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Numerical Investigation on the Impact of Hot Water Injection During Viscous Dissipation under Non Isothermal Conditions

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Abstract

The present studies explore the impact of injection velocity on the temperature field distribution and viscous dissipation using hot water flooding in thin homogeneous reservoir. Three different injection velocity 5.88×10^{-6} m/s, 8.82×10^{-6} m/s and 11.76×10^{-6} m/s were utilized to understand and check the feasibility of higher injection rate in reservoir or real field scenario. The impact of injection velocity on temperature field distribution and viscous dissipation were investigated. The temperature of the reservoir and the injection temperature were kept constant at 20 ºC and 90 ºC respectively for all injection scenario. It was observed when the injection velocity is 5.88×10^{-6} m/s and increased to 8.82×10^{-6} m/s, there is uniform heating of reservoir with almost no jump in temperature profile but when the injection velocity is increased to 11.76×10^{-6} m/s, the temperature field distribution had taken sudden jump or channeling like temperature field distribution near to the production well. It was also observed that the viscous dissipation was dominating near to the production well in all injection scenario which shows that the convection effect dominates over conduction near to the production well. But the viscous dissipation at the injection velocity 11.76×10^{-6} were seen to have sudden shock or fall at 250 m and started falling down for next 12 m and then started increasing again after the 262 m from the injection well. This phenomenon caused viscous friction between adjacent layers of the fluid because of different velocity which result in decrease of viscous dissipation. But the viscous dissipation again started to increase after around 262 m due to the inertial effect of production well which increased the convection effect. From the present investigation, it can be understood that the high viscous dissipation near to the production well causing significant temperature rise at high injection rates which is resulting in temperature jump near to the production well which implies that the higher injection rate needs proper planning to avoid the improper heating near the production well to maximize the production and profit.

Keywords: *Hot water flooding; Non isothermal reservoir; Numerical investigation; Viscous dissipation; Temperature channelling.*

1. Introduction

The primary energy consumption of the world is about 575 quadrillion Btu (British Thermal units) in 2015 and is supposed to grow by 15.3% from 2015 to 2035, and which further expected to reach 736 Btu by 2040 [1]. The total crude oil resources are approximately 9-11 trillion barrels (bbls) in the world, among which more than 2/3 are heavy oil and bitumen [2].

The dependency on the fossil fuel such as oil and natural gases cannot be replaced by the new energy sources completely [3]. Wind energy and solar energy is not sufficient enough to meet the demand effectively and efficiently to each sector. Fossil fuel are found in the various form such as natural gas, light crude oil and heavy crude oil. As the light crude oil is reaching to the peaks. It provides a sight that the demand of fuel can be fulfilled by heavy oil in future. Heavy oil consists of 70% of oil resources and has been explored and used worldwide [4-5]. The most of the conventional reservoirs are heavy [6]. But the majority of heavy oil resources are found in the thin reservoirs [7]. Hence, it is required to explore the thin heavy oil reservoir at high scale to meet the demand of the industries and organization.

The primary goal of an oil field development is usually to maximize ultimate oil recovery, minimize capital expenditure and operating expenditure. Hot water flooding is a better alternative to the steam flooding in thin reservoir to minimize the capital expenditure and maximize oil recovery. Steam generally losses its energy to the overburden and underburden because of the low thickness of the pay zone. The steam channeling and steam override occur in the middle late stages of steam flooding which causes poor development effect, decrease the daily oil production, increased water cut and low cumulative oil-steam ratio [8]. The commercial thermal techniques such as Steam-Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) are highly feasible in heavy oil reservoir with pay zone thickness more than 15 m but are not economical in thin heavy oil reservoir of pay zone thickness less than 6 m due to poor thermal efficiency [9]. Hot water flooding can provide larger displacement efficiency than the steam flooding [10]. Hot water flooding was suitable in Henan oilfield thin reservoir of thickness and the permeability variation coefficient less than 5 m and 0.3 respectively [11].

Hot water flooding is a method of thermal enhanced oil recovery in which hot water is injected to the reservoir using injection well. Hot water flooding is performed mainly to reduce viscosity of the oil and provide better displacement efficiency. The economic life of individual wells may be increased to a factor of two by hot water flooding [12]. The effect of injection pressure, injection rate and injection temperature on the relative permeability, saturation front movement, recovery factor and etc. has been studied of the hot water flooding application at non isothermal conditions [13-14]. But the effect of injection velocity over the temperature and viscous dissipation has been seen missing in the previous studies.

The present studies consist of the application of injection of hot water into the reservoir using vertical well. The feasibility of high injection velocity and the problem associated have been investigated in thin reservoir. The impact of injection velocity on the temperature field and viscous dissipation have been studied using the aerial view of the reservoir.

2. Conceptual modeling

The reservoir is considered to be saturated by oil fully at initial condition. The reservoir is assumed to be homogeneous and thin reservoir. The rock properties are considered to be constant in the cross-sectional plane and properties are assumed to be varied as a function of location in the aerial plane. Besides the above statement, the conceptual model associated with the thin reservoir to perform hot water flooding in three-dimensional reservoir is always complex. The studies of fluid flow in three-dimensional reservoir are highly complex and the resulting mathematical and numerical model becomes complex, too [15]. Hence, two-dimensional reservoir with aerial plane is taken for the study of fluid flow in homogeneous reservoir for the sake of simplicity. The conceptual model diagram associated with the boundary condition is shown in Figure 1.

3. Mathematical modeling

3.1. Assumptions

[1] Reservoir is considered to have thin pay zone thickness.
[2] Reservoir is considered to have local thermal equilibrium.
[3] Reservoir is assumed to have same absolute permeability over the entire plan of studies.
[4] Capillary pressure is assumed to be null.
[5] Two-dimensional reservoir with aerial view.
[6] Reservoir is considered to be fully saturated with oil initially.

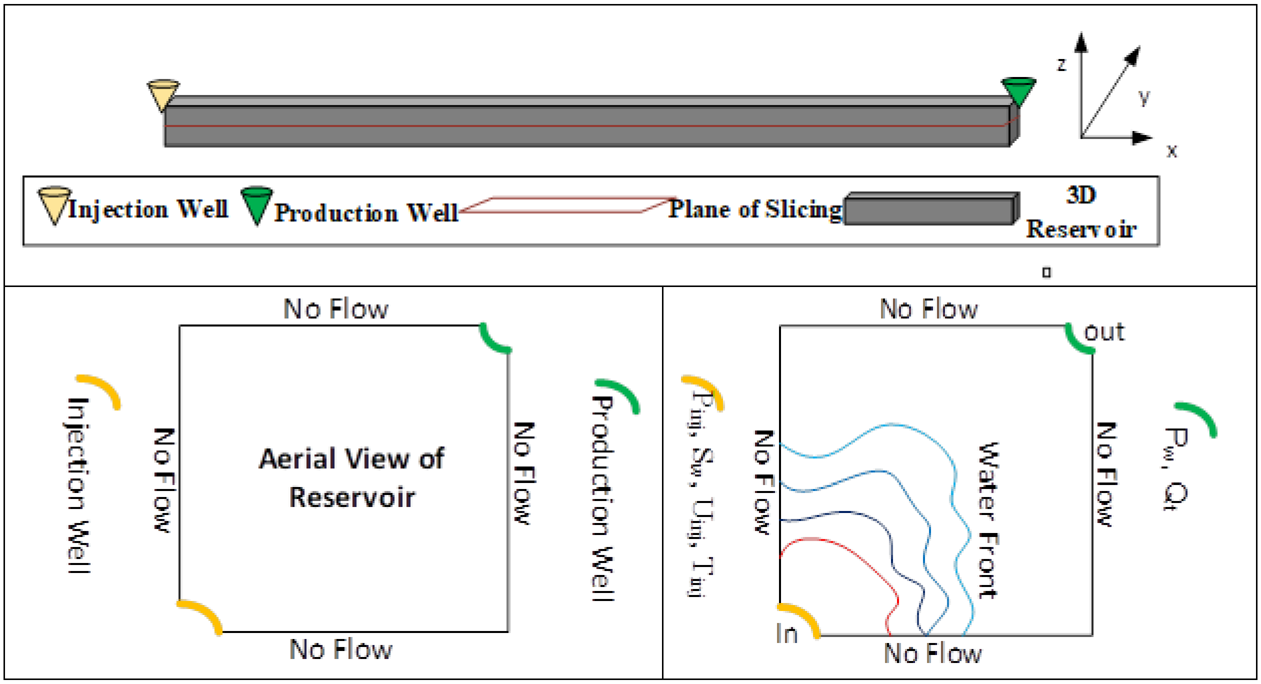

Figure 1. The figure illustrating the conceptual modeling and boundary condition of hot water flooding

3.2. Governing equations

Heat transfer and Multiphase flow are used in the present work. The following model equations are used to examine the temperature field distribution and viscosity of oil distribution in the porous media are represented in equations (1-6) [16].

$$A_l(\rho C_p)_d \frac{\partial T}{\partial t} + A_l \rho C_f u.\nabla T + \nabla(-A_l k_d \nabla T) = 0 \quad (1)$$

$$(\rho C_P)_d = \theta_f \rho_r C_r + (1-\theta_P)\rho C_f \quad (2)$$

and

$$k_d = \theta_P k_c + (1-\theta_P)K \quad (3)$$

The governing equation used in multiphase flow are based on the mass conservation and momentum conservation equation:

Oil phase equation;

$$\frac{\partial}{\partial t}(\emptyset_p \rho_o S_o) + \nabla.\{-\frac{K_{ro}\ k\ \rho_o\ (\nabla P_o - \rho_o g)}{\mu_o}\} = Q_o \quad (4)$$

Water phase equation;

$$\frac{\partial}{\partial t}(\emptyset_p \rho_w S_w) + \nabla.\{-\frac{K_{rw}\ k\ \rho_w\ (\nabla P_w - \rho_w g)}{\mu_w}\} = Q_w \quad (5)$$

The sum of oil phase and water phase saturation.

$$S_o + S_w = 1 \quad (6)$$

3.3. Mathematical coupled relationship

Porosity and permeability are taken as function of pressure to account the change of the rock properties with pressure. The mathematical relation to the porosity and permeability with pressure are represented in equations (7) and (8) [17-18].

$$\emptyset_p = \phi_i \times e^{C_t(P-P_i)} \quad (7)$$

$$K_f = K_i \times e^{C_t(P-P_i)} \quad (8)$$

Viscosity of water (μ_W) in the temperature range from 273.15K to 413.15K [19].

$$\mu_W = 2.79(1.38 - 0.021 \times T + 1.36 \times 10^{-4} \times T^2 - 4.65 \times 10^{-7} \times T^3 + 8.9 \times 10^{-10} \times T^4 - 9.08 \times 10^{-13} \times T^5 + 3.85 \times 10^{-16} \times T^6) \quad (9)$$

4. Numerical model

The porous media used in this study is two-dimensional with two vertical wells spaced 280 m apart. The properties of fluid and rock have been taken from the literature [20-22] are shown in Table 1. The average porosity and permeability are taken as 0.3 and 14 mD in XY plane initially at reservoir conditions.

In the present study, the injection velocity of 5.88×10^{-6} m/s is taken from the literature [20] which have been increased to 50% and 100% means 8.82×10^{-6} m/s and 11.76×10^{-6} m/s further to check the optimum condition or feasibility of higher injection rate in reservoir or real field scenario. The higher the injection velocity means lesser the production time. This helps the organisation to get maximum profit in minimum time.

The impact of injection velocity has been investigated to check their effects on the temperature field distribution and viscous dissipation in the homogenous reservoir. The aerial view of reservoir with dimension 200 m by 200 m is taken to carry out the numerical simulation which is represented in figure 1.b. Injection velocity of the fluid is varied to understand and analyse the effect of velocity on the temperature field distribution and viscous dissipation.

The studies on the variation of temperature field and viscous dissipation with space and time in homogenous porous media has been performed using Figure 2. The nonlinear system of equation is solved using the Parallel Direct Solver. The temporal step discretization was performed using the implicit backward differentiation formula.

Table 1. Rock and Fluid Properties

Parameter	Value	Reference
Porosity	26 %	[20]
Permeability	14 (mD)	[20]
Thermal conductivity of rock	2.25 (W/mK)	[20]
Injection reference velocity	5.88×10^{-6} (m/s)	[20]
Water density	1000 (kg/m^3)	[21]
Oil density	980 (kg/m^3)	[21]
Oil viscosity	0.1 (Pa.s)	[21]
Oil relative permeability	S_o^2	[21]
Water relative permeability	S_w^2	[21]
Initial reference pressure	2800 (kPa)	[22]
Initial reference temperature	293.15 (K)	[22]
Net pay thickness	4 (m)	[22]
Depth	334 (m)	[22]
Heat capacity of rock	2600 (kJ/m °C)	[22]
Thermal conductivity of oil	11.5 (kJ/m day °C)	[22]
Formation compressibility	10^{-6} (1/psi)	[17]

4.1. Initial and boundary conditions

Initial Conditions: Initially reservoir oil saturation, pressure and temperature are assumed to have 100%, 2800 kPa and 293.15 K.

$$T(x, y, 0) = T_{initial} \quad (10)$$

$$S_o(x, y, 0) = 1 \quad (11)$$

$$P(x, y, 0) = P_{initial} \quad (12)$$

Boundary conditions: The boundary condition has been applied in the present studies are Dirichlet and Neumann type boundary condition. The boundary conditions are taken carefully and represented in figure 1 (c).

Inlet and outlet boundary

$$T(In, t) = \text{Injection Temperature} \quad (13)$$

$$Q_t(out, t) = 0 \quad (14)$$

$$U_w(In, t) = U \quad (15)$$

$$S_w(In, t) = 1 \quad (16)$$

A commercial simulator COMSOL Multiphysics (6.0) is used to run the simulation. The computational domain is discretized into triangular grid. COMSOL Multiphysics 6.0 is used in the present study to analyse the multiphase fluid flow in a reservoir coupled with the heat transfer module under different injection conditions. Global definition shell is used to assign the primary variables. The rock and fluid properties variation are considered explicitly as dynamic local variables. Institute server Licences software is used for running the simulation and producing the simulated results. The flow diagram is represented for the execution of numerical model in COMSOL Multiphysics in Figure 2.

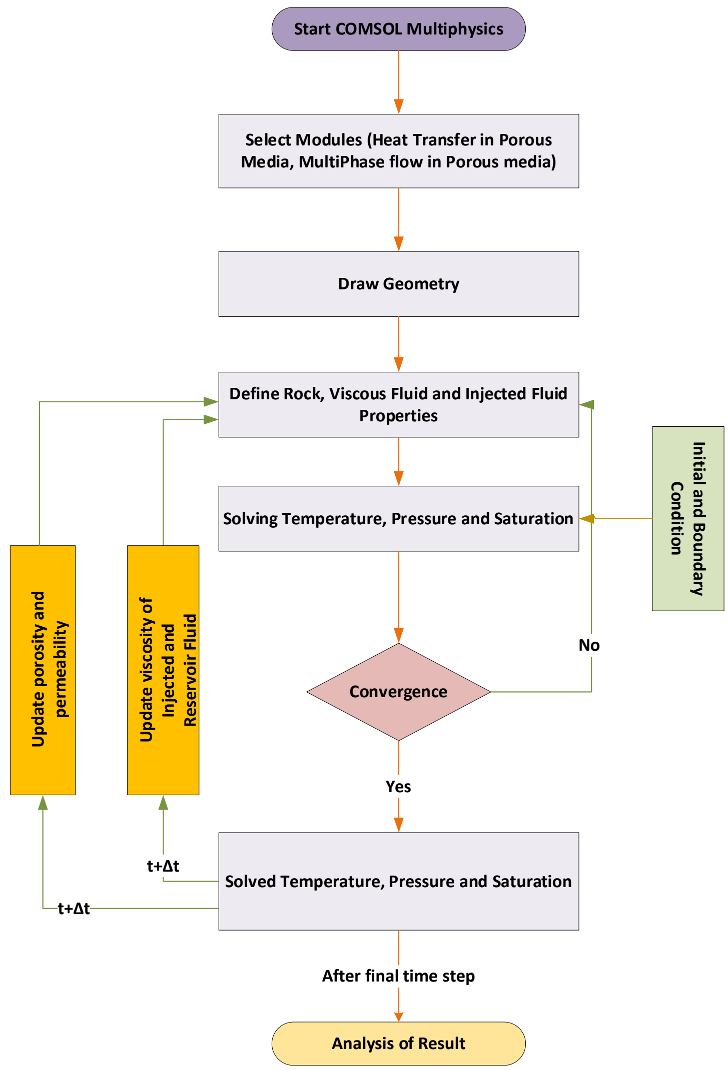

Figure 2. The flow diagram illustrating the implementation of numerical simulation in COMSOL Multiphysics

5. Results and discussion

5.1. Validation of model

In the present studies, we validated the multiphase flow through porous media under the coupled effect of heat transfer using the work of Nakornthap and Evans [23]. Nakornthap and Evans had used the field data of hypothetical oil reservoir. The result of the present model has small difference at lower temperature but the pattern of declination same. The difference in the result can be seen at lower temperature because the water from the well consist of salt and other impurities which makes the water hard and increase the surface tension at lower temperature. Surface tension is caused due to the increase in viscosity and unchanged inter-molecular bonding of water molecules. But it can be seen that at higher temperature that the difference in viscosity is very small because the water containing impurities becomes soft and behave likes no impurities are dissolved and surface tension is reduced. Hence, the result of present model is in close agreement with the field data of hypothetical oil reservoir of Nakornthap K and Evans RD.

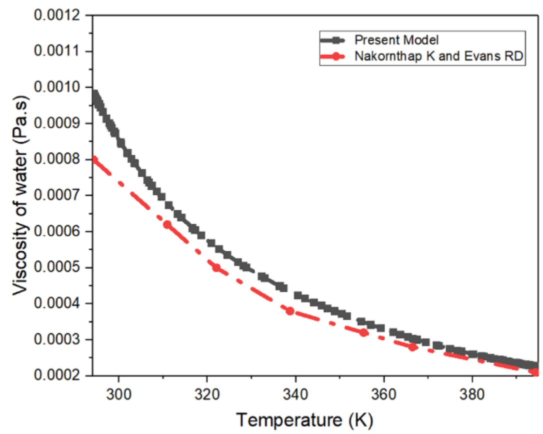

Figure 3. Comparison of simulated result and field data of Nakornthap and Evans

5.2. Effect of injection velocity on temperature field distribution

The temperature field distribution is represented in Figure 4. The depth of temperature field distribution has been impacted by the injection velocity. The temperature field distribution with time is found to be increasing when the injection velocity are 5.88×10^{-6} m/s, 8.82×10^{-6} m/s and 11.76×10^{-6} m/s. It has been noticed that the temperature of the reservoir increasing constantly when the velocity of injection 5.88×10^{-6} m/s which is represented in Figure 4 (a1-a4), whereas it can be understood from the Figure 4 (b1-b4) that as the injection velocity is increased to 8.82×10^{-6} m/s, the temperature field distribution verge to start conning like channel. Further when the injection velocity is increased to 11.76×10^{-6} m/s, the temperature field distribution has increased in quick time but have taken sudden jump or conning like temperature field distribution near to the production well which is represented in Figure 4 (c3) and (c4). It can be analyzed that the profile of heat distribution near to the injection well is uniform whereas it is making jump or forming conning like distribution near to the production well. It is due to the higher fluid flow rate near to the production well which causing increase in viscous dissipation.

On the other hand, convective heat transfer always takes place in the direction of velocity whereas conductive heat transfer can take place in the perpendicular direction of the velocity of the fluid. But as the fluid is jumping to the production well indicates the convection effect of the fluid is dominating over the conduction. It can be easily understood by the concept of Prandtl number. The Prandtl number nearer to the injection well is less because of higher decrease in the viscosity of the fluid but it is high closer to the production well because of lower decrease in viscosity.

$$Pr = \frac{viscous\ diffusion\ rate}{thermal\ diffusion\ rate} = \frac{\mu_f . C_p}{K'}$$

where 'Pr' represents the Prandtl number, 'μ_f' represents viscosity of fluid, 'C_p' represents the specific heat at constant pressure and 'K'' thermal conductivity of fluid.

High Prandtl number means either high viscous diffusion rate or low thermal diffusion rate which states that the momentum diffusivity dominates over thermal diffusivity. Hence, the increase in the value of Prandtl number implies that the heat transfer is more favorable to occur by fluid momentum rather than by thermal diffusion. So, it can be understood that the convection heat transfer effect dominates near to the production well resulting in temperature field jumping or channelling nearer to the production well.

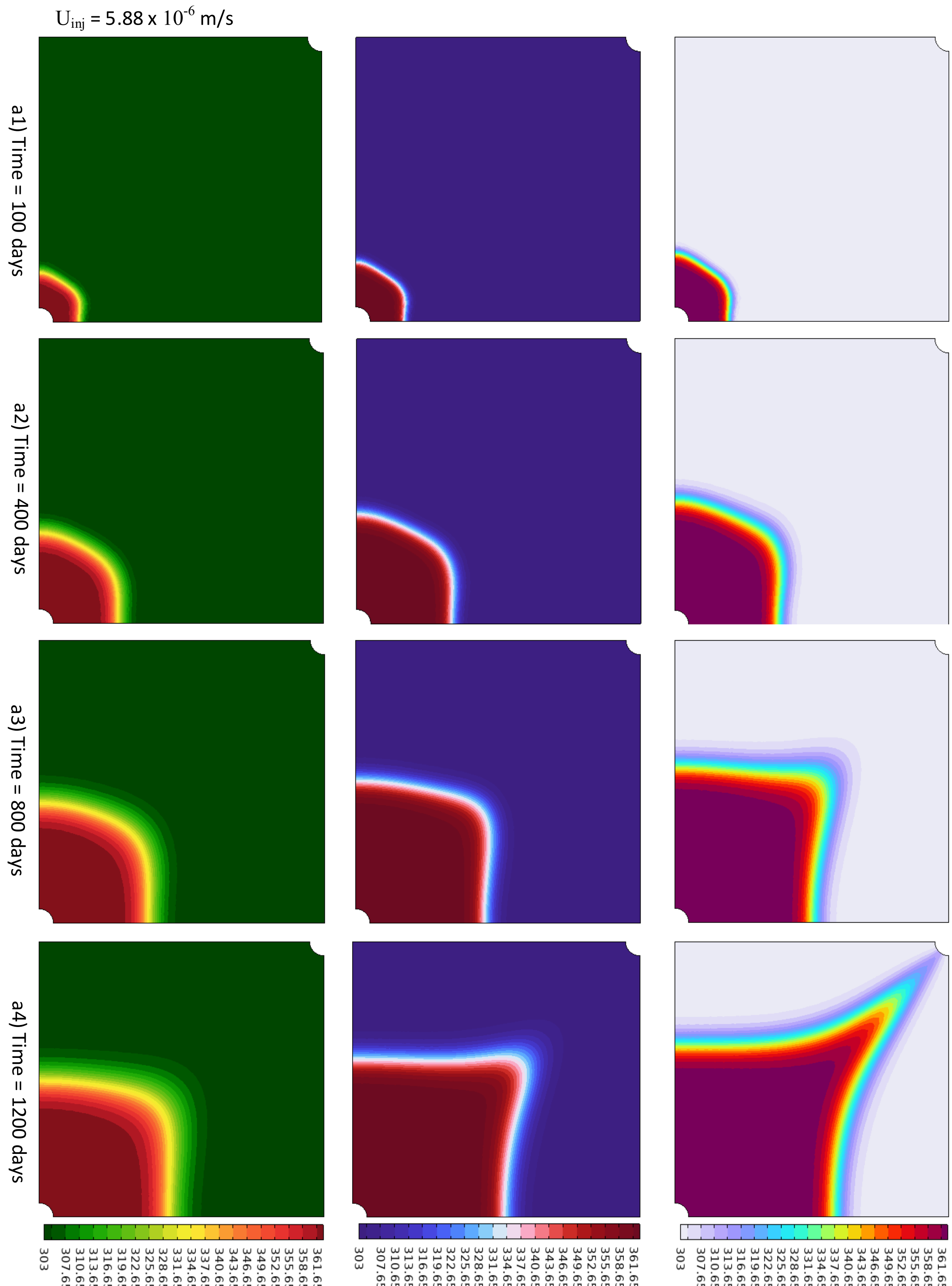

Figure 4. The figure illustrating spatiotemporal variation of the temperature (K) in porous media

5.3. Effect of injection velocity on the viscous dissipation

It can be seen that the viscous dissipation is almost negligible up to 150 m towards the production well from the injection well with time proceed to 100 days, 400 days, 800 days and 1200 days shown in Figure 5 (a), (b), (c) and (d) simultaneously. But it is found to be increasing in the direction of production well after 150 m of injection well. Viscous dissipation mostly dominating nearer to the production well in Figure 5 (a), (b), (c) and (d). The physical significance of higher viscous dissipation near to the production well is very low conduction heat transfer.

$$Br = \frac{Viscous\ dissipation}{Conduction} = \frac{\mu_f V^2}{K.\Delta T}$$

where '*Br*' represents Brinkman number, 'μ_f' represents viscosity of fluid, '*V*' characteristic speed of fluid and 'K' thermal conductivity and 'ΔT' differential temperature.

The lower conduction heat transfer causes to increase in the Brinkman number. Higher Brinkman number implies that the viscous dissipation is dominating nearer to the production well which causes the higher convection heat transfer effect than conduction. This causes viscous friction between adjacent layers of the fluid because of different velocity which result in decrease of viscous dissipation for short duration.

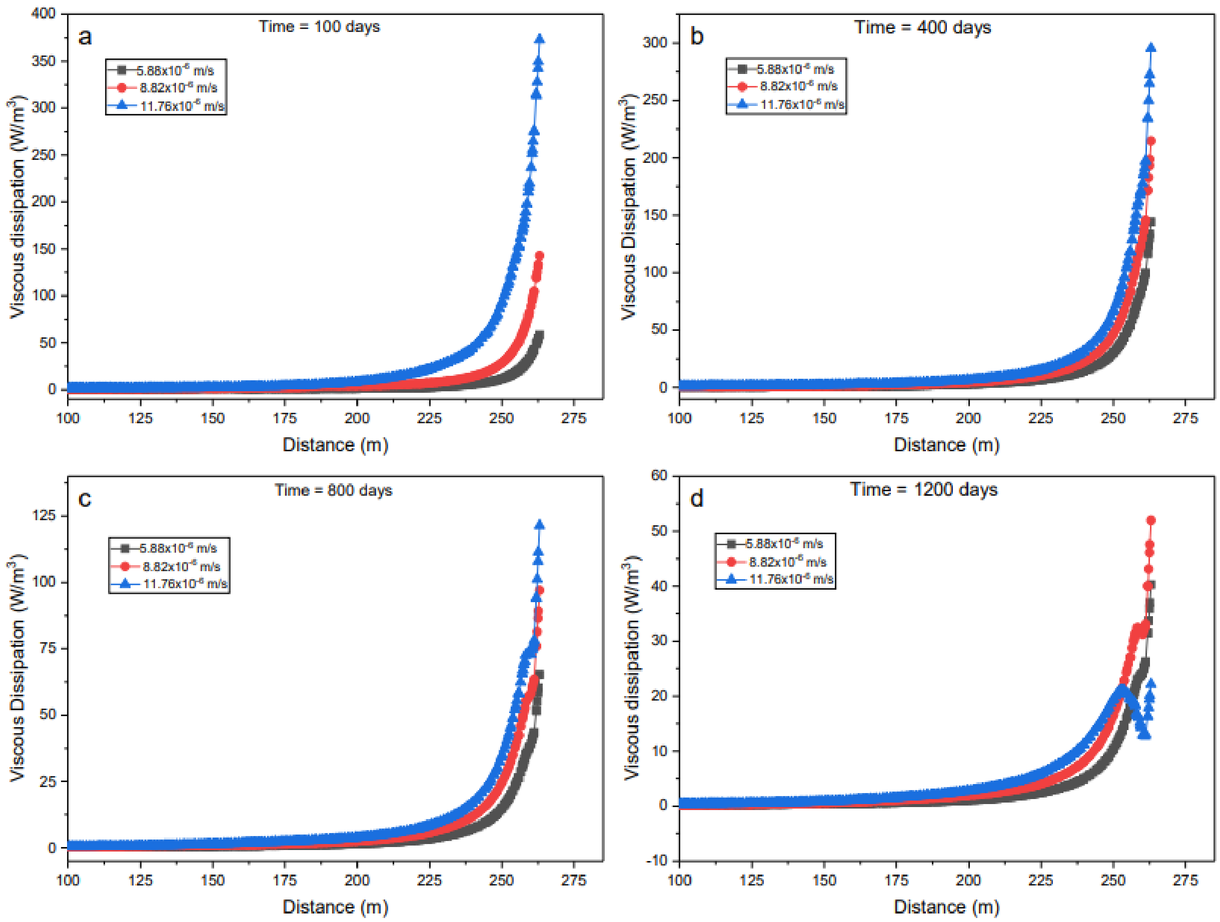

Figure 5. The figure illustrating the viscous dissipation (W/m^3) in porous media

At the same time, it can be seen in Figure 5 (d) that the viscous dissipation is rising continuously but got sudden shock at 250 m and started falling down for next 12 m and then started increasing again after the 262 m from the injection well. It is due to the sudden jump or channeling of temperature at around 250 m causes the adjacent layer of fluids with different velocity which is equivalent to the two fluids passing each other. This phenomenon causes

viscous friction between adjacent layers of the fluid because of different velocity which result in decrease of viscous dissipation. But the viscous dissipation again starts to increase after around 262 m due to the inertial effect of production well. The inertial effect causes to increase in the velocity of the fluid near the vicinity of the well which result in increase of convection effect. The higher convection heat transfer result in increase of the Brinkman number which causes to start viscous dissipation to increase near to the vicinity of the production well.
On the other hand, Hetsroni *et al.* discussed that the viscous dissipation led to drastic change of flow and temperature fields in microchannels under some specific conditions [24]. Reddy *et al.* found that the viscous dissipation plays significant role in temperature rise at high rates [25]. Based on the above statement, it can be understood that the dominance nature of viscous dissipation nearer to the production well may result in significant temperature rise which may be the cause of jumping and channelling of temperature nearer to the production well.

6. Conclusions

Multiphase flow coupled with heat transport in porous media was utilised in the present work to analyse the viscous dissipation and temperature field distribution in a homogeneous reservoir. The coupled model was validated with the field data used by Nakornthap and Evans [23]. The coupled model was used to understand the effect of high injection rate on the viscous dissipation and temperature field distribution in porous media. The following observation has been noticed.

The magnitude of the viscous dissipation has been noticed higher nearer to the production well in compare to the production well which causes to increase in the value of Prandtl number which implies that the heat transfer is more favorable to occur by fluid momentum rather than by thermal diffusion nearer to the production well.

The convection heat transfer and the conduction effect are found to be dominating in same fashion near to the injection well because of lower Prandtl number effect whereas convection heat transfer may be dominating near to the production well due to high fluid momentum which is causing temperature field jump or channeling near to the production well.

The sudden shock (fall and rise pattern) like behaviour in the viscous dissipation curve has been noticed when the injection velocity is kept 11.76×10^{-6} m/s, caused by the viscous friction between adjacent layers of the fluid because of different velocity which result in decrease of viscous dissipation for short duration.

The channeling of the temperature field will cause increase of water cut in field scenario and result in decrease of oil recovery as well as impact the separation cost of water at group gathering station after certain period of production.

The high viscous dissipation near to the production well causing significant temperature rise at high injection rates which is resulting in temperature jump near to the production well which implies that the higher injection rate needs proper planning to avoid the improper heating near the production well to reduce the production time and to maximize the production and profit.

Nomenclature

ϕ_i	*Initial porosity of homogeneous media*
K_i	*Initial permeability of homogeneous media*
$\emptyset_p$	*Transient porosity*
K_f	*Transient permeability*
K_d	*Effective thermal conductivity*
K_c	*Thermal conductivity of rock*
K_f	*Thermal conductivity of fluid*
K_{ro}	*Relative permeability of non-wetting phase*
K_{rw}	*Relative permeability of wetting phase*
K	*Effective thermal conductivity of fluid*
S_o	*Saturation of oil*
S_w	*Saturation of water*
ρ_o	*Density of oil*

ρ_r	*Density of rock*
ρ_w	*Density of water*
ρCf	*Effective heat capacity of fluid*
C_f	*Heat capacity of fluid*
C_r	*Heat capacity of rock*
A_l	*Area of flow*
T	*Temperature*
u_w	*Velocity of water*
Q_o	*Volumetric rate of oil*
Q_w	*Volumetric rate of water*
Q_t	*Heat flow rate*
k	*Absolute permeability of rock*
P_o	*Pressure of oil*
P_w	*Pressure of water*
g	*gravity*
μ_o	*Viscosity of oil*
μ_W	*Viscosity of water*
θ_P	*Volume fraction of rock in porous media*
$(\rho C_P)_d$	*Effective total heat capacity*
P_i	*Initial reference pressure*
C_t	*Formation compressibility*

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