OPTIMIZATION AND ENERGY EFFICIENCY INVESTIGATION OF AN INDUSTRIAL GAS CONDENSATE SEPARATION PLANT

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REFERENCE NO	ABSTRACT
INDS-01	Simulation of an industrial gas condensate separation unit is performed using Aspen Plus by evaluating several equations of state (EoS) from classical and advanced models, namely, PR EoS, CPA EoS, and PC-SAFT EoS. The results show that all models are capable in giving good approximation of the actual data, however, CPA EoS gives the most accurate results. The influence of reflux ratio and feed condition on product and heat duty of the plant are investigated through sensitivity analysis. It is found that, increasing the feed temperature reduces reboiler duty, however, it has insignificant effect on condenser duty. Also, higher feed flowrate increases heat duty for each splitter and air cooler. Reducing reflux ratio decreases heat duty in each splitter. Additionally, reducing the reflux ratio in second splitter will result in higher production of desired hydrocarbons. Finally, in the specified optimum conditions, the required energy reduces by more than 20%.
Keywords: Gas condensate separation unit, Aspen Plus Simulation, Thermodynamic evaluation	

1. INTRODUCTION

Natural gas has emerged as a new sustainable source of energy [1]. It has many advantages than other fossil fuels such as low price and negligible pollutant emission to the environment [2]. Generally natural gas contains impurities such as water, acid content such as CO_2, H_2S, sulphur compounds such as mercaptans as well as salts and nitrogen . Purification of natural gas is required to facilitate natural gas processing, reducing pollutant emission to the environment and to get a valuable product [3, 4]. This includes phase separation process to get liquid heavy condensate. H_2S and CO_2 as well as mercaptan removal is necessary because of processing and environmental problems such as catalyst corrosion, global warming and acid rains [5-7]. The treated gas condensate will undergo a further processing which is called gas condensate stabilization [8]. The aim of this unit is to separate raw condensate from natural gas, to get different hydrocarbons and pure components by increasing the quantity of intermediate (C_3 to C_5) and heavy components (C_{6+}) through separation of the very light hydrocarbon gases such as methane, ethane and propane [8]. Based on purpose of the unit, there could be more than two main streams. In such cases including this work, each product stream contains group of hydrocarbons with more similar molecular weight.

Stabilization tower is the most essential equipment in stabilization unit [9]. Two main technologies in gas condensate stabilization process are flash vaporization and fractionation which are described briefly. In flash vaporization process, usually the raw condensate from upstream enters the flash drum which will result in partially separation of light hydrocarbons by means of decreasing the pressure. Removal of light hydrocarbons is necessary for transport and storage purposes [10]. After that, the stream will be stabilized more by separation of different hydrocarbons through sequential separation. The latter which is also called distillation condensate stabilization, in compare to the flash vaporization is more efficient which helps

producing liquids with suitable vapour pressure [10]. In condensate stabilization process, vapour pressure of condensate liquid is reduced which will prevent the vapour phase production in atmospheric conditions. Condensate stabilization procedure is a mature process. Different aspects of gas condensate stabilization unit are studied by several authors.

PC-SAFT EoS was used by several authors and compared with cubic equation of states such as PR and SRK. Atilhan et al. simulated phase envelope and density of natural gas mixtures [11]. In another study done by Karakatsani and Kontogeorgis, CPA EoS in combination with van der Waals−Platteeuw (vdW-P) model was used to predict phase behaviour of natural gas system which contains water [12]. In a work done by Rahmanian et al. effect of several parameters including temperature, pressure and flow of the feed as well as reboiler duty on Reid Vapour Pressure (RVP), liquid recovery and the sulphur content has been investigated by HYSYS simulation [13]. In this work, the steady state simulation of a gas condensate separation plant performance is carried out by using several EoS. In doing so, the PR, CPA and PC-SAFT EoS are implemented in Aspen Plus V9 to predict the plant data and to find the most suitable thermodynamic model. Then, the best EoS is used to find the effect of different parameters on plant performance. A sensitivity analysis is performed to inspect the influence of operational parameters. Effect of feed conditions such as feed flow rate and feed temperature as well as reflux ratio on heat duties and final product flow has been investigated.

2. PROCESS DESCRIPTION

The gas condensate stabilization unit aims at removing light and heavy components from raw gas condensate feed which contains three major groups of components classified as light ends, heart cut stream and heavy ends. The obtained naphtha heart cut which contains the main feed for the aromizing unit is then routed to the downstream units [14] . The plant is designed to process 568182 kg/h of gas condensate. This capacity corresponds to a production of 94205 kg/h of para-xylene, 54433 kg/h of benzene, and 12626 kg/h of ortho-xylene.

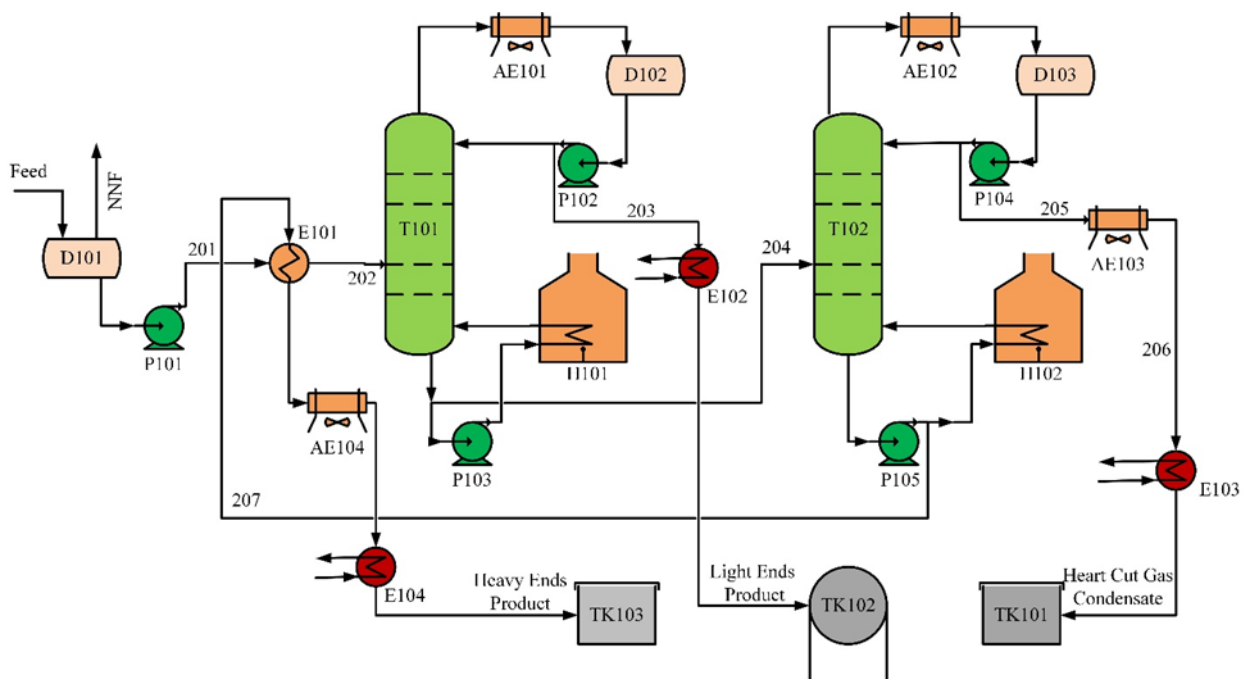Schematic diagram of gas condensate separation unit is shown in Fig. 1.

Fig. 1. Schematic diagram of gas condensate pre-fractionation unit.

The gas condensate feed composition and conditions are reported in Table 1.

Table 1. Gas condensate feed specifications.

Composition			
Component	Mole percent	Component	Mole percent
C_3	0.7	C_7 naphtene	2.7
I-C_4	2.9	C_8 naphtene	3.6
N-C_4	8.0	C_9 naphtene	1.1
I-C_5	5.7	C_{10} naphtene	0.8
N-C_5	6.4	Benzene	0.5
I-C_6	5.1	Toluene	0.8
N-C_6	4.0	EB	0.1
I-C_7	5.2	P-xyl	0.2
N-C_7	5.2	M-xyl	0.4
I-C_8	5.9	O-xyl	0.2
N-C_8	4.6	C_9 aromatic	0.6
I-C_9	5.2	C_{10} aromatic	0.4
N-C_9	3.6	N-C_{11}	3.6
I-C_{10}	3.9	C_{12}-C_{16}	10.2
N-C_{10}	2.4	C_{17}-C_{21}	2.6
MCP	0.4	C_{22}^+	1.4
CH	1.4	Total	100
Conditions			
Mole flow (kmole/h)		4822.39	
Mass flow (kg/h)		568182	
Temperature (°C)		47	
Pressure (bar g)		3.5	
Density (kg/m^3)		695	

The characteristics of splitters are given in Table 2.

Table 2. Specifications of two splitter columns.

	T101	T102
Number of stages	49	44
Feed stage	32	20
Condenser pressure (bar g)	6.7	1.4
Condenser heat duty (bar g)	26.6	47.9
Reboiler pressure (MW)	7.3	1.8
Reboiler heat duty (MW)	59.1	30.8

3. METHODOLOGY
3.1. Thermodynamic models
The phase behaviour prediction of hydrocarbons and thermodynamic properties by means of equations of state (EoS) is an essential step in chemical, petrochemical and petroleum industries [15]. Two class of EoS are widely used in simulating natural gas processes, namely, classical models and advanced models. In case of classical models, Peng-Robinson (PR) EoS and Soave-Redlich-Kwong (SRK) EoS are the most popular representative EoS due to their simplicity and are widely used in simulating the gas processing processes [16-19]. This class of EoS is based on the early work done by van der Waals [20]. Advanced model EoS which are based on association theory placed in second category [21]. In this study, PR EoS from classical models and Cubic Plus Association (CPA) EoS [22], along with Perturbed-Chain Statistical Association Fluid Theory (PC-SAFT) EoS [15] from advanced models are chosen for phase behaviour and thermodynamic modelling of gas condensate pre-fractionation unit. These models are described briefly in follow.

3.1.1. PR EoS
The PR EoS was developed in 1976 by Ding-Yu Peng and Donald Robinson [18]. The PR EoS has become one of the most useful models in natural gas systems. Along with to academic fields, it is successfully applied for thermodynamic calculations in industrial purposes [23]. The PR EoS formula is shown by Equation.1 [18].

$$P = \frac{RT}{v - b} - \frac{a(T)}{v(v + b) + b(v - b)} \tag{1}$$

In Equation. 1 parameters P, R, T, v, a and b are pressure, gas constant, absolute temperature, volume, van der Waals covolume, respectively [18].

1.1.1. CPA EoS
CPA EoS is another popular equation of state in modelling the petroleum processes [24]. This thermodynamic model which is suggested by Kontogeorgis et al., is composed from the SRK EoS and Wertheim theory [22]. In a mixture, self-association (between molecules of same compounds) and cross-association (between molecules of non-similar compounds) can occur as a result of hydrogen bonding interactions. In CPA EoS, SRK EoS considers the physical interactions and Wertheim theory takes into account the chemical or association parts. The resulting equation is not cubic due to the associating parts from Wertheim theory [25].

$$P = \frac{RT}{v - b} - \frac{a}{v(v + b)} +$$
$$\frac{RT}{v} \rho \sum_A [\frac{1}{X^A} - \frac{1}{2}] \frac{\partial X^A}{\partial \rho} \qquad (2)$$

In Equation. 2, P, R ,T ,v ,a ,b, ρ, and X^A are pressure, gas constant, absolute temperature, volume, energy parameter, van der Waals covolume, molar density and mole fraction X^A of molecules not bonded at site A [22].

1.1.2. PC-SAFT EoS
SAFT EoS is based on the first order perturbation theory of Wertheim [22, 26, 27]. Several modifications of SAFT EoS are developed such as SAFT-VR, LJ-SAFT, soft-SAFT, simplified SAFT and PC-SAFT [28, 29]. Among different modifications of SAFT EoS, PC-SAFT EoS which was introduced by Gross and Sadowski [16] is the leading modified version. Expressing PC-SAFT EoS in terms of compressibility factor (Z) as follows [15]:

$$Z = Z^{id} + Z^{hc} + Z^{disp} \qquad (3)$$

where $Z = \frac{Pv}{RT}$ and $Z^{id} = 1$ is the ideal gas compressibility factor, Z^{hc} and Z^{disp} are hard chain and dispersive compressibility factors, respectively [15].

3.2. Simulation procedure
In order to use PR, CPA, and PC-SAFT EoS in simulation software, some of pure component parameters and binary interaction coefficients are taken from references [30-32] as the Aspen plus does not provide all required parameters. Fig. 2 shows the Aspen plus simulation flow sheet diagram of the process.
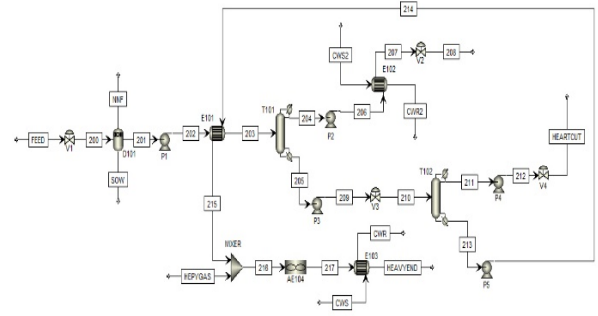

Fig. 2. Aspen Plus simulation flow sheet diagram of the process.

Due to lack of information for a number of heavy components, PC-SAFT pure parameters for C_{25} are replaced with parameters of most similar components when applying PC-SAFT EoS. Also, no more parameters than what Aspen Plus provides have been used when using CPA EoS. In addition, in case of unknown heavy components the most appropriate structure has been considered.

4. Results and Discussion
The results of this work is presented in two parts. The first part is thermodynamic modelling and comparison of implementing different thermodynamic models in Aspen Plus. In this part, simulation of gas condensate pre-fractionation unit is performed using different thermodynamic models and the results were compared to actual plant data for identifying the most accurate model in plant behaviour prediction. The second part is dealing with investigating effect of different operation parameters on plant performance. In this part, sensitivity analysis cases were done using best thermodynamic model obtained from the first part.

4.1. Thermodynamic modeling and simulation validation
Generally, all EoS are in a good agreement with plant data in predicating the total flow rate of streams and composition of each stream, however, the best overall results are obtained by CPA EoS. The simulation results for predicting the flowrate of each stream is shown in Fig. 3.
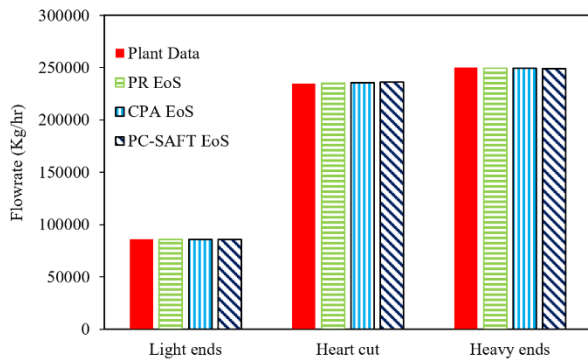
Fig. 3. Products flowrate comparing simulation results and plant data.

Fig. 4. shows the simulation results and actual plant data for predicting the light ends product using different EoS.
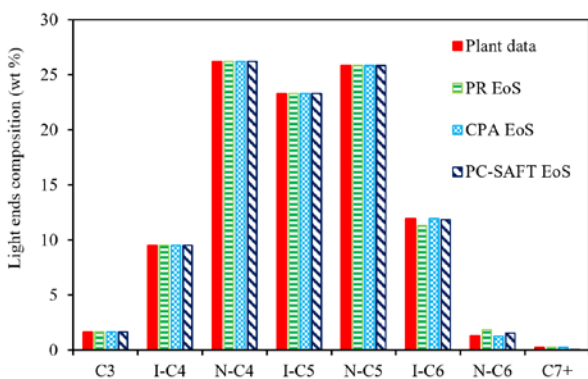

Fig. 4. Composition of light ends product comparing plant data and simulation results.

Fig. 5. shows the results for the top product of second splitter which is also called heart cut stream. Accurate prediction of this stream due to its importance is vital, because this stream is routed to the next units and directly affected to plant productions (i.e. p-xylene, benzene and o-xylene).
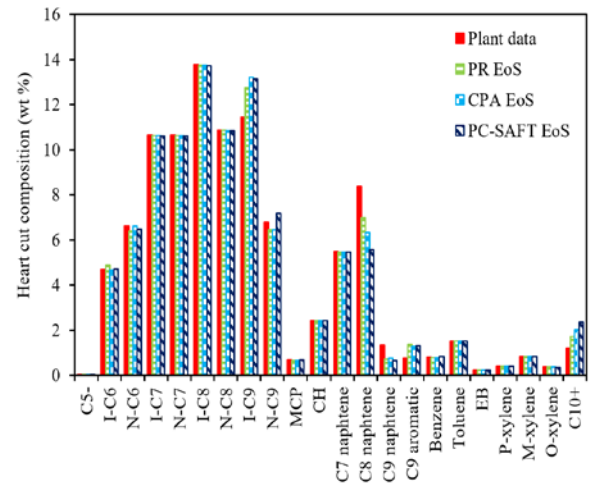

Fig. 5. Composition of heart cut product comparing plant data and simulation results.

Fig. 6 shows the results for the bottom product (i.e. heavy ends) from the second splitter.

1.2. Sensitivity analysis
By comparing the results obtained from simulation using each EoS in previous section, the CPA EoS is chosen to implement the sensitivity analysis as it gives the lowest over all error in predicting the composition.
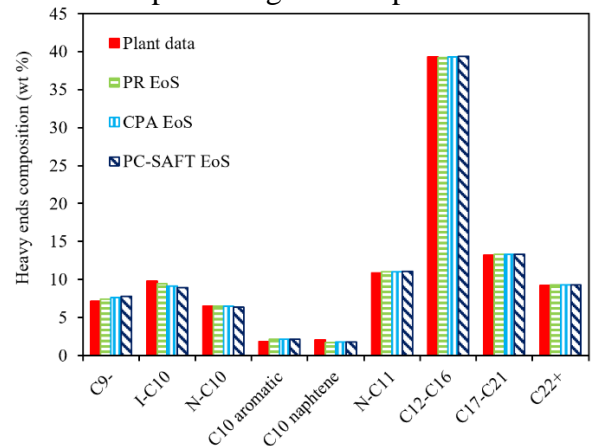

Fig. 6. Composition of heavy ends product for simulated cases by different EoS and plant data.

The effect of parameters which directly affect product quality and heat duties of each splitter including reflux ratio and feed conditions such as temperature and flow rate are investigated.
Fig. 7 shows the envelope curve of the input feed to the condensate stabilization unit. The figure shows that with increasing the feed temperature to over 120 °C, the feed will be in liquid phase region and well away from two

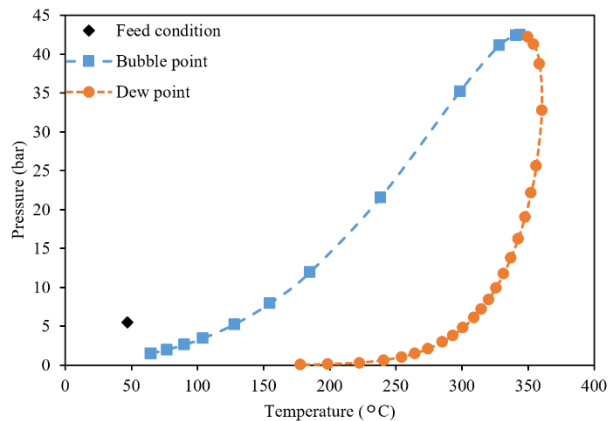phase region which makes the separation of components easier.

Fig. 7. P-T diagram based on feed composition using CPA EoS.

Fig. 8 shows the Aspen Plus simulation result of the effect of main feed temperature on heat duties of first splitter reboiler and condenser. It indicates that as the feed temperature increases about 20 °C, the reboiler heat duty decreases by 15%. However, feed temperature shows insignificant effect on condenser duty.
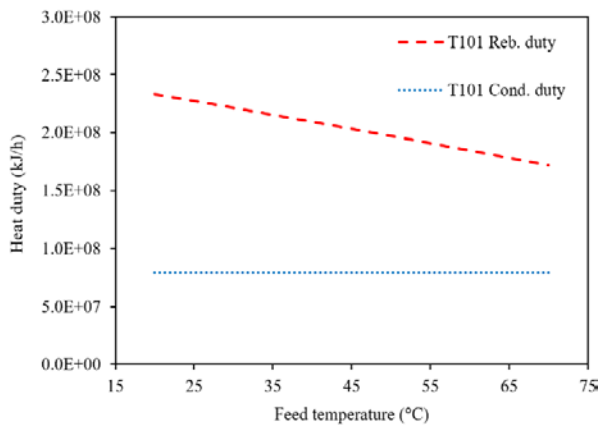

Fig. 8. Effect of feed temperature on T101 reboiler and condenser duty.

Fig. 9 shows the effect of feed flow rate on both splitters heat duties. The input feed for the condensate stabilization unit is provided from other processing units. Thus, the feed flow may change from time to time. Investigating the effect of feed flow on heat duties shows that 10% increase in feed flow rate will result in 10% more heat duty in condenser and reboiler in each splitter.
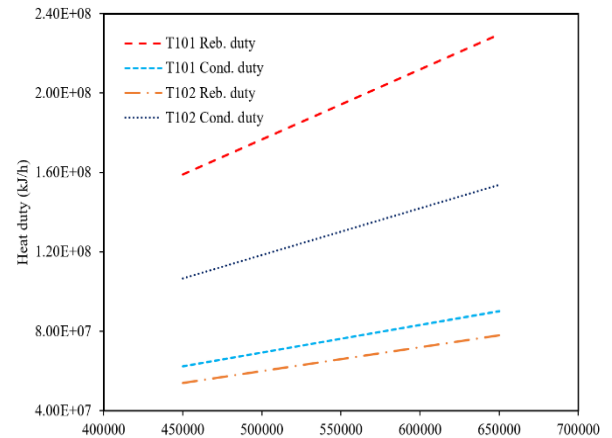

Fig. 9. Effect of feed flow rate on distillation columns heat duties.

Fig. 10 shows the effect of reflux ratio on heat duties and production rate for first splitter (T101). The vertical axis on left side shows the heat duty of T101, while the vertical axis on the right side shows the light end product flow variation with respect to reflux ratio. The figure indicates that 40% increase from the operating reflux ratio will result in 11% increase in reboiler heat duty and 29% increase in condenser heat duty.
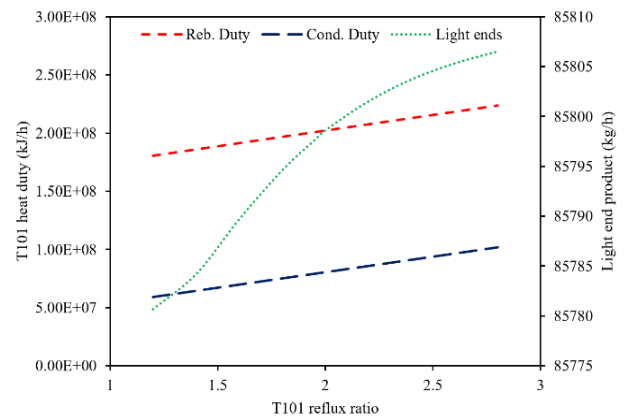

Fig. 10. Effect of T101 reflux ratio on T101 heat duties and light end production.

Fig. 11 shows the effect of reflux ratio on second splitter (T102) heat duties and products rate. The vertical axis on left side shows the heat duty trend with respect to reflux ratio in T102 while the vertical axis on right side shows the T102 products flow changes with increasing the reflux ratio. 14% increase in reflux ratio will result in 39% and 79% increase in reboiler and condenser heat duty, respectively. The aim of this unit is to

increase the heart cut stream which contains the required components such as xylene isomers for other processing units. The figure shows reducing the reflux ratio result in higher heart cut product as well as lower reboiler and condenser heat duty.
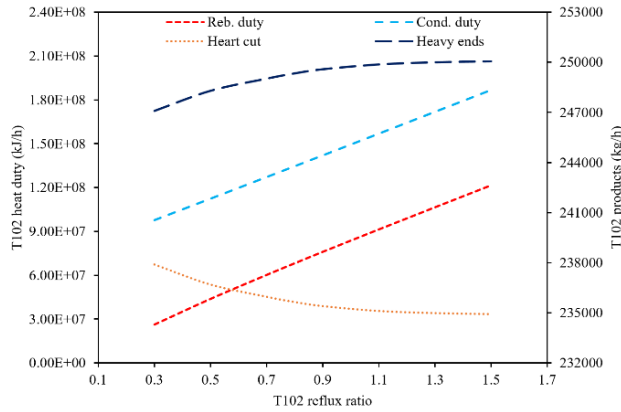

Fig. 11. Effect of T102 reflux ratio on heat duties and production rate.

Fig. 12 shows energy consumption with respect to variation of reflux ratio of both columns. As one can see, by 38.4% reduction in reflux ratio in T101 tower when it changes from 1.98 to 1.2 and 62.5% reduction in reflux ration in T102 tower it reduces from 1.2 to 0.3 they will result in 23.2% reduction in total energy consumption of the unit. Also, the heart cut stream flowrate which contains the required feed for other units will increase by 1%. Thus, the optimum results are obtained when the reflux ratios are 1.2 and 0.3 in T101 and T102, respectively.
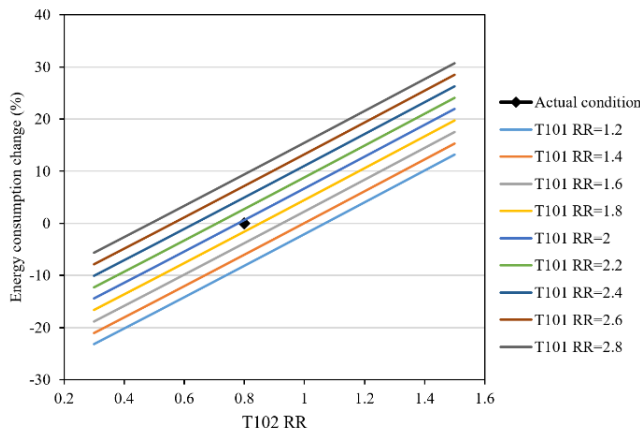

Fig. 12. Energy consumption variation with respect to reflux ratio.

Detailed results of the effect of reflux ratio on energy consumption of the unit is given in Table 3.

Table 3. Comparison between actual and optimum conditions.

Case	Energy Consumption	Stream flowrate
Unit	(kJ/hr)	(kg/hr)
Actual	2.03E+08	235648
Optimum	1.24E+08	237905
Change	-38.85 %	1 %

The energy efficiency of the plant is calculated using the following equation [33]:

$$\eta = \frac{Output\ Energy}{Input\ Energy}\%100 \qquad (4)$$

Where η is the energy efficiency. The results are shown in Table 4. As it is shown in Table 4 the energy efficiency of the plant in actual conditions is 78.56% and in optimum conditions it is 81.71% indicating lower energy consumption particularly in the reboilers and higher energy efficiencies due to optimum reflux ratios.

Table 4. Energy efficiency of the plant

Stream/Component	Enthalpy	
	(kJ/hr)	(kJ/hr)
	Actual	Optimum
Feed	1.15E+09	1.15E+09
Light ends	2.06E+08	2.06E+08
Heart cut	4.30E+08	4.34E+08
Heavy ends	4.80E+08	4.75E+08
Reboiler 1001	2.03E+08	1.88E+08
Reboiler 2001	6.75E+07	2.63E+07
Total input enthalpy	1.42E+09	1.36E+09
Total output enthalpy	1.12E+09	1.12E+09
η (%)	78.56	81.71

Fig. 13 shows the air cooler heat duty trend with respect to feed flow rate, indicating 13% increase in the air cooler heat duty with increasing the feed flow rate by 14% from the actual feed flow rate. The figure shows the air cooler heat duty will change linearly with respect to changes in feed flow.
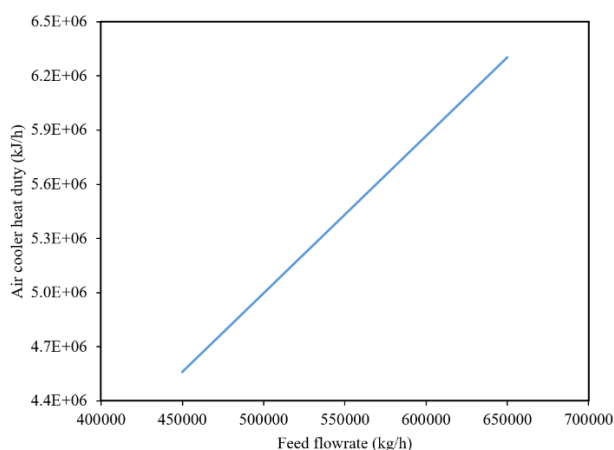
Fig. 13. Effect of feed flow rate on air cooler heat duty.

5. CONCLUSION

The purpose of this work was to simulate the gas condensate pre-fractionation unit in Aspen Plus using several thermodynamic EoS from different categories to implement sensitivity analysis on operational parameters. In doing so, three EoS including PR, CPA and PC-SAFT were used in Aspen Plus and simulation results were compared with plant data from Borzouyeh petrochemical plant, Asaloyeh, Iran. The simulation results indicate that all the equations are capable in giving good approximation of plant data while best approximation is obtained by using CPA EoS. Then, influence of reflux ratio and feed conditions including feed flow rate and feed temperature on heat duties of reboiler and condenser, air cooler duty and product flow is examined. Analyzing the influence of operational parameters indicates that increasing feed temperature will result in lower reboiler duty and has insignificant effect on condenser duty. Increasing the feed flow rate increases the heat duties of reboiler and condenser in both distillation columns. Higher reflux ratio results in higher heat duties in both distillation columns. Also, it results in more top product in T101, lower top product flow rate and higher bottom product in T102. Higher feed flow rate results in higher air cooler heat duty. Finally, at optimum conditions indicated in this work, more than 30% of the energy consumption of the unit could be saved.

Nomenclature

Abbreviation
CPA	Cubic Plus Association
disp	dispersive
EoS	Equation of State
hc	hard chain
id	ideal
PC-SAFT	Perturbed-Chain SAFT
PR	Peng-Robinson
RK	Redlich–Kwong
RVP	Reid Vapour Pressure
SAFT	statistical association fluid theory
SRK	Soave-Redlich-Kwong

a	energy parameter
b	van der Waals covolume
m	number of segments per chain
P	Pressure
R	Gas constant
T	Absolute temperature
v	volume

Greek letters
ρ	Density
η	Energy efficiency

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