Riemann Solution for system of balance law modeling steam injection with several components and phases into a porous medium.

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Abstract

Generally, more than 50% of all the oil contained in the reservoirs cannot be recovered by primary and secondary techniques. In the case of the heavy oil, the recovered amount is not 30% of the total.

This is a problem, because most of the reserves that are discovered nowadays consist basically of this type of hydro-carbon. With the decline of the light oil reserves, the exploration of heavy oil and similar will be indispensable for the maintenance of the demand each day increasing of this material in the world.

The great difficulty of the recovery of the heavy oil is basically because this is very viscous relatively to the injected fluid to dislocate it in the secondary process (in general gas or water) and therefore has little mobility. An applied sufficiently useful form for the reduction of viscosity is the heating of the oil in the well and one technique applied for that is the vapor co-injection.

These physical phenomena are modeled by a class of balance equations where the balance represents the mass interchange between phases in porous media.

We present a new general theory which deals with Riemann solution for a large class of balance equations. As applications of this theory, we present a model of steam/water/nitrogen injection in a horizontal porous media. The systems of equations are based on mass balance, energy conservation and Darcy law of force. We neglect compressibility, heat conductivity and capillarity effects. We develop the general theory for a 4x4 system of balance equations. We solve the Riemann problem with application to clean up sites.

1. INTRODUCTION

The most part of the oil in the world is heavy oil. This oil is a class of hydrocarbons with large chain of carbons and hydrogen. A common characteristic of heavy oils is that they are much viscous. Several techniques to improve the oil recovery have been developed. Important techniques are the called thermal methods. Thermal methods are divided into two large groups. One group encompasses the techniques in which heat is injected into the porous medium, a category encompassing steam injection. In other group heat is generated locally in the porous medium, usually by means of combustion.

In oil recovery, combustion utilizes a small part of the oil in the reservoir. Air is injected and the oxygen participates in the chemical reactions.

In such of hot fluids and gases undergoing mass gain, loss or transfer, flows involving chemical reactions a system of balance laws is required to describe the flow.

In our work, we are interested in models for flow in porous media of form:

\[ G_i + ( uF )_i = Q, \]

for such flows \( Q \) represents mass transfer of chemical components between phases with no net gain or loss of component mass, as well as conservation of total energy. The variable \( u \) representing the Darcy speed also appears, but only in particular way within the flux term:

The variables in (1) are \( V \in \Omega \subset \mathbb{R}^m \) and \( u \in \mathbb{R} \). In this model, the variable \( u \) is not constant, generically. System of type model thermal compositional flows in porous media. The variable \( u \) is called speed because this is its interpretation in many applications; the pair \( (V, u) \) in \( R^{m+1} \) is called state variable. \( G \) and \( F \) are the vector-valued functions \( G = (G_1, G_2, \cdots, G_{m+1})^T: \Omega \rightarrow \mathbb{R}^{m+1} \) and \( F = (F_1, F_2, \cdots, F_{m+1})^T: \Omega \rightarrow \mathbb{R}^{m+1} \), where \( uF_i \) is the flux for the conserved quantity \( G_i \) and \( \partial G_i / \partial t \) is the corresponding accumulation term, for \( i = 1, 2, \cdots, m+1 \). On the right hand side in \( Q = (Q_1, Q_2, \cdots, Q_{m+1})^T: \Omega \rightarrow \mathbb{R}^{m+1} \), the first \( m \) terms represent mass transfer and \( Q_{m+1} \) represents energy conservation. Generically for a thermally
isolated system, the first \( m \) equations represent mass balance for different chemical components in different phases and the \((m+1)\)-th equation represents the conservation of total energy, which usually can be represented by setting \( Q_{m+1} = 0 \). The functions \( G \), \( F \) and \( Q \) are continuous in the whole domain \( \Omega \), but later we will see that they are only piecewise \( C^2 \). The equations are supplemented by relationships expressing local thermodynamic equilibrium in each of the \( C^2 \) parts.

The solution \( V(x,t) \) and \( u(x,t) \) for \( x \in R \) and \( t \in R^+ \) needs to be determined. The terms \( Q \) often generate fast variations in the solution due thermodynamic processes; this is another reason to regard the solution as distributions and must be taken in the weak sense. Despite the fact that the variable \( u \) does not appear in the accumulation term, but only in the flux term and despite the presence of the transfer term \( Q \) formally breaking scale invariance, we are able to solve the complete Riemann problem associated to Eq.(1). In fact, a general theory to deal this class of equations is proposed in , extending recent works of Bruining (2003, 2006) et. al.

This theory encompasses and generalizes the bifurcation phenomena for systems that change type discovered over the last two decades, see Isaacson et. Al. (1992) and references therein. Modern theory of conservation laws was used for the study of combustion by Mota et. al. (2002) , focusing on the study of the internal structures of combustion front which is a classical problem in engineering, see Souza et. al. (2006).

In the last decades, steam injection has been adapted for clean-up of organic contaminants from the subsurface, the so called groundwater remediation. The organic pollutants are referred to as non-aqueous phase liquids; they are divided into two large groups: DNAPL and LNAPL. The DNAPL's are denser than water; examples of DNAPL are chlorinated solvents. It is very difficult to decontaminate soils containing these substances because they can enter deeply underground. The LNAPL's are the substances less dense than water, such as gasoline and oil.

Traditional remediation of contaminated sites consists of groundwater extraction and clean up of the drained liquid; this technique is called pump-and-treat, see EPA Report (1996) and references therein. The material is treated and discharged in another place. This method is very expensive and time-consuming, for example, in the Visalia test site, in California, polluted with creosote (a NAPL fluid), the estimated costs for pumping and treating are \( US 26,000 \) per gallon of creosote and the expected time for this procedure is 3250 years. It is inefficient to clean up sites contaminated with DNAPL's (dense non aqueous phase liquids). So removal of contaminants with steam is considered as an alternative; for the same site in Visalia, the estimated cost per gallon of creosote removed with steam is \( US 130 \) and the time to clean up is approximately 3 years, see Cummings.

In Davis (1998), Davis described the mechanism of steam injection. For clean up, steam is injected in the soil by using wells. Initially the steam heats the formation around the wells. The steam condenses as the latent heat of vaporization of water is transferred from the steam to the region around the wells. As more steam is injected, the hot water moves into the formation, pushing the water initially present in the rock, which is at the ambient temperature. When the porous medium at the injection region has absorbed enough heat to reach the temperature of the injected steam, steam itself actually enters the medium, pushing the cold water and variables \( V \) the bank of condensed steam in front of it. When these hot liquids reach the region that contains the volatile contaminant, the contaminant is displaced.

Since the temperature of the volatile contaminant increases part of this contaminant evaporates originating a gaseous flow with organic components.

Notice that in this model there appear several physical situations and that there is mass transfer between the phases. The total energy is conserved, a fact that is modelled by using the conservation law for energy. The conservation of mass in the flow together with Darcy's law for porous media have motivated the introduction of equations of type (1). In , we propose a general formalism for solving this class of equations. We consider the different physical situations as simple connected subsets state of \( R^n \). Physical situations are adjacent in state space. There exists a linear map \( E \) that takes the system of balance laws (1) into a system of conservation laws:

\[
EG_i + (uEF)_i = 0, \tag{2}
\]

associated to each physical situation. After this elimination, further simplifications using thermodynamical constraints may occur in each physical situation is described by \( V \) a set of that is a subset of the set of original variables. Of course, each of the systems of type (2) has fewer equations than the complete system (1).

Since models with many components (such as oil, water, nitrogen) and many phases (heavy and volatile oil, water and steam, gaseous nitrogen) have very long construction, we present here a representative model that captures several phenomena of complete model. The physical model is for steam and nitrogen injection based on mass balance and energy conservation equations. We study the three possible physical phase mixture situations: the single-phase gas situation, \( spg \); the two-phase situation, \( lp \); and the single-phase liquid situation, \( sp\). For each physical situation, we reduce the four balance equations system presented in Section 2 to a system of
conservation laws of type (1) supplemented by appropriate thermodynamical constraints between variables, such that Clausius-Claperyon law. Here $V = (V_1, V_2)$ is a subset of the variables: gas saturation $s_g$, steam composition $\psi_{gw}$ and the temperature $T$ and it represents the unknowns in each physical situation; $G = (G_1, G_2, G_3)$ and $F = (F_1, F_2, F_3)$ are the accumulation vector and the flux vector, respectively; $u$ is a total velocity. The state of the general system is represented by $(s_g, \psi_{gw}, T, u)$. Equation (1) has an important feature, the variable $u$ does not appear in the accumulation term, it appears isolated in the flux term, thus this equation has an infinite speed mode associated to $u$; nevertheless we are able to solve the Riemann problem for Equation (1), which is a mathematical novelty.

In Section 2, we present the physical model that describes the injection of steam and nitrogen in a one-dimensional horizontal porous rock filled with water; we present also the model equations for balance of water, steam, nitrogen and temperature. The full system is not a system of conservation equations, since there is a water mass source term $q_{aw} \rightarrow$, which is the condensation rate between the water and steam phases. In Section 3, we describe three physical situations in which the balance system reduces to conservation systems of type (1).

In Section 4, we study the type of waves that appear in the solution. It is remarkable that in the two phase situation there is an evaporation rarefaction wave; we show also an example of the Riemann solution for a mixture of steam and nitrogen in the $spg$ into a rock filled with water. In Section 5, we draw the summary and conclusions.

2. Physical Model

We consider the injection of steam and nitrogen in a one dimensional horizontal porous rock core filled with water. The core consists of rock with constant porosity $\phi$ and absolute permeability $\kappa$. We assume that the fluids are incompressible and that the pressure changes are so small that they do not affect the physical properties of the fluids. We are interested in scales dictated by field reservoirs. The effect of spatial second derivative terms (capillary pressure, heat conductivity, etc) is to widen the heat condensation front, while the convergence of the characteristics tries to sharpen it. The balance of these effects yields the width of the condensation front. In the field this width is typically a few tenth of centimeters; on the other hand, the distance between injection and production wells is of the order of 1000 meters. Thus this widths is negligible, so we can set it to zero and simplify our analysis with no error of practical importance, thus we disregard the diffusive terms, so that the Riemann solution can be found.

Darcy’s law relates pressure gradient in each fluid phase with its seepage speed:

$$u_w = -\frac{kk_{rw}}{\mu_w} \frac{\partial p}{\partial x}, \quad u_g = -\frac{kk_{rg}}{\mu_g} \frac{\partial p}{\partial x}. \quad (3)$$

The fractional flow functions for water and steam are given by:

$$f_w = \frac{k_{rw}/\mu_w}{k_{rw}/\mu_w + k_{rg}/\mu_g}, \quad f_g = \frac{k_{rg}/\mu_g}{k_{rw}/\mu_w + k_{rg}/\mu_g}. \quad (4)$$

Using Darcy’s law (3) and (4) we can write $u_w$ and $u_g$ as:

$$u_w = uf_w, \quad u_g = uf_g, \text{ where } u = u_w + u_g \quad (5)$$

is the total or Darcy velocity; $s_w$ and $s_g$ are the water and gas saturation.

2.1. Model Equations

Using (5), we write the equations of mass balance for liquid water, gaseous steam and gaseous nitrogen as:
where \( q_{g \rightarrow w, w} \) is the water mass source term (the condensation rate between the water and steam phases); \( \rho_w \) is the constant water density, \( \rho_{gw} \) (\( \rho_{gn} \)) denote the concentration of steam (nitrogen) in the gaseous phase (mass per unit gas volume); in the presence of liquid water, thermodynamic considerations specify how these concentrations depend on temperature, see Bruining and Marchesin (2006). The saturations \( s_w \) and \( s_g \) add to 1.

By (4), the same is true for \( f_w \) and \( f_g \). The equation of energy conservation is based on an enthalpy formulation. We neglect heat conduction, so the energy conservation is given by:

\[
\frac{\partial}{\partial t} [ \varphi (H_w + s_w H_g + s_g H_g) ] + \frac{\partial}{\partial x} (u f_w H_w + u f_g H_g) = 0.
\]

Here \( H_w = \rho_w h_w \), \( H_g = \rho_{gw} h_{gw} + \rho_{gn} h_{gn} \), \( H_r \) is the rock enthalpy per unit volume and \( \hat{H}_r = H_r/\varphi \); \( h_w \), \( h_{gw} \) and \( h_{gn} \) are the enthalpies per unit mass of water in the liquid aqueous phase, of water in the gaseous phase and of nitrogen in the gaseous phase; these enthalpies depend on temperature, see Lambert (2006).

Again, there is only one thermodynamic variable, which is the temperature. Since \( s_w = 1 \) and \( s_g = 0 \), we have \( f_w = 1 \) and \( f_g = 0 \). From Equation (7), \( q_{g \rightarrow w, w} \) vanishes. One can prove that the total Darcy velocity \( u \) is independent of position. We assume that rock and water enthalpy depend linearly on temperature, see Lambert (2006), so Equations. (6) - (8) become:

\[
\frac{\partial}{\partial t} T + \frac{\partial}{\partial x} (u_w T) = 0, \quad \text{where} \quad \lambda_T^w = u_w \frac{C_w}{\varphi C_w + C_r},
\]

where we use \( u_w \) to indicate that the velocity is spatially constant in the \( sp \), \( V \) is the temperature \( T \); \( C_w \) and \( C_r \) are water and rock capacity.

Figure 1 shows the three physical situations in the variables \( V = (T, \psi_{gw}, s_w) \).
Figure 1. a) Left: Phase space for $V = (s, \psi, T)$ and physical situations in admissible regions. Figure 2. Right: The physical region in the $\{T, \psi_{gw}\}$ plane where the spg occurs satisfying thermodynamical constraints, see Lambert (2006). The wide curve represents the temperature saturation for a mixture of water and nitrogen. The horizontal rarefaction curves are associated to $\lambda_T$; the arrows indicate the direction of increasing speed. The vertical lines are contact discontinuity curves associated to $\lambda_\psi$, in which $\psi_{gw}$ changes, $T$ and $u$ are constant. $I_T$ is the thermal inflection manifold.

3. Riemann Problem

We are interested in the Riemann problem associated to (6) - (8), which is the solution of these equations with initial data

$$
\begin{aligned}
(s_L, \psi_L, T_L, u_L) & \quad \text{if} \quad x > 0 \\
(s_R, \psi_R, T_R, u_R) & \quad \text{if} \quad x < 0, 
\end{aligned}
$$

where $s = s_w$ is the water saturation and $\psi = \psi_{gw}$ is the steam composition. The speed $u$ is specified at the injection side. The general solution of the Riemann problem associated to Equation (2) consists of a sequence of elementary waves, namely shocks and rarefactions.

3.1. Shock waves

Discontinuities or shocks appear in solution of the Riemann problems and need to satisfy the Rankine-Hugoniot conditions (RH), see Lambert (2006), which can be written as:

$$
\nu^s \left( (G^+ - G^-)w^s - u^s (F^+ - F^-)w^s \right) = u^s (F^+ - F^-)w^s - u^s (F^+ - F^-)w^s,
$$

where $(V^+, u^+)$ is the state on the right of the shock and $(V^-, u^-)$ is the state on the left of the shock; $v^s$ is the shock speed; $G^+$ ($G^-$) and $F^+$ ($F^-$) are the accumulation and flux terms on the right (left) of the shock, which in general have different expressions in each physical situation. We specify the left conditions for the variables $V$ and $u$, but the right conditions are specified only for $V$. The speed $u^s$ is always obtained from the RH condition (12). For a given state $(V^-, u^-)$, the set of states $(V^+, u^+)$ that satisfies the RH condition (11) forms the Rankine-Hugoniot curve, which is denoted by $H(V^-, u^-; V^+, u^+)$. This locus in $V$ does not depend on the Darcy speed $u$. The expressions for the RH curve, the shock speed $v^s$ and $u^s$, for $[G_i] = G^+_i - G^-_i$ for $i = 1, 2$ are:
3.2. Characteristic speeds

In each physical situation a system of conservation laws in different forms must be used to find the characteristic speeds. If we assume that the solution is sufficiently smooth, we differentiate all equations in (2) with respect to their variables, obtaining a system of the form:

\[
B \frac{\partial}{\partial t} \begin{pmatrix} V \\ u \end{pmatrix} + A \frac{\partial}{\partial x} \begin{pmatrix} V \\ u \end{pmatrix} = 0,
\]

where the matrices \( B \) and \( A \) (which depend on \( V \)) are the derivatives of \( G(V) \) and \( uF(V) \) with respect to the variables \( V \) and \( u \). Since \( G(V) \) does not depend on \( u \), the last column in matrix \( B \) is zero. The characteristic values \( \lambda \) and vectors \( \tilde{r}_i \), (where \( i \) is the label of each eigenvector) for the following system are the rarefaction wave speeds and directions:

\[
A \tilde{r}_i = \lambda B \tilde{r}_i \quad \text{where} \quad \lambda \text{ is obtained by solving } \det(A - \lambda B) = 0.
\]

For each \( i \), the rarefaction waves in the \( \{x,t\} \) plane are solutions of

\[
\begin{pmatrix} \frac{dV}{d\xi} \\ \frac{du}{d\xi} \end{pmatrix} = \tilde{r}, \text{ with increasing } \xi \text{ satisfying } \xi = x/t = \lambda(V(\xi),u(\xi)).
\]

It is remarkable that in \( V \) the rarefaction curves do not depend on the Darcy speed \( u \) and that \( u \) does not change sign on the rarefaction waves. From this property, which is valid also to shocks, it is possible to show that the Riemann solution can be solved only in the space of variables \( V \); then \( u \) can be calculated as a function of \( V \), see Lambert (2006). It is also remarkable that in the \( tp \) situation there is an evaporation rarefaction wave.

We have some interesting results:

**Theorem 1:** Let \( u_L \) be positive. The primary variables \( V \) in the shock and rarefaction curves do not depend on the left Darcy speed \( u_L \). The Riemann solution has the same sequence of waves and states for all Riemann problems with initial data satisfying:

\[
\begin{cases} 
(V_L, \cdot) & \text{if} \quad x < 0 \\
(V_R, \cdot) & \text{if} \quad x > 0.
\end{cases}
\]

**Theorem 2:** Assume that \( u_L \neq 0 \). If the Darcy speed \( u_L \) in the initial data is modified while \( V_L \) and \( V_R \) are kept fixed, the Darcy speed \( u_R \) as well as the Riemann solutions are rescaled in the plane \( \{x,t\} \), while the wave sequences and the values of \( V \) are kept unaltered.
4. The Riemann solution for steam and nitrogen injection

We consider the injection of a mixture of steam and nitrogen in the superheated state below the boiling temperature of pure water at prevailing pressure into a rock saturated with water:

\[
\begin{cases}
  (0, \psi_L, T_L, \cdot) & \text{if } x = 0 \text{ (the injection point)}, \\
  (1, \psi_{gw}(T_R), T_R, \cdot) & \text{if } x > 0.
\end{cases}
\]  

(17)

4.1 Waves in the solution

A Riemann solution is a sequence of elementary waves \( W_k \) for \( k = 1, 2, \cdots, m \) (shocks and rarefactions) and constant states \( W_k \) for \( k = 1, 2, \cdots, m \) :

\[
W_L \equiv W_0 \xrightarrow{w_1} W_2 \xrightarrow{w_2} \cdots \xrightarrow{w_m} W_m \equiv W_R. 
\]  

(18)

We represent any state by \( W \). The wave \( w_k \) has left and right states \( W_{k-1} \) and \( W_k \) and speeds \( \xi_k^- < \xi_k^+ \) in case of rarefaction waves and \( v = \xi_k^- = \xi_k^+ \) in case of shock waves. The left state of the first wave \( W_1 \) is \( (V_L, u_k) \) and the right state of \( W_m \) is \( (V_R, u_R) \), where \( u_R \) needs to be found. In the Riemann solution it is necessary that \( \xi_k^+ \leq \xi_{k+1}^- \); this inequality is called geometrical compatibility. When \( \xi_k^- < \xi_{k+1}^- \) there is a separating constant state \( W_{k+1} \) between \( W_k \) and \( W_{k+1} \). If \( \xi_k^+ = \xi_{k+1}^- \) there is no actual constant state in physical space, so the wave \( W_k \) is a composite with \( W_{k+1} \).

4.1.1 Single-phase gaseous situation

There are two waves: a thermal and a compositional wave. On the thermal wave, the temperature and speed change while the gas composition is constant. The characteristic speed is denoted by \( \lambda_T \). On the compositional wave, the gas composition changes while the temperature and speed are constant. This wave has speed denoted by \( \lambda_c \). The characteristic speeds are positive and \( \lambda_c > \lambda_T \).

![Figure 3: Left: The condensation shocks \( S_c \) in the \( tp \) situation. The state indicate in each curve is the initial point for \( S_c \). The Buckley-Leverett curves are in the vertical lines with constant temperature. Figure 4: Right: The states and curves in the \( tp \) situation.](image-url)
4.1.2 Two-phase situation

There are two waves: an evaporation rarefaction wave and a saturation (Buckley-Leverett) wave, both isothermal. On the evaporation rarefaction wave, the saturation, temperature and speed change. The characteristic speed is denoted by $\lambda_e$. The condensation shock is denoted by $S_e$ and its speed is $v_e$. On the saturation wave, the water saturation changes, but the saturation and speed are constant. The characteristic speed is denoted by $\lambda_{BL}$ (Buckley-Leverett); this rarefaction wave is represented by $R_{BL}$. The shock is the Buckley-Leverett shock $S_{BL}$ and its speed is denoted by $v_{BL}$.

4.1.3. Shock between regions

Between the $spg$ and $tp$ situations, there is a condensation shock with speed $v^{GT}$, which is denoted by $S_{GT}$.

4.2. Riemann Solution

We consider the Riemann problem with left and right states in the form (17): $L$ has $\psi_L = 0.1$, $T_L = 340K$ and $R$ has $T_R = 300K$.

Since $L$ is in the $spg$ situation, see Figure 4, $S_{GT}$ connecting $L$ and an intermediate state $E_1$. This state is obtained on the $S_{GT}$ shock where $\psi^{GB}(L; E_1) = \lambda_{BL}(E_1)$. This state is obtained by the intersection of the Rankine-Hugoniot curve $S_{BL}$ from $L$ with the coincidence curve between $v_{BL}$ and $\lambda_{BL}$. We can verify that $\psi^{GB}(L; E_1) < \lambda_T(L)$.

From $E_1$ there exists an isothermal rarefaction $R^{BL}$ up to $E_2$, with fixed temperature $T_{E_1}$. The state $E_2$ is obtained using the “left characteristic shock curve”.

The “left characteristic shock curve” is constructed by the coincidence between the state $P_1$ on the $R^{BL}$ (from $E_1$) and the state $P_2$. The state $P_2$ belongs to the evaporation shock $S_e$ (from $P_1$) and the vertical line from the right state $R$, in which the equality $v_e(P_1; P_2) = \lambda^{BL}(P_1)$ is satisfied. The vertical lines represent isothermal Buckley-Leverett shock and rarefaction curves.

Thus the state $E_2$ is obtained from the intersection between the vertical line starting at the right state $R$ and the “left characteristic shock curve”, see Figure 4.

The state $E_3$ is obtained from the intersection between the $S_e$ starting at $E_2$ and the vertical line from the right state $R$. From $E_3$ there is an isothermal rarefaction up to $E_4$. The state $E_4$ is obtained as to satisfy the equality $\lambda^{BL}(E_4) = v^{BL}(E_4; R)$. The solution is summarized in the Figures 5 and 6.

Condensation of water occurs in the shocks $S_{GT}$ and $S_e$ between the states $L - E_1$ and $E_2 - E_3$.

5. Summary and Conclusions

We have described a solution of the Riemann problem for the injection of a mixture of nitrogen and steam into a porous rock filled with water and sketched a systematic theory for the Riemann solution. The set of solutions depends $L^1$ continuously on the Riemann data. It is a step towards obtaining a general method for solving Riemann problems for a wide class of balance equations with phase changes, see Lambert (2006).

Practically, this solution shows that in principle it is possible to clean up NAPL’s from soil with a mixture of nitrogen and steam at moderate temperatures, ($67^\circ C$).
Figure 5: Left: Riemann solution in phase space $V$, described in Section 6. In the Riemann solution, we have removed the surface in the phase space of Figure 2. Figure 6: Right: The saturation, temperature and gas composition profiles for some $t > 0$. In both Figures, the numbers 1 to 4 indicate the intermediate states $E_1$ to $E_4$.

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Solução de Riemann para sistemas de leis de balanço modelando injeção de vapor com diversas fases e componentes em um meio poroso.

Resumo

Geralmente, mais da metade de todo o petróleo contido nos reservatórios não pode ser recuperado pelas técnicas primárias e secundárias conhecidas. No caso do petróleo pesado, a quantidade recuperada não chega a um terço do total.

Isto é um problema, pois a maior parte das reservas que são descobertas hoje em dia constitui-se basicamente desse tipo de hidrocarboneto. Com o declínio das reservas de óleo leve, a exploração de óleo pesado e afins será indispensável para a manutenção da demanda cada vez mais crescente desse material no mundo.

A grande dificuldade da recuperação do óleo pesado é basicamente porque este é muito viscoso relativamente ao fluido injetado para deslocá-lo no processo secundário (em geral gás ou água) e portanto tem pouca mobilidade. Uma forma bastante útil aplicada para a diminuição da viscosidade é o aquecimento do óleo These physical phenomena are modeled by a class of balance equations where the balance represents the mass interchange between phases in porous media.

Nós apresentamos uma nova teoria que trata com soluções de Riemann for uma larga classe de leis de balanço. Como aplicação dessa teoria, nós apresentamos um modelo de injeção de vapor/água/nitrogênio em um meio poroso horizontal. O sistema de equações são baseados em leis de balanço de massa, conservação de energia e lei de Darcy para a velocidade. Nós negligenciamos compressibilidade, condutividade de calor e efeitos de capilaridade. We neglect compressibility, heat conductivity and capillarity effects. Nós desenvolvemos uma teoria geral para um sistema 4x4 de equações. Nós resolvemos o problema de Riemann com aplicação a limpeza de solos.

Fluidos multifásico, injeção de vapor, Problema de Riemann, Leis de Balanço.

Os autores são os únicos responsáveis pelo conteúdo deste artigo.