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New universal two-phase choke correlations developed using non-linear multivariable optimization technique

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ABSTRACT

Production of hydrocarbons from the reservoir must go through surface chokes. The choke is installed to control the surface flow rate of the hydrocarbons and produce it at the optimum flow rate. Thus, the production rate follows the recommendation of the production engineers to prevent problems such as water coning. Accurate prediction of the surface flow rate is crucial as it will lead to fulfil the development plan's goals of the reservoir and optimize the production. Many correlations were developed to predict the flow rate through surface choke and most of them used one set of data from a single reservoir to develop the correlation. Using these correlations, which are based on limited data, might give results with high error. A new optimization technique is used to develop two universal choke correlations for better prediction of the two-phase flow rate for the oil wells. These correlations predict the liquid flow rate as a function of gas-liquid ratio, choke diameter, wellhead pressure, and oil API gravity. A total of 835 field tests from five different reservoirs were used in developing these correlations, thus covering a wide range of data sets. The new choke correlations proved to predict the flow rate with higher accuracy than the existing correlations by approximately 9%. The results from this study will greatly assist petroleum engineers to have particular estimations of liquid flow rates from wellhead chokes.

Keywords: choke correlation; hydrocarbons; optimization; two-phase flow.

INTRODUCTION

For any oil and gas well performance, there is a production system that should be optimized to produce a well with the best performance. One of the production system's elements that has to be optimized is the surface choke or the wellhead's choke. The choke is a type of restriction that regulates the production according to the size of the choke, following the recommendations after considering different parameters. The recommendations come after analyzing the choke performance for different scenarios. For studying and analyzing the choke performance, many correlations were developed to predict the two-phase flow rate through choke with respect to the most important parameters, which are gas-liquid ratio, wellhead pressure, and choke size.

The fluid flow through chokes will occur if there is a pressure difference between the upstream and the downstream pressure of the choke. When there is a sufficient pressure difference, flow through choke will begin, and flow is under subcritical conditions. As the downstream pressure is decreasing, the flow rate will increase, and still the flow is under subcritical conditions as long as the flow rate is depending on both upstream and downstream pressure. The situation will continue until a condition is reached where further reduction in downstream pressure will not affect the flow rate (Figure 1), and from this point, the flow rate is under critical condition, and at this point the speed will reach the speed of sound. It is known that the speed of sound will be observed when the upstream pressure is at least twice the downstream pressure. Gilbert (1954) suggested that the upstream pressure should be at least 70% higher than the downstream pressure for the flow through the choke observes critical flow.

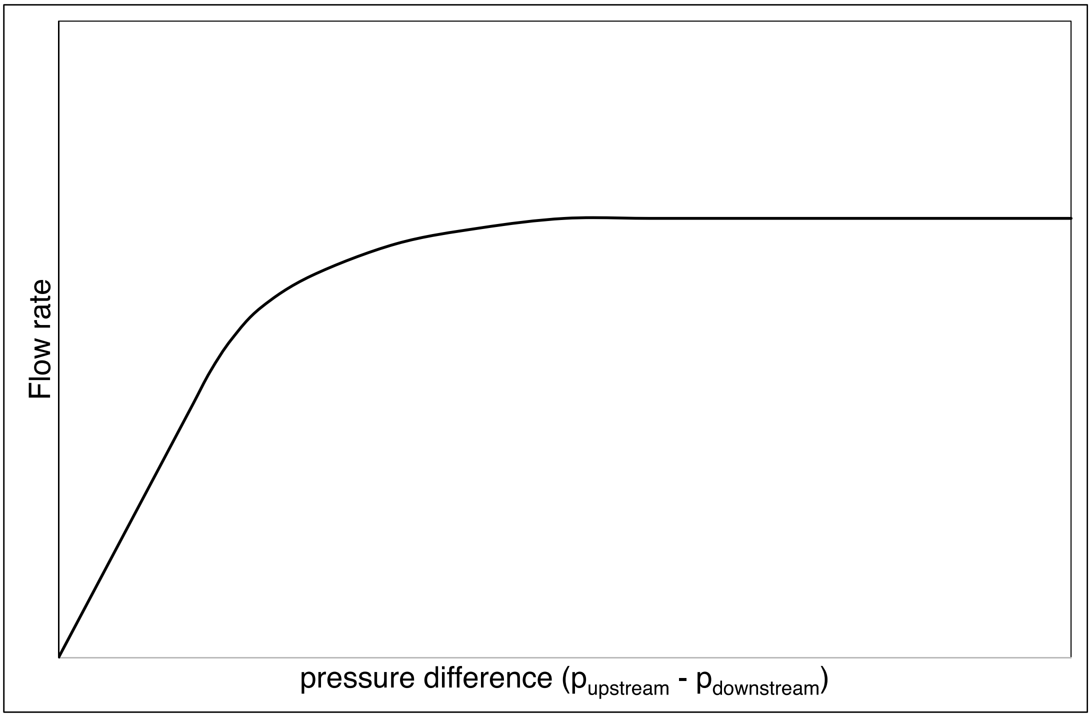

Fig. 1. The flow rate behaviour vs. pressure difference.

The choke should be operating under critical conditions, and this prevents the fluctuations of the downstream pressure from affecting flow rate. Also, operating chokes under critical conditions is a type of protection for the facilities from slugging.

Most developed correlations used data from a single reservoir or a single field. This implies that using the correlations with similar data that were used to develop the correlation will result in similar errors, but using new data from different fields with different data ranges will result in higher errors due to the different trends of the new data compared to the original data. Hence, using data with wider ranges, and from different regions and fields, will minimize the error when it is used for new data, and the correlations become more universal.

The data used for this study was collected from five studies (Al-Attar & Abdulmajeed, 1988, Alrumah & Bizanti, 2007, Ashford, 1974, Bizanti & Mansouri, 2000, Poettman and Beck, 1963), and they cover different geographical regions around the world. The total number of data points is 835. The new developed correlations are compared to 11 existing correlations listed in Table 1 with their coefficients. All 11 existing correlations used the format of Equation 1.

Table 1. The coefficients of the existing choke correlations.

No.	Correlation	Empirical Coefficients				
		A	B	C	D	E
1	Alrumah & Bizanti	188	0.0632	1.9465	0.9661	---
2	Achong	3.82	0.65	1.88	1	---
3	Baxendell	9.56	0.546	1.93	1	---
4	Bizanti & Mansouri	17.73	0.946	1.43	1.678	---
5	Gilbert	10	0.546	1.89	1	---
6	Owolabi et al.	35.72	0.289	1.83	1	---
7	Ros	17.42	0.5	2	1	---
8	Al-Attar & Abdulmajeed	61.47793	0.471	1.63	0.831	---
9	Dhefaf Sadiq	$5.25\text{x}10^{-5}$	-0.101	0.704	-0.69	---
10	Pilehvari	1	2.111	0.313	46.666	---
11	Al-Attar & Abdulmajeed (including API)	0.8756	1.796	0.2693	29.79116	0.43957

$$q_L = \frac{(p_{WH})^D \, (d_c)^C}{A\,(R_{GL})^B} \tag{1}$$

Where (p_{WH}) is wellhead pressure, (d_c) is the choke diameter, and (R_{GL}) is gas-liquid ratio

BACKGROUND

The first author to develop an empirical correlation for choke performance for the two-phase flow was Gilbert (Gilbert, 1954). The correlation calculates liquid flow rate when wellhead pressure, gas-liquid ratio, and the choke diameter are given, and it does not include any of the fluid properties. The empirical correlation is based on field and laboratory data. Gilbert assumed in the developed correlation that the flow rate is in the critical flow region, and under this region, change in downstream pressure will not affect the liquid flow rate. Gilbert's equation has the format of Equation 1, where coefficients A, B, C, and D should be determined according to the data used. After Gilbert's work, many authors (Baxendall, 1958, Ros, 1960, Achong, 1961, Pilehvari, 1981, Owolabi et al.,1991, Bizanti & Mansouri, 2000, Alrumah & Bizanti, 2007, Sadiq, 2012, Bairamzadeh & Ghanaatpisheh, 2015) used the same equation form, but with different data to develop new empirical correlations with different coefficients. Al-Attar & Abdulmajeed (Al-Attar & Abdulmajeed, 1988) used Gilbert's equation to develop a new correlation with different coefficients and developed another correlation, which is similar to Gilbert's equation that also included a fluid property, which is the API gravity, to the equation, to have the following equation form:

$$q_L = \frac{(p_{WH})^D \, (d_c)^C \, (API)^E}{A\,(R_{GL})^B} \tag{2}$$

The results concluded that including the API improves the prediction of the oil flow rate and gives more accurate performance.

Also, Beiranvand et al. (Beiranvand et al., 2012) used 748 actual data points for an offshore field in Iran to develop two new correlations. The first developed correlation was similar to Gilbert's equation but with updated coefficients, and in the second developed correlation, Gilbert's equation was used with adding new parameters, which were free water and sediment and emulsion (BS&W) (Equation 3).

$$q_L = \frac{(p_{WH})^D (d_c)^C \left(1 - \frac{BS\&W}{100}\right)^F}{A(R_{GL})^B} \tag{3}$$

The two correlations were developed using Levenberg-Marquardt algorithm. Beiranvand and Khorzoughi (Beiranvand & Khorzoughi, 2012) took production tests of 182 test data from one of the southern offshore fields of Iran, and they used these data to generate a new correlation. The developing process started with Gilbert's equation, and ended adding new parameters (basic sediment and water (BS&W), temperature (T), and standard condition temperature (TSC)) to the equation (Equation 4), as these additional parameters proved to result in more accurate predictions, and their effects should not be neglected.

$$q_L = \frac{(p_{WH})^D (d_c)^C (1 - \frac{BS\&W}{100})^F \left(\frac{T}{T_{SC}}\right)^G}{A(R_{GL})^B} \tag{4}$$

where (q_L) is the gross liquid flow rate, which includes oil and water.

In this study, two correlations were developed following the format of Equation 1 and Equation 2, but with updated coefficients and better predictions.

METHODOLOGY

The data points for the two-phase flow through choke as a non-linear function of 3 and 4 independent variables have been investigated using developed universal choke correlations depending on their functionality. The universal choke correlations were first developed to fit the observed data by using linear regression, then implementing multivariable non-linear optimization model on the developed model to improve it. The objective function used for the optimization model was defined as mean absolute percentage error (MAPE) (Equation 5). Equation 5 calculates the error between the computed (predicted) liquid flow rate and the observed (measured) liquid flow rate.

$$MAPE = \frac{\sum_{i=1}^{N} \left| \frac{q_i^{predicted} - q_i^{observed}}{q_i^{observed}} \right|}{N} \tag{5}$$

where N is the total number of data points. The $q_{predicted}$ is calculated based on Equation 1, where the coefficients (A, B, C, and D) were initially estimated using linear regression and then optimized using the built-in function "Solver" for non-linear optimization in Microsoft Office Excel 2010 (Alenezi et al., 2009). Equation 2 determines the dependency of liquid flow rate of surface choke on four independent variables (p_{wh}, d_c, R_{GL}, API) with predefined coefficients. The optimized values of these coefficients reflect the reliance on independent variables (weak, moderate, strong, direct inverse, linear, logarithmic, exponential, power function, etc.). The MAPE provided equal weight to all points irrespective of their magnitude and sequence. Non-linear optimization is a trial and error procedure that will have an infinite number of combinations, and local minima, which are related to initial guess, but the global minima yields the only solution that represents the correct functionality of the dependent variable (Liquid Flow rate of choke) as a function of p_{wh}, d_c, R_{GL}, and API. Coefficient of determination (R^2) has also been evaluated for the predicted and observed q vectors, and strict specified criteria were used for the adequacy of the proposed non-linear equation. A non-linear optimization technique provided the best estimates of the coefficients for the choke correlations.

RESULTS AND DISCUSSION

The field data used in this study consists of 835 data points. These data points were collected from five different regions from around the world with wide ranges. The data were used to develop two new correlations for the two-phase flow through choke. First, linear regression was used to develop the correlations by estimating the new coefficients. Then, the results of the linear regression were improved using non-linear optimization techniques. Table 2 shows the minimum and maximum values of the data collected. It can be seen from Table 2, the data is in a wide range, for example, the flow rates are ranging from 10.5 to 6892 STB/D. It was the aim of the research to lower the MAPE to less than 10%. However, due to the wide range and the large number of data collected, the aim was not met.

Table 2. The range of data used in the current correlations.

Item	Equivalent choke size, 1/64 in. D	Wellhead pressure, psi	Gas/liquid ratio, scf/STB	Oil API	Flow rate, STB/D
Min	4.2	85	102	11	10.5
Max	90.5	4374	18579	56	6892

The coefficients for the correlations that fitted the operational data satisfactorily are tabulated in Table 3. Several data exhibited very high error, and for that, it was removed, and the final data considered for the development after that was 809 data points. These data are sufficient to develop universal choke correlations that can be used for any new data resulting in high accuracy. Using linear regression, two new correlations were developed: Correlation 1A and Correlation 2A. Correlation 1A has an MAPE of 27.5%, and correlation 2A, which includes the API gravity, has an MAPE of 22.8%.

Table 3. Correlations' coefficients resulted from linear regression.

Correlation	A	B	C	D	E	R^2
1A	2.644174	0.51975	1.8536	0.79998	----	0.839
2A	71.15411	0.54892	1.9697	0.83441	0.84253	0.903

For improving the correlations, a non-linear optimization technique was used to update the correlations' coefficients by minimizing the MAPE, leading to the update of the correlations' coefficients accordingly. The updated correlations' coefficients, after implementing multivariable non-linear optimization model, are tabulated in Table 4.

Table 4. Correlations' coefficients resulted from non-linear optimization techniques.

Correlation	A	B	C	D	E	R^2
1B	3.337139	0.553744	1.883216	0.848836	----	0.837
2B	249.8503	0.61029	2.0346	0.91772	1.104824	0.908

The MAPE was noticeably reduced for both correlations 1A and 2A. For correlation 1B, the MAPE was reduced to 26.9%, and for correlation 2B, it was reduced to 21.8%. Figure 2 and Figure 3 show the model performance by plotting the predicted values as a function of the measured values for different production rates without and with API gravity, one of the influencing parameters. The majority of the predicted data values fall within ±20% of the scatter band. It is also observed that the suggested model represented the data well at lower production rate values (<20%), whereas there is wide scatter in the high range of production (>20%) rate and at the middle production without employing API gravity (Figure 2). However, by employing the API gravity, most of the data, even in the middle ranges, fit well with the model (Figure 3). The model has the best fit to the experimental data in the lower production rate. These differences in the quality of fit exist because of the wide range of data points, as can be seen in Table 2. It was proven that, by adding one parameter (API gravity) to the correlation, it improved the fit of the observation data points. Since the data points have a wide range of the API from 11 to 56, a very important property in determining type of flow (laminar/turbulent), this parameter is extremely important in choke correlations.

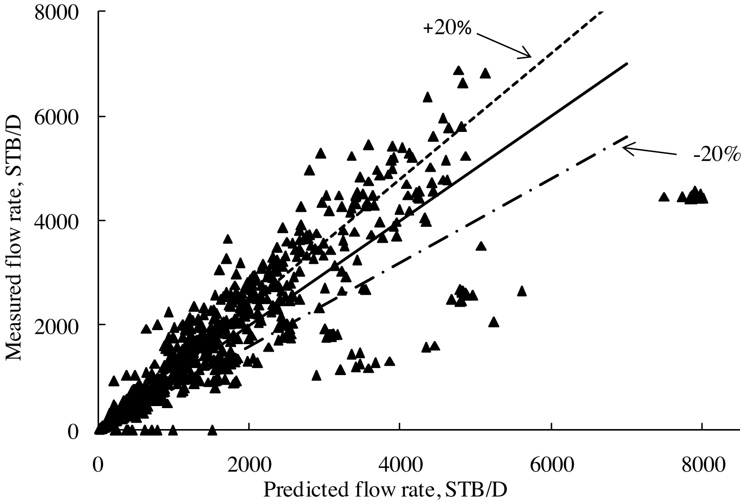

Fig. 2. Measured and predicted values with ±20% scatter lines (dashed) for the choke correlations without considering API gravity as influencing parameter.

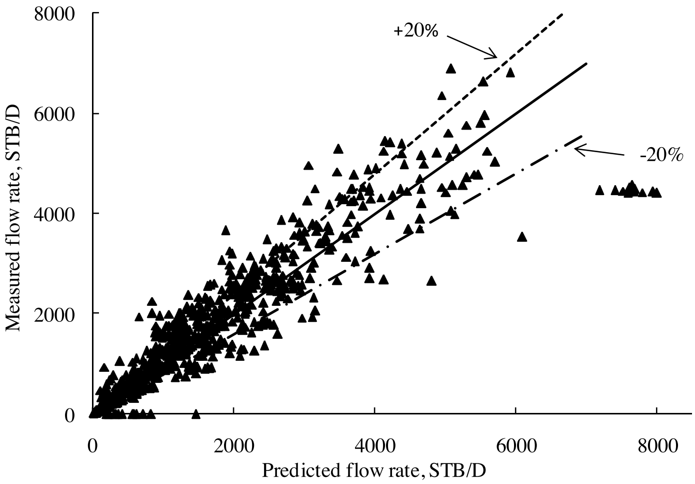

Fig. 3. Measured and predicted values with ±20% scatter lines (dashed) for the choke correlations with employment of API gravity.

Table 5. ‘t’ and ‘p’ values for the new models.

	Experimental		New Model		New Model with API	
	‘t’ value	‘P’ value	‘t’ value	‘P’ value	‘t’ value	‘P’ value
Experimental			1.949	0.52	2.511	0.12*
New Model					-0.06	0.952
New Model with API						

Paired sample t test between experimental model and new model with API (Table 5) showed significant difference in reduction in error score ($t = 2.522$; $P = 0.12$), while there is no significant difference observed between experimental models with the New model (without API) or between New model and New model with API.

The two correlations have better predictions and lower error than existing correlations as shown in Table 6.

Table 6 also shows a comparison between the new developed models with existing models, and the table shows that Gilbert’s model has the lowest MAPE compared to the existing models. It is important to indicate that Al-Attar & Abdulmajeed (1988) compared between three correlations, 1- Gilbert (1954), 2- Ashford (1974), and 3- Poettmann and Beck, (1963), and these three correlations have different format and different input parameters. The conclusion from this comparison is that Gilbert’s correlation overall is the best correlation among the three. In another study (Ghassan and Maha, 1991) a comparison was made for 10 existing correlations, and they are Gilbert (1954), Ros (1960), Baxendall (1958), Achong (1961), Poettmann and Beck (1963), Omana et al. (1968), Ashford (1974), Pilehvari (1981), Sachdeva et al. (1986), and Hazim-Ghassan (Al-Attar & Abdulmajeed, 1988). The study found that Gilbert’s correlation had better accuracy than other correlations for the choke sizes of 10/64” and above.

The first new model (Correlation 1B) has lower MAPE than Gilbert’s model. Also, including API in the model proved its effectiveness to improve the performance of the model, and to reduce the error. This is observed from the lower MAPE of the second new correlation (Correlation 2B), which has the lowest error compared to all models in Table 6.

Table 6. Comparison of the choke correlations.

No.	Correlation	MAPE (%)
1	Alrumah & Bizanti	53.90%
2	Achong	33.24%
3	Baxendell	30.46%
4	Bizanti & Mansouri	46.73%
5	Gilbert	28.44%
6	Owolabi et al.	29.76%
7	Ros	29.76%
8	Al-Attar & Abdulmajeed	96.36%
9	Dhefaf Sadiq	797.26%
10	Pilehvari	115.10%
11	Al-Attar & Abdulmajeed (including API)	84.39%
12	Correlation 1B	26.89%
13	Correlation 2B	21.78%

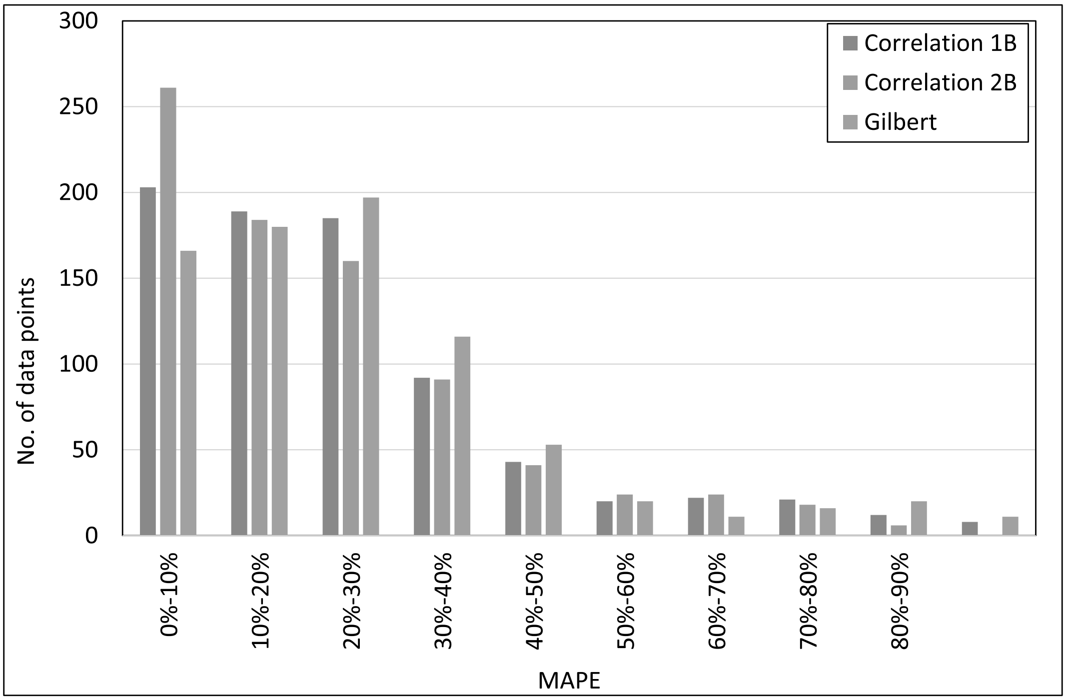

Fig. 4. Histogram of MAPE of the new correlations compared to Gilbert's correlation.

Figure 4 shows comparison between the new correlations and Gilbert's correlations. Gilbert's correlation has the lowest MAPE compared to the existing correlations tabulated in Table 6. The figure shows that more than 50% of the predicted data using "Correlation 1B" has an MAPE error less than 20%.

CONCLUSIONS

From five different regions, 835 data points were collected and then used to develop two universal choke correlations. These correlations predict the liquid flow rate at the wellhead choke. These relationships have higher quality of being close to the actual values and better collations for possible future event than existing relationships. Including the API gravity proved to better estimate the flow rate, and ignoring it will result in higher error. Using more accurate correlations will help engineers determine accurately the choke size for the desired flow rate, which is determined according to the production system analysis for the optimum production of flow rate. The results from this investigation are absolutely covered the way that aimed to have a simple predictive tool, with low dependent parameters, to monitor the operational conditions and phase behavior in the fields from petroleum reservoirs that will assist petroleum engineers.

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تطوير علاقات ارتباطية عالمية جديدة للخانق السطحي للتدفق ذو الحالتين باستخدام تقنية تحسين غير خطية لمتعدد المتغيرات

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الخلاصة

إنتاج المركبات الهيدروكاربونية من المكمن يجب أن يمر بالخانق السطحي. يتم تركيب الخانق للتحكم بمعدل تدفق المركبات الهيدروكاربونية على السطح، حتى يعطي أنسب معدل تدفق. لذلك، يتم تحديد معدل الانتاج حسب توصيات مهندس الإنتاج، حتى يتم تجنب بعض المشاكل من مثل تكوين الماء المخروطي. التنبأ الدقيق لمعدل التدفق السطحي مهم وأساسي لأنه يؤدي إلى تحقيق أهداف خطة التطوير للمكمن، وتحقيق الإنتاج الأمثل. العديد من العلاقات الارتباطية التي تم تطويرها للتنبؤ بمعدل التدفق خلال الخانق السطحي، والعديد منهم اعتمد على معلومات من مكمن واحد لتطوير هذه العلاقة الارتباطية. واستخدام هذه العلاقات الارتباطية المعتمدة على معلومات مكمن واحد، من المحتمل أن تتنبأ بنتائج ذات خطأ كبير. تقنية تحسين جديدة تم استخدامها لتطوير علاقتين ارتباطيتين للخانق لتنبؤ أفضل لمعدل التدفق لذو الحالتين (غاز وسائل) في آبار النفط. هذه العلاقات الارتباطية تتنبأ بمعدل تدفق السائل بمعلومية نسبة الغاز والسائل، وطول قطر الخانق، وضغط رأس البئر وكثافة النفط. تم استخدام عدد 835 اختبار حقلي من خمسة مكامن مختلفة لتطوير هذه العلاقات الارتباطية حتى يتم تغطية مجال واسع من الحالات. أثبتت العلاقات الارتباطية الجديدة قدرتها على التنبؤ بمعدل التدفق مع دقة أعلى من العلاقات الارتباطية الحالية بنسبة 9%. النتائج من هذه الدراسة سوف تساعد بشكل كبير مهندسي البترول على أن يكون لديهم تقديرات معينة لمعدلات تدفق السائل من رأس البئر.