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Heat conduction and liberation of porous rock formation associated with fines migration in oil reservoir during waterflooding

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ABSTRACT

Permeability damage due to fines migration will impair the well productivity, which ultimately ruin the well life and creates economic loss. In clay bearing oil and gas fields, fine particles that resting on the rock surface are under the regime of the four forces, namely, electrostatic, gravity, drag, and lift. Former two forces keep the fines attached to the rock surface, while the latter two forces contribute in the detachment of fine particle from rock surface/pore wall. Fines are also detached and migrated due to permeating fluid that are strained in the pore throat during suspension transport. Thereby, declining the permeability level and reducing the oil and gas flow, and water-cut. In reservoir engineering viewpoint, thermal conduction is the transfer of heat from the source or surrounding rock to reservoir rock or it is an ability of porous rock to pass and distribute the heat to pore walls. In contrast, heat rejection is the liberation of heat energy from the porous surface to the pore space or surroundings due to invasion of external fluid to pore wall that in turn detaches the fines from pore wall and lead to a suspension flow in the interspace of the porous rocks. This type of modelling should be applied against fines displacement in oil reservoirs during waterflooding. Hence, this paper presents classical heat and mass transfer theory based analytical modelling to investigate the effects of waterflooding on migration of fine particles in oil reservoirs. Additionally, experiments were conducted to validate these fines behaviors against the analytical cum thermodynamic models, and it showed good correlation.

1. Introduction

Obviously the only source of heat transmission and distributions in subsurface geological formations is the geothermal gradient. It is the rate of temperature increase with regards to increasing depth in the interior of the earth. Away from the boundaries of tectonic plates, it is about 25 °C per km of depth or 1°F per depth of 70 feet near the surface in the most places of the world (Fridleifsson et al., 2008). This geothermal gradient should not be confused with hot dry rock in geothermal reservoirs where the potential heat can be liberated to strata and surface. It can be penetrated from the inner core to oil and gas bearing reservoirs through the mechanisms of radiation, conduction, and convection. Globally, it is believed that the earth internal heat originates through radioactive decay. K-40, U-238, U-235, and Th-232 are the major heat producing isotopes in the earth (Sanders, 2003). At the earth center, there may be 7000 K of temperature and pressure could climb upto 360 GPa due to tremendous heat is generated by radioactive decay (Alfe et al., 2002). Temperature within the earth increases with depth and heat flows constantly from its sources within the earth, to be specific from the inner core to the surface (Pollack et al., 1993). By this, it means that the heat will flow through the petroleum bearing reservoirs (including, oil, gas, and water) and thus, have an evidence to support that heat passes through the porous rocks which is extremely needed for thermodynamic modelling of hydrocarbon reservoirs. This is applicable to actual oil and gas fields, but an industrial oven is sufficient and a potential heat source for laboratory based analysis like rock core analysis. Small particles such as clay, quartz or other similar materials are called fines, which exist naturally in petroleum and geothermal reservoirs (inside the walls of porous rocks). The fines migration includes its release from porous media with motion of permeating fluid and capturing at some pore sites. Fines may also be from external sources like during the drilling process or in-situ sources during hydrocarbon production. Kaolinite and illite are the common clays which are presented in porous media and like colloids, generally, fines have a size of the order 1 μm and a net surface charge (Raha et al., 2007).

There were many reports on fines detachment at this condition due to decline in surface charge and non-isothermal temperature and these

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two parameters are critical on the release mechanism of fines from rock surface (Schembre and Kovscek, 2005). Even lab based mathematical modelling on fines migration was conducted by You et al. (2016). The objective of this model is to predict the productivity of the well with alteration in ionic strength and with an analytical model, they have achieved an excellent adjustment in breakthrough concentration and permeability from coreflood experiments and acquired maximum retention function of multi-sized fine particles which enables to calculate its size distribution. From the author's findings, it was observed that during fines transport there were large periods of permeability stabilization, and higher temperature decreases the maximum retention concentration that ultimately causes permeability damage when compared with conventional reservoirs. Overall, the laboratory data are in accordance with a developed analytical model. Fines migration during soaring reservoir temperature had a significant impact on well productivity, which, consequently, declines the fluid flow.

Rosenbrand et al. (2015), studied the different effects of salinity, fluid velocity and temperature on the permeability decrease by fine particle migration in Berea Sandstone. The authors have conducted serious of coreflood test containing kaolinite particles and heated the core at 20 °C and 80 °C and found that those varying parameters has a significant effect on fines detachment and mobilization. Author's state that fines transport would increase the solid, specific area with fluid contact and decrease the permeability. Fines migration during waterflooding was given much importance in recent years and with that many analytical models were developed (Bedrikovetsky and Caruso, 2014; Kalantariasl et al., 2014). Since for many decades the oil and gas industry uses water to mobilize the oil in the reservoir during its pressure reduction. At the same time, the water salinity and chemistry play a vital role in detachment and the mobilization of reservoir fines (Chequer et al., 2018). Additionally, fines detachment and suspension in the carrier fluid reduces the mobility ratio of the carrier fluid (water) and displacing fluid that is the oil (Yuan and Shapiro, 2011). Also, Zhao et al. (2017) reported that fines will be plugged in the porous media during high temperature regardless of water salinity. The knowledge of its literature studies is crucial for formation damage quantification and mitigation. In contrast, there were also reports on improved oil recovery by fines assisted waterflooding (Hussain et al., 2013). Zeinijahromi et al., (2011), analyzed the induced formation damage effects on water cut during waterflooding. It was revealed from various literatures that there were fines migration during coreflood test with changes in water chemistry and temperature. In this case, the authors have given importance to mobility control during waterflooding. In earlier research, the particle detachment model was combined with a Dietz model for a layer cake reservoir under waterflooding with constant injection and production rate to examine the fines migration effect and induced permeability reduction in the sweep efficiency of the reservoir. In authors' work, they developed and extended an analytical model to waterflooding with pressure drop between injection and production wells. In author's adopted Dietz model assumes a displacement in each layer like a piston. In other words, the displacement front is trailed by connate water saturation and lead by residual oil saturation. It can be seen from this figure that permeability arises with respect to depth. The constant pressure condition across the layer cake relates to infinite vertical permeability or thin reservoir and it was assumed that in reservoir pore, connate water with oil is beyond the water oil front and behind the water front with residual flows. Zeinijahromi et al. (2016), investigated the fines migration effects on relative permeability of oil-water during two-phase flow in porous media. Since the effect of fines transport on oil recovery and relative permeability during two phase flow is still incoherent. The formation water salinity can vary from the injected water and subsequently, affecting the relative permeability. The authors conducted coreflood with piecewise constant declining of water salinity without oil for identification of fines mobilization. For recovery evaluation exclusive of ion exchange process, the oil is displaced with formation water in sister cores and oil is displaced again by water with different salinity after resaturation. The relative permeability was stated through modified JBN method for coreflood test with the migration of fines and it was observed at high saturations that water relative permeability curve declines due to fines migration and straining that causing water permeability deterioration.

Revil (2007), studied and reviewed the thermodynamics of water and ions transport in porous media. The author analyzed the porous deformation and elasticity with respect to heat flux and conductivity. This author develops the concept of non-equilibrium thermodynamics to thermoporoelastic deformation during the transport of ions and water in porous media and from his modelling and analysis it was revealed that the charged porous media depend on internal energy and temperature, and heat conduction affects the poroelastic deformation of porous medium. The charge flow amount per unit surface area and time is represented by as follows:

$$J^{m} = \sum_{i=1}^{Q} \rho_i \lambda_i u_i \tag{1}$$

Where, J^m indicates the conduction current, ρ_i is the partial component of bulk density and λ_i is velocity, and u_i is the charge per unit mass of ith component. The conduction current density is equal to the total current density and the colloidal suspension in porous media is described by the condition of global electroneutrality that is the grains net charge is counterbalanced by the pore water net charge. Water and ion transport in porous media results in entropy production that in turn depends on the porous medium internal energy. Therefore, we can observe that fluid transport in porous media is greatly influenced by heat flux in pore walls. So the main objective of this paper is to apply a thermodynamic framework to fines detachment and transport phenomena during a water invasion at extreme temperatures. As this helps in the determination of possible formation damage occurrence during the oil production process.

2. Thermal conductivity modelling for natural reservoir fines

This section analyzes the heat/thermal conduction and subsequent, fines migration in porous rocks. Fig. 1 shows the combined thermodynamic system model, including heat conduction, transfer and rejection/liberation for oil reservoirs.

We are aware that excess amount of heat was absorbed by pore walls (heat sink). During waterflooding the heat content in the pore wall will be liberated or rejected to the surrounding porous interspace. The thermal conductivity of pore walls (act as a heat pump) plays a major role in heat rejection which consequently delivers heat to in-situ fine particles and oil for migration and mobilization. In thermal conductivity aspect, the net work done to migrate the fine particle from rock surface is given by the equation (2). This was framed in accordance with Fig. 1.

$$\eta_{\phi K} = \frac{W_K}{q_w} \tag{2}$$

Where,

$\eta_{\phi K}$ = *Thermal efficiency of porous media with respect to thermal conductivity*

W_K = Net work transfer to migrate the reservoir fines in porous media, and

Q_3 = Heat rejection to porous media

3. Effects of waterflooding on fines migration in porous media

This section analytically explores the fines migration due to water flooding and subsequent, oil recovery in and through porous media. The modelling and investigation is based on the theory of thermal

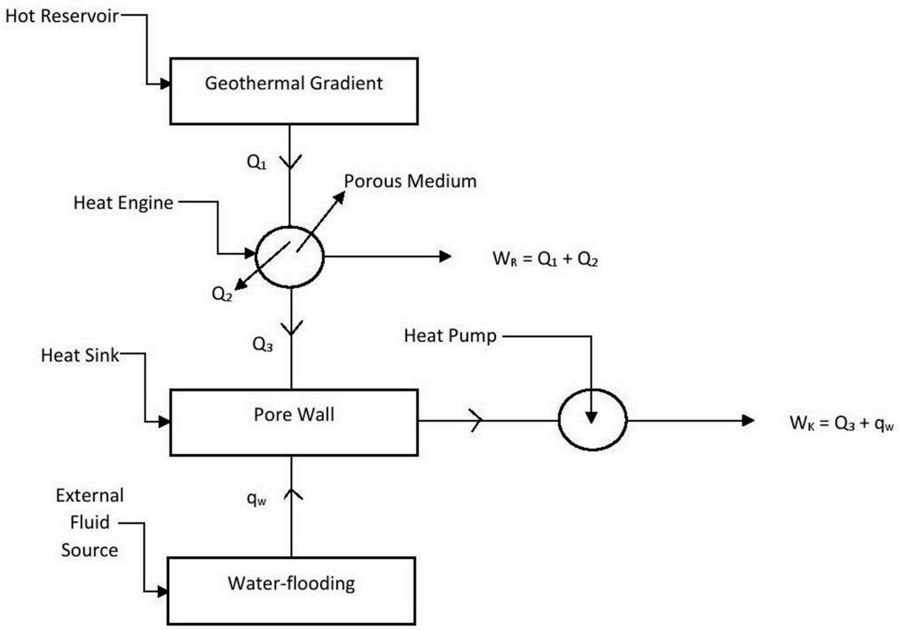

Fig. 1. Combined system heat transfer model for oil reservoirs.

conductivity.

3.1. Thermal conductivity of pore wall

As it was mentioned in the previous chapters that pore wall thermal conductivity play a vital role in the liberation of fines and this general mechanism was explained in the previous section. This section aims to make an analytical investigation for this scenario and for that this paper has derive an equation (analytical model) of uniform and variable thermal conductivity of pore wall.

3.2. Uniform thermal conductivity

Consider a pore wall of homogeneous nature which the heat is flowing only in x-direction.

Let,

A = Cross sectional area of the pore wall
L = Texture of the pore wall
K = Thermal conductivity of the pore wall, and
t_1, t_2 = Temperatures maintained at two ends of the pore wall

The general heat conduction equation in Cartesian coordinates is given by

$$\frac{\partial^2 t}{dx^2} + \frac{\partial^2 t}{dy^2} + \frac{\partial^2 t}{dz^2} + \frac{q_g}{K} = \frac{1}{\alpha}.\ \frac{\partial t}{\partial \tau} \tag{3}$$

If the heat conduction takes place under the conditions, steady state $\left(\frac{\partial t}{\partial \tau} = 0\right)$, one dimensional.$\frac{\partial^2 t}{dy^2} = \frac{\partial^2 t}{dz^2} = 0$ and with no internal heat generation $\left(\frac{q_g}{K} = 0\right)$ then the above equation reduced to

$$\frac{\partial^2 t}{dx^2} = 0 \ or \quad \frac{d^2 t}{dx^2} = 0$$

By integrating the above differential twice, we get

$$\frac{dt}{dx} = C_1 \ and \quad t = \ C_1 x + C_2 \tag{4}$$

Where C_1 and C_2 are the arbitrary constants. The values of these constants may be calculated from the known boundary conditions as follows:

At $x = 0$ $t = t_1$
At $x = L$ $t = t_2$
Substituting the values in the equation (3), we have

$$t_1 = 0 + C_2 \ and \quad t_2 = C_1 L + C_2 \tag{5}$$

After simplification, we have,

$$C_2 = t_1 \ \ and \ \ C_1 = \frac{t_2 - t_1}{L} \tag{6}$$

Thus, the equation (4) reduces to:

$$t = \left(\frac{t_2 - t_1}{L}\right) x + t_1 \tag{7}$$

Also, we can find the heat through the plane wall by using Fourier's equation as follows: Hence, the equation (7) indicates the temperature distribution across a pore wall is uniform or isothermal.

$$Q = -KA\frac{dt}{dx} \tag{8}$$

Where, $\frac{dt}{dx} = Temperature\ gradient$

But,

$$\frac{dt}{dx} = \frac{d}{dx}\left[\left(\frac{t_2 - t_1}{L}\right)x + t_1\right] = \frac{t_2 - t_1}{L} \tag{9}$$

$$Q = \frac{(t_1 - t_2)}{(L/KA)}$$

Therefore, the above equation directs the condition for uniform thermal conductivity of pore walls.

3.3. Variable thermal conductivity

Temperature variation in terms of rock surface temperature (t_1,t_2).

Let the thermal conductivity across the pore wall vary with temperature according to the relation

$$K = K_i\,(1 + \beta t) \tag{10}$$

In most cases, the thermal conductivity is found to vary linearly with temperature.Where,

$K_0 = Thermal\ conducitivity\ of\ pore\ wall\ at\ initial\ temperature$

By using Fourier's equation,

$$Q = -KA\frac{dt}{dx} \quad \textit{this can be writtern as}:$$

$$Q = -K_i\,(1 + \beta t)\frac{dt}{dx}.\,A$$

$$\frac{Q}{A}.\,dx = -K_i\,(1 + \beta t)dt$$

$$\frac{Q}{A}\int_0^L dx = -K_i\int_{t_1}^{t_2}(1 + \beta t)dt$$

$$\frac{Q.\,L}{A} = -K_i\left[t + \frac{\beta}{2}t^2\right]_{t_1}^{t_2}$$

$$\frac{Q.\,L}{A} = -K_i\left[(t_2 - t_1) + \frac{\beta}{2}(t_2^2 - t_1^2)\right]$$

$$= K_i\left[(t_2 - t_1) + \frac{\beta}{2}(t_1 - t_2)(t_1 + t_2)\right]$$

$$= K_i\left[1 + \frac{\beta}{2}(t_1 + t_2)\right](t_1 - t_2)$$

$$= K_i[1 + \beta t_m](t_1 - t_2)$$

Where,

$$t_m = \frac{t_1 + t_2}{2} \tag{11}$$

$$Q = K_i(1 + \beta t_m).\,\frac{A(t_1 - t_2)}{L}$$

From equation (10) t is replaced by t_m, then

$$K_m = K_i(1 + \beta t_m) \tag{12}$$

Therefore,

$$Q = K_mA\left[\frac{t_1 - t_2}{L}\right] \tag{13}$$

Where K_m is known as mean thermal conductivity of the pore wall.

Further, if t is the thermal conductivity of the pore surface where a fine particle resting is denoted as x, then the below equation becomes

$$\frac{Q.\,L}{A} = -K_i\left[(t_2 - t_1) + \frac{\beta}{2}(t_2^2 - t_1^2)\right] \tag{14}$$

$$\frac{Qx}{A} = -K_i\left[(t - t_1) + \frac{\beta}{2}(t^2 - t_1^2)\right]$$

Equating the values of Q and rearranging, we get

$$\left[(t_2 - t_1) + \frac{\beta}{2}(t_2^2 - t_1^2)\right]\frac{X}{L} = \left[(t - t_1) + \frac{\beta}{2}(t^2 - t_1^2)\right]$$

Solving the above equation for t, we get

$$t = \frac{1}{\beta}\left[(1 + \beta t_1)^2 - \{(1 + \beta t_1)^2 - (1 + \beta t_2)^2\}\frac{x}{L}\right]^{1/2} - \frac{1}{\beta} \tag{15}$$

Theoretically speaking, equations (14) and (15) indicate that even a fine particle at a particle point in pore wall may conduct heat. These equations can be used to calculate the thermal conductivity of fine particles, which are clay materials like kaolinite, illite, montmorillonite, etc. Without checking these equations against experimentation, we assume and agree that these equations are valid. Since all clays can conduct heat depends upon its physical and chemical properties, and also with regards to surrounding systems (William et al., 2014).

Variation of temperature in terms of heat flux (Q):

Fourier's equation for heat conduction is given by:

$$Q = -KA.\,\frac{dt}{dx} = -K_i(1 + \beta t)A.\,\frac{dt}{dx} \tag{16}$$

$$Q.\,dx = -K_i(1 + \beta t)A.\,dt \tag{17}$$

Integrating both sides, we get

$$Q.\,x = -K_iA\left(t + \frac{\beta}{2}t^2\right) + C \tag{18}$$

Where, C = Constant of integration.

To evaluate C, applying the condition: At $x = 0,\ t = t_1$, we get

$$C = K_iA\left(t_1 + \frac{\beta}{2}t_1^2\right) \tag{19}$$

Substituting the values of the constant C in eq (17), we get

$$Q.\,x = -K_iA\left(t + \frac{\beta}{2}t^2\right) + K_iA\left(t_1 + \frac{\beta}{2}t_1^2\right) \tag{20}$$

Dividing the both sides by K_iA and rearranging, we obtain,

$$\frac{\beta}{2}t^2 + t + \left[\frac{Q.\,x}{K_iA} - \left(t_1 + \frac{\beta}{2}t_1^2\right)\right] = 0 \tag{21}$$

By solving the above quadratic equation, we have

$$t = \frac{-1 + \sqrt{1 - 4 \times \frac{\beta}{2}\left[\frac{Q.x}{K_iA} - \left(t_1 + \frac{\beta}{2}t_1^2\right)\right]}}{2 \times \left(\frac{\beta}{2}\right)}$$

$$t = -\frac{1}{\beta} + \left[\frac{1}{\beta^2} - \frac{2}{\beta}\left(\frac{Q.\,x}{K_iA} - t_1 - \frac{\beta}{2}t_1^2\right)\right]^{1/2}$$

$$= -\frac{1}{\beta} + \left[\frac{1}{\beta^2} - \frac{2}{\beta}t_1 + t_1^2 - \frac{2Qx}{\beta K_iA}\right]^{1/2}$$

$$= -\frac{1}{\beta} + \left[\left(t_1 + \frac{1}{\beta}\right)^2 - \frac{2Qx}{\beta K_iA}\right]^{1/2}$$

Therefore,

$$t = -\frac{1}{\beta} + \left[\left(t_1 + \frac{1}{\beta}\right)^2 - \frac{2Qx}{\beta K_iA}\right]^{1/2} \tag{22}$$

In reality, the variation of temperature is high and the average value of K for the given temperature range is generally used as given in equation (12). For the case, temperature variation of K is non-linear, then

$K = K_if(t)$, and

$$\frac{Q}{A}\int_0^L dx = -\int_{t_1}^{t_2}[K_if(t)dt]$$

Or,

$$Q = \frac{A}{L}\left[-\int_{t_1}^{t_2}[K_if(t)dt]\right]$$

But,

$$Q = K_mA\left(\frac{t_1 - t_2}{L}\right) \tag{23}$$

By equating the above two equations, we get

$$K_m = \frac{1}{(t_1 - t_2)}\left[\int_{t_1}^{t_2}[K_if(t)dt]\right] \tag{24}$$

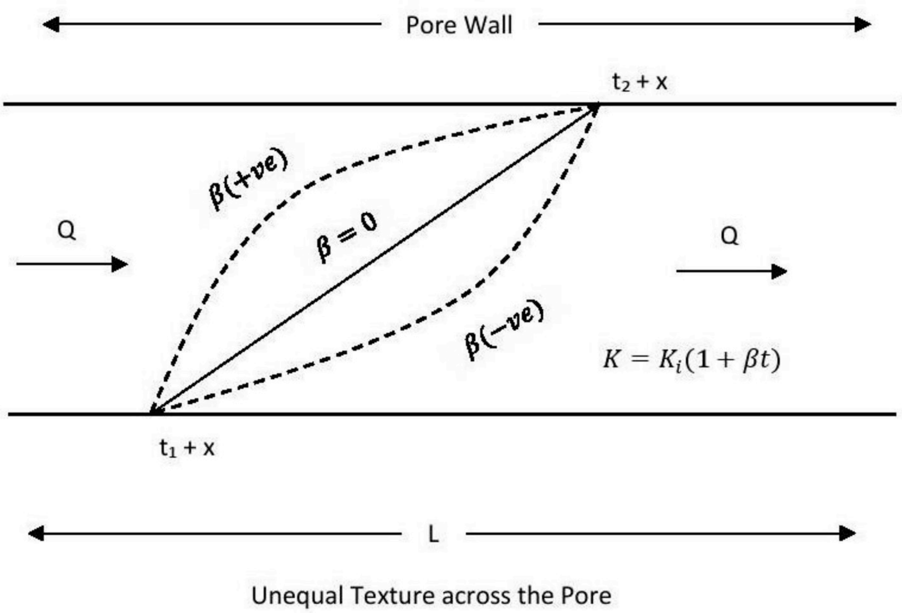

Fig. 2. Non-linear variation of pore wall thermal conductivity.

$$= \frac{1}{(t_1 - t_2)} \int_{t_2}^{t_1} [K_i f(t) dt]$$

The effect of + β and –β is the function for non-linear temperature variation in pore wall, as it is shown in the Fig. 2.

3.4. Heat rejection from pore wall

This section explores the pore wall heat rejection (due to water-flooding) to porous interspace where the fine particles are held. The analytical based heat and mass transfer modelling aims to find the heat exchange between the pore walls and its impact on fines migration. Fig. 3 shows the porous medium which is converted into a 2-dimensional plane (from capillary bundles) for modelling purposes.

Consider a porous medium of pore chamber A_1 and pore throat A_2, emissivities ε_1 and ε_2 and their surfaces maintained at temperature T_1 and T_2 respectively.

Now, by reciprocity theorem, we have

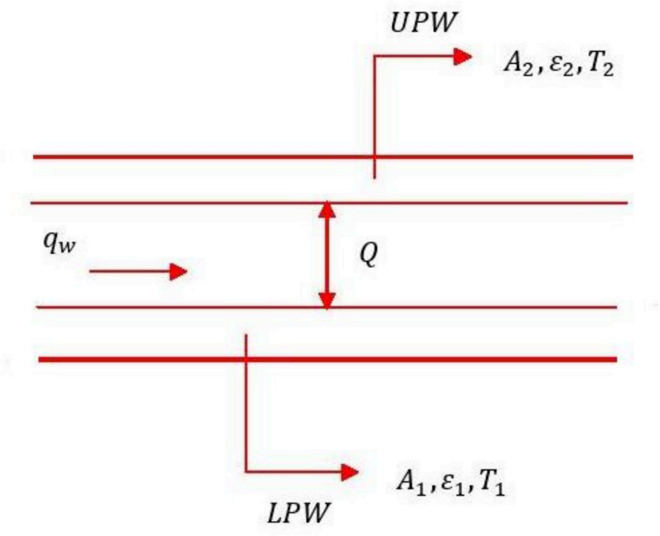

Fig. 3. Heat exchange (radiant) between upper and lower pore walls.

$$A_1 F_{1-2} = A_2 F_{2-1}$$

But,

$$F_{1-2} = 1$$

Therefore,

$$F_{1-2} = \frac{A_1}{A_2} \tag{25}$$

Assume the heat emitted or rejected within the porous media:
Lower pore wall (LPW) emits heat = E_1
Upper pore wall (UPW) absorbs heat = $\alpha_2 E_1 = \varepsilon_2 E_1$
Therefore, $\alpha_2 = \varepsilon_2$
UPW reflects heat = $E_1 - \varepsilon_2 E_1 = E(1 - \varepsilon_2)$
LPW absorbs energy = $E_1(1 - \varepsilon_2) F_{2-1} \alpha = E_1(1 - \varepsilon_2)\frac{A_1}{A_1}\varepsilon_1$
LPW reflects energy = $E_1(1 - \varepsilon_2) - E_1(1 - \varepsilon_2)\varepsilon_1 \frac{A_1}{A_2}$

$$= E_1(1 - \varepsilon_2)\left[1 - \varepsilon_1 \frac{A_1}{A_2}\right]$$

It can be shown that the heat absorbed the lower pore wall (LPW) on the second reflection will be

$$= E_1(1 - \varepsilon_2)^2 \varepsilon_1 \frac{A_1}{A_2}\left[1 - \frac{A_1}{A_2}\varepsilon_1\right]$$

This absorption and reflection continue indefinitely, so we can find the total energy loss by the lower pore wall considering infinite time's absorptions and reflections.

Therefore, heat loss by the LPW to pore chamber is given by

$$Q_{dl} = E_1 - E_1(1 - \varepsilon_2)\frac{A_1}{A_2} - E_1(1 - \varepsilon_2)^2 \varepsilon_1 \frac{A_1}{A_2}\left[1 - \frac{A_1}{A_2}\varepsilon_1\right] + \ldots\ldots\ldots$$

$$= E_1\left[1 - \frac{A_1}{A_2}\varepsilon_1(1 - \varepsilon_2) - (1 - \varepsilon_2)^2 \varepsilon_1 \frac{A_1}{A_2}\left\{1 - \frac{A_1}{A_2}\varepsilon_1\right\} + \ldots\ldots\ldots\right]$$

$$= E_1\left[1 - \frac{A_1}{A_2}\varepsilon_1(1 - \varepsilon_2)\left\{1 + (1 - \varepsilon_2)\left(1 - \frac{A_1}{A_2}\varepsilon_1\right)\right\} + \ldots\ldots\ldots\right]$$

$$= E_1\left[1 - \frac{A_1}{A_2}\varepsilon_1(1 - \varepsilon_2)\left\{1 - (1 - \varepsilon_2)\left(1 - \frac{A_1}{A_2}\varepsilon_1\right)\right\}^{-1} + \ldots\ldots\ldots\right]$$

$$= E_1\left[1 - \frac{\frac{A_1}{A_2}\varepsilon_1(1-\varepsilon_2)}{\left\{1-(1-\varepsilon_2)\left(1-\frac{A_1}{A_2}\varepsilon_1\right)\right\}}\right]$$

$$\mathrm{Q}_{dl} = \frac{E_1\varepsilon_2}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2} \tag{26}$$

Similarly, total heat lost by the upper pore wall (UPW) to pore throat is:

$$\mathrm{Q}_{al} = \frac{\varepsilon_1 E_2.\ \frac{A_1}{A_2}}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2} \tag{27}$$

The total radiative heat transfer between the LPW and UPW is:

$$\mathrm{Q}_j = \mathrm{Q}_{dl} - \mathrm{Q}_{al}$$

$$= A_1\left[\frac{E_1\varepsilon_2}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2}\right] - A_2\left[\frac{\varepsilon_1 E_2.\ \frac{A_1}{A_2}}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2}\right]$$

$$\mathrm{Q}_j = \frac{A_1E_1\varepsilon_2 - A_2E_2\varepsilon_1}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2}$$

Also, by using Stefan-Boltzmann law, we can find Q_j, its is demonstrated below:

$$E_1 = \varepsilon_1\sigma T_1^4 \ \ and\ E_2 = \varepsilon_2\sigma T_2^4 \tag{29}$$

Therefore,

$$\mathrm{Q}_j = \frac{A_1\varepsilon_1\varepsilon_2\sigma T_1^4 - A_2\varepsilon_1\varepsilon_2\sigma T_2^4}{\frac{A_1}{A_2}\varepsilon_1 + \varepsilon_2 - \frac{A_1}{A_2}\varepsilon_1\varepsilon_2} \tag{30}$$

$$= \frac{\varepsilon_1\varepsilon_2A_1A_2\sigma(T_1^4 - T_2^4)}{\left[\frac{A_1}{A_2}\varepsilon_1\varepsilon_2\left(\frac{1}{\varepsilon_2}-1\right)\right] + \varepsilon_2}$$

$$\mathrm{Q}_j = \frac{A_1A_2\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}-1\right)} \tag{31}$$

$$\mathrm{Q}_j = f_{1-2}A_1A_2\sigma(T_1^4 - T_2^4) \tag{32}$$

Where,

$$f_{dl-al} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}-1\right)}$$

The above equation is the interchange factor or equivalent emissivity for radiant heat exchange between upper and lower pore walls. Fig. 4 shows the forces exerted on the attached fines during flow in porous rocks which are under the torque balance governance and heat rejection to surroundings which are indicated with red arrows.

4. Mechanism of permeability decline

In this section, we will see the mechanism of permeability decline due to fines migration.

We know very well that,

$\mathrm{W_K}$ = Work done by porous medium to migrate the fine particles with regard to rock surface thermal conductivity.
$\mathrm{Q_{abs}}$ = Amount of heat absorbed in pore wall
$\mathrm{q_w}$ = Amount of fluid flow (water-flooding) in porous media

We can derive the fines migration due to heat rejection from Fig. 1 and equation (2). By taking this equation, we have,

$$\eta_{\phi K} = \frac{W_K}{q_w} \tag{33}$$

We know, $\mathrm{W_K} = \mathrm{Q_{abs}} + \mathrm{q_w}$Where,

Substituting the value of W in equation (33), then

$$\eta_{\phi K} = \frac{Q_{abs} + q_w}{q_w} \tag{34}$$

Therefore, the above equation can be used to calculate the displacement of a fine particle in porous medium due to heat rejection from pore wall. For continuous increase of heat rejection to permeating fluid and particles in porous media, then the equation can be written as follows:

$$W_r = \frac{\gamma}{\gamma+1}.\ \frac{\Delta p}{q_w}\left[\left(\frac{T_{Kh}}{T_{Ki}}\right)^{\frac{\gamma+1}{\gamma}} + 1\right] \tag{35}$$

Where,

$\mathrm{W_r}$ = Total work done (heat rejection) to displace all fines in pore surface and for migration in porous space.
γ = Continuous heat rejection to porous media from rock surface (without any interval)
1 = Constant term for additional time, which indicates heat transfer rate for every second.
Δp = Change in pressure inside porous media.
T_{Kh} = Final and highest thermal conductivity of rock surface.
T_{Ki} = Initial thermal conductivity of rock surface.

The equation (35) is applicable for combined heat and mass transfer system model. Fig. 5 presents the fine particles straining and permeability decrease in porous medium due to heat rejection from pore wall (heat sink).

It can be observed from the figure that the pore wall act as a heat sink ($\mathrm{Q_3}$). When water influx enters the pore space, while splashing and flushing ($\mathrm{q_w}$) with pore walls/rock surface the heat will be rejected or liberated to porous interspace. Consequently, the fine particle attached on the rock surface will be migrated and suspended due to higher thermal conductivity of rock, water, heat transfer (from pore wall), and weakened electrostatic force. The suspended particles will be transported in the porous media along with heat energy. At some point in porous media, the fine particle will be strained (σ_s) in pore throat and thereby reducing the permeability. Fig. 6 shows the water and oil relative permeability profiles with respect to water saturation.

It can be seen from the figure that there is a gradual increase in water relative permeability for 4% Sodium Chloride water and even it is observed in fresh water. But, in particular, point of water saturation (in 0.5–0.6 range) the relative permeability of water smoothly drops (which is indicated in green arrows), this is due to the huge amount of heat liberated from pore walls and subsequently, enhancing the fluid and porous medium temperatures. In this case, it should be noted that the thermal conductivity of fresh water is much higher than the water with 4% Nacl solution. Naturally, saline waters are less in thermal conductivity and on the other side, fresh water exposes a good characteristic of thermal conductivity. For the oil relative permeability case, both curves are in decline at various levels of water saturation. Here it can be observed that in addition to fresh water, saline water is also showing deterioration behavior. This is because when a reservoir is at high temperature, the saline content in water will be reduced or altered and as result the saline water exhibits a good thermal conductivity (Mideen, 2015). Overall, both cases contribute in the migration of fines due higher heat conduction and liberation of water. At a particular point these fine particles are captured in the pore throat and subsequently, reducing the relative permeability of oil and water.

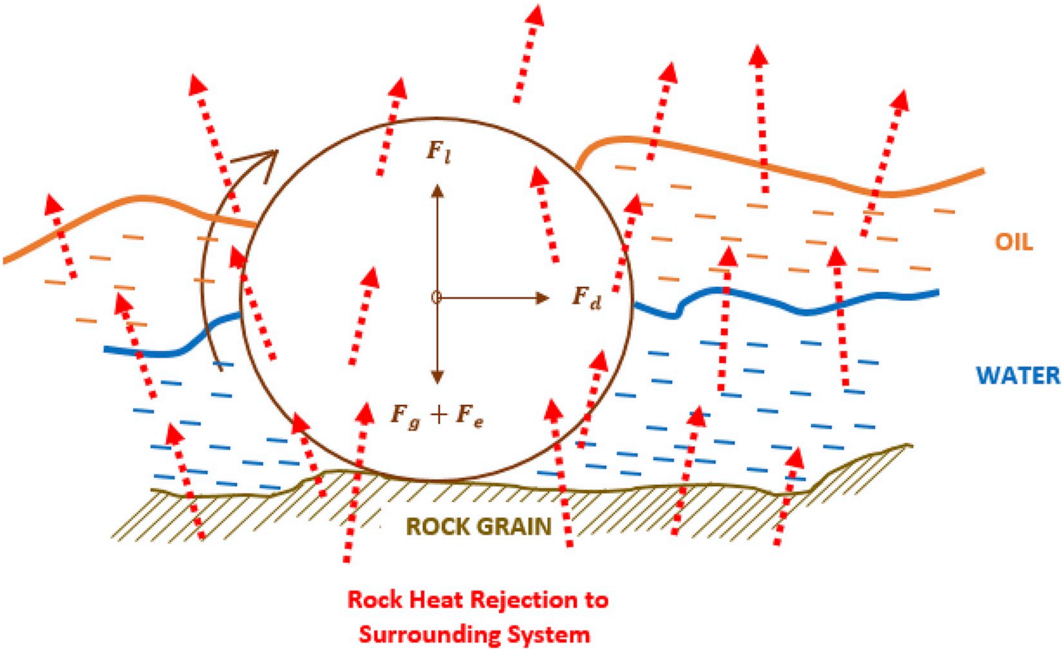

Fig. 4. Forces Exerted on the Attached Fine Particle during Transport in Porous Media (under the Regime of Torque Balance) and rock heat rejection to surroundings (Red Arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Results and discussions

Integrated heat and mass transfer system analytical model indicates that the variable thermal conductivity of pore walls has a major role in not only in fines migration and weakening of electrostatic force, but also for accelerating the rate of fluid transport in porous media. It can be understood from the modelling that the sandstone pore wall/rock surface acts as good heat sink systems which can absorb heat from geothermal radiation. Subsequently, it has an ability to release heat (known as heat rejection) to fluid and particles in porous space and thereby, enhancing its thermal conductivities. Electrostatic force which is responsible for attaching particles to rock surface gets weaken due to variable thermal conductivity of rock. As a result the fine particle is liberated and transported through porous space and strained at pore throat. Ultimately, deteriorating the permeability and well productivity. It was also observed that the water relative permeability curve for fresh water drops after reaching a peak curve for higher water saturation. It is obvious that fresh water is good in thermal conductivity when compared to saline water and in other side, decline curve behavior was noticed for both fresh and saline water for oil relativity permeability. Also, in the second case, the fluid thermal conductivity played a vital role in that behavior. Interestingly, at elevated reservoir temperature the saline content in water decreases and improving its abilities to conduct heat. On the whole, it can be inferred that thermal conductivity of pore wall make a significant contribution in the liberation of fines in porous media. In order to validate this we have conducted additional experiments. Fig. 7 shows the change in the water salinity with regards to increasing temperature. The electrical conductivity instrument was used to measure the water salinity.

It can be seen from the Fig. 7 (a) that the saline content declines for elevating temperatures for fully (100%) Nacl saturated water and this is without fines concentration. Initially, at 40 °C the saline content of water was found to be 268 µS/cm and 202 µS/cm for the time 120s and 600s. Also, it should be noted that water salinity decreases for increasing time. Then at 60 °C the salinity falls to 173 µS/cm at 120s and subsequent recordings are 165 µS/cm, 153 µS/cm, 140 µS/cm, and 128 µS/cm for the time 120s, 240s, 360s, 480s, 600s. After that the salinity declines rapidly for increasing temperature and finally reaching to 42 µS/cm, 39 µS/cm, 32 µS/cm, 26 µS/cm, and 20 µS/cm for these increasing times. It can be observed that at 120 °C the water salinity decreases heavily. It can be explicitly stated that both in laboratory and field investigations the temperature has a severe effect on the alteration of physical and chemical properties of a reservoir fluid and in-situ fines as well. Even Xie et al. (2017) has stated that during higher reservoir temperature the low saline water has a high impact on kaolinite bearing sandstone rocks and also, indicated that the saline content and chemistry of water vary at high temperature. Therefore, it can be implicated that at between 100 °C and 120 °C the saline content of water is very low and during this phase, the fines over the rock surface detaches easily and flow in a permeating fluid. Additionally, at this time the

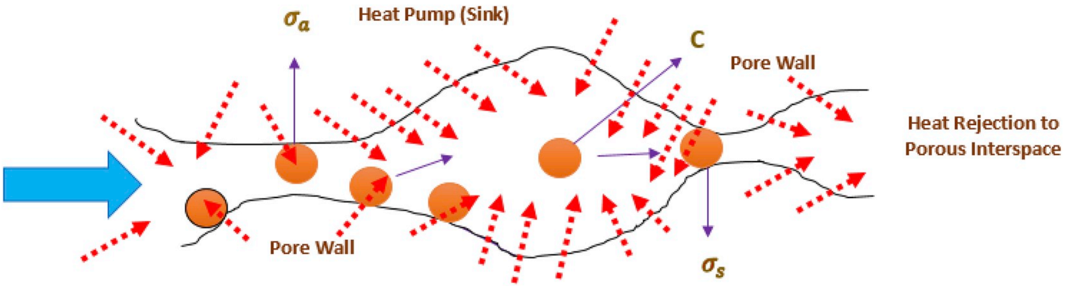

Fig. 5. Fines straining and permeability decline in porous media; pore wall heat rejection (red arrows) due to water-influx (Blue arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

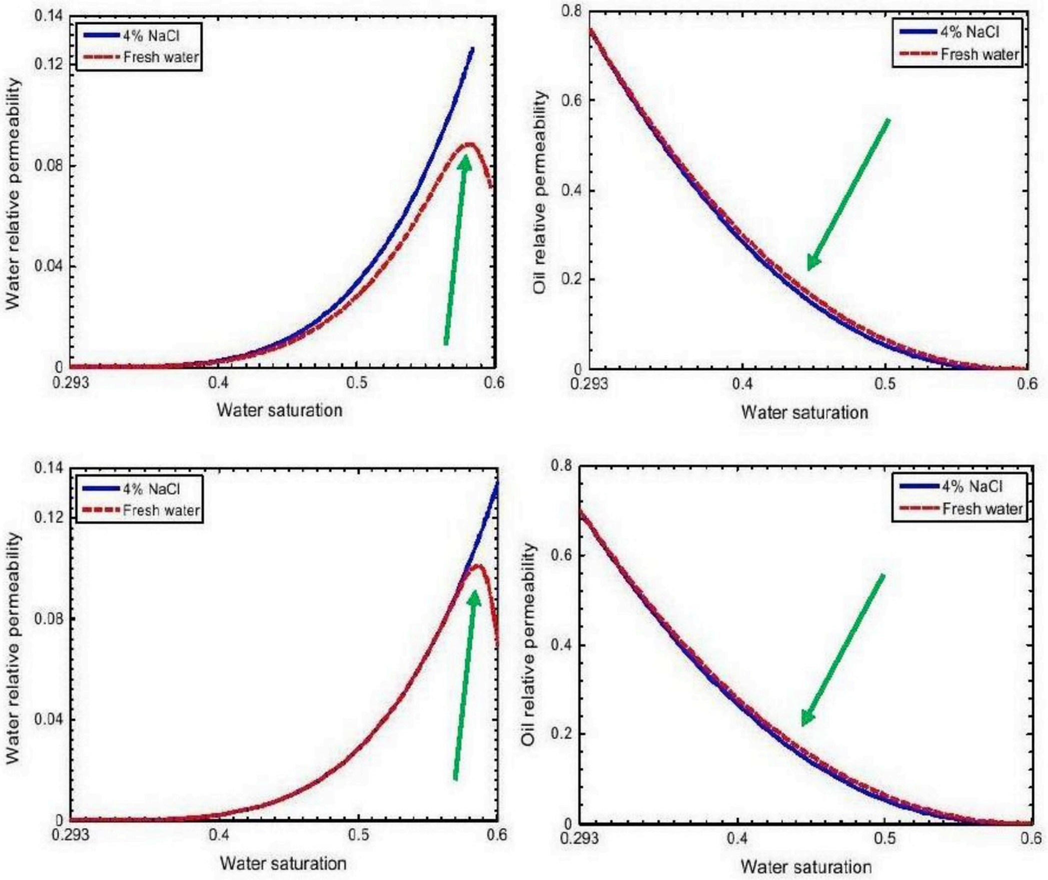

Fig. 6. Water saturation Vs water and oil relative permeability for fresh and 4% NaCl water (Hussain et al., 2013).

electrostatic force that holds a fine particle on the rock surface gets weakened. Similar behavior was observed in Fig. 7 (b), which indicating the reduction of water salinity with fines concentration. We have added the kaolinite clay to saline water and have measured the water salinity. As usual, the water salinity decreases for increasing temperature and the difference being that the great amount of reduction in the salinity. By comparing these two images, it can be stated that the salinity of water deteriorates in a great degree with fines presence.

Fig. 8 shows the variation of thermal conductivity with respect to increasing fines concentration for fresh and saline waters as a function of temperature. Already we have seen in the Fig. 7 that increasing temperature decreases the water salinity and with consequence of fines concentration the salinity drops sharply. Similarly, the thermal conductivity of the water increases with increasing fines concentration. Generally, the thermal conductivity of fresh water is higher than saline water. The decreasing water salinity increases the water thermal conductivity. It can be observed from both figures (a) and (b) that the thermal conductivity of water is higher for high temperatures. Even in this case, the thermal conductivity of fresh water is higher than the saline water regardless of the fines concentration increase. A maximum of 3.2 W/m-k, 2.8 W/m-k, 2.8 W/m-k, 2.7 W/m-k, and 2.6 W/m-k was recorded for 40 °C, 60 °C, 80 °C, 100 °C, and 120 °C at 25 ppm in fresh water. Similarly, 2.7 W/m-k, 2.6 W/m-k, 1.8 W/m-k and 1.7 W/m-k was noted for 40 °C, 60 °C, 80 °C, 100 °C, and 120 °C in saline water. Furthermore, Moktader and El Sayed (2011) has studied the thermophysical properties of sandstone reservoir rocks. The authors mentioned in their research that high amount of heat flow in porous sandstone rock increases the thermal conductivity of the rocks. Also, have indicated that higher heat capacity in rocks has the potential to deteriorate the sandstone permeability and permeability with respect to increasing depth. Even Mohamed et al. (2003) reported that in water flood oil reservoirs the combined salinity and temperature effects has dramatically reduced the specific gravity, surface tension, dynamic and kinematic viscosity of the fluids. Therefore, it can be inferred that the subsurface temperature gradient can alter the physico-chemical properties of reservoir fluids.

It can be seen from the Fig. 9 that there is a close correlation between analytical and experimental models. The correlation was plotted between the temperature and water salinity. Major factors such as time, heat flux, viscosity and density was taken for the calculation. Overall, all models revealed good agreement and there were no major differences between the model accuracies. Therefore, it can be inferred that this model is reliable for field and laboratory investigations on low salinity fines suspension transport and drift in porous rocks during higher reservoir temperature. Overall, this paper has successfully demonstrated the heat and mass transfer effect on fines migration in oil reservoirs during inflated reservoir temperature.

6. Conclusions

First and foremost a classical thermodynamic framework was applied to fines migration phenomena during extreme reservoir temperatures. Specifically, combined heat and mass transfer model was applied in oil reservoirs containing natural reservoir fine particles and subsequently, it will be liberated by waterflooding. In this case, the developed analytical model indicates that the uniform and variable thermal conductivity have significant impact on fines detachment and migration in porous media. We feel this case is quite dangerous when compared with gas fields. Since during waterflooding, during the invasion of porous rocks, that impulsion in pore wall will release a

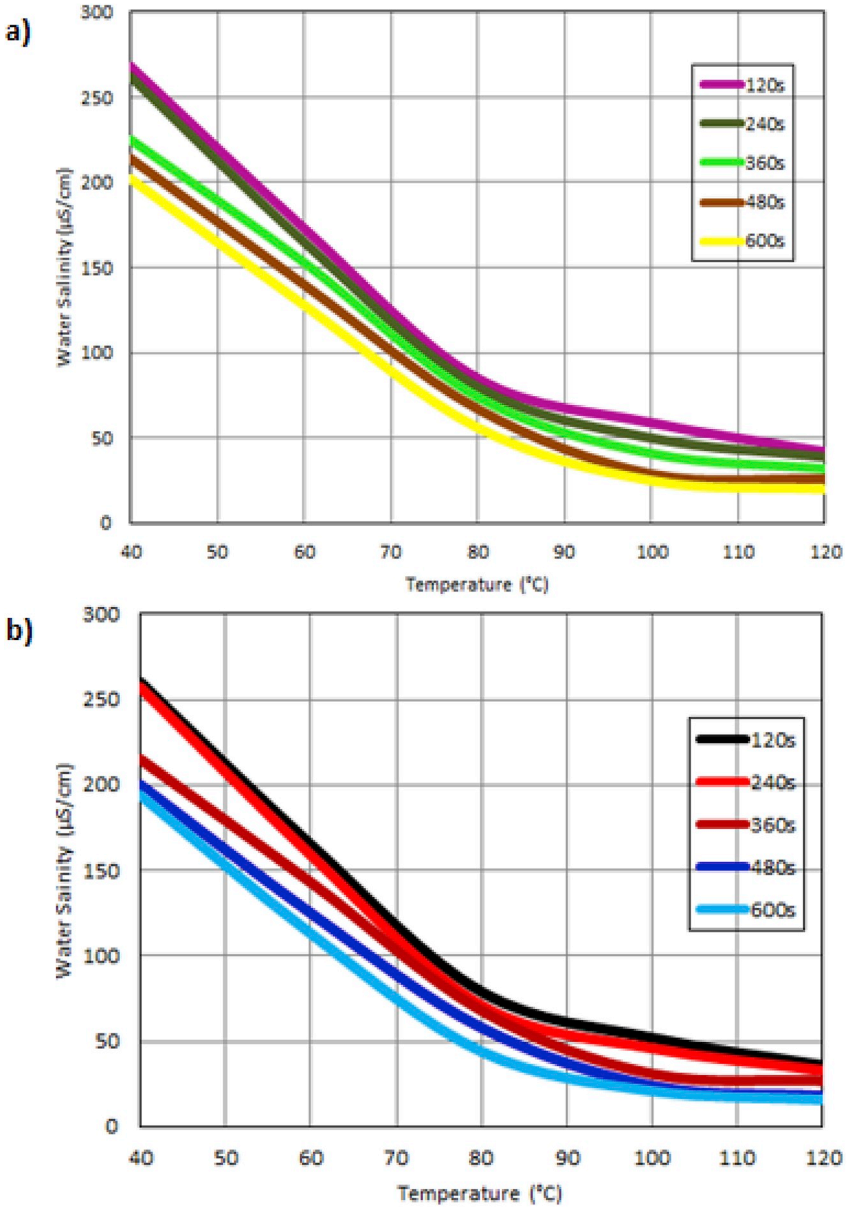

Fig. 7. Variation of water salinity and electrical conductivity with respect to increasing temperature: a) No Suspended Fines, b) Presence of Suspended Fines.

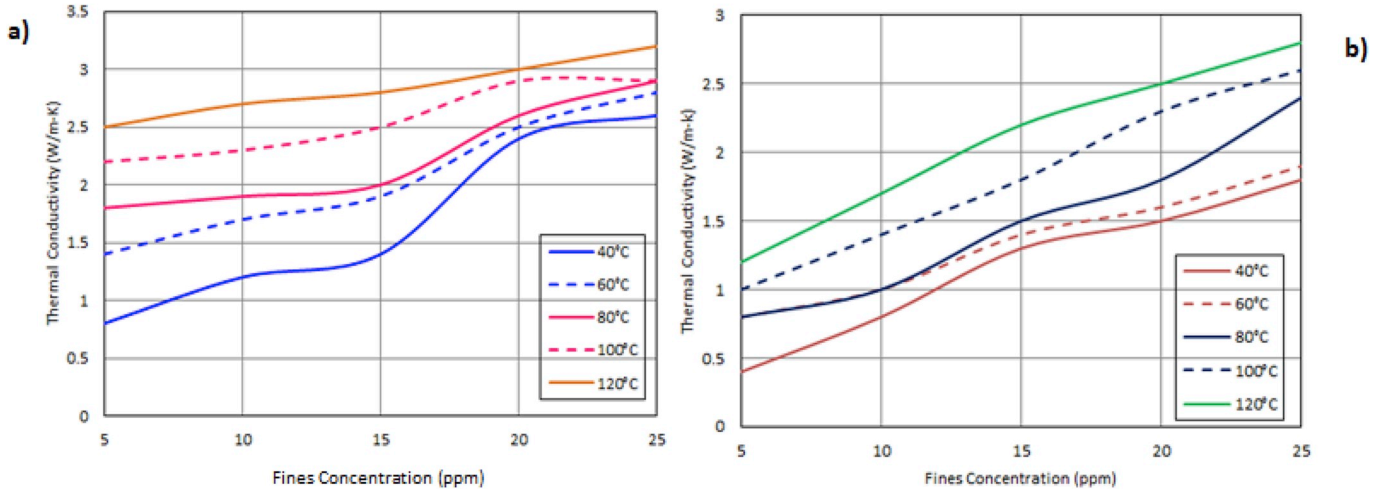

Fig. 8. Variation of thermal conductivity with respect to increasing fines concentration: a) Fresh Water, b) Saline Water.

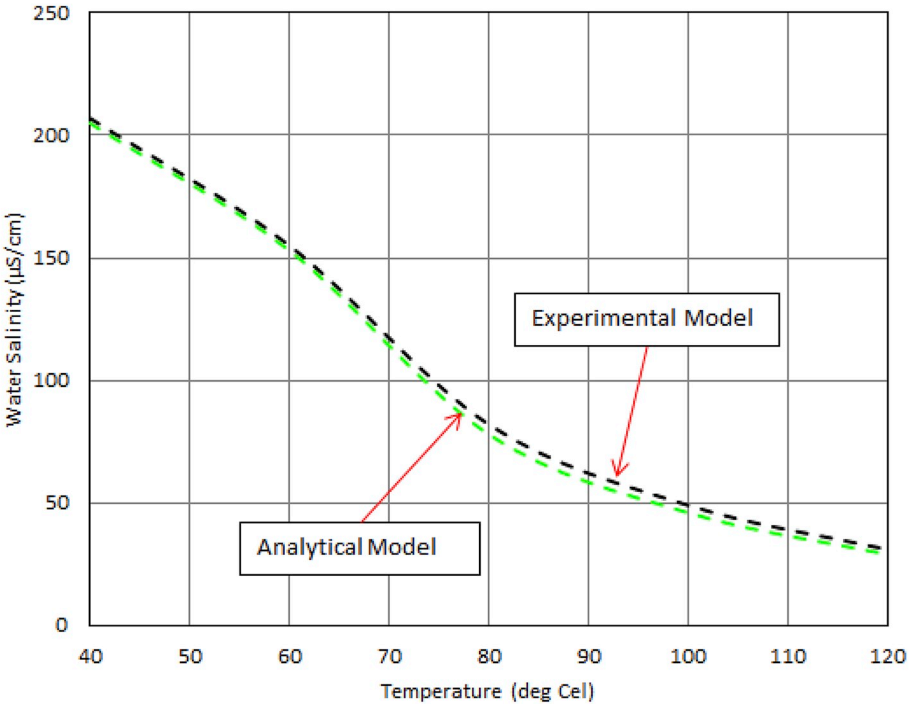

Fig. 9. Model Validation.

tremendous amount of heat energy known as heat rejection. Which consequently liberate the fines from pore walls and then it will be transported to pore throat by carrier fluid. Also, it was observed that during waterflooding, there is a significant drop in water salinity. At elevated reservoir temperature, the salinity of water changes rapidly (Mideen, 2015; Rosenbrand et al., 2015). Furthermore, the thermal conductivity of fluid increases due to decrease in the water salinity level. The thermal conductivity of fresh water is higher than some percentage of saline water. The experimental test has proven this behavior. The oil and water relative permeability curve decline behavior was highly observed for fresh water with increasing water saturation. Therefore, after radiation, thermal conductivity of rock and fluid are dictating factors in the detachment and migration of fine particles. Finally, this paper has led to the elucidation and development of a new theory called waste heat recovery in porous media, which describes the role of waste and available heat on fluid and particle mobilization in porous rocks. This will be critically explored in future works.

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Nomenclature

F	Force
Q	Heat flow rate
E	Energy
LPW	Lower pore wall
UPW	Upper pore wall
A	Cross sectional area of the pore wall
L	Texture of the pore wall
K	Thermal conductivity of the pore wall, and
Q_1	Heat transfer by radiation
Q_2	Heat transfer by conduction
Q_3	Heat rejection/liberation
C, $C_1$and C_2	Constants of integration
A_1	Area of pore chamber
A_2	Area of pore throat
ε_1 and ε_2	Emissivity factors
T_1 and T_2	Initial and final temperature
E_1	Initial energy
E_2	Final energy
T_{Kh}	Final and highest thermal conductivity of rock surface
T_{Ki}	Initial thermal conductivity of rock surface
W_r	Total work done (heat rejection) to displace all fines in pore surface and for migration in porous space
K_o	Initial pore wall with initial thermal conductivity
K_m	Mean thermal conductivity of pore wall
K_i	Initial pore wall with varying thermal conductivity
Q_{dl}	Heat loss by LPW
Q_{al}	Heat loss by UPW
Q_j	Total radiative transfer between LPW and UPW
Q_{abs}	Heat absorption by pore wall
W_K	Network transfer to migrate the reservoir fines in porous media
t_1, t_2	Temperatures maintained at two ends of the pore wall
v_r	Velocity component in radial direction
v_θ	Velocity component in tangential direction
q_w	Water flow rate
β	Formation damage coefficient
$+\beta$ and $-\beta$	Formation damage coefficient with respect to non − linear temperature
A	Heat diffusion
T	Surface heat flux
I	Initial time/state/condition
X	x direction
Y	y direction
Z	z direction
γ	Continuous heat rejection to porous media from rock surface

	(without any interval)
ρ	Density
a	Area of flow rate
ω	Scalar function of space and time
v	Volume
r	Radius
s	Entropy
ψ_1	Surface potential of fine particle
ψ_2	Surface potential of porous rock
J^m	Conduction current
ρ_i	Partial component of buld density
λ_i	Charge per unit mass
u_i	Velocity of the ith component
$\eta_{\phi K}$	Thermal efficiency of porous media with respect to thermal conductivity
Δp	Change in pressure inside porous media

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