PREDICTION OF OPTIMUM SEPARATION CONDITIONS FOR SEQUENTIAL FIELD SEPARATION SYSTEM

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ABSRACT

A study has been done for finding the optimum separators pressures of degassing stations. The optimum operation pressures are determined by employing Constrained Rosenbrock (1966) method using the maximum API, minimum GOR and minimum B_{ob} as objective functions and separators pressures as the decision variables. The optimization of separators pressures requires equilibrium flash calculation under different conditions of pressures and temperatures to determine the conditions that will yield the most stock tank liquid. Equilibrium flash calculation is achieved by solving the equation of state. In the current study, Soave – Redlich – Kwong (1972) and Peng – Robinson (1976) have been used with the black and volatile oils respectively.

Two computer models are used to find the optimum separators pressures. The first model is OSPB which can be used with black oils while the second is OSPV that employs volatile oils. Application of these models shows improvement of the all objective functions for oils. Two checking techniques (the plotting & sensitivity analysis test) proved the validity of these optimization models.

الخلاصة

الدراسة تهدف لإيجاد الضغوط المثلى لمراحل محطات العزل._التحديد للضغوط المثلى للعازلات أنجز بواسطة استعمال تقنية روزنبروك المقيدة التي حددت القيم المثلى عند اعلى وزن نوعي للنفط وعند اقل نسبة غاز الى النفط المنتجة واقل معامل تكوين حجمي للنفط التي اعتمدت كدوال الهدف و ضغوط العازلات كمتغيرات قرار. تحقيق أمثلية ضغوط العازلات يتطلّب حسابات التوازن تحت ظروف مختلفة من الضغوط ودرجات الحرارة لتحديد الظروف التي بواسطتها سيتجمع اكبر قدر من السائل في العازلة الأخيرة. حساب توازن الطور يجب أنْ تنجز بحل معادلة الحالة في العمل الحالي. معادلات سواف – ريدلخ – يونك و بينك – روبنسن استعملتا مع النفوط الثقيلة و الخفيفة على التوالي.

تم أنجاز نموذجان لإيجاد ضغوط العازلات المثلى. النموذج الأول هو OSPB الذي يُمكِنْ أنْ يُستعمل مع النفوط الثقيلة بينما النموذج الثاني هو OSPV الذي يتعامل مع النفوط الخفيفة. إستعمال هذه النماذج المُقترَحة احدث تحسن جيد لكل الدالات المعيارية للنفوط . استعملت تقنيتين للتدقيق (التسقيط، إختبار تحليل الحساسية) و قد أثبتتا صلاحيةَ هذه النماذج في تحقيق الأمثلية.

KEY WORDS

optimum, separator, equation of state, flash, Constrained.

INTRODUCTION

The optimization of phase separation practices is important because by varying the blend of surface oil and gas produced per reservoir volume, an operator may markedly affect the total value of the mix. The total value of the mix is affected by the fractional volumes produced of each phase as well as the quality of each phase. The fractional volume of each phase is important because traditionally the market has paid a significant premium for hydrocarbons in the liquid phase.

An important concept in surface phase separation is that the fractional liquid recovery will always be enhanced by adding more separators between the wellhead and the stock tank. In a stage separation process, the light hydrocarbons molecules that flash are removed at relatively high pressure, keeping the partial pressure of the intermediate hydrocarbons lower at each stage.

An equally important concept is that for a finite number of separators, there is an optimal combination of discrete separator pressures that will maximize the fractional liquids recovery. At the optimal combination of separator pressures, the API gravity of the crude will be maximized and the gas-oil ratio will minimized.

Whinery and Campbell (1958) developed a method for determining the optimum second stage pressure in three stages separation system. Their method is simple, accurate and eliminates the need for flash vaporization calculations.

Penick and Thrasher (1977) suggested finding the optimum separator pressure by plotting equilibrium ratio versus pressure. Since K – value is defined as the ratio of mole fraction of a component in the vapor to the mole fraction of that component in the liquid, then when K – values are applied in a conventional equilibrium flash calculation the condition which gives the greatest proportion of a component in the liquid phase is a condition whose K – value is the lowest.

AL-Ameeri (1981) proposed a mathematical model capable of finding the optimal pressures for gas-oil separation systems. The primary objective of designing this model was to solve the problem of excess natural gas that is faced by many oil producing countries in Middle East and elsewhere in the world. The objective function was minimizing gas – oil ratio. The investigator used the Fibonacci method as optimization technique.

Jalali, Van Wassenhove, Romano and Pickles (1997) constructed algorithm to predict optimum separator pressure in North Sea field for the first – stage. In addition, they suggested simple formulation to the same aim. The objective function was the oil production.

Palke and Horne (1997) made integrated production model composed of several components. It included separator model. The authors used Redlich – Kwong equation of state to determine phase properties and the nonlinear optimization techniques are mathematical methods of determining the set of decision variable values that maximizes an objective function value.

MATERIAL BALANCE

The stage separation unit can be described with a group of material balance equations.

- An over all material balance.
- The component material balance.
- A restrictive equation on the phase composition.

The general equation to calculate the vapor mole fraction can be written as

$$f(v) = \sum_{i=1}^{NC} \frac{z_i(1 - K_i)}{1 + v(K_i - 1)} = 0 \qquad (1)$$

The above equation can be solved by Newton-Raphson method and False position method. The first method is the most common used technique for locating roots of nonlinear equations. The assumed value of v must be between zero and one. The False position predicts the initial value of the vapor

fraction after some iterations. The resulted value is adopted as initial guess in the Newton-Raphson method which in turn find the true value.
In the Newton-Raphson method, a calculated value of the root for iteration k+1 is computed from the following relation:

$$v^{k+1} = v^k - \frac{f(v^k)}{f'(v^k)} \qquad (2)$$

where the derivative of equation (1) is:

$$f'(v) = \sum_{i=1}^{NC} \frac{z_i(1-K_i)^2}{[1+v(K_i-1)]^2} \qquad (3)$$

and convergence is achieved when both:

$$\left|v^{k+1} - v^k\right| \le \varepsilon \qquad (4)$$

and

$$f(v^{k+1}) \le \varepsilon \qquad (5)$$

where ε is a small tolerance. In this study, ε was set equal to 10^{-10}. Empirical correlations can be used to provide an initial estimate of the equilibrium ratios. The Wilson equation (1968) has been used in this study.

EQUATION OF STATE

Phase equilibrium calculations require solution of equations of state to evaluate the relevant properties pertaining to liquid and vapor. Furthermore recent advances in computer implemented equations of state have made predictions of phase behavior easier and more reliable.
Several forms of equation of states have been presented to the petroleum industry. In this study the most widely used; Soave – Redlich – Kwong and Peng – Robinson have been used with the black and volatile oils respectively. The cubic equation for the Z factor is solved to obtain Z factor for liquid and vapor phases.
SRK equation of state presented in the following form.

$$Z^3 - Z^2 + \left(A - B - B^2\right)Z - AB = 0 \qquad (6)$$

Peng-Robinson proposed the following equation of state:

$$Z^3 + (B-1)Z^2 + \left(A - 3B^2 - 2B\right)Z - \left(AB - B^2 - B^3\right) = 0 \qquad (7)$$

where A and B are calculated from equations (6) and (7).

C_n^+ Properties

Equations of state have generally been recognized by the petroleum industry as important analytic expressions used in describing behavior of the complex hydrocarbon mixtures. An important consideration in using equations of state is the difficulty in characterizing the heavy fractions of hydrocarbon mixtures. These fractions, usually lumped as heptane plus (C_7^+), are difficult to define without an extended molar analysis of the plus fraction. A conventional laboratory hydrocarbon analysis of oil, gas, or condensate system usually reports the composition of the system (methane through heptane plus), with molecular weight and specific gravity of heptane plus fraction.

Three correlations used to predict properties for lumped fraction during this study, namely Riazi and Dubert (1980), Mahdi (2002) and Edmister (1984). Riazi and Dubert developed an empirical equation which is useful for predicting the critical properties for the plus fraction. This correlation used with PR EOS. Mahdi suggested modification of Riazi and Duubert correlation to predict the critical properties of the heavy fractions. The modified equation has been used with SRK EOS. Edmister suggested approximation correlation for finding the acentric factor. This correlation has been used with PR EOS and SRK EOS.

Computer Models of Surface Calculation

In this work, two computer models were used to achieve the surface separator calculations namely SFSRK model and SFPR model. The first model has been used to treat black oils and the second for treatment of volatile oils. The computer models have achieved all aims of surface separator calculation that illustrated in this chapter. **Fig. (1)** shows the flow chart for the computer models SFSRK and SFPR.

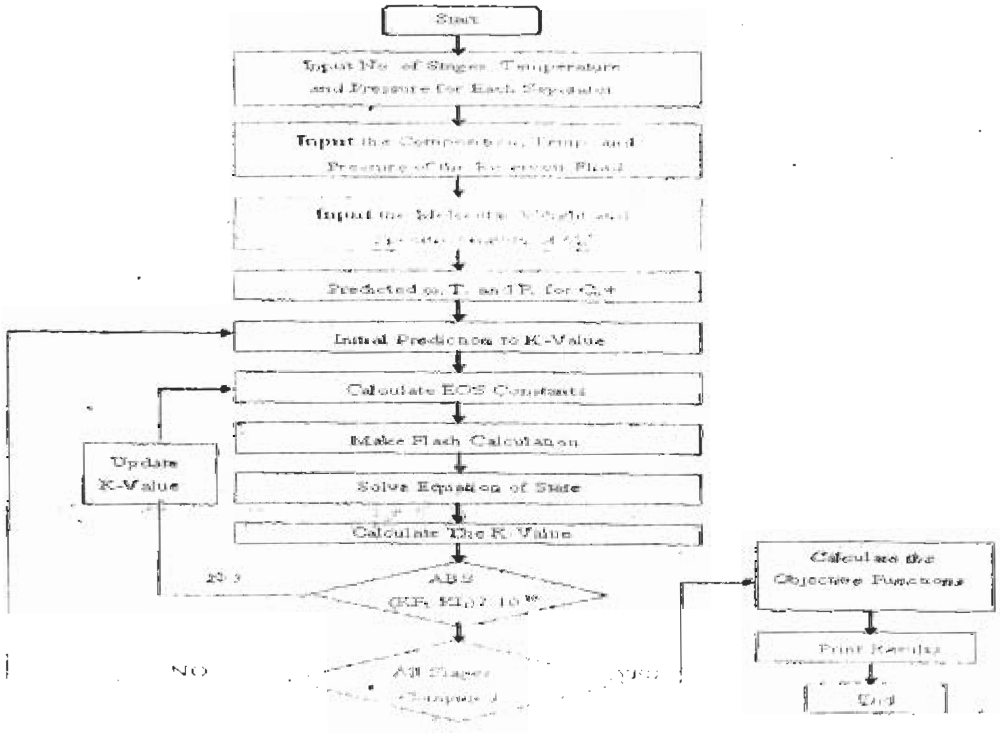

Fig. (1) The Flow Chart of the Computer Models

The Steps For Optimization Of Separators Pressures

The optimization of separators pressures included the following steps:

1- Analysis of the process, in which the important variables and specific characteristics of the problem are defined.
2- Definition of an objective function or performance criterion and expression of the criterion as a mathematical function.
3- Development of a mathematical process model that relates the input-output variables and lists the constraints.
4- Application of an optimization procedure to the mathematical formulation of the problem.

Analysis of the Separation Process in the Separators

Well fluid from various oil wells enters the first stage in a single stream with a given composition, temperature and pressure. Temperature and pressure of the entering feed are usually higher than those of the first stage. The drop in the pressure causes flash vaporization of the well fluid. Off-gases from the first stage, which contain a high percentage of light components such as methane, ethane and propane (C_1, C_2 and C_3), flow to gas plant where compression and refrigeration processes. Crude oil leaving the first stage flows to the second stage which is held at a lower pressure. Again pressure drop causes flash vaporization of feed. This process continues up to the final stage N, which is the stoke tank. The stock tank is usually operated at atmospheric pressure, and its temperature is close to ambient temperature.

Decision Variables for the Process Under Study

From the formulation of the problem, the decision variables of the process are the pressures for stages separation except the stock tank because the last stage has constant pressure that equals atmospheric pressure. Equation (8) and **Table (1)** show the variables in this problem, respectively.

No. of decision variables = No. of stages -1 (8)

Table (1) The Definitions of the Decision Variables

No. of stages	Decision variables
2	P_1
3	P_1, P_2
4	P_1, P_2, P_3
– – –	– – –
N	P_1, P_2, ..., P_{N-1}

Objective Functions

The calculation of optimum separators pressures must satisfy four objective functions which are

1- Stock tank oil gravity (API).
2- The recovery liquid volume in the stock tank per volume of reservoir voidage.
3- Total gas-oil ratio (GOR).
4- Oil formation volume factor (B_{ofs}).

The objective functions must be at maximum values for the first and second functions and at minimum values for the third and fourth functions.

The Constraints

The constraints of the optimization of separators pressures may be divided into:

1- The constant constraints: this type related to manufacture pressure where the first stage pressure must not exceed the maximum pressure specified by the manufacture.

$P_{1st} < P_{man}$ (9)

where

P_{man} = manufacture pressure, psia.

The pressure of separator prior to the stock tank must not be below the stock tank pressure that approximately equals atmospheric pressure.

$$P_{N-1} > P_N \qquad (10)$$

2- The variable constraints: each stage except the stock tank plays role in this type where the pressure of separator must not exceeds the pressure of the previous separator.

$$P_i > P_{i+1} \qquad (11)$$

Optimization of Separator Pressure

The problem of optimization of separator pressure has the following properties.

1- Nonlinear.
2- Multivariable.
3- Constrained.
4- The solution is to find a maximum of two functions (API, SPM) and a minimum of two functions (GOR, B_{ob}).
5- The degree of complexity is very high.

The method chosen should be:

a- Nonlinear programming.
b- Multivariable.
c- Constrained.
d- Free of derivative.

The technique must find the maximum and minimum solution.

Among the optimization techniques, the Constrained Rosenbrock method is adopted to solve this problem because it achieves all required conditions.

Computer Models of Optimization Process

The major object for this study is to construct computer models to find the optimum separators pressures. Two models achieved during this study for the above purpose one is for the black oils and the other one is for the volatile oils.

OSPB is the computer model that treat the black oils. This model consist of two parts, first part is Constrained Rosenbrock technique and the second is SRK EOS and its correlations. Constrained Rosenbrock technique finds the optimum values of separator pressures while SRK EOS calculates the fluid properties (objective functions).

OSPV is the computer model that designated to optimize the operating pressures of the separators when volatile oils pass through it. The model consists of two main sections. The first section represents Constrained Rosenbrock technique that finds the optimum values of the separator pressures while the second includes PR EOS and its correlations. The above computer models provide the following values:

1- Maximum API.
2- Maximum quantity of liquid per produce mole (SPM).
3- Minimum Oil Formation Volume Factor at the bubble point (B_{ob}).
4- Minimum Produced Gas-Oil Ratio (GOR).

EFFICIENCY OF EQUATOIN OF STATE

In this study, two equations of state are used to perform the phase equilibrium calculations namely Soave - Redlich - Kowng and Peng - Robinson. The main point in accuracy of all results of equilibrium calculations would be the composition of gas and liquid at each stage because all of these results will depend on these compositions.

Station No.1 is used for testing the efficiency of SFSRK model where this station represents three-stage system. Actual pressures of station equal 162 psia, 73.5 psia and 14.7 psia during summer season and 172 psia, 73.5 psia and 14.7 psia during winter season. Actual temperatures of station equal 140 °F, 140 °F and 134.6 °F during summer and 104 °F, 104 °F and 100.4 °F during winter in the 1st, 2nd and 3rd stages respectively.

Black oil sample is used for the comparison between actual and theoretical results. **Fig. (2)** and **Fig. (3)** show the plot of experimental and predicted results at all stages during summer and winter respectively. The comparison is done between actual and theoretical vapor mole fraction of individual component at each stage during summer and winter. Theses plots show very good agreement between the calculated and measured values.

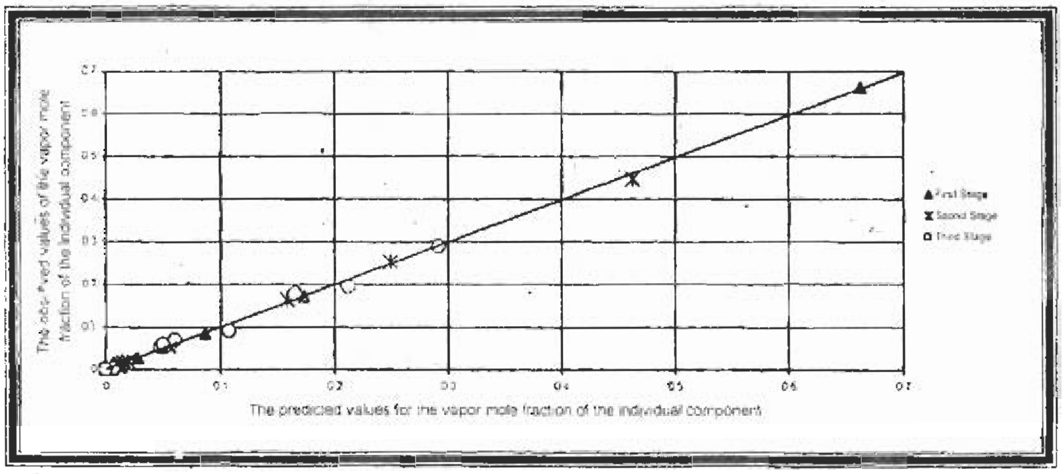

Fig. (2) Comparison between Observed and Predicted Vapor Mole Fraction of Individual component for Black Sample at All Stages of Station No.1 (summer)

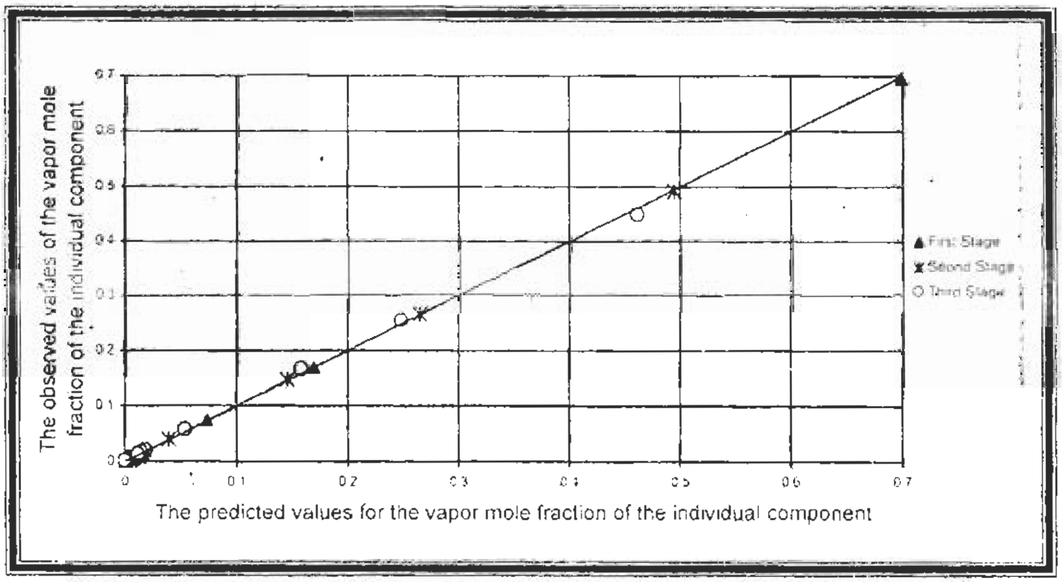

Fig. (3) **Comparison between Observed and Predicted Vapor Mole Fraction of** Individual component for Black Sample at All Stages of Station No.1 (winter)

During this study, the PR EOS becomes important part of SFPR, the computer model. The SFPR computer model has been operated to predict liquid mole fraction of individual component at the same conditions of actual pressures and temperatures. Data from station No.2 were adopted for the comparison between the experimental and predicted results of volatile sample when passing through five stages during summer and winter. Actual pressures of this station equal 615 psia, 200 psia, 65 psia, 28 psia and 15 psia during summer and winter. Actual temperatures of this station equal 140°F, 130°F, 125°F, 120°F and 120°F during summer and 120°F, 110°F, 105°F, 100°F and 100°F during winter.

The comparison is accomplished between experimental and calculated liquid mole fraction of individual component for all stages during summer and winter as shown in **Fig. (4)** and **Fig. (5)** which demonstrate the good match between them.

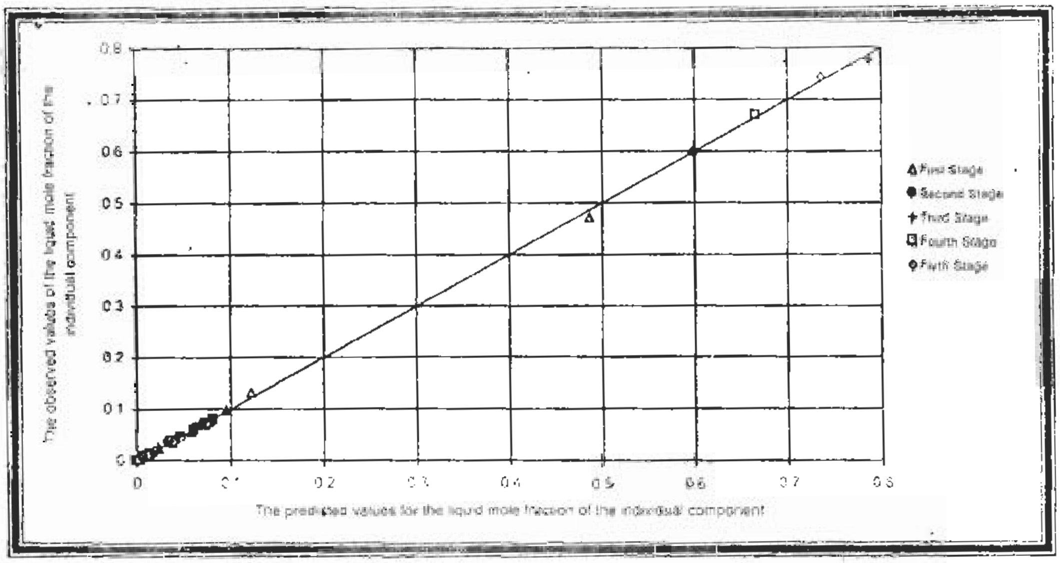

Fig. (4) Comparison between Observed and Predicted Liquid Mole Fraction of Individual component for Volatile Sample at All Stages of the Station No.2 (summer)

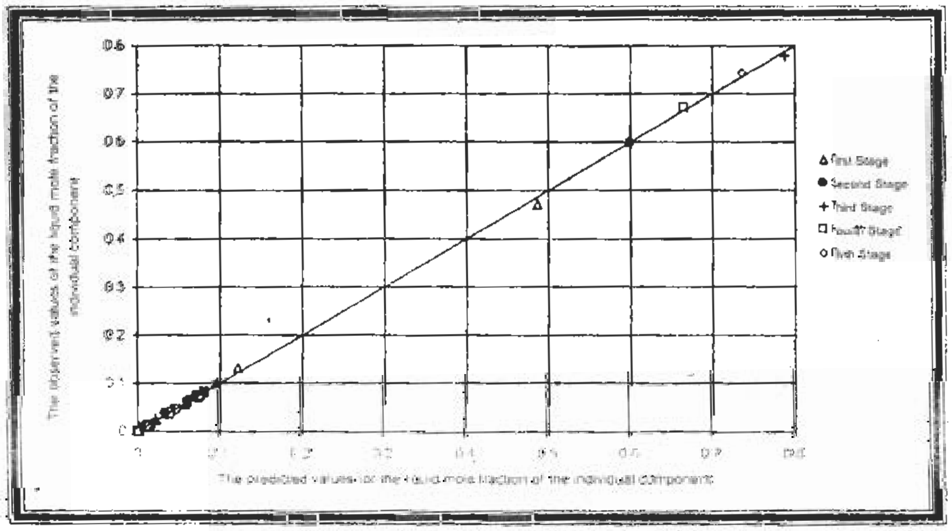

Fig. (5) Comparison between Observed and Predicted Liquid Mole Fraction of Individual component for Volatile Sample at All Stages of the Station No.2 (winter)

DETERMINATION OF OPTIMUM SEPARATORS PRESSURES

During this study, the optimum separator pressure was determined by applying models OSPB and OSPV that adopted the constrained Rosenbrock technique. The first model provides the optimum pressures when the black oil passes through the separators. Black oil sample is used to test the efficiency of OSPB computer model for station No.1. The optimum pressures and their objective functions corresponds to this station are calculated by OSPB computer model while the values of API, GOR, B_o and SPM at the actual pressures for summer and winter are calculated by SFSRK computer model. **Table (2)** includes the optimum and actual pressures and their objective functions for stages of this station during summer and winter. **Table (2)** shows the increasing in API and SPM and the decreasing in GOR and B_o when the pressures changed from the actual case to the optimal case.

The second model has been used for volatile oils to predict the optimal pressure for each stage of the separation train. **Table (3)** shows actual and optimum separators pressures and the objective functions at both set of pressures of the station No.2 (Five Stages). Volatile oil sample is passing through this station. **Table (3)** demonstrates the increment in API and SPM and the decrement in GOR and Bo when the actual pressures replaced by the optimal.

Varying the Number of Stages (N)

Fig. (6) illustrates the effect of the number of stages on the API. In this figure the maximum percent change in API, over the search interval, is taken as a measure of the sensitivity of the objective function. **Fig. (6)** suggests that the maximum API increased with the increase in the number of stages while the sensitivity decreases in sharply manner.

The increasing of number of stages does not affect the value of API after particular limit because the aim of the optimization is to obtain a maximum amount of intermediate components as liquid phase. When this aim achieved at particular number of stages, the addition of stages will have no effect on the results.

CONCLUSIONS

The most important Conclusions that can be demonstrated from the current study are

1- In the current study an optimization models of separators pressures with black and volatile oils are constructed and called OSPB and OSPV model respectively. These models have been used for two, three or more stages.

2- Equations of state for Peng-Robinson and Soave – Redlich – Kwong are good tools in performing flash calculations of the volatile and black oils respectively.

3- Constrained Rosenbrock technique is a suitable method to find optimum separator pressure because it satisfies all required conditions related to the problem.

4- The models OSPV OSPB, SFPR and SFSRK give good results with the oils samples.

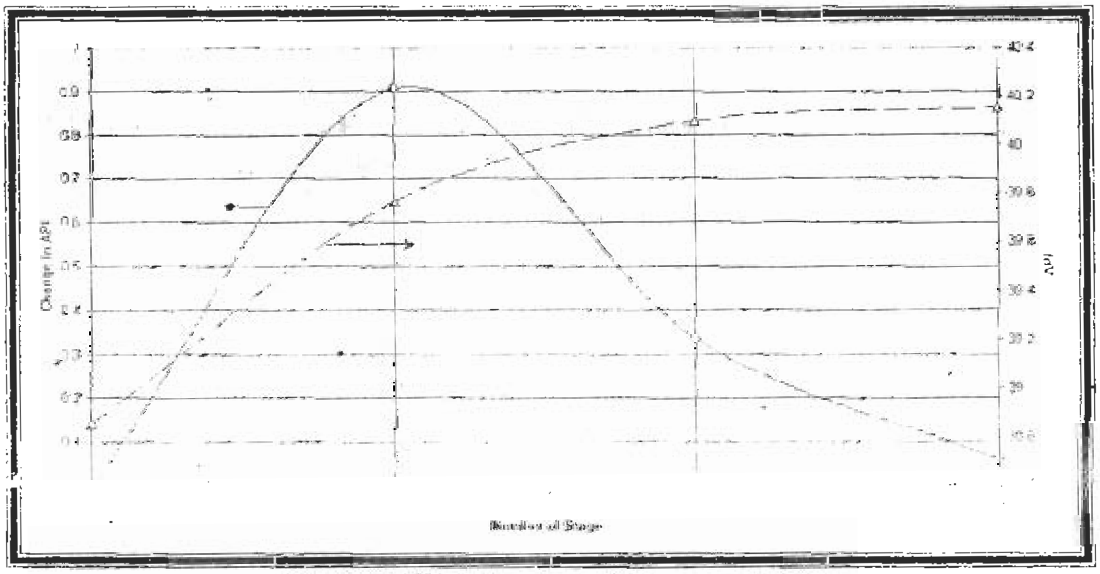

Fig. (6) Effect Number of Stages on API

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Table 2 Comparison between the Optimal and Actual Case for the Station No.1

Season	Stage	Optimum					Actual				
		Pressure psia	API	GOR scf/STB	B_o bbl/STB	SPM STB/mole	Pressure psia	API	GOR scf/STB	B_o bbl/STB	SPM STB/mole
Summer	First	161	36.9	536	1.319	853	162	36.8	541	1.323	846
	Second	41					73.5				
	Third	14.7					14.7				
Winter	First	145	37.3	516	1.303	886	172	37.2	521	1.3065	879
	Second	40					73.5				
	Third	14.7					14.7				

Table 3 Comparison between the Optimal and Actual Case for the Station No.2

Season	Stage	Optimum					Actual				
		Pressure psia	API	GOR scf/STB	B_o bbl/STB	SPM STB/mole	Pressure psia	API	GOR scf/STB	B_o bbl/STB	SPM STB/mole
Summer	First	600	39.2	1505	1.799	626	615	39.1	1512	1.804	623
	Second	140					200				
	Third	45					65				
	Fourth	22					28				
	Fifth	15					15				
Winter	First	595	40.1	1453	1.766	651	615	39.476	1461	1.771	647
	Second	147					200				
	Third	48					65				
	Fourth	21					28				
	Fifth	15					15				

NOMENCLATURE

English Symbols

Symbol	Definition	Unit
K	Equilibrium ratio	-
NC	Number of components in the system	-
P	Pressure	psia
V	Vapor mole fraction	-
Z	Mole fraction of mixture	-
Z	Compressibility factor	-

Greek Symbols

Symbol	Definition	Unit
E	Error fraction	-

Subscript Symbols

Symbol	Definition
i	Component index
j	Component index
k	Iteration index
v	Vapor

Abbreviations

Symbol	Definition
EOS	Equation of state
PR	Peng-Robinson
SPM	Stock tank oil per mole
SRK	Soave-Redlich-Kwong