in current model was found to be 4593kJ/s and 0.5237kg/s, respectively as compared to the results of previous study, i.e. 4815kJ/s and 0.516kg/s

3.4 Validation of collin system

The collin system shown in Fig-6(a) & 6(b) is validated against the theoritical study of Sargolzaei et al. [10].

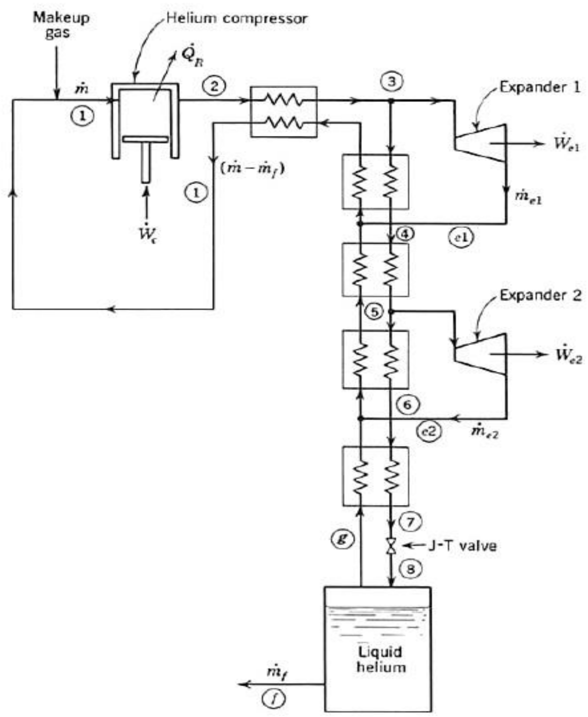

Fig: 6. (a) Schematic of Collin system

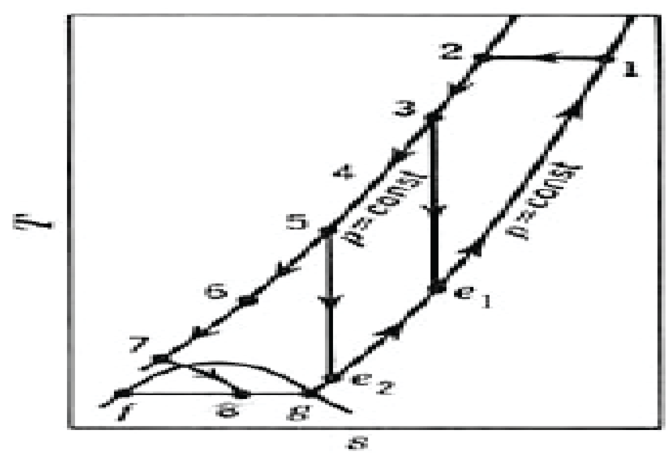

Fig: 6(b) T-S Diagram of Collin system

In the system, calculated values of second law efficiency of helium system (Collin system) found to be maximum i.e. 3.269 % at cycle pressure ratio of 11 bar. While in previous study, the maximum second law efficiency of the helium liquefaction system was approx. 7.1 % at cycle pressure ratio of 14 bar. There is marginal difference between the results of current study and previous one. Moreover, the trend of second law efficiency of current study follows the same trend as that of previous study results

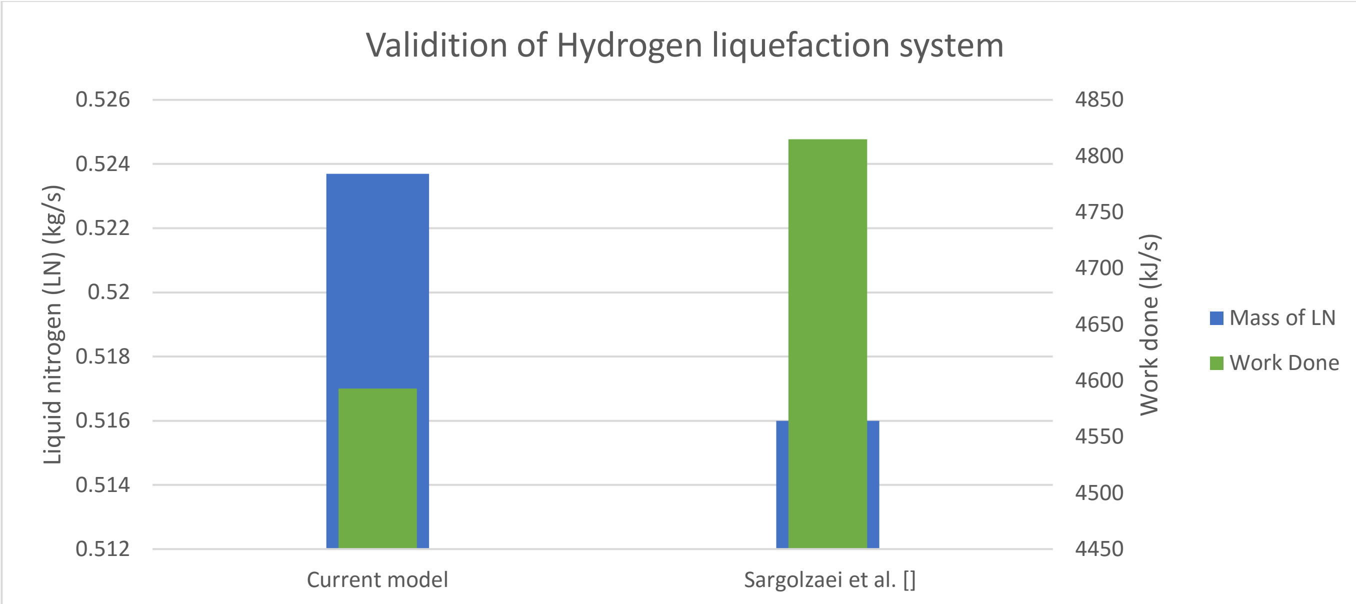

Fig.7 Validation results of liquid nitrogen and work done in current model and literature

The collin system shown in Fig-6(a) & 6(b) and Fig-7 respectively is validated. In the system, calculated values of second law efficiency of helium system (Collin system) found to be maximum i.e. 3.269 % at cycle pressure ratio of 11 bar. While in previous study, the maximum second law efficiency of the helium liquefaction system was approx. 7.1 % at cycle pressure ratio of 14 bar. There is marginal difference between the results of current study and previous one. Moreover, the trend of second law efficiency of current study follows the same trend as that of previous study results. Moreover, liquefaction rate of improved Collin system fig-6(a) & 6(b), with respect to expander flow ratio of first expander (r1) compared with the results of previous study results related to liquefaction rate. It has been observed that calculated liquefaction rate in current study was found to be 0.04 at expander flow ratio (r1) of 0.4. While as comparison with the past literature, it has depicted that the liquefaction rate was almost same for as that of currentmodel.In addition, results of exergy destruction of heat exchangers i.e. HX1, HX2, HX3, HX4, and HX5 of Collin system are compared with exergy destruction of all the same heat exchangers in the same type of helium liquefaction system. The comparative analysis shows that exergy destruction graph of HX3 and HX5 gradually decreasing in the current study between the cycle pressure ratio of 5 to 29 as same as that of previous study results of HX3 and HX5 between the cycle pressure ratio of 12 to 24 shown in Fig-9 & Fig-10 respectively .

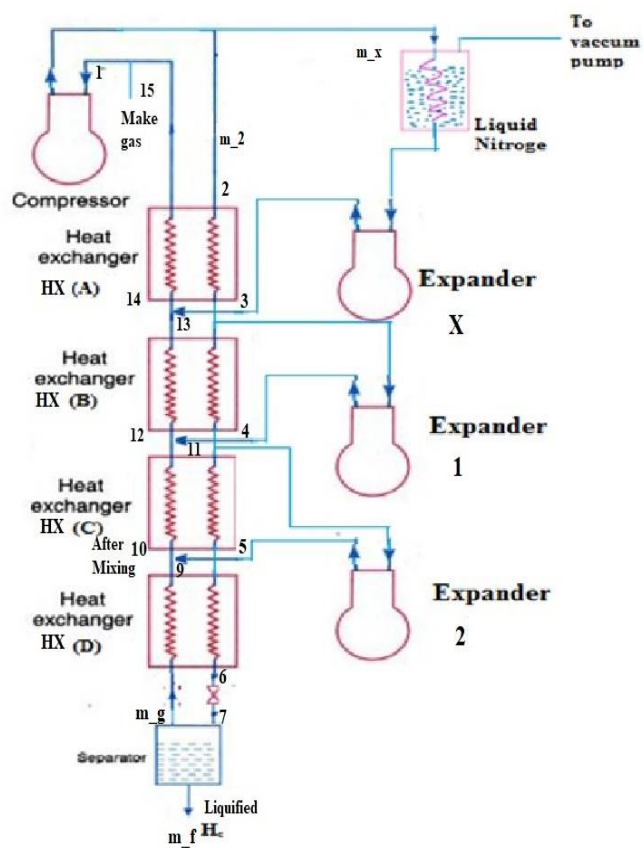

Fig: 8 Block diagram of modified Helium liquefaction system

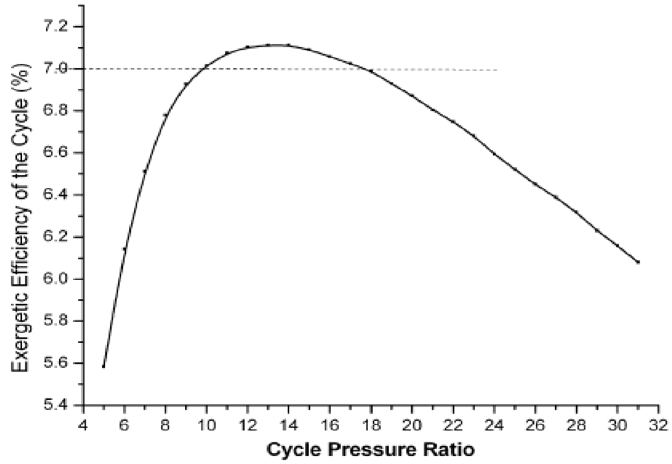

Fig.9 Validation results of exergy efficiency by R.J. Thomas et al. [11]

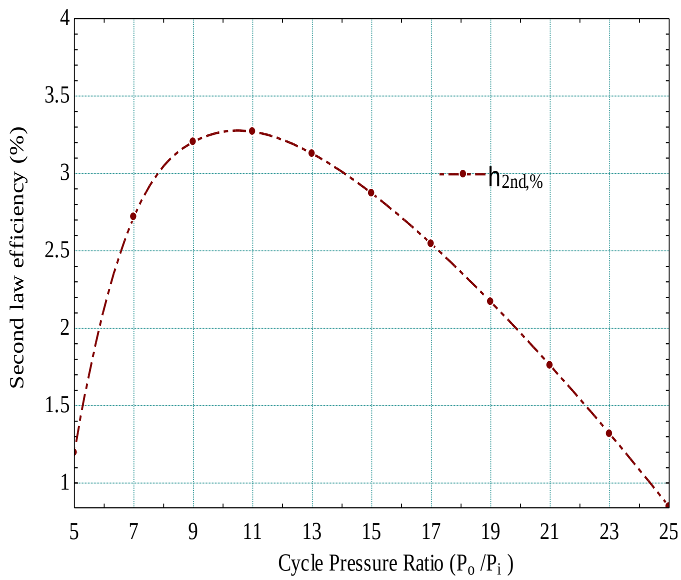

Fig.10 Validation results of exergy efficiency in current model

On the other hand, the exergy destruction rate of HX1 and HX3 does not vary so much or almost constant according to current study as same as results of HX1 and HX3 as observed from literature work [10].

4. Conclusions

Exergy analysis of cryogenics systems in which first six system with different gases and rest systems such as hydrogen, Collin, improved Collin system are evaluated on the basis of pressure ratio, compressor outlet temperature, and expander mass flow ratio. Experiment has been done on the vapor compression system to give valuable suggestion for increasing efficiency of cryogenics systems. Following results are concluded from study.

(1) During off design condition, performance of cycle does not hamper within the specific range of cyclic pressure ratio, for considered system there is always appropriate operating pressure ratio range for each working gas on which system work better

(2) All six system are compared on the basis of performance parameters at different pressure ratio, form the data observation it observed that simple Claude cycle is most suitable system because the three heat exchanger help in achieving more refrigerant effect which is in turn optimize the performance of the system.

(3) During PR increase, there is an imbalance in mass flow of forward and return stream of heat exchanger HX. Second law efficiency with the help of increasing pressure ratio which variate and create specific heat imbalance to overcome the mass imbalance.

(4) Variation in expander mass flow has highly influence the refrigeration effect of expander and overall performance of system. Optimum range of expender flow fraction (r) producing refrigeration effect is 0.55 to 0.7. Liquid production rate is highly influenced by refrigeration effect of expander.

(5) Inlet temperature of expander also plays an important factor to determine the refrigeration effect while other parameters in the system are constant. As the mass flow fraction increases through EXP, the output temperature of expander T_e also decreases which in turn lower the inlet temperature of input temperature of $T_{in\ EXP}$.

(6) In all gases methane gas show highest performance parameters in most of system while argon show lowest.

(7) The performance of hydrogen liquefaction cycle does not much deteriorate during off design condition when it is operated in selected operated range of PR 20-52 bar (the compressor suction pressure is atmospheric).

(8) Exergetic efficiency of the heat exchanger (HXD) at the lowest temperature of a hydrogen liquefier can be improved by increasing the pressure ratio because the mass imbalance gets compensated by the specific heat imbalance.

(9) While designing the hydrogen liquefaction cycle, owing to their lower exergetic efficiencies, additional care should be taken for ensuring superior heat transfer performance by the high temperature heat exchanger HXA and the lowest temperature heat exchanger HXD.

(10) Initial feasible range of pressure ratio in hydrogen liquefaction system is 20 to 87 bar, COP of the system decrease at very rapid rate but after that the rate of reduction in COP with increase PR start becoming constant with very less change while the second law efficiency show a constant reduction with increase in PR.

(11) Design parameter NTU for HX is carefully study for best performance of system. NTU term continuously decrease in hydrogen liquefaction system upto 70 bar for the J-T heat exchanger HXD and minimum at 70 bar while the variation in NTU term for HXA and HXB is quite different due to the different cold stream temperature of exchangers.

(12) Improved Collin system show high efficiency as compared to Collin system, the nitrogen chamber and extra expander gives extra refrigerant effect.

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