Evaluation of the subject geological area suitability for oil recovery by High-Pressure Air Injection method

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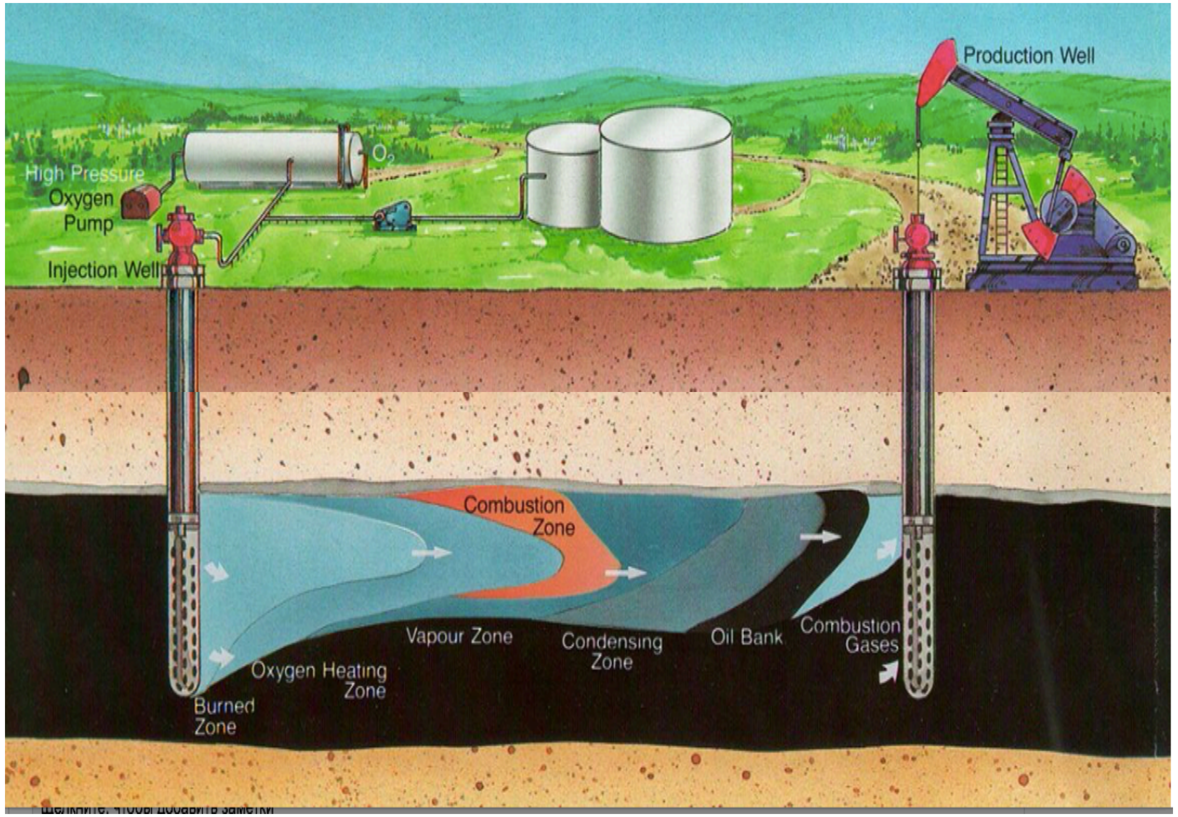
Aims

- To investigate the feasibility of High-Pressure Air Injection (HPAI) method for target field;
- To conduct a laboratory-scale High Pressure Ramped Temperature Oxidation (HPRTO) and Medium Pressure Combustion Tube (MPCT) experiments and their consequent 3D digital modeling;
- To conduct field-scale modeling using four different thermal EOR scenarios (on the basis of MPCT results).
- To examine the development system of four different subsections of the field where HPAI can be profitable.
- To identify the risks and main uncertainties.

High-Pressure Air Injection method

- High-Pressure Air Injection (HPAI) is one of the thermal production methods with a possibility to reduce the production cost since the process is without steam and water cycling.
- Advantages: high recovery coefficient, less energy and water consumption for oil production.
- HPAI has already been effectively applied for different types of reservoirs development and proven to be economically feasible. However, a clear understanding of the process mechanism is still a challenge.
- The main mechanism of the HPAI process is the thermal drive imposed by the combustion kinetics, oil swelling and viscous drive caused by the flue gas, as well as steam distillation at elevated temperatures.

HPAI Mechanism



Schematic representation of HPAI process

- Compressed air is injected into a high gravity, high-pressure oil reservoir, where some portion of oil reacts with the oxygen at elevated temperatures.
- As a result, the flue gas mixture mobilizes the oil and sweeps it towards the production end. Injected air spontaneously ignites the oil-in-place due to high-pressures and high-temperatures. If the oil is not reactive the ignition is generally provided using downhole heater or burner.
- Specifically designed compressors are used for air injection at desired pressure levels and volumes.

Keys for successful HPAI implementation

Keys for Successful Project Design:

- Air Compressors;
- Screening Air Injection Prospects;
- Laboratory Screening of Candidate Reservoirs;
- Numerical Modeling;
- Selection of Injectors.

Keys for Successful Project Operation:

- Monitoring HPAI Projects;
- Operating Strategies;
- Oil Displacement by Elevated Temperature Zone;
- Operating Team.

- The two key requirements for successful HPAI process implementation are that the oil must be able to sustain the combustion reactions, and that sufficient air must be injected to maintain the oxidation reaction in the bond scission or combustion mode.

These requirements can be only accessed through direct laboratory testing at the conditions that are close to reservoir conditions.

Methodological approach

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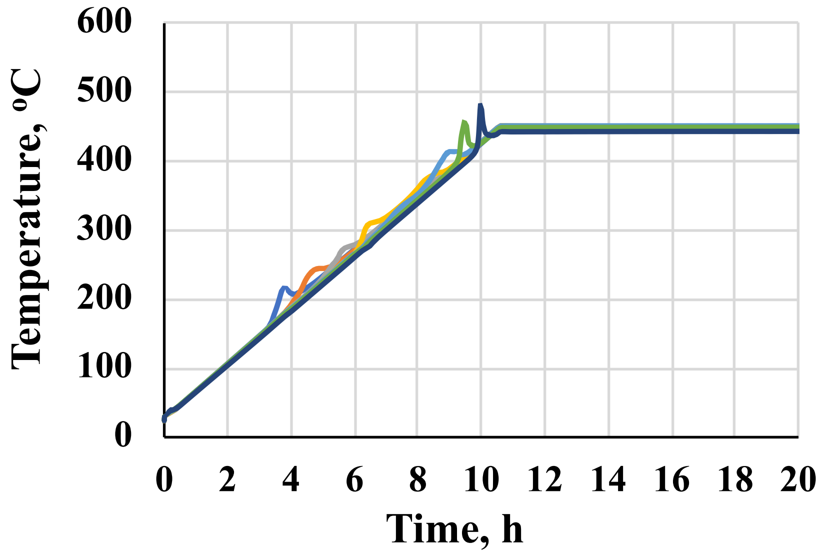
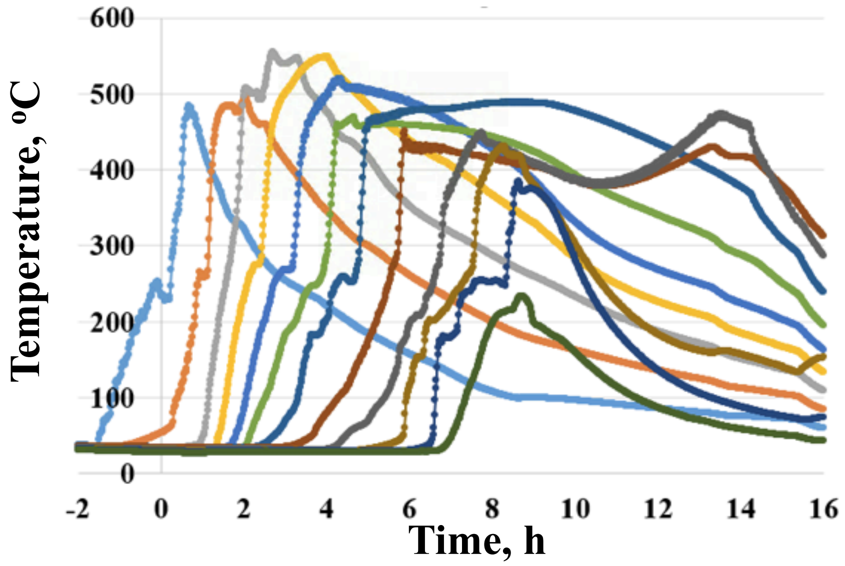
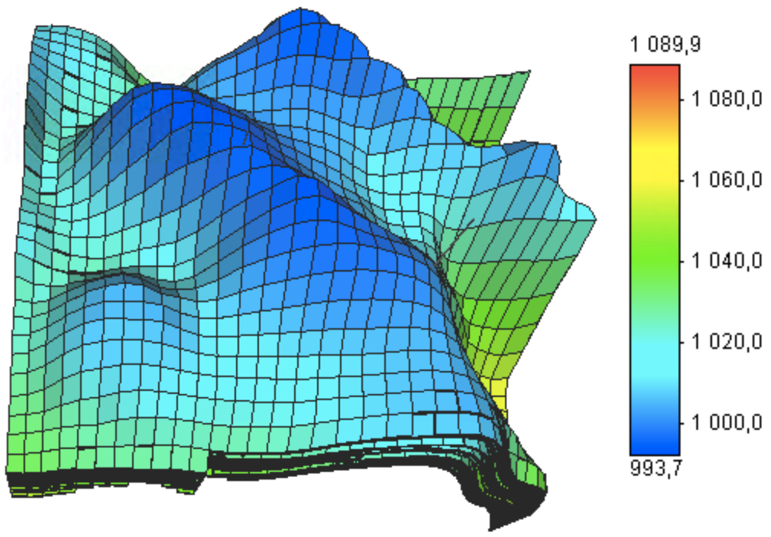
HPDSC* → HPRTO → MPCT → Field



HPRTO temperature profiles



MPCT temperature profiles



Field-scale modeling

Details on the construction and validation of laboratory-scale numerical models of HPRTO and MPCT experiments are presented in paper: Khakimova, L, Askarova A., et. al, *High-pressure air injection laboratory-scale numerical models of oxidation experiments for Kirsanovskoye oil field*. https://doi.org/10.1016/J.PETROL.2019.106796

*HPDSC - High Pressure Differential Scanning Calorimetry

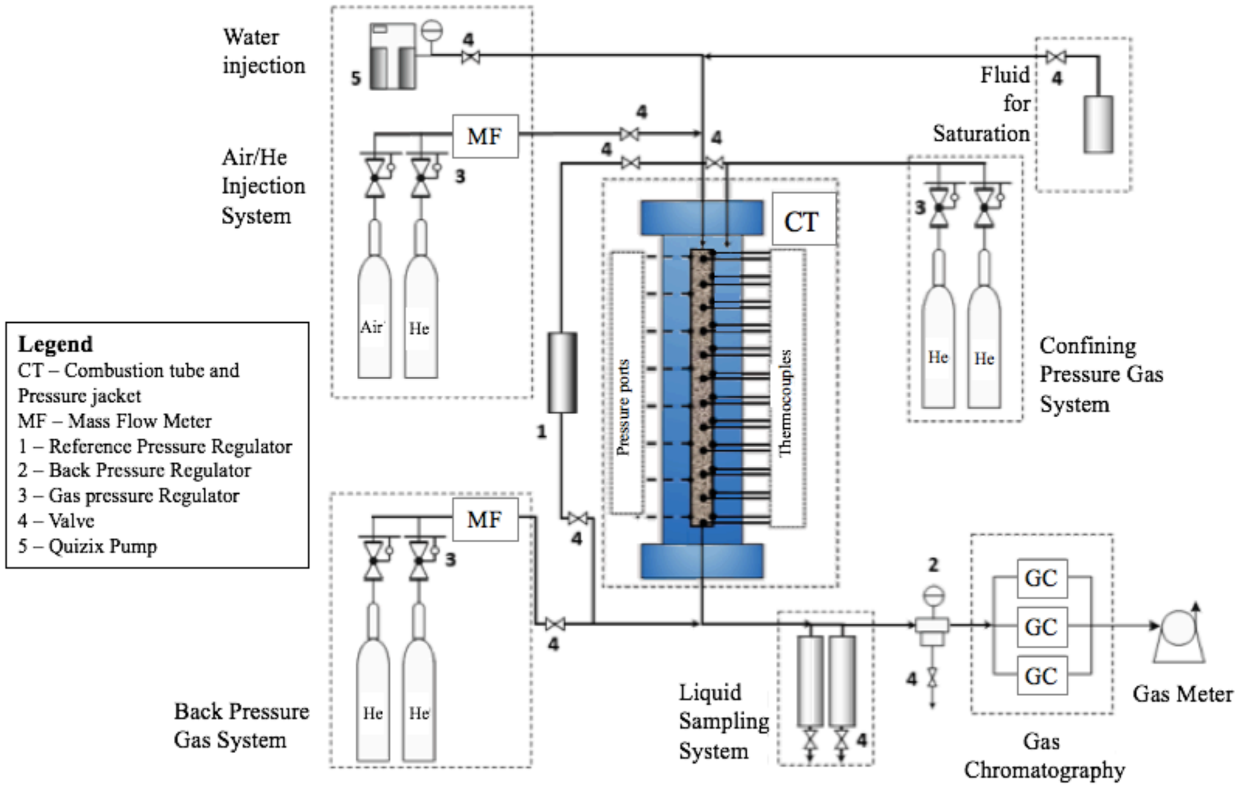
Laboratory experiment

MPCT specifications

Internal diameter x Length, mm	99.6 **x** 1837
Reactor volume, l	14.3
Reactor material	Inconel steel
Maximum pressure, MPa	21
Maximum operating temperature, °C	1200
A number of wall thermocouples, pcs.	12
A number of internal thermocouples, pcs.	12
The number of pressure ports in the reactor, pcs.	8

Schedule of experiment

Time, h	Event
0	Start of the pressure rise in the system
3.48	Start of the He injection
3.77	Start of the first zones heating
5.18	Start of the air injection with a rate 314 st.l/h
5.36	Beginning of the combustion in Zone 1
13.58	Combustion front propagation in Zone 10, switch to He injection
18.48	End of He injection, the start of the pressure drop
23.98	End of the pressure drop, end of the experiment



Schematic diagram of the MPCT setup

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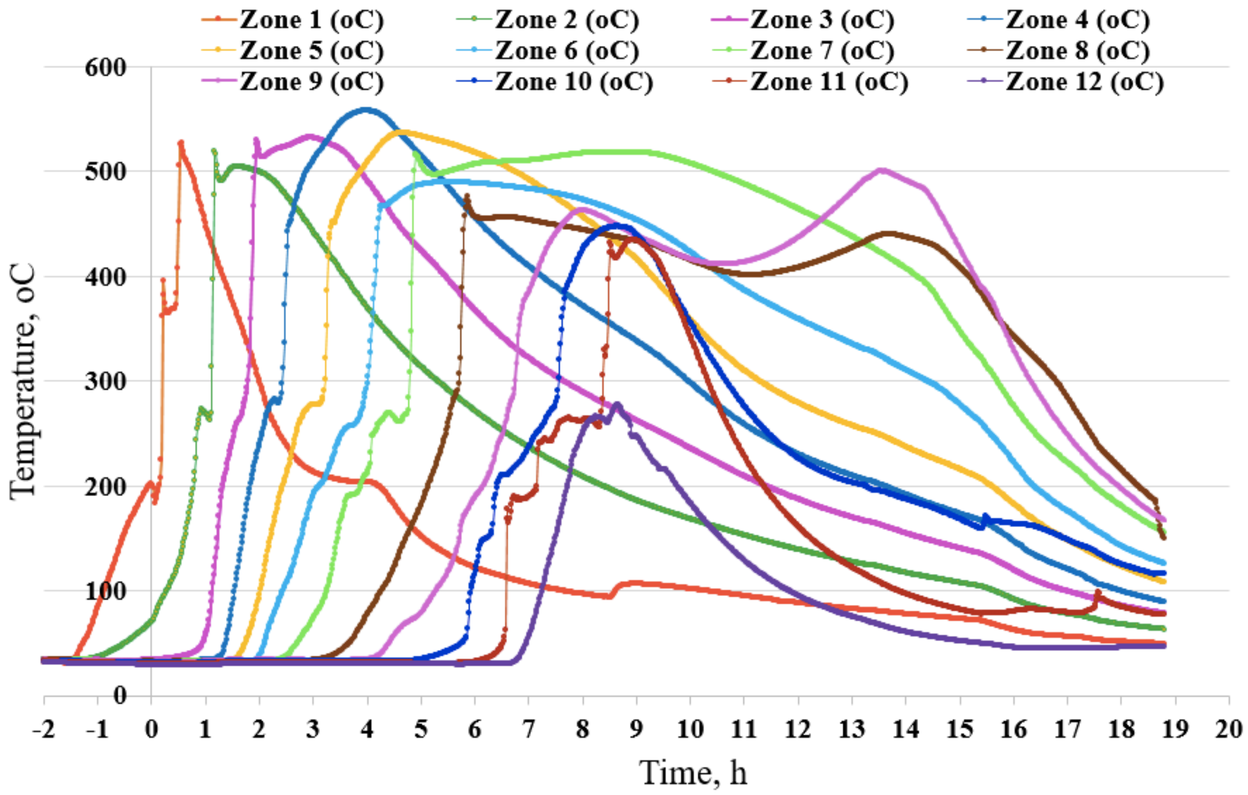
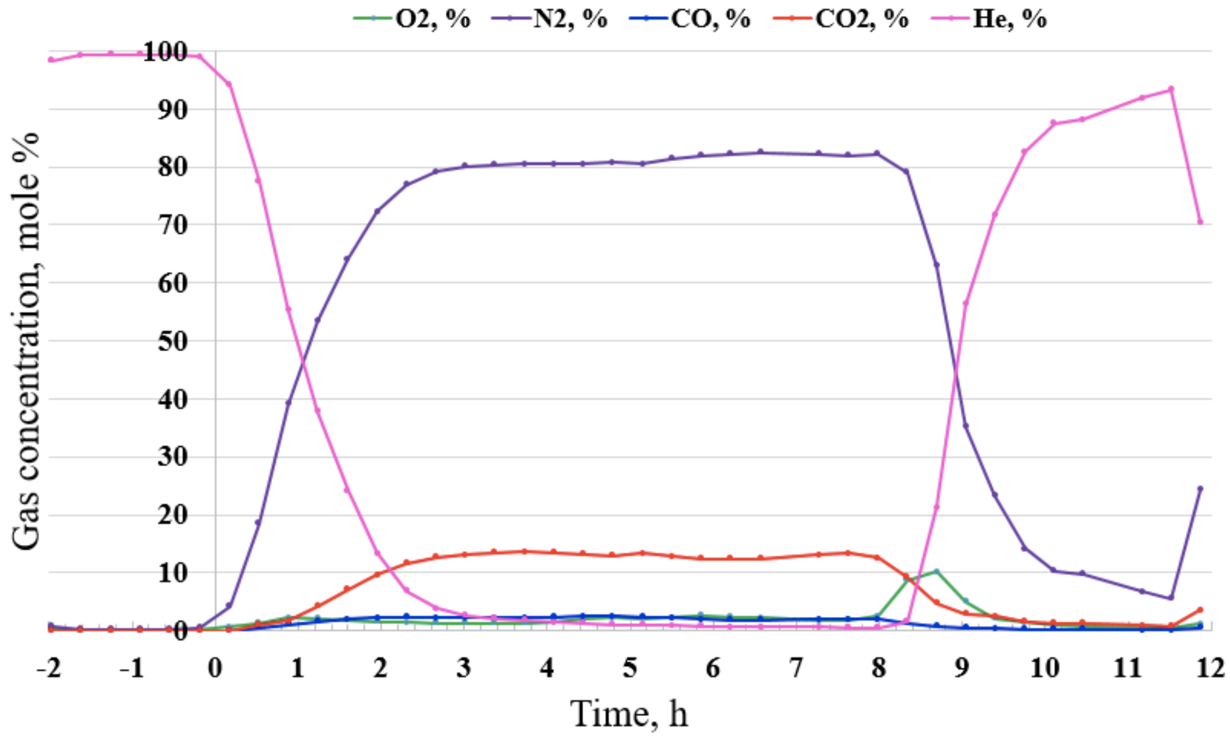
Experimental results



Temperature profiles on the centreline



Combustion gas mole concentrations

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Numerical model

Kinetic reaction parameters

Reaction	Frequency factor, $1/kPa^n/day$	Activation energy, kJ/mole	Enthalpy, kJ/mole
1	6.62E+15	181041	0
2	9.60E+09	86730	5.87e+5
3	2.16E+11	1.856e+5	3.14e+6
4	1.68E+11	3.476e+5	4.71e+5

Reaction scheme:

1. <u>Thermal cracking</u>

Asphaltenes → 3.04 **Maltenes** + 3.72 **CO_2** + 0.1 **H_2S** + 8.73 **Coke**

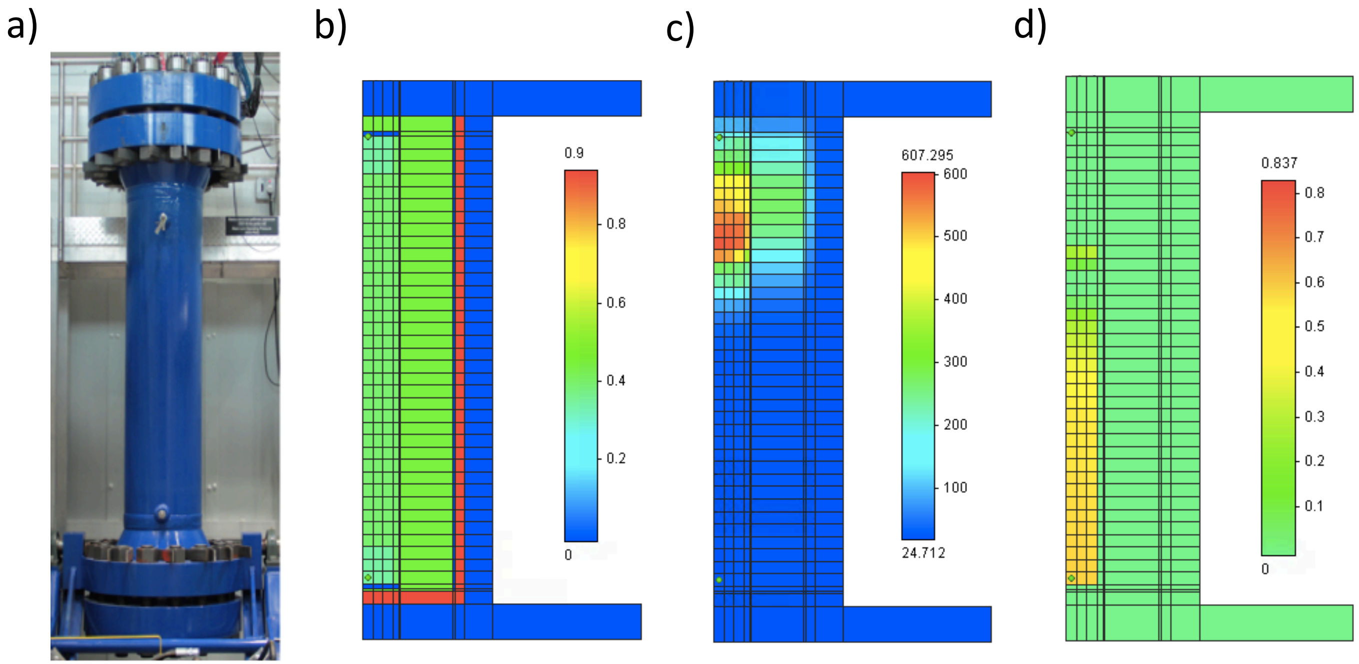
1. <u>Low-temperature oxidation (LTO)</u>

Maltenes + 1.25 **O_2** → 0.282 **Asphaltenes**

Asphaltenes + 7.5 **O_2** → 106.6 **Coke**

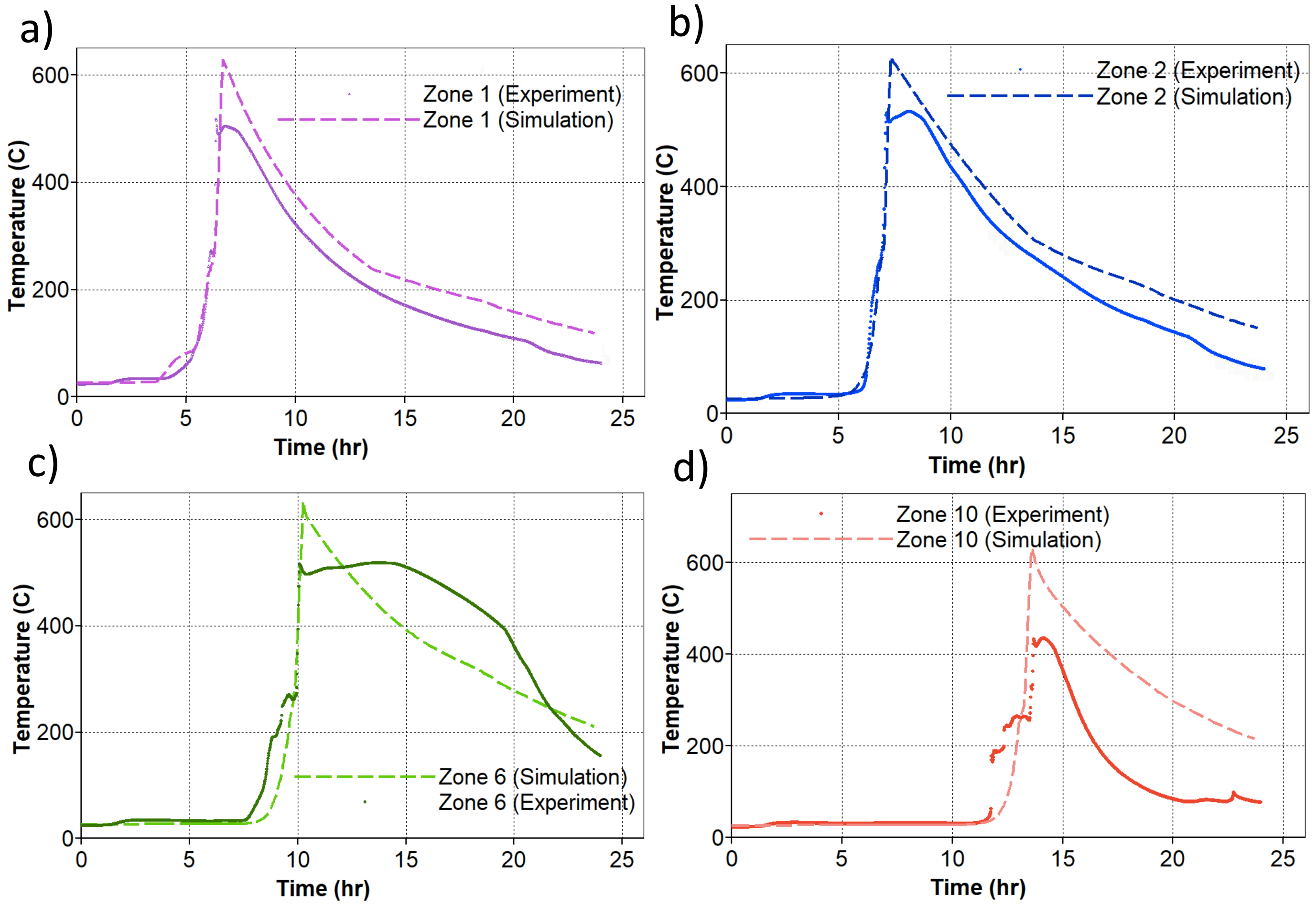
1. <u>High-temperature oxidation (HTO)</u>

Coke + 1.2 O_2 → 1.0 **CO_2 +** 0.249 **H_2O**

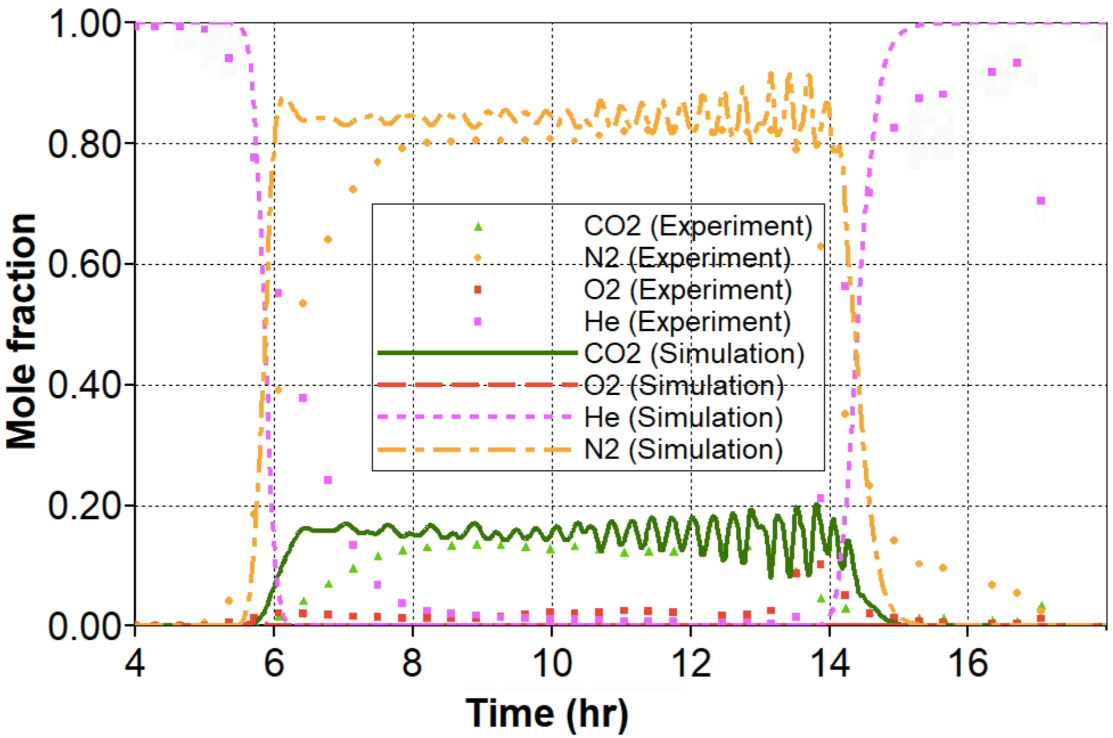


Medium Pressure Combustion Tube Installation (a) and the numerical model of the MPCT experiment in CMG STARS: Initial porosity (b), temperature over time (c), oil saturation over time (d)

Numerical model results

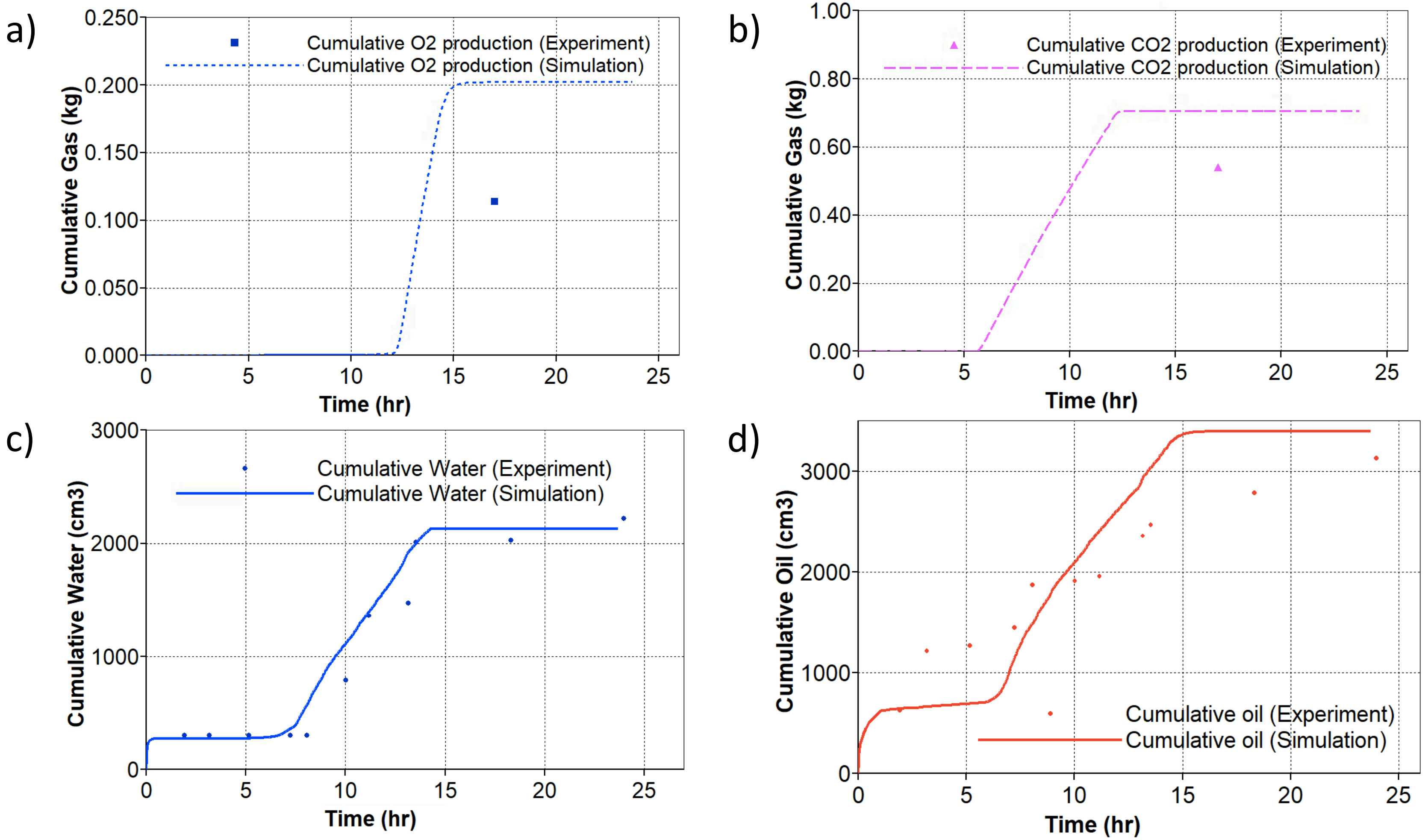


Temperature profiles: a) Zone 1; b) Zone 2; c) Zone 6; d) Zone 10



Comparison of the experiment and simulation results for gas mole concentrations

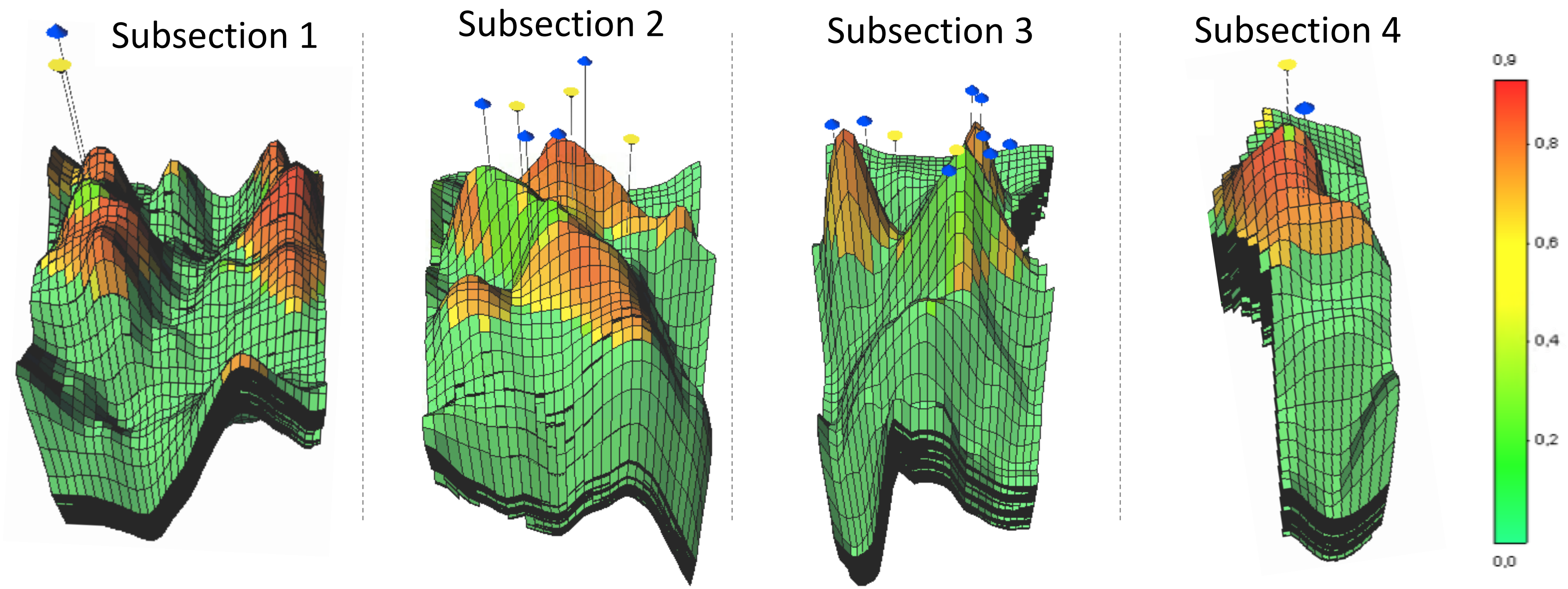
Numerical model results



Cumulative production of: a) O_2; b) CO_2; c) water; d) oil

There is a discrepancy in the mole concentrations of O_2 and CO_2, which emphasizes the necessity of further investigation of phase transition behavior of target oil. However, this model repeats general features of the MPCT experiment (temperature peaks, front velocity, cumulative oil, and water), which are the most important characteristics of the oil recovery process by HPAI and could be tested in the full-field model.

Field-scale modeling



Model characteristics

Model characteristics	Subsection 1	Subsection 2	Subsection 3	Subsection 4
Number of active grids	20486	40434	14447	13327
Average porosity, %	11.2	12	12.1	12.1
Average permeability, mD	59	84	94	82

Recovery scenarios:

1) Primary recovery method
2) Air injection
3) Water injection
4) Simultaneous injection of air and water

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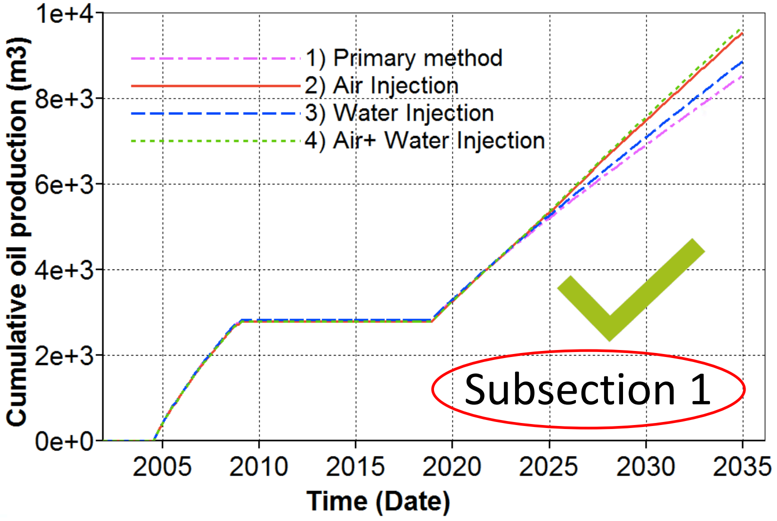
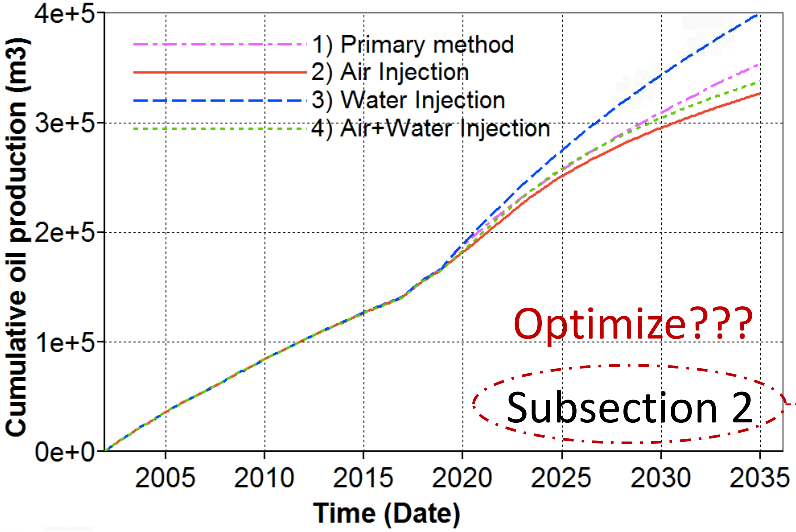
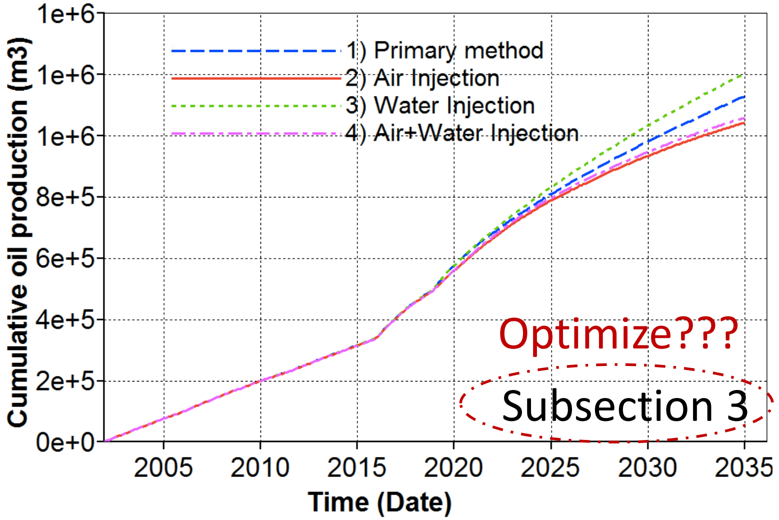
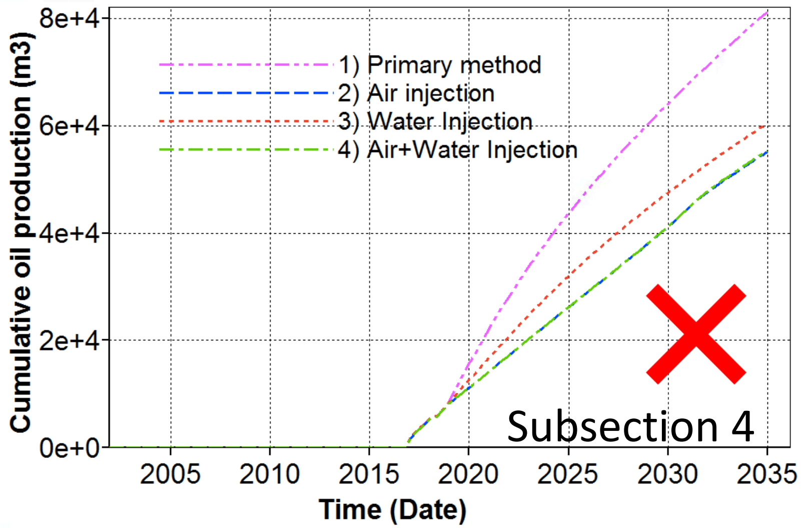
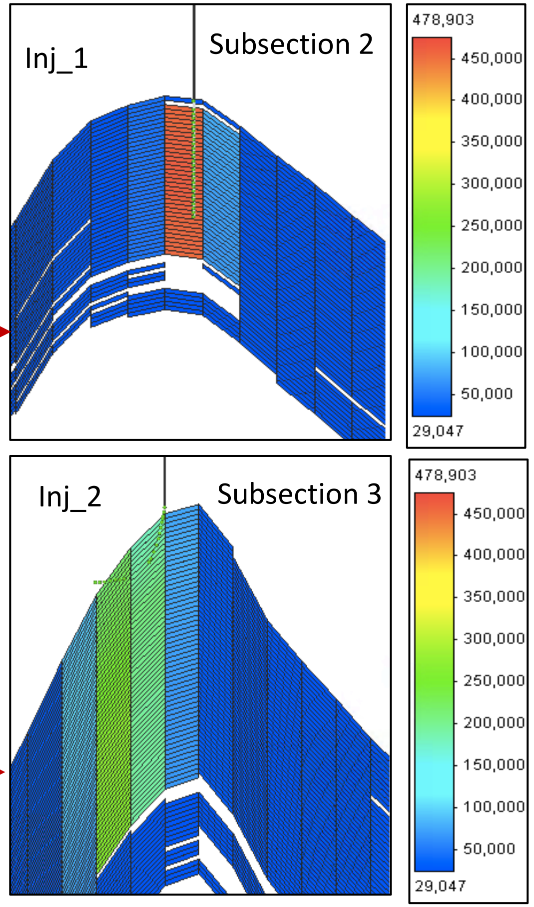
Cumulative oil production











Temperature profiles for air injection (Subsection 2&3)

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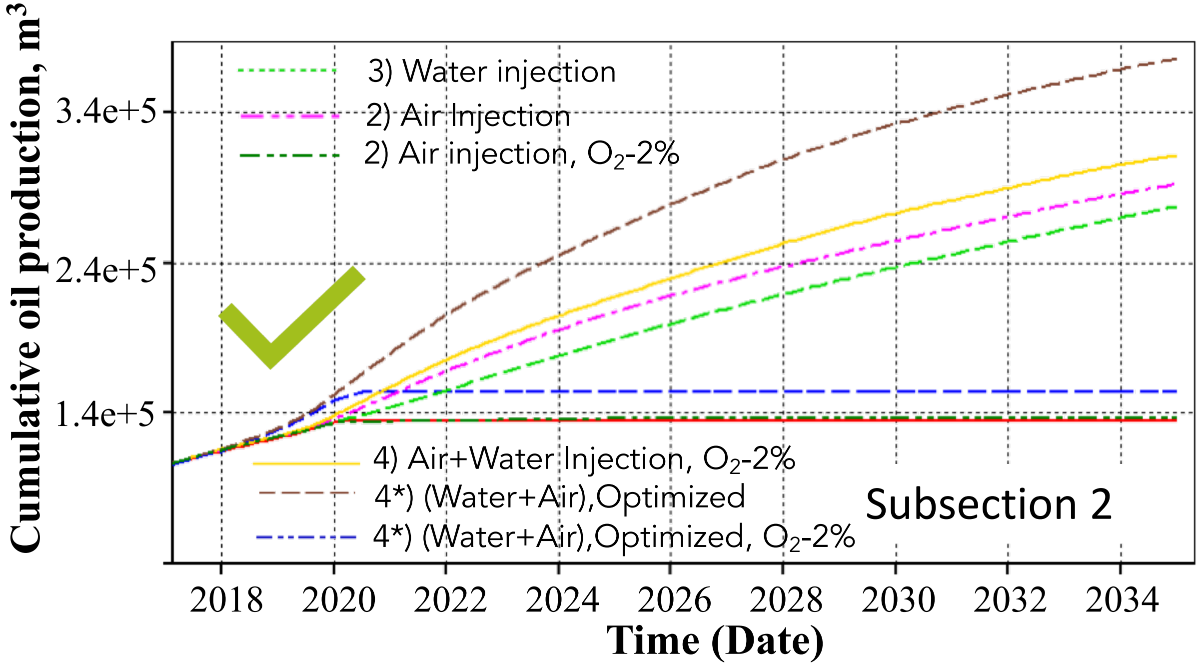
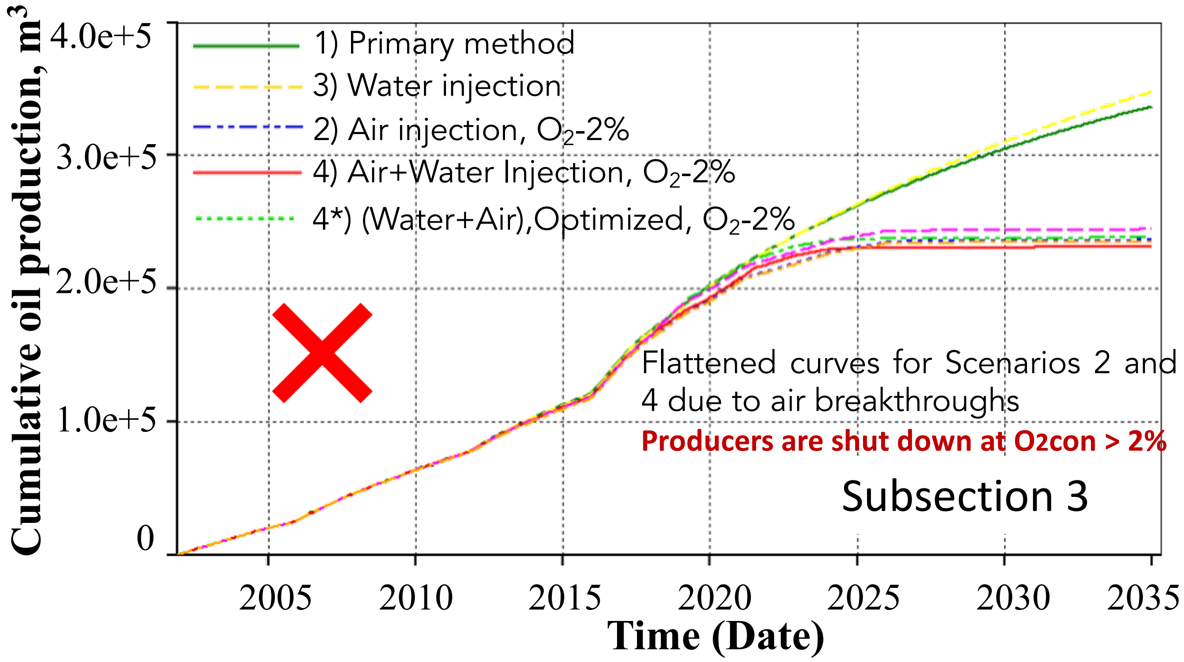
Field-scale simulation results

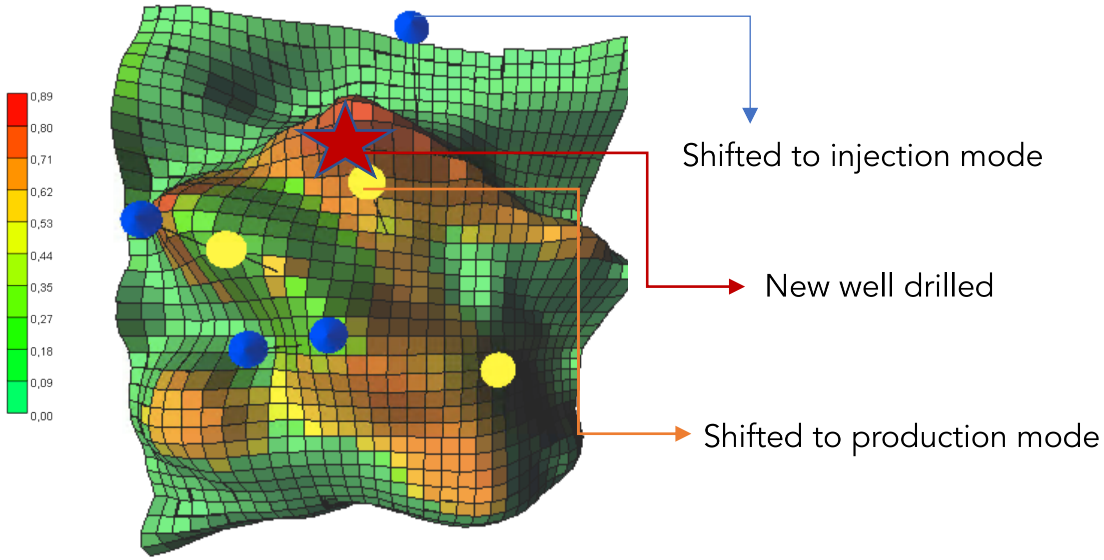




Total cumulative oil production of the field for 4 different cases

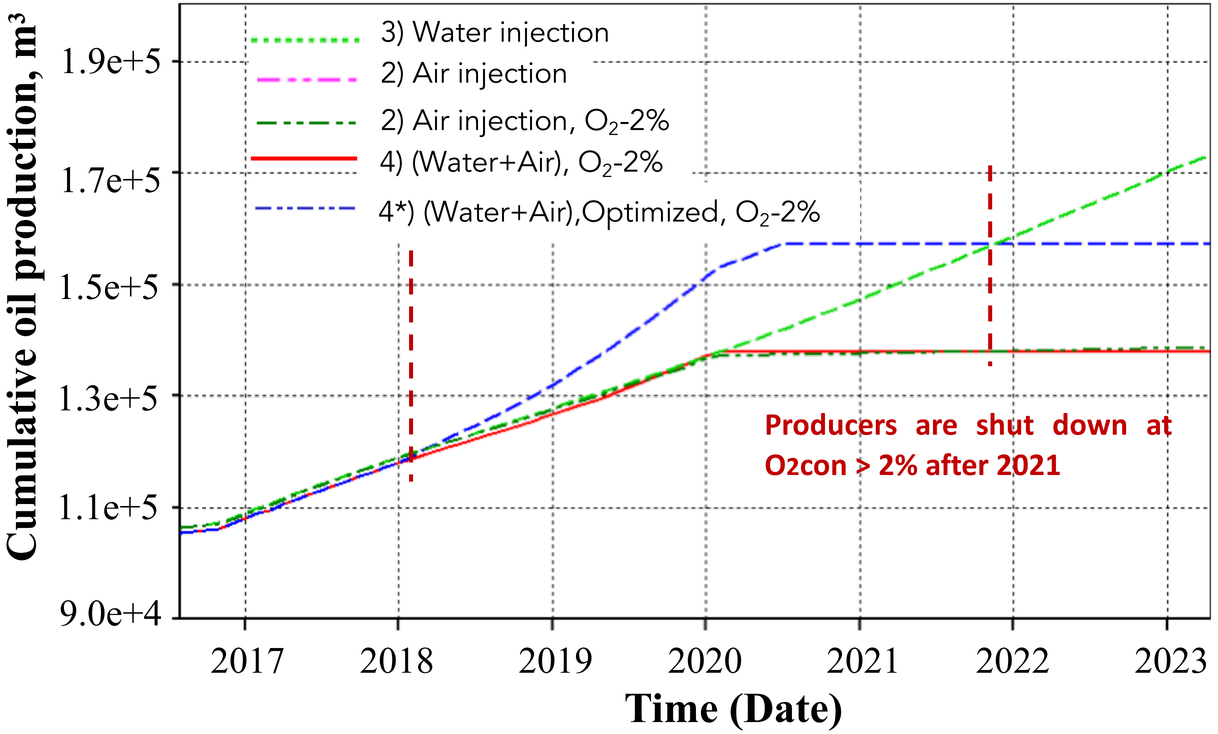
- High temperatures in air-injection well cross sections indicate combustion existence. However, the amount of oxygen is insufficient to maintain pressure at a distance of more than 50 m from the well (due to insufficient injectivity of injection wells) in Subsections 2,3,4. Combustion stops and air breaks into the producing wells. In the long run, the water injection and primary production demonstrate a better efficiency and more profitable with the given development system of Subsections 2,3,4. It should be noted, the efficiency of water injection is overestimated, since in practice it does not show such effectiveness. Lack of water availability is another drawback of Scenario 3.
- Optimization of Subsection 2 and 3

Optimization



Results of the rearrangement for Subsection 3:

The development system of this uplift was changed as follows: 1 injection well was shifted to production mode (yellow), another well to injection mode (blue), an additional production well was drilled that allows 16% more oil to be produced before 11.2021. In this case, an economics should be calculated both for Scenario 3 and Scenario 4 until 11.2021 to estimate the efficiency.



Cumulative oil production for Subsection 3 before air breakthrough

Conclusion

- Consequent laboratory-scale HPRTO and MPCT experiments and their further 3D digital modeling were conducted;
- A kinetic model of reactions occurring during combustion and of the field was validated against experimental results;
- Adapted fluid model, relative permeability, kinetic model, and operational parameters obtained during the numerical simulation was used for the field upscaling.
- Four different Scenarios were proposed and calculated for four individual Subsections of the field. In Subsection 1 – Scenario 2 and Scenario 4 add 9% and 10% respectively, to cumulative oil production in comparison with Scenario 3.
- Air breakthrough into production wells occurs within 2-3 years after the start of injection. Injection of air into the reservoir does not lead to an increase in oil recovery in the long run for Subsections 2,3,4, due to rapid breakthroughs of air into producing wells (oxygen concentration limit is 2%);
- For the Subsection 3, the optimization with transferring injection well for production, production well into injection mode, as well as drilling an additional well, can lead to higher oil production (+16 %) until 2021 (after which production wells were shut off due to air breakthrough);
- Currently, the main uncertainties that significantly affect the results are relative permeability curves in the oil-gas system, possible air breakthroughs into production wells, injectants (water and air) availability, and their costs.