Research Article

Process system analysis on oil processing facility and economic viability from oil well-to-tank

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Abstract

Hydrocarbon processing from extraction to the final product is an important aspect that needs an optimised technology for consumption-led market growth. This study investigated real data from the oil processing facility and analysed the simulation model for the entire crude oil processing unit based on the process system engineering aspect using Aspen HYSYS. The study mainly emphasises the process optimisation in processing the hydrocarbon for the maximum yield of the product with less energy consumption. The investigation also includes a thorough economic analysis of the processing facility. The datasets for oil properties are obtained from a modern petroleum refinery. The investigation comprises of varying transient conditions, such as well shutdowns using three oil reservoirs (low, intermediate, and heavy oil). The impact of various conditions, including process heating, well shutdown, oil combinations, presence of water on the production, is analysed. The results indicate that the factors involving crude oil processing are significantly affected by the process conditions, such as pressure, volume, and temperature. The vapour recovery unit is integrated with the oil processing model to recover the separator's gas. The optimisation analysis is performed to maximise the liquid recovery with Reid vapour pressure of 7 and minimum water content in oil around 0.5%. Economic analysis provided an overall capital cost of $ 9.7 \times 10^6$ and an operating cost of 2.1×10^6 for the process configuration. The model results further investigate the constraints that maximise the overall energy consumption of the process and reduce the operational cost.

1 Introduction

Energy is one of the essential constituents of any socio-economic structure, and its consumption directly affects economic growth [1, 2]. Energy-intensive applications require an uninterrupted and continuous supply either in renewable or non-renewable [3]. Due to the slow depletion of fossil fuels, the world is gradually shifting towards renewable, sustainable, and clean energy sources. However, a tremendous increase in the exploration of oil and gas has also been noticed in the last decade due to the promising outcomes and elevation in the market demand. The global energy demand is still highly dependent on petroleum production.

A complete petroleum production chain consists of geological surveys, extraction, refining, and transportation

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[4]. Petroleum productions mainly rely on naturally occurring energy resources [5–7]. Organic matter generally consists of rich gas and crude oil, the primary energy production source [8]. Many liquid-based fuels can be refined from crude oil for different applications [9]. However, environmental considerations must be considered without damaging the environment for using fossil fuel combustion to produce energy [10].

The oil reservoirs contain hydrocarbons, but many inorganic chemicals, including CO_2, N_2, H2S, etc. These inorganic constituents must be removed to commercialise the petroleum products for different applications [11]. The first phase of the petroleum industry is to perform detailed exploration-based geological surveys at various locations. Drilling procedures and a careful analysis of the oil reserve are performed in the next phase by analysing the exploration [12–15]. The extraction of oil from the well and the preliminary phase separation processes are implemented after developing the drilling facility. The upstream oil production and the stabilisation of oil and gas commence in this phase [16, 17]. This process separates crude oil, gas, and water from the feed mixture. Then, it processes them into marketable products and byproducts, whereas few inorganic and harmful contaminants are separated initially and disposed of in an environmentally acceptable manner. A schematic of the oil processing facility from the reservoir to the transportation is shown in Fig. 1

It is necessary to analyse complete process parameters before final design and commissioning of the oil facility. During the extraction process, the oil facility's overall production may change with time [18] due to the change in oil composition, gas, and water in the reservoir.
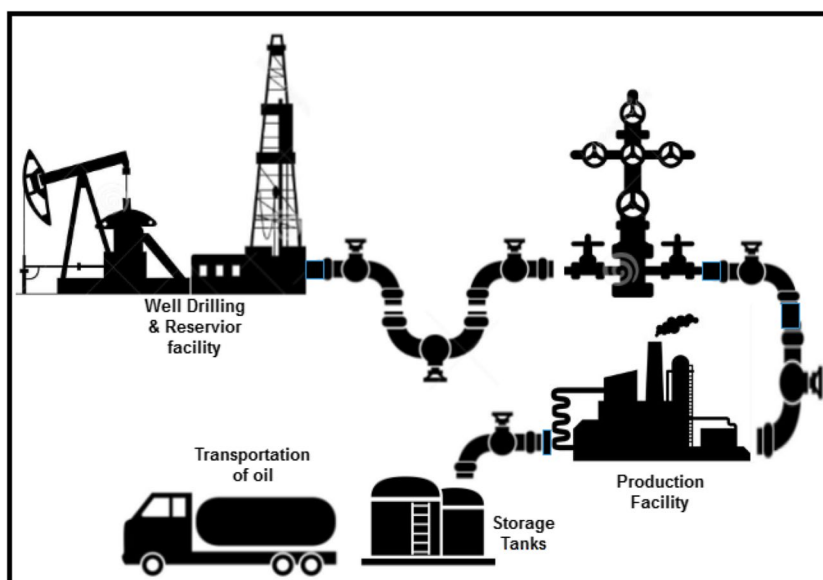
The production of oil can be closed during well shutdowns, breakdowns, or maintenance works. The total production can also be reduced due to the imposed constraints [19]. Therefore, the processing facility should be flexible to achieve maximum performance at any given time. The flexibility of the system can easily be tested by performing computational analysis or process simulations. It is a significant way to analyse production constraints using sensitivity and performance analysis, and measures can be taken based on a smooth production process. The process simulation has become an essential tool for designing, scale-up, and optimising chemical processes [20]. The primary advantage of process simulations is facilitating the engineering team to successfully execute repetitive and complex tasks in a relatively shorter time.

Qeshta et al. [21] performed a parametric study for sweetening liquefied-sour-gas using Aspen HYSYS. It was concluded that the design specification could be maintained if the concentration of H_2S in sweet LPG is under 0–10 ppm permissible limit. Martinovic et al. [22] used Aspen plus to simulate and analyse techno-economically two alternative ways for processing used oil to make biodiesel. In another study, Tran et al. [23] performed simulations on Aspen HYSYS for techno-economic analysis of biodiesel production from grease trap waste and reported promising results.

The presented study analyse process design, operation, and monitor process performance of up-stream oil-production facility. To the author's knowledge, this research is not subjected to investigation yet, hence describing the novelty of this work. Various process configurations are simulated to optimise the production at a minimum energy cost. Aspen HYSYS (V9.0) is utilised in the present research, an important process simulation tool widely used in different studies [24–26]. A systematic study is performed to analyse and optimise different process aspects

Fig. 1 The schematic of the oil processing facility

and developed a rigorous optimised process model. The case data is obtained from one of the renowned petroleum refineries in Pakistan. The emphasis is on the major design challenge in the oil-field during the blending of different oils and water. The presented specific case study has not been subjected to investigation before, which corresponds to this research's novelty to the author's knowledge. The optimisation and performance analysis incorporated with the economic analysis contributes to understanding the process constraints and their optimisation in oil and gas industries.

This research is focused on the below-mentioned significant contributions:

1. Process configuration of three-stage separation and vapour recovery from the three-stage separator.
2. Optimum pressure/temperature selection for maximum oil recovery.
3. Effect of temperature on various parameters of oil separation and production quality.
4. Performance analysis concerning production state and well shutdowns and optimisation.
5. Economic analysis of the overall development of the processing facility.

2 Process and operating parameters

The crude oil processing begins at the drilling wells when the crude is pumped out from the well and routed to the processing facility at certain pressure and temperature. The oil obtained from the wellhead consists of complex mixtures of straight- and branched-chained hydrocarbons, water, and other contaminants. The significant emphasis at this initial stage is to make it suitable for the downstream refinery sector. Hence, a process simulation approach is applied to model the raw oil properties and process constraints for the separation process. In this view, three separate cases were proposed based on the hydrocarbon feed mixture variation to illustrate the distinct conditions and their effect on the processing. Case-I gives details about the oil mixture composed of heavy crude oil having higher viscosity and API less than 20°; case-II describes the intermediate type of oil mixed with API higher than 20°. However, less than 40 °C and Case-III depict the lighter crude oil having a lower viscosity than the heavy crude oil and API slightly higher than 40°. Table 1 illustrates the composition of the oil mixtures for each case, and Table 2 represents their properties.

The combination of oil and water in the production units and their variations are incorporated in the process model to obtain tangible results, shown in Fig. 2. The fluctuation of water content in 3 types of oil has also been

Table 1 Feed Composition of the oil from the wellhead

Component	Case-I	Case-II	Case-III
Nitrogen (N_2)	0.57	0.34	1.67
Carbon dioxide (CO_2)	2.46	0.02	2.18
Methane (CH_4)	36.37	34.62	60.51
Ethane (C_2H_6)	3.47	4.11	7.52
Propane (C_3H_8)	4.05	1.01	4.74
Isobutane (i-C_4H_{10})	0.59	0.76	0
n-butane (n-C_4H_{10})	1.34	0.49	4.12
Isopentane (i-C_5H_{12})	0.74	0.43	0
n-pentane (n-C_5H_{12})	0.83	0.21	2.97
n-Heptane (C_7)	1.62	1.16	1.38
C_7+	47.96	56.85	14.91
Total	100	100	100

included in Fig. 2 at five production units. These Production states classify the water and oil content in various proportions from production states 1 to 5 illustrates the consecutive increase in water content and a decrease in oil content with the last stage of production marks the maximum water content.
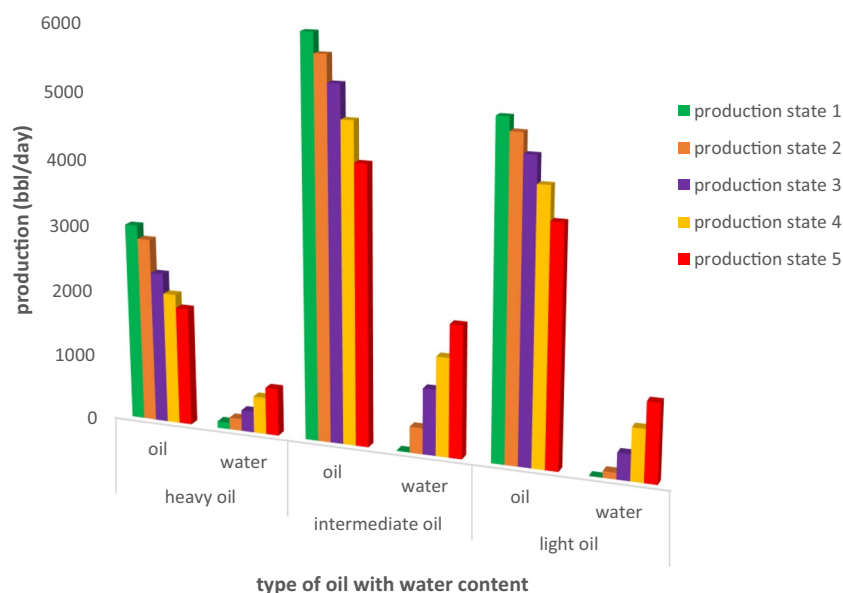
3 Simulation model

The simulation's primary goal is to carry out a virtual experiment to separate gas from the oil phase. The separated product can be unrouted to the downstream sector for refining and maximising the profit from hydrocarbon production [25]. Peng-Robinson equation of state is applied to the model as the thermodynamic property package. This state equation is the most appropriate model for hydrocarbon processing and has been applied in previous studies [26–29] for modelling different aspects and constraints of the process. This model's ascendency over other models in the Aspen database is the ability to handle a larger range of temperature and pressure and the largest database of binary interaction parameters for a wide range of components. The hypothetical components are defined with the help of temperature ranges which automatically generate the range of components for the actual representation of the oil stream. To make the process more realistic, a generalised real-time process condition was selected, detailed in Table. 3.

The simulation scheme starts with a Lumper unit operation model in Aspen HYSYS, which is used to attach multiple feed streams with different compositions and combine them into a single stream. C1 to C7 hydrocarbon components are combined in the present study, whereas the heavy components (C7 +) are de-lumped to eight hypothetical cuts. This scheme is executed to observe and

Table 2 Properties of the modelled oil

Properties	Case-I	Case-II	Case-III
Specific gravity	0.9594	0.92	0.799
Molecular weight	171.4	–	46.69
API gravity	19°	23.6°	47°
Asphaltene content in oil (fraction)	0.1688	–	–
Reservoir temperature	100 °C	95 °C	119 °C
Saturation pressure	2950 psia	2810 psia	4677 psia
Gas to oil ratio (ft^3 bbl^{-1})	–	300	2.909
Formation volume factor of oil (rB STB^{-1})	–	1.16	2.704

Fig. 2 Amount and oil and water content at varying production states

Table 3 Properties of the modelled oil

Parameter	Value
Temperature	15.56 °C
Pressure	1000 psia
Oil flow rate	153,603 lb h^{-1}
Oil volumetric flow rate	14,110 barrel day^{-1}
Gaseous content flow rate	14.453 MMSCFD
Petroleum property (API)	58.14°

analyse the combined behaviour of lumped components. Three different oil types based on composition were mixed introduced into the heating unit (Fig. 3). An Inlet heater is introduced to control the stabilised product's vapour pressure. This heater maximises the amount of oil content that remains in the liquid state and enhances the separation process's efficiency. As the temperature is higher, around 65.56 °C, separation increases for oil having higher viscosity and lower API, providing an opportunity to remove impurities, such as water and sand. At this temperature,

wax, hydrate, and foam formation and accumulation can be prevented. The stream is at ambient conditions, which increases the viscosity causing difficulty to separate the phases. Therefore, the fluid is heated before the separation.

The oil stream is then introduced with a series of horizontal multistage separators working on the pressure swing principle, removing lighter hydrocarbon components at relatively high pressure. The stream discharge from the bottom goes to the next separator, where further traces of lighter hydrocarbons are removed.

The process ensures to remove the lighter component from the oil mixtures at each stage by maximising the partial pressure of the intermediate components. LP separator is operating near the atmospheric pressure to directly send the oil obtained from the separator to the storage tank.

It was observed from the simulation that the tank oil becomes more stabilised (i.e. higher Reid vapour pressure-RVP, lower API, and high oil production) by increasing the number of separators. The three-staged horizontal separators are considering as the optimal
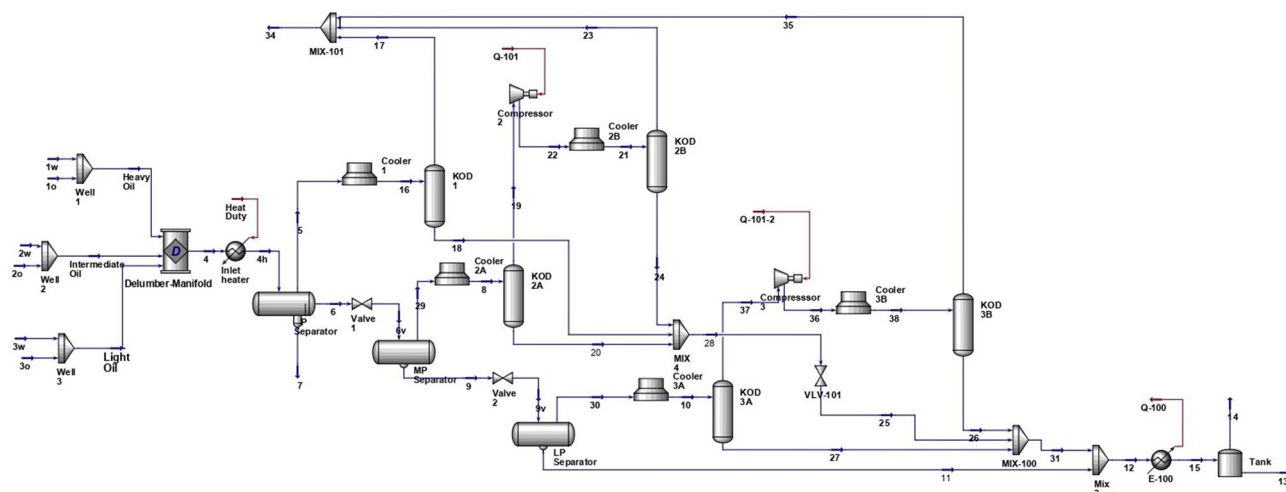
Fig. 3 Process configuration of the oil processing unit combined with vapour recovery unit

separator-stage. In HP (high pressure) separator, all droplets greater than 0.2386 mm (≤ 500 microns) are settled. This ensures that selected separators are adequately sized, and the water–oil specification is satisfied in the HP separator. The bottom stream from the separators is then sent to the two-phase separator.

The lighter hydrocarbon vapours produced from three separators have high gas to oil ratio. VRU (vapour recovery unit) was further integrated with the process model comprising vertical separators known as knock-out drums (KOD). KODs are added downstream of the vapour outlet of HP (high pressure), MP (medium pressure), and LP (lower pressure) separators. KOD recovers condensates from the vapours and contributes liquid recovery at the tank, shown in Figs. 4. The process consists of the separator adjusted at an optimal value that ensures the high recovery of liquid, less water content (≤ 0.5 wt.%) with less Reid vapour pressure (≤ 7) of the final product.

The vapour stream from the top of 5 KODs is mixed using a mixer and introduced into the fuel gas network for its further utilisation. In contrast, the gas content can be recycled back to the reservoir facility for reinjection into the reservoir. It consists of high pressure, which is essentially vital for the reinjection process. Therefore, the low-pressure gas is further recompressed to elevate the pressure. The obtained water is contaminated and cannot be disposed of directly into the environment; therefore, it is sent to the water processing unit.

The temperature at the outlet of compressors 2 and 3 is approximately 400 °C, which can cause corrosion, pitting, and damaging the pipeline structure due to the presence of H_2. Three possible ways can avoid this
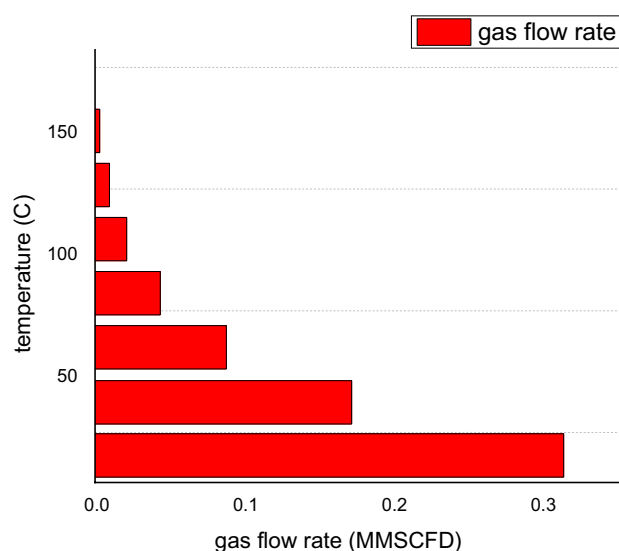

Fig. 4 Effect of temperature on vapour flow rate

challenge; (1) stainless steel material should be used as the material of construction for pipelines which can increase the effective cost of the system, (2) provide a multistage compressor which can also increase capital and operational cost or (3) providing an intermediate cooling system at the compressor outlet with a series of coolers and heat exchanger, which may be an efficient choice to provide the effective and optimal solution of the heat integration system. The finished oil obtained after the separators still contains a considerable amount of impurities in water and salt that has to undergo further treatment and then to storage tanks.

4 Results and discussion

4.1 Process constraints optimisation

4.1.1 Pressure constraint

The number of stages for the effective separation depends on the well and gas to oil ratio pressure. A two-stage process is usually used when the oil to gas ratio is medium, and pressure in the well is lower. In contrast, the three-stage separation process is used for a slightly higher gas to oil ratio with high well pressure [17]. In this study, the maximum gas to oil ratio is set to approximately 4 to control the inter-stage temperature using a three-staged separation operation. Campbell [31] proposed an equation for the number of stages, given in Eq. (1).

$$R = \sqrt{((n * P1)/P)} \tag{1}$$

where, R = pressure ratio, P_1 = stage pressure (high-pressure end), P = tank pressure, n = number of stages excluding tank.

According to Arnold [16], the lowest pressure usually obtained at the lower stages was in the range of 25–50 psia corresponding to the tank pressure. The pressure at any corresponding stage can be evaluated using Eq. (2) [32].

$$Pr = (Pr - 1)/R \tag{2}$$

Pr is the pressure at stage r. Initially, the three-stage separator is developed, and the temperatures and pressure in the unit are optimised with fewer vapours. Then, KODs are added to maximise liquid flow rate recovery. Different cases are simulated in this research work by varying temperature and pressure parameters to maintain high liquid recovery and lower energy utilisation. The pressure limits of separators are HP separator 975–1500 psia, MP separator 230–700 psia and LP separator 10–180 psia [33]. To ensure high oil recovery, the temperature and pressure conditions at the separator inlet are optimised, as shown in Table 4, which provides a final oil having the optimal constraints as illustrated in Table 5.

4.1.2 Effect of temperature

Specific conditions are required in the separator for the effective removal of gaseous or lighter components from the oil phase [33]. As the separator inlet temperature is increased, it would result in a high vapour flow rate. Paraffin hydrate forming and foaming issues arise at considerably lower temperature flow assurance since lower temperature reduces the oil viscosity, further affecting the oil

Table 4 Optimal temperature and pressure values

	Temperature (°C)	Pressure (Psia)
HP separator	121.11	1000
MP separator	118.77	240
LP separator	115.27	58
Tank	15.56	14.7
KOD 1	34	997
KOD 2A	190	240
KOD 2B	88	617
KOD 3A	34	58
KOD 3B	66	887

Table 5 Optimal oil conditions

Optimised oil constraints	
Oil [bbl/day]	10,175
API	27.22
RVP	6.832
Water content in oil	0.0045

flow rate, API, and RVP of the final oil product. Increasing separator temperature would lead to excess vaporisation due to the volatility of the components. The lower temperatures would trigger flow assurance issues due to paraffin, hydrates, and foam. It can be observed from Fig. 4 that an increase in temperature at the HP separator results in removing more vapours and provides stabilised oil. The vapour load on MP and LP separators reduce when the gas/lighter components are removed in the HP separator.

Increasing HP separator temperature lowers the RVP and API, providing more stabilisation to the liquid oil. Hence, it ensures that the lighter components are removed, and resulting in oil (heavy) stable content in MP and LP separators, shown in Fig. 5. It is evident from Fig. 6 that the lower temperatures exhibit higher liquid recovery resulting in higher RVP (depicted in Fig. 6).

The higher temperature also provides an added advantage of separating both continuous phases because the temperature has an inverse impact on the viscosity of oil in comparison to water resulting in more oil because at higher temperature oil and water viscosity decreases, which provides help in separating both the phases as can be seen from Fig. 7. As the temperature increases the oil and water viscosity decreases which increase the phase separation providing us higher water content which can be removed easily from the HP separator. It can be observed from Fig. 8 that the rise in temperature causes more oil recovery compared to the water. The continuous increase in temperature also reduces separator size due to the decrement in the oil's viscosity. Hence, it lowers the liquid residence time,
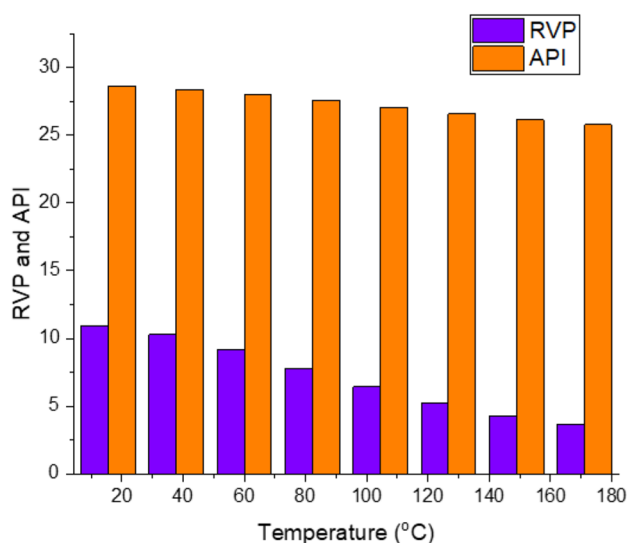
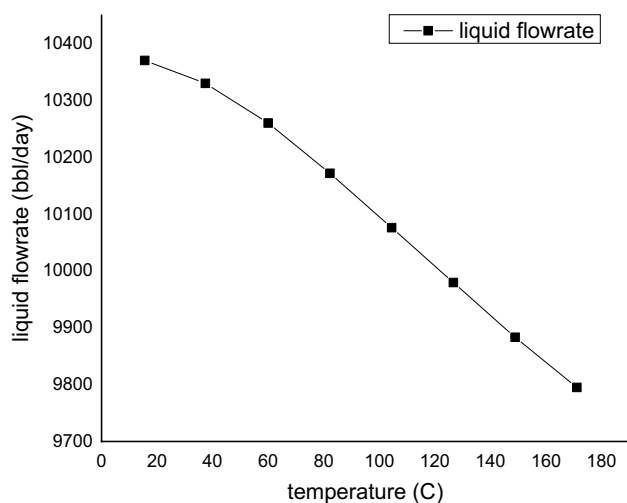**Fig. 5** Effect of temperature on RVP and API

Fig. 6 Effect on oil production concerning temperature

reducing the length of the separator, as shown in Fig. 9. The temperature analysis further ensures that the higher temperature facilitates us with certain advantages: less vapour load in the tank, more stabilised oil, and less energy requirement at the compressors.

4.1.3 Performance analysis of the production states and well shutdowns

Production state 1 indicates the lowest water content, whereas production state 5 exhibits the highest water content. Wells 1 and 3 are closed to observe the effect on the overall production process when oil with less API (heavy) and oil having higher API (lighter) are

blended [32]. It can be observed from Fig. 10 that the API decreases due to an increase in water content in oil. Similarly, RVP decreases and produces stabilised oil concerning production states. Since shutting Well 3 removes light oil and heavy oil will be produced in the system. Figure 10 shows decreased API and RVP. Similarly, shutting Well 1 removes heavy oil, and the light oil will be produced in the system showing increased API and RVP.
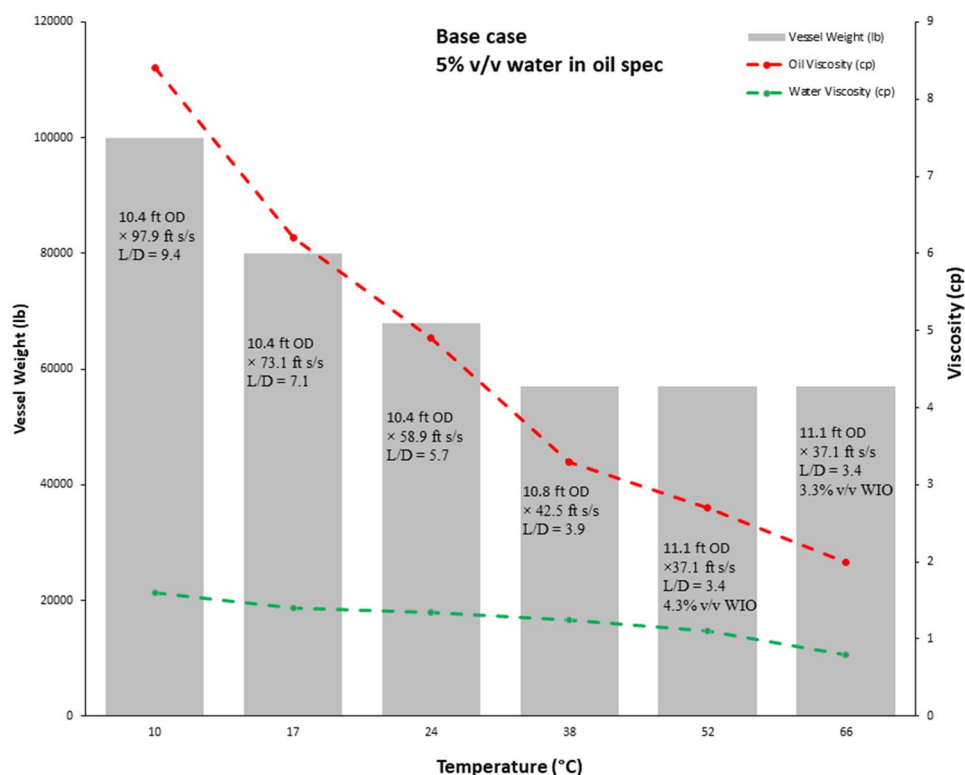
It is observed from Fig. S1 that oil content in the system decreases concerning production states; hence fewer vapours released from horizontal separators will enter the compressors, the decreased vapour flow rate in the compressor will decrease the power consumption of the compressor. It can be observed from Fig. 11 that compressor energy consumption becomes low due to less formation of vapours. The heavy oil system produces fewer vapours. Therefore, it requires less power as compared to the light oil system. The heavy oil has higher water content compared to various production states (shown in Fig. S2). Hence, oil production decreases with production states.

4.1.4 Pressure analysis on wells under high and low water content

The pressure analysis is performed on well 1 and well 3 under different conditions of water content. To maximise the recovery of gas and performance of the process, certain adjustments are required in terms of pressure to achieve the maximum oil flow rate and stable RVP. In the present research, two cases were observed. In the first case, well 1 is shut down, causing a decrease in HP Separator and KOD pressure. In the second case, well 3 is shutdown causing HP separator pressure to decrease with KODs and increasing pressure in other separators, i.e. MP and LP. The results illustrate that, in both cases, the pressure is reduced simultaneously with flow rate and lowering the energy consumption by the compressor. In the second case, KOD (2A, 3A), compressor (2, 3), cooler (2A, 3A) can be bypassed due to the low volatility of oil, which makes the process energy-efficient and hence optimises the process. The detailed configuration can be referred in Fig. S3.
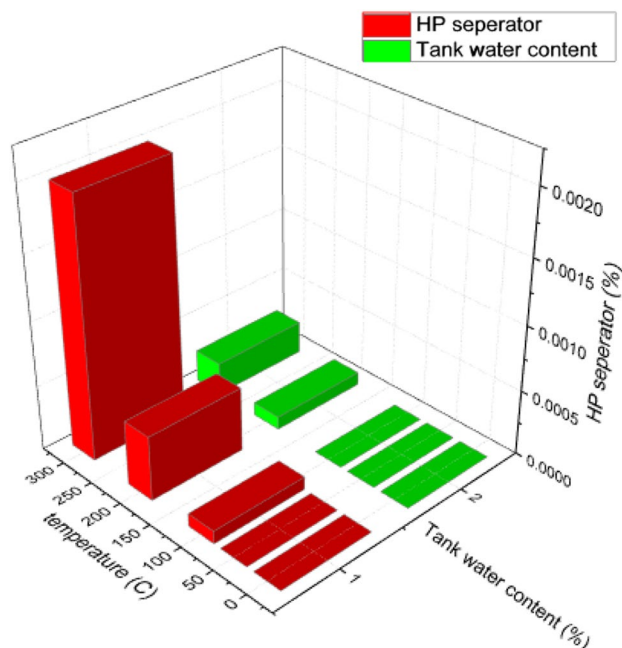
4.2 Economics analysis

The capital investments are estimated during project initialisation using available preliminary data. Aspen economic analysis allows the sizing of equipment and generates the estimated equipment cost. The size of equipment is generated based on the operating conditions. This feature allows the estimating of the project cost. The Aspen

Fig. 7 Effect of viscosity concerning temperature

Economic Analyzer optimises the design based on certain aspects. It simulates different scenarios, analyses the effect on essential equipment for the process, and links the data directly to equipment design and cost.

Fig. 8 Effect of temperature on the water content in oil

The economic conditions are based on the utility requirements, raw material cost, equip mental material cost based on the standard design and sizing, process maintenance cost, etc. The total project estimations using Aspen economic analyser are tabulated in Table 6. The optimal process of equipment and energy are selected based on economic analysis.

5 Conclusions

The current study provides an approach to solve real-time petroleum production. Three different oil-producing wells data were used to analyse API and RVP due to an increase in water content in oil that would provide a more stabilised product. It results in a more stabilised product. A performance-based analysis was also done results reveal that shutting down well 1 provides the lighter hydrocarbon-based product with higher API and RVP. It can be concluded that to produce more rich content and stabilised products in terms of petroleum quality measuring constraints, and it must shut well 3. Pressure analysis provides an idea of the optimal and stabilised product recovery from different oil wells. Overall, the temperature analysis further ensures that the higher temperature facilitates us with certain advantages: less vapour load in the
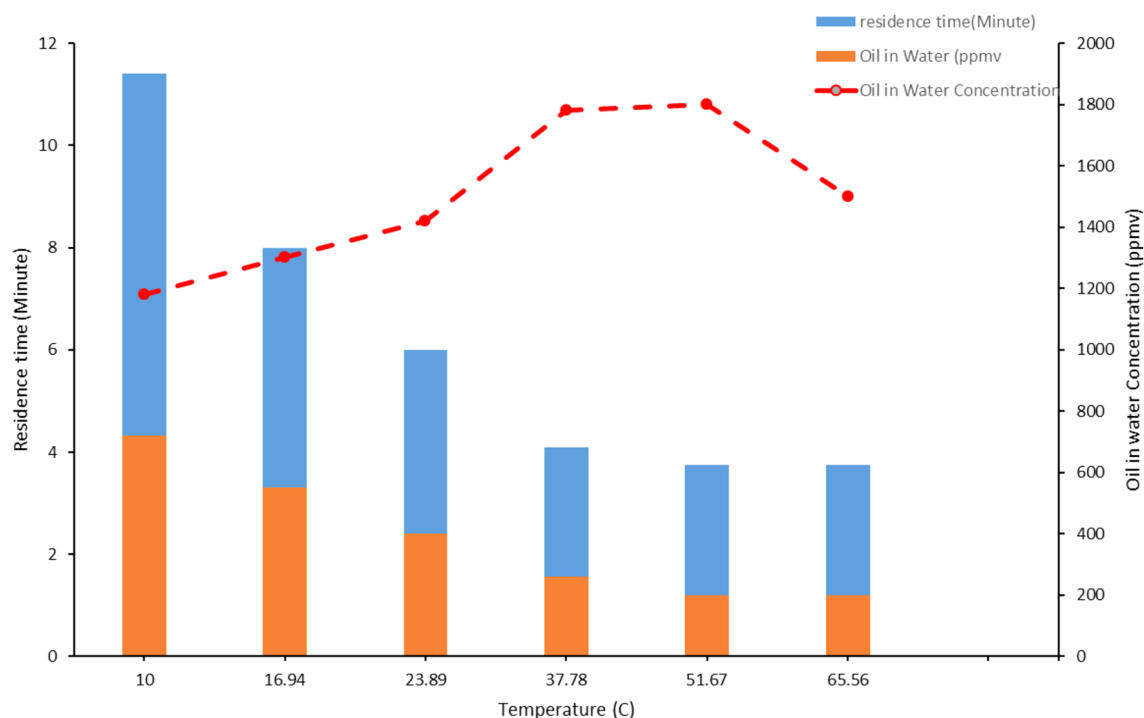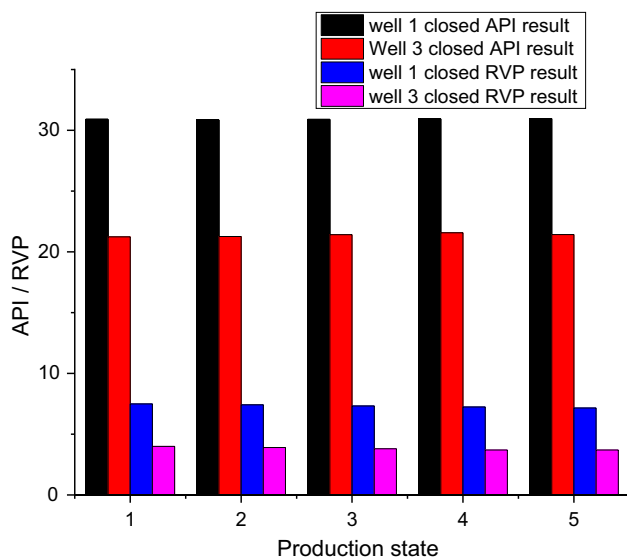
Fig. 9 Effect of temperature on separator size

Fig. 10 Effect on API and RVP concerning various production states

Fig. 11 Compressor power versus various production states

tank, more stabilised oil, and less energy requirement at the compressors.

Process optimisation analysis is performed for compressor's energy consumption on production states to provide an energy-efficient solution for maximal production. The economic analysis further provides an analysis-based concept on the actual plant reliability by calculating the

process's various economic aspects. Hence, this developed model signifies and analyses different scenarios to maximise the production and recovery rate on both technical and economic aspects. The proposed simulation model can be integrated with crude distillation units where further analysis can be done to obtain various crude products. Furthermore, it can be utilised for the optimisation of crude oil products.

Table 6 Economic aspects of the process

Summary	
Plantlife	5 years
Operational hour	8760 h/year
Rate of return	20%/year
Constraints	US $
Total capital cost	9.7×10^6
Total operating cost	2.1×10^6
Total utility cost	7.20×10^5
Equipment cost	2.18×10^6
Total installed cost	4.05×10^6

The authors intend to further extend this investigation considering heat integration across several units of the petroleum processing industry using several datasets. It is believed that the economic analysis considering all units of the processing facility can be a further step towards more realistic and insightful outcomes.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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