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Fines surface detachment and pore-throat entrapment due to colloidal flow of lean and rich gas condensates

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ABSTRACT

This paper describes about the lean and rich gas condensate effects on fines migration in porous rocks. Fines detachment from rock surface and pore throat entrapment are frequent causes of formation damage and well productivity loss. In condensate reservoirs, there is a large volume of liquid formation during reservoir pressure depletion. This will result in liquid loading and production decline. In this work, we critically discuss the fines migration and the permeability decrease mechanism in the gas condensate reservoir. For this purpose, we numerically simulated a condensate reservoir, which is capable of undergoing a phase transition from gas to liquid as a function of pressure depletion, temperature, and time. We have implemented CFD modeling to simulate this retrograde condensation process. The major results revealed that there is a high amount of heat release during phase transition. This heat release and condensed liquid flow detached the fines from the rock surface and finally, get trapped in the pore-throat. Our models have been validated against the experiments and showed good agreement. Overall, this work may serve as a base to re-examine the gas condensate reservoir behavior with fines transport in porous rocks.

1. Introduction

Gas production from a condensate reservoir is a critical process and before the start of production it is essential to understand its phase behavior. During decline in reservoir pressure there will be a formation of liquid from the condensates and thereby, decreasing the well productivity. The retrograde condensation process can be classified into lean and rich gas condensates. In the case of lean gas condensate, less condensate liquid is produced, whereas, more liquid oil is produced in rich gas condensate. Initially, a retrograde gas condensate reservoir has a fluid in single phase, when reservoir pressure decreases it changes to two phases that is gas and condensate. Extra condensate is formed in well, tubing and separators with alterations in pressure and temperature. Kalugin et al. (2015), developed a mathematical model and optimized the development of gas-condensate field. The authors developed an algorithm for recovering more condensate gas from the wells. The model has been validated with experimental work and it showed good agreement. The model revealed about 12% increase in the recovery of condensate gas was achieved and its possibility was demonstrated. Zhou et al. (2016), developed optimization methods for the prediction of liquid loading in deep gas condensate wells. They studied this problem in Yakela-Dalaoba deep condensate gas reservoir. Specifically, the authors have analyzed the gas well behavior, liquid loading effect, critical flow rate, kinetic energy factor, wellbore pressure and temperature. For this gas reservoir, they established a model of modified pseudo single-phase to calculate the temperature and pressure distribution in high gas-liquid ratio wellbores and suitable techniques for computing the temperature and pressure distribution in low-gas liquid ratio wellbores are optimized by error analysis. Results revealed that the modified model of pseudo single-phase coupling is appropriate for pressure and temperature distribution calculations in high gas-liquid ratio wells, while Hasan's and Hagedorn-Brown's methods are suitable for low gas-liquid ratio wells. On the whole, the both models are suitable for gas wells liquid loading prediction in Yakerla-Dalaoba reservoir. Condensate reservoirs are prone to formation damage.

Generally, the first occurrence of formation damage was first reported in 1944 by Johnston and Beeson and they identified an impairment in permeability of clay-bearing reservoirs with pore water salinity decrease after testing of 1200 core samples (Johnston and Beeson, 1945). Typically, formation damage of a reservoir consists of four mechanisms, namely mechanical, biological, chemical, and thermal (Civan, 2007). Usually, a condensate reservoir undergoes

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damage through mechanical and thermal mechanisms. For detailed classifications of the these damage mechanisms, the reader is advised to see the reservoir formation damage-fundamentals, modeling, and mitigation by Faruk Civan.

Permeability impairment and well productivity decline due to fines migration falls under the mechanical mechanism and usually thermal mechanism consist of dissolution, mineral transformation, asphaltene precipitation and wettability change. Presently, the fines migration process should not be confused with thermal mechanisms. But, this report attempts to associate the migration of fine particles in porous media with thermal mechanisms. For that purpose, thermodynamic modeling is applied to understand this phenomenon from a new dimension. Even in-situ reservoir temperature plays a vital role in detaching fines from the pore wall (Amaerule et al., 1998; Rosenbrand et al., 2015) and therefore, the temperature should be taken as a major parameter/factor into an account for modeling and analyzing the colloidal flows and fines migration in porous space. There are dozens of papers related to formation damage in several scientific archives, but this report model is only limited to fines migration in porous media. Mobilization of fine particles within a rock interspace result in pore throats plugging and bridging.

Small particles such as clay, quartz or other similar materials are called fines, which exist naturally in petroleum and geothermal reservoirs (porous media). 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). It is obvious that fluid in porous media flow through tortuous paths and this along with inertial effects cause fines to collide with pore walls. After each collision, fine particle loses momentum and requires to be accelerated again by hydrodynamic forces. Due to this occurrence, the average velocity of fines is lesser than that of the fluid. This fines retardation with respect to fluid may increase in the fines concentration in some regions which in the end, result in the plugging of porous media and this effect is important in the fluid flow towards the near wellbore region (Kampel, 2007). Fig. 1 shows the fine particle behavior due to condensed liquid flow in a single pore chamber system.

It can be seen from the figure that the pore wall attached fine particles are under the dominance of the four forces, namely lift, electrostatic, gravity, and drag, which are denoted as F_l, F_e, F_g, and F_d respectively. These four major forces are determined by the torque balance that in turn constitute to the mechanical equilibrium of attached particles (Zeinijahromi et al., 2015). Also, the pore-throat captured particles are also seen. Additionally, detached and suspended particles are presented in this figure.

A fine particle is firmly attached to the rock surface/pore wall under the influence of the electrostatic force. There are two common scenarios in which the fines get detached easily. Firstly, when the reservoir temperature is higher the electrostatic force which holds the fine particle over the surface gets weakened and as a result, the particle will detach and move freely. Secondly, during water or gas flooding the permeating fluid will detach the fines from the rock surface regardless of the holding strength of the electrostatic force. Consequently, the fines will be suspended in the permeating fluid and will be carried away by its flow velocity. After that it will be strained or captured at a particular point that is pore throat and subsequently, reducing the permeability of fluid flow and ultimately, declining the well productivity. This is the simple mechanism of fines detachment, transport, and capture in the porous interspace.

Civan (2007), analyzed the non-isothermal impairment of porous media due to fines migration and deposition and also studied their dispersive transport. He claims the occurrence of this phenomenon was due to variation in temperature and fines mobilization by dispersion and advection. Author developed an analytical model to predict the fines detachment and transport in porous medium and compared with numerical results which he obtained through finite difference numerical scheme. Modeling was performed with and without the consideration of temperature variation and dispersion mechanism. From the numerical results it was revealed that a correlation was occurred between varying temperature and fines dispersive mechanics. The difference in porous temperature causes fine particles to disperse which experiencing a spreading effect and then, impairing the permeability. Overall, Civan research demonstrated that the porous medium temperature variation has a potential effect on fines migration and permeability reduction because it harms the porous matrix thermal deformation, pore throat constriction, and the filter coefficient. Therefore, from his findings, we all can understand that permeability damage is severe under non-isothermal and elevated temperature. Zeinijahromi et al., (2012), examined the impairment of well due to migration of fines in gas fields. The authors have developed an analytical model to predict the detachment and migration of fines in porous media during

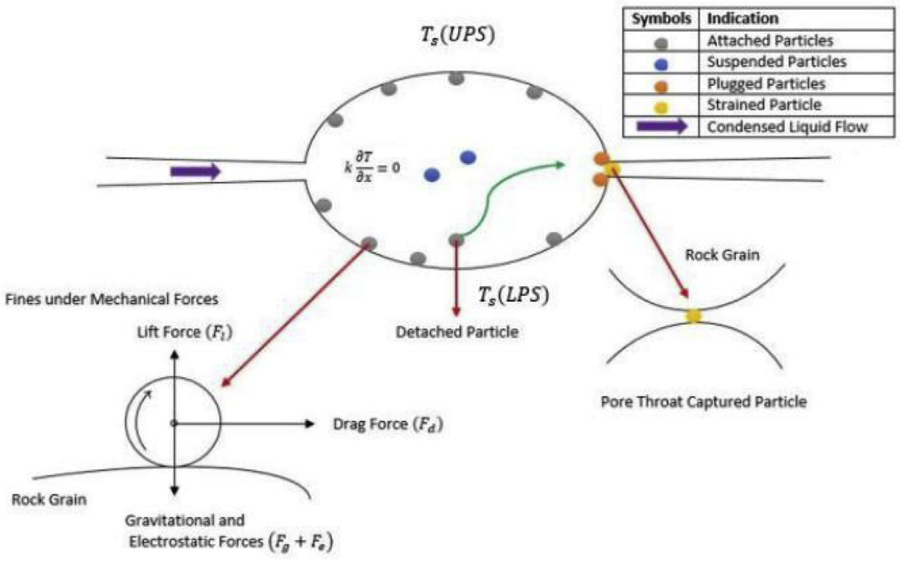

Fig. 1. Fines behavior due to condensed liquid flow in single pore chamber system.

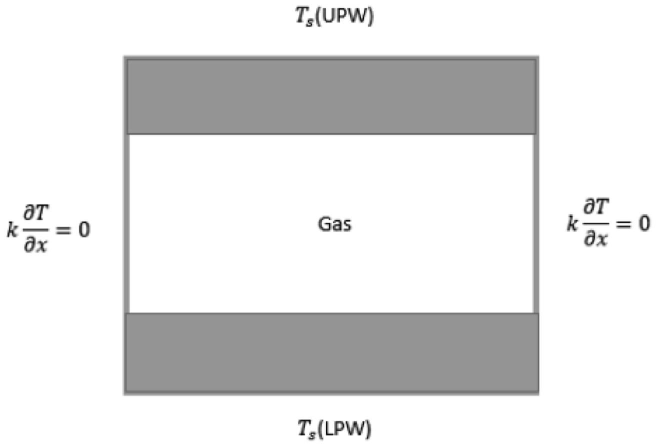

Fig. 2. Gas condensate reservoir in CAD (computer aided design) geometry.

gas flow and analyzed its subsequent capture in pore space by size exclusion which causing a decline in rock permeability during production of gas. Initially, fines were under the dominance of torque balance over the rock surface embedded with connate water. The developed model is for the steady state gas production with a steadily accumulating strained fines that showed linear growth in skin factor against the amount produced in-situ fine particles. Also, they have developed a mathematical model for gas production with retained fines accumulation and well productivity. Overall, they have validated the developed analytical model with well productivity of field data which reveals good agreement. Zeinijahromi et al. (2015), studied the sweep efficiency improvement of edge water drive reservoirs using induced fines migration. The problem they identified is that from adjacent aquifer the intruding water exceed beyond the oil phase and as a result, there is a considerable volume of the trapped residual oil left. The early occurrence of these water fingers triggers the premature production of water, which simultaneously leads to well shutdown. The authors proposed an innovative solution to tackle this problem. They applied the concept of induced formation damage by injecting slow saline water into the water-up wells which creates a barrier of low permeability layer against the water fingers. This was numerically studied by them and its outcomes reveals that small volume of low salinity water injection provides a prolongation in the life of the well that consequently gives approximately 3–5% linear recovery, but not exponential when compared with normal depletion. The liquid and ion transport in porous media results in entropy production that in turn depends on the porous medium internal energy. The charge flow amount per unit surface area and time is represented by as follows (Revil, 2007):

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

Where, J^m indicates the conduction current, ρ_i is the partial component of bulk density and u_i is velocity, and λ_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 condensed liquid net charge. Fines adhering to the surfaces of the pore of the relatively higher porosity and permeability porous formations can be released by colloidal and hydrodynamic forces, and these forms of induced fines are identified to be a more common occurrence in sandstone formations, especially water-wet rocks (Khilar and Fogler, 1998).

Generally, a combination of formation damage may occur in a single reservoir system. For instance, Restrepo et al. 2007, employed chemical and statistical simulation techniques to characterize the skin factor in BP (company) operated fields in Columbia, South America. It was founded from this research that the damage zones were influenced by five mechanisms such as mineral scales, organic scales, fines blockage, induced damage, and fluid blockage at specific time. Finally, the author's model is helpful in the diagnosis of the causes of well productivity decline. But, if we try to associate this literate information to this work, we can only consider fines and fluid blockages at a specific time mechanism for analyzing the permeability damage in lean and rich condensate reservoirs. Whereas, other mechanism like mineral and organic scales are unworthy of consideration at this present time.

The aim of this paper is to analytically and numerically investigate the fines migration phenomenon in condensate reservoirs as a function of time, pressure, and temperature. To the best of our knowledge, condensate reservoir formation damage due to fines migration has not been reported in any scientific archives. So that this paper makes an audacious attempt to examine the phase transition of reservoir fluid that condenses to a liquid, and also, how the heat transfer during fluid phase change affects the stability of the fine particle that resting on pore wall was modeled and investigated. We have simulated a two dimensional condensate reservoir model, which is capable of undergoing a lean and rich phase transition from gas to liquid, and how its enthalpy triggering the fines transport and permeability deterioration was critically analyzed. Importantly, we have studied the thermodynamics behind the phase transition of the condensate reservoir fluid and its impact on fines. Overall, we have verified and validated our models with the experiments. Hence, this paper may induce the readers to focus on this fines migration phenomenon in different subsurface conditions.

The structure of this paper is described here. The next section presents about the research methodology which was applied in this paper. The third section presents an analytical model for fines migration under the influence of condensates and the fourth section critically discusses about the model results. Finally, the fifth section concludes the paper.

2. Materials and methods

A two-dimensional CFD model using COMSOL 5.0 code to simulate the dynamic condensation of a gas reservoir. A 2D computer aided design (CAD) geometry has been created to simulate the reservoir, shown in Fig. 2. In that T_s indicates the surface temperature of the lower and the upper pore wall denoted as LPW and UPW. Whereas, $k\frac{\partial T}{\partial x}$ indicates the change in thermal conductivity of surfaces where the reservoir fluid makes the contact with regards to x coordinate. A layout has been made in such a way that during transient calculations the fluid properties are calculated with the given reservoir temperature at any given time during the iterative calculation. Flow simulation has not been carried out in order to simplify the time consuming velocity distribution. Hence temperatures along the pore wall boundary have been specified by using the value obtained by empirical correlation of Dittus-Boelter equation.

Numerical simulation of gas condensation is carried out using the FEM (Finite Element Analysis) based commercial Multiphysics software COMSOL 5.0. An axis-symmetric (2D) geometry which represents the flow from gas condensates in the porous space is modeled. Material properties of the governing equations are given as inputs to the solver and to account for the time dependency of the problem as well as for the liquid flow and the heat transfer in the porous media. A transient analysis under fluid-thermal interaction was used, which enable us to solve both the Navier-Stokes equation and the energy equation of condensate liquid conduction and convection. The geometry is created using the following initial and boundary conditions:

1) Initial reservoir temperature is 293 K.
2) Top and bottom pore walls are made adiabatic.
3) No-slip conditions on the pore surfaces.
4) Convection effect within the reservoir was not taken into an account.
5) Thermal properties of rock, fine particle, and liquid condensate are

Table 1
2D CAD reservoir mesh details.

Mesh Inputs	Values
Triangular Elements	810
Edge Element	208
Vertex elements	4
Domain element statistics -	
Number of elements	810
Minimum element quality	0.8732
Average element quality	0.9185
Element area ratio	0.5495
Mesh area	0.009 m^2
Maximum growth rate	1.579
Average growth rate	1.023

given.

The input profiles for mesh input and phase change setting properties are mentioned in a separate attachment. Table 1 indicates the mesh details for this condensate reservoir.

3. Analytical model

This section presents an analytical model for retrograde condensation and fines detachment in porous media.

Firstly, the FEM based governing equations for condensation process is mentioned below:

$$d_z\rho C_p\frac{\partial T}{\partial t} + d_z\rho C_p u.\ \nabla_T = \nabla.\ (d_z k\nabla_T) + d_z\ Q + Q_{vd} + Q_p + Q_{oop} \tag{2}$$

$$\rho = \theta_{\rho phase1} + (1-\theta)_{\rho phase2} \tag{3}$$

$$C_p = \frac{1}{\rho}(\theta_{\rho phase1}C_{\mu phase1} + (1-\theta)_{\rho phase2}) + L\frac{\partial\psi_m}{\partial T} \tag{4}$$

$$k = \theta k_{phase1} + (1-\theta)k_{\rho phase2} \tag{5}$$

$$\psi_m = \frac{1}{2}\frac{(1-\theta)\rho_{\rho phase2} - \theta\rho_{phase1}}{\theta_{\rho phase1} + (1-\theta)_{\rho phase2}} \tag{6}$$

Then, the temperature of the liquid and gas phases in porous media must equal the temperature inside the porous medium, which is at the condensation point, T_c and therefore, the boundary conditions at the interface can be expressed as:

$$T_l(x,t) = T_g(x,t) = T_c, \quad x = c(t) \tag{7}$$

Where, $T_l(x,t)$ *and* $T_g(x,t)$ are the temperatures of the liquid and solid phases respectively. The density of condensates usually differs between the liquid and gas phases and henceforth, density change always accompanies the phase change process. The density change that occurs during gas-liquid phase change will produce an extra increment of motion in the liquid-solid (rock) interface. The density of porous rock is greater than the liquid density (i.e $\rho_r > \rho_l$) the resulting extra motion of the interface is along the positive direction of the x-axis. Assuming that the velocity of the rock-liquid interface due to phase change is $u_p = ds/dt$, while the extra velocity of the rock-liquid interface due to density change is u_ρ . The density change must satisfy the conservation of mass at the interface, that is:

$$\rho_r(u_p - u_\rho) = \rho_l u_p \tag{8}$$

The extra velocity induced by the density change can be obtained by rearranging equation (8) as shown below:

$$u_\rho = \frac{\rho_r - \rho_l}{\rho_r}u_p \tag{9}$$

This is always valid for the case $\rho_r > \rho_l$, except only the extra velocity becomes zero. Another necessary boundary condition is the energy balance at the rock-liquid interface. If the enthalpy of the liquid and rock phases at the condensation point are h_l and h_r, the energy balance at the rock-liquid interface can be expressed as:

$$q_l'' - q_r'' = \rho_l u_p h_l - \rho_r(u_p - u_\rho)h_r \quad x = r(t) \tag{10}$$

Where, $q_l'' - q_r''$ are the heat fluxes in the x-direction in the liquid-rock interface.

Substituting equation (9) into (10), one obtains

$$q_l'' - q_r'' = \rho_l h_{rl}\frac{dr}{dt} \quad x = r(t) \tag{11}$$

Where, $h_{rl} = h_l - h_r$ is the latent heat of condensation. If convection in the liquid phase can be neglected and heat conduction is the only heat transfer mechanism in both the liquid and rock phases, the heat flux in both phases can be determined by Fourier's law of conduction.

$$q_l'' = -k_l\left[\frac{\partial T_l(x,t)}{\partial x}\right]_{x=r(t)} \tag{12}$$

$$q_r'' = -k_r\left[\frac{\partial T_r(x,t)}{\partial x}\right]_{x=c(t)} \tag{13}$$

The energy balance at the rock-liquid interface for a retrograde condensation can be obtained by substituting equations (12) and (13) into equation (11), i. e

$$k_r\frac{\partial T_r(x,t)}{\partial x} - k_l\frac{\partial T_l(x,t)}{\partial x} = \rho_l h_{rl}\frac{dr}{dt} \quad x = r(t) \tag{14}$$

The condensate accumulation in the pore chamber by taking fines into an account can be obtained by similar procedure (the energy balance equation at the interface):

$$k_r\frac{\partial T_r(x,t)}{\partial x} - k_l\frac{\partial T_l(x,t)}{\partial x} + \frac{\partial u}{\partial T}\left[\underset{\alpha}{\rightarrow} + \underset{\beta}{\rightarrow} + \underset{\gamma}{\rightarrow}\right] = \rho_r h_{rl}\frac{dr}{dt} \quad x = r(t) \tag{15}$$

The only difference between equations (14) and (15) is the density on the right hand side of the equation. If the temperature distributions in the liquid and rock interfaces are known, the location of the rock-liquid and the fine particle interface can be obtained by solving equation (14) and/or (15). It should be noted that density change causes advection in the liquid phase, which further complicates the problem. For the condensation problem, if the heat transfer mechanism in the liquid phase is convection, the heat flux in the liquid phase can be obtained by the following equation:

$$q_l'' = h(T_K - T_r) \tag{16}$$

Where h and T in equation (16) are the convective heat transfer coefficient and the bulk temperature of the liquid phase respectively. The energy balance at the rock-liquid interface is

$$k_r\frac{\partial T_r(x,t)}{\partial x} + h(T_c - T_r) + \frac{\partial u}{\partial T}\left[\underset{\alpha}{\rightarrow} + \underset{\beta}{\rightarrow} + \underset{\gamma}{\rightarrow}\right] = \rho_l h_{rl}\frac{dr}{dt} \quad x = r(t) \tag{17}$$

Now, assuming n is a unit vector along the normal direction of the solid-liquid interface, the boundary conditions at the interface can be expressed as:

$$T_l(x,y,t) = T_s(x,y,t) = T_c \qquad x = r(y,t) \tag{18}$$

$$k_r\frac{\partial T_r(x,y,t)}{\partial n} - k_l\frac{\partial T_l(x,y,t)}{\partial n} = \rho_l h_{rl} v_n \qquad x = r(y,t) \tag{19}$$

Where, v_n is the rock-liquid interface velocity.

It is apparent that equation (19) is not convenient for numerical solution because it contains temperature derivatives along the n-direction. If the structure of the rock-liquid interface can be expressed as

$$x = r(y,t) \tag{20}$$

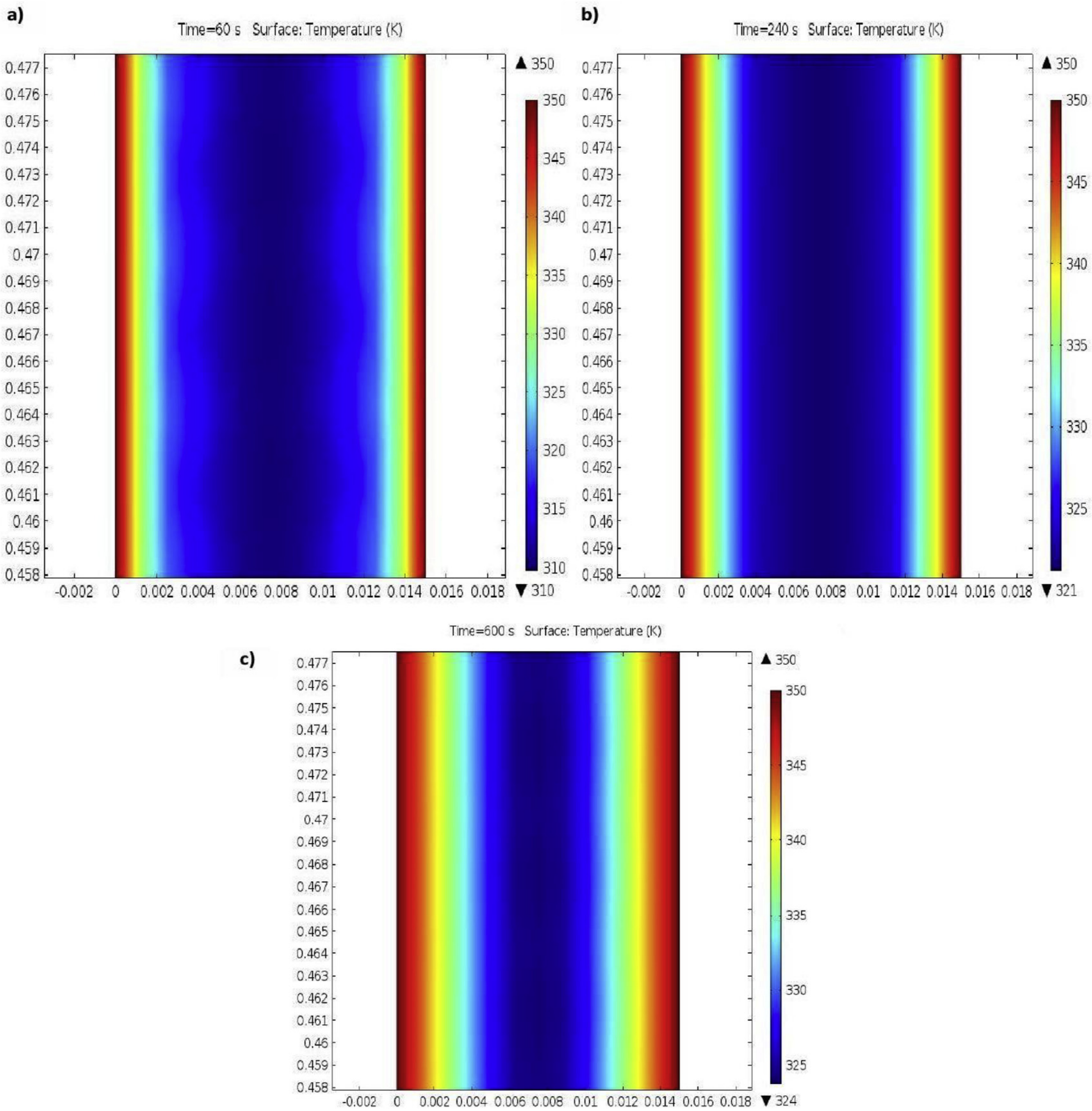

Fig. 3. Temperature distributions during fluid phase transition at time 60s (a), 240s (b), and 600s (c).

Equation (20) can then become the following form

$$\left[1+\left(\frac{\partial r}{\partial x}\right)^2\right]\left[k_r\frac{\partial T_r}{\partial x}-k_l\frac{\partial T_l}{\partial x}\right]=\rho_l h_{rl}\frac{dr}{dt}\qquad x=r(t) \tag{21}$$

Similarly, retrograde condensation in three dimensional coordinates with an interface is described by

$$z=r(x,y,t) \tag{22}$$

Then, the energy balance equation at the interface can is

$$\left[1+\left(\frac{\partial r}{\partial x}\right)^2+\left(\frac{\partial r}{\partial y}\right)^2\right]\left[k_r\frac{\partial T_r}{\partial x}-k_l\frac{\partial T_l}{\partial x}\right]=\rho_l h_{rl}\frac{dr}{dt}\qquad z=r(x,y,t) \tag{23}$$

The impulse of condensed liquid on the pore wall liberates heat release. This is required to detach fines from pore wall and this can be mathematically mentioned as below:

$$\eta_{\phi k}=\frac{W_k}{q_{cl}} \tag{24}$$

Where, $\eta_{\phi k}$ is the thermal efficiency of porous rocks with respect to thermal conductivity of rock and W_K presents the net work done to migrate the reservoir fines in porous media. We assume that the total radiative heat transfer between upper and lower pore walls cause the fine particles to suspend in the condensed liquid. This condition is written as follows:

$$\underset{\beta_{ql}}{\rightarrow}=\frac{A_1E_1\varepsilon_2-A_2E_2\varepsilon_1}{\frac{A_1}{A_2}(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)}+\frac{4}{3S_L}\pi r^2(r+h)+(1-\phi)k \tag{25}$$

Finally, pore throat capture can be mentioned as follows:

$$\underset{\gamma\ ql}{\rightarrow}=\frac{\sigma\zeta_m}{4t}[T_{r2}-T_{r1}]-\Delta ds \tag{26}$$

Hence, equation (26) indicates the condition for pore throat-entrapment. Therefore, an analytical model was successfully modeled for gas phase transition and subsequent fines migration.

4. Results & discussions

This section critically analyzes the numerical results which were obtained from the CFD COMSOL model.

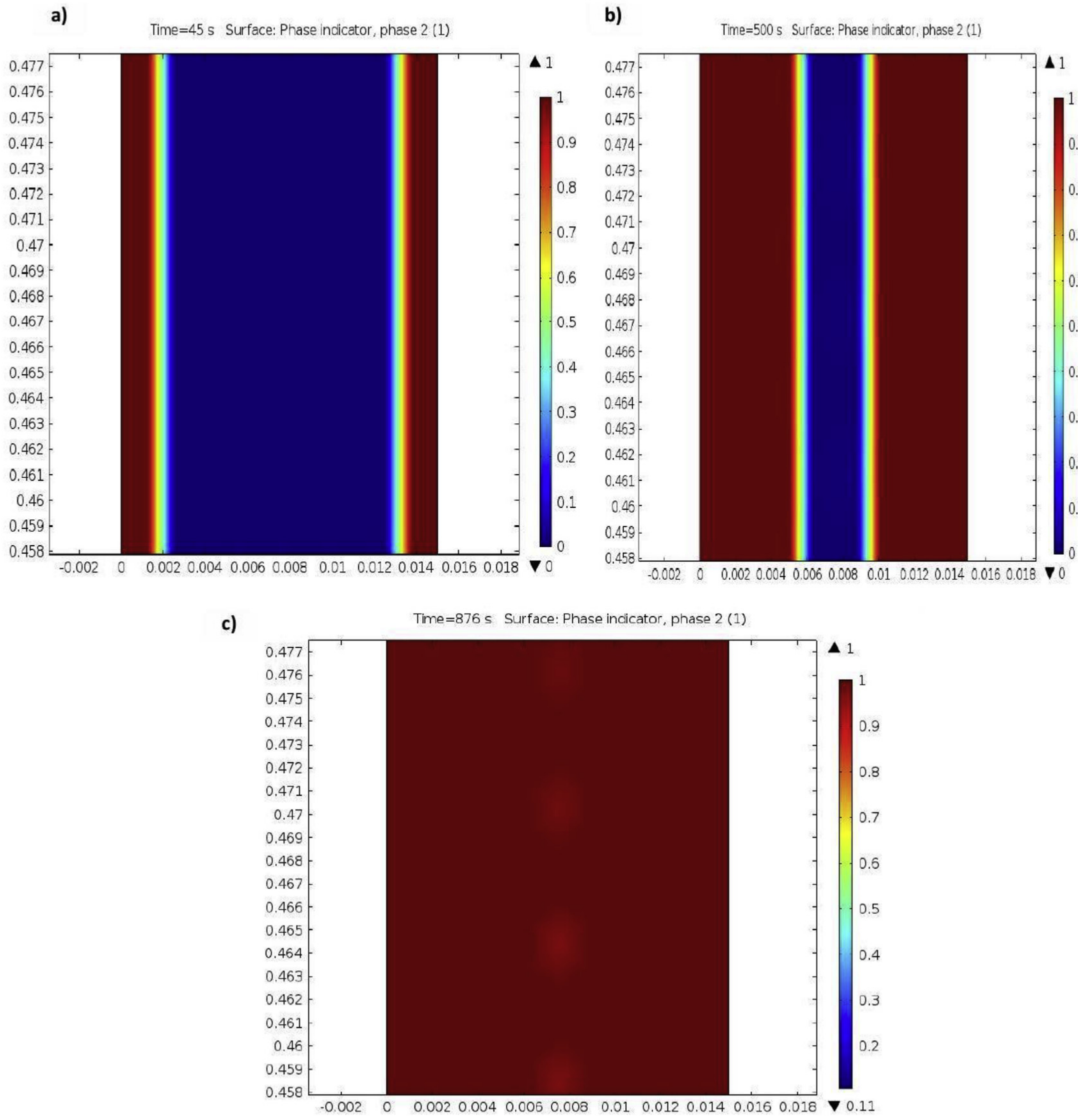

Fig. 4. Lean and rich liquid condensate phase transition at time 45s (a), 500s (b), and 876s (c).

4.1. *Effect of lean and rich condensate colloidal forces on fines migration*

Fig. 3 shows the temperature distributions during lean condensate phase transition at time 60s, 240s, and 600s. It can be seen from the figures that during the start of fluid phase transition the surface temperature is in the range 345 K–350 K on the radial sides of all time. This transient behavior of porous surface affects the mechanical stability of the fine particle. It can be observed from the left figure that at 60s there is no much difference, nor variation in the porous surface temperature.

In this condition, the fine particle may undergo an oscillation, but there will not be any disturbance in the torque balance of fines over pore wall. In the middle figure a slight variation in surface temperature can be observed, but its value somewhat remains the same. The temperature variations are at different pore chamber zones. The right image indicates a high variation of surface temperature for about 600s. Usually, the temperatures at the sides are higher and gradually decreases at center zones. The corner temperatures are between 350 K and 345 K and finally it get stabilizes to 325 K. At middle and right surface temperature regimes the fine particle may lose its mechanical stability. Since at this time the electrostatic attraction, which hold the fine over the rock surface gets declined. Consequently, the fines will be detached and suspended in a condensate.

Fig. 4 shows the lean and rich liquid phase transition at time 45s, 500s, and 876s. It can be seen from figure (a) that the gas phase indicated in blue gets decreases slightly for decreasing pressure. So at 45s the gas phase condensed into some quantities of liquid, which is indicated in maroon color. At 500s the gas is partially condensed into a liquid, as shown in figure (b). The first two figures are indicating the colloidal force of lean gas condensates. While the figure (c) indicating the rich gas condensates. In which, the gas phase is completely condensed into a liquid phase. As it is mentioned in the introduction section itself, that the lean condensate is characterized by less liquid formation out of the gas reservoir and rich condensate is characterized by high liquid formation. Both conditions will trigger the liquid loading near the wellbore region. But, this paper only focuses on the fines migration mechanisms. It can be seen that figure (a) and (b) indicates a lean phase transition and (c) shows a rich condensation. For a better and enlarged view of these figures, a reader is advised to see the files in a separate attachment.

Generally, a structure/geometry of porous media can be best represented by a series of capillary bundle tubes with mixing chamber (Bashtani et al., 2013; Santos et al., 2008; Dullien, 1992). Some portion of this model is already presented in Fig. 2. In both lean and rich condensate conditions the fines get detached and will be suspended in

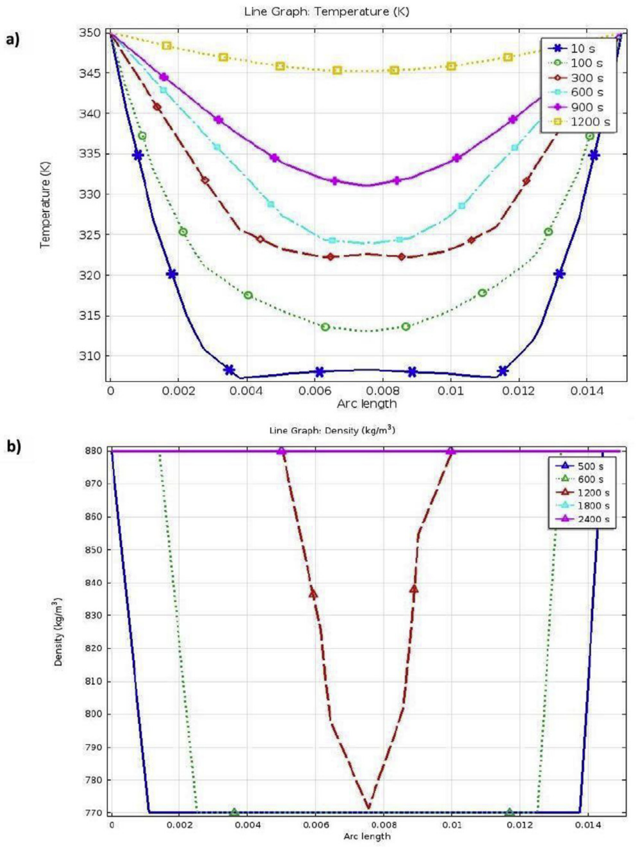

Fig. 5. Temperature distribution along cross section of porous media at various time steps (a) and density of condensed liquid and fines interface in porous media (b).

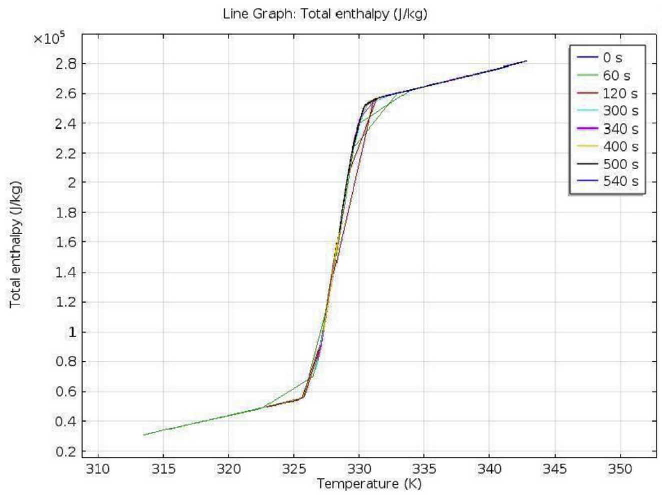

Fig. 6. Total enthalpy in porous media due to condensate formation.

liquid. It can be assumed that during lean condensate flow a few particles get detached from the rock surface and multiple particle detachment and suspension occurs in rich gas condensates. Additionally, during the gas phase change into lean condensate there will be few amounts of heat release to the pore chamber. The high heat release rate can be achieved during rich condensate transition. This type of heat release from one phase to another is called as a phase change heat transfer. This topic is almost unprecedented to the reservoir engineering community. The combined heat and condensed liquid flow, enhances the pore temperature and as a result the fines get detached and suspended. Later, due to inertial force it gets plugged and strained in the pore throat (Kampel, 2007). Also, during particle detachment there is an increase in the surface energy and entropy of pore chamber, where the condensed liquid and heat is stored. During particle capture at the pore-throat, the surface energy and entropy get decreased to a great extent. Subsequently, declining the porosity, and permeability, which altogether contribute to the well productivity loss.

Fig. 5 shows the temperature distribution along the cross section of porous media at different time steps and lean condensate liquid density and fine particle interface in porous media. It can be seen from the figure (a) that the temperature varies in increasing capillary bundle tube arc length. It is mathematically defined as the pore chamber of radius r with central angle θ radians or a portion (length of the arc divided by the radius of the arc) of a pore chamber in which the condensation has occurred. Actually, it is measuring the condensation from a pore point by taking its length, radius, and angle into an account.

Initially the temperature is around 350 K, but it suddenly decreases for increasing arc length. At 10s fluid phase transition time, the initial temperature was measured to be 352 K and it declines to 335 K for 0.001 arc length and further decreases to 307 K for the arc length of 0.003. Then, it linearly stabilizes till 0.011 arc length and after that it rises to 320 K at 0.013 arc length and then rises up to 358 K. A flat "U" shaped curve was obtained and similar curves were observed for another phase transition times like 100s, 300s, 600s, 900s, and 1200s. The only difference between the initial and other fluid phase transition time are, the fewer declines in the temperature level. For instance, 300s showed moderate temperature decline and 1200s showed least fall in the temperature. The fine particle may get detach, suspends, and strained in any zone of the capillary model arc length. Higher temperatures lead to high transfer in porous media and therefore, the fine particle can be transported at a higher rate in porous media along with condensate carrier fluid.

It can be seen from the right side figure that the liquid and fine particle interface density decreases for increasing arc length. At 500s fluid phase transition time there is huge interfacial density difference. In this case also, a flat "U" shaped curve was acquired, which indicates the possibility of Non-Newtonian flow in the porous medium due to density differences. A similar curve was obtained for another phase transition time, but the 2400s time showed a flat or linear behavior, which indicates no change in the density. But, the 1200s phase transition time exhibited different behavior. Till some point, this line also showed a linear behavior, but at the arc length of 0.006 it plummets to 835 kg/m^3 density. Then, finally touching to 771 kg/m^3 at the arc length of 0.008. After that, as usual, it climbed to initial position. Generally, the suspended fines in the liquid condensates will increase the density of the overall fluid in pore chamber. The suspended particles will oscillate and collide with the pore walls and sloshing of liquid condensate fluid may occur in the pore chamber (Abbaspour and Hassanabad, 2010; Greenspan, 2005). As a result, there will be a loss in fluid momentum and surface energy as well. In this case, it takes long time for fines to get trapped in pore throat.

Fig. 6 shows the total enthalpy in porous media due to the formation of condensates. It can be seen from this figure that the liquid condensate enthalpy raises both linearly and exponentially for increasing porous medium temperature. Typically, gas reservoir has good enthalpy and during phase transition that is converting to liquid due to reservoir pressure depletion the gas phase will emit high amount of enthalpy. This release of energy may generate a non-isentropic flow, which also detach the fines from pore surface. From Fig. 6, it was noticed that at 314 K temperature and for 120s phase transition time, the enthalpy is around 0.3×10^5 J/KG and it rises to 0.5×10^5 J/KG. This growth is linear and after that it suddenly exhibited an exponential growth till 2.5 J/KG. Later it again showed a linear growth till 2.81×10^5 J/KG at a temperature of 343 K. A similar curve was exhibited for other phase transition times. It may be inferred that the linear line of enthalpy may be attributed to the formation of lean condensates, whereas the

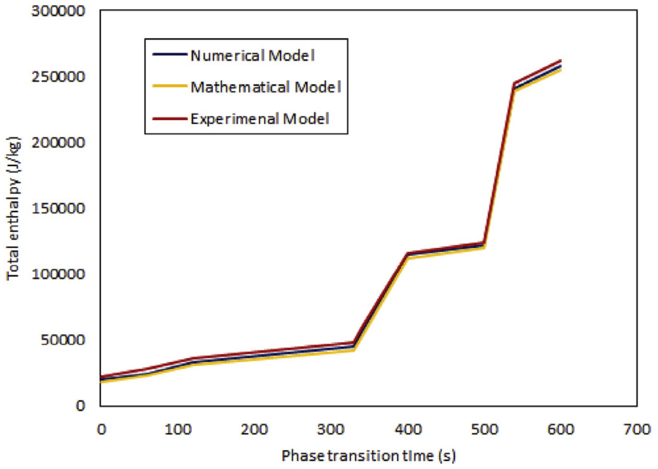

Fig. 7. Model correlations for a condensate reservoir.

exponential and upper linear areas are attributed to the rich gas condensate formation. It can be seen from Fig. 7 that there is a close correlation between numerical, mathematical, and experimental models. The correlation was plotted between the phase transition time and total enthalpy. Major factors such as temperature, pressure, heat release rate, and mass flow rate 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 the fines induced reservoir formation damage of condensate reservoirs. Overall, this paper has successfully demonstrated the fines migration and transport mechanisms due to the colloidal force of condensate fluids in porous media.

5. Conclusions

Firstly, analytical model describing particle detachment and pore throat entrapment due to lean and rich condensates in porous media was successfully derived. Also, the numerical phase transition of lean and rich condensates was modeled. During fluid phase transition there is a release of heat in porous media. This heat release along with condensed liquid detached the fines. Then, the suspended fines will be transported in pore space and later captured in pore-throat and thereby, reducing the permeability. Overall, contributing in the loss of well production. The enthalpy release from lean and rich condensates enhances the porous reservoir temperature. During temperature rise, there will be a decline in the electrostatic temperature and as a result the fine particles easily get detached from the pore surface. Additionally, the detached particle increases the surface energy and entropy in the pore chamber, which gives the space for liquid and heat storage. All models were examined for validation and revealed good agreement. To the best of our knowledge, this is the first paper to elucidate the importance of the impacts of fines lean and rich gas condensates on fines migration and permeability damage. For many decades, damages occurred in condensate reservoirs are seen in a traditional way, but this paper has handled this problem in an unconventional thinking that is form a thermodynamic viewpoint. Therefore, this paper has given a theoretical, analytical, and numerical framework for fines migration mechanism due to lean and rich gas condensates in porous media.

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Appendix B. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jngse.2018.05.030.

Nomenclature

CAD	Computer aided design
CFD	Computational fluid dynamics
UPW	Upper pore wall
LPW	Lower pore wall
FEM	Finite element analysis
A_1	Area of upper pore wall
A_2	Area of lower pore wall
E_1	Energy in upper pore wall
E_2	Energy in lower pore wall
T	Temperature
Q	Heat flux
L	Arc length
x	x direction
y	y direction
z	z direction
c	Phase change factor
k	Thermal conductivity
r	Radius
n	Serial number of fluid flow rate
s	Surface
t	time
u	Velocity
v_n	Rock liquid interface velocity
T_s	Surface temperature
T_K	Temperature at permeable zone
T_r	Temperature at radial zone
T_c	Temperature of condensed liquid
T_g	Temperature of gas phase
T_l	Temperature of liquid phase
d_z	Arc length distance in z direction
C_p	Specific pressure at a particular phase
Q_p	Heat flow at a particular phase
Q_{vd}	Heat flow in specifc arc length
Q_{oop}	Heat flow in pore space
S_L	Surface energy with respect of pore length
W_k	Presents the net work done to migrate the reservoir fines in porous media
J^m	Conduction current
h_{rl}	Latent heat of condensation
k_l	Lqiuid thermal conductivity
k_r	Rock thermal conductivity
ρ_i	Partial component of bulk density
λ_i	Charge per unit mass of the ith Component
u_i	Velocity of the ith component
h_l	Liquid enthalpy
h_r	Rock enthalpy
u_p	Fluid phase change velocity
u_ρ	Density change
$q_l'' - q_r''$	Differences in the liquid and rock heat fluxes
$T_{r2} - T_{r1}$	Difference between the pore throat and chamber radius
ϕ	Porosity
π	3.14
σ	Stress
θ	Angle
μ	Viscosity
ρ	Fluid density
∇	Change in physical variable

∇_T	Temperature Change
ψ_m	Change in the mass of the phases
ρ_r	Rock density
ρ_l	Liquid density
$\eta_{\phi k}$	Thermal efficiency of porous rocks with respect to thermal conductivity of rock
q_{cl}	Phase change fluid flow
ζ_m	Fine momentum
ε_1	Radiation emission from upper pore wall
ε_2	Radiative emission from lower pore wall
$\rightarrow =$	Fines attachement in vector quanity
$\overset{\alpha}{\rightarrow}$	Fines detachment in vector quanity
$\overset{\beta}{\rightarrow}$	Fines straining in vector quanity
$\overset{\gamma}{\rightarrow}$	Suspended fines in a condensed liquid and flow as well
$\overset{\beta_{ql}}{\underset{\gamma\ ql}{\rightarrow}}$	Fines straining due to phase change fluid flow

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