RGNZ/MGPB

Numerical investigation on the impact of initial water saturation distribution on hot water flooding performance under non-isothermal conditions

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 550.8
DOI: 10.17794/rgn.2023.2.11
Original scientific paper

Md Irshad Ansari [1] **and Suresh Kumar Govindarajan** [2]

[1] *Research Scholar, Reservoir Simulation Laboratory, Petroleum Engineering Programme, Department of Ocean Engineering, Indian Institute of Technology, Madras, India, 0000-0002-1784-1151*

[2] *Professor, Reservoir Simulation Laboratory, Petroleum Engineering Programme, Department of Ocean Engineering, Indian Institute of Technology, Madras, India, 0000-0003-3833-5482*

Abstract

The heterogeneity in the spatial distribution of initial water saturation influences the performance of hot water flooding. The prospect of a reduction in oil recovery arises from the development of viscous instability. In the present study, a numerical simulation model has been developed by coupling heat transport, and multiphase flow in porous media integrated with the non-isothermal flow, and the numerical model has been verified with the existing analytical solution by Buckley and Leverett. The formation of a wavy temperature profile at the condensation front was found with a decreased depth of temperature penetration. The average rise of temperature is drastically affected by the spatial distribution of initial water saturation. The formation of viscous fingering was highly dominating in the reservoir, with initial water saturation randomly distributed and causing the front to move in an irregular pattern from the initial stage of the flooding. The heterogeneous reservoir with initial water distribution showed the earlier formation of viscous fingering than the homogeneous reservoir. The heterogeneity in the spatial distribution of initial water saturation had caused viscous instability, lower viscosity reduction, lower displacement sweeps efficiency, and higher residual oil saturation. The present study is limited to spatial distribution in initial water saturation to a certain degree of heterogeneity. The heterogeneity in the spatial distribution of initial water saturation highly impacted the production performance of hot water flooding. The present study provides an idea for the implementation and future development of hot water flooding in a randomly initial water saturation distributed environment.

Keywords:
numerical simulation; displacement sweep efficiency; heterogeneity; hot water flooding; transient temperature.

1. Introduction

Heavy oil is becoming one of the essential energy resources as conventional oil has been depleting significantly in recent years (**Huang et al., 2023**). The world's heavy oil reserves are approximately 5.6 trillion barrels. Heavy oil has a viscosity range of 50 to 50000 mPa.s (**Mai and Kantzas, 2009**). Generally, crude oil with a viscosity higher than 100 mPa·s can be assumed as heavy oil. The challenge is recovering such high viscosity of heavy oil from the deep reservoirs (**Wang et al., 2021**).

The homogenous reservoir description is straightforward. The properties of the reservoir do not change as a function of spatial location in the homogenous reservoir. The reservoir fluid and rock properties remain uniform inside the reservoir at each location. On the other hand, the reservoir properties such as permeability, porosity, thickness, saturation, rock characteristics, rock facies, faults, and fractures vary as a function of spatial location in the heterogenous reservoir (**Ahmed, 2010**). Reservoir heterogeneity performs a necessary function in the buildup and production of hydrocarbon reservoirs and limits the seepage factors of oil, gas, and water, dictates the grade of the reservoir, and controls the grade of the reservoir (**Wang, 2021**). So, the understanding of the heterogeneity of reservoirs is an initial step toward the better development of oil fields and their performances. Understanding reservoir heterogeneity provides insight to the reservoir engineer to execute the project efficiently and effectively.

Hot water flooding is one of the techniques of tertiary hydrocarbon recovery. It is now adopted as a relatively economical thermal recovery method as it comprises sensible heat only (**Zhao and Gates, 2013; Wang et al., 2021; Farouq Ali 1974; Han et al., 2017; Gai et al., 2012**). The water injected inside the reservoir transfers heat energy to the reservoir fluid. The reservoir fluid temperature increases, and hence, the temperature of the reservoir fluid increases, and the viscosity of the reservoir fluid decreases. The decreased viscosity of the reservoir fluid makes fluid more movable inside the reser-

---

Corresponding author: Md Irshad Ansari
e-mail address: oe19d021@smail.iitm.ac.in

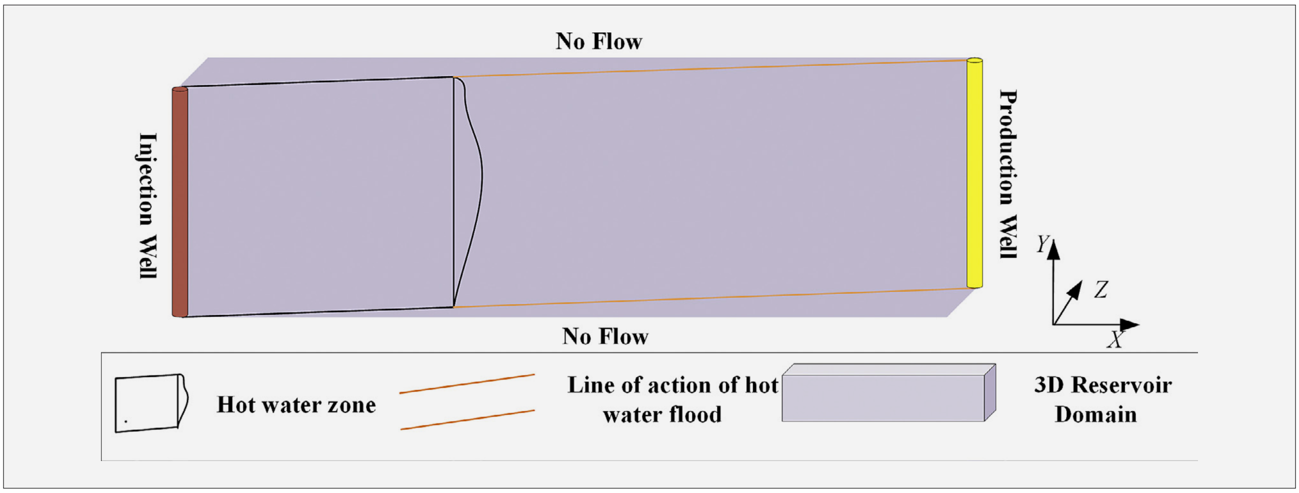

Figure 1: The conceptual model illustrating hot water flooding in 3D cross-sectional homogenous and heterogenous porous media

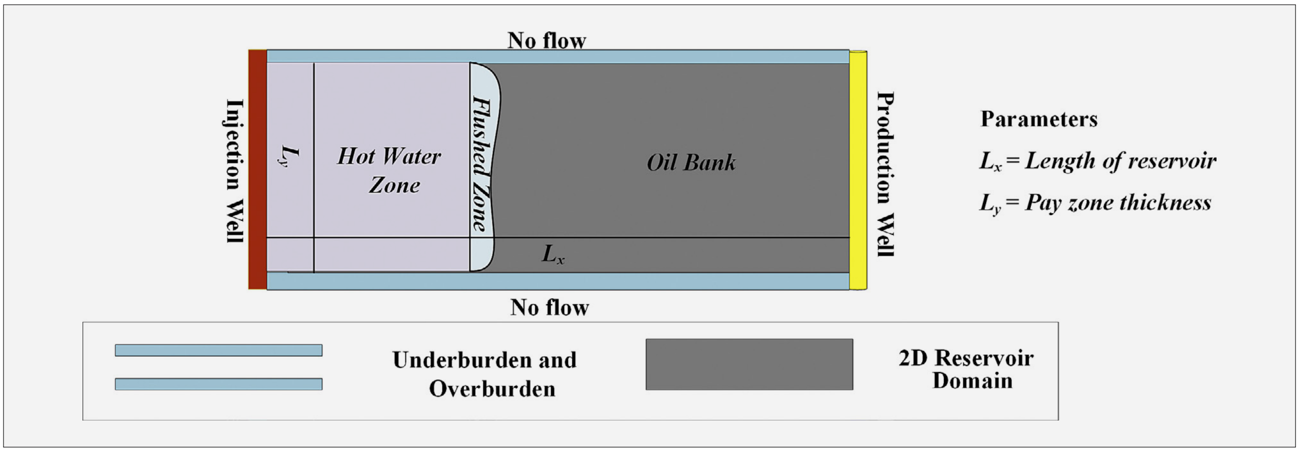

Figure 2: The conceptual model illustrating hot water flooding in 2D cross-sectional homogenous and heterogenous porous media specified dimensions based on assumptions

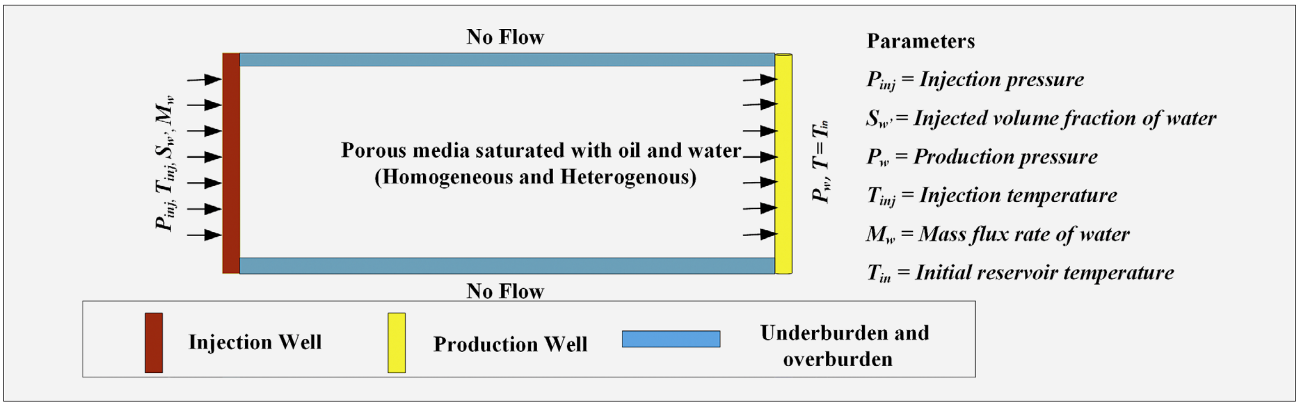

Figure 3: The conceptual model illustrating hot water flooding in 2D reservoir homogenous and heterogenous porous media with desired boundary conditions

voir, which helps increase hydrocarbon production through the production well. Heating also reduces the interfacial tension and residual oil saturation, which cause an improvement in the displacement sweep efficiency. However, quite limited research was reported regarding the application of hot water flooding in petroleum reservoirs (**Wang et al., 2021**).

Hot water flooding is affected by the mobility ratio due to the difference in heavy oil and water mobility. The viscosity of heavy crude oil is higher than water, and therefore water mobility is higher than heavy oil. It is one of the reasons which causes water fingering through the reservoir. It is required to control the hot water injection rate inside the reservoir to reduce the effect of water fingering (**Mai and Kantzas, 2009**).

The hot water injected into the reservoir delivers less heat to the reservoir fluid than the steam flooding because of the absence of latent heat in hot water, and hot water has difficulty causing the overlap of gravity flow. Hence, it is less effective in reducing the heavy oil viscosity. However, at the same time, hot water flooding has an advantage over steam flooding because it can be applied to a thin pay zone (**Zhao and Gates, 2015**). Water viscosity is much higher than steam, so it gives better displacement sweep efficiency than steam (**Martin et al., 1967**). The injection pressure of hot water flooding is higher than steam flooding at any particular temperature. As the pressure of water flooding is higher, it makes hot water remain at a higher temperature during a hot water state. Hot water is also cheaper to inject in comparison to steam, because of the low cost of pumping and the supports of high hydrostatic pressure gradients on the injection pressure (**Zhao and Gates, 2015; Wang et al., 2021; Wu & Liu, 2019**). The temperature distribution of hot water on the reservoir tells the thermal influence of hot water inside the in-situ fluid and the temperature of the oil layers (**Han et al., 2017**).

Presently, numerous research published focused on hot water flooding in the reservoir, mainly focused to thermal recovery mechanisms by experimental techniques. The hot water recovery mechanisms are analyzed by performing several laboratory experiments (**Ashrafi et al., 2012; Jensen et al., 1992; Karimaie and Torsæter, 2007; O'Carroll and Sleep, 2009; Luo and Torabi, 2013; O'Carroll and Sleep, 2007; Pang et al., 2015; Tang and Kovscek, 2004**). Nevertheless, the transient temperature effect was ignored while experimenting, whereas the effect of injection velocity and reservoir parameters on the recovery of the reservoir were analyzed in previous studies of hot water flooding. The impact of the oil recovery highly depends on the micro distribution of initial oil and water in porous media (**Liu et al., 2023**). Heterogeneity due to porosity and permeability were studied associated with the reservoir, but heterogeneity associated with the spatial distribution of initial water saturation was seen as missing in the previous studies.

Modelling is a systematic representation of field conditions with the help of set of mathematical governing equations. The set of governing equations are discretized using explicit or implicit formulations (**Srinivasa Reddy & Suresh Kumar, 2015**). The multiphase flow modelling in porous media is challenging. Understanding these mediums is an open challenge. Several researchers worked in the field of contaminant transport, CO_2 sequestration, and the recovery of petroleum by secondary and tertiary enhanced methods (**Gudala and Govindarajan, 2021; Kumar and Reddy, 2017; Pavan et al., 2022; Vulin et al., 2018; Ansari & Govindarajan, 2022; Cheng et al., 2023; Sivasankar & Suresh Kumar, 2018; Arnaut et al., 2021; Duru et al., 2022**). The objective of the present study is to understand the effect of heterogeneity associated with initial water saturation on the thermal and rheological state of reservoir fluids, residual oil, and water saturation and displacement efficiency, which are important parameters to decide the production forecasting of oil. In the present study, temperature profiles and viscous fingering in a randomly distributed environment have been studied. The water front movement has been visualised at the different spatiotemporal variation conditions. The effect of the rise of the temperature on the average viscosity of the heavy oil has been analyzed and its effect on the residual oil saturation and displacement efficiency have been investigated under non-isothermal conditions.

2. Conceptual Model

The representative elementary volume in the 'XY' and 'XZ' planes is considered initially. It is considered that the porosity, initial water saturation, and permeability are the same at each location on the 'XZ' plane, but porosity and initial water saturation are assumed to be different in the 'XY' plane at a different location. As the rock properties considered in the 'XZ' plane are the same and the 'XY' plane is different, studying a two-dimensional reservoir gives a better understanding of the heterogeneity of the reservoir. Hence, we have converted the three-dimensional reservoir into a two-dimensional reservoir model. The schematic of conceptual modelling has been represented in **Figures 1, 2,** and **3**.

3. Mathematical modelling

3.1 Assumptions

The reservoir is assumed cross-sectional two dimensional in view under local thermal equilibrium ($T_s = T_f = T$). It is considered to have no heat source and have a high heat transfer coefficient. The overburden and underburden heat transfer is considered negligible. The viscosity of oil and water is assumed to follow linear interpolation with the temperature, as shown in **Table 1**.

3.2 Governing equations

The mathematical equations employed in the present study to analyze the pressure, temperature, and saturation variation of water in the reservoir are described in **Equations 1, 6, 7** and **8** (**COMSOL Multiphysics**). The governing equation for the heat transport in porous media at local temperature equilibrium is represented in **Equation 1**.

$$A_m\left(\rho C_p\right)_{ek}\frac{\partial T}{\partial t}+A_m(\rho_{w'}C_{w'}+\rho_{o'}C_{o'})u.\nabla T+\nabla q=0 \quad (1)$$

Where:

q - the conduction heat transport (W),

$\rho_{w'}$ - the density of water (kg/m^3),

$\rho_{o'}$ - the density of oil (kg/m^3),
$C_{w'}$ - the heat capacity of water (J/kgK),
$C_{o'}$ - the heat capacity of oil (J/kgK),
A_m - area of flow (m^2),
u - the convection velocity of the fluid (m/s),
T - temperature of the rock and fluid at local thermal equilibrium (K).

The conduction heat transport equation is taken from Fourier's law of heat conduction which is represented below.

$$q = -A_m K_{ek} \nabla T \tag{2}$$

Effective heat capacity $\left(\rho C_p\right)_{ek}$ at constant pressure and effective thermal conductivity K_{ek} are represented in **Equation 2** and **Equation 3** respectively.

$$\left(\rho C_P\right)_{ek} = (1-\theta_{P'})\rho_{w'}C_{w'}S_{w'} + (1-\theta_{P')}\rho_{o'}C_{o'}S_{o'} + \theta_{p'}\rho C_P \tag{3}$$

and

$$K_{ek} = \theta_{P'}k_s + \left(1-\theta_{P'}\right)k_w S_w + \left(1-\theta_{P'}\right)k_o S_{o'} \tag{4}$$

Where:

$\theta_{P'}$ - the volume fraction of rock,
ρ - the density of rock (kg/m^3),
k_s, k_o and k_w - the thermal conductivity of rock, oil, and water (W/mK),
$C_{p'}$ - the heat capacity of rock (J/kgK).

For no heat flow across overburden and underburden.

$$-n.Q = 0 \tag{5}$$

Where 'Q' heat flux crossing the top and bottom boundaries.

The governing equations which are solved in multiphase flow are based on the mass conservation and the momentum conservation equations. The mass conservation and momentum conservation equation for both the phase are written below in **Equation 6, Equation 7** and **Equation 8.**

$$\frac{\partial}{\partial t}\left(\Phi\rho_{o'}S_{o'} + \Phi\rho_{w'}S_{w'}\right) + \nabla\cdot\left(\rho_{o'}u_{o'} + \rho_{w'}u_{w'}\right) = Q_{o'} + Q_w \tag{6}$$

$$u_{o'} = -\frac{k_{ro'}K(\nabla p_o - \rho_{o'}g)}{\mu_{o'}} \tag{7}$$

$$u_{w'} = -\frac{k_{rw'}K(\nabla p_w - \rho_{w'}g)}{\mu_{w'}} \tag{8}$$

Where:

Φ - reservoir porosity,
$S_{o'}$ and $S_{w'}$ - saturation of oil phase and water phase,
$Q_{w'}$ and $Q_{o'}$ - mass flux rate of water and oil phase (kg/m^{2}s),
K - the permeability of the reservoir (m^2),
g - the gravitational acceleration (m/s^2),
$u_{o'}$ and $u_{w'}$ - velocity of oil and water phase (m/s),
$\mu_{w'}$ and $\mu_{o'}$ - the dynamic viscosity of water and oil phase (Pa.s),
p_o and p_w - oil and water phase pressure field (Pa),
$k_{ro'}$ and $k_{rw'}$ - the relative permeability of oil and water phase.

The flow across top and bottom boundaries (overburden and underburden) conditions;

$$-n.Q_{w'} = -n.Q_{o'} = 0 \tag{9}$$

The fluid flow is analyzed in the presence of capillary effect. The influence of capillary pressure on the fluid flow is added using the Brooks and Corey model in momentum equation, which are written in **Equation 12, Equation 13** and **Equation 14 (Brooks and Corey, 1964)**.

$$S_{nw} = \frac{(S_{w'} - S_{rw})}{(1 - S_{rw} - S_{ro})} \tag{10}$$

$$S_{no} = \frac{(S_{o'} - S_{ro})}{(1 - S_{rw} - S_{ro})} \tag{11}$$

$$Pc = P_{ec'}(S_{no})^{\frac{-1}{\varepsilon}} \tag{12}$$

$$K_{ro'} = (S_{no})^{(3+\frac{2}{\varepsilon})} \tag{13}$$

$$K_{rw'} = S_{nw}{}^2(1 - \left(1 - S_{nw}\right)^{\left(1+\frac{2}{\varepsilon}\right)}) \tag{14}$$

Where:

S_{nw} and S_{no} - normalized water and oil saturation,
S_{ro} and S_{rw} - residual oil saturation and irreducible water saturation,
$P_{ec'}$ - entry capillary pressure (Pa),
Pc - capillary pressure (Pa),
ε - pore size distribution index.

3.3 Mathematical relation for the coupled impacts on the reservoir fluid and rock properties

The porosity and permeability are varied as a function of transient reservoir pressure which is represented in **Equation 15** and **Equation 16 (Nabizadeh et al., 2022; Wang et al., 2016)**. The thermal conductivity of reservoir rock and water varied as a function of temperature, which is represented in **Equation 17** and **Equation 18 (Gudala et al., 2022)**. The viscosity of reservoir fluid and injected fluid is taken as a function of temperature, which is shown in **Table 1 (Nakornthap and Evans, 1986)**.

$$\Phi = \Phi_{0'}e^{C(P-P_0)} \tag{15}$$

$$K = K_{0'}e^{C(P-P_0)} \tag{16}$$

$$k_s = 2.6 - 0.0025(T - 293.15) \tag{17}$$

$$k_w = -0.869 + 0.009T - \left(1.58\times10^{-5}\right)T^2 + 7.98\times10^{-9}T^3 \tag{18}$$

Where:

Φ_{0}, - initial porosity,

K_0 - initial permeability (m^2),

C - compressibility of rock (Pa^{-1}),

P_o - initial pressure of the reservoir (Pa),

P - transient pressure of the reservoir (Pa).

Table 1: Viscosity temperature relation of hot water and oil at various temperatures

Temperature (K)	μ_o (Pa·s)	μ_w (Pa·s)
294.261	0.03090	80×10^{-5}
310.928	0.01995	62×10^{-5}
322.039	0.01412	50×10^{-5}
338.706	0.00977	38×10^{-5}
355.372	0.00759	32×10^{-5}
366.483	0.00631	28×10^{-5}
394.261	0.00354	21×10^{-5}

4. Numerical model

4.1 Description of homogenous and heterogenous porous media

The two-dimensional oil-wet porous media with an average initial water saturation of 0.15 is assigned for the studies. The cap rock configuration has been considered tight enough not to cause a disturbance to the initial water saturation. The spatial distribution of initial water saturation is randomly assigned using a uniform probability distribution. The randomness in saturation has been adopted to consider the effect of the wettability, interfacial tension but more importantly capillary pressure, which is the result of pore-system morphology of reservoir system (**Liu et al., 2023**). According to pore system morphology, the presence of overburden pressure may cause the shrinkage of the pore at lower depths which reduces the flow of water through the lower zone whereas the flow is enhanced at the higher rock zone. For the numerical simulation, the cross-sectional view of the porous media with a dimension of 100 m by 30 m has been taken in two-dimension, which is shown in **Figures 2** and **3**.

The representation of schematic of distribution of initial water saturation have been represented in **Figure 4**. The fluid and rock properties are selected to meet the condition of unconventional reservoir having sandstone rock and heavy viscous oil, have been taken from literature are shown in **Table 2** (**Cheng et al., 2013; Nassan, 2018; Gudala and Govindarajan, 2021; Helland and Skjæveland, 2006; Iyi et al., 2022; Marotto and Pires, 2018; Mohammadi and Ameli, 2019; Pang et al., 2021; Zhao and Gates, 2015; Nabizadeh et al., 2022; Liu et al., 2020**). The implementation of the simulation was performed in COMSOL Multiphysics. The simulation was carried out after performing the mesh convergence studies.

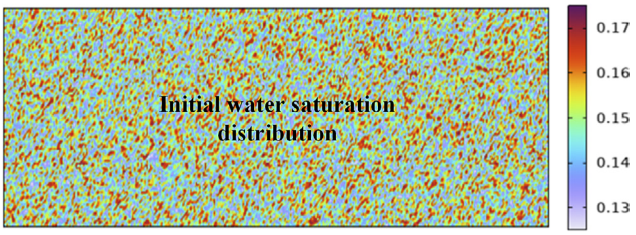

Figure 4: Schematic of heterogeneity associated with initial water saturation

Table 2: Physical properties of the fluids and formation matrix

Parameter	Value
Initial porosity	0.26
Initial oil saturation	0.85
Water density (kg/m^3)	1000
Oil density (kg/m^3)	980
Rock density ($kg/m^{3)}$	2600
Specific heat capacity oil (J/KgK)	2785.5631
Specific heat capacity rock (J/KgK)	720
Specific heat capacity water (J/KgK)	4200
Initial permeability (mD)	14
Initial reservoir temperature (°C)	50
Entry capillary pressure (kPa)	10
Pore size distribution index	2
Thermal conductivity of oil (kJ/m day ˚C)	11.5
Injection temperature (˚C)	120
Injection pressure (MPa)	30
Initial reservoir pressure (MPa)	20
Production pressure (MPa)	10
Inlet velocity (m/s)	2.94×10^{-6}
Compressibility of rock (Pa^{-1})	1.45×10^{-9}
Residual oil saturation	0.15

Initial conditions: Initially reservoir water saturation, temperature and pressure are assumed to have 15%, 50˚C and 20 MPa.

Boundary conditions: The Dirichlet and Neumann type boundary condition has been applied in the simulation. The overburden and underburden is assumed as a no flow condition. The boundary conditions are taken carefully as represented below.

Left and right boundary

$$T\,(0, y, t) = Injection\ Temperature \qquad (19)$$

$$T\,(x=L, y, t) = Initial\ reservoir\ temperature \qquad (20)$$

$$Q_w\,(x=0, y, t) = \rho_w \times U\,(x=0, y, t) \qquad (21)$$

$$S_w\,(x=0, y, t) = 1\text{-}S_{ro} \qquad (22)$$

$$-\eta.\,(\rho_o, u_o)\,(x=0, y, t) = \eta.\,(Q_o)\,(x=0, y, t) = 0 \qquad (23)$$

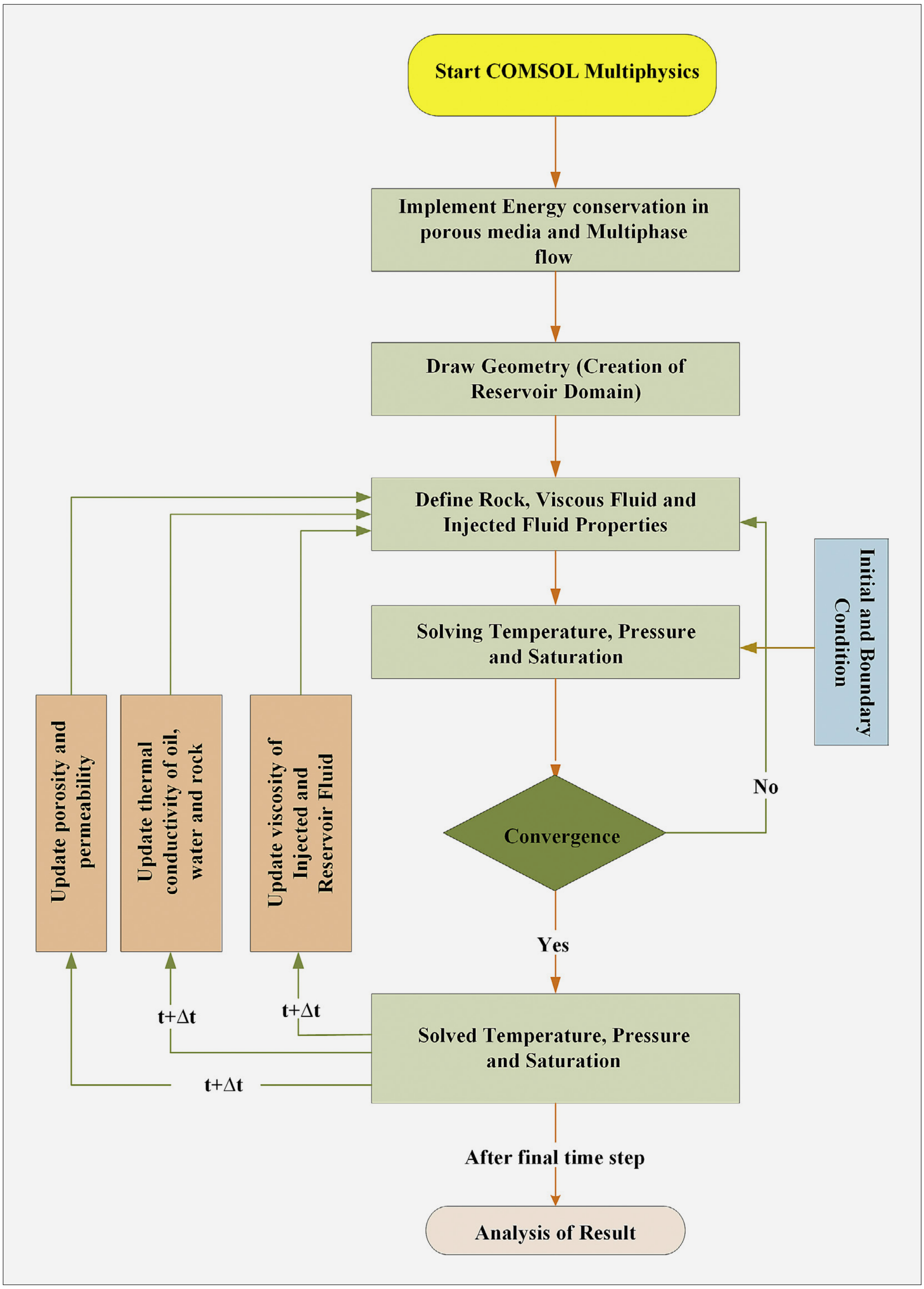

Figure 5: Workflow chart of coupled energy transport and multiphase flow model

Where:

Q_w - mass flux rate of water (kg/m^{2}s),
$\rho_{w'}$ - the density of water (kg/m^3),
U – inlet velocity (m/s),
$S_{w'}$ - water phase saturation,
S_{ro} – residual oil saturation,
$\rho_{o'}$ - the density of oil (kg/m^3),
u_o - oil phase velocity (m/s),
$Q_{o'}$ - mass flux rate of oil (kg/m^{2}s).

4.2 Execution of COMSOL Multiphysics

COMSOL Multiphysics was employed in the present work to study the multiphase fluid flow in a reservoir under the coupled effect of the heat transfer. It was applied in the porous media applications in the educational sector, research organizations and industries (**Gudala & Govindarajan, 2021**). The multiphase module was utilized in this work, coupled with heat transfer. The Brooks and Corey model was implemented to incorporate the effect of capillary pressure on the saturation of water on the application of hot water flooding. The variation of the rock and fluid properties was considered explicitly as non-static local variables. The basic flow sheet is shown for the numerical model implementation in COMSOL in **Figure 5**. The temporal step discretization was performed using the implicit backward differentiation formula. The nonlinear system of equation was solved using the Parallel Direct Solver with a pivoting perturbation of 10^{-13} in alliance with the Newton nonlinear method.

5. Results and discussion

The impact of a fully coupled multiphase flow and heat transfer in a porous medium was investigated effectively at variable porosity and permeability in homogenous and heterogenous reservoir under transient temperature and pressure condition. The transient temperature and pressure plot have been presented in **Figures 7, 8, 9** and **10**.

5.1 Validation of model

In this work, saturation front displacement was validated using a two-phase Buckley-Leverett flow equation in one dimension (**Buckley and Leverett, 1942**). The numerical values used to find the waterfront displacement were kept the same except for viscosity. The viscosity of the fluid was kept constant to neglect the effect of temperature to meet the result of the analytical solution of the Buckley Leverett. The present work water front displacement was verified using the analytical solution of front displacement using Buckley Leverett flow equation. It was observed that the frontal displacement of the present work had shown excellent agreement with the analytical solution represented in **Figure 6**. The frontal advancement was verified for 50 days. Buckley Leverett frontal advance was studied accurate even for the certain degree of heterogeneity (**Singh, 1970**). Hence, the same model has been extended after gaining the confidence in one dimension study to two dimensions for further investigation of certain degree of heterogeneity in initial water saturation on the performance of hot water flooding under non-isothermal conditions.

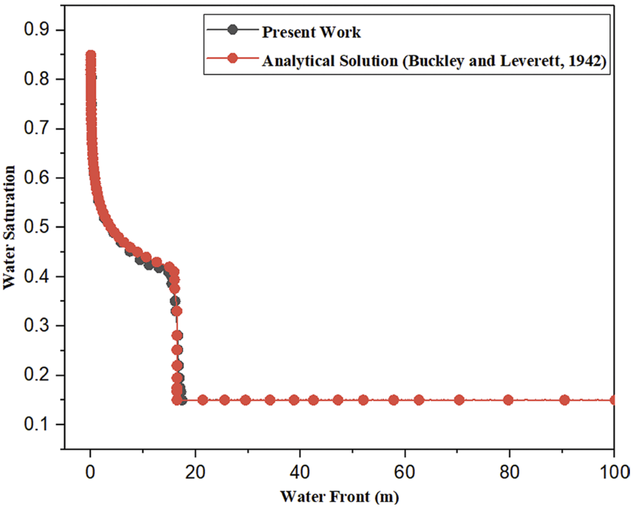

Figure 6: Verification of water saturation profile of the present numerical model with Buckley and Leverett (1942).

5.2 The influence of heat transfer on temperature field distribution in porous media

The heat transport equation was coupled to multiphase flow in porous media to understand the disturbance of initial water saturation on the temperature distribution. The depth of penetration of the temperature and the nature of the profile is shown in **Figures 7** and **8**.

The temperature distribution was found to propagate rapidly in the upper layer of the reservoir. The rapid temperature transition in the upper layer was due to the density difference of hot fluid and higher conduction heat transfer. In a homogenous reservoir, the temperature front was observed to penetrate 40.5 m in the reservoir in 320 days, whereas the temperature front was observed to reach 31 m in a heterogenous reservoir with random

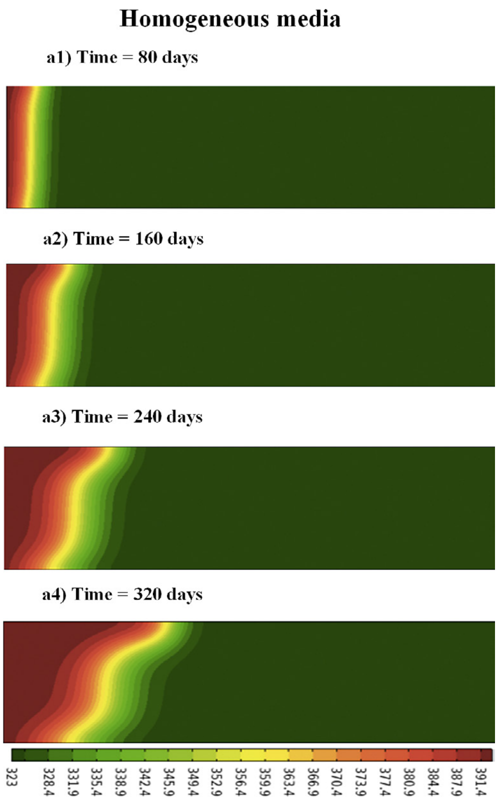

Figure 7: Spatiotemporal variation of Temperature (K) in a homogeneous reservoir

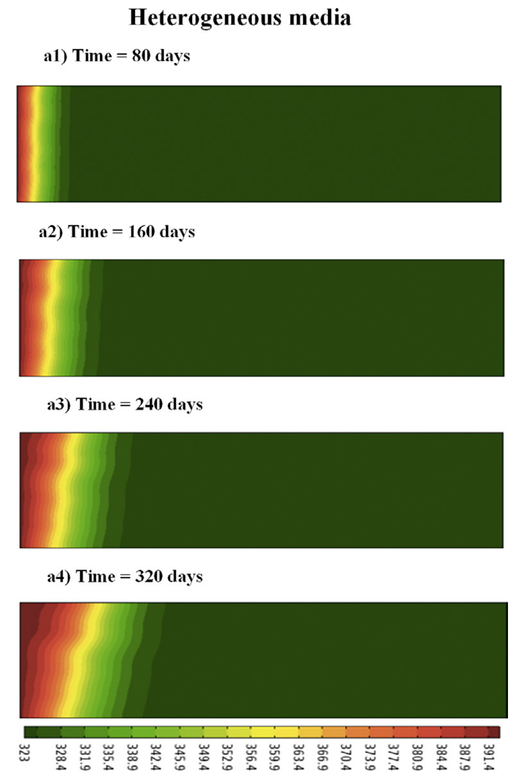

Figure 8: Spatiotemporal variation of Temperature (K) in a heterogeneous reservoir

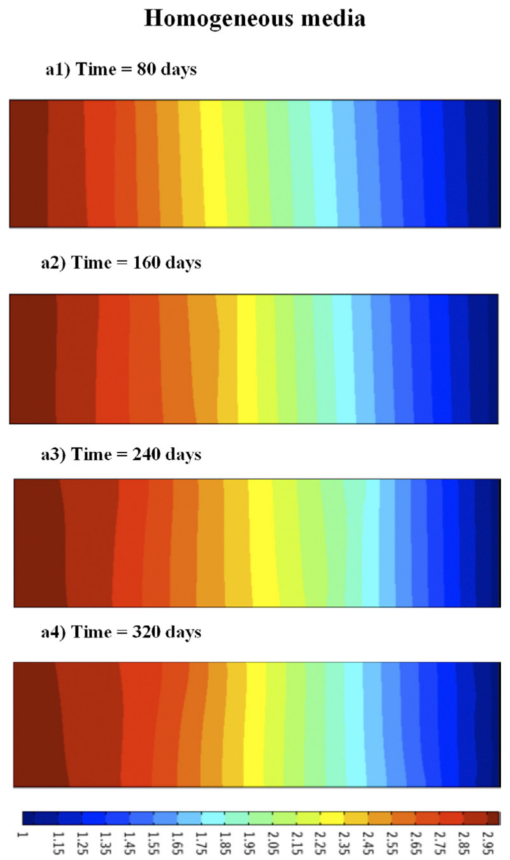

Figure 9: Spatiotemporal variation of Pressure (10^{-1} MPa) in a homogeneous reservoir

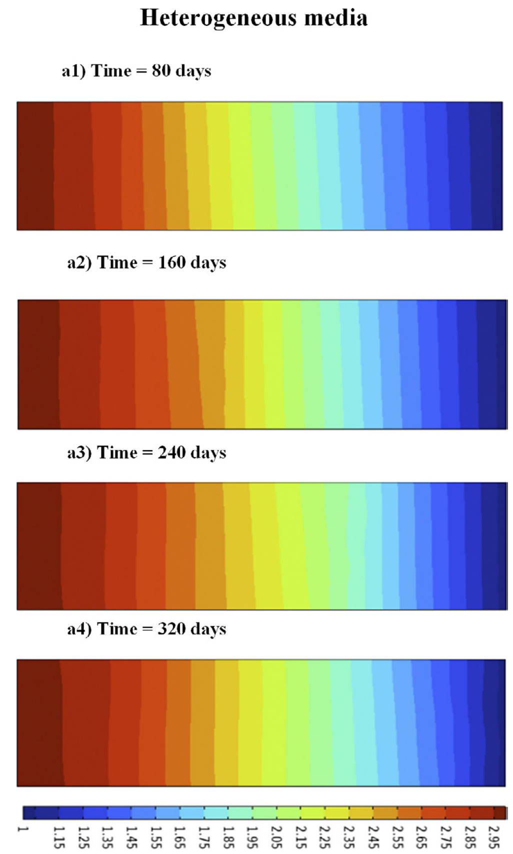

Figure 10: Spatiotemporal variation of Pressure (10^{-1} MPa) in a heterogeneous reservoir

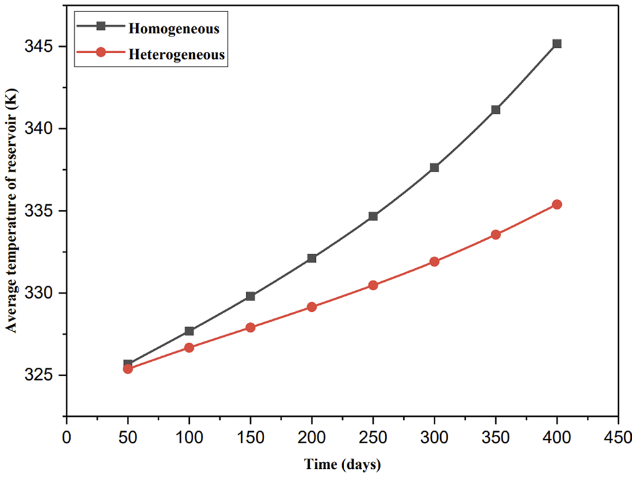

Figure 11: Schematic illustrating the variation of average temperature of reservoir with time enhancement

initial water saturation distribution in the upper layer in 320 days. The temperature front was observed to follow the same trends in the middle layer and bottom layer of the reservoir. The bottom layer of the reservoir was observed to have less temperature penetration depth in each situation. The heat transfer in the reservoir was observed to dominate in the upper layer regardless of heterogeneity.

The average temperature of the reservoir was observed to be drastically impacted by the initial water saturation distribution. The average temperature of a reservoir with time elapsed has been presented in **Figure 11**. The average temperature of the reservoir was highly degraded when the heterogeneity in initial water saturation was incorporated. The uneven distribution of water might cause a disturbance to the relative permeability, which caused the improper displacement of the temperature front and reduced heat transfer. It shows that the heterogeneity in initial water saturation is of huge concern in the planning and development phases.

5.3 The effect of heterogeneity on water saturation front and viscous instability

The saturation front displacement was analyzed in the homogeneous and heterogeneous reservoirs. The effect of heterogeneity on the saturation front and viscous instability was analyzed under transient pressure and temperature condition using **Figures 12** and **13**. The saturation front was observed to be smooth till 245 days and started to develop viscous instability after 245 days in a homogeneous reservoir. In contrast, heterogeneity due to initial water saturation formed viscous instability at 117 days. In a heterogeneous reservoir, the saturation front disturbance started early because of the variation of the water saturation in the reservoir. The relative permeability of water was enhanced in the region having high water saturation. The uneven nature of the relative permeability of the waterfront at a spatial location causes viscous instability. The oil's viscosity reduction was observed more at the location of viscous instability because of the viscous dissipation, which makes the water saturation front move fast and becomes responsible for forming the viscous shielding and fingering. Viscous shielding dominated in the heterogeneous reservoir due to disturbance in the initial water saturation. The viscous dissipation effect was almost negligible in the homogeneous reservoir, which makes the water saturation front move smoothly inside the reservoir. Heterogeneity is caused by the viscous shielding and fingering effect in the reservoir from the early period of flooding.

5.4 The effect of time elapsed on the viscosity of oil, residual oil saturation and displacement sweep efficiency

The viscosity of oil was observed to reduce with time enhancement. The homogeneous reservoir was found to have a drastic reduction in viscosity, whereas the heterogeneous reservoir found a slow decline in viscosity which is presented in **Figure 14**. The magnitude of the viscosity reduction was found not significant in the heterogeneous reservoir compared to the homogeneous reservoir, which reduces the mobility of the oil phase and causes the reduction in the recovery factor.

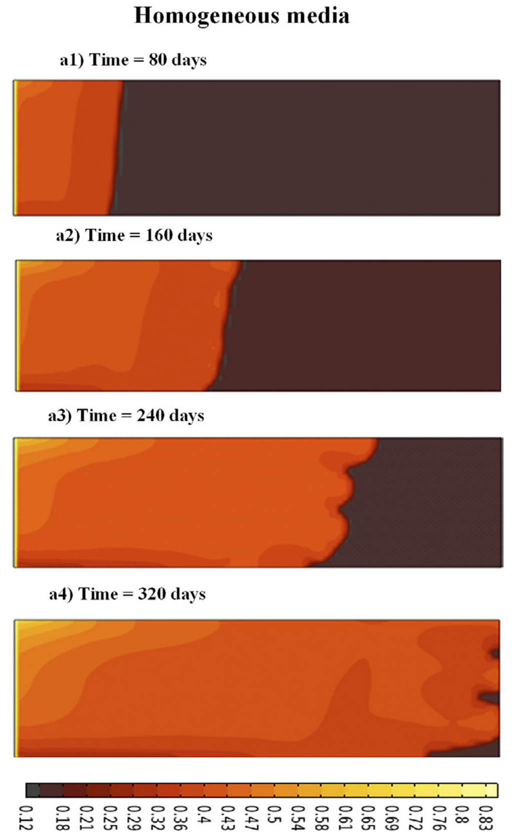

Figure 12: Spatiotemporal variation of water front displacement in a homogeneous reservoir

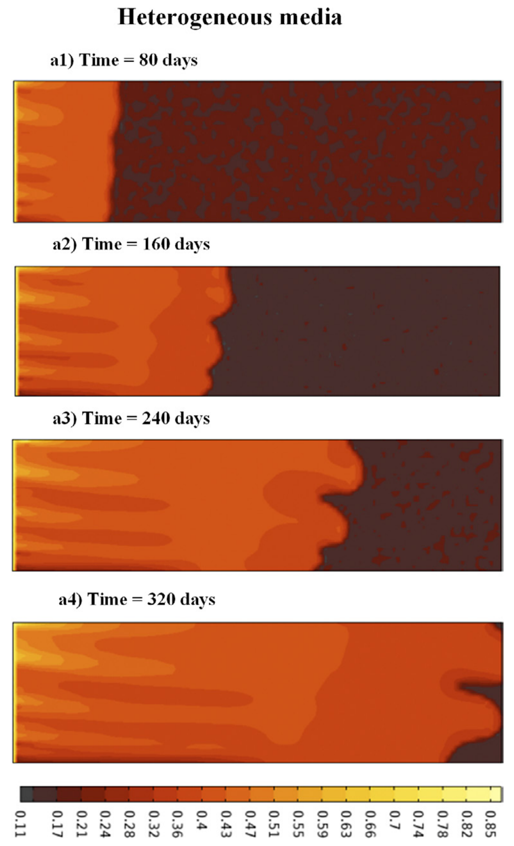

Figure 13: Spatiotemporal variation of water front displacement in a heterogeneous reservoir

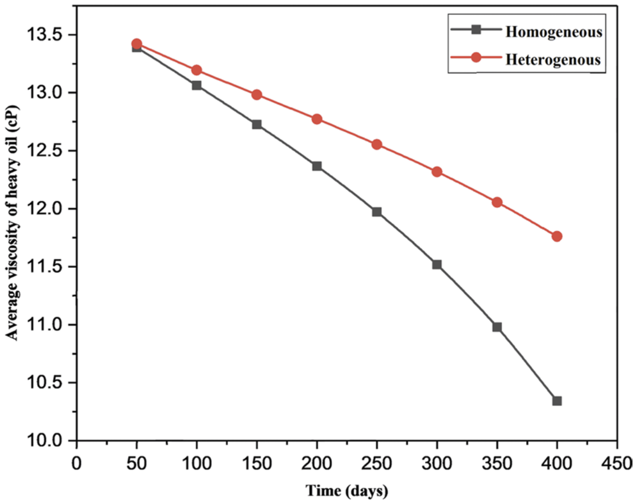

Figure 14: Schematic illustrating the variation of average viscosity of oil with time enhancement

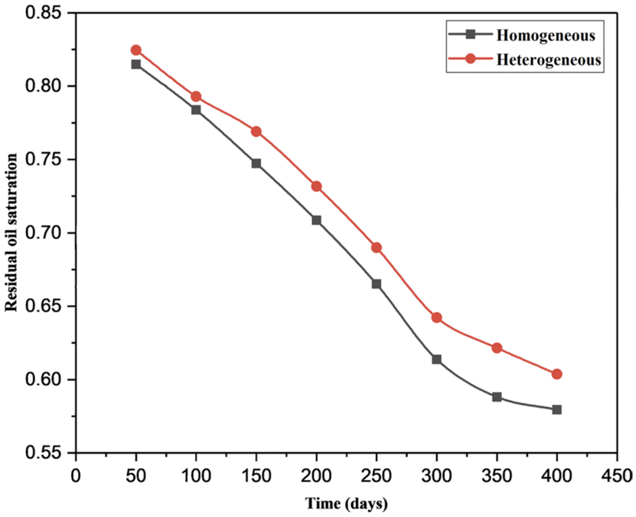

Figure 15: Schematic illustrating the variation of residual oil saturation with time enhancement

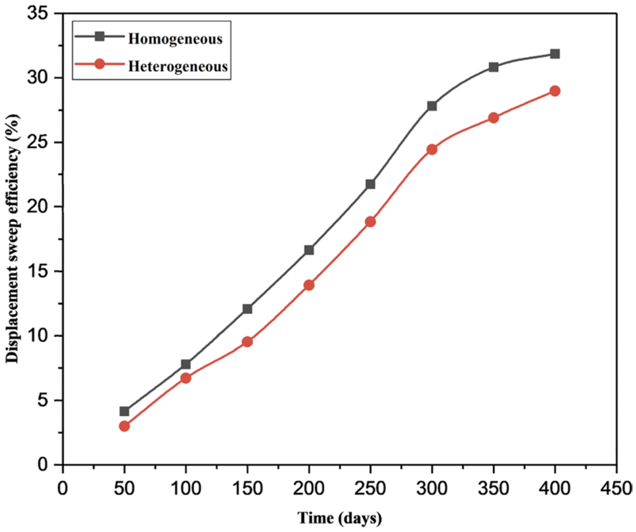

Figure 16: Schematic illustrating the variation of displacement sweep efficiency with time enhancement

The residual oil saturation was noted to fall mainly in the homogeneous reservoir compared to the heterogeneous reservoir. The difference in residual oil saturation decline of the heterogeneous reservoir was observed at 1.2 % constant till 100 days. The difference in residual oil saturation started increasing and was observed at 2.9 % till 300 days, and later it reached 5.7% compared to the homogeneous reservoir. The fall in residual oil saturation was noticed to be impacted by the disturbance in initial water saturation. It can be analyzed from **Figure 15** the initial water saturation distribution impacted the residual oil saturation drastically.

The displacement sweep efficiency was noted to decline with the reservoir incorporated with heterogeneity. This happened because of the disturbances associated with the reservoir. The initial water saturation distribution played a crucial role in reducing oil recovery. The front was noted to sweep rapidly in the region of significant water saturation compared to the region where the initial water saturation was low. Hence, the displaced fluid saturation was observed to fall, which caused an increase in the residual oil saturation inside the reservoir. The heterogeneous reservoir with initial water saturation randomly distributed was observed with a low decrement in the residual oil saturation. The heterogeneity owing to initial water saturation affected the displacement efficiency of hydrocarbon drastically, which could be interpreted from **Figure 16**.

6. Conclusions

A numerical study has been performed to understand the impact of heterogeneity in the spatial distribution of initial water saturation on the production performance of hot water flooding under non-isothermal conditions. Very few earlier studies on the detailed spatial distribution of initial water saturation are associated with the development of present numerical work toward the performance of hot water flooding in estimating the displacement sweep efficiency and viscous instability. The purpose of the present study is to analyze the role of the spatial distribution of initial water saturation on the temperature profiles and viscous fingering in a randomly distributed environment and understands its impact on the displacement sweep efficiency and residual oil saturation. COMSOL Multiphysics has been employed which uses the finite element method to solve the coupled heat transport and multiphase flow integrated with the non-isothermal flow. The spatial distribution in initial water saturation is incorporated into the coupled model using an active local variable. The water front displacement was validated against the Buckley Leverett frontal advance to gain confidence in simulating the hot water flooding.

The heterogeneity in the spatial distribution of initial water saturation highly impacted the production performance of hot water flooding. The temperature of the reservoir increased with the time hot water elapsed, and the depth of penetration of temperature also increased with time. The temperature penetration depth was reduced with the initial water saturation distribution and was dominating on the upper layer of the reservoir in both cases. The amount of energy exchanged was impacted by the disturbance in initial water saturation. In a homogeneous reservoir, the saturation front movement was initially smooth but started forming viscous instability after 245 days. The heterogeneous reservoir showed the formation of viscous instability after 117 days. The presence of a randomly initial water saturation environment significantly impacted displacement sweep efficiency and residual oil saturation inside the reservoir. The relative decrease in displacement efficiency in heterogeneous media was 10.20% in comparison to the homogeneous media. Heterogeneity has shown a very crucial effect on the saturation front movement and caused early viscous instability, hence impacting the production performance. Production forecasting can be achieved effectively and efficiently if the heterogeneity of the reservoir owing to the spatial distribution in initial water saturation is kept in attention while designing and executing the project.

The present study is limited to a certain degree of heterogeneity in the spatial distribution of initial water saturation. It is recommended to explore the spatial distribution of initial water saturation along with the porosity and permeability distribution in sandstone and carbonate reservoirs with or without geomechanical consideration to analyze the overall effect on the production performance at a higher degree of heterogeneity.

Acknowledgement

The authors greatly acknowledge the research support from Indian Institute of Technology, Madras.

Conflict of interest

The authors declare that there is no financial or personal interest to research work associated with this paper.

7. References

Ahmed, T. (2010): Fundamentals of Rock Properties, Reservoir Engineering Handbook. 4th ed.

Ansari, M. I., & Govindarajan, S. K. (2022): One-dimensional heat distribution simulation in heavy oil reservoirs during steam flooding methods. OCEANS 2022 - Chennai, 1–8. https://doi.org/10.1109/OCEANSChennai45887.2022.9775245

Arnaut, M., Vulin, D., José García Lamberg, G., & Jukić, L. (2021): Simulation Analysis of CO2-EOR Process and Feasibility of CO2 Storage during EOR. Energies, 14(4), 1154. https://doi.org/10.3390/en14041154

Ashrafi, M., Souraki, Y. & Torsaeter, O. (2012): Effect of Temperature on Athabasca Type Heavy Oil – Water Relative Permeability Curves in Glass Bead Packs. Energy and Environment Research, 2 (2).

Brooks, R.H. & Corey, A.T. (1964): Hydraulic Properties of Porous Media. Hydrology Paper, Vol. 3, Colorado State University, Fort Collins.

Buckley, S. E., & Leverett, M. C. (1942): Mechanism of Fluid Displacement in Sands. Transactions of the AIME, 146 (01), 107–116.

Cheng, C. -L., Perfect, E. & Mills, R. T. (2013): Forward Prediction of Height-Averaged Capillary Pressure–Saturation Parameters Using the BC-vG Upscaler. Vadose Zone Journal, 12 (3): 1–9.

Cheng, L., Luo, Z., Xie, Y., Zhao, L., & Wu, L. (2023): Numerical simulation and analysis of damage evolution and fracture activation in enhanced tight oil recovery using a THMD coupled model. Computers and Geotechnics, 155, 105244. https://doi.org/10.1016/j.compgeo.2023.105244

Duru, U. I., Ikpeka, P. M., Ndukwe-Nwoke, C., Arinkoola, A. O., & Onwukwe, S. I. (2022): QUANTITATIVE RISK ASSESSMENT OF THE EFFECT OF SAND ON MULTIPHASE FLOW IN PIPELINE. Rudarsko-Geološko-Naftni Zbornik, 37(4), 37–52. https://doi.org/10.17794/rgn.2022.4.4

Farouq Ali, S. M. (1974): Heavy oil recovery-principles, practicality, potential, and problems. United States.

Gai, P. Y., Yin, F. H., Hao, T. T., & Zhang, Z. P. (2012): Experimental Research on Hot Water Flooding of Different Rhythm Heavy Oil Reservoir after the Steam Injection. Advanced Materials Research, 550–553, 2878–2882.

Gudala, M., & Govindarajan, S. K. (2021): Numerical Investigations on Two-Phase Fluid Flow in a Fractured Porous Medium Fully Coupled with Geomechanics. Journal of Petroleum Science and Engineering, 199: 108328.

Gudala, M., & Govindarajan, S. K. (2021): Numerical investigations on a geothermal reservoir using fully coupled thermo-hydro-geomechanics with integrated RSM-machine learning and ARIMA models. Geothermics, 96, 102174.

Gudala, M., Govindarajan, S. K., Yan, B. & Sun, S. (2022): Numerical Investigations of the PUGA Geothermal Reservoir with Multistage Hydraulic Fractures and Well Patterns Using Fully Coupled Thermo-Hydro-Geomechanical Modeling. Energy, 253: 124173.

Han, B. -B., Cheng, W. -L. & Nian, Y. -L. (2017): Experimental Study on Effect of Temperature Field on Recovery of Reservoir Using Hot Water Flooding. Energy Procedia, 142: 3759–65.

Helland, J. O. & Skjæveland, S. M. (2006): Physically Based Capillary Pressure Correlation for Mixed-Wet Reservoirs from a Bundle-of-Tubes Model. SPE Journal, 11 (02): 171–80.

Huang, Z., Zhao, Q., Chen, L., Guo, L., Miao, Y., Wang, Y., & Jin, H. (2023). Experimental investigation of enhanced oil recovery and in-situ upgrading of heavy oil via CO2- and N2-assisted supercritical water flooding. Chemical Engineering Science, 268, 118378. https://doi.org/10.1016/j.ces.2022.118378

Iyi, D., Balogun, Y., Oyeneyin, B. & Faisal, N. (2022): A Numerical Study of the Effects of Temperature and Injection Velocity on Oil-Water Relative Permeability for Enhanced Oil Recovery. International Journal of Heat and Mass Transfer, 191: 122863.

Jensen, T. B., Sharma, M. P., Harris, H. G. and Whitman, D. L. (1992): Numerical Investigations of Steam and Hot-Water Flooding in Fractured Porous Media. In SPE/DOE Enhanced Oil Recovery Symposium. Society of Petroleum Engineers.

Karimaie, H. & Torsæter, O. (2007): Effect of Injection Rate, Initial Water Saturation and Gravity on Water Injection in Slightly Water-Wet Fractured Porous Media. Journal of Petroleum Science and Engineering, 58 (1–2): 293–308.

Kumar, G. S. & Reddy, D. S. (2017): Numerical Modelling of Forward In-Situ Combustion Process in Heavy Oil Reservoirs. International Journal of Oil, Gas and Coal Technology, 16 (1): 43.

Liu, G., Wang, H., Tang, J., Liu, Z., & Yang, D. (2023): Effect of wettability on oil and water distribution and production performance in a tight sandstone reservoir. Fuel, 341, 127680. https://doi.org/10.1016/j.fuel.2023.127680

Liu, Z., Wang, Q., Luo, W., Gao, M., & Cai, H. (2020): A New Method for Potential Evaluation of Compound Flooding of Tertiary Oil Recovery. Journal of Physics: Conference Series, 1673, 012034.

Luo, W. & Torabi, F. (2013): Coupling of Solvent and Hot Water to Improve Heavy Oil Recovery: Experimental and Simulation Studies. In All Days. SPE.

Mai, A. & Kantzas, A. (2009): Heavy Oil Waterflooding: Effects of Flow Rate and Oil Viscosity. Journal of Canadian Petroleum Technology, 48 (03): 42–51.

Marotto, T. A. & Pires, A. P. (2018): Mathematical Model for One-Dimensional Oil Displacement by Steam Injection with Solvent Addition. Journal of Petroleum Science and Engineering, 169: 374–87.

Martin, W.L., Dew, J.N., Powers, M.L. & Steves, H.B. (1967): Results of a Tertiary hot waterflood in a thin sand reservoir. J can Petrol Technol, 20 (7):739-50

Mohammadi, K. & Ameli, F. (2019): Toward Mechanistic Understanding of Fast SAGD Process in Naturally Fractured Heavy Oil Reservoirs: Application of Response Surface Methodology and Genetic Algorithm. Fuel, 253: 840–56.

Nabizadeh, A., Abbasi, M., Siavashi, J., Sharifi, M. & Movaghar, M. R. K. (2022): Fluid Flow Modeling through Pressure-Dependent Porous Media: An Analytical Solution and a Computational Fluid Dynamics Approach. Groundwater for Sustainable Development, 18: 100776.

Nakornthap, K. & Evans R. D. (1986): Temperature-Dependent Relative Permeability and Its Effect on Oil Displacement by Thermal Methods. SPE Reservoir Engineering, 1 (03): 230–42.

Nassan, T.H. (2018): Simulation of 1-D heat distribution in heavy oil reservoirs during steam injection process. Expert from the Proceedings of the COMSOL Conference in Lausanne.

O'Carroll, D. M. & Sleep, B. E. (2007): Hot Water Flushing for Immiscible Displacement of a Viscous NAPL. Journal of Contaminant Hydrology, 91 (3-4): 247–66.

O'Carroll, D. M. & Sleep, B. E. (2009): Role of NAPL Thermal Properties in the Effectiveness of Hot Water Flooding. Transport in Porous Media, 79 (3): 393–405.

Pang, Z., Liu, H., & Zhu, L. (2015): A Laboratory Study of Enhancing Heavy Oil Recovery with Steam Flooding by Adding Nitrogen Foams. Journal of Petroleum Science and Engineering, 128: 184–93.

Pang, Z., Wang, L., Yin, F. & X. Lyu. (2021): Steam Chamber Expanding Processes and Bottom Water Invading Characteristics during Steam Flooding in Heavy Oil Reservoirs. Energy, 234: 121214.

Pavan, T. N. V., Devarapu, S. R., & Govindarajan, S. K. (2022): Comparative analysis on impact of water saturation on the performance of in-situ combustion. Rudarsko-Geološko-Naftni Zbornik, 37(4), 167–175.

Singh, K. K. (1970): Comparison of the Buckley-Leverett technique with a numerical simulation model containing heterogeneity and capillary pressure. Masters Theses, 7162. https://scholarsmine.mst.edu/masters_theses/7162.

Sivasankar, P., & Suresh Kumar, G. (2018): Modelling the influence of interaction between injection and formation brine salinities on in-situ microbial enhanced oil recovery processes by coupling of multiple-ion exchange transport model with multiphase fluid flow and multi-species reactive transport models. Journal of Petroleum Science and Engineering, 163, 435–452. https://doi.org/10.1016/j.petrol.2018.01.004

Srinivasa Reddy, D., & Suresh Kumar, G. (2015): Numerical Simulation of Heavy Crude Oil Combustion in Porous Combustion Tube. Combustion Science and Technology, 187(12), 1905–1921.

Tang, G.-Q. & Kovscek, A. R. (2004): An Experimental Investigation of the Effect of Temperature on Recovery of Heavy Oil from Diatomite. SPE Journal, 9 (02): 163–79.

Vulin, D., Gaćina, M., & Biličić, V. (2018): SLIM-TUBE SIMULATION MODEL FOR CO2 INJECTION EOR. Rudarsko-Geološko-Naftni Zbornik, 33(2), 37–48. https://doi.org/10.17794/rgn.2018.2.4

Wang, C., Liu, Y. Du, Y., Gao, Y. & Sun, Y. (2021): Heavy-Oil Recovery by Combined Geothermal Energy and Cosolvent/Water Flooding. Energy, 228: 120681.

Wang, L. (2021): Study on Reservoir Heterogeneity in Block S. IOP Conference Series: Earth and Environmental Science, 770 (1): 012020.

Wang, Y., Li, X., Zheng, B. & Ma, C. F. (2016): An Experimental Investigation of the Flow–Stress Coupling Characteristics of Soil–Rock Mixture Under Compression. Transport in Porous Media, 112 (2): 429–50.

Wu, Z., & Liu, H. (2019): Investigation of hot-water flooding after steam injection to improve oil recovery in thin heavy-oil reservoir. Journal of Petroleum Exploration and Production Technology, 9(2), 1547–1554.

Zhao, D. W. & Gates, I. D. (2013): Stochastic Optimization of Hot Water Flooding Strategy in Thin Heavy Oil Reservoirs. In All Days. SPE.

Zhao, D. W. & Gates, I. D. (2015): On hot water flooding strategies for thin heavy oil reservoirs. Fuel, 153, 559–568.

SAŽETAK

Numeričko modeliranje utjecaja početne distribucije zasićenja vodom na izvedbu zavodnjavanja toplom vodom u neizotermnim uvjetima

Heterogenost u prostornoj distribuciji početog zasićenja vodom utječe na izvedbu zavodnjavanja toplom vodom. Smanjenje iscrpka nafte proizlazi iz povećanja nestabilnosti viskoznosti. U ovom je istraživanju razvijen numerički simulacijski model, koji uključuje prijenos topline i višefazni protok u poroznoj sredini integriran s neizotermnim protokom, pri čemu je navedeni numerički model potvrđen postojećim analitičkim rješenjem Buckleya i Leveretta. Sa smanjenem dubine prodiranja topline utvrđeno je stvaranje valovitog temperaturnog profila na fronti kondenzacije. Na prosječni porast temperature drastično utječe prostorna raspodjela početnog zasićenja vodom. U ležištu s nasumično raspoređenim početnim zasićenjem vodom domininantno je bilo prstoliko prodiranje vode (engl. fingering) koje je od početne faze zavodnjavanje uzrokovalo pomicanje fronte u nepravilnom obrascu. Heterogeno ležište s početnom raspodjelom vode pokazalo je raniju pojavu prstolikog prodiranja utisnute tople vode od homogenog ležišta. Heterogenost u prostornoj distribuciji početnog zasićenja vodom uzrokovala je nestabilnost viskoznosti, manje smanjenje viskoznosti, niži koeficijent istiskivanja fluida i veću zasićenost zaostalom naftom. Ovo istraživanje je ograničeno na prostornu distribuciju početnog zasićenja vodom do određenog stupnja heterogenosti. Heterogenost u prostornoj distribuciji početnog zasićenja vodom uvelike je utjecala na proizvodni učinak zavodnjavanja toplom vodom. Ovo istraživanje daje ideju za implementaciju i budući razvoj zavodnjavanja toplom vodom u poroznoj sredini s nasumično raspodijeljenim početnim zasićenjem vodom.

Ključne riječi:
numerička simulacije; koeficijent istiskivanja fluida; heterogenost; zavodnjavanje toplom vodom; neustaljena temperatura

Author's Contribution

Md Irshad Ansari (Research Scholar) - conceptualization, validation, formal analysis, and writing. **Suresh Kumar Govindarajan** (Full Professor) - conceptualization, formal analysis, and manuscript final correction.