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Comparative Analysis of the Refrigeration of Natural Gas Using Propane Pre-Cooled Mixed Refrigerant and C_1-C_3 Cascade Refrigerant

Edeh Ifeanyichukwu[1*] and Obetta Collins Emeka[2]

[1]Department of Chemical Engineering, University of Port Harcourt, Rivers State, Nigeria

[2]Centre for Gas, Refining and Petrochemicals, University of Port Harcourt, Rivers State, Nigeria.

***Corresponding Author**
Edeh Ifeanyichukwu, Department of Chemical Engineering, University of Port Harcourt, Rivers State, Nigeria.

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Abstract
The liquefied natural gas remains the most viable means of global distribution of natural gas. Unfortunately, the liquefying process consumes high amount of energy impacting negatively on the economic viability of the LNG business. Based on this, the current work assesses the selection of propane pre-cooled mixed refrigerant [C_3MR] and methane, ethane and propane [C_1-C_3] refrigerant cascade system as a refrigerant with essential benefits in LNG production. The process was simulated using Aspen HYSYS, and its economic tool was used to carry out the techno economic analysis and estimate the duties of the two processes. The results obtained showed that the production cost were $20,345,490 and $114,796,200 for C_1-C_3 cascade refrigeration system and C_3MR, respectively. The duty were 568.721 MW and 626.462 MW for the C_1-C_3 cascade refrigeration system and C3MR, respectively. This shows that C_1-C_3 cascade refrigeration system performed better than the C_3MR. Therefore, the former refrigerant is preferred in a liquefying process than the latter as it is cheaper, consumes less amount of energy and is more environmentally friendly.

Keywords: *Natural Gas; Liquefaction; Mixed Refrigerant; Cascade; LNG*

Introduction

Natural gas [NG] appears to be the cleaner and fast-growing fossil fuel. The drive for the rapid growth of natural gas as a major source of power generation is due to its low environmental impact, i.e. less emission of the acidic oxides compared to other fossil fuels. This made LNG industry to benefit most from the undiluted increase in natural gas consumption worldwide [1]. As a result of high demand for natural gas [NG], the liquefied gas [LNG] has been widely in use in comparison with other fossils fuels. The liquefaction of natural gas helps to reduce the cost of transportation, danger of high flammable natural gas and negative environmental impacts of using natural gas [2]. When natural gas is cooled down to a temperature of about -162 oC at 101.325 kPa, it is converted into a liquefied natural gas [LNG] with a reduction in its volume by a factor of 1/600 [3].

Due to the suitability for transportation over a long distance, LNG has become a global commodity making global natural gas market more integrated. It is expected that LNG will account for 15 % of the global natural gas consumption in 2035, with an annual growth of 3.9 % in LNG market [3]. Liquefying natural gas is highly profitable, although cost intensive. For years, researchers have worked on different practical processes to liquefy natural gas more efficiently. Their works have resulted in notable increase in liquefaction cycles with reduced capital and operating costs, and have improved energy efficiency [4]. In liquefying natural gas, cryogenic liquefiers and refrigerators are being utilized involving single component fluids system and mixed refrigerant [MR] systems [5]. The propane mixed refrigerant [C3-MR] process is the most commonly used refrigerant and it involves the propane and the mixed refrigerant cycles, respectively. The former precools the natural gas to approximately -35 oC and partially condenses the mixed refrigerant in the propane kettles, while the latter supplies the required cooling in the main cryogenic heat exchanger to liquefied natural gas at -160 oC [6].

The C_3-MR refrigerant cycle is very efficient in the arid and tropical regions having rich and lean natural gas feed in the absence or presence of liquefied petroleum gas extraction within a wide range of temperature. Its major drawbacks are the large volume of propane and space that are required [7]. The cascade circuit is typically made up of successive stages, each with successively colder refrigerants. These refrigerants are pure [methane, ethylene and propane] with different boiling points and each stream has an independent compression system. With these refrigerants, the natural gas is cooled to -35 oC, -90 oC and -155 oC in propane, ethylene and methane cycles, respectively

[8]. The process requires a minimum compressor shaft power [9]. The major disadvantage of the cascade circuit is the huge amount of capital cost required and its efficiency increases with increasing capital expenditure. Cascade processes are suitable for large production capacities. Statistics hold that 42 % of the LNG total projects lie on the costs of liquefaction and refrigeration. However, natural gas liquefaction is energy consuming and any process to reduce the high energy consumption will promote economic benefits investigated the makeup for large scale use of LNG as compared with different alternative fuels in terms of safety, cost, availability, performance and economy. Engine was also compared against fuel consumption, cost saving and emissions. LNG appears to perform better than heavy fuel oil due to fuel cost reduction by 31% per year. The emission from LNG complies with the current international maritime organization regulation evaluated the selection of C3-MR and cascade cycle in natural gas liquefaction process using Aspen Hysys V7.3 by Peng-Robinson equation of state. The parameters evaluated were the specific horse power, LNG production and revenue of LNG obtained from the two processes [3,10,11].

The results obtained showed that pure refrigerant cascade had lower specific horse power than the C3-MR by 69%, C3-MR produced more LNG [2.86 MTPA/Train] than the pure refrigerant cascade [2.64 MTPA/Train], and the revenue from the C3MR process was more than that of pure refrigerant cascade by 94%. The current work investigated the comparative analysis of the refrigeration of the natural gas using propane precooled mixed [C3MR] refrigerant and C1-C3 cascade refrigerant through simulation in Aspen HYSYS. The production rate, power requirement and cost of production involved in each process were determined to help in the selection of a more economical refrigeration system.

Methodology

Determination of physical properties of the feed and refrigerants

Physical properties of the feed These were determined using the Peng – Robinson equation of state and Lee – Kesler –Pocker equation in the liquefaction process simulation in Aspen HYSYS. The thermodynamic properties such as temperature, pressure, entropy and enthalpy were determined as it relates to natural gas processes [12,13]. The Peng-Robinson equation is presented in Equation 1 and Lee-Kesler-Pocker in Equation 2.

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \quad 1$$

Where P = pressure, T = temperature, R = gas constant, and a and b are constants relating to gas species and are given below

$$a = \sum_{i=1}^{N} \sum_{i=1}^{N} x_i x_j (a_i a_j)^{0.5} (1 - k_{ij})$$

$$b = \sum_{i=1}^{N} x_i b_i$$

$$Z = Z^0 + \frac{\omega}{\omega^r} (Z^r - Z^0) \quad 2$$

Where; Z = compressibility factor, ω=acentric factor, 0 and r denote relevant parameters.

2.1.2 Physical properties of the refrigerants

These were special gases whose bubble point temperatures were used to pre-cool and sub-cool natural gas stream to a very low temperature of about -155 OC in exchangers [Table 1].

Table 1: Mixed refrigerant composition [NLNG, 2018]

Component	Mole fraction
Methane	0.5054
Ethane	0.3383
Propane	0.0717
Nitrogen	0.0846

Liquefied Natural Gas Production

The production of the liquefied natural gas was simulated using C1-C3 and C3MR refrigeration systems. An overview of the production process is presented in Fig. 1, and a more detailed descriptions are given in sections 2.2.1 and 2.2.2. The feed conditions included pressure [5000 kPa], temperature [25 oC], molar flow rate [1.352 x 105 kmol/h], mass flowrate [2.511 x 106 kg/h] and vapor phase fraction [0.9842]. The natural gas composition is presented in Table 2, and thermodynamic property package used was Soave-Redlich-Kwong [SRK].

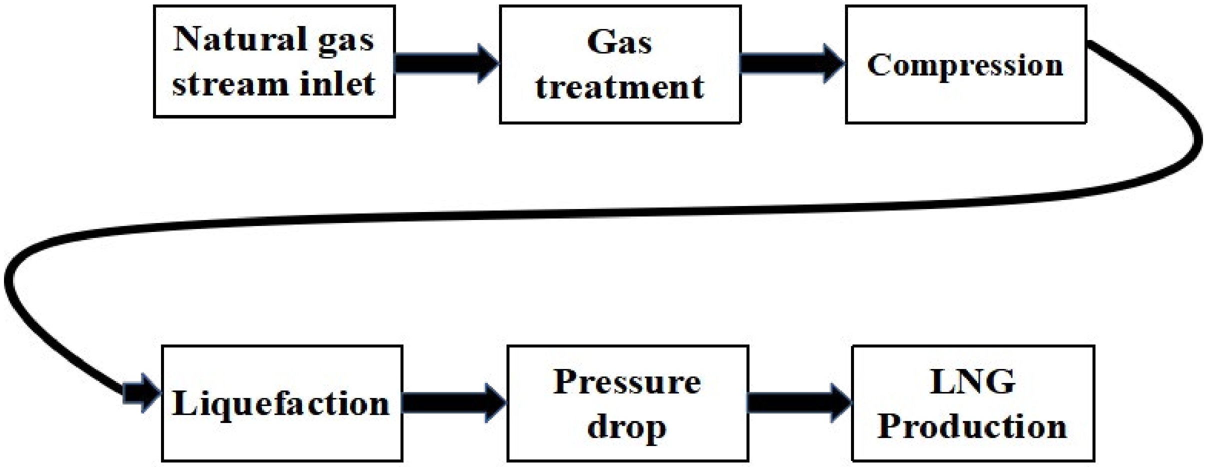

Figure 1: Schematic illustration of the liquefied Natural Production

Table 2: Natural gas composition

S/N	Component	Composition (mol. %)
1.	Methane	0.883
2.	Ethane	0.0551
3.	Propane	0.008
4.	n-Buthane	0.0075
5.	i-Butane	0.0057
6.	C_{5+}	0.0090
7.	H_2O	0.0166
8.	CO_2	0.0151

Production of liquefied natural gas using C_1-C_3 refrigeration system

The feed [natural gas] stream was sent into a gas sweetening section to remove CO_2 and then to the dehydration unit to exclude water which is represented in the Aspen HYSYS design as a separator [Figure 2]. In the dehydration unit, water exit as a bottom product and the gas leaves the separator as an overhead product. The gaseous product from the dehydration unit is sent to the Natural gas liquid [NGL] unit modeled with a component splitter. The NGL recovery unit removes the natural gas liquid as a bottom product and the overhead product containing methane and ethane were sent to the refrigeration section for liquefaction. The inlet gas temperature was reduced to –161.3 oC by the refrigeration process. At this temperature, the entire gas stream was transformed to liquid now called liquefied natural gas [LNG]. The liquefied stream was sent

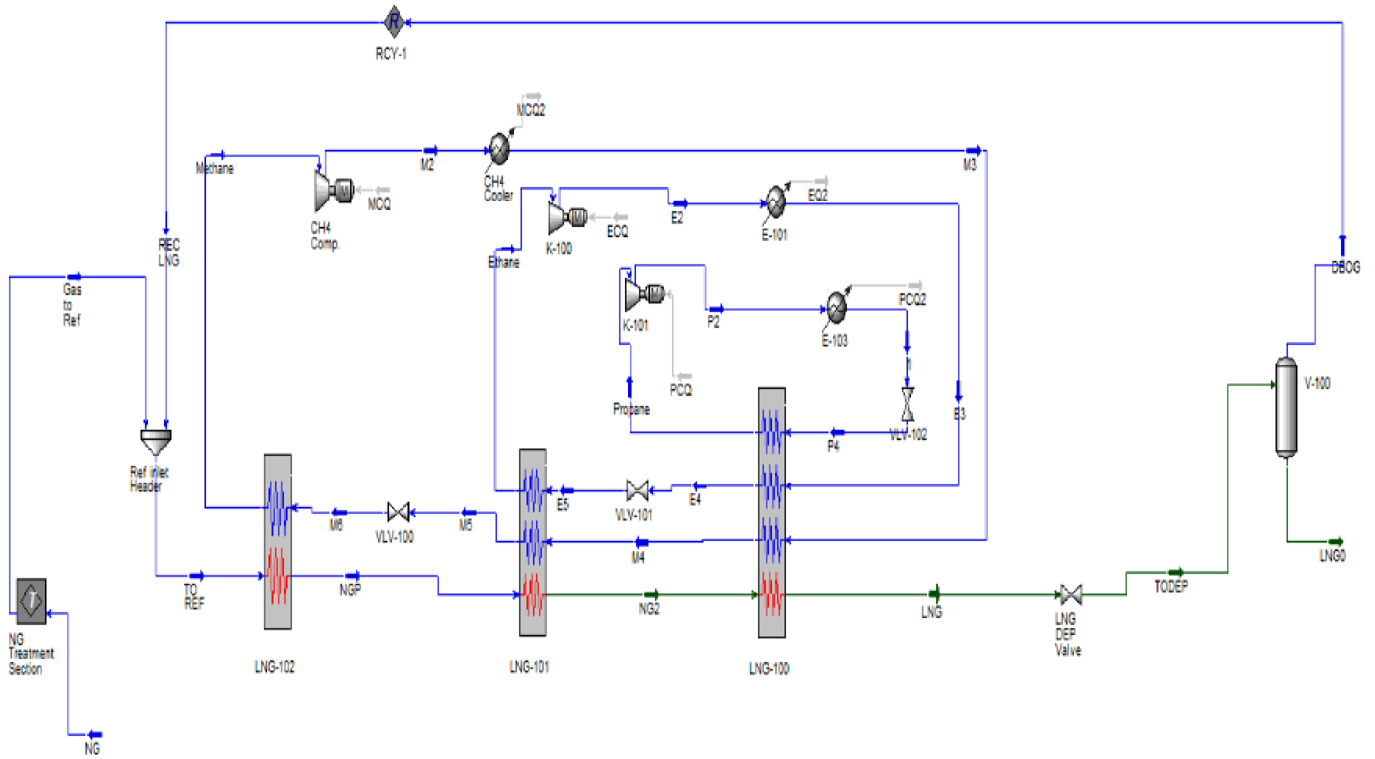

Figure 2: Schematic of $C_1 - C_3$ cascade refrigeration system

through a valve where the joule Thompson effect occurred to reduce the pressure and further a flash drum to remove any form of a vapor [boil-off gas] that might have arisen during pressure reduction and to prevent pump cavitations during shipment. While the LNG is withdrawn from the bottom of the flash drum the boil-off gas is collected overhead and sent to back through compressors to the refrigeration section of the plant for re-liquefaction.

Production of liquefied natural gas using propane pre-cooled mixed refrigerant [C3MR] system

The C3 refrigeration system cools the MR and the NG streams from the treatment section to -37.37 oC and -35.50 oC respectively. As shown in Figure 3, the pre-cooled mixed refrigerant enters into the separator [V-100-3], separating it into a light vapor phase mixed refrigerant [LVPMR] and a heavy phase mixed refrigerant [HPMR], to provide the cooling for the approaching natural gas stream in main cryogenic heat exchanger [LNG-100-3]. The resultant LNG stream [LNG 3-2] sub-cools to -89.64 OC. This process is repeated till the final LNG stream sub-cools to -155.6 OC, which finally undergoes a pressure drop through a J-T valve [VLV-103-2] to achieve a liquefied natural gas [LNG] result with a temperature of -163.8 OC. The LNG was passed through a flash drum to vapourize the entrained vapor [boil-off gas] in the LNG. While the LNG was recovered from the bottom and sent to the storage tank, the boil-off gas was flared.

Pressure Relief Valve

The LNG pressure and temperature were reduced using the pressure relief valve before entering the flash drum as the designed pressure is less than the pressure of the entering LNG. The underpinning mathematical equation in HYSYS is given in Equation [2.2]

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H = \frac{V}{C_P}(\propto T - 1) \qquad 2.2$$

H = U + PV

Where: μ_{JT} = J-T coefficient expressed in oC/bar (SI units: K/Pa)

C_P = Heat capacity, V = volume

(∂T/∂P) H =Temp. and press. gradient, □ = Coefficient of thermal expansion

In the J-T expansion valve, enthalpy (H) is constant; U = Internal energy

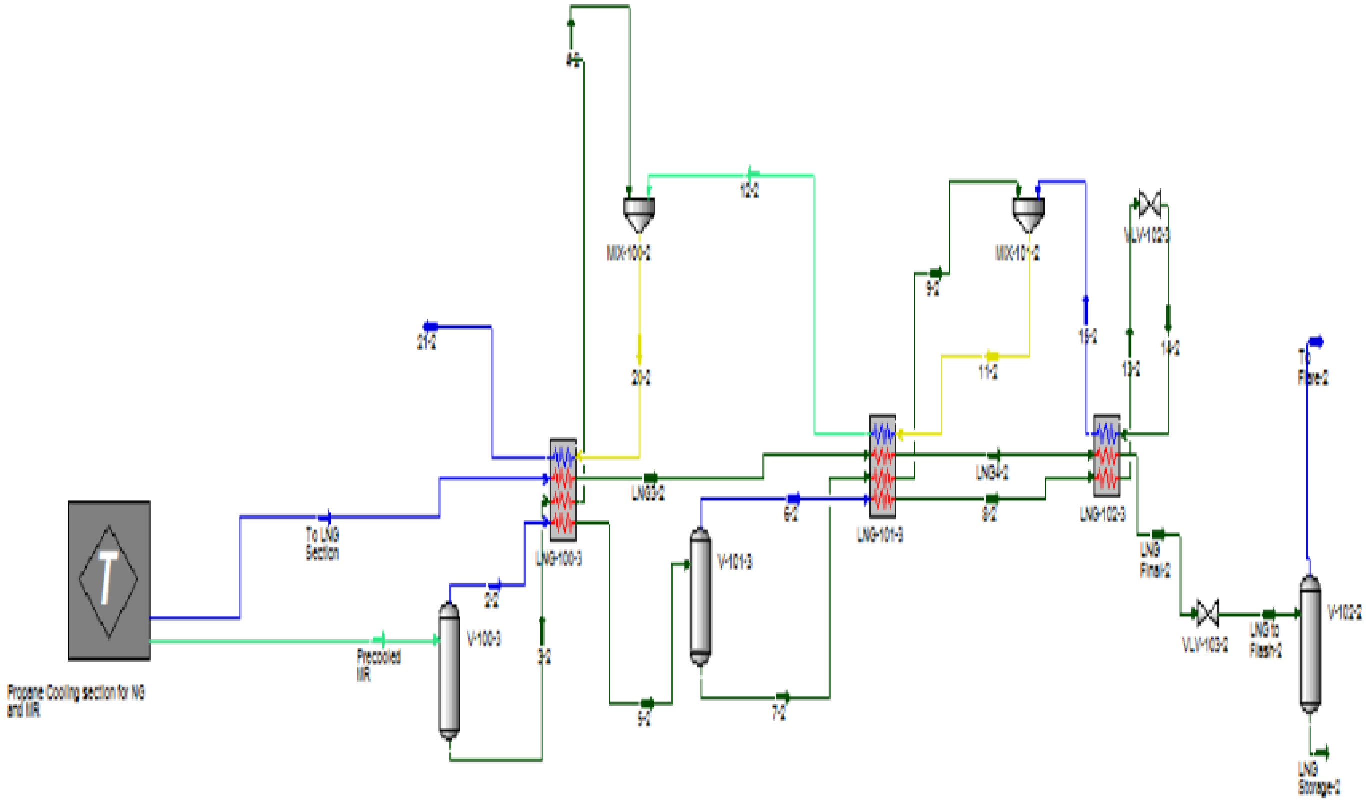

Figure 3: The C3MR process flow diagram simulated using Aspen HYSYS

Determination of the Amount of Power required during the refrigeration Processes

The rating of some unit operations [compressors, coolers and heat exchangers] of the process was performed to determine the power consumed per unit. This was done by clicking on the respective unit operations in Figures 2 and 3 above and taking records of the duties [kw].

The cost estimation of the Refrigeration Processes

The cost estimation of the unit operations such as compressors, heat exchangers, coolers, separators and valves were performed to determine the capital and the operating costs through the use of Aspen HYSYS economic rating. This was carried out by clicking on the economics and the drop down bar on economic active to activate the mapping, sizing and evaluation status on the Aspen HYSYS flow sheet. To obtain the summary, the economics ribbon tab was used. The total cost comprises the capital cost which is the purchasing costs of the main items like the exchangers, compressors and coolers etc, while the operating cost encompasses of charges of electrical duties, consumption of materials and maintenance per annum.

Results and discussion

The LNG production

The quantity of LNG obtained from the natural gas using C_3MR refrigeration unit was 3.2 x 10^5 kg/hr [or 1.870 x 10^4 kmol/h] comprising 94.66 % methane and 4.270 % ethane at -163.8 OC and 80 kPa, and that from C_1-C_3 was 1.9 x 10^6 kg/hr [1.216 x 10^5 kmol/h] containing 98.16 % methane and 1.840 % of ethane obtained at -161.3 oC and 100 kPa. The results show that the use of C1-C3 cacasde refrigeration system resulted to a higher throughput of LNG.

Cost Estimation and rating of both Refrigeration Processes to determine the best Economic Importance

From the result obtained, as presented in Table 3, the total cost of the two processes are given as 114,796,200 [USD] and 20,345,490 [USD] for C3MR and C_1-C_3 processes respectively. According to literature, obtained a total production cost of 165,731,974 [USD] as compared with C_3MR and C_1-C_3 with least total cost of production of LNG as 114,796,200 [USD] and 20,345,490 [USD] respectively [4]. See Table (3).

Table 3: Cost estimation and power rating of the two processes

Parameter	C_3MR	C_1-C_3
Total capital cost (USD) Total operating cost (USD)	92,106,100 22,690,100	18,524,700 1,820,790
Total cost (USD)	114,796,200	20,345,490

The power requirement of the C_3MR and C_1-C_3 refrigerants in the production of LNG using the natural gas received at a temperature of 25 oC, pressure of 5000 kPa and molar flow of 1.352 x 10^5 kmol/h is presented in Fig. 1. The figure shows that using C1-C3 will require higher amount of energy by 93.12% compared to C3MR refrigerant due to higher number of compressors, coolers and heat exchangers involved. The result was expected, since the mass flow rate of the LNG produced using C_1-C_3 was greater than that obtained from C3MR by 84.03% requiring more energy input [14-22].

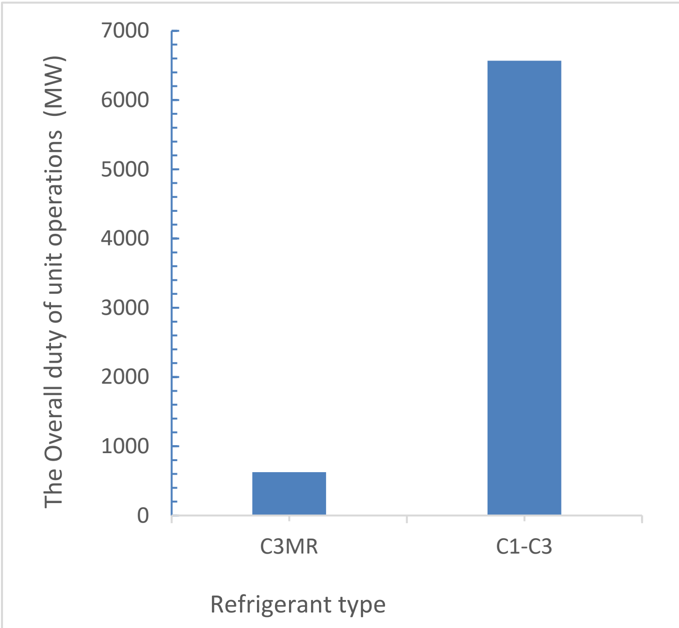

Figure 1: Comparing the power requirement of the LNG production using C3MR and C1-C3 refrigerants

Conclusion

Owing to the large cost implication of the LNG plants, efforts are being made through research work to cut cost of liquefaction through simulation. Two major refrigeration systems were compared to find out the most economical process of natural gas liquefaction. Results obtained depict that the two processes [C3MR and C1-C3]; Produced LNG at -163.8^{O}C, -161.3^{O}C and duties at 626.462MW, 568.721MW respectively. Therefore, the C_1-C_3 cascade system is cheaper to operate than C_3MR system.

Nomenclature

C_1	Methane	P	Pressure (kPa)
C_2	Ethane	P_c	Critical pressure
C_3	propane	R	Gas constant
C_3MR	Propane precooled mixed refrigerant	ω	Acentric factor
MR	Mixed refrigerant	T	Temperature (°c)
LNG	Liquefied natural gas	T_c	Critical temperature (°c)
NG	Natural gas	T_r	Reduced temperature
H_2O	Water	LVPMR	light vapor phase mixed refrigerant
CO_2	Carbon iv oxide	HPMR	Heavy phase mixed refrigerant
N_2	Nitrogen	SRK	Soave-Redlich-Kwong
C_p	Heat capacity	μ_{JT}	J-T coefficient oc/bar

U	Internal energy	$\propto$	Coefficient of thermal expansion
H	Enthalpy	V	Volume

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