Advancing Hybrid Cryogenic Natural Gas Systems: A Comprehensive Review of Processes and Performance Optimization

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Supplementary Materials

This document reviews various studies on optimization analysis and pinch techniques for heat recovery in cryogenic natural gas systems. A comparison of the physical and chemical properties of LNG, diesel, gasoline, and LPG is provided in Table S1. Also, the classification of LNG based on density and composition (i.e., light, medium, and heavy) is shown in Table S2. Process flow diagrams for the main processes are included, such as the Axens Liquefin process for natural gas liquefaction (Figure S1) and nitrogen removal from natural gas (Figure S2). Figure S3 depicts cryogenic distillation techniques for nitrogen removal, illustrating single- and double-column configurations. Moreover, a process flow diagram for hybrid NGL and LNG production based on the C3MR refrigeration cycle is presented in Figure S4. A simple block flow diagram of an integrated helium production unit for removal of N_2, H_2, and CO_2 is displayed in Figure S5. Figure S6 shows a simplified schematic of the LNG/NGL process integrated with a distillation-based HeXU unit.

S1. Introduction

Vatani et al. [1] designed an integrated system for producing NGLs, LNG, and NG for residential and industrial consumption by utilizing the C3MR refrigeration cycle. The SPC and C_2H_6 recovery efficiency were calculated at 0.414 kWh/kg LNG and 93%, respectively. Their study led to optimization of the SPC as the target function by connecting the HYSYS simulation software with the genetic algorithm (GA) optimization approach in m-file MATLAB code. Ghorbani et al. [2] designed and optimized integrated process structures involving NGL recovery, LNG, and N_2 removal. By simultaneously designing these units and integrating their processes, they minimized the number of required equipment and reduced energy consumption [3]. They introduced a robust systematic approach that combined mathematical methods with thermodynamic insights

to design and optimize the cryogenic cycle and its operational parameters [3, 4]. Pinch and exergy analyses were integrated with meta-heuristic algorithms, developing a comprehensive nonlinear method to evaluate the advantages and disadvantages of different configurations of multi-component refrigerant cryogenic systems [5-7]. This method facilitated the integration of the cryogenic system with the core process, resulting in the optimal design and arrangement of the multi-component refrigeration system for ultra-low-temperature NG processes [8]. Furthermore, using absorption refrigeration cycles (ARCs) as an alternative to conventional condensation cooling systems within the integrated process structure was explored [4, 9, 10]. This approach aimed at reducing energy demand by removing parts of the condensation cooling systems, thereby lowering energy consumption in these units while also enabling the utilization of waste energy from the unit through ARCs [11, 12].

Tables

Table S1. Physical and chemical property comparison of LNG, diesel, gasoline, and liquefied petroleum gas, modified from Ref. [13].

Properties	LNG	Diesel	Gasoline	LPG
Auto-ignition temperature (°C)	540	316	257	545-450
Flash temperature (°C)	-187	60	-45	-104
Boiling temperature (°C)	-160	204	32	-42
Flammable range (%)	5-15	N/A	1.3-6	2.1-9.5
Stored pressure	Atmospheric	Atmospheric	Atmospheric	Pressurized
Toxic	No	Yes	Yes	No
Carcinogenic	No	Yes	Yes	No
Health hazards	None	None	Eye irritant	None

LPG: Liquefied petroleum gas

Table S2. The classification of LNG according to its density and composition, modified from Ref. [14, 15].

	Type of LNG		
Components (%)	**Light**	**Medium**	**Heavy**
CH_4	98.60	92.30	85.87
C_2H_6	1.18	5.00	8.40
C_3H_8	0.10	1.50	3.00
C_4H_{10}	0.02	0.60	1.20
C_5H_{12}	–	0.10	0.23
N_2	0.10	0.50	1.30
Density (kg/m^3) (-162 °C/1.3 bar)	427.58	451.58	474.87
LHV (kJ/kg)	49935	49557	48984

Figures

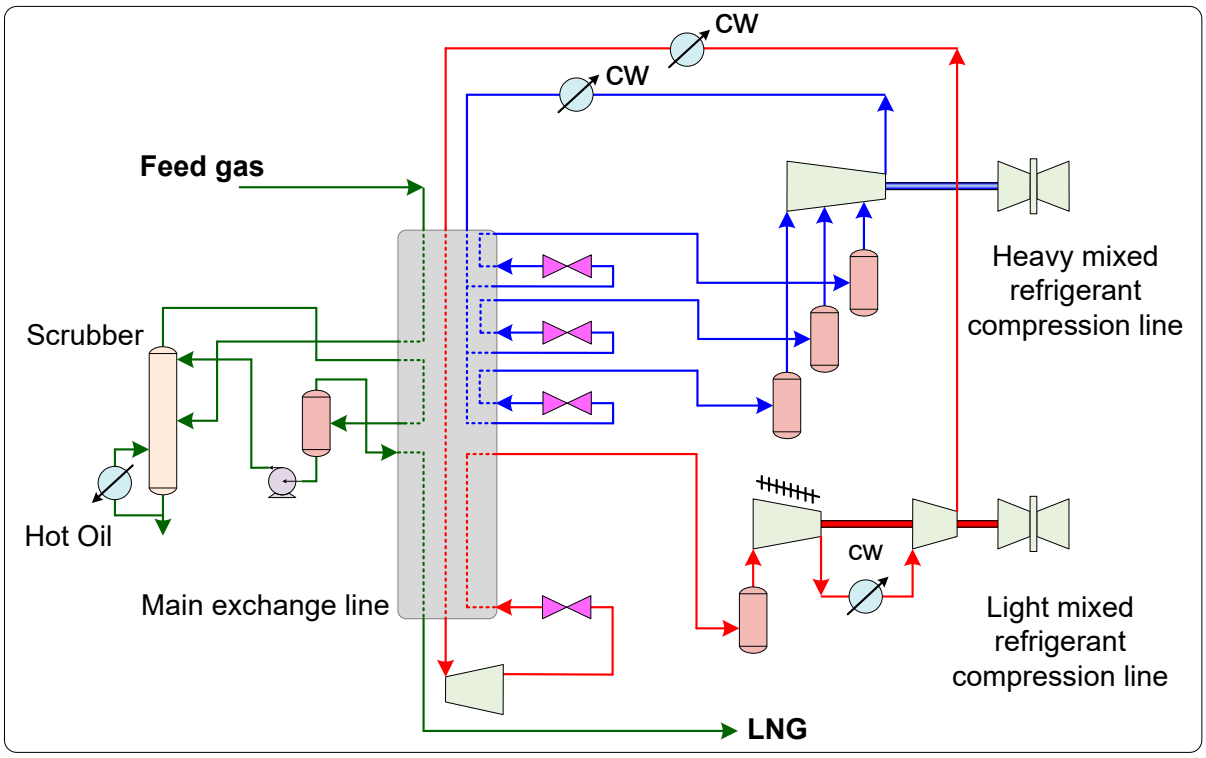
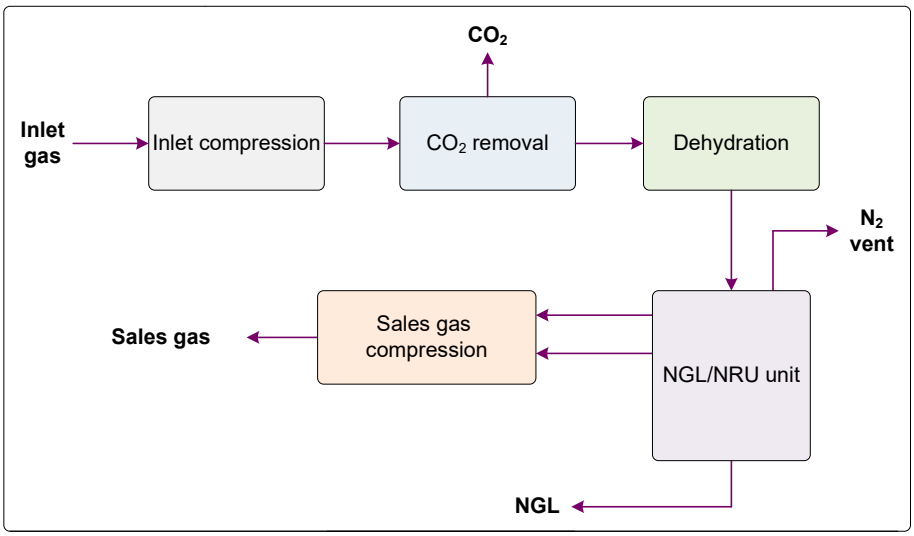
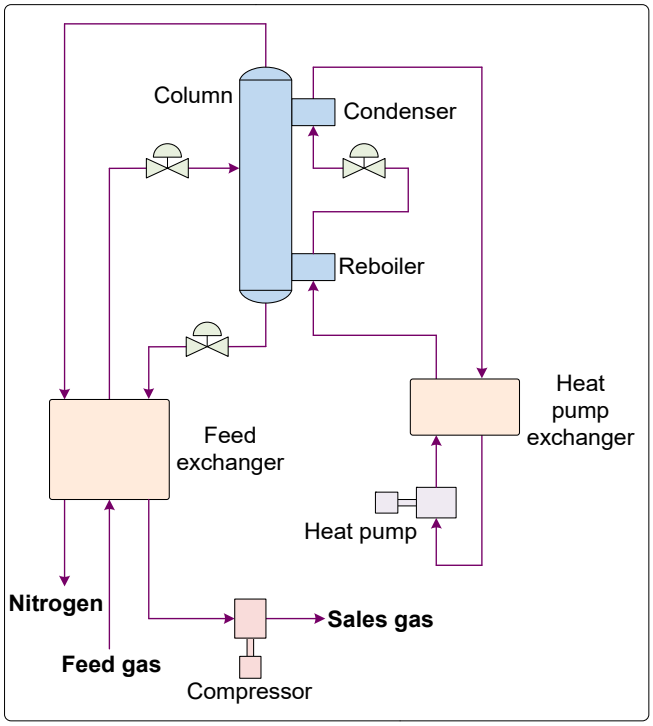


Figure S1. Process flow diagram of Axens Liquefin process for natural gas liquefaction, modified from Ref. [16].

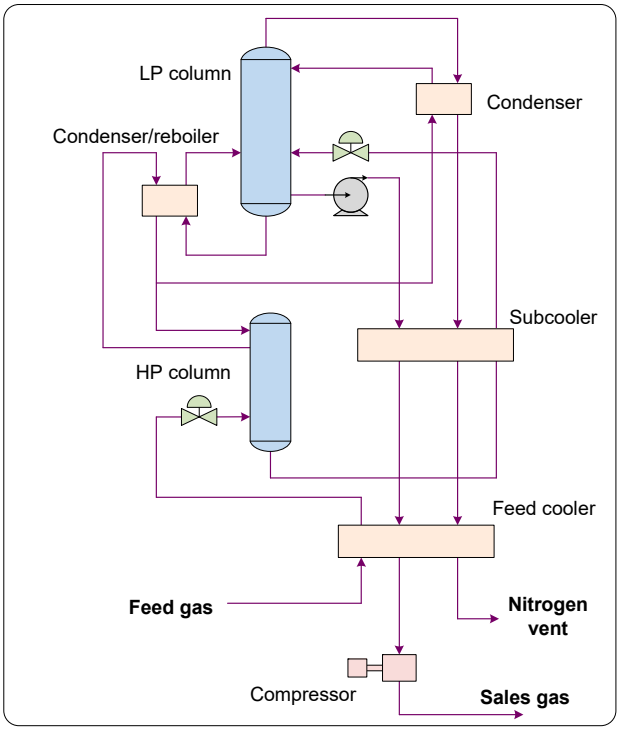


CO_2: Carbon dioxide, N_2: Nitrogen, NGL: Natural gas liquids, and NRU: Nitrogen rejection unit

Figure S2. Process diagram for N_2 removal from natural gas [17].

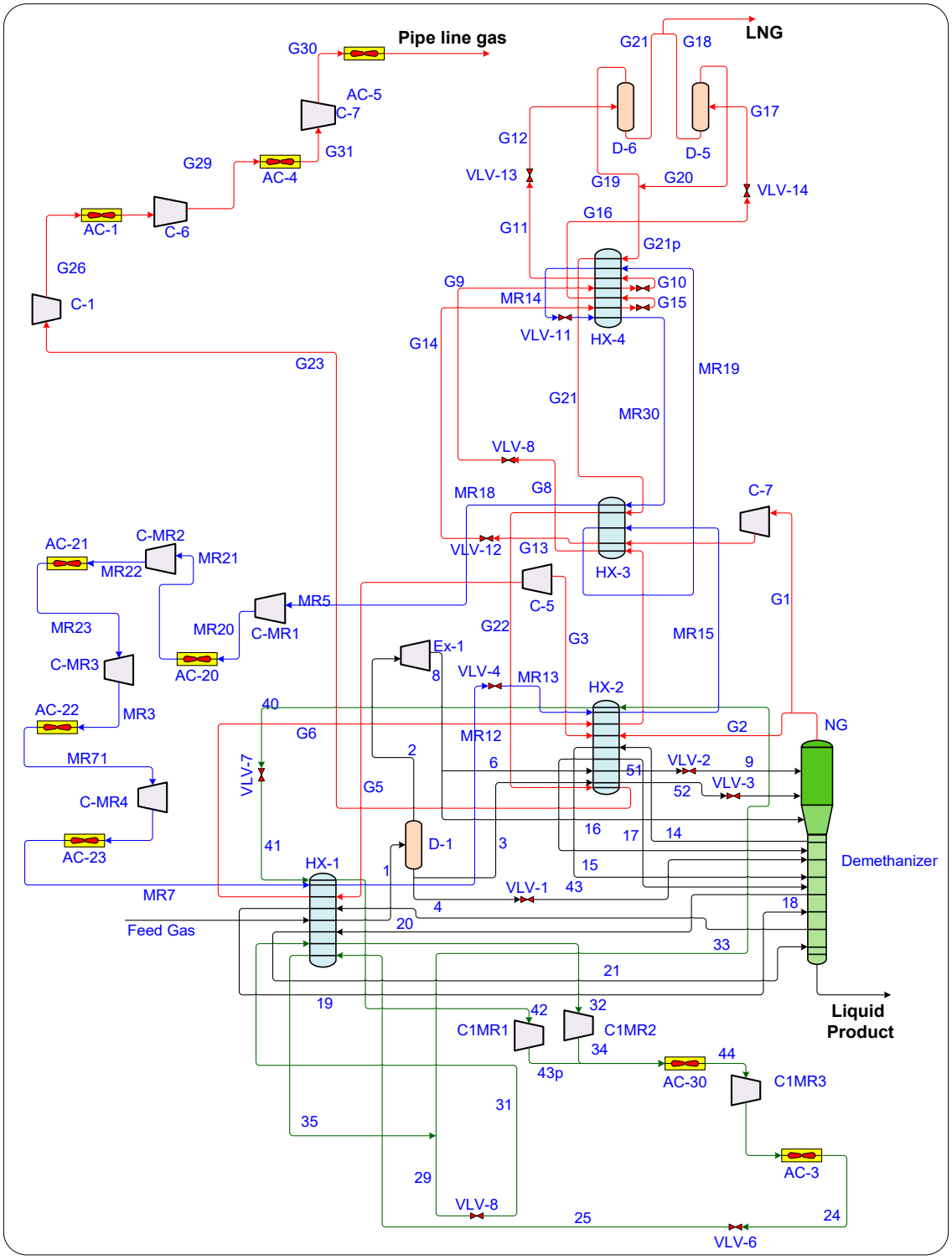


(a)



(b)

Figure S3. Cryogenic distillation technique for N_2 removal from natural gas: (a) single column and (b) double columns, modified from Refs. [17, 18].



LNG: Liquefied natural gas, NG: Natural gas, MR: Mixed refrigerant, C: Compressor, AC: Air cooler, HX: Heat exchanger, D: Flash drum, EX: Expansion device, and VLV: Valve

Figure S4. Process flow diagram for the hybrid NGL and LNG production based on the C3MR refrigeration cycle, modified from Ref. [19].

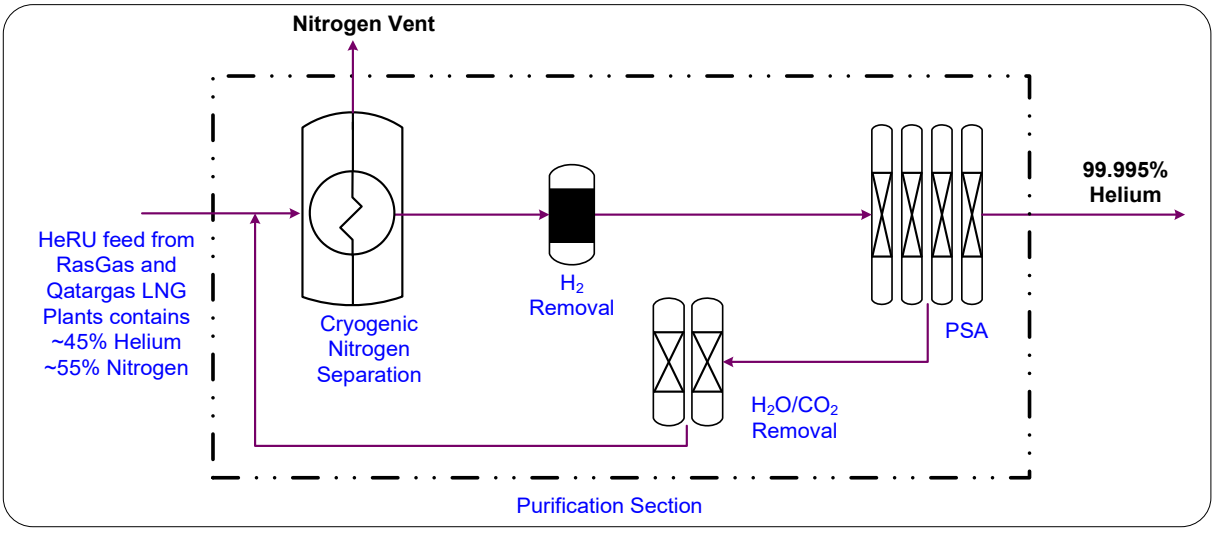


Figure S5. Block flow diagram of an integrated helium production unit, removing N_2, H_2, and CO_2, modified from Ref. [20].

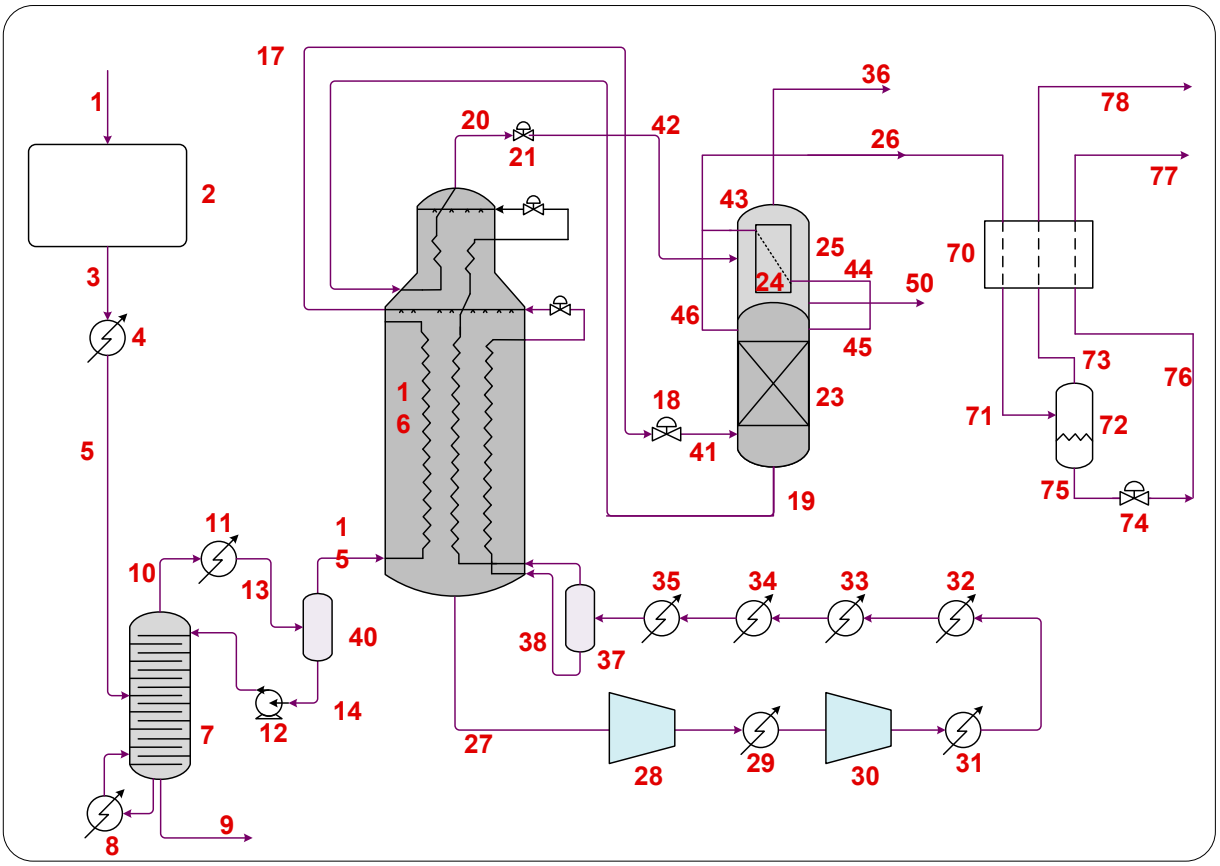


Figure S6. A simplified schematic of the LNG/NGL process integrated with a distillation-based HeXU, modified from Ref. [21].

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