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GAS WELL PRODUCTION ENHANCEMENT ON THE APPLICATION OF INNOVATIVE STRUCTURAL AND THERMAL INSULATION NANO-COATINGS

М. І. Фик, Стефан Паліс, Ю. І. Ковальчук. ЗБІЛЬШЕННЯ ДЕБІТУ ГАЗОВОЇ СВЕРДЛОВИНИ ПРИ ЗАСТОСУВАННІ ІННОВАЦІЙНИХ СТРУКТУРНО-ТЕПЛОІЗОЛЮЮЧИХ НАНО-ПОКРИТТІВ. *Наведено результати розробки спрощеної прикладної математичної моделі неізотермічного свердловинного ліфтингу природного газу в умовах розробки виснаженого газоконденсатного родовища. Спрощене моделювання базувалося на відомих рівняннях Дарсі, Бернуллі, Адамова, Веймаута, Шухова і Рейнольдса. Базові рівняння бралися в нелінійній формі з перевіреними в промисловій практиці спрощеннями, що значно скоротило час обчислень і дало можливість вирішувати завдання в загальній постановці. При цьому враховували також застосування трьох основних покриттів: гладкі, теплоізолюючі і турбулізуючі. Велика частина параметрів і вихідних даних – типові для родовищ України з середньою величиною запасів. Представлено перевірку теоретичних експериментів ключових параметрів моделі і ефектів від застосування різних спеціальних сучасних покриттів труб. Модель побудована на базі емпіричних формул, перевірених промислової практикою. Показано, що можливий підбір комбінацій спеціальних властивостей покриттів для отримання максимального економічного ефекту в натуральних одиницях сирої продукції, особливо, на етапі останньої стадії компресорної розробки родовища.*

***Ключові слова**: видобуток газу, компресор, температурний градієнт, свердловина, ізоляція, шорсткість поверхні, покриття.*

М. И. Фык, Стефан Палис, Ю. И. Ковальчук. УВЕЛИЧЕНИЯ ДЕБИТА ГАЗОВОЙ СКВАЖИНЫ ПРИ ПРИМЕНЕНИИ ИННОВАЦИОННЫХ СТРУКТУРНО-ТЕПЛОИЗОЛИРУЮЩИХ НАНО-ПОКРЫТИЙ. *Приведены результаты разработки упрощенной прикладной математической модели неизотермического скважинного лифтинга природного газа в условиях разработки истощенного газоконденсатного месторождения. Упрощенное моделирование базировалось на известных уравнениях Дарси, Бернулли, Адамова, Веймаута, Шухова и Рейнольдса. Базовые уравнения брались в нелинейной форме с проверенными в промышленной практике упрощениями, что значительно сократило время вычислений и дало возможность решать задачи в общей постановке. При этом учитывали также применение трех основных покрытий: гладких, теплоизолирующих и турбулизирующих. Большая часть параметров и исходных данных – типичные для месторождений Украины со средней величиной запасов. Представлено проверку теоретическим экспериментом ключевых параметров модели и эффектов от применения различных специальныхсовременных покрытий труб. Модель построена на базе эмпирических формул, проверенных промышленной практикой. Показано, что возможен подбор комбинаций специальных свойств покрытий для получения максимального экономического эффекта в натуральных единицах сырой продукции, особенно, на этапе последней стадии компрессорной разработки месторождения.*

***Ключевые слова**: добыча газа, компрессор, температурный градиент, скважина, изоляция, шероховатость поверхности, покрытие.*

Introduction

At the late stage of gas condensate fields' exploitation deterioration in hydraulic and gas-dynamic efficiency of jointing flow line pipe lifts and gas collectors leads to the decrease in the total flow rates of pattern wells. There are many technical ways to improve a hydraulic efficiency of complicated gas collecting systems in gas condensate fields. The cardinal method of diameters increase and additional link is expensive or impossible in some cases. It is rather difficult to replace the installed flow compressor pipes (FCP) into wells, subways, special ducts with other diameter, as well as to build locks or correct the structure in the complicated terrain conditions.

As for the thin coatings with specific thermophysical, geometrical and structural properties, there is an opportunity to have simpler solutions to optimize hydraulic efficiency of pipe system and particular pipeline sections. The most popular methods of field experience include thermo-insulation, smooth coating and turbulence-insulating coating [1-6].

Because of a complicated strict mathematical modelling it is often a problem to evaluate the effects of the standard pipes replacement into the pipes with special coatings. The simplified modelling of complex results when using multiple technologies at the same time is a rare case of the sequential but not simultaneous implementation of certain technologies. However, new materials such as nanoceramics and ceramic insulation require new approaches to modelling and forecasting economic effects.

Many former CIS countries, as well as the former German Democratic Republic have experience in the transition to a compressor stage of oil-gas field development. To do this, it is necessary to consider several methods of parallel hydraulic optimization in conditions of a lower operating pressure wells and manifolds.

Nevertheless, the authors made some attempts to analyse the correlation between the results from different methods to optimize hydraulics using nanotechnology and other modern coatings. The result has been obtained, and some positive effects sharing the technology are exposed briefly in this article. The main fact is that the calculations result showed a significant increase in computational and theoretical well production in complex use of the special few (two or three) coatings in comparison with the particular applied coatings.

1. The basic elements of research problem description

The base application object is averaged well in Mashevsky field in Poltava region in Ukraine. General description of the field is following: the average depth of productive horizons is up to 4 km; the length of a particular gathering lines up to 2.5 km; the used FCP diameter- 63 mm; the reservoir temperature - 70-80 degrees Celsius and wellhead pressures 1-3 MPa. The wells work quite steadily with the consequent pressure reduction at the wellhead and in the layer.

Simplified modelling is based on the famous equations by Darcy, Bernoulli, Adam, Weymouth, Shukhov and Reynolds. Basic equations were taken in a non-linear form with proven simplifications in a field experience that significantly reduced the computing time and made it possible to solve problems in a general setting. In this case the use of three main surfaces is considered: smooth, heat-insulating and turbulizing. Most parameters and initial data are typical for Ukrainian deposits with an average value of mass flow rate.

The universal formula of Higher Scientific Research Institute of gas [16-17] is taken as the base to evaluate the hydraulic efficiency dependence on the rough surface. The choice is explained by the gas velocity increase and Reynolds` numbers at the late stage of field exploitation, under conditions of relatively dry gas. The thermal conductivity was calculated by Shukhov`s formula with a generalized parameter from the external environment to the transported working substance. The degree of turbulence is characterized and modelled by the traditional Reynolds` number. The main task of the work is the coating modelling with the inner surface of the FCP with a thin ceramics coating with specific properties. This makes certain changes in well production from the modified geometry and physical properties of the inner surface of the tubing.

2. Hypothesis and the main exploration objectives

The authors have suggested that the combined methods application to increase the hydraulic efficiency of jointing flow lines pipe lifts and gas gathering collectors may differ slightly from the last method. Thus, the formulae structure has shown that the total effect of several technological coatings in parametric data conditions may exceed the effect of a partial coating application, for example, smooth coating with low equivalent roughness. The hypothesis has been shortened to a possible profitable coating use only in the area of inflow by the vertical section of tubing gas well. In the authors` opinion, the problem of shortening to the narrow application will allow to show the results with economic effect determination in natural calculation of the additional natural gas production (daily production rate), excluding other cases with hydraulic losses.

3. Relevance

The actuality of the work is to reduce production costs and transport of different gas mixtures. Under certain conditions, this also allows you to reduce the used pipe diameters, the total cost of transport networks. In particular, the problem is relevant in the production intensification and petroleum products transportation, especially when the pipes are placed in inaccessible places since it is very costly to repair and replace pipes.

Scientific relevance is to solve the gas dynamic problem by means of empirical and linear equations without many other possible solutions, such as systems equations of stability testing. The authors didn’t find the analogues of simultaneous solution to these inflow problems into the reservoir and the horizontal layer, lifting on tubing, flowline transport in the conditions of declining gas production in the gas condensate field.

The relevance in the application sense is to suggest a theoretical development under optimal properties and coating of the inner surface of the pipe with a few calculated properties (structural and geometric, stylus, thermo-physical) that can be done with one nonoceramic layer. On the basis of the proposed model we can forecast the new hydraulic properties after nanoceramics application, the right "drawing", thickness, smoothness and thermal coating conductivity. Here, there can be one layer, but the material itself in the various sections of the pipe can substantially differ by the set of gas-dynamic and thermal properties. From the point of view of economy and technology, of course, it is important to assess a priori the advantages of different combinations of several new coating properties.

In particular, as a result of a gas well’s operation improvement it has been determined that the thermal insulation is more important in the upper part of the lifting tube (from the middle to the wellhead) and the flow pattern improving with correct "drawing" and roughness is critical for a lower part (at the borehole bottom). It is necessary to note the experimental works, confirming the importance of the site installation turbulizing with the intensification of heat exchange processes [9, 11, 14, 18].

4. Description of the mathematical model

In some scientific works a significant difference in viscosity and flow resistance coefficient is pointed out under non-isothermal flow of hydrocarbon mixture within the reservoir drainage area and the lifting tubes with vertical, inclined and horizontal sections [7-12]. For a variety of fields a mathematical model that takes into account the proven empirical dependence and equations of non-isothermal lifting will be effective as far as the temperature difference between bottom hole and the wellhead is considerably bigger than temperature difference between the reservoir and the bottom hole. There is a case for small flow rates and reservoir pressure depletion at the late stage of gas condensate fields' exploitation. We distinguish the following scientific and applied analytics to non-isothermal flow of a dual mode according to [13-16]:

1. If there are two modes in the pipeline, the flow temperature at the end of the pipeline with a non-isothermal current[13] is :

$$t_{\kappa} = t_0 + (t_H - t_0) \cdot e^{S_{u.l}} \cdot \left(\frac{t_{KP} - t_0}{t_H - t_0}\right)^{1 - \frac{S_{u.l}}{S_{u \cdot t}}} \tag{1}$$

Where $S_{u.l}$, $S_{u.t}$- Shukhov parameter for laminar and turbulent flow regime.

To determine the hydraulic resistance coefficient of non-isothermal flow based on experimental data the formula was obtained [14]:

$$\lambda_{\Gamma} = a^{\bullet} \left(\frac{8\,\mathrm{Re}}{I + 2\left(1 + \sqrt{9 + I}\right)} \right)^{b^{\bullet}} \left(\frac{\mu_{\omega}}{\mu_f} \right)^{0{,}62} \tag{2}$$

Where $a^{\bullet} = 2{,}9He^{-0{,}403}$; $b^{\bullet} = 1{,}26He^{-0{,}265}$; He – Hedstrema number

2. Physical formula of wellhead pressure for non-isothermal downhole lifting [7, 15]:

$$P_2 = P_1^2 \cdot \left(\frac{T_1}{T_2}\right)^{\psi} - \frac{8\lambda\_(P, T, \upsilon, z\_D, k\_) \cdot Zskv(\mathrm{P}, \mathrm{T})^2 \cdot R\_^2 \cdot \left(\frac{T_1 - T_2}{\ln\left(\frac{T_1}{T_2}\right)} \right)^2}{9{,}8 \cdot D^5 \cdot \pi^2} (Mqs\_)^2 \cdot \left[\left(\frac{T_1}{T_2}\right)^2 - \left(\frac{T_1}{T_2}\right)^{\psi} \right] \tag{3}$$

They are as functions of the following variables:

$$\psi = \frac{-2 \cdot 9{,}8 \cdot Hskv}{Zskv\left[\frac{2}{3} \cdot \left[P_1 + \frac{(P_2)^2}{P_1 + P_2} \right], \frac{T_1 - T_2}{\ln\left(\frac{T_1}{T_2}\right)} \right] \cdot R\_ \cdot (T_1 - T_2)} \tag{4}$$

$$Zskv(P, T) := \frac{0{,}1 \cdot P}{Pnk} + \left(0{,}4 \cdot \log\left(\frac{T}{Tnk}\right) + 0{,}73 \right)^{\frac{P}{Pnk}} \tag{5}$$

$$\lambda\_(P, T, \upsilon, z\_, D, k\_) := 0{,}067 \cdot \left(\frac{158}{\mathrm{Re}\_(P, T, \upsilon, z\_, D)} + \frac{2 \cdot k\_}{\mathrm{D}} \right)^{0{,}2} \tag{6}$$

Where the first level functions are set:

$$\mathrm{Re}\_(P, T, \upsilon, z\_, D) := \left(\frac{D \cdot \upsilon \cdot P}{\eta\_(P, T) \cdot z\_ \cdot R\_ \cdot T} \right) \tag{7}$$

$$\eta\_(Psr, Tsr) := 5.1 \cdot 10^{-6} \cdot \left[1 + \rho\_n \cdot (1.1 - 0.25 \cdot \rho\_n)\right] \cdot \left[0.037 + \frac{Tsr}{Tnk} \cdot \left(1 - 0.104 \cdot \frac{Tsr}{Tnk} \right) \right] \cdot \left[1 + \frac{\left(\frac{Psr}{Pnk}\right)}{30 \cdot \left(\frac{Tsr}{Tnk} - 1 \right)} \right] \tag{8}$$

Where the following parameters identifier and functions are used:

P, P_1, P_2, P_{sr}, P_{nk} – bottom hole pressure, wellhead, the average in the pipe, pseudocritical; T, T_1,

T_2, T_{sr}, T_{nk} – working gas temperature, surface gas temperature, the average pressure piping, pseudocritical; D – pipe diameter; Z_{skv}, z_ – compressibility; H_{skv} – depth; R_ – gas constant; u-gas Velocity; k_ – roughness; $M_{qs\_}$ – mass gas flow rate; q_n - density at normal conditions; Re_ – Reynolds number; ɳ_ – dynamic viscosity.

3. Tested experimental formula (7) is the mathematical model of unsteady nonisothermal motion of a gas-liquid mixture in the book by Yakovleva E. I. [16].

To close the equations system (1-4) it is necessary to note that the equation (2-3) takes into account the law of mass conservation and mechanical energy, and the equation (1-4) – heat balance and impulses movement. In equation (3), the equation of state crude product – a mixture is also taken into account. Thus, when considering the first system of equations (1-4), it is represented fully closed, but as far as the equation (2) is based on the dynamics and the dynamic viscosity differences, the mathematical model is supplemented by another appropriate equation based on empirical research, about a point of dry gas [17].

Nonlinear equations systems solution given by a mathematical model of non-isothermal lifting in condensate wells is done by using advanced algorithmic techniques in Mathcad program, by rank-Kut 4th order with the addition developed by the authors of the initial and boundary conditions in accordance with the physical sense.

5. The research results

1. Downhole lifting was studied using the developed mathematical models by objects of Mashevsky gas field development, which showed a good value for the simulation adequacy and close agreement between calculated and thermometer measured, manometric and flow-measuring parameters.

There presented the dependences in Fig. 1-2, gas condensate wells change debit in changing the roughness of the pipe’s inner surface and the thermal insulation coating (temperature changes in the wellhead);

2. Diagram 1-2 shows that the technological ways of correlation to improve the hydraulics by coating has a positive sign. For example, Figure 1 shows that roughness of reducing in the inner tube surface heat insulation begins to work better (continuous red line), the diagram 2 – wellhead gas temperature increase contributes to a better effect from the smooth surface, etc. [19].

Three simultaneous technological coatings use with roughness minimization heat loss and turbulence condensation of towards the axis direction exceeds the total effect more than for each parameters individually (using specific technologies).

It should be noted, that the difference between the classical isothermal methods of "medium depth well" flow rate calculation (logarithmic temperature averaging) and the authors’ "analogue well" flow rate calculation reaches 30% (for the late operation stage). When FCP is used with an inner polymer

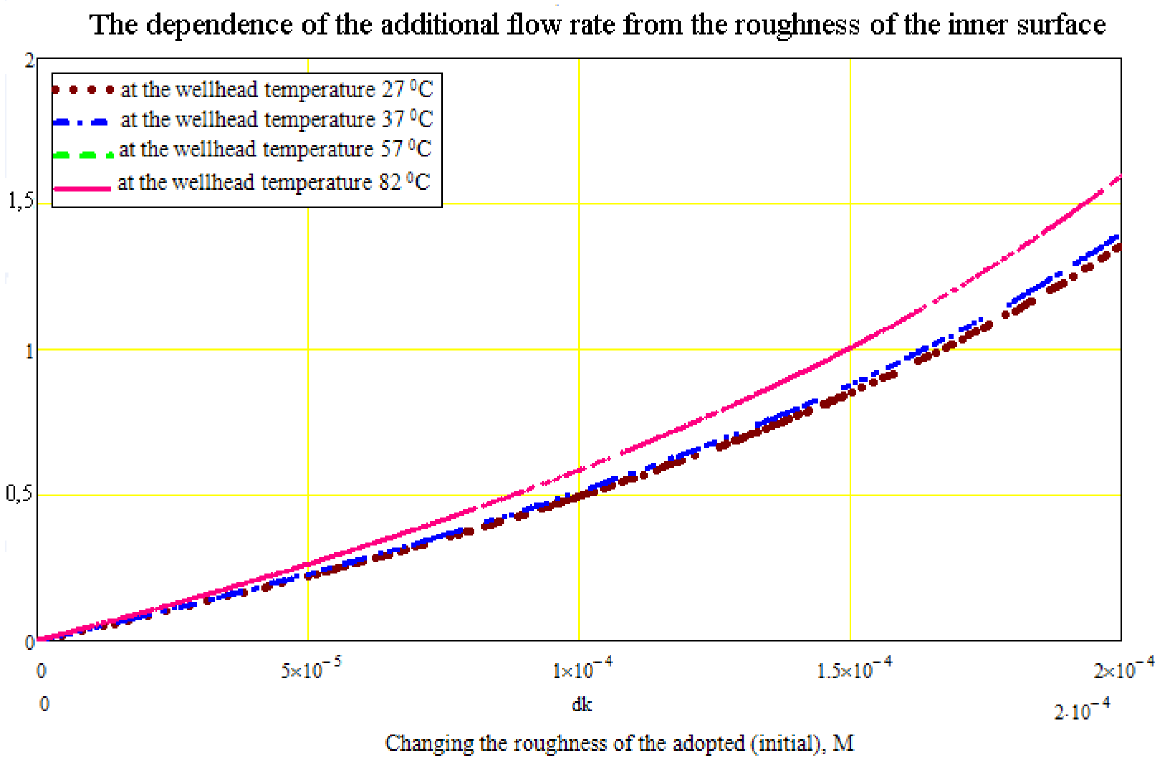

Fig. 1. Dependence of extended flow rate from the roughness changes in the internal tubing surface (compared with the standard) at different temperatures in the wellhead

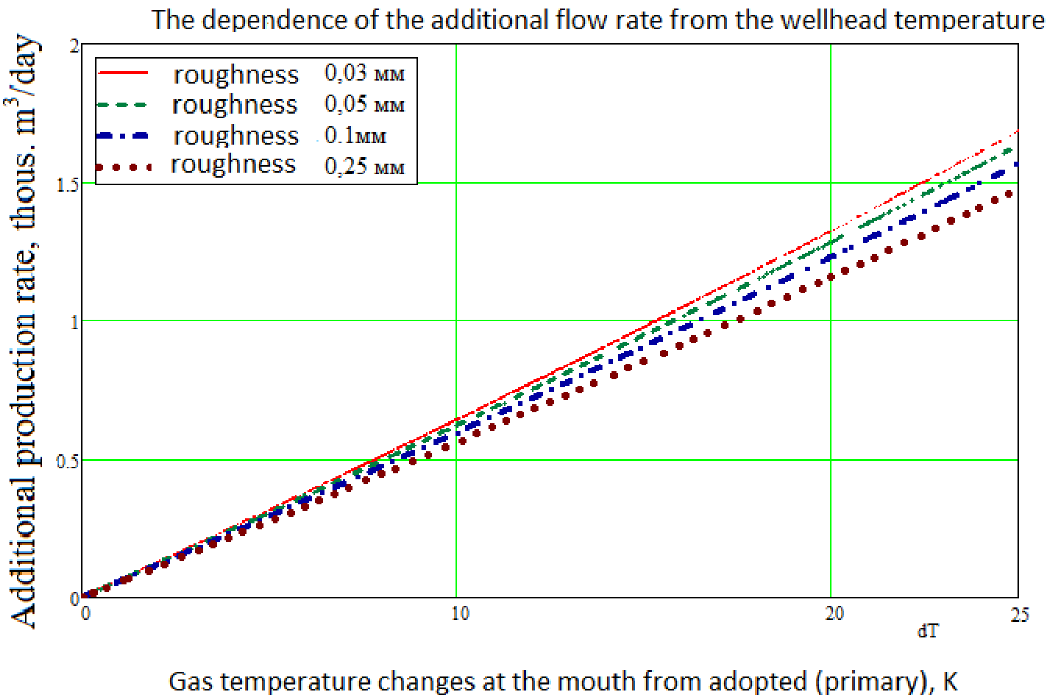

Fig. 2. Dependence of extended flow rate from the temperature variation at the wellhead (compared to the actual average) with different surface roughness of the inner tubing

When FCP is used with an inner polymer (smooth) nano-coating, thermal insulator is in the top of the nano-ceramics tubing, where the lower part of it is narrower by the diameter with turbulizing "figure." The intense turbulence flow can be carried out by conventional methods with the special liners installation. However, according to the authors` calculations, "figure" in the form of a ceramic spiral at calculation step and the projection height, which is applied along the tubing at the first few hundred meters, will work better. At the same time the most important operational parameters to be taken into consideration in the physical and mathematical models calculation, where the water of production stream by water and hydrocarbons, is geothermal gradient by the actual depth. At the bottom of the tubing after passing through the perforations and the filter at the bottom hole the gas is cooled by Joule-effect where gas should be heated by deep heat at the first section of lifting up. Such self-heating can be "organized" by a heat-conducting plug installation in the space near the bottom hole.

As far as great pressure drops are presented inside the lifting tube, periodic removal of abrasive mechanical impurities is possible, so the inner coating should be made in severe environment where innovative metal-ceramic coating, nano-ceramic and nano-composite materials comply to it.

These facts show that "classical" methods of the field development indicators calculation at a substantially non-isothermal-lifting in the late operation stage are impossible to apply and also in the conditions of special intensification methods use in bore-hole gas production. The authors recommend to use the more accurate express-predicting method with precision engineering, more sensitive to the basic regime and physical-chemical parameters of the mathematical model. It is based on adapted empirical formulae and equations in relation to the non-isothermal transport of wet gas-mixtures.

Conclusions

1. The authors' lifting modelling in the gas condensate well at the late field operation stages gives the difference (correction) in the production rate by 15-30% relative to analogues of conditionally non-isothermal type. The essential difference is the moisture content rate, viscosity and the actual geothermal gradient in the dynamics.

2. Test results of the theoretically developed model on the Mashevsky`s condensate field wells make it possible to assert that it has high efficiency and sufficient accuracy for engineering and applied calculation.

3. Modelling allows to choose more optimal pipes for well tubing (gas condensate wells) by geometrical, heat and hydraulic parameters. This enables to increase the production rate of wells in equal conditions by 10-15%.

4. Technical key to a significant flow rate increase of the gas condensate wells at the late operation stage might be nano-technological coating.

5. The developed mathematical model can be used for other non-isothermal gas-mixtures in transport intensification calculated in the conditions of constant or variable longitudinal thermo-gradients.

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