Effect of Oil Composition on Light Oil Recovery by Air Injection

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Outline

- Motivation
- Hypotheses
- Theory
- Analytical model
- Numerical model
- Results and discussion
- Conclusions

Extraction of petroleum: primary, secondary, and enhanced

Primary recovery

Natural mechanisms due to underground pressure (displacement by water, expansion of natural gas, gravity drainage). Recovery factor: 5-15%

Secondary recovery

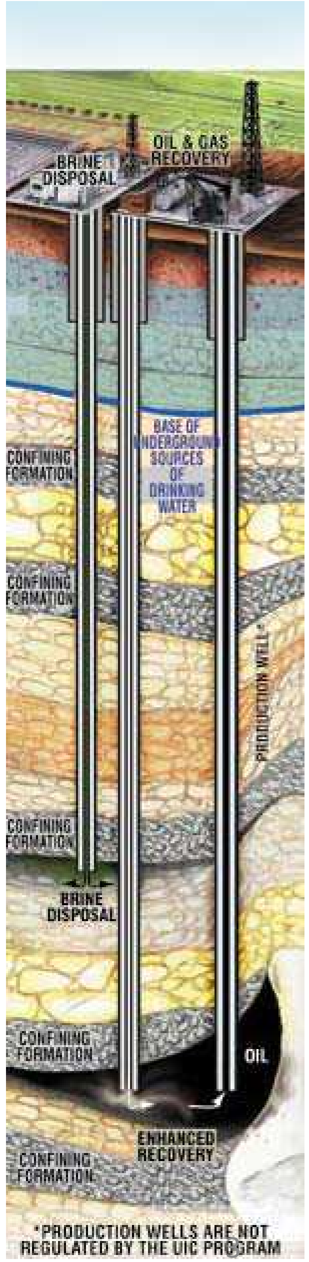
Injecting fluid (water, natural gas, air, carbon dioxide) with an artificial drive. Recovery factor : 30%

Enhanced oil recovery

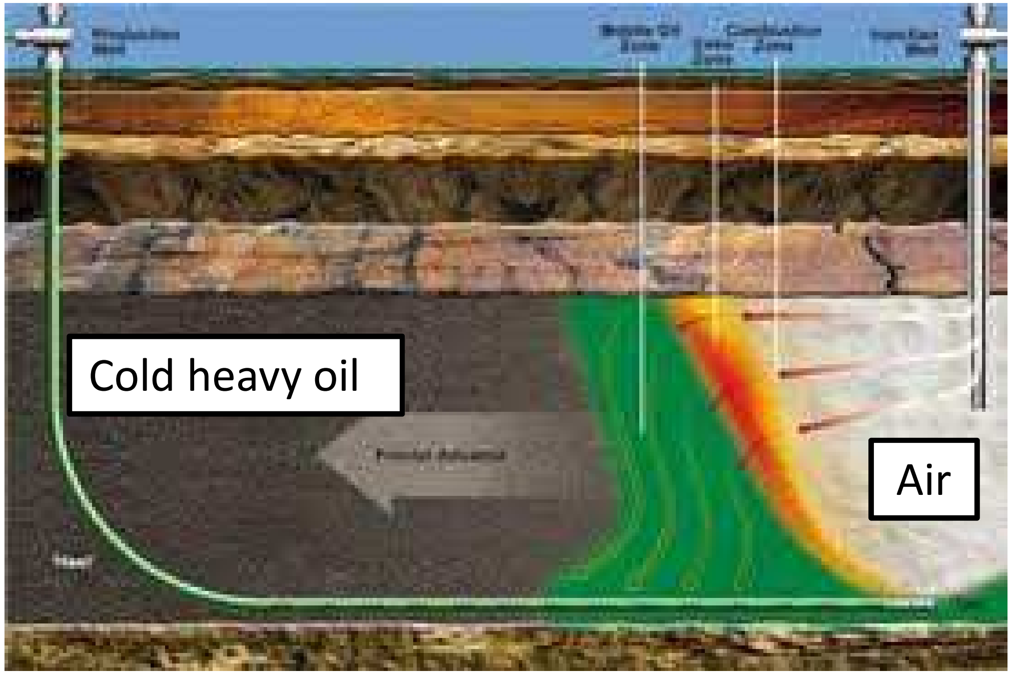
Thermal methods (steam injection).

In-situ combustion (air injection).

Chemical methods (using detergents mobilizing residual oil).
Carbon dioxide flooding (pressures near critical point).
Recovery factor : 5-15%



Mechanisms for In-situ combustion for oil recovery



High-temperature oxidation (400-600 °C)

Fuel: solid coke formed due to cracking of oil.

Representative reaction: $C+O_2 \rightarrow CO_2$

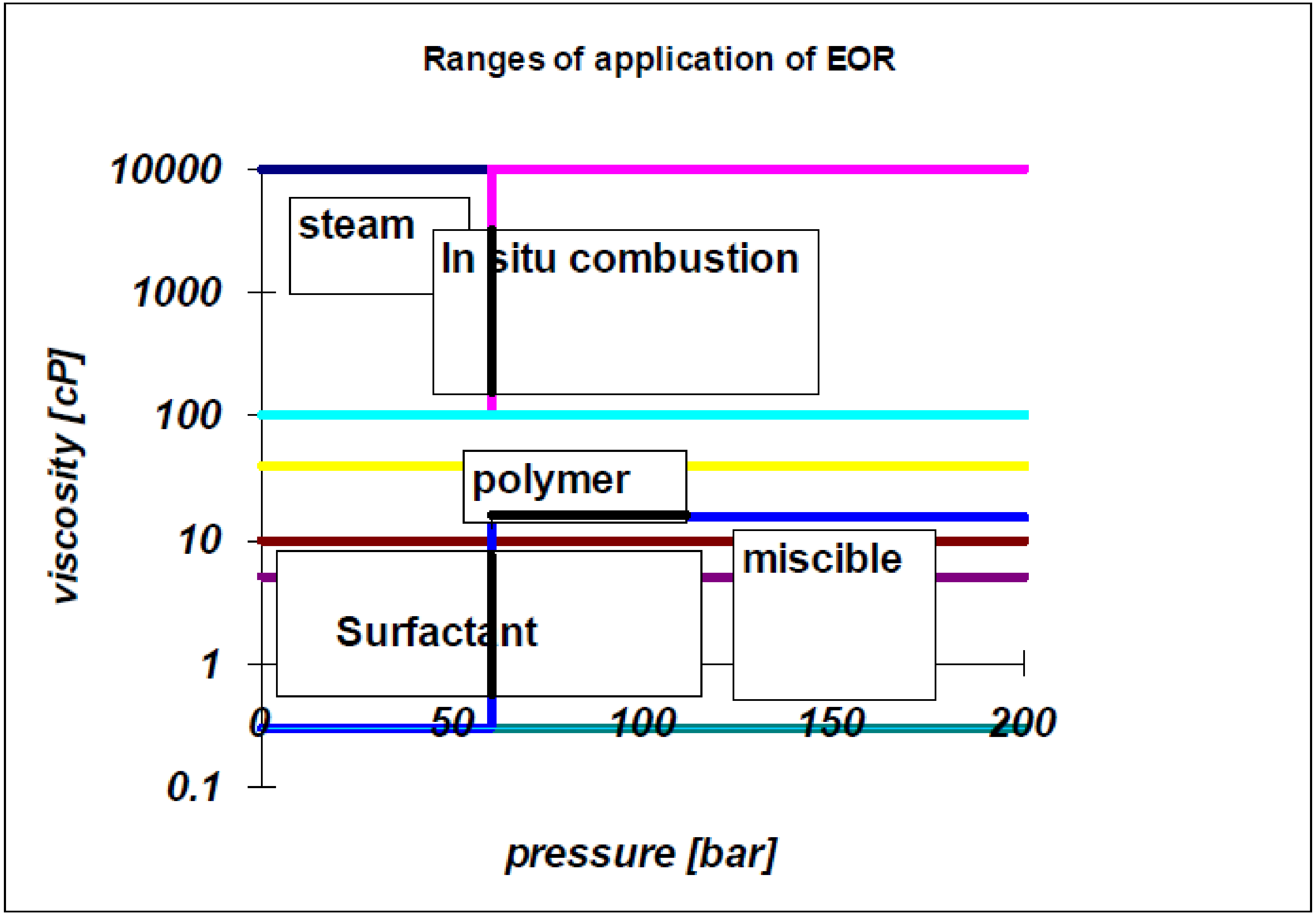
Low-temperature oxidation (150-350 °C)

Fuel: liquid oil (reaction in gaseous phase is negligible)

Representative reaction:

hydrocarbon + $O_2 \rightarrow$ oxygenated hydrocarbon

Reason to use combustion



Advantages of air injection

- Applicable to
  - Highly heterogeneous
  - Low permeable
  - Useful for heavy oil, medium oil and light oil
  - Combines effect of gas displacement with combustion recovery

Classification according to Chemical reactions

High-temperature oxidation (HTO: 400-600 °C)

Fuel: solid coke formed due to cracking of oil.

Representative reaction: $C+O_2 \rightarrow CO_2, H_2O$

Medium-temperature oxidation (MTO: < 400 °C)

Fuel: hydrocarbons formed from pyrolysis or present in the reservoir

hydrocarbon + $O_2 \rightarrow CO_2, CO, H_2O$

Low-temperature oxidation (LTO: 150-350 °C)

Fuel: liquid oil (reaction in gaseous phase is negligible)

Representative reaction:

hydrocarbon + $O_2 \rightarrow$ oxygenated hydrocarbon (alcohols, Aldehydes, acids and so on)

	Light oil	Heavy oil
LTO	Full H/C bond breaking	Generating partially oxygenated compounds such as alcohols, ketones, aldehydes and small amounts of CO_2
MTO	Small Hydrocarbon oxidation	
HTO	Negligible	Coke burning generating CO_2 and H_2O
Cracking/ Prolysis	Forming smaller hydrocarbons	Forming Coke
Distillation	Evaporation/ condensation	Negligible

Hypotheses

- Air injection at medium pressures leading to Medium Temperature Oxidation (MTO) is applicable for efficient light oil recovery
- Interaction between combustion and vaporization is the primary mechanism in the MTO process, whereas in HTO combustion is more important.
- Relatively small amounts of light oil increase the recovery efficiency
- It is possible to determine the bifurcation point between MTO and HTO in two-component oil mixtures

Model

- Conservation laws (accumulation, convection, diffusion and source term for reaction and vaporization) for four components:
  - light and medium oil in oleic phase, and oxygen, light oil in gaseous phase and the rest (nitrogen + combustion products)
- Energy balance
- Thermodynamic relations
- Constitutive relations

1D model for oxidation and vaporization in porous medium

two pseudo-components liquid fuel mixture (light and medium)

Time: t

Space: x

Dependent variables:

Liquid fuel saturation s_o

Darcy velocity of gas u

Gaseous fuel molar fraction Y_l

Oxygen molar fraction Y_k

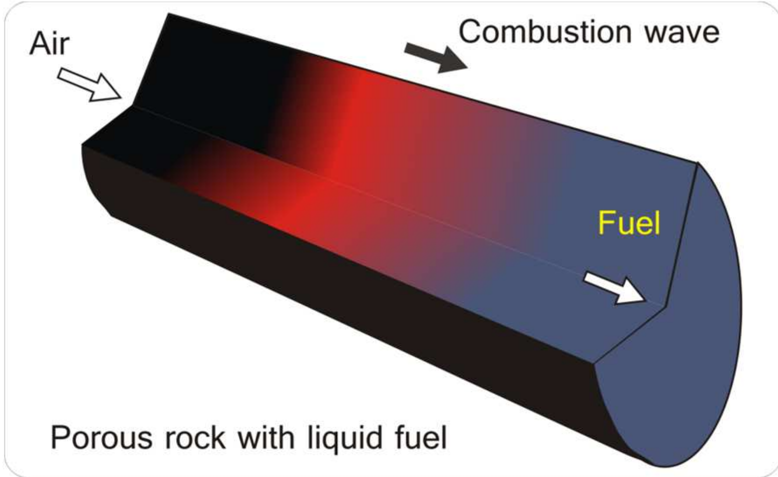
Temperature T

Medium oil fraction ψ_m

Light oil fraction ψ_l

ν_{ol}(light hydrocarbons)+O_2→ν_{gl}(gaseous products)

ν_{om}(medium hydrocarbons)+O_2→ν_{gm}(gaseous products



Oil Mass Balance equations:

$$\begin{aligned}\partial_t(\varphi\rho_{om}s_o)+\partial_x(\rho_M u_{om}) &= -\nu_{om}W_{rm},\\ \partial_t(\varphi\rho_{ol}s_o)+\partial_x(\rho_L u_{ol}) &= -\nu_{ol}W_{rl}-W_v,\end{aligned}$$

$$u_{om}=\psi_m u_o-\varphi s_o D_o\partial_x\psi_m,\quad u_{ol}=\psi_l u_o-\varphi s_o D_o\partial_x\psi_l,$$

Gas mass Balance equations :

Gaseous hydrocarbon $\partial_t(\varphi\rho_{gl}s_g) + \partial_x(\rho_g u_{gl}) \quad = \quad W_v,$

Oxygen $\partial_t(\varphi\rho_\kappa s_g) + \partial_x(\rho_g u_{g\kappa}) \quad = \quad -W_{rm} - W_{rl},$

Remaining gas $\partial_t(\rho_r s_g) + \partial_x(\rho_g u_{gr}) \quad = \quad \nu_{gm}W_{rm} + \nu_{gl}W_{rl},$

$$W_{rl} = A_{rl}\varphi X_l \rho_o s_o \left(\frac{P_g Y_\kappa}{P_{atm}}\right)^n \exp\left(-\frac{T_l^{ac}}{T}\right),$$

$$W_{rm} = A_{rm}\varphi X_h \rho_o s_o \left(\frac{P_g Y_\kappa}{P_{atm}}\right)^n \exp\left(-\frac{T_m^{ac}}{T}\right)(\quad W_v = k_l(Y_l^{eq} - Y_l)\rho_g s_o^{2/3} X_l$$

$$u_{gi} = Y_j u_g - \varphi D_g s_g \partial_x(Y_j) \quad (j = h, o, r)$$

Energy balance:

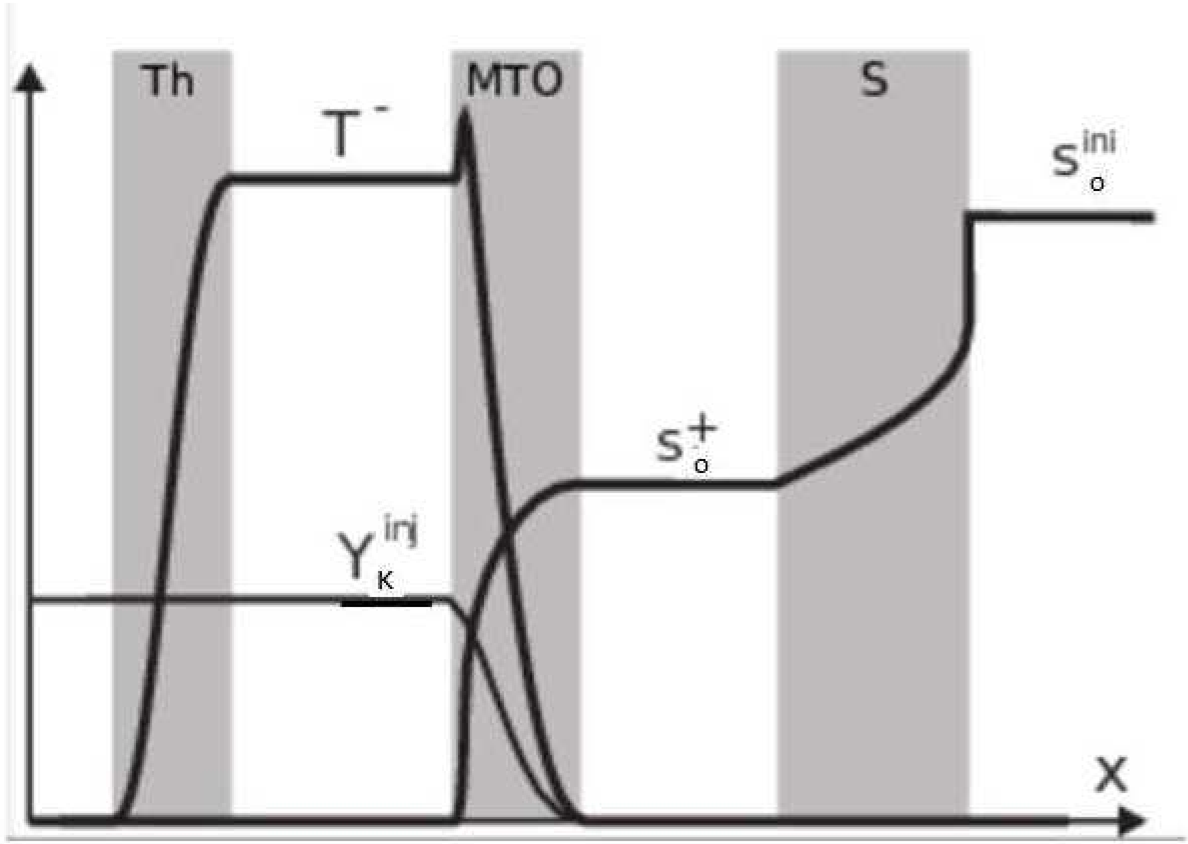
$$\frac{\partial}{\partial t}(C_m + \varphi c_l \rho_l s_l + \varphi c_g \rho_g s_g)\Delta T + \frac{\partial}{\partial x}(c_l \rho_l u_l + c_g \rho_g u_g)\Delta T = \lambda \frac{\partial^2 T}{\partial x^2} + Q_r W_r - Q_v W_v$$

Analytical solution = sequence of moving waves

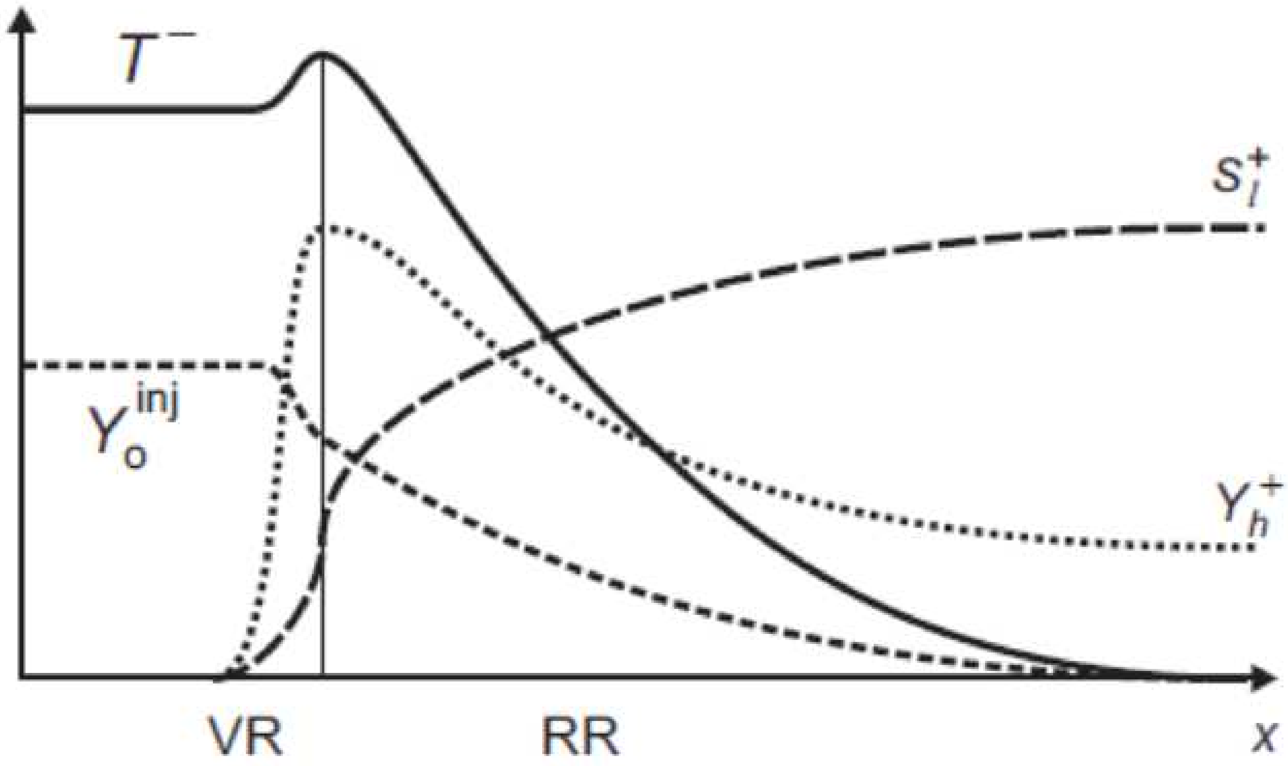
- Algebraic structure of equations (in dimensionless form)
- All dependent variables are functions of moving coordinate $\xi = x\text{-}vt$, replacing $\partial / \partial x$ by $d/d\xi$ and $\partial / \partial t$ by $-v d/d\xi$

➢ A.A. Mailybaev et al., Recovery of light oil by medium temperature oxidation, Transport in porous media, 2013

Typical wave sequence: thermal (Th), MTO and saturation (S) waves



Blow up of MTO region

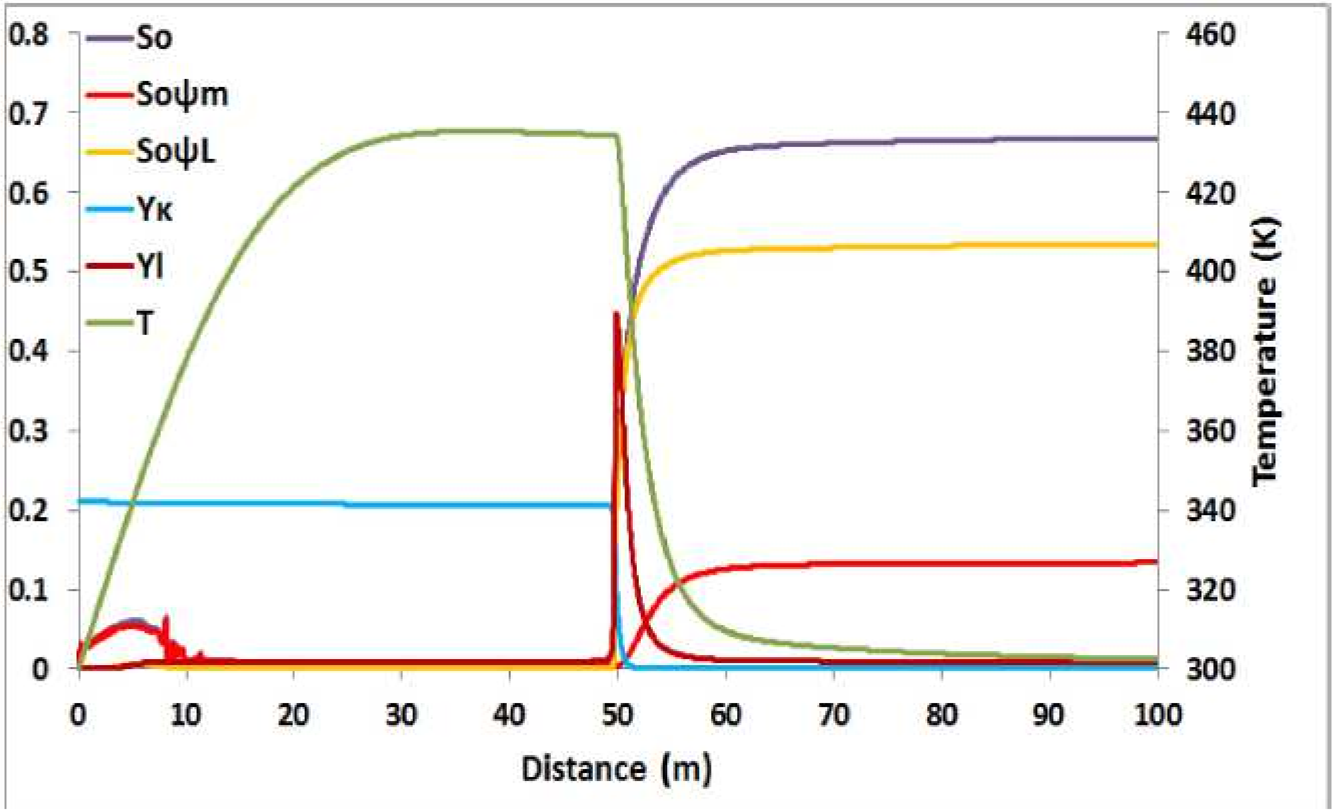


The thin region VR is dominated by vaporization and the much wider region RR is dominated by MTO reaction (with slow condensation). The VR is much thinner than the RR, because it is assumed that vaporization rate is much faster than the reaction rate

Numerical approach

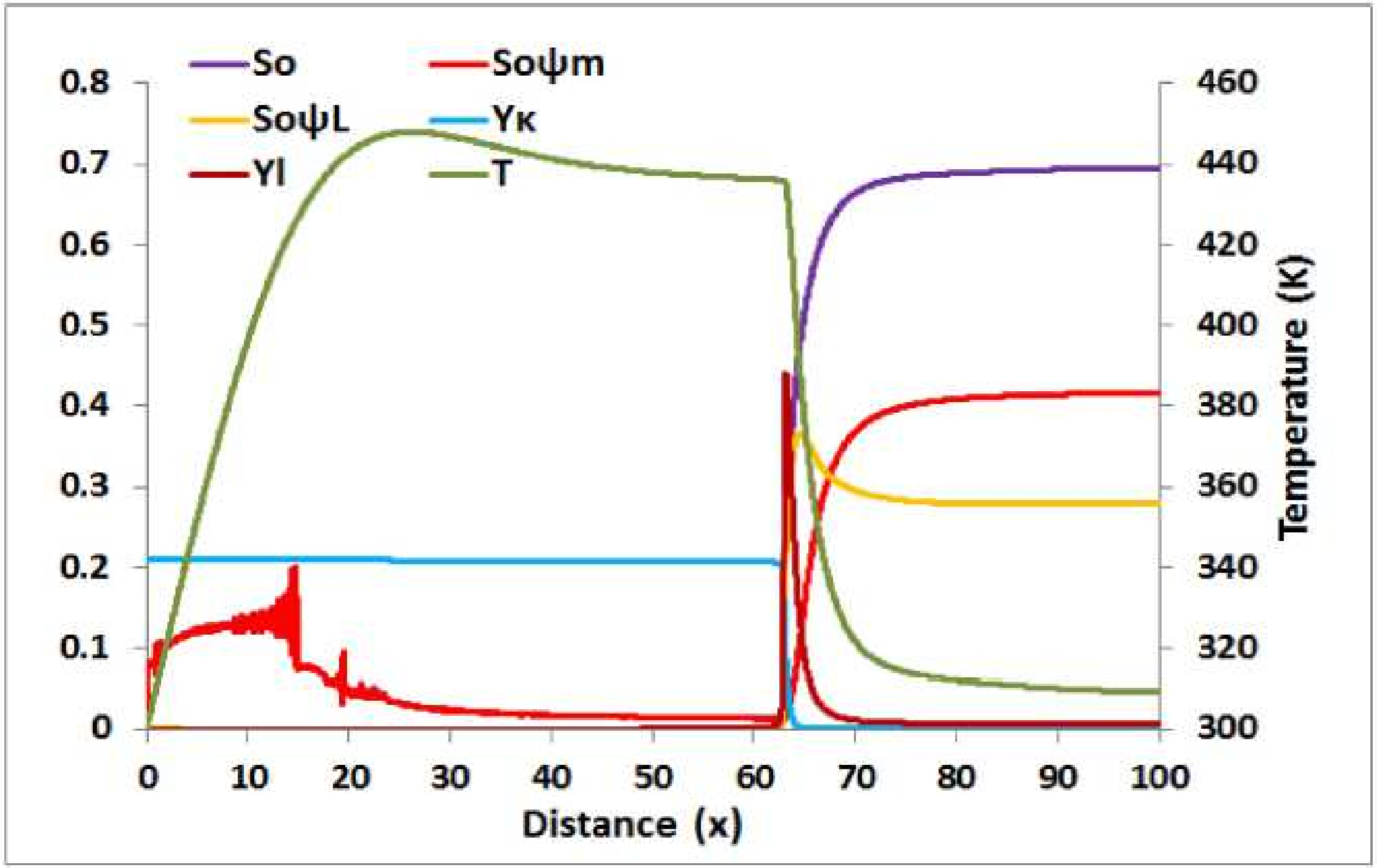
- Include mass diffusion and thermal diffusion
- Vaporization rates
- Results for two components
  - Effect of light component fraction
  - The effect of air injection rate
  - Effect of pressure

Base case: Numerical results for 80 % light fraction



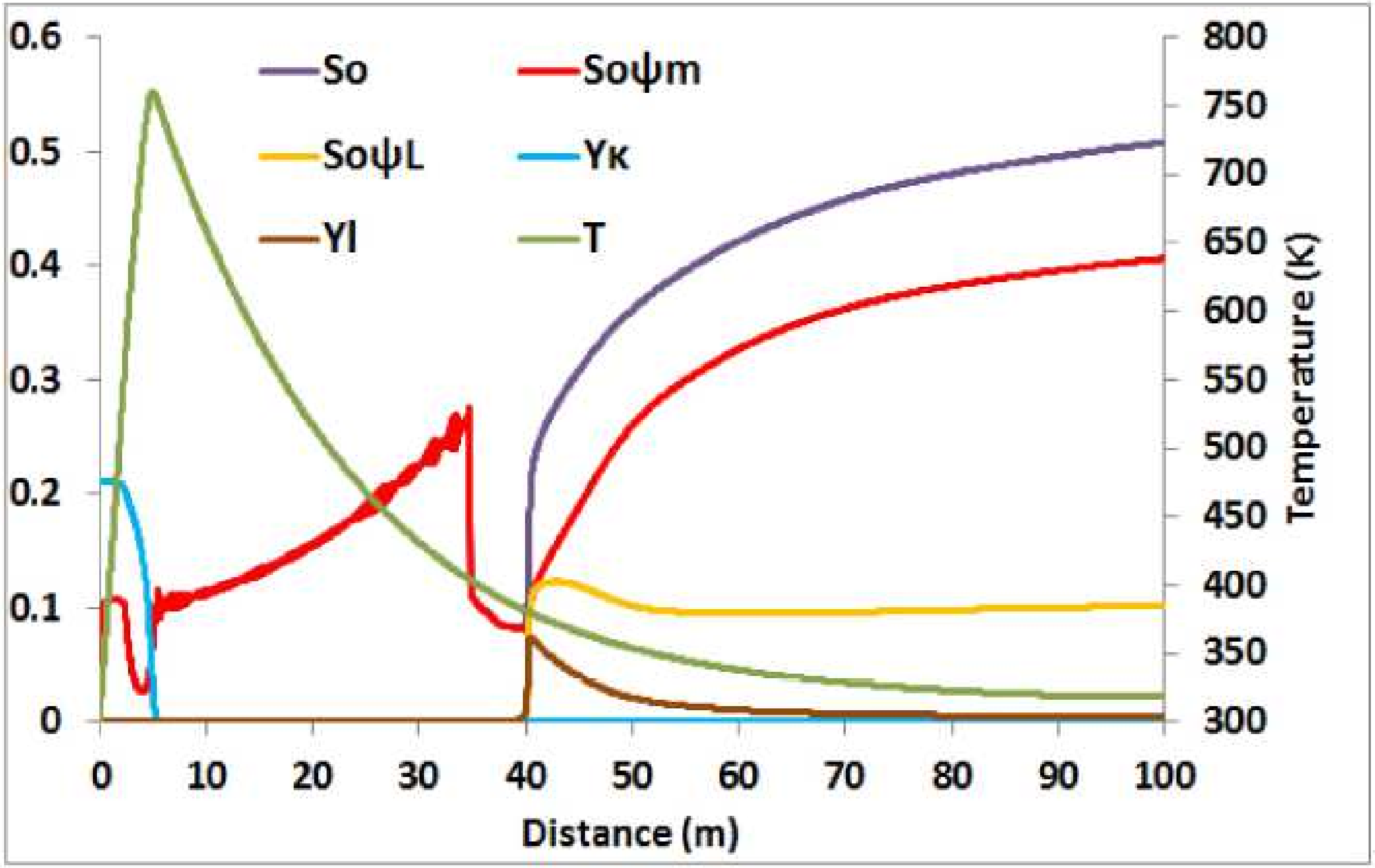
t=9.7x10^{7}sec, initial medium component fraction of ψ_m^{ini}=0.2, base pressure (10 bar) and basel injection rate u^{inj}

Effect of the light (volatile) component fraction



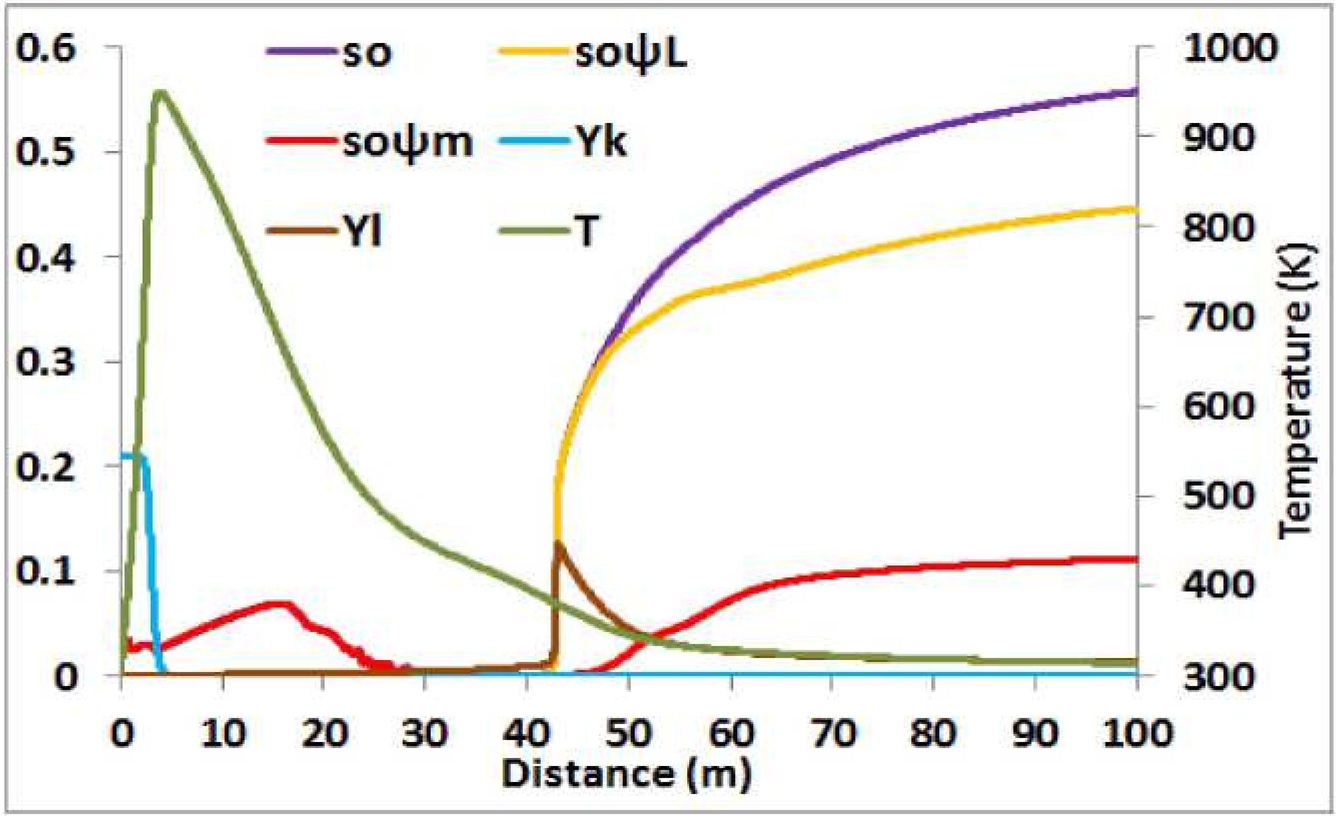
t=1.4x10^{8}sec, initial medium component fraction of ψ_m^{ini}=0.6, , base pressure (10 bar) and basel injection rate u^{inj}

Effect of the light (volatile) component fraction



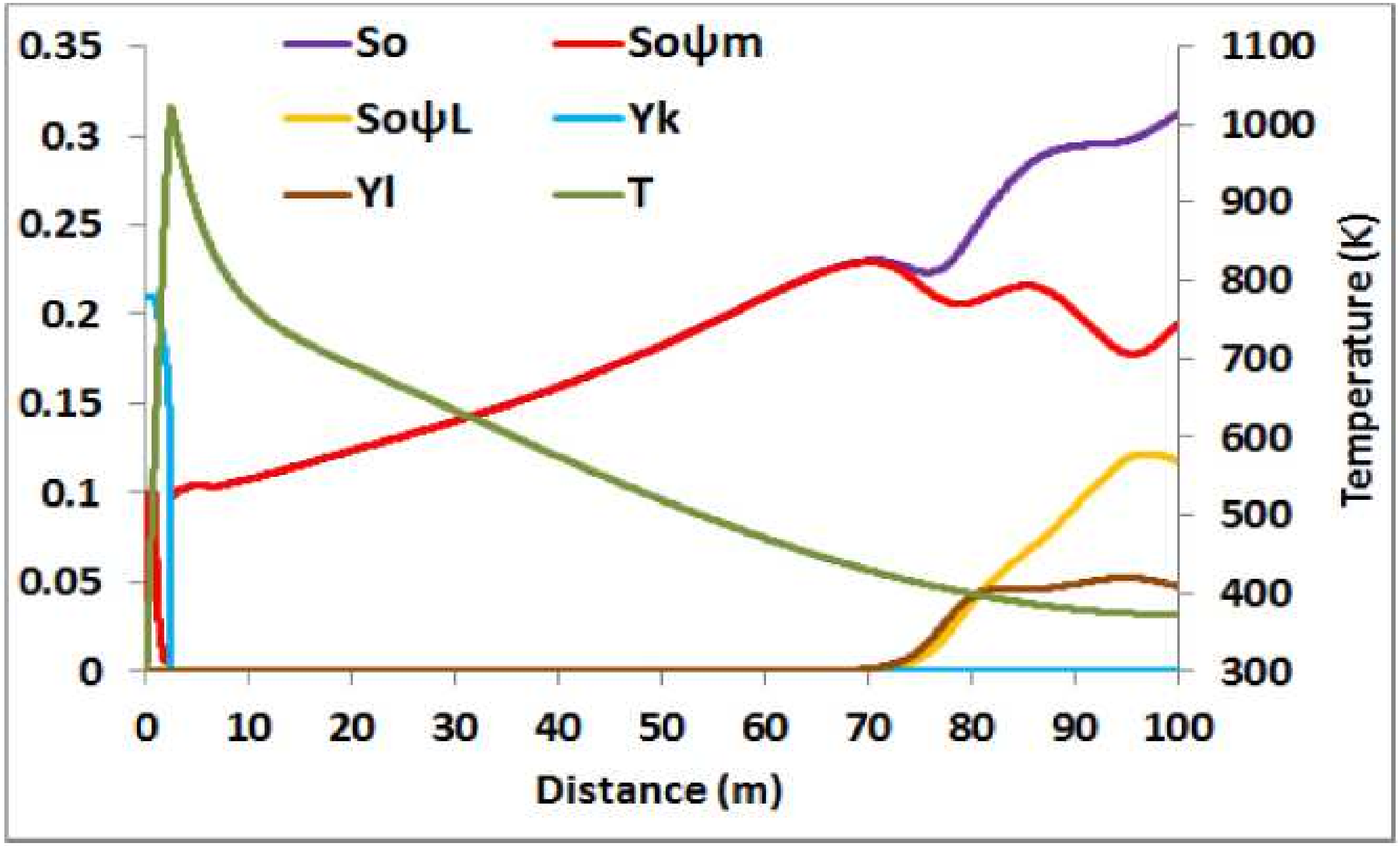
t=2.1x10^{8}sec, initial medium component fraction of ψ_m^{ini}=0.8, , base pressure (10 bar) and basel injection rate u^{inj}

Effect of air injection rate 80% light component



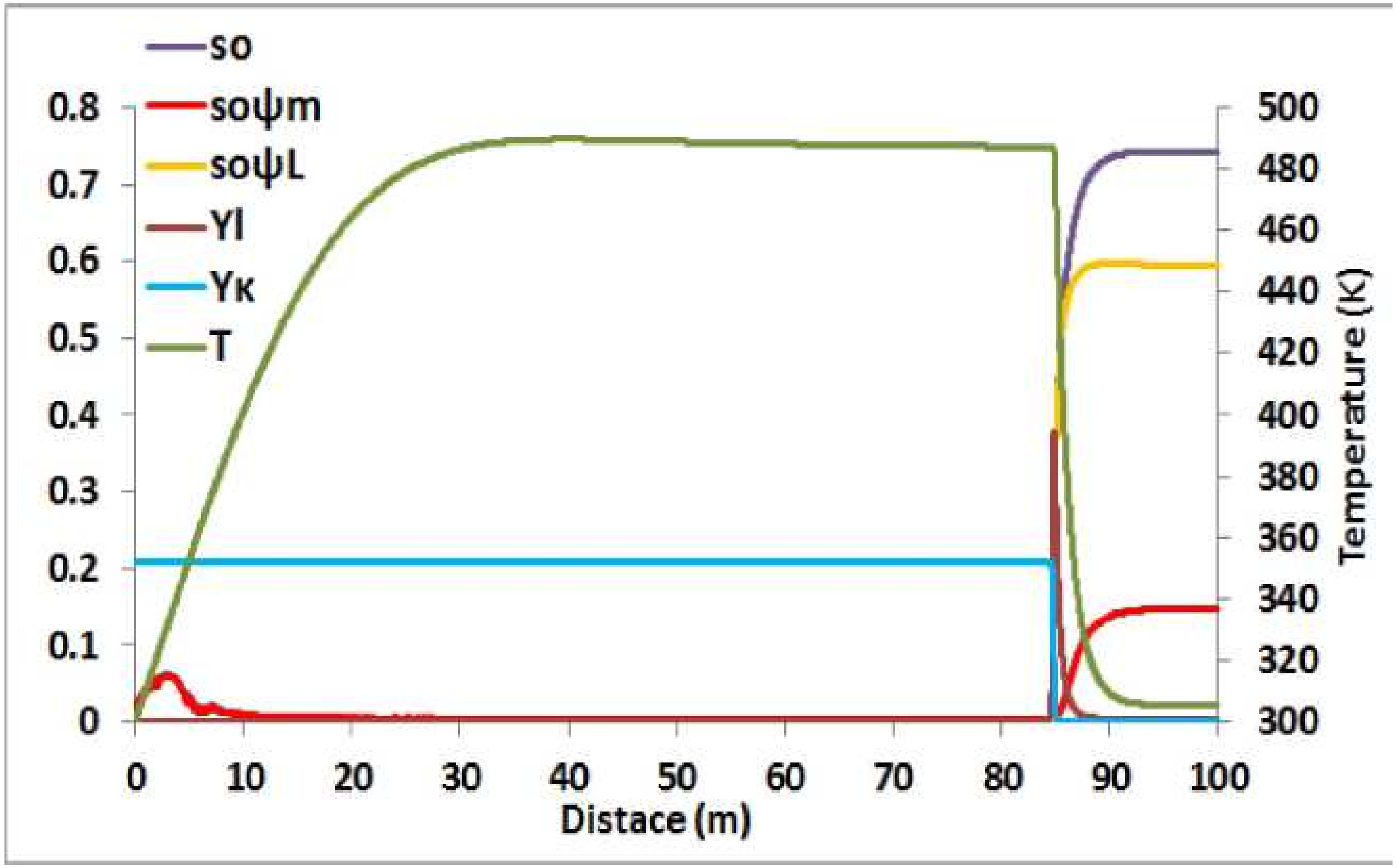
t=4.6x10^{7} sec, initial medium component fraction of ψ_m^{ini}=0.2 , base pressure (10 bar) and higher injection rate 3xu^{inj}

Effect of air injection rate 20% light component



t=1.26x10^8 sec, initial medium component fraction of ψ_m^{ini}=0.8 , base pressure (10 bar) and higher injection rate 3xu^{inj}

Effect of pressure



$t=8x10^7$ sec, initial medium component fraction of $\psi_m^{ini}=0.2$, higher pressure (30 bar) and base injection rate u^{inj}

Conclusions

- Oil recovery by air injection is a promising method to improve recovery of light/medium oil; it can be modeled as a medium temperature oxidation (MTO) process.

- The MTO combustion completely displaces the oil at the expense of small amounts of burned oil.

- The solution consists of three waves, i.e., a thermal wave, an MTO wave and a saturation wave separated by constant state regions, while the order between vaporization and oxidation in the MTO wave changes for different sets of conditions.

- For a predominantly light oil mixture, vaporization occurs upstream of the combustion process. The combustion front velocity is high as less oil remains behind in the combustion zone.

- The MTO wave is less efficient for light oil recovery under higher air injection rates, but the recovery is faster at higher pressure.

- For oil with more non-volatile component, the vaporization moves to the downstream side of the combustion zone in the MTO wave. As more oil stays behind in the combustion zone, the velocity of the combustion zone is slower, albeit with much higher temperatures. Due to high temperatures, we conjecture a transition to the HTO region in this case

- Numerical 1-D simulations can find bifurcation points. These simulations show that there is a bifurcation point, determined by the fraction of the medium component, where the character of the combustion process changes from a vaporization-dominated to a combustion-dominated process.

Thanks

Appendix

Thermal wave speed, αg<<1

$$v_T = \alpha_g u^{inj}$$

$$\Psi_g^+ = \frac{1 + (\nu_g - 1) Y_o^{inj}}{1 - Y_h^{eq}(0)}, \qquad \theta^- = \frac{q_r Y_o^{inj} - q_v Y_h^{eq}(0) \Psi_g^+}{v - \alpha_g}.$$

$$\psi_l = u_l - v s_l, \quad \Psi_g = U_g - v S_g, \quad \Psi_{gh} = U_{gh} - v Y_h S_g, \quad \Psi_{go} = U_{go} - v Y_o S_g$$

Algebraic structure of equations (in dimensionless form)

Conservation laws:

$$\frac{\partial}{\partial t}\left[(1+\alpha s+\alpha_g S_g)\theta+\gamma Y S_g+\sigma\gamma X S_g\right]+\frac{\partial}{\partial x}\left[(\alpha f+\alpha_g F_g)\theta+\gamma Y F_g+\sigma\gamma X F_g\right]u=0$$

$$\frac{\partial}{\partial t}(1+X+(\nu_g-1)Y)S_g+\frac{\partial}{\partial x}(1+X+(\nu_g-1)Y)F_g\; u\;=0$$

$$\frac{\partial}{\partial t}(s+\beta X S_g)+\frac{\partial}{\partial x}u(f+\beta X F_g)=0$$

Balance laws:

$$\frac{\partial}{\partial t}X S_g+\frac{\partial}{\partial x}uXF_g = \frac{w_v}{\varepsilon}$$

$$\frac{\partial}{\partial t}Y S_g+\frac{\partial}{\partial x}uYF_g = -w_r$$

Small parameter:
ε << 1
(vaporization is much faster than oxidation reaction)

Initial conditions (reservoir):

$$t=0,\ x\geq 0:\quad \theta=Y=0,\quad s=1$$

$\theta = (T\text{-}T_{res})/T_b$

Boundary conditions (injection):

$$t\geq 0,\ x=0:\quad \theta=0,\quad Y=u=1,\quad s=0$$

Traveling wave equations

All dependent variables are functions of $\xi = x - vt$

Convenient notation for relative fluxes:

$$\psi = uf - vs, \quad \psi_g = uF_g - vS_g, \quad \psi_Y = Y(uF_g - vS_g)$$

Conservation laws

$$\psi + \beta\psi_X = 0$$

$$\psi_g - \psi_X + (\nu_g - 1)\psi_Y = 1 + (\nu_g - 1)Y^-$$

$$v(\theta^- - \theta) - \alpha_g(\theta^- - \psi_g\theta) - \gamma(Y^- - \psi_Y) + (\sigma\gamma - \alpha\beta\theta)\psi_X = 0$$

Balance laws

$$\frac{d\psi_X}{d\xi} = \frac{w_v}{\varepsilon},$$

$$\frac{d\psi_Y}{d\xi} = -w_r,$$

Limiting states for a combustion wave

$$\xi \to -\infty: \quad \theta^-, \quad s^- = \psi^- = 0, \quad X^- = 0, \quad \psi_Y^- = Y^-, \quad \psi_g^- = 1 \qquad \text{(no fuel)}$$

$$\xi \to +\infty: \quad \theta^+ = 0, \quad s^+, \quad X^+ = X_{eq}(0), \quad Y^+ = 0, \quad \psi_g^+ \qquad \text{(no oxygen)}$$

Conclusions

- There exists a traveling combustion wave in the medium-temperature oxidation model. The wave speed and parameters are determined by explicit equations.
- Wave sequence solution for physically relevant initial conditions contains the thermal wave, resonant combustion wave and saturation wave.
- Thin vaporization region is located upstream of the reaction region.
- MTO combustion displaces all the oil, inclusive residual oil a cost of small amounts of burned oil.