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Thermal Energy Storage-Heat Exchanger (TES-HEX) System in a Natural Gas Processing Plant to Avoid Thermal Fatigue and Gas Degradation

Mohammed A. Al-Tayyar[1*], Saif W. Mohammed Ali[2], Hussam H. Jabbar[3]

[1] Department of Petroleum Engineering, Faculty of Engineering, University of Karbala, Karbala 56001, Iraq
[2] Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Kufa, Najaf 54001, Iraq
[3] Department of Energy Engineering, Faculty of Engineering, University of Baghdad, Baghdad 10071, Iraq

Corresponding Author Email: mohammed.a.hashim@uokerbala.edu.iq

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ABSTRACT

The current study proposes a solution to the thermal fatigue that caused failure in the Brazed Aluminum Heat Exchanger (BAHX) located in the Natural Gas Line (NGL) producer train plant or the Enterprise Products Midstream gas plant (PGP), which was installed in Pascagoula, Mississippi, USA, to fit the Iraqi environmental conditions. Thermal Energy Storage (TES) system would be integrated into the BAHXs to store any implausible increase in the heat that can cause thermal fatigue. Simultaneously, part of the stored heat is used in the distiller to avoid any excessive heat for the separation process. The study was performed under different mass flows of NG and different inlet temperatures. The effect on the purity of Compressed Natural Gas (CNG) and thermal properties was taken into consideration, too. The degradation of other product components, like Liquid Petroleum Gas (LPG), was also studied in the current work. Different Phase Change Material (PCM) types were investigated to be used in the TES systems, where a novel parameter was differentiated called the PCM parameter to characterize the PCM physical properties. It was found that 6346 kW of heat can be stored at half the processed flow rate, while this amount can approach 25386 kW of heat storage if the flow rate is doubled. Stream temperature and mass flow rate increase as maximum possible heat storage increases, but at different inclinations and gradients. The best PCM parameter was found to be placed within (1.8-3.6 °F/min) of the Rate of Change (ROC), where the values range between (2788 kJ/K – 2777 kJ/K). 17.6% is the maximum LPG mole fraction form 1th stage of the distiller.

1. INTRODUCTION

The growing reliance on fossil fuel-based energy, as opposed to renewable sources, is anticipated to have detrimental environmental and health consequences. To mitigate these effects and comply with regulatory limits on toxic pollutants such as CO_2, H_2S, SO_2, and particulate matter associated with natural gas processing, effective control measures are essential. One viable approach is to enhance natural gas treatment processes through strategies such as acid gas removal and thermal management of products. These improvements not only enhance byproduct sustainability and equipment efficiency while reducing exergy destruction but also contribute to improved economic performance.

Poe and Mokhatab [1] outlined key principles for understanding the complex systems involved in natural gas processing, emphasizing integrated design, advanced control systems, and real-time optimization to ensure safe, efficient, and profitable operations. Stewart and Arnold [2] provided a comprehensive guide to natural gas processing and sweetening, focusing on acid gas removal (H_2S and CO_2), dehydration, Natural Gas Liquid (NGL) recovery, and overall process design.

AlNouss and Al-Sobhi [3] assessed the sustainability of recent acid gas treatment technologies—specifically targeting CO_2 and H_2S in Liquefied Natural Gas (LNG) production using Aspen HYSYS. The study introduced innovations such as Acid Gas Enrichment (AGE) and Tail Gas Treatment Units (GTU), designed to lower emissions and enhance sulfur recovery. These advancements were found to benefit the environment and contribute to improved sustainability.

A proposed optimized design for Acid Gas Removal Units (AGRUs) in natural gas production to meet environmental regulations while minimizing energy consumption and utility costs is presented by Cho et al. [4]. Their study included a sensitivity analysis, revealing that structural modifications can enhance acid gas removal. Key parameters such as solvent flow rate, temperature, condenser duty, and heat recovery were found to influence both energy efficiency and removal performance.

Given the critical role of moisture content in natural gas production and the limitations of online sensors that often necessitate manual measurement, Ren et al. [5] suggested a machine learning-based approach to predict the water dew point in dehydration units. By automatically collecting process parameters, the method enables real-time prediction using existing Supervisory Control and Data Acquisition (SCADA) data, aiming to enhance both safety and operational efficiency.

Zarezadeh et al. [6] presented an optimized approach for pretreating natural gas, specifically sweetening and dehydration before liquefaction, aimed at reducing energy and exergy losses. For the sweetening unit, key optimization variables included MDEA concentration, piperazine concentration, and the operating pressures of the absorber and regenerator. In the dehydration unit, inlet and regeneration temperatures were identified as critical parameters influencing performance.

To enhance system efficiency, reduce power consumption, and minimize equipment requirements, Ghorbani et al. [7] proposed an innovative and optimized integrated process that combines NG, NGL recovery, and Nitrogen Rejection Unit (NRU). Exergy analysis revealed that the major losses occurred in components such as air coolers, heat exchangers, compressors, expanders, valves, and columns. Sensitivity analysis identified the recycle stream temperature, flow rate, and NRU operating pressure as key parameters affecting energy consumption.

Petropoulou et al. [8] focused on reducing energy consumption while evaluating the economic feasibility of a natural gas dehydration unit using triethylene glycol (TEG). The study involved simulating and optimizing the TEG process by comparing two thermodynamic models. Seven operational parameters were analyzed, namely, stripping gas rate, reboiler temperature, regenerator pressure, regenerator feed temperature, surge drum temperature, contactor temperature, and contactor pressure. The findings highlighted the importance of accurate thermodynamic modeling for designing efficient dehydration systems. Demonstrating that optimization strategies can effectively lower energy usage and operating costs without increasing capital investment.

A turboexpander with a Mechanical Refrigeration (TEMR) scheme was used to enhance the energy efficiency of a Natural Gas Processing Unit (NGPU) [9]. The Energy, Economic, Recovery, Quality, Safety, and Production were evaluated as key criteria of this study. The optimized criteria at the operational conditions reduced energy consumption and enhanced economic expenses. However, these improvements come with trade-offs, including minor decreases in NGL recovery and elevated safety risks.

Shoghl et al. [10] examined a three-stage Joule–Thomson (JT) throttling process in an NGL recovery unit to maximize NGL recovery, improve exergy efficiency, and evaluate phase behavior. The proposed configuration comprised three JT valves, three separators, and a heat exchanger, and its performance was assessed under seven different pressure-drop scenarios. The study found that optimal design should prioritize a balance between recovery efficiency and energy savings, rather than relying solely on cooling capacity. Jourablou et al. [11] examined the nitrogen expansion cycle used in mini-LNG plants, focusing on its sensitivity to ambient temperature and feeding gas pressure. Their study found that stable LNG production is maintained between 5–15 °C but declines significantly above 15 °C due to reduced cooling efficiency and lower turbine power output. Additionally, feed gas pressures above 35 bar support stable production, while pressures below 30 bar led to sharp declines due to pressure drop effects. The study also concluded that water cooling is more efficient and recommended for nitrogen expansion units, as the cooler is the primary source of exergy losses. Abubakar et al. [12] simulated a system designed to simultaneously recover CO_2 and produce sweet, carbon-neutral natural gas from wet natural gas. The study found that discharge pressure and feeding temperature impact the compressor's power requirements. Additionally, the performance of the heat exchanger was influenced by temperature and pressure, which directly affect vapor fraction and heat duty.

The corrosion caused by CO_2 on carbon steel was studied by Hamad and Mohammed [13]. The effect of CO_2 depends on several factors, such as temperature and the duration of exposure to corrosive media. The study identified that the corrosion rate increases as the temperature increases.

The natural gas processing stages, including acid gas removal, require specialized equipment capable of handling fluctuations in temperature and pressure, as well as managing byproducts. However, the absence of online monitoring for certain parameters and the lack of a reliable safety process often led to incidents, such as the one in Pascagoula, Mississippi [14]. The incident report identified thermal fatigue in the brazed aluminum heat exchanger (BAHX) as the root cause, resulting from temperature fluctuations. These fluctuations caused small cracks that eventually developed into hydrocarbon leaks. The unrepaired presence of such cracks can contribute to the catastrophic failure of the equipment.

To overcome this problem, a novel design will be presented in this paper that utilizes the Phase Change Material (PCM), which is capable of storing excess energy during the acid gas removal process. The Thermal Energy Storage (TES) unit is proposed to be integrated into BAHXs to store the excessive heat. A novel parameter is derived from the current study called the PCM parameter to characterize the proper PCM properties. The study is performed under different inlet conditions and different ROCs. The effect of utilizing part of the energy storage on the purity of CNG product and liquefied petroleum gas (LPG) degradation is considered in the present work too.

BAHXs are designed to operate under higher pressure that approaches 100 bar and a temperature range of -269 to 204 °C [15]. Literally, PCM material is used to be integrated with these kinds of heat exchangers to recover any excessive heat. The main issue with these PCM-heat exchanger integrated units is the lower layer efficiency; therefore, a number of projects were studied to enhance the thermal performance, including different configurations of fins; plain, triangular, perforated, and serrated are among these shapes. Løvseth et al. [16] made different approaches to create the most efficient and feasible LNG, including modeling and optimizing the heat exchanger processes. Skaugen et al. [17, 18] utilized dynamic flow sheet simulation tools to emulate the thermodynamic processes in BAHXs. It was found that static instability and process efficiency are traded off in such a way that obtaining higher instability requires lower process efficiency. Skaugen et al. [17, 18] also used the ASPEN PLUS tool to process the BAHXs in the LNG system. Optimization models were developed by previous studies [19-22] to obtain the most efficient and feasible geometries of heat exchangers with regard to recording best thermal performance for these types of heat exchangers. Entropy and exergy analysis are the base theories that were used to analyze the overall performance and the optimization algorithm viability. Integrating PCM as a thermal storage material has been a fashionable trend when it is associated with a heat exchanger in cryogenic systems. A mixture of Propane-Methanol was proposed by Li et al. [23] under low-temperature conditions and high heat capacity. It was found that in the case of transferring heat between gaseous and solid phases, the required storage volume becomes 10 times that of liquid and gaseous phases. Therefore, utilizing liquid phases is more feasible and compact economically for heat exchangers, as stated by Araki et al. [24].

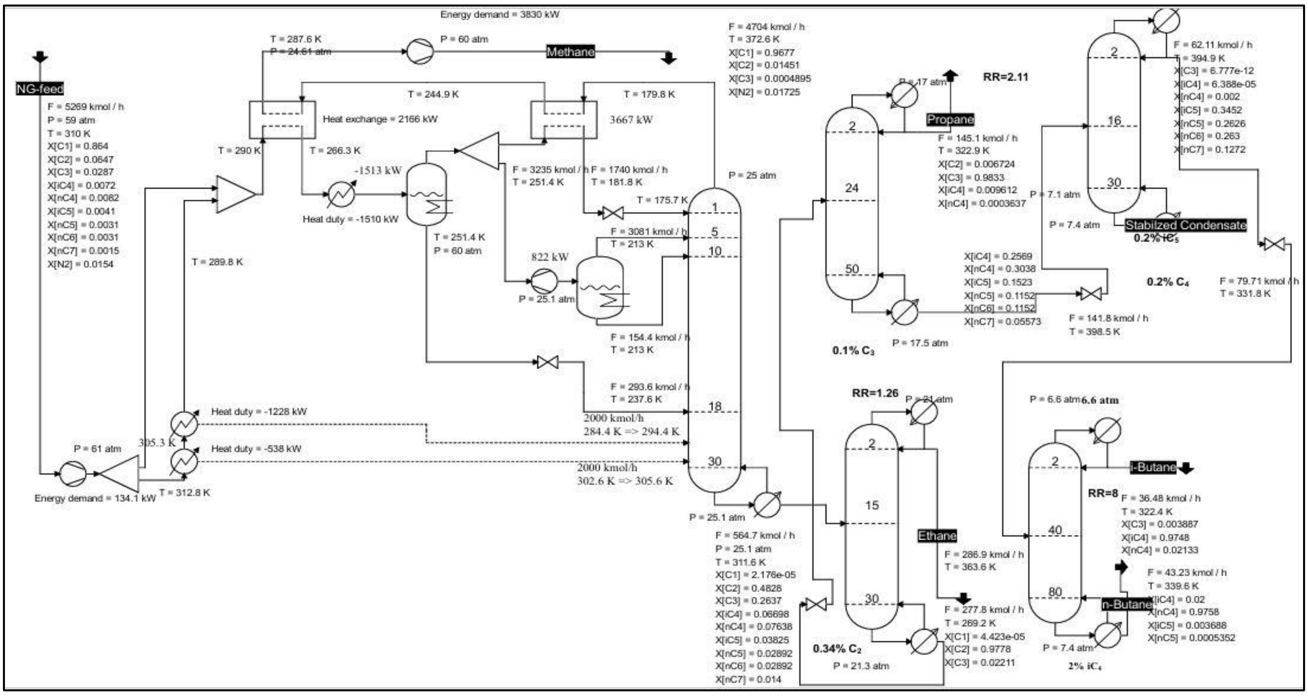

Figure 1. Dynamic flow sheet represents the Midstream gas processing unit [25]

2. METHODOLOGY

The Midstream gas processing plant, which is shown in Figure 1, was built virtually via dynamic flow sheet software called COFE version 3.9.0.5. The unit mainly consists of seven units. The first unit is to reduce the inlet temperature of the feed NG stream to about 290 K before entering the first stage of BAHX. Another reduction in the exit stream temperature would be processed before entering the second stage of BAHX to approach 251 K. Both heat exchangers represent the second unit to process the NG stream, where it would exchange heat with the final produced pure gas stream (97% of methane) to raise its temperature to 287 K. The demethanizing processing unit is the third unit, which is used to extract the Methane gas stream mentioned above. On the other hand, the residues would be processed in the last four units to extract Ethane, Propane, and two stages of Butane extraction, respectively.

Table 1 illustrates the components' mole fractions and flow rates (kmol/h) of the processed feed NG stream to the unit. The maximum mole fraction in the feed NG stream is the fraction of Methane (CH_4 = 0.864), representing (4553.416 kmol/h) of the processed gas, while the minimum is the fraction of (Heptane = 0.001), representing (7.9035 kmol/h) of the total processed gas. The remaining percentages represent all other gas components.

Table 2 shows the standard specification limits of the BAHX that would be used in the NG processing unit, after which the BAHX is exposed to the danger of thermal and structural fatigue [26-28]. As it is shown in Table 2, the maximum allowable pressure for BAHX ranges between (1200–480 Psig), while (1050–570 Psig) represents the most frequent normal range that can be reached. It was shown that heat can be transferred at a rate equal to 108 °F per hour or at a normal range between (1.8–3.6 °F/min). On the other hand, if ROC passes the (7 °F/min) threshold, this will subject the BAHX to a possible thermal shock. The expected inlet temperature of the NG feed stream ranges between (250–290 K), where any increase above this range refers to thermal fatigue danger.

Table 1. The feed stream components of the processed natural gas (NG) [25]

NG Feed Components	Mole Fraction	Compounds Flow (kmol/h)
Methane (CNG (C1))	0.864	4552.416
Ethane (C2)	0.0647	340.9043
Propane (LPG(C3))	0.0287	151.2203
Butane (C4)	0.0072	37.9368
n-Butane (nC4)	0.0082	43.2058
Pentane (C5)	0.0041	21.6029
n-Pentane (nC5)	0.0031	16.3339
n-Hexane (nC6)	0.0031	16.3339
Heptane (C7)	0.0015	7.9035
N7	0.0154	81.1426

Table 2. Brazed aluminum heat exchanger (BAHX) specifications and feed properties [26-28]

Property	Specification Limits Range	Frequent Repeated Value
Over pressurization limits	1200 – 480 Psig (Ibf/in2)	1050 – 570 Psig (Ibf/in2)
Rate of Change (ROC °F/min)	1.8 -7 °F/min	1.8 – 3.6 °F/min
Inlet stream temperature (K)	250-290 (K)	250-290 (K)

3. THE ECONOMIC FEASIBILITY ANALYSIS AND MODEL VALIDATION

3.1 Economic feasibility

Regarding the economic feasibility of integrating such system, it was demonstrated that adopting solutions to avoid thermal fatigue in BAHXs unit would cost much lower price than the operation and maintenance costs of these kinds of heat exchangers as was stated by Vicente and Jeffery [29] that these projects would save about \$3.5 millions over ten years and also extent the life span of BAHXs units where the cost of each unit requires more \$10 million.

3.2 Validation

To validate the obtained values of ROC (F/min) of the temperature model developed in the current study, the range of obtained data was compared against the data recorded by Decker [30]. It was shown that the data obtained from the current work are very close to the range of ROC (F/min) gotten by Douglas D., as explained in Table 3 below.

Table 3. Validation of the current work data

ROC (F/min) Form Current Study	ROC (F/min) Form Douglas [13]	Error %
1.8 to 3.8 with maximum value 8	2-5 with maximum value 9–10	15 % to 24%

4. MATHEMATICAL MODELING

4.1 Assumptions

The presented mathematical model would be developed under the following assumptions:

a. The maximum temperature difference between streams and metals does not exceed 50 °F (28 °C). If the difference exceeds the limit, the stream flow must be slowed down until the difference is adjusted within the limited range.

b. The flow cycles are frequent (steady state flow) in such a way that the stream temperature fluctuation is limited to 1.8 °F (1 °C).

c. The rate of change (ROCs) of inlet and outlet temperature for startup and shutdown are limited to 1.8 (°F/min) with allowance up to 8 (°F/min).

d. Energy conversion is considered to be ideal as unity ($\eta = 1$).

The present theoretical work was governed by three systems of equations. The governing equations for the cooling and heat exchange of the NG processing were the first system of equations, which were used in the early stages of NG processing. Secondly, the PCM material in the TES system was solved theoretically using heat balance in a storage system. Finally, inside the gas distiller column, the product separation between column stages was treated using mass and heat balance as described below.

4.2 Heat balance inside the cooling and heat exchanging process

In the early stages of NG processing, there are two working fluids that are operated on: the hot fluid stream and the cold fluid stream. Thus, the equations below represent the above-mentioned processes [31, 32]:

$$Q_{h-c} = \dot{m}_{cold}\, Cp_{cold}\,(Tc_{out} - Tc_{in}) \quad (1)$$

where, $Q_{h-c}, \dot{m}_{cold}$, and Cp_{cold} are the heat transfer, mass flow rate, and heat capacity of the cold gas stream, while Tc_{out} and Tc_{in} represent the outlet and inlet cold stream temperatures. On the other hand, on the hot side of the cooling and heating process, the equation would be as below:

$$Q_{c-h} = \dot{m}_{hot}\, Cp_{hot}\,(Th_{out} - Th_{in}) \quad (2)$$

where, h refers to the hot stream, and c refers to the cold stream.

As thermal fatigue happens in the heat exchanger, the temperature jumps to its highest value. When this process occurs, there would be a possibility of storing the residual heat in the TES unit using PCM material. The maximum allowable energy storage ($Q_{storage}$) that can be processed in this stage can be calculated as:

$$\begin{aligned} &Q_{storage} \\ &= Q_{heat-jump-with\,fatigue} \\ &- (Q_{c-h}\ or\ Q_{h-c})_{normal-without\,fatigue} \end{aligned} \quad (3)$$

4.3 The energy equation of Phase Change Material and Phase Change Material parameters

Regarding PCM modeling with Heat exchanger details and according to Zhang and Ge [33], the energy equation can be represented as:

$$\begin{aligned} \rho\frac{\partial H}{\partial t} = \frac{\partial}{\partial n}\left(k\frac{\partial T}{\partial n}\right) - \frac{\partial}{\partial n}(\rho u H) \\ = Q_{charge-or-Discharge} \end{aligned} \quad (4)$$

where, $H = C * T$.

$$\eta = \frac{E_{storage}}{\int_0^t Q dt} \quad (5)$$

$$Q_{charge-or-Discharge} = \frac{E_{storage}}{v(volume)} \quad (6)$$

$$Q_{storage} = E_{storage} = Q_{charge-or-Discharge} \times v \quad (7)$$

$$\rho c v \frac{\partial T}{\partial t} = Q_{storage} \quad (8)$$

Thus, the energy stored in the PCM material was simply governed by the equation below [34]:

$$Q_{storage} = \frac{dT}{dt}\rho c v \quad (9)$$

As $\frac{dT}{dt}$ is the ROC of temperature with time, while (ρ), (c), and (v) are the density, heat capacity, and volume of the energy storage material. A novel parameter was differentiated in the current work called the PCM parameter, to characterize the proper PCM material that can be integrated in the TES unit.

This parameter can be calculated as below:

$$\text{PCM parameter} = \rho cv = \frac{Q_{storage}}{\frac{dT}{dt}} \left(\frac{kJ}{K}\right) \quad (10)$$

4.4 Mathematical modeling of the distiller column

Generally, the distiller column is operated under simple mass and heat balance. However, as the column consists of a number of stages in addition to using an extra amount of energy to separate between phase products and breaking down the chemical bonds, this may seem to increase the complexity of the equation system somehow. Thus, the mathematical modeling of a distiller can be derived as below [35]:

$$V_{j+1}Y_{i,j+1} + L_{j-1}X_{i,j-1} + F_jZ_i - (1 + r_j^v)V_jY_{i,j} - (1 + r_j^L)L_jX_{i,j} = 0 \quad (11)$$

$$V_{j+1}q_{j+1}^v + L_{j-1}q_{j-1}^L + F_jq_j^F - (1 + r_j^v)V_jq_j^v - (1 + r_j^L)L_jq_j^L - Q_j = 0 \quad (12)$$

where,

$$r_j^v = \frac{U_j}{V_j}, r_j^L = \frac{W_j}{L_j} \quad (13)$$

j is the stage inside the column, while X_i and Y_i are the rates (i) of the product compositions of (L) phase and (V) phase, respectively. F_j and Z_i are the added streams to the column at the stage j and its product rate, respectively. W_j and U_j are the streams at the column exit. Finally, q represents the phase enthalpy while Q_j is the heat added for the separation process.

5. RESULTS AND DISCUSSION

5.1 Effect of inlet conditions

Figure 2 shows the effect of feed stream inlet conditions on the maximum allowable heat storage in the proposed integrated system. The figure demonstrates that as the inlet temperature increases, the maximum allowable energy storage increases linearly for all studied flow rates. The system also investigates the maximum allowable amount of heat storage at different rates of NG processing discharge: 0.5, 1, 1.5, and 2 of the processed NG discharge. As illustrated, as the flow rate increases, the maximum allowable storage amount increases too. However, the slope and gradient for higher discharge are steeper than the slopes for lower discharge. This seems to be dependent on the temperature difference of the heat exchanger.

5.2 The calculated Phase Change Material parameter

Figure 3 shows the calculated PCM parameters at different rates of change (ROC) values and different inlet conditions, respectively. It was shown in Figure 3(a) that as (ROC) increases, the calculated PCM parameter is reduced linearly. Mathematically, this comes from the fact that ROC is placed in the denominator of the PCM parameter equation. However, as was stated in Table 2, the most frequently repeated normal value of ROC ranges from (1.8–3.6 °F/min); thus, the most appropriate PCM parameter ranges from (2788 kJ/K – 2777 kJ/K). Therefore, even the proposed PCM parameter would not be feasible if the PCM parameter is not placed within the above-mentioned range, as any reduction below this range still exposes the system to sudden thermal fatigue. Figure 3(b) demonstrates the effect of inlet mass flow rate and inlet temperature on the required PCM parameter to stabilize the system and avoid sudden thermal fatigue. It was shown that increasing the processed NG flow rate and feed inlet temperature requires storage material that has a higher PMC parameter. However, as the processed NG rate increases, the slope and magnitude of the PCM parameter increase too.

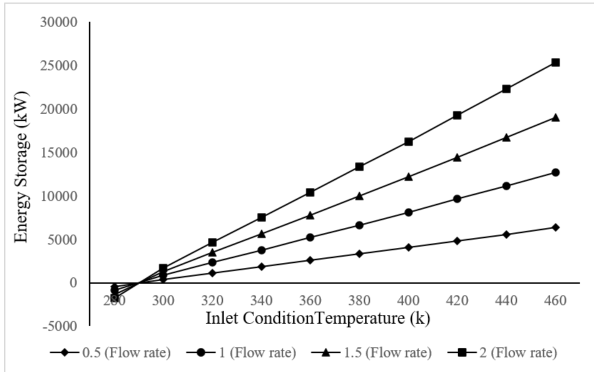

Figure 2. The maximum possible energy storage at different inlet conditions

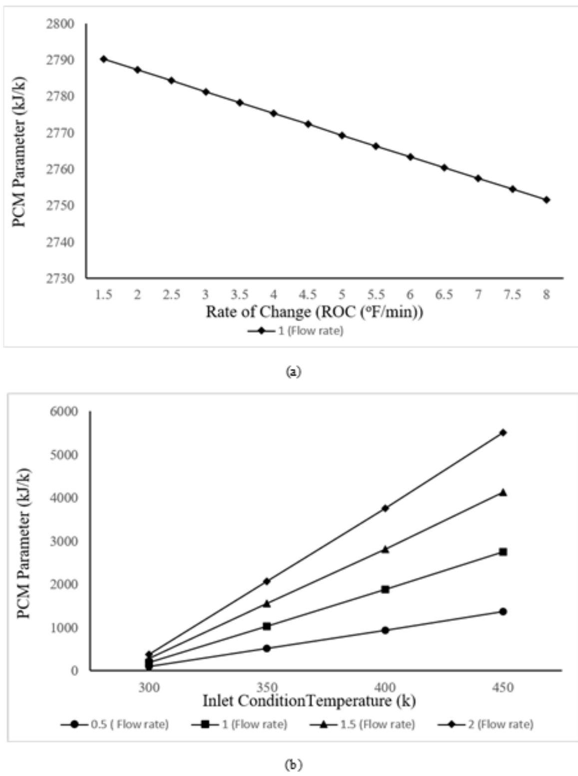

Figure 3. The calculated phase change material (PCM) parameters (a) at different rates of change (ROC) and the processed flow rate, (b) at different inlet conditions and the highest maximum ROC (8 °F/min)

5.3 Effect of the processed energy on the product's purity

The effect of utilizing part of the stored energy on the produced phases' mole fractions along the distiller column's stages, the temperature of the exit CNG stream, the purity of the exit CNG stream, and the degradation of the LPG stream is shown in Figure 4, respectively. As the stages of distiller column are numbered for (1) to (31) starting from the distiller top until distiller bottom, the highest CNG mole fraction (0.96889) would be at the top exit stream and starts decreasing along the column till reaching its minimum values at the bottom of the column (stage 31) where all other products phases fractions would be processed in another column distillers. This explains why LPG mole fraction behaves in contradictory trends with CNG behavior, where LPG mole fraction increases from the top at its minimum value to reach its maximum value at the distiller's bottom stages, as was shown in Figure 4(a).

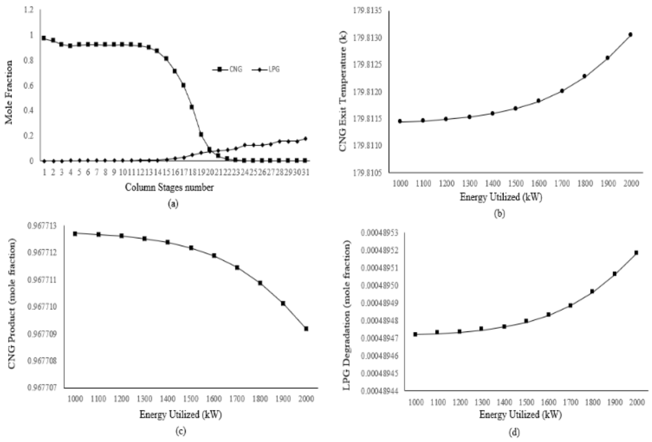

Figure 4. Produced components properties, (a) Compressed natural gas (CNG) and liquid petroleum gas (LPG) products along column stages, (b) CNG exit temperature at different utilized energy, (c) CNG phase fraction at different utilized energy, (d) LPG degradation at different utilized energy

Figure 4(b) illustrates the effect of utilized energy on the CNG exit stream temperature. It is shown that as utilized energy increases, an exponential increase is noticed in the exit temperature. However, the increase in temperature is insignificant, as most of the energy utilized is consumed to separate between stream phases rather than the temperature increase. The effects of the utilized energy on the purity of the CNG exit stream and degradation of the LPG stream are shown in Figure 4(c) and (d), respectively. As shown in the figures, increasing the processed energy in the column distiller unit leads to exponential reduction trends in the CNG mole fraction and exponential increase trends in the LPG mole fraction. This comes from the fact that any increase in the processed energy will affect the strength of chemical bonds between components, leading to the breaking down of these bonds. In addition, the increase in the utilized energy would lead to an increase in the vaporization rate of the other phases, causing degradation in the LPG phase and other products.

6. CONCLUSIONS

A proposed solution for the failure that occurred at the Enterprise Products Midstream gas plant (PGP), Pascagoula, Mississippi, USA, was investigated in the present study. The failure was caused by thermal fatigue and residues in the BAHX unit of the PGP plant. The current study proposed integrating a TES system into the BAHX unit. The maximum allowable heat storage was investigated under different processing mass flow rates and inlet temperatures. In addition, a novel parameter, referred to as the PCM parameter, was developed to facilitate the selection of a suitable PCM for the TES system. The effect of utilizing part of the stored heat in the CNG distillation column on CNG product purity and LPG degradation was also investigated. The remarks below were concluded from the current study:

- The increase in the processed NG feed discharges and temperature leads to an increase in the stored heat for all mass flow rates. However, as mass flow increases, the curve's inclination increases too.
- At a lower inlet temperature, the effect of the processed NG discharges would not be significant.
- As the ROC increases, the maximum suitable PCM parameter is reduced. Indeed, the most proper PCM parameter is placed within (1.8-3.6 °F/min) ROC, as was reported from the literature, which ranges between (2788 kJ/K – 2777 kJ/K).
- As the inlet mass flow and temperature increase, the most suitable PCM parameter increases too at different slopes, where at a lower slope, the effect of inlet conditions is not noticeable.
- The partially stored heat utilized in the distiller column has a positive effect on CNG exit stream temperature, where it increases exponentially at a low and insignificant rate, and most of this heat is used for the separation process.
- Contrary to the previous point, the partially utilized heat negatively affects the CNG exit stream purity, where the mole fraction is reduced exponentially. On the other hand, the utilized heat causes degradation in the LPG fractions from the residue stream, where it increases exponentially with the CNG exit stream.
- Furthermore, the results indicate that integrating the TES system into the BAHX has the potential to mitigate thermal fatigue by improving thermal management under different operating conditions. The operating ranges and PCM selection criteria identified in this study can serve as practical guidelines for plant operators when selecting suitable operating conditions and evaluating TES implementation in natural gas processing plants.

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