Indirect estimation of the production rate of wells with low flow rate

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Abstract. The problem of measuring the flow rate of wells with low production rates is relevant for many oil fields. Conventional flow meters are not suitable for such cases, and installing an additional flow meter for each well is impractical. At the same time, wells with sucker-rod pumping units (the majority of wells) are outfitted with dynamographs for continuous diagnostics of the pumping equipment state. Dynamograms allow determining the theoretical flow rate of the well easily, however, a mathematical model is required to estimate the actual flow rate. For the correction of flow rate obtained from dynamograms, the authors of this study propose using models based on regression equations that link the calculated values with the measurements made by a reference instrument. The results of the experiments have confirmed the eligibility of this approach.

1. Introduction

The modern information and measurement systems (IMS) use measurements of any parameters not only to obtain information about these parameters but also to evaluate other values, which are impractical or impossible to measure. Such an approach became possible due to the widespread introduction of various mathematical models and new information technologies in automated process control systems. It should be noted that this approach is justified both for complex production processes having dozens of measured and analyzed interrelated parameters, as well as relatively simple processes. This article discusses the possibility of estimating the flow rate of oil wells based on the dynamometry results.

The main and most important property of any operating well is its flow rate. As per preliminary national standard PNST 360-2019 "Measurement of the amounts of oil and oil gas extracted from depth. General metrological and technical requirements" [1], the well flow rate is the amount of oil well production obtained per day. The flow rate characterizes the efficiency of the field operation, as well as the dynamics of its production. The continuous flow rate monitoring allows applying correct control actions on the reservoir. During oil field development, the flow rate of wells decreases, technologically meaning the transition from the fountain method of production to the pump method using electric centrifugal pumps (ECP) or sucker-rod pumping units (SRPU). In the Russian Federation, about 75% of wells are currently being operated using SRPU. Additionally, more than a third of wells have low flow rates. For instance, according to the 2018 Energy Bulletin prepared by the Analytical Center under the Government of the Russian Federation, the percent of wells with low flow rates in the Russian Federation in 2017 was about 30 to 40%.

Flow rate reduction poses the additional problem of flow rate measurement, because most flow rate
meters are either generally unsuitable for small flow rate, or do not provide the required measurement accuracy [2-7]. Also, all wells operated using SRPU have real-time dynamometry registration. Therefore, the attractiveness of the concept of using a dynamogram to estimate the flow rate [8-11] is clear, although the correctness of such an estimate from the point of view of the metrological properties is non-obvious [10] and requires additional research.

2. Relevance and research objectives

An ever-increasing number of wells with low flow rates requires the development of another approach to flow rate measurement. The measurement frequency for such wells is established by the local specifications of oil producing companies. For example, JSC Tatneft and Bashneft state that if an automated control system is installed for monitoring and sending the data to control centers, fluid flow rate measurements at wells with flow rates over 5 tons/day shall be carried out daily, and once a week for wells with flow rates below 5 tons/day [12]. This leads to a situation where conventional automated group measurement units (AGMU) do not work properly, while the installation of a dedicated flow meter (counter) for each well is not feasible technically or economically. Therefore, the search for a new solution allowing to estimate the flow rate indirectly using the measurement results for any other parameters is an urgent scientific and practical task.

The flow rate can be estimated using dynamograms, which are recorded during normal operation to diagnose the current state of the pumping equipment. In this case, the estimation accuracy is determined by the adequacy of the applied mathematical model. The purpose of this study is to carry out a comparative analysis of various models based on the results of an active experiment, and evaluate the feasibility of using dynamograms for flow rate estimation.

3. Materials and methods

3.1. Theoretical substantiation of dynamogram usage for flow rate estimation

The main element of the SRPU is a sucker-rod pump (SRP), which scheme is shown in figure 1 [13]. The rod pump piston contains a check valve (discharge) allowing liquid to pass only in one direction (up). The valve's shut-off element is a ball and a valve seat. As the piston travels down, the ball moves up, the valve opens allowing the fluid to pass through the piston. When the piston travels up, the ball is pressed to the saddle, and the valve closes affected by the fluid head. SRP operation is ensured by the reciprocating movement of a plunger driven by a surface drive via a column rod linkage. The higher part is a polished rod that passes through the packer assembly at the wellhead and is connected to the pump unit balance-beam head via an equalizer and a flexible cable suspension.

![Figure 1. SRP schematics.](image1.png)

![Figure 2. Theoretical and real dynamograms.](image2.png)
The dynamogram is a graph of load changes on the connecting rod depending on its stroke, which represents the dependence of the rod suspension point travel (S) on the rod load at the suspension point (P). The theoretical dynamogram of the normal unit operation is based on the consideration of gravity, elasticity, friction and the Archimedes Law, and represents an ABCD parallelogram (Figure 2). Its left part describes the pump operation when the plunger is in the lower position and, accordingly, the operation of the pump's suction valve. While the right side describes the pump operation when the plunger is in the upper position and, accordingly, the operation of the pump's discharge valve. AB and CD — sections of loading and unloading; BC and DA — sections of constant load when traveling up and down; ABC and CDA — sections of suspension point traveling up and down. Load changes on the polished rod during one complete operation cycle of the pumping unit are due to the complex interaction of a large number of different factors. The theoretical dynamogram of the normal pump operation is obtained under the following conditions [9]: the sucker-rod pump is properly functioning and sealed, the pump cylinder is fully filled with a degassed and incompressible fluid from the well, the polished rod travels with a speed that causes no inertial and dynamic loads, friction forces are zero in the underground part of the unit.

As can be seen from the real dynamogram ABC'D', straight lines turn wave-like due to the action of the friction forces, as well as inertial and dynamic effects arising in real conditions.

When determining the flow rate by the dynamogram, the amount of fluid in the sucker-rod pump cavity during pumping is taken for the flow rate. Using a dynamogram, the flow rate can be determined by various methods. For example, the theoretical flow rate \( Q_T \) is determined by the equation

\[
Q_T = 1440 \cdot \frac{\pi}{4} \cdot D^2 \cdot L \cdot N,
\]

where \( D \) is the plunger diameter; \( L \) is the plunger stroke; \( N \) is the number of pumping cycles per minute. The stroke length is determined by the dynamogram, while the number of pumping cycles — according to the dynamograph's readings. This flow rate value is theoretical because the pump filling coefficient is assumed to be 1, which does not happen in practice. Therefore, the actual flow rate can be accurately found only after the pump filling is determined reliably. It should also be noted that, in fact, all methods allow to determine the performance of the sucker-rod pump for the well fluid (liquid and gas), which is equal to the flow rate.

When calculating the real flow rate, several additional coefficients are introduced into equation (1) taking into account such factors as leak-tightness of the pumping equipment, fluid shrinkage, the ratio of the plunger stroke to the polished rod stroke (pump filling coefficient). The effective plunger stroke is determined graphically using the dynamogram, while the existing techniques differ from each other only by the method of how this parameter is defined. The common disadvantage of these techniques is that the operator is required to identify the movement of discharge valve closing visually using some reliable region on the real dynamogram, which leads to significant errors. Furthermore, rod linkage deformation is not taken into account as well.

3.2. Existing mathematical models for flow rate determination using dynamograms

Several mathematical models are used to increase the accuracy of the real flow rate estimation using a dynamogram.

To improve the accuracy of determining the moment of discharge valve closing, [9] proposes to record a real dynamogram, then construct an individual theoretical mathematical model of the pumping unit taking into account the specified weight and dimensions of the equipment and coefficients simulating the normal operation, then define the initial degree of pump filling and correct this value further using the trial-and-error method to achieve the maximum coincidence of real and calculated (according to the model) dynamograms. The disadvantage of this method is a large amount of calculations associated with the analytical model description complexity, as well as a large number of parameters used.

In [14], the algorithm is proposed for determining the flow rate based on an energy approach. It is
based on the measurement of work spent on lifting the fluid. If the pumping unit efficiency is 100%, then this work that can be estimated by the dynamogram area is equal to an increase in the potential energy of the fluid lifted from the depth. Using daily values, it is possible to estimate the mass of the lifted liquid, that is, the flow rate. In this case, the pump filling coefficient shall be determined experimentally.

In [15], the mathematical model addresses the effect of work performed by free gas and leaks in well tubing. The smart leak detection process includes the valve testing procedure and the subsequent dynamic calculation of leaks using the depth dynamogram. The described method requires a special "Naftamatica" controller and a highly skilled operator.

3.3. Experimental studies of an oil well with low flow rate
The experiment was conducted at one of the wells of NGDU Elhovneft. During one month, a dynamogram was recorded for a well with a flow rate not exceeding 4 m³/day by the installed dynamograph. DinamoGraph software was used for the calculations [16]. It is included in the stationary dynamometry system and performs reading, processing and storing data on pump unit rod load changes in time obtained both in the form of individual files generated by the remote control system and copied from the memory of the portable data collection module. Flow rate meter was used as a working standard (reference flow rate meter) intended for measuring oil flow rate with a maximum permissible relative error limit not exceeding 2%.

The results of the experiment are shown in figure 3.

![Figure 3](image.png)

These data show that the well operation is unstable — the load on the polished rod, water content in oil, the dynamic level, gas saturation of the fluid, pump operation, gas-liquid mixture movement in well tubing are changing, which leads to the flow rate changes.

4. Results and discussion
According to the results of the experiment, the flow rate values calculated according to dynamograph data and measured using the flow meter are consistent with each other. This means that the reliability of the flow rate calculation results using the dynamogram can be increased by determining the mathematical dependence for these values and then adjust the dynamogram processing results according to this dependence.

The first possible mathematical model is a linear model — the linear regression equation of the form

\[ y = a + bx. \]

Coefficients \( A = 3.639 \) and \( B = 0.016 \) are true for the obtained mean values \( \bar{x} = 2.78 \) and \( \bar{y} = 3.68 \). The linear correlation coefficient \( r_{xy} = 0.68 \), and the mean error of approximation \( \bar{\Delta} = 7.64 \% \). A test by the Fisher criterion confirmed the importance of the regression equation, and the accuracy of the found dependence according to the Student's \( t \)-test.
The quadratic model is the regression equation in a form of a polynomial function of the form:

\[ y = b_2 x^2 + b_1 x + b_0 \]

with regression coefficients \( b_2 = 0.644; \) \( b_1 = -4.345; \) \( b_0 = 10.039. \)

The correlation index for this model is \( R = 0.75. \) It is closer to unit compared to the correlation index of the linear regression. It means that the relation between the considered signs is closer, i.e., the found regression equation is more reliable [17]. Test by the Fischer criterion also confirmed the significance of the regression equation.

The third model is based on a neural network. Neural networks (NN) refer to the class of approximators and "black boxes" approximating certain functions of the form \( Y = F(X), \) where \( Y \) is the output variable vector, \( X \) the input variable vector [18-19].

The approximation process implies selecting \( w_{ij} \) weighting coefficients and is called NN training. NN can function in two modes — operation mode when signals are fed to the input and the output provides the calculation results, as well as training mode when the weights are adjusted so the output signals better correspond to the desired values.

The structure of the proposed three-layer NN is presented in table 1, while figure 4 shows the neural model obtained using the SPSS Statistics software.

| Layer               | Property                          | Value                        |
|---------------------|-----------------------------------|------------------------------|
| Output layer        | Covariates                        | Dynamometry system           |
|                     | Number of neurons\(^a\)           | 1                            |
|                     | Covariate scaling method          | Corrected and normalized     |
|                     | Number of hidden layers           | 1                            |
| Hidden layers       | Number of neurons in hidden layer \(^1\) | 2                            |
|                     | Activation function               | Hyperbolic tangent           |
|                     | Dependent variables               | Flow rate meter              |
|                     | Number of neurons                 | 1                            |
| Output layer        | Scaling method for quantitative dependent variables | Standardized |
|                     | Activation function               | Unit matrix                  |
|                     | Error function                    | Sum of squares               |

The model parameters are given in table 2.

To assess the adequacy of the considered models, mean squared error values and flow rate trends were calculated for each of them (figure 5): (a) is linear model \( (\sigma = 7.44 \%) \), (b) is quadratic model \( (\sigma = 6.39 \%) \) and (c) is neural network model \( (\sigma = 6.13 \%) \). \( \sigma \) is standard deviation here.
Table 2. Neural model parameters.

| Predictor                  | Predicted value |     |     |
|---------------------------|-----------------|-----|-----|
|                           | Hidden layer 1  |     |     |
|                           | H (1:1)         |     |     |
|                           | H (1:2)         |     |     |
|                           | Flow rate meter |     |     |
| Output layer              | (Offset)        | -1.458 | -0.162 |
| Dynamometry system        | 1.898           |     | 0.039 |
|                           | (Offset)        |     |     |
| Hidden layer 1            | H (1:1)         | 1.868 | 2.259 |
|                           | H (1:2)         |     | 0.488 |

Figure 5. Comparative analysis of measured and calculated values for different models.

As can be seen, the neural network model has the smallest mean squared error. Slightly less accurate results are provided by the quadratic model, which is clearly demonstrated on the graphs. The obtained results lead to several practical recommendations.
First of all, the results confirm that a dynamogram allows estimating the flow rate of wells with a low flow rate with the accuracy acceptable for practical use without installing a dedicated flow meter. Flow rate meter installation is only relevant when a dedicated real dynamogram is needed. Flow rate values subsequently calculated using the dynamometry results can be relatively simply corrected, for example, using a neural network model.

It should also be noted that the quadratic model, which is even easier to use compared to the neural network, provides almost the same accuracy and in some situations may be the best option.

5. Conclusions
The concluded research leads to several important conclusions.

Firstly, using the dynamometry results to estimate the flow rate of low flow rate well is more than justified, because they provide the accuracy sufficient for practical purposes (with a properly selected mathematical model) and allow to avoid the installation of a dedicated fluid flow rate meter on the well.

Secondly, the proposed selection of a mathematical model using the regression equations that link the calculated flow rate values with the values measured using the reference meter significantly facilitates this process, does not require incorporation of multiple dynamic or difficult to determine parameters, and at the same time provides acceptable accuracy.

Thirdly, in any case, we are specifically talking about estimating (calculating) the flow rate, and not measuring it, therefore, the dynamography cannot be considered as a flow rate measurement tool, as it is correctly noted by [10].

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