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Software for adapting the material balance model of a gas field development object using the Monte Carlo method

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Abstract

The publication is a logical continuation of works on the creation of convenient software for operational analysis and forecasting of indicators of a separate gas field development object based on the material balance model. The main requirements for such a software object were accessibility, low costs for hardware and software, ease of use for a researcher without special computer and mathematical knowledge, a minimum of input data, which in turn protects against unreliable, and sometimes unavailable model parameters. The software, with a minimum of information and labor costs, allows to identify the mode of operation of the deposit, estimate the initial gas reserves, determine the activity of the water-bearing zone, give a forecast of gas and condensate production according to the modes of operation of the wells.

Keywords: engineering solutions, formation pressure, material balance equation, water influx.

Introduction

The first step in designing improved oil and gas field development systems is to analyze existing experience. This stage is usually called "field development analysis". Based on the results of the analysis, the drive mechanism of recovery, hydrocarbon reserves, formation pressure dynamics, etc. should be established or evaluated. Material balance methods are an effective tool for such analysis.

Software for creating a material balance model of a gas reservoir development object is based on a theoretical model that includes [1−3]:

the main material balance equation of a gas deposit, which expresses the fundamental law of conservation of mass of a substance, in relation to a gas deposit;

equation of gas flow to the well;

model of the water-bearing zone according to Fetkovich [4];

Soave–Redlich–Kwong equation of natural gas state with new correlations for calculating pseudocritical gas characteristics and acentricity factor [5];

equation of gas movement in the tubing strings of the well.

The system of equations is closed regarding the pressure difference between formation and working pressure at the wellhead, supplemented by initial approximations for formation pressure and gas reserves in the development object.

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The program package is written in Python language and compiled into an executable application file for the Win 10 operating system. The software supports three dialogue languages – English, Ukrainian and Russian. By default, Windows interface language is connected. A unified International System of Units is used for all data (SI).

Database

The database of the project on creation a material balance of the gas deposit object of development is created as an Excel workbook. The output data are grouped by type in the separate Excel sheets.

Names of sheets, names of columns and the order of strings on the sheet are strictly regulated - they are keys or identifiers of variables when selecting data by the calculation module. The used previously prepared templates significantly reduce the probability of errors in names when creating a new project.

Data sheet on modeling object «Globals» contains general gas object parameters such as an average formation depth, formation temperature, initial gas reserves, initial reservoir pressure, water-bearing zone potential, water-bearing zone production rate, relative gas density, average temperature at the wellhead, the tubing diameter, the coefficient of hydraulic resistance of the tubing, the coefficient of wells operation and some others.

The well test data sheet "WellTestData" contains data on reservoir pressure measurements at the object, in particular, a text identifier of the measurement, for example, a well number, and a prefix to the identifier, which can, for example, characterize the method of determining the reservoir pressure (bottom-hole measurement or wellhead calculation), a weighting coefficient for strengthening or, on the contrary, excluding the influence of one or another measurement on the results of model adaptation, the date of the measurement and the value of the measured formation pressure. It is correct if this pressure is given to the middle of the perforation interval.

The dates sheet and actual production "Calculated" includes the sequence of dates for which the material balance calculation will be performed, including the actual production periods and the forecast period, the actual accumulated gas condensate and water production on the corresponding date, the number of operational wells, the working pressure at the wellhead.

The "CondFactor" gas-condensate characteristic sheet contains data for further calculation of condensate production for the forecast period.

The program provides the calculation of the gas-condensate factor, using the data of gas-condensate researches, which should be summarized as the versus of the gas-condensate factor on the formation pressure. If such a versus exists and is given on the "CondFactor" sheet, then it is used to calculate condensate production. If the data on the "CondFactor" sheet is not given, then the condensate is calculated based on the actual data of the dynamics of gas and condensate production.

The program allows forecasting by combining wells into groups with the same operating modes and similar productive characteristics. In order for the sheet to be identified as mode data for a separate group of wells, its name must contain the letter combination "Group" or "iWell". If there is a forecast period, then there must be at least one mode sheet. The number of mode sheets is not limited. For the wells for the period between two forecast dates, one of four operating modes can be set, namely: constant working pressure mode with the mandatory working pressure parameter "pHead", constant depression mode on the formation (mandatory depression parameter "dpRob"), mode of constant bottom-hole pressure (mandatory parameter of bottom-hole pressure "pBottom") and mode of constant daily flow rate well (mandatory parameter operating flow rate of one well "q").

Algorithm of approximation and forecasting

The finite-difference approximation of the material balance equations system along the time axis allows to use the implicit algorithm on each time layer and explicit when moving from one to another time layer. The transcendental nature of the equations system requires the use of several iterative processes to find a solution at each time layer. Selection of iterative algorithms ensures the stability of the calculation scheme in a wide range of initial approximations. Algorithms provide approximation of formation pressure dynamics in the development object and forecasting the main indicators of gas production depending on the specified modes of operation of the wells.

The initial values of recoverable reserves and formation pressure are used as the initial conditions. The joint solution of the system of material balance equations at the end of the time layer determines the residual gas reserves, formation pressure and water influx volume, which in turn become the initial conditions for the next time layer.

The model adaptation algorithm is reduced to finding the values of initial gas reserves, initial formation pressure, potential of the water-bearing zone and its productivity index, at which the objective function is minimized, namely the residual root mean square error of the model between the measured and forecasted values formation pressure in the deposit.

The selection of an effective extremum search algorithm is mainly determined by the topography of the response function. The expressed non-monotonic nature of surfaces with the presence of many local minima [1] excludes the use of gradient methods and requires the use of stochastic methods, in particular random search by the Monte Carlo method.

The minimizer software module sequentially sets random values of the optimized parameters and evaluates the objective function. If it decreases, the value of the mathematical expectation of the parameter changes and, in accordance with the given relaxation multiplier, reduces the value of the variance of the parameter for the next sample. Finding the minimum is like shooting in four-dimensional space. The mathematical expectations of the variables is the center of the four-dimensional sphere where the shot is directed, and the variance is the radius of the shot's dispersion. A shot (attempt) is the calculation of an objective function for certain values of variables. The first shot gives the first initial value of the objective function. With each subsequent shot, one of the variables is successively randomly changed and a new value of the objective function is determined. If the new value of the objective function (shot accuracy) is better than its previous value, the mathematical expectation of the variable is redefined to the current value, and the variance for that variable is reduced. Otherwise, the current values of the objective function, the mathematical expectation, and the variance of the variable are kept unchanged.

In the case when only the initial gas reserves of the development object are optimized in the model, the dichotomy method is used to find their minimizing value, assuming that their initial approximation is close to the global minimum of the objective function.

When generating a random value, it is assumed that the amount of gas reserves, the initial formation pressure and the potential of the water-bearing zone are subject to the normal distribution law, and the productivity index of the water-bearing zone is subject to the logarithmic normal law. For the first sample, the values of gas reserves and initial formation pressure, which ensure fast convergence of the algorithm, are given by the available data on the deposits, for the potential of the water-bearing zone, it is close to the value of the pore gas-bearing volume, and the productivity index is equal to zero. The initial values of variances are set by software.

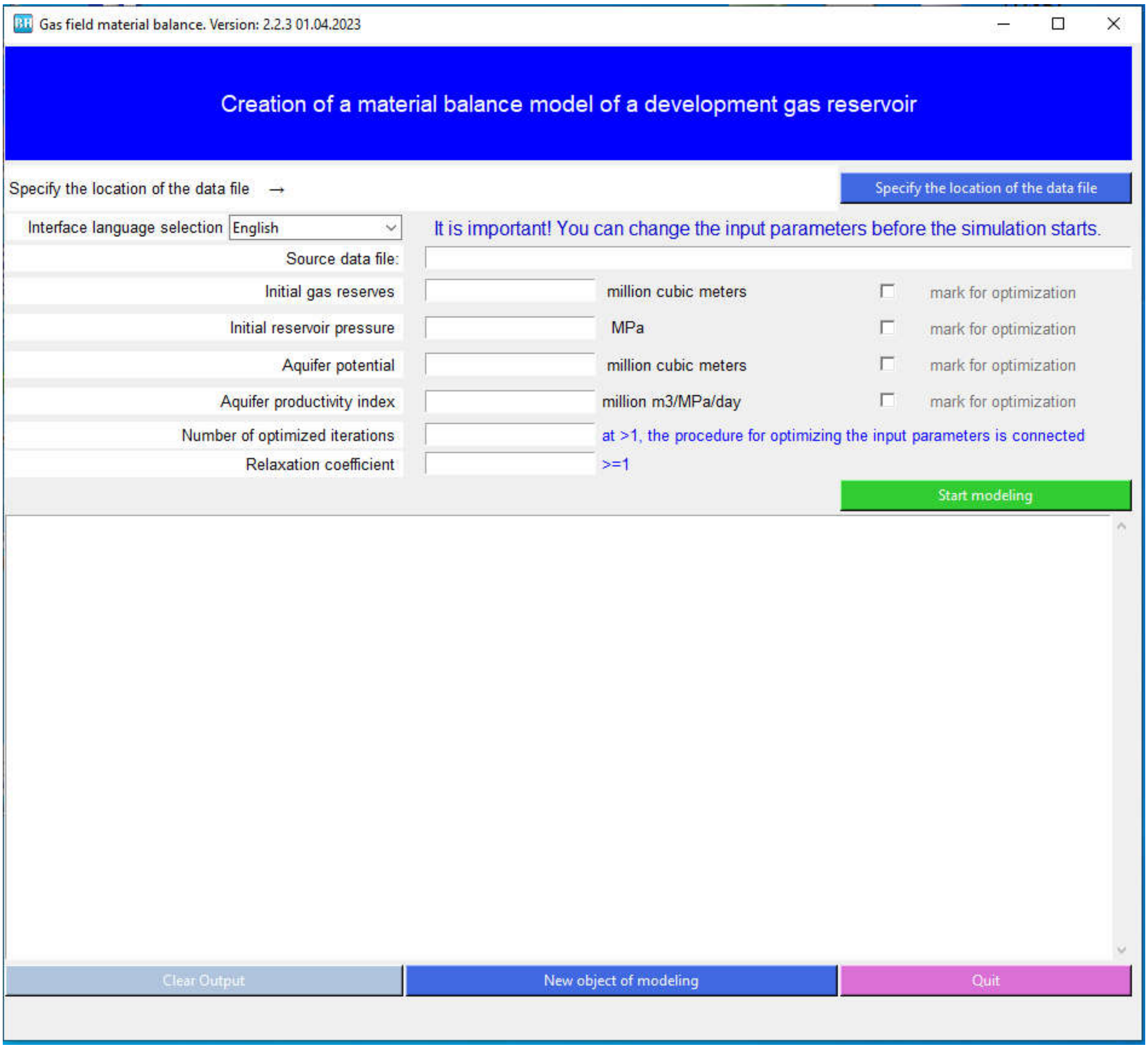

Figure 1 – Screenshot of the program's dialog box

Use of the program

The material balance modeling program does not require special installation. It is necessary to place the folder with the program modules and the folder with the source data files in a convenient place. Find and run the executable file. In the author's version, it is called Start_MBE_dialogs.exe. If desired, the user can change its name. The Windows console will open, which will later display information useful for tracking the progress of the program and the cause of possible errors. In a few seconds, the material balance dialog box will open.

At the beginning, the box (Figure 1) contains a title, several blank data input fields, four check buttons of optimization parameters, command buttons and an information panel kind of a message box.

After selecting the file with the initial data of the model in the data input fields the values of the four main parameters of the model: initial gas reserves, initial formation pressure, potential of water-bearing zone and its productivity index will display. Before starting the modeling, their values can be changed directly in the dialog box. By default, if otherwise is not specified in the input file, the water-bearing zone productivity index value is set to zero, which corresponds to a model with a pure gas drive mechanism. Two fields and four check buttons next to the model parameters are designed to control the optimization module. By default, one optimization iteration is set. In this case, the program performs a simple approximation of the production history and forecast for a given period according to the values of the model parameters in the data file and the dialog box.

To enable the model optimization procedure, it is necessary to set the required number of iterations, usually no more than 200 are sufficient for the Monte Carlo method, and mark the parameters to be optimized in the checkboxes. After the command to start the modeling, the program performs a formal check of the input data for the presence of errors and, if they are found, issues a message about the need to correct them.

The duration of the modeling depends primarily on the number of iterations and the number of dates during the actual development period for which formation pressure is calculated. Messages characterizing the

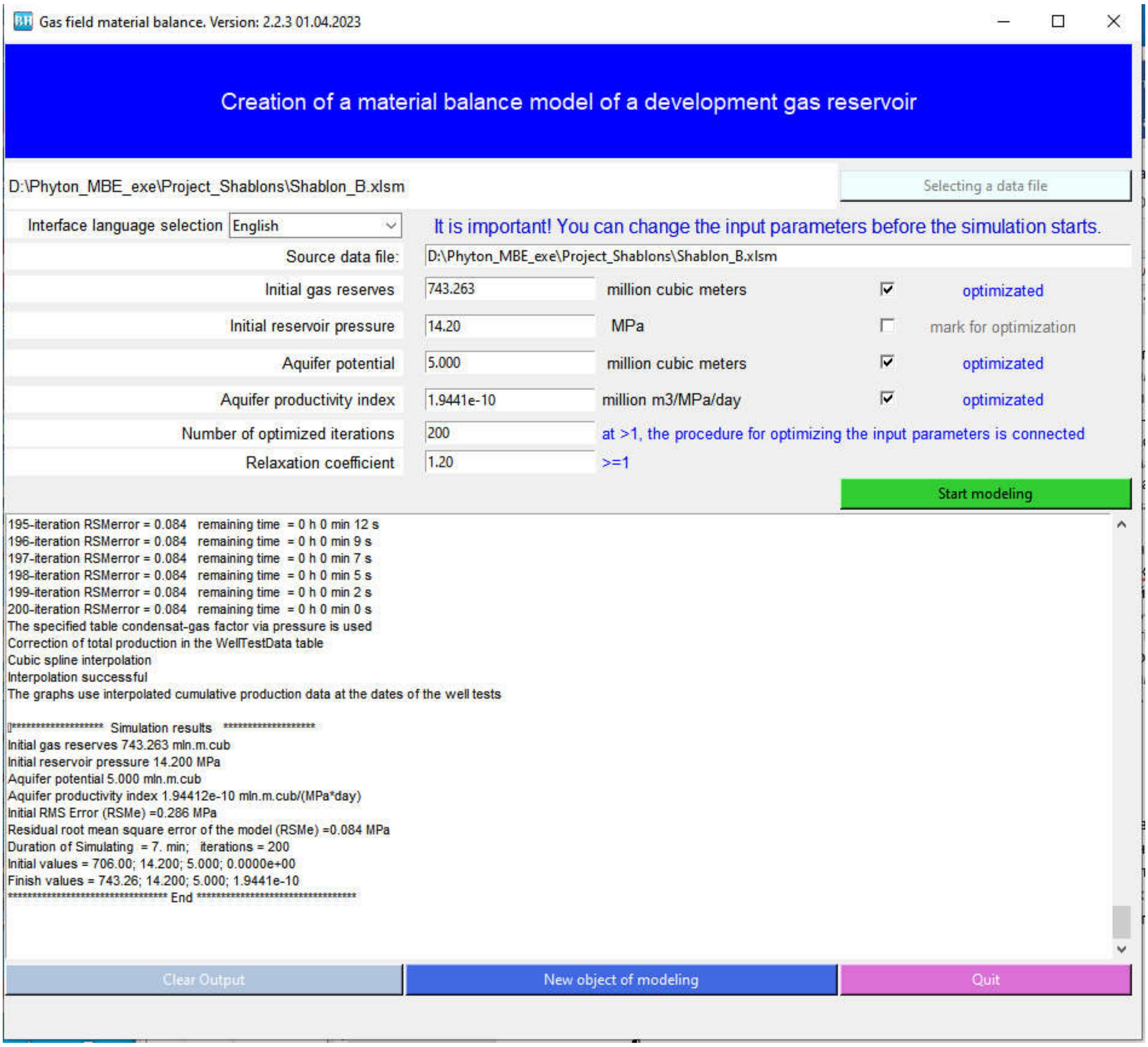

Figure 2 – Screenshot of the program's dialog box after optimization

optimization process and its duration will appear on the Windows console, and after completion, the optimization results will appear (Fig. 2). In addition, two boxes with graphs illustrating the modeling results will be displayed (Fig. 3, 4).

After each modeling procedure is completed, the results are saved in an Excel format file with a unique name that includes the name of the output data file followed by the suffix "_out-" and the first free number starting from zero. The location and name of the file in which the modeling results are saved, is displayed on the information panel. The files are stored in the "Out_files" subdirectory, which is automatically created in the project's output directory. The structure of the modeling results file repeats the structure of the input data file with the addition of modeling results. The resulting output file "*_out-*.*" can be used as the input data file when running the modeling program again.

In the resulting file, on the "Globals" sheet, an "ini_values" column is added with the initial parameters, and a "values" column contains the new parameters used in this modeling.

On the "Calculated" sheet, for the entire forecast period, columns with modeling results that characterize the object as a whole appear, namely: the average gas flow rate for all wells; condensate-gas factor; total accumulated gas production at the end of the calculation period; residual gas reserves at the end of the period; summarised; accumulated production of condensate since the beginning of development; total production of condensate for the period; volume of water inflow from the step-out zone at the end of the calculation period; estimated formation pressure at the end of the period; average bottom-hole pressure across the wells; average working pressure across the wells; average calculated depression per formation; calculated reduced pressure at the end of the period; pore volume filled with gas.

The well test data sheet "WellTestData" will display information about the measured and forecasted values of formation and reduced or effective formation pressure (p/z); accumulated gas production on the date of pressure measurement, obtained by interpolation of actual production data; accumulated gas production used in graphing. By default, interpolated values of the

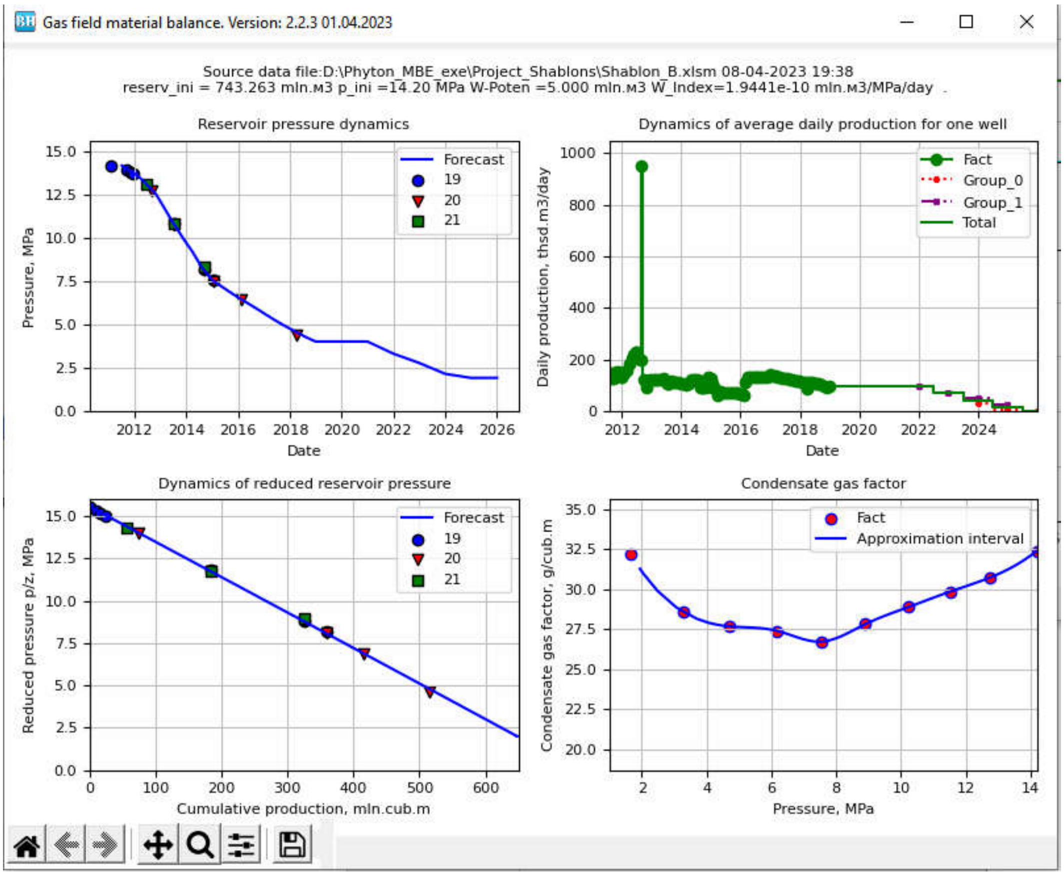

Figure 3 – Screenshot of the box of the resulting graphs of indicators on the object

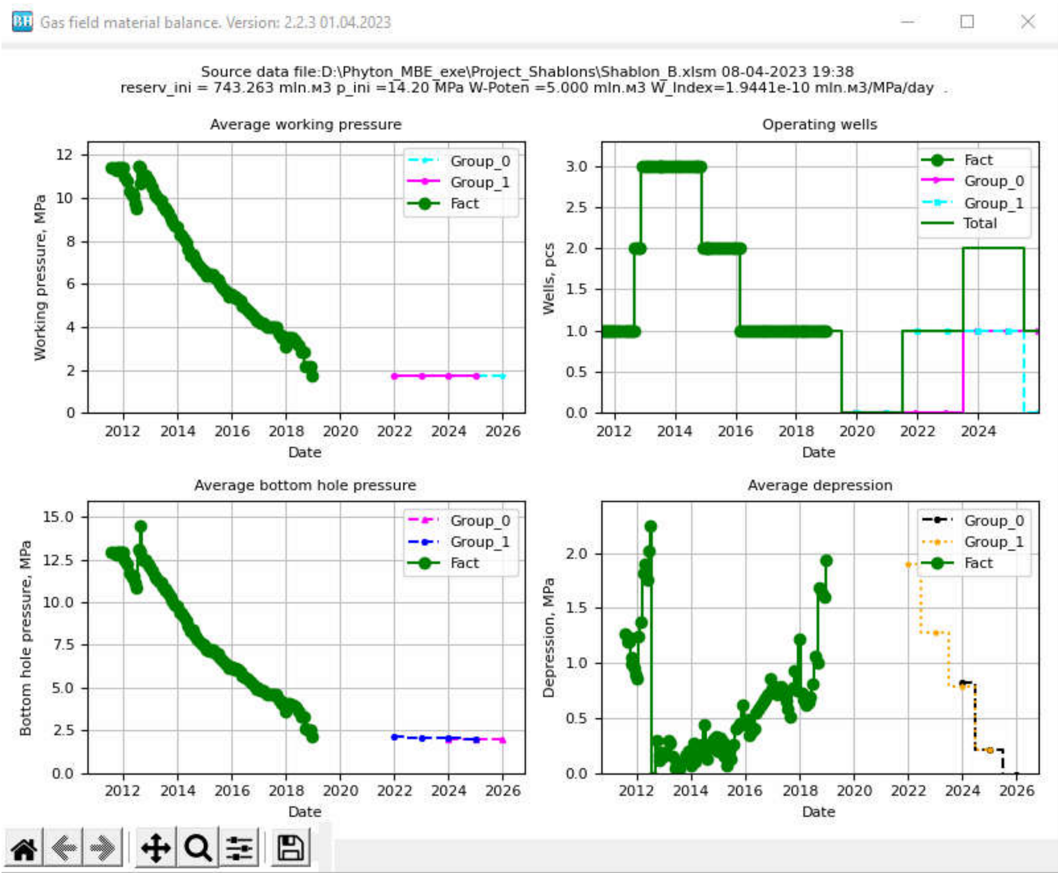

Figure 4 – Screenshot of the box of the resulting graphs of indicators on groups of wells

accumulated production are initially used for the graph displayed in the dialog box based on the modeling results. In the case of unsuccessful interpolation (most often in the case of gross errors in the research data), the entered values of the accumulated gas production are used.

In the book of resulting data, a "pz_Data" sheet is also formed to facilitate the researcher in creating his own illustrations of formation pressure from the accumulated since the beginning of development. This sheet also shows the main characteristics of the model and the value of the coefficient of determination after its adaptation.

On the sheets with modes for groups of wells for the forecasted period, the values of filtration resistances adopted during modeling for this group of wells will be displayed. If they were not specified by the researcher in the source data file, a one-term gas influx formula will be used with the productivity index identified at the last date of the actual production approximation period. In addition, for each date of the forecasted period, the average daily flow rate of one well in the group will be indicated; total gas production by all wells of the group for the period between two forecasted dates; average estimated bottom-hole and working pressures; average estimated depression per layer.

If the model optimization procedure is used in the modeling, the resulting file contains a "Shots" sheet with information about each iteration in the Monte Carlo method.

Examples

The material balance model is created for a separate object of development, which means a deposit, formation, possibly several deposits or formations, which are developed by a single grid of wells and belong to a single hydrodynamic system. The most important characteristic of a development object is its energy mode, which indicates the nature of the forces or the source of energy that cause the flow of liquids and gases to the bottom-hole of the wells. The results of the modeling of the material balance make it possible to determine both the boundaries and the mode of development of the object.

Figures 5–8 illustrate the use of the software for several typical cases. The gas mode of deposit development is characterized by a linear dependence of the reduced formation pressure (p/z) on the accumulated gas from the object, therefore this dependence is used to estimate recoverable gas reserves based on the historical data of formation pressure measurement in the wells used to develop the object. In the standard procedure, to build such a dependence, it is necessary to bring the measured formation pressures in all wells by interpolation or extrapolation to one range of dates, usually at the end of the year, then to obtain the average formation pressure for a specific date, to weight measurements of the correspondingly accumulated productions of the wells. This is a relatively complex procedure, so researchers avoid it by building (p/z) dependences separately for wells, followed by a simple summation of reserve estimates. In the program, the creation of this dependence is carried out in the reverse way by means of spline interpolation, the actual accumulated production of the object as a whole is determined for each date of formation pressure measurement. In the next by values of the accumulated production, corresponding to the measurement date, the forecasted pressure value obtained as a result of modeling the material balance is determined. Further, such an algorithm provides a correct comparison of measured and forecasted values of formation pressure, which is the basis of statistical assessments of the material balance model.

In the given example (Fig. 5), after adaptation of the deposit model, which is adjusted when the water-bearing zone is disconnected, the coefficient of determination of the model R^2 is 0.9959, which indicates the high reliability of the model and the possibility of a conclusion about the development of the object in the gas mode.

The results of the adaptation of the deposit model with an active water pressure system are illustrated in Figure 6. After the adaptation of the model according to the initial reserves, the potential of the water-bearing zone and its productivity index, the model is characterized by the adjusted coefficient of determination $R^2 = 0.925$. The adaptation of the model only according to the initial reserves in the gas mode of development gives the coefficient of determination $R^2 = 0.487$. The use of the adjusted coefficient of determination is associated with the comparison of models with different numbers of adapted variables. The amount of reserves turns out to be overestimated by 1.5 times. A statistical comparison of the residual deviations according to Fisher's test gives the reason to accept hypothesis that the model of the water pressure mode is statistically better than the model of the gas pressure mode of operation of the deposit.

The use of the material balance method can be a tool for the correct assessment of the efficiency of works to increase gas production from a separate well or the object as a whole. Such works, with a positive result, lead not only to an increase in the flow rate of the well, which is usually used to quantify the effectiveness of the work, but also to a change in the volume of drained reserves, which will ultimately affect the final conclusion about the effectiveness of the work. In this case, the dynamics of formation pressure changes are approximated in two stages. First, the period before the start of work is approximated, after which the next period is approximated, taking into account the production accumulated in the previous period and the formation pressure at the end of it. In the case shown in Fig. 7, the works led to an increase in the volume of drained reserves by more than 4.5 times. In the same way, it is possible to make a correct assessment of the effectiveness of the commissioning of a new well – an increase in the final production of gas from the object or the development of the object will only accelerate.

An adequate material balance model provides important information about the operation of an underground gas storage facility. In the example of an underground gas storage, created on the basis of a depleted

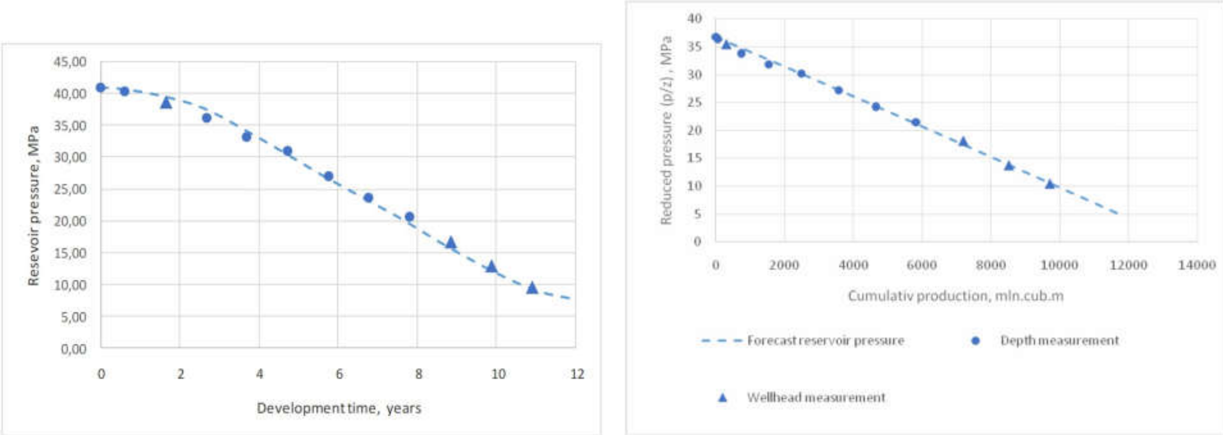

Figure 5 – Results of the model adaptation in gas mode deposit operation

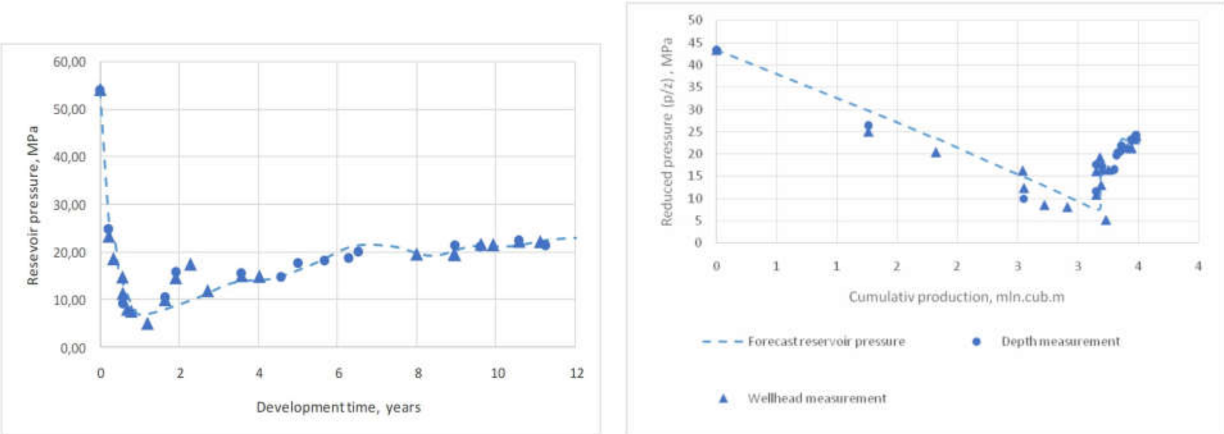

Figure 6 – Results of adaptation of the reservoir model with an active aquifer

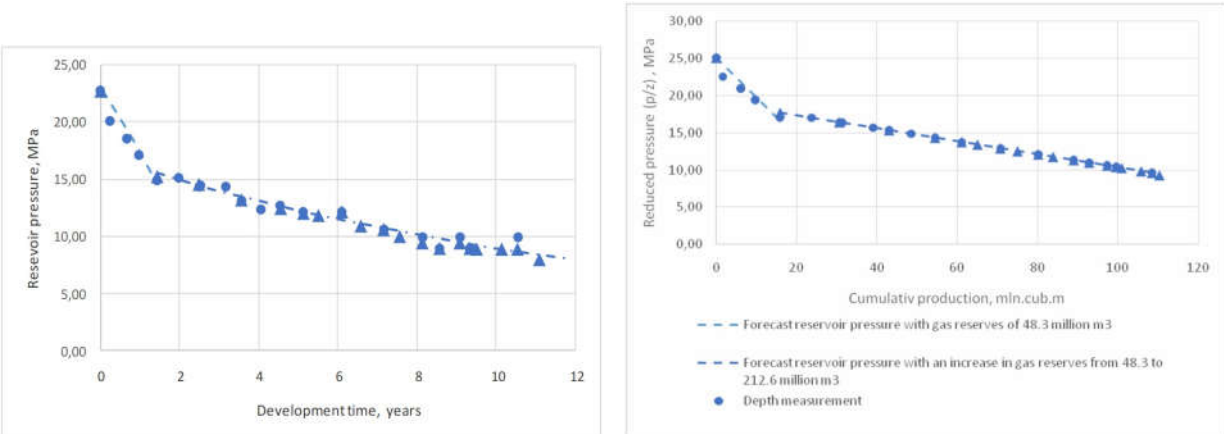

Figure 7 – Results of model adaptation when draining reserves are changed as a result of gas production stimulation

gas field (Fig. 8), the model was adapted to the data on the change in formation pressure during the development of the field. Two models were compared - operation of the deposit in a purely gas pressure mode (the productivity index of the water-bearing zone was assumed to be zero) and operation of the deposit in a mixed water-gas pressure mode. According to the results of adaptation, the model of the gas pressure mode was characterized by the residual root mean square error RSME = 0.1634 MPa and the adjusted coefficient of determination R^2 = 0.9997, and the model in the mixed mode was characterized by RSME = 0.0570 and R^2 = 0.9999, respectively. At first sight, the smaller residual error for the gas pressure mode attracts attention, but according to Fisher's test, the difference between the variances is not statistically significant. The distribution of models for the period of operation of the deposit in the underground gas storage mode with parameters adapted during the period of deposit development showed that the model of the gas

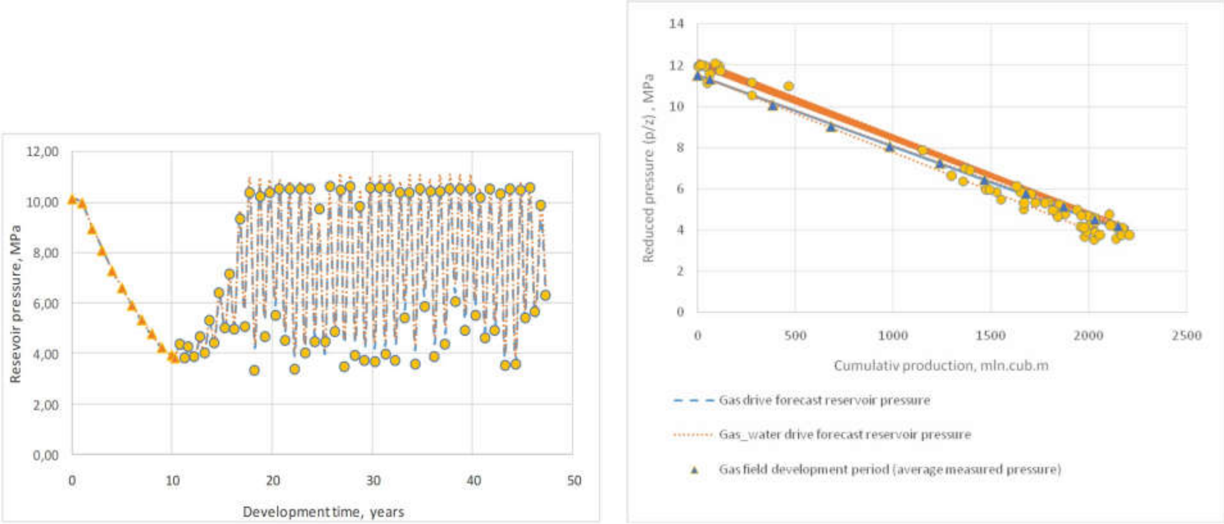

Figure 8 – Results of the adaptation of the underground gas storage model

pressure mode has already a smaller residual dispersion RSME = 0.3453 MPa and the adjusted coefficient of determination $R^2 = 0.9600$, while the model in the mixed mode was characterized accordingly RSME = 0.4637 MPa and $R^2 = 0.9157$. Both coefficients of determination are statistically significant, and residual errors are statistically the same. In the next stage, the models were adapted for the entire period, including both the period of development of the deposit and the period of its operation in the gas storage mode. As a result, the gas pressure mode model was characterized by RSME = 0.3108 MPa and $R^2 = 0.8472$, and the gas pressure mode model was characterized by RSME = 0.3008 MPa and $R^2 = 0.9081$. Statistical estimates do not favor one model. This is a typical case when the assessment of the adequacy of the model goes beyond statistical estimates and requires the involvement of additional data, for example, on the dynamics of formation pressure in the border and step-out areas. In any case, discrepancies between actual and calculated data are only a statistical criterion for optimization. The model must also meet the criteria of adequacy, among which the most important is the physical content of the model and the forecasting results obtained with its help.

Conclusions

The designed software provides the researcher with a convenient tool for using the material balance method in the analysis and forecasting gas deposit development. With a minimum of information and labor costs, it allows to identify the mode of operation of the deposit, to estimate the drained gas reserves in the deposit, to determine the activity of the step-out waters, to build a forecast of gas and condensate production in accordance with the established modes of operation of the wells and their productivity.

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Програмне забезпечення для адаптації моделі матеріального балансу об'єкту розробки газового родовища методом Монте-Карло

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Публікація є логічним продовженням робіт зі створення зручного програмного забезпечення для оперативного аналізу і прогнозування показників окремого об'єкту розробки газового родовища на основі моделі матеріального балансу. Основними вимогами до такого програмного об'єкту були доступність, невисокі витрати на технічне і програмне забезпечення, зрозумілість у використанні для дослідника без особливих спеціальних комп'ютерних і математичних знань, мінімум вхідних даних, що в свою чергу захищає від недостовірних, а інколи і недоступних параметрів моделі. Програмне забезпечення при мінімумі інформаційних та трудових витрат дозволяє ідентифікувати режим роботи покладу, оцінити початкові запаси газу, визначити активність водоносної області, дати прогноз видобутку газу та конденсату відповідно до режимів роботи свердловин.

Ключові слова: водоприплив, пластовий тиск, рівняння матеріального балансу, технічні рішення.