Two-Dimensional COMSOL Simulation of Heavy-Oil Recovery by Electromagnetic Heating

M. Carrizales*[1], and Larry W. Lake[1]
[1]The University of Texas at Austin,
*Corresponding author: The University of Texas at Austin, 1 University Station, C0300, Austin, TX 78712, carrizalesmaylin@mail.utexas.edu

Abstract: Introducing heat to the formation has proven to be an effective way of lowering the oil viscosity of heavy oils by raising the temperature in the formation. The application of electrical energy has gained more interest during the last decade because it offers fewer restrictions for its successful application compared to the conventional steam flooding methods [1-2]. Although this recovery technique has been studied before [2-8], there are no commercial reservoir simulators yet available to model the response of a reservoir when it undergoes EM heating. This paper presents the use of COMSOL Multiphysics to simulate single-phase flow in a reservoir when an EM source is applied. Starting from mass and energy balance, and Darcy's law we modeled the effect on EM heating on temperature, pressure and flow rate for a 2D axis-symmetric system (r and z coordinates). Numerical results from COMSOL Multiphysics [9] were validated with analytical solutions for simplified cases developed earlier [10]. We determined temperatures, pressures and the ultimate oil production obtained from a reservoir when EM heating is applied.

Keywords: Heavy-oil recovery, Electromagnetic heating, single-phase flow.

1. Introduction

Thermal oil recovery methods add heat to a reservoir to reduce oil viscosity and make oil more mobile. Thermal recovery involves different well-known processes such as steam injection, in situ combustion, steam assisted gravity drainage (SAGD), and a more recent technique that consists of heating the reservoir with electrical energy [2, 5, 8]. Steam flooding leads in development and application by far; however, the use of electric heating for heavy-oil reservoirs can be especially beneficial where conventional methods can not be used because of large depth, thin formations, formation discontinuity, no water available, reservoir heterogeneity, or excessive heat losses. Chakma and Jha [8] showed that EM heating is an effective way to introduce energy to the reservoir in a controlled manner and that this energy can be directed into a specific region. Hence, the application of electrical energy has gained more interest lately.

In this study, EM heating refers to high-frequency heating, radio frequencies (RF) and microwave (MW) are examples, that is produced by the absorption of electromagnetic energy in the formation. The amount of heat absorbed will depend on the absorption coefficient of the medium, which in turn, will depend on the electrical properties that vary with temperature and water saturation. In this work, water saturation is very low and assumed to be immobile; therefore, electrical properties vary only with temperature.

Although several authors have dealt with the possibility of using EM heating to enhance recovery from heavy oil reservoirs [1-8], there are no comprehensive models or commercial tools yet available that couples EM heating to reservoir simulation. This study was carried out with COMSOL to solve an EM heating model that couples fluid flow and the thermal response of a reservoir when an EM source is applied at a vertical wellbore. The model consists of two non-linear partial differential equations (PDE's) derived from an energy balance, where the energy from the antenna is added as a source term, and a mass balance in which fluid flow is described by Darcy's law. These equations are coupled through the dependency on the flow velocity to solve for temperature as well as the dependence on temperature to calculate the flow velocity through the viscosity in Darcy's law. In solving this model, we used COMSOL because of its flexibility when coupling Multiphysics. Numerical results were validated with analytical solutions for a one-dimensional EM heating model previously developed [10].

2. Use of COMSOL Multiphysics

COMSOL offers two options for the solution of the proposed model. For a single-phase flow model, fluid flow and heat transfer can be taken from the Earth Science Module or modeled using the PDE for time dependent problems application [9]. Although using the Earth Science Module can be simpler and faster than inputting specific PDE's into COMSOL Multiphysics, the latter seems to be more convenient for our future goal of modeling multiphase fluid flow coupled to EM heating using COMSOL Multiphysics.

Symmetry is conventionally assumed in a reservoir at the wellbore for single-well numerical reservoir simulation. Taking advantage of this condition, we modeled only half of the reservoir in the radial direction assuming the well with the EM source is located at the center of the reservoir (See Figure 1). The model consists of three layers (z-direction); the top and bottom are non-reservoir layers used merely to account for heat transfer by conduction (heat losses) through the interior boundary formed with the middle layer. The middle layer corresponds to the reservoir of interest, where the EM energy source is applied, and fluid flow occurs. EM energy flow is counter-current, which means it flows opposite to the fluids to be produced.

2.1 Governing equations

The EM model is derived from a mass balance on the oil phase where fluid flow is described by Darcy's law, and a total energy conservation equation that includes heat transport by convection, conduction and the EM energy as a source term.

The overall energy conservation equation is obtained from an energy balance done on two phases, a so-called "photon" phase that transports the EM energy, and the conventional "material" phase where the reservoir and the fluids reside [11]

Assuming there is only an oil phase flowing with oil as a single component in the reservoir, with no gas dissolved in it; the mass balance for oil can be written as

$$\frac{\partial}{\partial t}\left(\phi\rho_o\right)+\nabla\bullet\left(\rho_o\vec{u}_o\right)=0 \qquad (2.1)$$

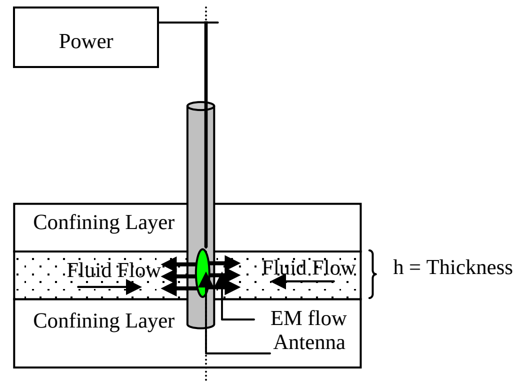

Figure 1. Schematic view of EM heating for counter-current flow. An antenna is placed at the center of the producing well in front of the target zone confined by the adjacent layers.

Here, $\vec{u}_o$ represents the volumetric oil rate, which can be expressed by Darcy's law as

$$\vec{u}_o=-\frac{\vec{\vec{k}}k_{ro}}{\mu_o}\cdot(\nabla p_o+\rho_o\vec{g}\nabla z) \qquad (2.2)$$

where ϕ and $\vec{\vec{k}}$ denote the porosity and absolute permeability tensor of the porous system, while ρ_o, μ_o, k_{ro}, p_o represent the density, dynamic viscosity, relative permeability, and pressure of the mobile phase (oil), and $\vec{g}$ is the gravitational vector (pointing downward). The medium is isotropic, $\vec{\vec{k}}=k\vec{\vec{I}}$, and gravity effects are ignored.

Expanding the derivative, and replacing Darcy's velocity in equation (2.1), we obtain what is usually called the pressure equation as

$$\left(\phi c_o\right)\frac{\partial p}{\partial t}-\frac{k_o}{\mu_o}\nabla\bullet(\nabla p_o)=0 \qquad (2.3)$$

where $c_o=-\frac{1}{B_o}\frac{\partial B_o}{\partial p}$ and represents the oil compressibility, and B_o is the oil formation volume factor. Fluid properties are constant; except for the oil viscosity, which is determined according to the following relationship

$$\mu_o=De^{F/T} \qquad (2.4)$$

where D and F are empirical constants determined from two measured viscosities at known temperatures (absolute).

Equation (2.3) models the oil flow in the reservoir. Since the idea of EM heating is to introduce heat to the reservoir, we need the conservation of total energy equation to complete the model. For the single flow of oil, the total energy in the system made of the contribution of energy transport by conduction, convection, and EM heating is given by

$$M_T \frac{\partial T}{\partial t} + M_o \overrightarrow{u_o} \bullet \vec{\nabla} T + H_o \vec{\nabla} \bullet \left(\rho_o \overrightarrow{u_o} \right) - \vec{\nabla} \bullet \left(k_{T_{eff}} \vec{\nabla} T \right) = -\vec{\nabla} \bullet \vec{q}_{EM} \tag{2.5}$$

Where $M_T = \left(\phi M_o S_o + (1-\phi) M_s \right)$

Here, M is the volumetric heat capacity, H is the enthalpy, and $k_{T_{eff}}$ is the effective reservoir thermal conductivity that comprises the rock (index “s”) and the oil (index “o”). The term on the right side of equation (2.5) represents the EM heating source, and its expression is derived in the following section.

2.2 Electromagnetic (EM) Heating Term

The term $\vec{q}_{EM}$ on the right side of equation (2.5) is the gain in heat content because of the power applied through the "photon" phase as discussed by Bird et al. [11]. This term can be obtained from a separate energy balance on the photon phase assuming steady-state since the mass of the photons is negligible [4, 11]. The mathematical formulation for this term can be also derived from the solution of Maxwell’s equations or from the application of Lambert’s law [6].

The gain in heat content provided from the EM source can be mathematically expressed in multiple ways; however, which of these is the most accurate expression, especially in a multi-dimensional flow, is still unknown. For this work, the energy balance on the photon phase is expressed as:

$$\nabla \bullet \vec{q}_{EM} = -\alpha \left| \vec{q}_{EM} \right| \tag{2.6}$$

where the term $\left| \vec{q}_{EM} \right|$ is the magnitude of the EM flux vector. In a 1D radial system, assuming that energy flows from the EM source in the horizontal direction only, equation (2.6) can be written as:

$$\frac{1}{r} \frac{\partial \left(r q_{EM} \right)}{\partial r} = -\alpha q_{EM} \tag{2.7}$$

Integration of equation (2.7) gives:

$$r q_{EM}(r) = C e^{-\alpha r} \tag{2.8}$$

where C is an integration constant that can be evaluated with the following boundary condition:

$$q_{EM}(r_w) = P_0 \tag{2.9}$$

Using the above boundary condition, equation (2.8) can be rewritten as:

$$q_{EM}(r) = \frac{P_0 e^{-\alpha (r - r_w)}}{r} \tag{2.10}$$

where P_0 is the incident power radiated at the wellbore, α is the EM absorption coefficient, r is the radial distance, and r_w is the wellbore radius. Then, the energy contribution beacause of the EM source applied in a radial system can be expressed as:

$$\nabla \bullet \vec{q}_{EM} = -\alpha \frac{P_0 e^{-\alpha (r - r_w)}}{r} \tag{2.11}$$

This expression represents the source term in the energy balance for a radial system. The EM absorption coefficient is derived from Maxwell’s equations [5] and has the following expression

$$\alpha = 2\omega \sqrt{\frac{\varepsilon \mu'}{2}} \left[\sqrt{1 + \left(\frac{\sigma}{\varepsilon \omega} \right)^2} - 1 \right]^{1/2} \tag{2.12}$$

where ω is 2π times the frequency, ε is the real part of the complex permittivity, μ' is the real part of the complex magnetic permeability, and σ is the dielectric conductivity of the medium, which is a function of temperature.

2.3 Initial and Boundary Conditions

The EM heating model described by the equations above would not be complete without a description of the initial and boundary conditions used to solve the system. The primary variables solved for are pressure and temperature assuming single-phase flow. Constant temperature and pressure throughout the reservoir are taken as the initial state.

In solving the pressure equation, the pressure at the external boundary (r_e) is kept constant. At the wellbore, a constant flowing bottomhole pressure (p_{wf}) was used. At the interior boundaries (z=h, and z=0) between the reservoir and the adjacent formations, a no-flow boundary condition was imposed for the solution of the mass balances, so no crossflow is allowed.

For the solution of the energy equation, temperature is kept constant and equal to the initial temperature at the external boundary of the reservoir, at the top of the overburden, and at the bottom of the underburden. At the wellbore, convective flux was used as the condition to obtain the temperature distribution. Convection heat loss occurs only in the radial direction. Conduction heat loss through the adjacent formations is included by setting the continuity of heat as a boundary condition between the reservoir and the top and bottom formations.

3. Numerical Simulations

The numerical implementation of the model previously derived was accomplished by using the PDE application in general form provided by COMSOL Multiphysics.

We first validated the implementation of the numerical model in COMSOL with analytical solutions for transient flow for a special 1D simplified case (See Appendix). Then, we used the 2D numerical model to study the effect of EM heating on recovery, with sensitivities on the input power and the frequency of the EM source.

The domain is a 2D, three layer system with a radial extent of 50 ft, and a total reservoir vertical extension of 426 ft. Fluid, rock, and electrical properties used were collected from various published papers. **Table 1** summarizes the basic data used for a hypothetical reservoir under consideration.

4. Results and Discussion

4.1 Validation

Figure 2 shows a comparison between the numerical solution for temperature obtained from COMSOL and the analytical solution derived for a 1D radial EM heating model neglecting conduction, and using a constant production rate condition at the wellbore of 20 bbl/day. Numerical and analytical results are in good agreement.

Using the same properties input in the model solved by COMSOL with a domain of 164 ft of length, a sealed external boundary, and assuming no heat is introduced to the reservoir, we carried out a 2D simulation using the reservoir simulator STARS [12] to compare the results for pressures, and oil rate obtained during cold production from both solutions. Figures 3-4 show a comparison of the pressure with distance, and the oil rate obtained. A no flow condition at the external boundary was imposed for a proper comparison with the results from STARS. A reasonable agreement is shown, which allows confirming the validity of the model implemented in COMSOL for the simulation of the 2D heavy oil recovery by using EM heating.

Table 1: Basic data of a hypothetical reservoir used for the validation of the EM heating model.

Property	***Value***
Oil density, lbm/ ft^3	62.4
Permeability, md	1,000
Porosity, fraction	0.38
Well radius, ft	0.3
Initial pressure, psi	300
Initial temperature, F	100
Wellbore pressure, psi	17
Oil compressibility, 1/psi	5E-06
Thermal conductivity, lbf/s.F	0.38
Oil volumetric heat capacity, lbf.ft/ft^3.F	1.9E04
Empirical constant D for viscosity correlation, cp	2.2E-06
Empirical constant F for viscosity correlation, F	1.14E04
Initial viscosity, cp	3,780
Power input, Watt	63,000
Absorption coefficient @ 915 MHz, 1/ft	0.04

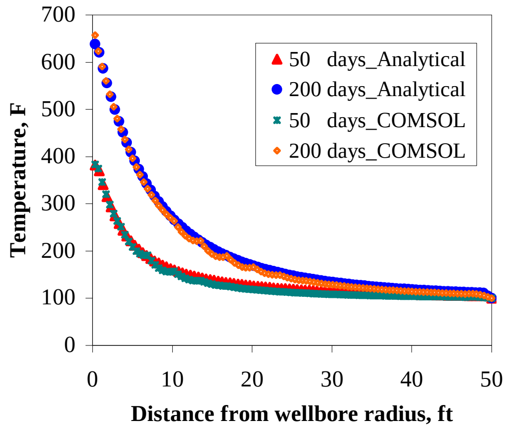

Figure 2. Comparison of transient temperature profiles for counter-current radial flow obtained with COMSOL vs. analytical solutions for the special case of no conduction.

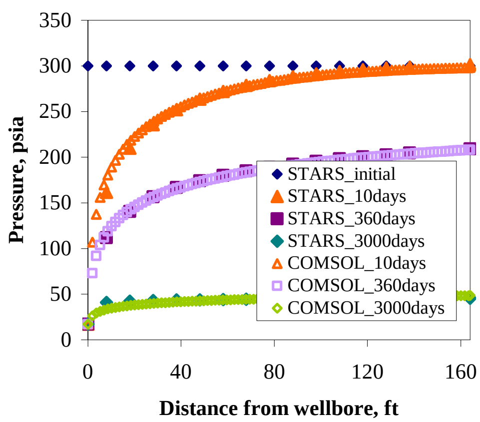

Figure 3. Comparison of transient pressure profiles for counter-current radial flow obtained with COMSOL vs. STARS for cold production (No EM heating).

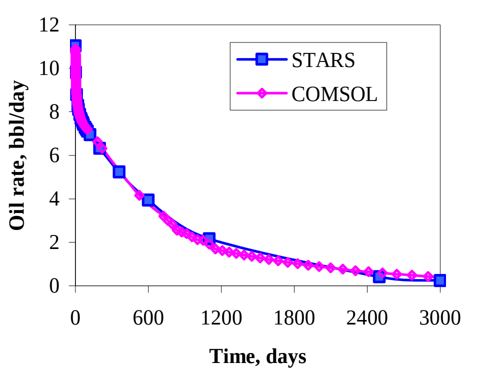

Figure 4. Comparison of oil production obtained with COMSOL vs. STARS for the cold case (No heating).

4.2 Two-dimensional EM Heating Case

Our main objective here is to use COMSOL to simulate a 2D reservoir undergoing EM heating. Once the implementation in COMSOL was validated for the no heating case, we added the EM source term to study the effect of EM heating on temperature, pressure, and oil rate produced. Data for this problem is shown in Table 2, a radial extent of 100 m (328 ft) was used. Figures 5 and 6 are surface plots of temperature and pressure; the distance coordinates (r, z) are displayed in meters. Figure 5 shows the temperature distribution for a 2D reservoir after 3 years of EM heating. The temperature at the wellbore reaches a maximum of 245. 11 *˚F*, and about 142 *˚F* at 20 m from the wellbore, which means a considerable area of the reservoir is heated to an effective temperature in terms of viscosity reduction. Since vertical heat loss by conduction is allowed, the temperature in the reservoir (middle layer) close to the confining layers, where no heating is conducted, is lower than at the center of the reservoir.

This result shows the ability of focusing the heat introduced to the reservoir with EM heating avoiding excessive heat losses as is often the case of steam injection.

Figures 6 and 7 show the pressure profile obtained for the EM heating case and the production rate from EM heating compared to cold production rate. Since there is no flow in the confining layers, only the producing layer is shown. Figure 8 shows an improvement in cumulative oil production from EM heating of about 5.4 times cold production.

Table 2: Basic data of a hypothetical reservoir used for the study of EM heating for heavy-oil recovery

Property	***Value***
Permeability, md	1,000
Thickness, m	30
Porosity, fraction	0.38
Well radius, m	0.1
External radius, m	100
Initial pressure, psi	770
Initial temperature, F	100
Wellbore pressure, psi	215
Initial viscosity, cp	3,780
Power input, Watts	70,000
Absorption coefficient @ 915 MHz, 1/m	0.133

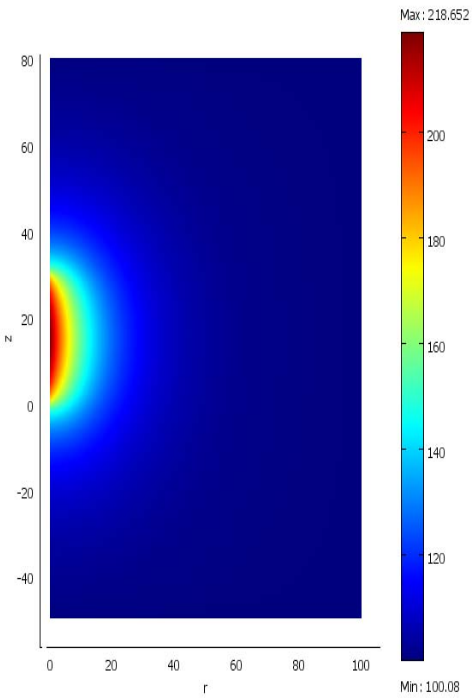

Figure 5. Temperature (˚*F*) profile for a two-dimensional reservoir after 3 years of EM heating obtained with COMSOL.

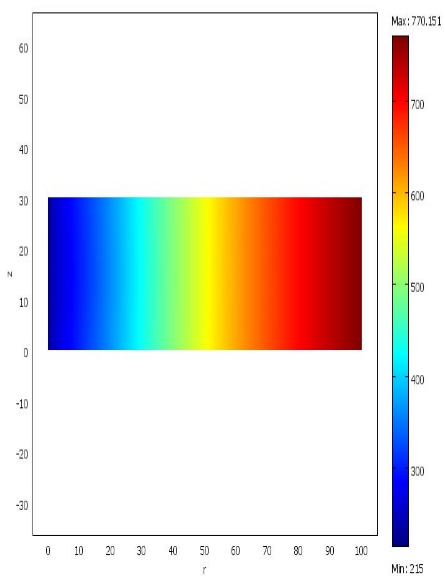

Figure 6. Pressure (psi) profile for a two-dimensional reservoir after 3 years of EM heating obtained with COMSOL.

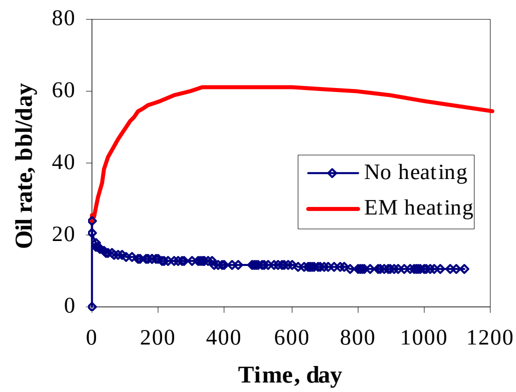

Figure 7. Oil rate comparison for the EM heating case and cold production (no heating).

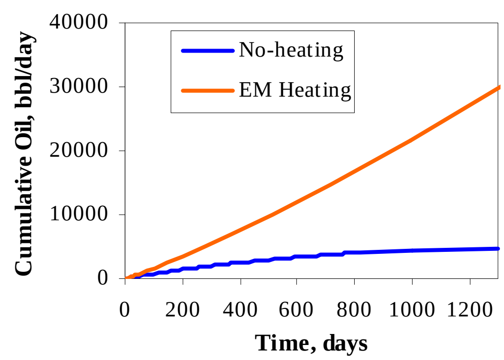

Figure 8. Cumulative oil production comparison for the EM heating case vs. cold production (no heating).

5. Conclusions

A 2-D numerical simulation of heavy oil recovery by EM heating using COMSOL, has been successfully conducted and validated with analytical solutions for a 1-D case, and with the reservoir simulator STARS for a 2-D case of cold production.

Results from this work are encouraging to the use of COMSOL for simulating EM heating for heavy oil recovery, and they will be extended to study multiphase flow and phase changes when an EM heating source is applied.

6. References

1. Hiebert, A.D., Vermeulen, F.E., Chute, F.S. and Capjack, C.E. Numerical Simulation Results

for the Electrical Heating of Atabasca Oil-Sand Formations. *SPERE* **1** (1): 76-84, (1986).

2. Sahni, A., Kumar, M., Knapp, R.B. and Livermore, L. Electromagnetic Heating Methods for Heavy Oil Reservoirs. Paper SPE 62550, (2000).

3. Abernethy, E.R. Production Increase of Heavy Oil by Electromagnetic Heating. *J. Cdn. Pet. Tech* **15** (3): 91-97 (1976)

4. Araque, A. and Lake, L.W. Aspectos Relevantes Sobre Flujo de Fluidos Bajo Calentamiento Electromagnético. PDVSA-Intevep, INT 9388. (2002)

5. Kim, E.S. Reservoir Simulation of in situ Electromagnetic Heating of Heavy Oils. PhD dissertation, Texas A & M U., College Station, Texas. (1987).

6. Ovalles, C., Fonseca, A., Lara, A., et al. 2002. Opportunities of Downhole Dielectric Heating in Venezuela: Three Case Studies Involving Medium, Heavy, and Extra-Heavy Crude Oil Reservoirs. Paper SPE 78980, (2002).

7. McPherson, R.G., Chute, F.S. and Vermeulen, F.E. Recovery of Atabasca Bitumen with the Electromagnetic Flood Process. *J. Cdn. Pet. Tech* **24** (1): 44-51, (1985).

8. Chakma, A. and Jha, K.N. 1992. Heavy Oil Recovery From Thin Pay Zones by Electromagnetic Heating. Paper SPE 24817, (1992).

9. COMSOL Multiphysics, *COMSOL Multiphysics Modeling Guide Version 3.5a*, COMSOL AB (2007)

10. Carrizales, M., Lake, L.W., and Johns, R. Production Improvement of Heavy-Oil Recovery by Using Electromagnetic Heating. Paper SPE 115723, (2008)

11. Bird, R.B., Steward, W.E. and Lightfoot, E.N. *Transport Phenomena*, 506-507. New York City: John Wiley & Sons, Inc. (2002)

12. Computer Modeling Group, Ltd., STARS Users Guide, Version 2008, Calgary, Canada.

7. Acknowledgements

Larry W. Lake holds the W. A. (Monty) Moncrief Centennial Chair at The University of Texas.

8. Appendix

A. Transient Temperature. No Conduction

For counter-current radial flow, neglecting conduction, and introducing the EM source term, the energy balance reduces to

$$M_T\frac{\partial T}{\partial t}=\frac{M_o q_o}{2\pi h}\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\alpha P_0 e^{-\alpha(r-r_w)}}{2\pi r h} \quad \text{(A.1)}$$

where the total volumetric heat capacity (M_T) is given by

$$M_T=\phi M_o+(1-\phi)M_r$$

To simplify Eq. A.1, we defined the variable $\xi=r^2$, then $d\xi=2rdr$. Substitution of this into A.1 gives

$$M_T\frac{\partial T}{\partial t}=\frac{M_o q_o}{\pi h}\frac{\partial T}{\partial \xi}+\frac{\alpha P_0 e^{-\alpha(\xi^{1/2}-\xi_0^{1/2})}}{2\pi h\xi^{1/2}} \quad \text{(A.2)}$$

In dimensionless form Eq. A.2 can be written as

$$\frac{\partial T_D}{\partial t_D}-\frac{\partial T_D}{\partial \xi_D}=\frac{\alpha_D}{2\xi_D^{1/2}}e^{-\alpha_D\left(\xi_D^{1/2}-\xi_{Dw}^{1/2}\right)} \quad \text{(A.3)}$$

with BC's

$$\begin{cases}T_D(\xi_D,0)=0\\ T_D(1,t_D)=0\end{cases}$$

where:

$$t_D=\frac{M_o q_o}{\pi h M_T \xi_e}t\ ,\ \alpha_D=\alpha\xi_e^{1/2},$$

$$T_D=\frac{M_o u_o}{P_0}(T-T_o)\text{ , and }\xi_D=\frac{\xi}{\xi_e}.$$

Applying Laplace transforms, Eq. A.3 can be transformed into:

$$\frac{d\overline{T_D}}{d\xi_D}-s\overline{T}=\frac{\alpha_D}{2s\xi_D^{1/2}}e^{-\alpha_D\left(\xi_D^{1/2}-\xi_{Dw}^{1/2}\right)} \quad \text{(A.4)}$$

with BC

$$L\{T_D(1,t_D)\}=\overline{T_D}(1,s)=0\ .$$

Solution of Eq. A.4 using the given BC, gives:

$$T_D=\begin{cases}-e^{-\alpha_D\left[(t_D+\xi_D)^{1/2}-\xi_{Do}^{1/2}\right]}+e^{-\alpha_D\left[\xi_D^{1/2}-\xi_{Do}^{1/2}\right]} & \xi_D<1-t_D\\ e^{-\alpha_D\left[\xi_D^{1/2}-\xi_{Do}^{1/2}\right]}-e^{-\alpha_D\left[1-\xi_{Do}^{1/2}\right]} & \xi_D>1-t_D\end{cases}$$

(A.5)