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Reservoir simulation with the MUFITS code: extension for horizontal wells and fractured reservoirs

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Abstract

Two new modelling options developed recently within the MUFITS reservoir simulator are presented. The first wellbore friction option allows a simplified modelling of wellbore hydraulics that often needs to be accounted for in horizontal wells. The second option concerns the modelling of fractured reservoirs using the double porosity, the double permeability and more general multiple interacting continua approaches. Results of the options validation against benchmark problems are presented and internal structures that MUFITS builds in kernel for such reservoir models are demonstrated.

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Keywords: Reservoir simulation; MUFITS; horizontal wells; wellbore friction; fractured reservoirs; double porosity

1. Introduction

Reservoir simulation is required in many processes of subsurface utilization including petroleum or geothermal energy extraction, subsurface CO_2 disposal, and many others. These applications are complicated with multiphase behaviour of the flow in porous medium, phase transitions as well as different space and time scales associated with coupled reservoir-wellbore flows or fluid transport in fractured reservoirs. The software packages for numerical modelling of such flows in geophysical applications, that are called reservoirs simulators, are the only effective tools for prediction and optimization of subsurface processes [1,2]. Development of a reservoir simulator requires

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comprehensive testing techniques, verification and validation against benchmark problems. Most of such benchmark problems do not allow analytical solution. Therefore, the validation is conducted by means of intercomparison of the simulation results obtained with different simulators. A good agreement between the results magnifies the confidence in accuracy of reservoir simulators.

In this work, two recently developed options available with the free dynamic reservoir simulator MUFITS are presented [3]. This software is designed to provide to a wide scientific community an extended set of complicated modelling options that are more common for applied rather than for academic research. MUFITS includes different fluid properties modules (EOS-modules) for accurate prediction of the properties in different scenarios of subsurface utilization. It can be applied to petroleum reservoirs [4], underground CO_2 storage [5], and non-isothermal flows under sub- and supercritical conditions [6].

The first new extension of the simulator covers pressure loss due to the wellbore friction. This modelling option might be necessary in scenarios that include horizontal wells. The frictional pressure loss can have significant effect on production rates in the case of long perforated wellbore intervals. In order to develop the wellbore friction option, the multi-segment well approach has been introduced in MUFITS where the well is discretized in a sequence of the pipe segments (well segments) connected with the pipe junctions. The second extension of the code covers modelling fractured reservoirs using conventional double porosity, double permeability and multiple interacting continua approaches. The functionality of these options exceeds in some respects the capabilities of many other reservoir simulators. Both new options can be used with any EOS-module.

In the following sections, MUFITS is applied in the benchmark problems that were used for its validation. Both the simulation results and internal representation of the reservoir models in the simulator kernel using 3D graphs are presented. The simulator extension for building such graphs was one of the most time-consuming work with the simulator code when developing the options. Understanding of this internal representation may be useful when applying the simulator to a particular subsurface process.

2. Internal representation of reservoir models

MUFITS converts any reservoir model into a 3D graph when it loads the model into the simulator kernel [4]. The graph consists of a set of primitives. The graph nodes are the primitives corresponding to the reservoir fluid accumulation (accumulation term in the balance equations). The nodes can be the grid blocks, the pipe segments (well segments) or the stock tanks (Fig. 1). The graph edges are the elements associated with the fluid transport between any two connected nodes (transport term in the balance equations). The edges can be the interfaces between the grid blocks, the pipe junctions, the well completions, or the pumping devices. Using these primitives, a reservoir model of arbitrary complexity can be built. MUFITS builds the 3D graph using input data of general form provided by the modeller.

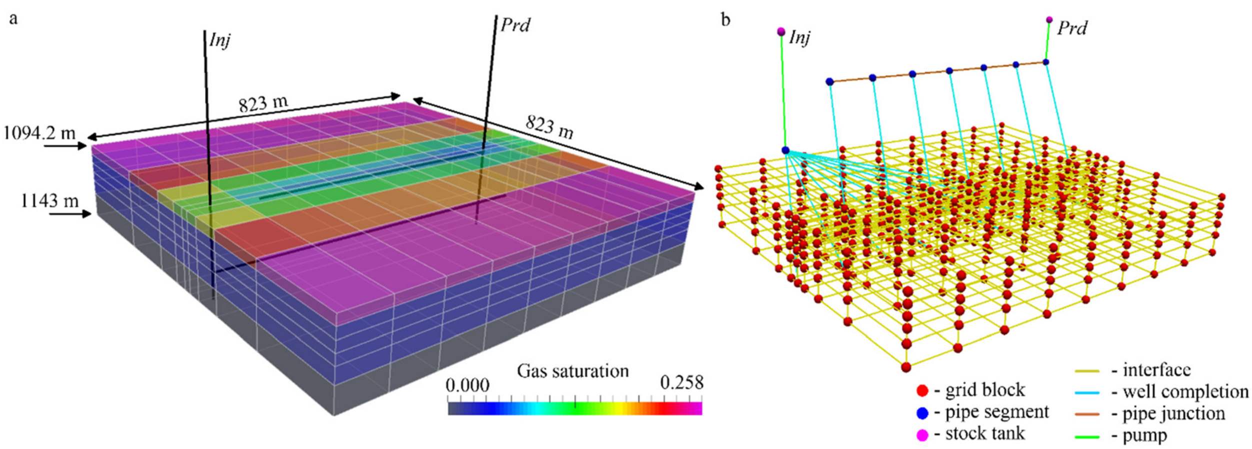

Fig. 1. (a) The gas saturation in the 7th SPE comparative study, case 4b at t=1500 days; (b) 3D graph built in MUFITS for this study.

3. Wellbore friction

There are two types of well models in MUFITS. The first model is the *Averaged Model*. If this model is used, there is no "grid" resolution along the wellbore. The wellbore consists of a single pipe segment. Thus, the wellbore hydraulics cannot be simulated using the *Averaged Model* because the reservoir fluid parameters are averaged along the wellbore. An example of this type of well is the *Inj* well in Fig. 1.

The second model is the *Multisegment Model*. In this case, the well is resolved into several pipe segments (well segments) connected with the pipe junctions. An example of this well type is the *Prd* well in Fig. 1. In the case of general position the fluid parameters vary with the pipe segments. The transport between the pipe segments (that is along the pipe junctions) is calculated in accordance with the Haaland's formula that accounts for frictional pressure drop [7]. A new pipe segment is created by MUFITS for any new well completion specified by the modeller. The well completions link the pipe segments with reservoir, i.e. with the grid blocks.

In order to verify the wellbore friction option, MUFITS was validated against the 7th SPE comparative study that considers coupled reservoir-wellbore flows [8]. This three-phase (water-oil-gas) benchmark problem involves production of hydrocarbons from a horizontal well *Prd* when coning tendencies are important. The water flow to the horizontal wellbore from the water zone below the water-oil contact is simulated with a line source of water. This source is modelled with the *Inj* well to that the *Averaged Model* is applied. The grid is refined closer to the wells for better accuracy. The pressure drop below bubble point due to production results in gas phase appearance near the wellbore. The results obtained with MUFITS are in good agreement with the results of other codes (Fig. 2). In particular, the calculated pressure drop along the wellbore is of the same order of magnitude as predictions of other codes.

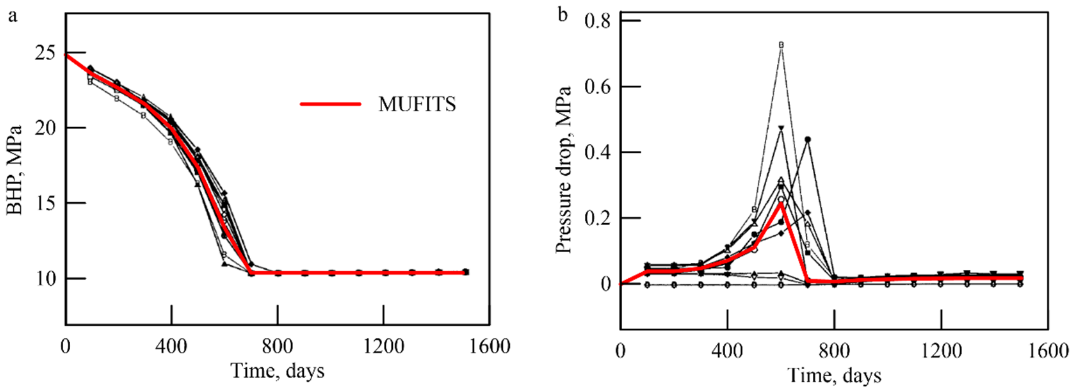

Fig. 2. Simulated bottom-hole pressure (BHP) and pressure drop in the wellbore in the 7th SPE study; case 4b. The red lines are the MUFITS results and black lines are results of other simulators. The background images showing results of other simulators are modified after Nghiem et al. [8].

4. Modelling fractured reservoirs

4.1. Overview

The multiple interacting continua (MINC) approach is applied for modelling fractured reservoirs in MUFITS [9]. Several continua, i.e. domains, are created by replicating the primary reservoir grid. One of these continua is used for modelling mass and heat transport in fractures and others are used for modelling the transport in matrix blocks. The simulator allows the following options for modelling the fractured reservoirs that in some respects exceed capabilities of other packages:

- The double porosity and double permeability options (transport in both the fracture and matrix continua) can be activated;

- The number of nested matrix blocks in the MINC approach can depend on the grid element;
- The MINC approach with multiple matrix continua can be used with the double permeability option;
- The double porosity and the double permeability options as well as the MINC approach in its general form can be used with local grid refinements in parallel simulations;
- The flow only through either the fracture or matrix continuum can be enabled in different regions of the reservoir;
- Wells can be completed both in fractures and in matrix grid blocks.

For modelling mass and heat exchange between the fracture and matrix continua (the fracture-matrix interflow), the simulator accounts for transport due to pressure difference between the continua, the capillary forces, the heat conduction, and the gravity drainage [10].

Further, three benchmark problems are considered in order to validate MUFITS and demonstrate its capabilities for modelling fractured reservoirs.

4.2. Five-spot geothermal production/injection

First, a benchmark study of five-spot geothermal production/injection is considered [11]. The problem involves a large fractured reservoir with wells arranged in a five-spot pattern. The domain used in the MUFITS simulations is shown in Fig. 3. The flow occurs only through the fracture continuum, whereas the matrix blocks are impermeable. In order to accelerate the simulation, only the heat conduction equation is solved in the matrix domain. For a more precise modelling of the thermal sweep the multiple interacting continua approach with the number of matrix continua equal to four is applied. Such subgridding of the original matrix domain allows a better prediction of the temperature distribution within the matrix blocks, where temperature decreases due to heat exchange with colder fracture fluid more rapidly closer to the fractures rather than to the block centers. All parameters of the benchmark study can be found in the work by Pruess et al. [11].

The 3D graph shown in Fig. 4 corresponds to this benchmark study. The fracture and four matrix continua are grouped in "layers" (domains) of grid blocks, where the top layer corresponds to the fractures and the bottom layer to the innermost matrix continuum. The grid blocks within the fracture domain are linked by using the interfaces enabling mass and heat transport in this continuum (the double porosity option). The grid blocks within each matrix domain are not linked because the double permeability option is not active.

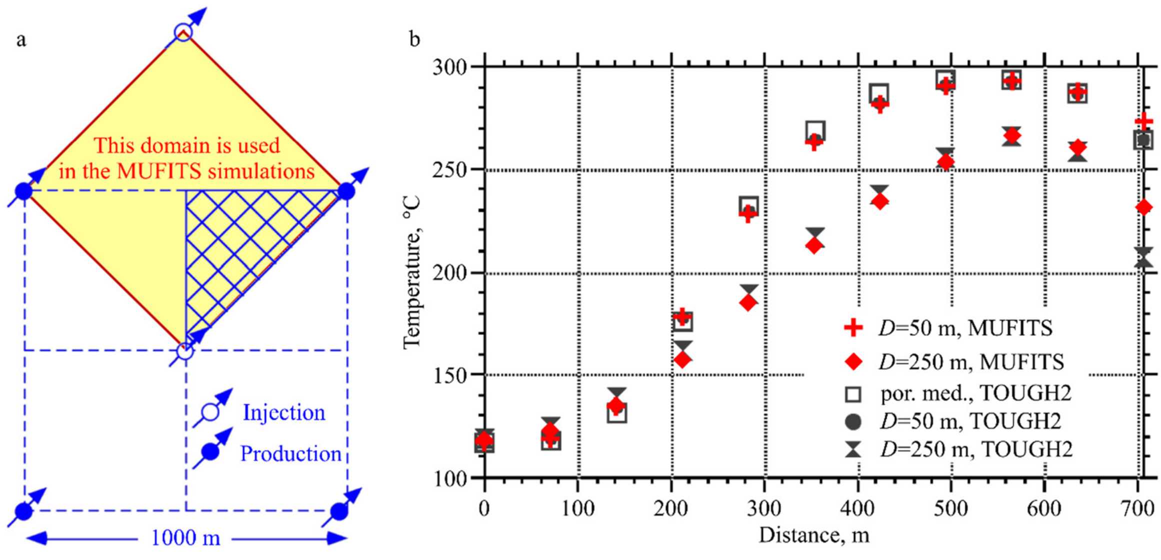

Fig. 3. (a) The domain used in this work is highlighted in yellow; (b) Results of the MUFITS simulations in comparison with TOUGH2. The background images showing the TOUGH2 results are modified after Pruess et al. [11].

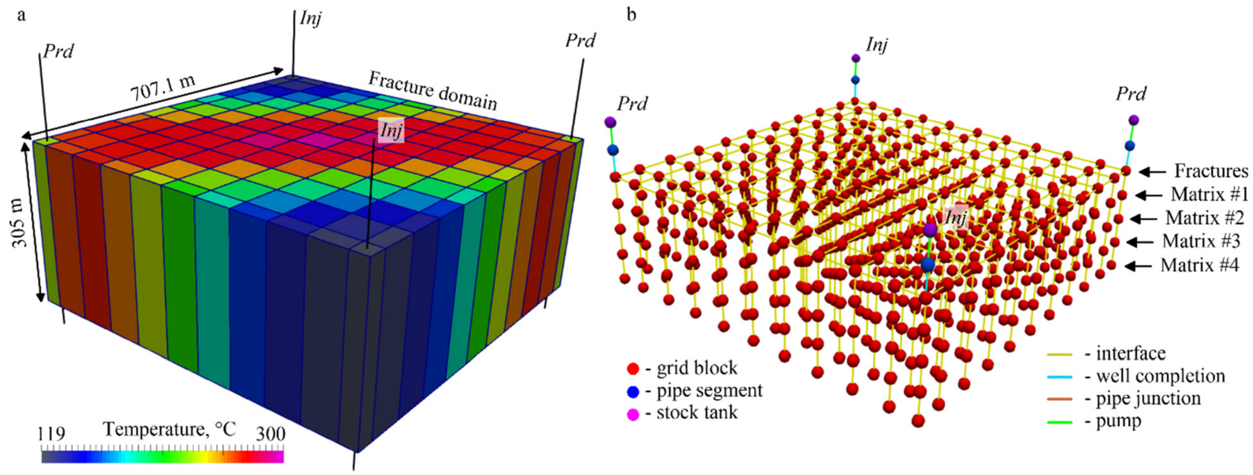

Fig. 4. (a) Simulated temperature distribution in the fracture continuum; (b) 3D graph corresponding to the reservoir model. The fracture and matrix grid blocks are grouped in five different "layers" of grid blocks.

The MUFITS predictions are in satisfactory agreement with the TOUGH2 code for both 50 m and 250 m spacing of the fractures (Fig. 3). The temperature distribution is shown in Fig. 3 along the straight line between the wells, where the injection well is on the left and the production well is on the right. The temperatures predicted with MUFITS near the production well are slightly higher than those predicted with TOUGH2. This deviation may be related to either different approximations of the grid blocks-wellbore flow used in two simulators or grid size effects.

4.3. 6th SPE comparative study: Water injection case

In oil and gas applications, the standard test for validation of double porosity simulations is the 6th SPE comparative study [12]. It considers a 2D cross-section study of a saturated oil reservoir (Fig. 5). Here, the problem statement specified by Firoozabadi and Thomas [12] is used with exception of relative permeability functions and well operational controls in the depletion case of the study. Instead of using complicated relative permeability for fracture-matrix flows as it is specified by Thomas et al. [13], the relative permeability in matrix continuum is simply applied if the flow direction is from matrix to fractures, and the relative permeability in fracture continuum is applied if the flow direction is from fractures to matrix. Thus, the simulation results cannot be compared with that published in the paper [12]. But, nevertheless, the results presented here can be applied for validation of other codes.

This problem is simulated using the double porosity option. MUFITS converts every primary grid element into a couple of grid blocks one belonging to the fracture and the other belonging to the matrix continuum. The corresponding graph built in the MUFITS kernel is shown in Fig. 5. The grid blocks corresponding to each continuum are grouped in vertical “slices”. The grid blocks belonging to the fracture continuum are linked to each other by using the interfaces, whereas the grid blocks in the matrix continuum are not linked because the double permeability option is not active. The *Inj* well is completed in all five layers of the fracture grid blocks, whereas the *Prd* well is completed only in the top three layers.

Here, two cases of this study are considered. The first case is the water injection scenario when the injection well (*Inj*) is placed on the left and the production well (*Prd*) is placed on the right (Fig. 5). The oil displacement results in a rapid water breakthrough at the production well through the fractures (Fig. 6). After the breakthrough, there is still a relatively large oil production rate due to the gravity drainage [10] which time scale is comparable with the time scale of the water breakthrough. The simulation results for the case study when the gravity drainage is inactive are also shown for demonstrating its influence on production rates. In this case the water breakthrough occurs earlier and the oil production rate is smaller. For comparison purposes the results of other simulators obtained in the original problem statement [12] are shown in Fig. 6 with grey curves. The latter results are available for twice as small period of time as it is used in this paper.

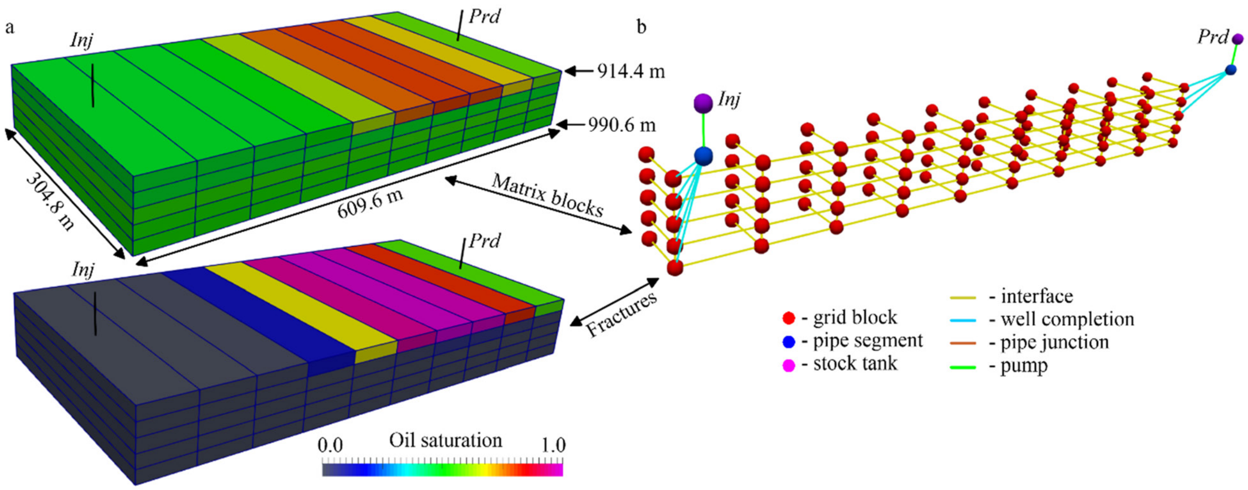

Fig. 5. (a) Oil saturation in the matrix (top) and fracture (bottom) domains at t=7305 days; (b) 3D graph created in MUFITS kernel. The fracture and matrix grid blocks are grouped in two vertical "slices" of grid blocks.

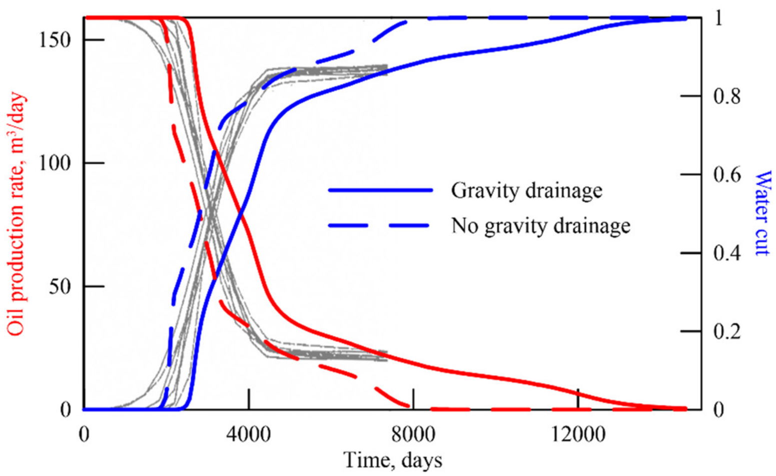

Fig. 6. Simulated with MUFITS oil production rate and water cut in the modified 6th SPE comparative study; water injection case. The solid lines are the results of simulations taking into account the gravity drainage, and the dashed lines are the results when gravity drainage is neglected. The background image showing results of other codes in a different problem statement (grey curves) is modified after Firoozabadi and Thomas [12].

4.4. 6th SPE comparative study: Depletion case

The second considered scenario of the 6th SPE Study is the depletion case. In this case the injection well (*Inj*) is completely isolated from the reservoir, whereas the bottom-hole pressure of the production well (*Prd*) is reduced stepwise. A modified scenario is considered where the bottom-hole pressure is at 37.92 MPa over the time $t \in [0,1]$ years, then it is reduced to 34.47 MPa and maintained over $t \in (1,3]$ years, and further it is reduced by 3.45 MPa every 2 years. The production results in reservoir pressure decrease below bubble-point pressure, and the gas phase appears. With decreasing reservoir pressure, the oil production rate also decreases, whereas both the gas production rate and the gas-to-oil ratio increase on average (Fig. 7).

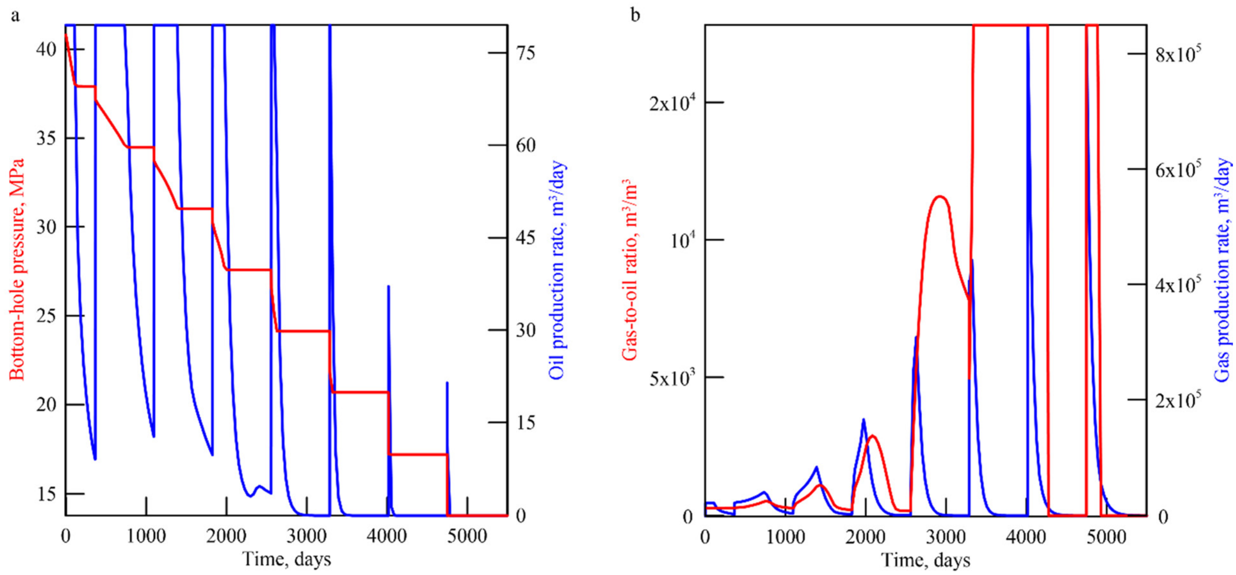

Fig. 7. Results of simulation in MUFITS of the modified 6th SPE study; depletion case.

5. Conclusions

This paper demonstrates that MUFITS is a robust software now capable of modelling horizontal wells and fractured reservoirs. The developed options can be applied in parallel simulations with any EOS-module and complicated nonuniform grids. The simulation results obtained with MUFITS for two benchmark problems, one concerning pressure loss in horizontal wells and the other concerning geothermal production from a fractured reservoir, are in good agreement with those produced with other simulators. Two benchmark problems simplifying the 6th SPE comparative study statement are proposed that can be used in future for intercomparison and verification of reservoir simulators.

Acknowledgements

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Supplementary materials

The simulator input data and animated figures for presented case studies can be found at MUFITS website [3].

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