Two-Phase Modeling of Gravity Drainage of Bitumen from Tar Sand Using In-Situ RF Electrical Heating

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Abstract: Two-phase movement of bitumen and air in tar sand porous deposit is modeled using COMSOL multiphysics. A system of non-linear PDE(s) for the movement of each of the phases is coupled with heat transfer equation to account for heat diffusion through the media. The deposit is heated volumetrically and locally by using in-situ RF technology that was developed by Pyrophase, Inc. The effects of variation in properties of bitumen and reservoir media due to temperature and pressure are considered. These properties are derived from experimental data (e.g. viscosity, capillary pressure and relative permeability) obtained from earlier measurements by IIT Research Institute (IITRI). The Van Genuchen model is used to relate the data to the parameters in the two-phase model. The COMSOL system demonstrates acceptable capability and flexibility in solving the equations and setting logical boundary and initial conditions to model flow under conditions of temperature and pressure variation.

Keywords: In-situ electrical heating, radio-frequency heating, multiphase flow modeling, gravity drainage, bitumen recovery, tar sand, IITRI.

1. Introduction

The existing world energy demand is currently dominated through the use of conventional hydrocarbon resources, which supply about 85 percent of the world's energy [1]. World energy consumption is projected to increase by 71 percent from 2003 to 2030 [1], while these conventional resources (especially oil) are diminishing. With the current high prices of crude oil, extraction of non-conventional hydrocarbon resources such as tar sand and oil shale become more economically feasible. The large amount of such resources around the world (especially in the US and Canada), are encouraging the energy producing companies to invest more on developing innovative technologies for extraction from these resources.

In-situ electrical heating technologies are among the most recent technologies used for bitumen recovery from tar sand and oil shale. These technologies have limited environmental impact because there is little disturbance of the land, and water and solvents are not used. IIT Research Institute (IITRI) back in the 80's was a pioneer in using radio-frequency (RF) energy to volumetrically heat a large block of tar sand or oil shale [2]. The in-situ RF technology is being further developed by the same team of inventors working for Pyrophase Inc. since then. In this technology, the non-conventional resource of tar sand is volumetrically heated to reduce the viscosity of the bitumen product, which then flows by gravity to collection points over a period of a few months. Capillary pressure and relative permeability of the oil and air affect drainage because these forces are comparable to the gravity gradient.

Modeling of such processes requires a simulator with multi-physics flexibility and computational capabilities. This work is focused on modeling of two-phase movement of bitumen and air/gas within the porous media of tar sand deposit. A uniform RF heating pattern is assigned for the heat transfer equation and this equation is coupled with the two continuity equations for the two existing phases.

2. Objective

The main objective of this work is to test the COMSOL modeling techniques in a 2D geometry by using two different heating methods for reducing the bitumen viscosity. In the first method, the heat source is assumed to be inside the production well using a hot pipe, as with RFT heating process (Pyrophase Inc. [3]). In this, a constant temperature is assumed at the boundary of the well. In the second method, a uniform heat distributed through the entire volume is assumed. According to the experimental results of tri-plate line RF heating of a tar sand and oil shale media (demonstrated by IITRI, 1982 [2]), this method can uniformly heat up the media with approximately a constant rate until the evaporation temperature of water is reached. The heating rate drops as the media dries up but uniform temperatures of more than 250º*C* can be reached with this method.

3. Description of the Geometry

A cylindrical perforated production well is assumed to be vertically inserted into a homogeneous tar sand reservoir while the media is heated. The geometry is symmetrical around the perforated; therefore the problem can be solved in 2D which significantly speeds up the numerical calculations (Figure 1).

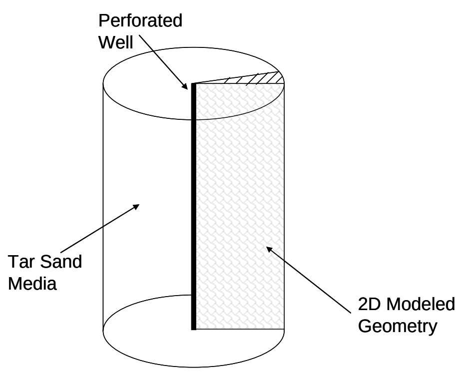

Figure 1. Cylindrical Geometry of the Tar Sand Media and the Perforated Well

COMSOL Multiphysics was used to solve the inter-connected equations numerically. Figure 2 represents the slice of the tar sand volume (shown in Figure 1) along with a perforated well (on the left side) in a 2D geometry. The mesh distribution used for the numerical calculations is also shown in this figure. For the first part of this study, a media with a diameter of 5 m and a depth of 2 m is numerically modeled and later the results are extended to a 45-m depth volume.

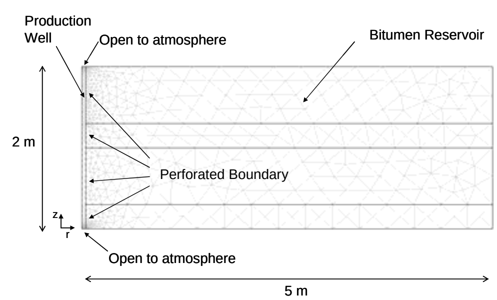

Figure 2. 2D Geometry Numerically Solved with COMSOL

4. Mathematical Model

4.1 Governing Equations

Two continuity equations can be derived for each of the wetting and non-wetting phases. By substituting Richard's equation (modified Darcy's Law) into a continuity equation, the following equations can be derived for each of the phases:

$$\frac{\partial(\rho_w \theta_w)}{\partial t} + \nabla \cdot \left[-\rho_w \frac{k_{rw} k_{abs}}{\eta_w} \nabla (p_w + \rho_w g D) \right] = 0 \tag{1}$$

$$\frac{\partial(\rho_{nw} \theta_{nw})}{\partial t} + \nabla \cdot \left[-\rho_{nw} \frac{k_{rnw} k_{abs}}{\eta_{nw}} \nabla (p_{nw} + \rho_{nw} g D) \right] = 0 \tag{2}$$

Where,

k_{abs}: Absolute Permeability, m^2

D: Elevation direction, *m*

k_{rw} & k_{rnw}: Relative permeabilities of wetting and non-wetting phases, *dimensionless*

θ_w & θ_{nw}: Volume fraction of wetting and non-wetting phases, *dimensionless*

η_w & η_{nw}: Dynamic viscosities of wetting and non-wetting phases, *Pa.s*

p_w & p_{nw} : Pressure of wetting and non-wetting phases, *Pa*

ρ_w & ρ_{nw}: Molar densities of wetting and non-wetting phases, kg/m^3

The capillary capacity of the wetting phase in contact with the non-wetting phase is defined as the slope of the capillary head curve versus the wetting phase volume fraction.

$$C_w = \frac{\partial \theta_w}{\partial h_c} = \rho_{H2O}\, g \frac{\partial \theta_w}{\partial p_c}$$

Where the capillary pressure is defined as $p_c = p_{nw} - p_w$. In this work, C_w is re-expressed in terms of ρ_{H2O} and p_c to be consistent with reference [4].

It is assumed that the wetting phase (i.e. bitumen) is incompressible but the non-wetting phase (i.e. air or gas) is compressible. According to the ideal gas law, variation in the non-wetting phase pressure and temperature has a direct effect on the density of this phase as follows:

$$\rho_{nw} = \frac{p_{nw}}{p_o}\frac{T_0}{T}\rho_o$$

Where the subscript "*o*" represents the non-wetting phase characteristics at ambient condition.

By substituting all the above assumptions into Equations 1 and 2, and by using the chain rule, the following equations can be derived:

$$\frac{C_w}{\rho_{H2O}g}\left(\frac{\partial p_{nw}}{\partial t}-\frac{\partial p_w}{\partial t}\right)+\nabla\cdot\left[-\frac{k_{rw}k_{abs}}{\eta_w}\nabla\left(p_w+\rho_w gD\right)\right]=0 \tag{3}$$

$$\rho_{nw}\frac{C_w}{\rho_{H2O}g}\left(\frac{\partial p_w}{\partial t}-\frac{\partial p_{nw}}{\partial t}\right)+\theta_{nw}\frac{\rho_o T_0}{p_o T}\frac{\partial p_{nw}}{\partial t}-\theta_{nw}\frac{\rho_o T_0}{p_o}\frac{p_{nw}}{T^2}\frac{\partial T}{\partial t} +\nabla\cdot\left[-\rho_{nw}\frac{k_{rnw}k_{abs}}{\eta_{nw}}\nabla\left(p_{nw}+\rho_{nw}gD\right)\right]=0 \tag{4}$$

The terms for compressibility of the non-wetting phase are the second and third terms on the left side of Equation 4. Equations 3 and 4 can be solved simultaneously for unknown pressures of the wetting and non-wetting phases.

Equations 3 and 4 show that the flow of each phase is initiated due to the pressure gradient (i.e. ∇p) as well as the fluid weight gradient (i.e. $\nabla(\rho gD)$). If there is a temperature gradient within the media, a significant gradient is generated in the fluid density that resulted in generation of a force in the opposite direction of the density gradient.

As mentioned before, two methods of heating are used in the media to increase the bitumen temperature. For the hot pipe method, the heat is generated at the boundary of the production well but for the volumetric RF heating method the heat is generated internally. An overall heat balance, including conduction and heat source terms, is defined as follow:

$$\rho_m C_{p,m}\frac{\partial T}{\partial t}+\nabla\cdot\left(-k_m\nabla T\right)=\dot{Q}_h \tag{5}$$

Where,

k_m : Heat conductivity of the reservoir media, *W/m°K*

$C_{p,m}$: Heat capacity of the reservoir media, *J/kg°K*

ρ_m : Density of the reservoir media, *kg/m^3*

$\dot{Q}_h$: Rate of heat generation due to volumetric RF heating, *W/m^3*

In COMSOL multiphysics, it is possible to define multi-dependent variables for each of the differential equations separately. For time-dependent equations, there is a matrix of mass coefficients for all the dependent variables that change with time. This matrix can be easily edited for any special purpose of modeling. To define equation 4 in COMSOL, for instance, the mass coefficients for each of the dependent variables are as follow:

$$for\ p_w:\quad \rho_{nw}\frac{C_w}{\rho_{H2O}g}$$

$$for\ p_{nw}:\quad -\rho_{nw}\frac{C_w}{\rho_{H2O}g}+\theta_{nw}\frac{\rho_o T_0}{p_o T}$$

$$for\ T:\quad -\theta_{nw}\frac{\rho_o T_0}{p_o}\frac{p_{nw}}{T^2}$$

4.2 Initial and Boundary Conditions

For Equations 3 and 4 the following initial conditions were assigned:

at t=0 $\quad p_w = \rho_w\, g(2-D) - p_{c,\text{int}}$

at t=0 $\quad p_{nw} = \rho_w\, g(2-D)$

According to experiments on Asphalt Ridge samples (IITRI Report [2]), about 10%*v/v* of the reservoir is occupied with air or volatile components. Since the average porosity of the media are about 26 to 32 percent, more than 30%*v/v* of the pore volume of reservoirs are initially empty. According to the van Genuchen model [5], the initial empty space corresponds to an initial capillary pressure ($p_{c,\text{int}}$) that, on average, initially is present all along the reservoir. Since the capillary pressure is defined as the difference between pressures of the wetting and non-wetting phases, the definition of initial pressures for the wetting and non-wetting phases should be consistent with this assumption (see above initial conditions).

Referring to Figure 2, the following expressions are the defined boundary conditions. No flow is assumed across the geometry boundaries. That corresponds to the case where another similar volume, using the same process, is adjacent.

At the top it is assumed that there is no flow of the wetting phase across the boundary, but the non-wetting phase can flow into the top of the perforated well:

$$\nabla\left(p_w+\rho_w gD\right)=0$$

$p_{nw} = p_{atm}$ (open to atmosphere)

At the bottom, both of the phases can flow in/out of the perforated well:

$p_w = p_{atm}$ (open to atmosphere)

$p_{nw} = p_{atm}$ (open to atmosphere)

In the first heating method, the heat is assumed to be generated inside the production well and gradually transfers across the media through conduction. Two constant temperature cases of 600º*C* and 300º*C* are assumed for the pipe at the boundary of the well, while the reservoir is initially assumed to be at ambient temperature. No heat flow is assumed across the geometry boundaries.

In the RF heating method, a uniform volumetric heat is assumed to increase temperature of the media. A constant heat rate of Q_h =30 W/m^3 is assumed for the entire volume. Ongoing RF modeling attempts from this author show that with an average electric field of 1000 *V/m*, the above heating rate is achievable for 45-m long tri-plate line electrodes.

4.3 Model Parameters

The following physical characteristics are used for the wetting phase, non-wetting phase and reservoir. The experimental data were obtained from IITRI report for Asphalt Ridge tar sand [2].

$\rho_w = 1000\ kg/m^3$ $\quad \rho_{nw,int} = 1.28\ kg/m^3$

$\rho_m = 2200\ kg/m^3$ $\quad C_{p,m} = 1300\ J/kg°K$

$k_m = 1.0\ W/m°K$ $\quad \eta_{nw} = 2e^{-5}\ Pa.s$

$\theta_s = 0.253$ $\quad \theta_r = 0.0127$

$k_{abs} = 9.8e^{-13}\ m^2\ (1\ Darcy)$

Figure 3 shows the changes in the bitumen viscosity as a function of temperature obtained experimentally by IITRI [2]. A constant viscosity of 6.0 *cP* is assumed for temperatures more than 150º*C*.

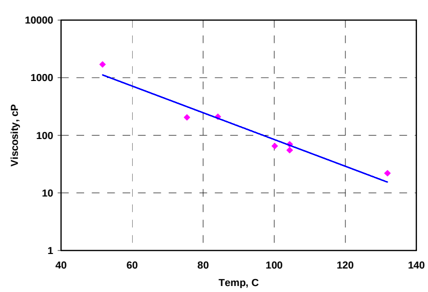

Figure 3. Bitumen Viscosity versus Temperature (IITRI Report [2])

As mentioned before, it is assumed that about 70 percent of the media porosity is initially occupied with bitumen and the rest is a mixture of air and volatile components [2]. To adjust the model parameters to the initial bitumen content, an initial capillary pressure of 2900 *Pa* is used through the entire media, corresponding to the initial volume fraction of the non-wetting phase.

5. Results and Discussions

Figures 4 through 7 show the changes in bitumen content and the temperature distribution after heating the reservoir boundary to 300º*C*. The background color shows the extractable (effective) bitumen volume fraction, in which red is 100 percent bitumen and blue is zero. The white lines indicate streamlines of velocity field of wetting phase across the reservoir and the black arrows show the flow direction of this phase. The strength of the bitumen velocity is proportional to dimensions of the arrows in each graph, independently. The colors of the vertical lines represent the temperature distribution, indicated by the scale on the far right side of each graph.

By decreasing the bitumen viscosity near the production well, bitumen flows into the well and drains at the bottom of the well. Gravity is the main force for flowing bitumen in the media but gas expansion, due to temperature, also affects the bitumen movement. Figures 5 though 7 represent that some of the bitumen flows to the bottom right side of the media, away from the production well (see the velocity streamlines). Because of the flow bottleneck at the boundary of the production well, there is accumulation of bitumen at the bottom of the media shown in red color in these figures (bitumen fraction, S_{ew}, close to 1).

Figures 8 through 11 show the same parameters for the case of volumetric heating of the media. In this case, temperature changes uniformly through the entire media. By using a heating rate of 30 W/m^3, temperature of 187º*C* is reached after 6 months (Figure 11).

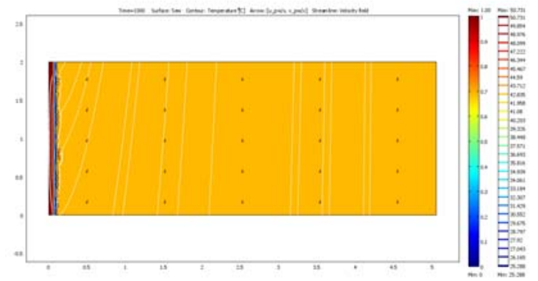

Figure 4. Hot Pipe Boundary Heating Result in Less than an Hour

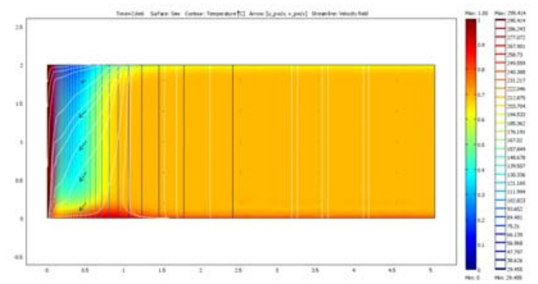

Figure 5. Hot Pipe Boundary Heating Result after One Month

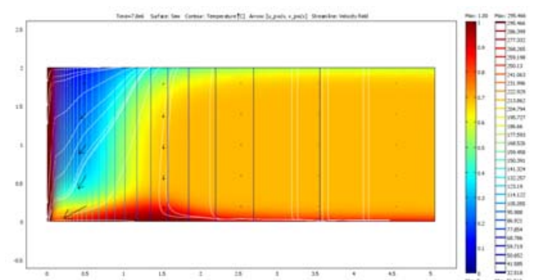

Figure 6. Hot Pipe Boundary Heating Result after Three Months

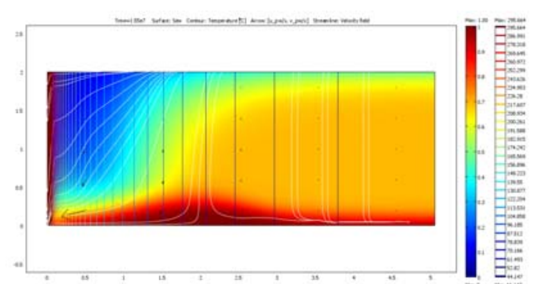

Figure 7. Hot Pipe Boundary Heating Result after Six Months

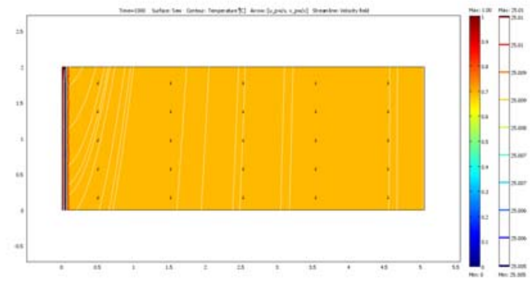

Figure 8. Volumetric RF Heating Result in Less than an Hour

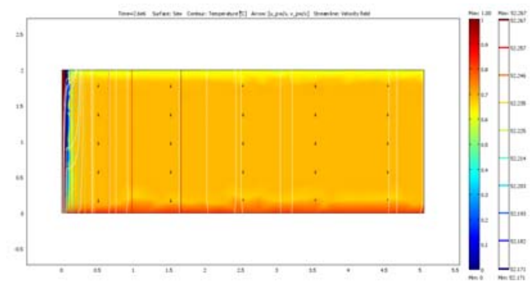

Figure 9. Volumetric RF Heating Result after One Month

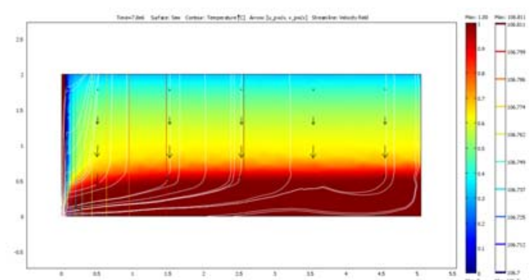

Figure 10. Volumetric RF Heating Result after Three Months

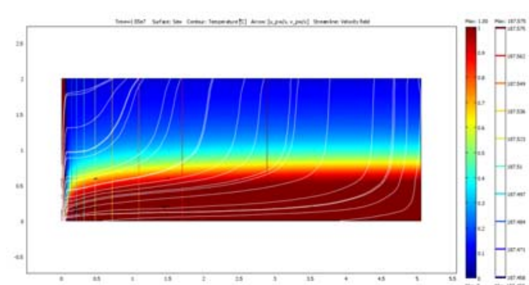

Figure 11. Volumetric RF Heating Result after Six Months

A similar case to Figures 4 through 7 is modeled by assuming boundary temperature of 600º*C*. Changes in the bitumen fraction are integrated along the entire media and compared for each of the cases in Figure 12. Initial bitumen content is assumed to be about 70 percent and it decreases as bitumen extracted from the media. Compared to the hot pipe boundary heating method, the volumetric RF heating method shows lower extracted bitumen at the first 150 days of production. The rate of bitumen extraction significantly increases for the volumetric heating method after 100 days of heating and it shows significantly higher bitumen extraction at the first year of production. This result represents that there is a delay time for the volumetric heating method until bitumen reaches its flowing temperature. Because of the volumetric heating, the part of media away from the production well (that contains a significant volume of the entire cylindrical media) can reach higher temperatures in less time, compared to the hot pipe boundary heating results.

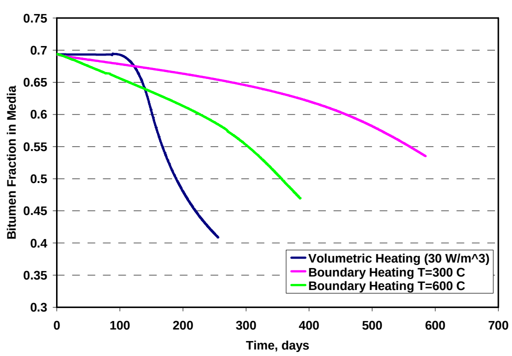

Figure 12. Integrated Bitumen Fraction for Three Modeling Cases

In this work, the two methods of heating are also modeled for a case of 45-m depth cylindrical media with 5 m radius to evaluate the effect of the height of bitumen layer on the bitumen production rate. Figures 13 and 14 show distribution of the bitumen fraction in a 45m-deep volume after one year of heating. Except for the media depth, Figures 13 and 14 are similar to Figure 2 with the perforated pipe on the left side. A significant advantage of the volumetric heating method in extracting higher bitumen fraction can be observed in these figures. Figure 15 confirms that there is a significant difference in the amount of the extracted bitumen between the RF volumetric heating method and the hot pipe boundary heating method.

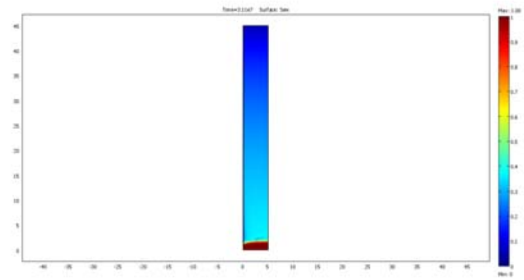

Figure 13. Bitumen Fraction in a 45-m Height Media after One Year (Production through Perforated Well Using RF Volumetric Heating Method)

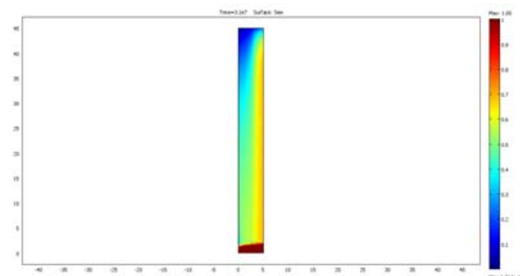

Figure 14. Bitumen Fraction in a 45-m Height Media after One Year (Production through Perforated Well Using Hot Pipe Boundary Heating Method at 600º*C*)

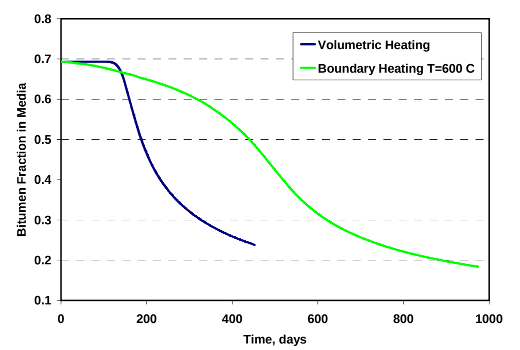

Figure 15. Integrated Bitumen Fraction for 45-m Depth Deposit

6. Conclusion

- A 2-dimensional cylindrical geometry was successfully modeled with COMSOL multiphysics to simulate two-phase movement of wetting and non-wetting phases in a porous media.
- With the help of COMSOL flexibility and capability, the compressibility effect of the non-

wetting phase and the effect of capillary pressure are considered in this modeling.

- Heating the media at the boundary of the production well, by maintaining a constant temperature of a hot pipe, causes bitumen to start flowing quicker compared to volumetrically heating the entire reservoir (Figure 12). The difference between the response times of the heating methods is less significant for the case of 45m-depth media (Figure 15).
- By using uniform heating rate of 30 W/m^3, the reservoir can reach temperatures of 107º*C* and 187º*C* after 3 months and 6 months, respectively.
- In the case of volumetric heating, the rate of bitumen extraction increases rapidly after 150 to 200 days of heating (Figures 12 and 15), when the bitumen viscosity drops to a low value by the increase in temperature.
- After a year of production, the volumetric RF heating method produces significantly higher bitumen fraction compared to the hot pipe boundary heating method (Figure 12), and this difference is more significant for 45m-depth media (Figure 15).

7. References

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