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Thesis Changes Log

Name of Candidate: Aysylu Askarova

PhD Program: Petroleum Engineering

Title of Thesis: Physical and numerical modeling of thermal methods of EOR and improvements of oil recovery

Supervisor: Associate Professor of Practice Alexey Cheremisin

The thesis document includes the following changes in answer to the external review process.

Dear Reviewers,
I would like to express my gratitude for your comments and suggestions to all of you! I found them very useful and implemented them in my thesis. Also, I would consider them in my future research work. Please find the responses to your comments.

Sincerely,
Aysylu Askarova

Reviewer: Dmitry Eskin

Comment 1. *Page 37, the description of a deep carbonate field. Could you describe a general approach for deep carbonate development? Please, formulate approach peculiarities.*
Response: The general description of the carbonate development added, as well as corresponding reference, page 41

Comment 2. *I suggest to extend the Chapter 3. A comparison between existing recovery techniques against the proposed recovery method (except a financial aspect) should be added*
Response: The description of each method is provided in Chapter 2. The application of each method depends on the specific reservoir, its geological properties, and oil samples. The general screening criteria are presented in Table 1, p.23., as well as in Figure 4. The fast screening and evaluation methodology is provided in Chapter 3 as an example together with a reasoning of the final choice of Hot Water Injection (HWI).

Comment 3. *Section 4.1, page 68. A discussion on heat losses to the surrounding formation is needed. A significant amount of injected fluid is required to reproduce experimental results at minimum heat losses. Since the rock is tight, inject of a significant amount of fluid is questionable.*
Response: Indeed, the fundamental physical processes, which are necessary to take into account during simulation of thermal recovery methods, are:
1) Three-phase multi-component fluid flow in the reservoir;
2) Phase-to-phase fluid transformations;

3) Heat transfer from heating agent to matrix and fluid;
4) Temperature and fluid, matrix properties change during thermal agency injection;
5) Kerogen pyrolysis by high temperatures and generating fluids from kerogen;
6) Porosity and permeability changing due to kerogen pyrolysis, compressibility, and thermal deformations;
7) Accounting for heat losses in surrounding formations.

All these phenomena were taken into account during the creation of the HDS model. Implementation of such technology requires the use of special equipment and thermally insulated tubing to provide minimal transport heat loss in well to avoid additional technical and economic constraints. The issue of heat losses was addressed in the simulation together with reservoir properties. The distribution of porosity, permeability, solid concentration, fluid saturation, as well as fluid injectivity was carefully determined in the experiment, and history matched in the target model. The heat losses from the heating agent to an ambient formation strongly affect the oil recovery efficiency and require accurate calculation. (Yusupov et al., 2020) The effect of different system parameters plays a crucial effect on flow behavior. For example, a hydrostatic pressure increase with well depth greatly contributes to a pressure change along with an injection tubing. The study by (Yusupov et al., 2020) demonstrates that the fluid (steam) quality increases with the well depth due to the specific behavior of both the liquid and vapor enthalpies near the critical point. The flow rate also an important parameter affecting the fluid quality distribution along the tube. Nevertheless, the study of heat losses within reservoir cross-section must be studied further.

Comment 4. *Section 4.2.1, 4.2.2. Please clarify the impact of an injected fluid on the pore connectivity after pyrolysis. How does porosity/permeability change during the experiment?*

Response:

Results of the open-system Rock-Eval pyrolysis showed how organic matter distribution changed after the test. X-ray computed microtomography of original and spent oil shales demonstrated the creation of extra pore space. Microstructural properties of oil shale samples were characterized based on the comparison of the same sections of samples before and after the treatment. Samples X_1 and X_2 were scanned and the porosity of the X_1 sample increased 3.3 times from 0.37% to 1.23%, specific pore surface was significantly raised. The porosity of X_2 increased 155.6 times from 0.0056% to 0.8716%, specific pore surface area raised from 10.9 m^2/m^3 to 897.8 m^2/m^3. 3D reconstruction of pore space shows interbedding behavior, which could be explained by observation, that pores and microfractures are generated primarily along with the organic-rich layers (Tiwari *et al.*, 2013). It should be noted that visible fractures appeared in almost all the samples. Porosity and specific surface area significantly rise due to artificial maturation of organic matter, pores, and microfractures generation primarily along the organic-rich layers.

Comment 5. *In Section 4.1.3, page 74 fix the numbering of Figure 28.*

Response: the numeration was corrected accordingly

Comment 6. *Page 93. Please correct the numbering: "2.5.1.1 Medium pressure combustion tube numerical model" to 5.1.3.2.*

Response: the numeration was corrected accordingly

Comment 7. *Page 93. Please, provide more details on development of the 3D digital model.*

Response: the details were added – pp.95-96.

Comment 8. *Page 98. Provide criteria for successful matching.*

Response: Generally, there is a lack of commonly accepted standards in terms of simulation modeling. There are no universal hard rules available in the literature due to the complexity of the problem. In addition, the requirements vary depending on the objectives, desired accuracy, and time/budget of the particular reservoir. History match tolerance depends upon drive mechanisms and related key parameters, reservoir characteristics, study objectives, and data quality. Simple measures should be determined to access the suitability of the developed model. For example, withdrawals for oil, water, and gas rates, and cumulative volumes should be matched (Baker et al., 2006).

Comment 9. Chapter 5.2. *A description of the economic feasibility assessment is needed.*
Response: Recent advances in air-injection based projects have allowed this method to be considered more seriously as a promising method for recovering heavy oil. It is believed that when the process is carried out correctly, the in situ combustion method reduces the density and viscosity of the oil, while not producing complex emulsions. At the same time, operating costs per cubic meter of oil produced is lower due to higher well production rates and lower cost of working fuel.
Methods for assessing the financial and economic efficiency of an investment project, taking into account the time factor, involve bringing costs and incomes, spaced over time, to a base point in time, for example, to the date of the start of the project. The most important parameters are the capital cost of the wells, the additional cost of compressed air, and the discount rate. It is very important to consider the possibility of reducing capital investments and provide a scheme with sufficient spacing between the wells.
The main difference between air injection into the reservoir is the absence of expenses for the transportation and storage of air, and the absence of expenses for the purchase of air. However, it is important to consider the capital and operating costs of air compression and injection.
The oil debit, the total well stock, the size of land plots for a given number of wells, and the volume of oil were determined by numerical modeling. The volume of oil is determined by taking into account the amount of oil produced, the rate of technological losses, and its consumption for their own needs, and the coefficient of change in oil production. Further, development indicators were calculated for each scenario, including active wells, cumulative oil, water, and liquid production, oil recovery factor, water cut, injected volumes of water, and air. That allows further economical assessment and a decision was made based on these results.

Comment 10. *Were the original reservoir properties (e.g., original porosity and permeability) preserved in the experiment (see Chapter 6)?*
Carbonate reservoirs are known to have vugs and microfractures causing high rock heterogeneity. Because the final goal of the experimental studies is modeling on the field scale, a difference between actual reservoir and experimental parameters can lead to poor model performance on the field scale.
Response:
The study was conducted using the oil samples from the reservoir under the study and restored state core at the reservoir pressure and conditions that would be encountered in the field. After packing, the tube was sealed, insulated, and inserted into the pressure jacket. Air was passed through the packed core, then vacuum was applied. Then the pack was saturated with brine and the porosity was determined (approximately similar for both experiments). Brine was further pumped to measure the pack permeability. It is hard to establish the same values during the experiments, but permeability variation is believed to be not very significant for the combustion process. Also, during numerical experiments, we can recreate the exact conditions on the validated numerical model. The actual value of permeability has very little effect on the mechanics of the combustion process. The only

requirement for permeability is that it must be adequate to permit air injection at a pressure compatible with overburden at an acceptable compression cost. (Sarathy, P.S., 2016) As was mentioned in Perry et a. (1960), permeability variation should not be high, but it is not critical as in water flooding.

Reviewer: Zhangxing Chen

Comment 1. *My only concern is that since such EOR methods as hot water injection (HWI), supercritical water injection, high-pressure air injection (HPAI), and in-situ combustion (ISC) have been widely applied and studied, this thesis needs to emphasize what the novel and new contributions it makes in the Abstract and Introduction.*

Response: the novelty and contributions were emphasized in Abstract (p.3) and Introduction (p.18-19).

Reviewer: Dmitri Koroteev

Comment 1. *Please, check for typos. There are quite a few of them.*

Response: the text of the dissertation was proofread

Comment 2. *Please consider and economical aspects of the thermal EOR in a more straightforward form. As simple as addressing the question "how much extra money we get applying thermal methods with respect to an additional cost associated with combustion initiation, infrastructure building, etc."*

Response: economical aspects were added in Chapter 5, p.103. The economic feasibility is usually conducted either by the company itself or is confidential information. We provide them with such data as oil debit, the total well stock, the size of land plots for a given number of wells, and the volume of oil were determined by numerical modeling.

Reviewer: Yuri Popov

Comment 1. *No corrections were requested*

Reviewer: S.M. Farouq Ali

Objectives

Comment 1.

p. 39 "The primary objectives of this study correspond to each thesis chapter: "The objectives section of thesis is extremely important. I ask my students to make it a separate chapter even if it is only one-page long. In this thesis, it is difficult to find the objectives reproduced below. The objectives should be written in numeric form (not bullets). The conclusions should also be short and listed numerically, with each conclusion following an objective with the same number.

Response: Chapter 3 with primary objectives was added. They_were rewritten in numeric form, one more objective was added. The conclusions were also shortened and listed numerically. Now they correspond to the objectives.

General Evaluation.

Comment 1. *p. 36 Combustion has a superior displacement efficiency over the steam injection process. (Belgrave, 2019). Maybe on the pore scale; in general, not true.*

Response: I agree with the comment. The sentence was corrected:

The project of BP Canada demonstrated the performance of the CSS followed by ISC on the Wolf Lake Air Project. The recovery factor increased from 15% to 30% after the application of ISC.

Comment 2. *Wettability changes? Reason for permeability damage after water injection?*

Response: Thank you for the comment. Additional paragraphs were added on pages 24-25.

Several factors must be considered during the water flooding process. Generally, during water flooding, higher pressure is maintained such that oil is swept towards the production end. This pressure in the reservoir causes stress redistribution and higher stress near the wellbore (material damage and permeability change). The pore structure of reservoir rocks can change after long-term water flooding due to the physical and chemical action of fluid and rocks, which will affect the displacement. Also, relative permeability can be changed due to the varying formation temperature. (Hao et al., 2016)

The wettability of the porous media affects the placement of the fluids in the porous media and relative permeability. It can be affected by various factors such as aging time between the fluids and the rock surface, surface heterogeneity, roughness, and mineralogy of the rock surfaces, the composition of the brine and crude oils. It determines the oil recovery factor and relative permeability curves. It can be explained by fluid-fluid and fluid-rock interactions that, in their turn, control rock wettability, capillary pressure, and relative permeability curves (Ehlirim, E.O. and Orisa, E.F., 2018).

It is shown that as wettability changes from oil-wet to water-wet, oil recovery and relative permeability to oil increases because the wetting phase adheres to the reservoir rock while the none wetting phase moves freely. Because the impact of wettability extends from pore scale to reservoir scale, wettability can affect the project economics. Through the parameters S_{wi} and S_{or}, wettability influences oil recovery. In addition, the relative permeabilities of oil and water vary with formation wettability. (Abdallah et al., 2007).

Comment 3. *It is noted that the results were very sensitive to relative permeabilities which were adjusted to get a match. Not a single set of relative permeability curves is shown in the thesis. Must show a set.*

Response: I agree with the comment. Adjusted relative permeability curves were added to the text: Figures: 14, 16,28

Comment 4. *What hot water-oil reactions were used in the numerical model? Must list them.*
The list of the reactions are given on pages 55, 79-80

Comment 5. *Your Conclusions are a rambling summary of results comprising two-and-a-half pages. Conclusions should be terse, numbered statements.*

Response: I agree with the comment. The summary of the results were revised, numbered and shortened. Each conclusion is matched to the objective with the same number.

Comment *6. Contributions: Aquathermolysis has been previously included in steam injection modeling by several investigators.*

Response:
I agree with this comment. An "aquathermolysis" kinetic model previously used only for steam injection and in this research it was adapted to hot water injection process. Thus, Aquathermolysis reactions were not used in the simulation of the HWI process.

Formatting, English.
Comment .
1) p.5 The list is not well-formatted, the word spacing is uneven. Also note the spelling mistake: Khakimova, T.Bondarenko, A.Cheremisin, A.Myasnikov, R.G. Moore,S.A. Raj Mehta, M. Ursenbah, D. Mallory, «Adaptation of laboratory experiments on modeling of thermal methods Ursenbach.
Response: The list was corrected accordingly

2) p. 6 Members of the Integrated Center of Hydrocarbon Recovery, in face of Not correct English
- It should be "the late Dr. John Belgrave"
Response: acknowledgments were corrected accordingly

3) p. 14 the estimates of technically recoverable crude oil and natural gas resources are deflectable
Response: "are deflectable and" was removed, the sentence was corrected accordingly

4) p. 15 The given research includes
Response: "The given research" was changed to "This research"

5) p. 19 of the industrial projects. Use "commercial" instead.
Response: the word *industrial* was changed as requested

6) p. 21 methods possess almost 50% of the word's EOR-based output
Response: – the word was changed to *hold*, the sentence was corrected accordingly was corrected accordingly

7) Fig. 3 No legend.
Response: The Figure 3 was corrected accordingly

8) Gasses
Response: The word was corrected

9) Pwaga, S., Lluore C., Hundseth O., Perales F.J., Idrees M.U., 2010. Comparative Study of Different EOR Methods. Incomplete reference
Response: The reference was corrected

10) p.28 During incomplete combustion, conversion of water into superheated steam with only partial heat recovery from the burning zone. Incomplete sentence.
Response: The sentence was corrected

"During incomplete combustion, water is converted into superheat into superheated steam with only partial heat recovery from the burning zone".

11) p. 31 In the paper (Bhat and Kovscek, 1998) a problem of a permeability increase and clogging due to silica dissolution and redistribution. Incomplete sentence.
Response: The sentence was corrected
"The paper (Bhat and Kovscek, 1998) discusses a problem of a permeability increase and clogging due to silica dissolution and redistribution".

12) p.33 hydrous pyrolysis water promotes thermal cracking reactions and inhibits carbon-carbon bond cross-linking
Response: The word was corrected accordingly

13) p. 34 A lot of numerical modeling studies are Many –
Response: The sentence was corrected accordingly

14) p.35 Suplacy de Barcau (Romania), Suplacu -was corrected accordingly
Response: The word was corrected accordingly

15) p.47 would filter through the sample pore matrix. Flow
Response: The word was corrected accordingly

16) p. 47 using a proprietary pressure-feed pump. What does that mean?
Response: The cement was injected using custom-made pump (cement gun)
"Following the core sample insertion into a vertically mounted core holder, the cement mixture was injected from bottom to top using a custom-made pressure-feed pump".

17) No brown curve in Fig. 15, above.
Response: The Figure 3 was corrected accordingly

18) p. 58 using standard methodic were –
Response: The word was corrected to methodology

19) p. 75 ties leads to the increase in cumulative oil production in 247 m^3. On the other hand, the calculation with KER component leads to a reduction in oil production in 346 m^3. By*
Response: The sentence was corrected accordingly

20) it was defined that the specification of initial matrix ??
Response: The sentence was corrected,

21) p. 83 has very high viscosity at low temperatures and can mobilize when temperature decrease.
Response: The sentence was corrected accordingly

22) p. 87 confined to the roofing of the Tournaisian stage.
Response: The sentence was corrected, the word roofing was replaced with "top"

23) Some figures are difficult to read, e.g. Fig. 39.
Response: Figures were increased as requested

24) p. 105 ISC is a very perspective EOR method for improving the oil recovery factor Use promising
Response: The word *perspective* was corrected accordingly

25) p. 113 C, which is represented by the horizontal dashed line in Figure 54. The time when each Should be 53.
Response: *The cross-reference was corrected accordingly*

26) p. 120 This numerical model comprehends the fluid and heat dynamics and comprises
Response: The sentence was corrected accordingly
Comprehends – was replaced by "describes": "This numerical model describes the fluid and heat dynamics and representative chemical reactions that take place within the core during the ISC process"

27) and a result unrealistic low viscosities in this range. Incorrect grammar.
Response: The sentence was corrected accordingly

However, there are instabilities at steam and combustion temperatures that result in unrealistic low viscosities in this range.

28) p. 122 experimental hearer profiles.
Response: The word was corrected accordingly

Reviewer: Mikhail Varfolomeev

Comment 1. *It is not very clear from HWI part why in some experiments aquathermolysis processes were observed and in some not.*
Response: The first numerical model described in Section 3.1.1 did not include a chemical reaction model, due to low temperatures (100-200°C are not sufficient, while 300°C level was the last stage held for a short period with a low amount of produced hydrocarbons).

Comment 2. *Also, author did not describe in details how each kinetic model was proposed and kinetic parameters were determined.*
Response: Both in HPAI and ISC experiments modeling the kinetic model was created based on HPRTO experiments initial guess that includes polymerization of Maltenes and Asphaltenes in low-temperature oxidation region, thermal cracking, and coke combustion in the high-temperature oxidation region (Belgrave et al., 1990) However, we assume, that for reverse combustion more work needs to be done to determine the kinetic model of reverse combustion, taking into account the possible vapor combustion.

Comment 3. *There is no information about reasons for choosing ignition temperature in HPAI and ISC experiments.*
Response: Usually, the ignition temperature can be determined using ARC experiments. In our case, we did not perform such experiments. We determined the ignition temperature at RTO by analysis of the peaks on temperature profiles (to avoid falling into the interval of low-temperature oil oxidation).