Water Influx Predictions in Reservoirs with Aquifer Drive Using the Two-Phase Reservoir Integral Type Pseudo-Pressure with Applicability in Gas Hydrate Reservoirs*

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Abstract

The application of the Kirchhoff transformation has proven to be a very effective tool in simplifying and solving complex diffusivity equations in reservoirs. Since its introduction by Ramey and Crawford (1966) in addressing the non-linear behavior of compressible fluids, it has seen many modifications and implementations in multiphase systems, from the Perrine type pseudo-pressure to the reservoir integral type pseudo-pressure also called the Mass balance Model (MBM) for pseudo-pressure as discussed by Kome and Amro (2014). Its applicability in addressing water influx from aquifers to oil and gas reservoirs has as of now not been addressed. Moreover, the models developed so far to address water influx such as the works of Schilthuis (1936), Everdingen and Hurst (1949), and Fetkovich (1971), have many limitations, such as imposing constant pressure at the reservoir-aquifer interface, single phase model used, no analytical approach of predicting excessive water cuts.

In this article, the MBM pseudo-pressure is used to address water influx in reservoirs with two-phase flow (Gas/Water or Oil/Water). The model response is derived by developing diffusivity equations for the composite reservoir system to address the communication between the hydrocarbon reservoir and the aquifer. The non-homogenous nature of the diffusivity equation of each phase makes the derivation of the solutions to the equations cumbersome. Nonetheless, the reservoir integral type pseudo-pressure, being very powerful, can be incorporated in the diffusivity equations of the phases and solutions to the models can rigorously be derived. Defining the boundary conditions for each phase is very crucial as the hydrocarbons in the hydrocarbon reservoir depict a no-flow boundary at the aquifer interface, whereas the water phase and the total system response of the hydrocarbon reservoir depict mass conservation at the hydrocarbon reservoir-aquifer interface.

Using this approach, the solutions to the phases in the hydrocarbon and aquifer are readily obtained and its applicability in gas hydrate reservoirs highlighted. The effects of the water influx from the aquifer are clearly seen with increasing water cut at the sandface. The effects of different outer boundary conditions in the aquifer are investigated.

The novel approach introduced in this work will help tremendously to improve the characterization of the reservoir with multiphase flow, mostly especially for reservoirs with aquifer drive.

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Outline

1. Introduction
   - Aquifer Influx Prediction Models
   - Gas Hydrate Reservoir Types
   - Multiphase Pseudo-Pressure
   - Objectives
2. Methodology
3. Results and Observations
4. Conclusion

INTRODUCTION

Aquifer Influx Prediction Models

- ✓ **Edgewater Aquifer Models**
  - ❖ van Everdingen and Hurst (vEH) (1949) for infinite to finite aquifer –CPIB &CRIB
  - ❖ Carter-Tracy Unsteady State Method (1960)
  - ❖ Fetkovich Pseudo-Steady State (1971)

- ✓ **Bottom Water Aquifer Models**
  - ❖ Coats (1962)- Analytical Model for infinite aquifer with CRIB
  - ❖ Allard and Chen (1988)- Numerical Model for infinite to finite aquifer and CPIB
  - ❖ Khosravi and Yildiz (2007)

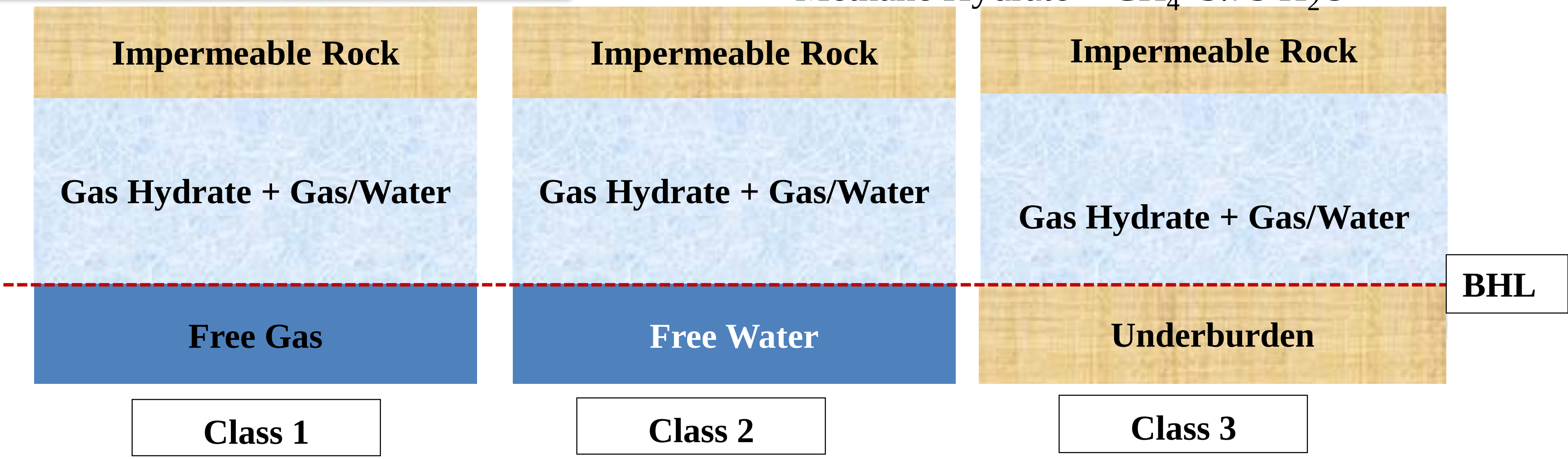
- ✓ **Other Aquifer Models**
  - ❖ Pot Aquifer
  - ❖ Schilthius (1936) Steady State

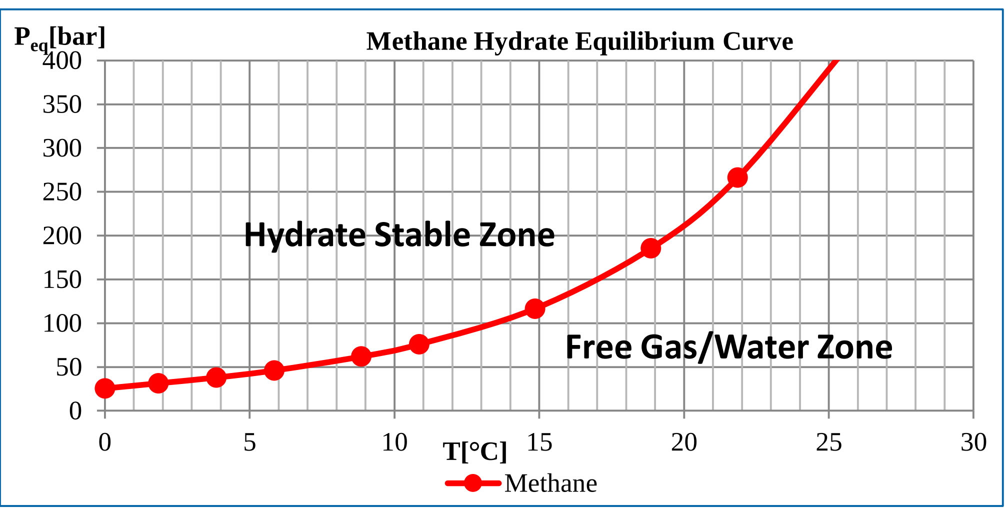
SINGLE PHASE MODELS !!!

INTRODUCTION

Gas Hydrates

Methane Hydrate = CH_4*5.75 H_2O





$$m_w = \left[\frac{n_w}{(n_g+n_w)} * \frac{M_w}{M_H}\right] m_H$$

$$m_w = f_{wH} m_H = 0.866 m_H$$

$$m_g = \left[\frac{n_g}{(n_g+n_w)} * \frac{M_g}{M_H}\right] m_H$$

$$m_g = f_{gH} m_H = 0.134 m_H$$

$$V_{w,st} = 0.866 \frac{\rho_H}{\rho_{w,st}} V_H$$

$$V_{w,st} \approx 0.79 V_H$$

$$V_{g,st} = 0.134 \frac{\rho_H}{\rho_{g,st}} V_H$$

$$V_{g,st} \approx 180 V_H$$

INTRODUCTION

Multiphase Pseudo-Pressure and the Reservoir Integral

Mass conservation

- $\dot{m}_t(r,t) = -2h\pi r * \left(\rho_{HC} * k\frac{k^*_{rHC}}{\eta_{HC}}\frac{\partial \rho_{HC}}{\partial p}\frac{\partial p}{\partial r} + \rho_w * k * \frac{k^*_{rw}}{\eta_w}\frac{\partial \rho_w}{\partial p}\frac{\partial p}{\partial r}\right)$
- $\dot{m}_t(r,t) = -2h\pi kr\frac{\partial \varphi}{\partial r} = -2h\pi kr\frac{\partial \varphi_{HC}}{\partial r} - 2h\pi kr\frac{\partial \varphi_w}{\partial r}$

Reservoir Integral/ Pseudo-Pressure

- $\varphi = \int\left[\left(\rho_{HC} * \frac{k^*_{rHC}}{\eta_{HC}}\frac{d\rho_{HC}}{\partial p} * \partial p\right) + \left(\rho_w * \frac{k^*_{rw}}{\eta_w}\frac{\partial \rho_w}{\partial p} * \partial p\right)\right]$
- $\varphi = \int \partial\varphi_{HC} + \int \partial\varphi_w$
- $\partial\varphi = \partial\varphi_{HC} + \partial\varphi_w$

INTRODUCTION

Objectives

- ✓ Improve water influx/water cut predictions and material balance methods in reservoirs
- ✓ Address the real constant pressure outer boundary problem for hydrocarbon reservoirs with aquifer support using multiphase models
- ✓ Improve decline curve analysis, production data and well test intepretation for multiphase regimes.

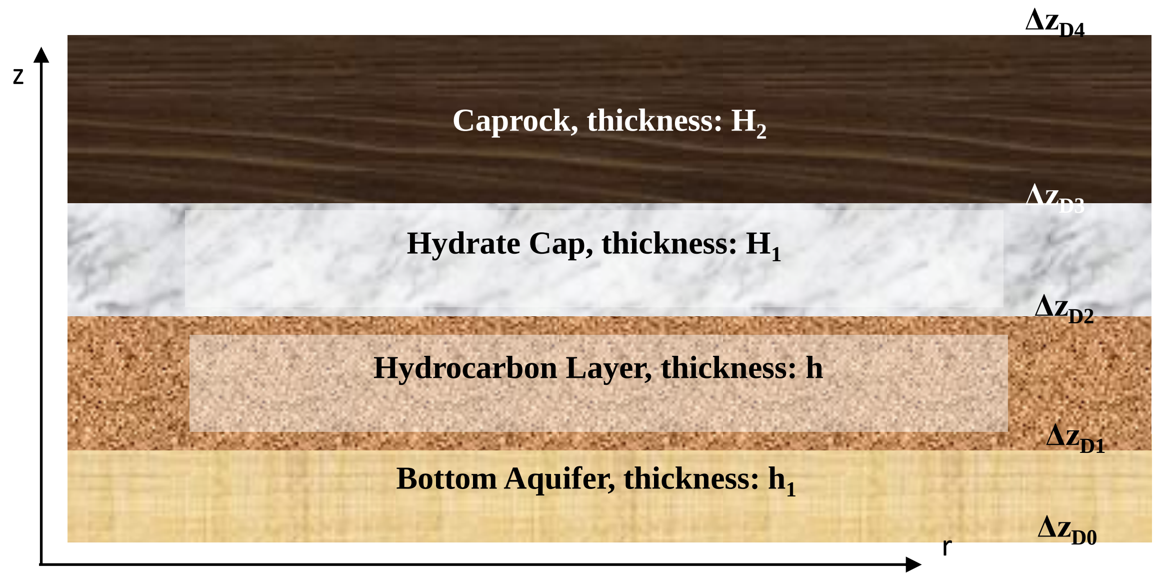
METHODOLOGY

- Reservoir Types
  - Gas hydrate reservoirs Class 1 and Class 2
  - Hydrocarbon Reservoirs: Dry Gas and Undersaturated Oil
- Aquifer Influx Models
  - Bottom Aquifer Model: vertical flow is considered dominant
  - Edge Aquifer Model: radial flow is considered dominant
- Two phase flow is considered in the producing layer
  - Gas and Water
  - Oil and Water
- Develop diffusivity equations for :
  - Response of total system (Hydrocarbon and Water) in producing layer
  - Response of the aquifer layer / reservoir
  - Responses of the different phases in the producing layer (gas/oil and water
- Pseudo-pressure for two phase regimes is used for linearization
- Laplace transformation is used to develop solutions for the composite reservoir with boundary conditions

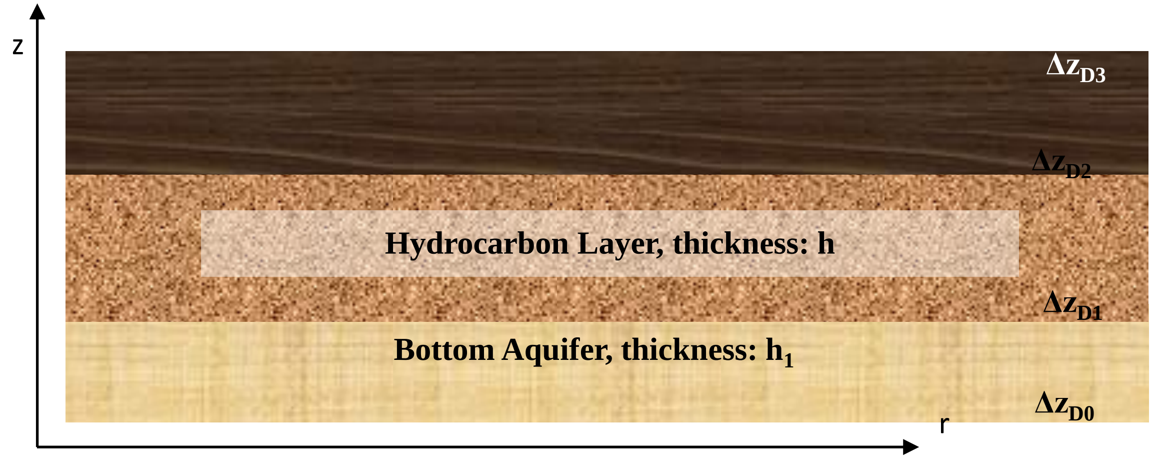
METHODOLOGY

Reservoir Types

Gas Hydrates



Conventional Reservoirs



METHODOLOGY

Diffusivity Equations

Total System Responses

Diffusivity Equation for Class 1 Gas Hydrate Reservoir: $r_w \le r \le r_e$, $h_1 \le z \le h + h_1$

$$\frac{1}{r}\frac{\partial[r*(\rho_g w_g+\rho_w w_w)]}{\partial r} - \frac{\rho_g w_{gH}}{h} - \frac{\rho_w w_{wH}}{h} - \frac{\rho_w w_{wA}}{h} = (c_T\rho)_T\frac{\partial p}{\partial t} \quad \text{.....A1: 1}$$

Diffusivity Equation for Class 2 Gas Hydrate Reservoirs: $r_w \le r \le r_e$, $h_1 \le z \le h + h_1$

$$\frac{1}{r}\frac{\partial[r*(\rho_g w_g+\rho_w w_w)]}{\partial r} - \frac{\rho_g w_{gH}}{h} - \frac{\rho_w w_{wH}}{h} = (c_T\rho)_T\frac{\partial p}{\partial t} \quad \text{.....A1: 2}$$

Diffusivity Equation for the Hydrate Cap Layer: $h + h_1 \le z \le h + h_1 + H_1$

$$\frac{\partial[(\rho_g w_g+\rho_w w_w)]}{\partial z} = (c_T\rho)_{TH}\frac{\partial p}{\partial t} \quad \text{.....A1: 3}$$

Heat Conduction Equation for Caprock Layer: $h + h_1 + H_1 \le z \le h + h_1 + H_1 + H_2$

$$\frac{\partial^2 \Delta T}{\partial z^2} = \frac{(\rho c_p)_{eff}}{\lambda}\frac{\partial \Delta T}{\partial t} \quad \text{.....A1: 4}$$

Diffusivity Equation for Hydrocarbon Reservoirs: $r_w \le r \le r_e$

$$\frac{1}{r}\frac{\partial[r*(\rho_{HC} w_{HC}+\rho_w w_w)]}{\partial r} - \frac{\rho_w w_{wA}}{h} = (c_T\rho)_{T,HC}\frac{\partial p}{\partial t} \quad \text{.....A1: 5}$$

Diffusivity Equation for Edge Aquifer: $r_e \le r \le r_{eA}$

$$\frac{1}{r}\frac{\partial\left[r*\left(\rho_w*k_A*\frac{k^*_{rw}}{\eta_w}\frac{\partial p}{\partial r}\right)\right]}{\partial r} = (\rho_w \varnothing_A c_{T,w})\frac{\partial p}{\partial t} \quad \text{.....A1: 6}$$

Diffusivity Equation for Bottom Aquifer: $0 \le z \le h_1$

$$\frac{\partial\left[\left(\rho_w*k_{A,v}*\frac{k^*_{rw}}{\eta_w}\frac{\partial p}{\partial z}\right)\right]}{\partial z} = (\rho_w \varnothing_A c_{T,w})\frac{\partial p}{\partial t} \quad \text{.....A1: 7}$$

Phase Responses

Diffusivity Equation of Fluid Phases in

Free Fluid Layer of the Hydrate-Capped Reservoir

Gas Phase

$$\frac{1}{r}\frac{\partial[r*(\rho_g w_g)]}{\partial r} - \frac{\rho_g \dot{w}_{gH}}{h} = [(c_T\rho)_{gH}]\frac{\partial p}{\partial t} \quad \text{.....A1: 8}$$

Water Phase

$$\frac{1}{r}\frac{\partial[r*(\rho_w w_w)]}{\partial r} - \frac{\rho_w w_{wH}}{h} - \frac{\rho_w w_{wA}}{h} = [(c_T\rho)_{wH}]\frac{\partial p}{\partial t} \quad \text{.....A1: 9}$$

Diffusivity Equation of Fluid Phases in the Hydrocarbon Reservoir

Hydrocarbon Phase

$$\frac{1}{r}\frac{\partial[r*(\rho_{HC} w_{HC})]}{\partial r} = [(c_T\rho)_{HC}]\frac{\partial p}{\partial t} \quad \text{.....A1: 10}$$

Water Phase

$$\frac{1}{r}\frac{\partial[r*(\rho_w w_w)]}{\partial r} - \frac{\rho_w w_{wA}}{h} = [(c_T\rho)_{wH}]\frac{\partial p}{\partial t} \quad \text{.....A1: 11}$$

METHODOLOGY

Laplace + Schapery Transformed Diffusivity Equations

Total System (Hydrocarbon +Water Phase)

$$\frac{\partial^2[p\widehat{\varphi_D}]}{\partial {r_D}^2}+\frac{1}{r_D}\frac{\partial[p\widehat{\varphi_D}]}{\partial r_D}-[\widehat{\omega_w}+\widehat{\omega_{HC}}][\widehat{p\varphi_D}]=0$$

Hydrocarbon Phase

$$\frac{\partial^2[p\widehat{\varphi_{DHC}}]}{\partial {r_D}^2}+\frac{1}{r_D}\frac{\partial[p\widehat{\varphi_{DHC}}]}{\partial r_D}-[\widehat{\omega_{HC}}][\widehat{p\varphi_D}]=0$$

Water Phase

$$\frac{\partial^2[p\widehat{\varphi_{Dw}}]}{\partial {r_D}^2}+\frac{1}{r_D}\frac{\partial[p\widehat{\varphi_{Dw}}]}{\partial r_D}-[\widehat{\omega_w}][\widehat{p\varphi_D}]=0$$

Edge Aquifer

$$\frac{\partial^2[p\widehat{\varphi_{DA}}]}{\partial {r_D}^2}+\frac{1}{r_D}\frac{\partial[p\widehat{\varphi_{DA}}]}{\partial r_D}-s_{Ar}[p\widehat{\varphi_{DA}}]=0$$

Bottom Aquifer

$$\frac{\partial^2[p\widehat{\varphi_{DA}}]}{\partial {z_D}^2}-s_{Av}[p\widehat{\varphi_{DA}}]=0$$

Heat Conduction from Caprock (hydrate dissociation)

$$\frac{\partial^2[p\widehat{T_D}]}{\partial {z_D}^2}-s_{cv}[p\widehat{T_D}]=0$$

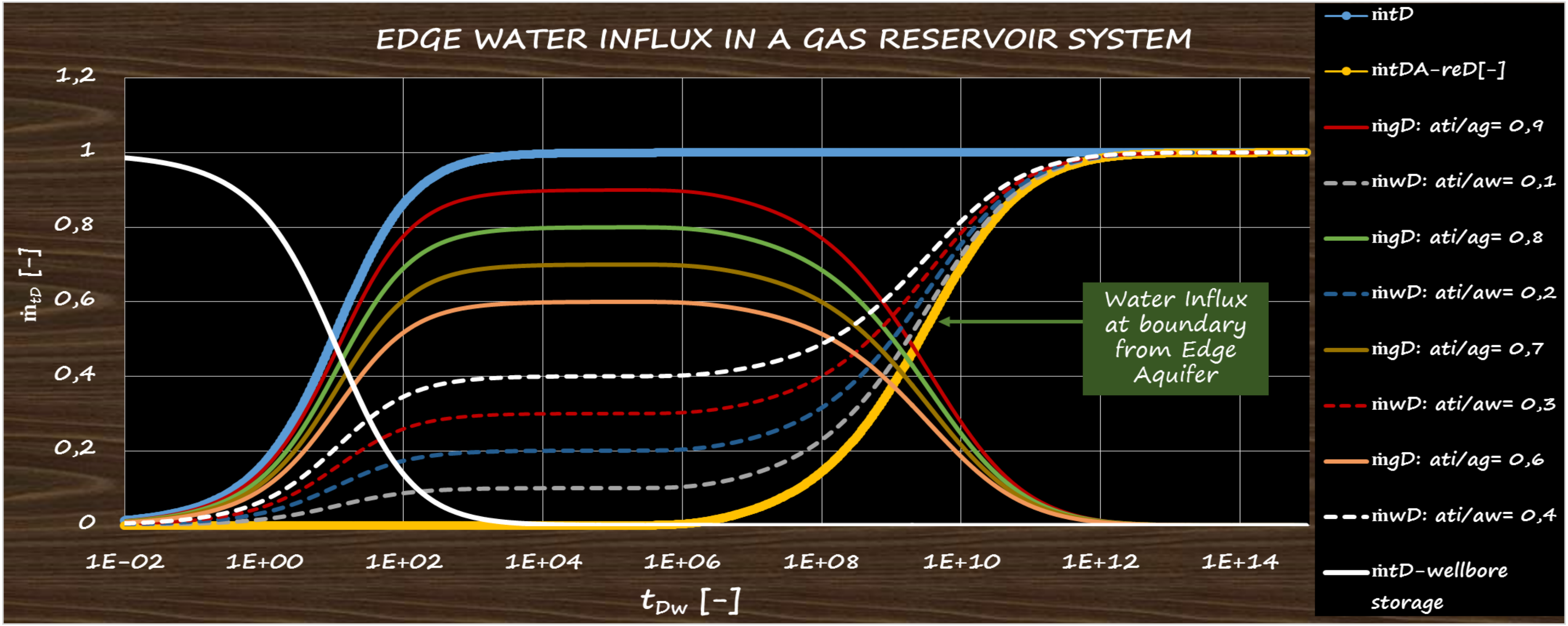
Hydrocarbon Reservoir	Gas Hydrates
$\widehat{\omega_w}=\left[p\left(\widehat{p\frac{a_{T,i}}{a_w}}\right)+\left[\widehat{\dot{Q}_{DA}}\right]\right]$	$\widehat{\omega_w}=\left[p\left(\widehat{p\frac{a_{T,i}}{a_w}}\right)+f_{wH}\left[\widehat{\dot{Q}_{Deff}}\right]+\left[\widehat{\dot{Q}_{DA}}\right]\right]$
$\widehat{\omega_{HC}}=\left[p\left(\widehat{p\frac{a_{T,i}}{a_g}}\right)\right]$	$\widehat{\omega_{HC}}=\left[f_{gH}\left[\widehat{\dot{Q}_{Deff}}\right]+p\left(\widehat{p\frac{a_{T,i}}{a_g}}\right)\right]$

$s_{Ar}=\frac{k}{k_A}\left[\frac{\lambda_{t,i}}{S_{t,i}}\left(\widehat{p\frac{S_A}{\lambda_A}}\right)\right]p$	$s_{Av}=\frac{k}{k_{A,v}}\frac{h^2}{r_w^2}\left[\frac{\lambda_{t,i}}{S_{t,i}}\left(\widehat{p\frac{S_A}{\lambda_A}}\right)\right]p$	$s_{cv}=p\left[\frac{h^2}{r_w^2}\frac{\lambda_{t,i}}{S_{t,i}}\frac{(\rho c_p)_{eff}}{\lambda}\right]$

RESULTS AND OBSERVATIONS

Case 1 : Edge Aquifer

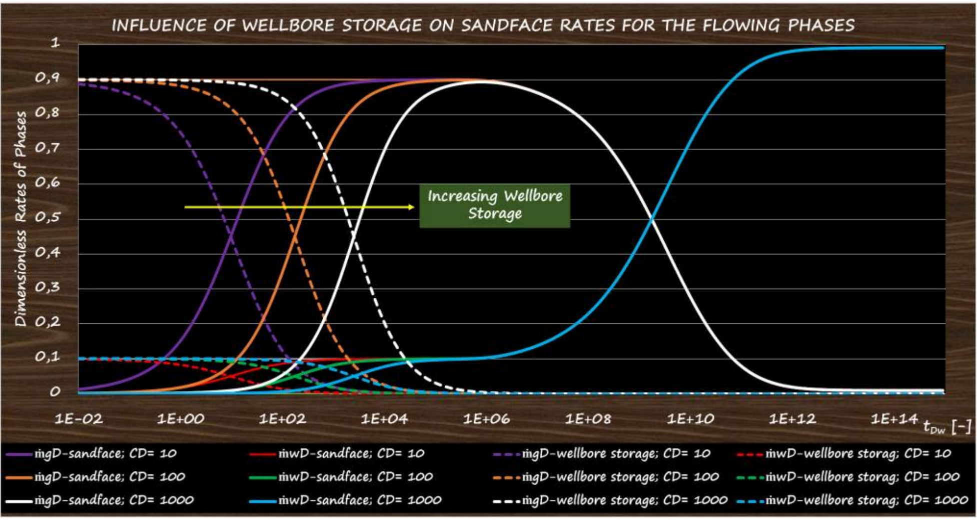
OBC-Aquifer	CPOB-Circular
Distance to Boundary; r_{eA} [m]	5000
Dimensionles Wellbore Storage Coefficient; C_D [-]	10
k[mD]	**1000**
kA[mD]	**1**
re[m]	500
r_w[m]	0,1

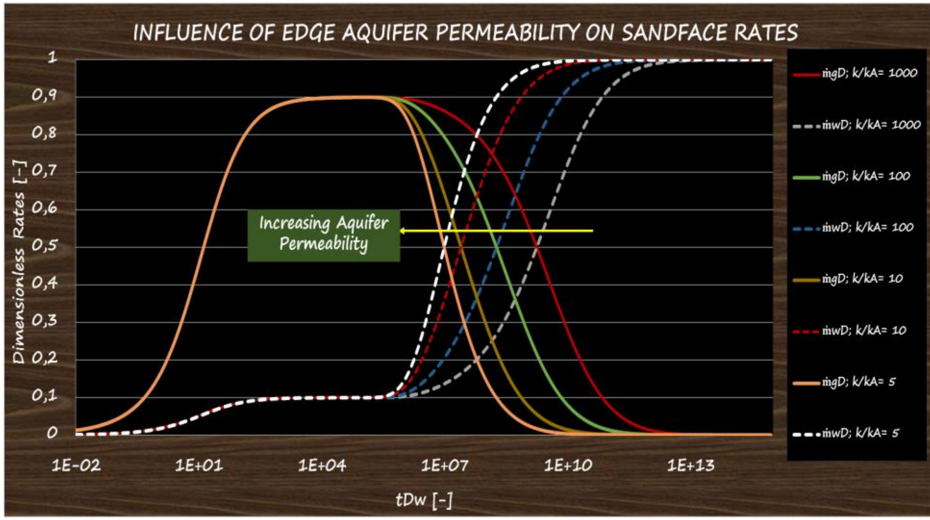


Results and Observations

Case 1 : Edge Aquifer

OBC-Aquifer	CPOB-Circular
Distance to Boundary; r_{eA} [m]	5000
ati/ag [-]	0.9
k[mD]	**1000**
kA[mD]	**1**
re[m]	500
r_w[m]	0.1

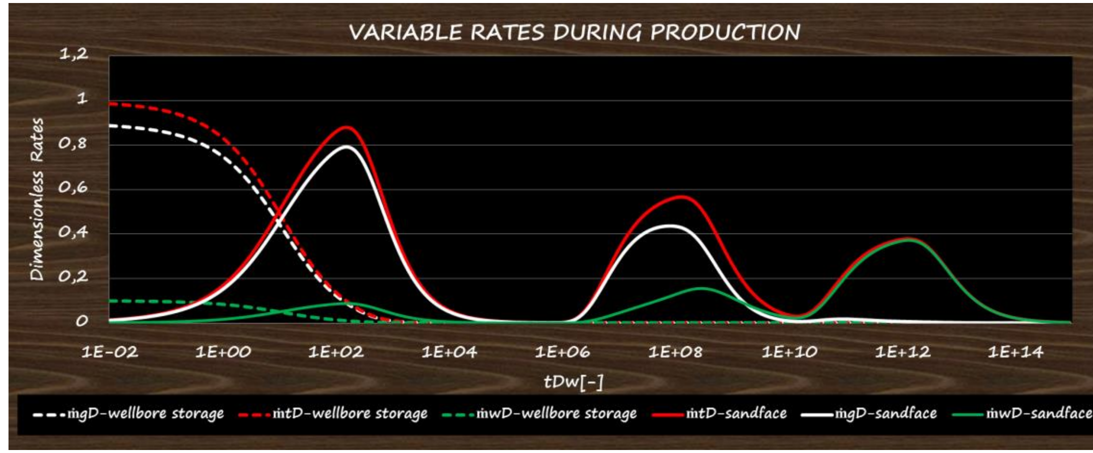


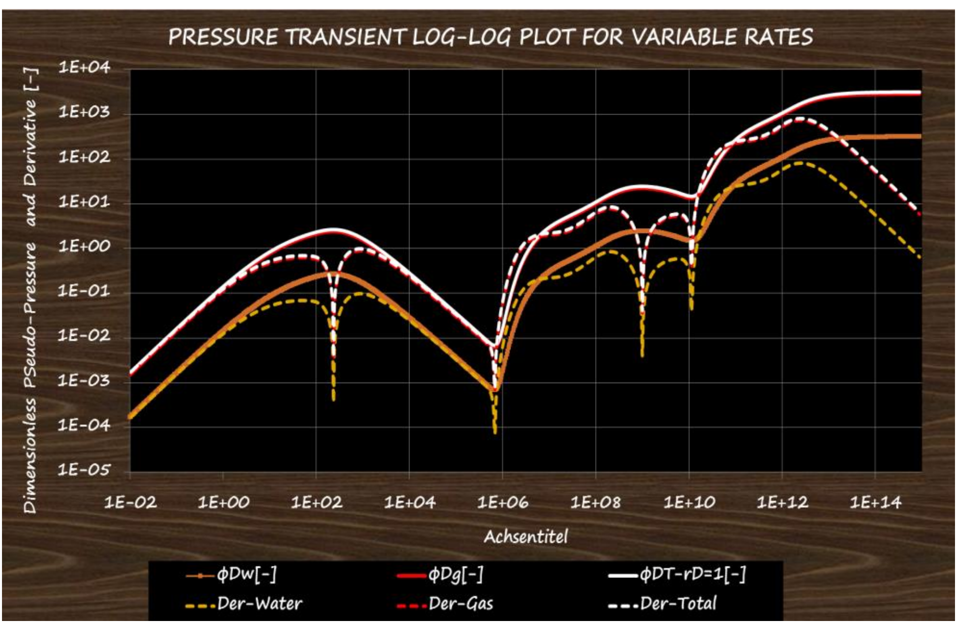


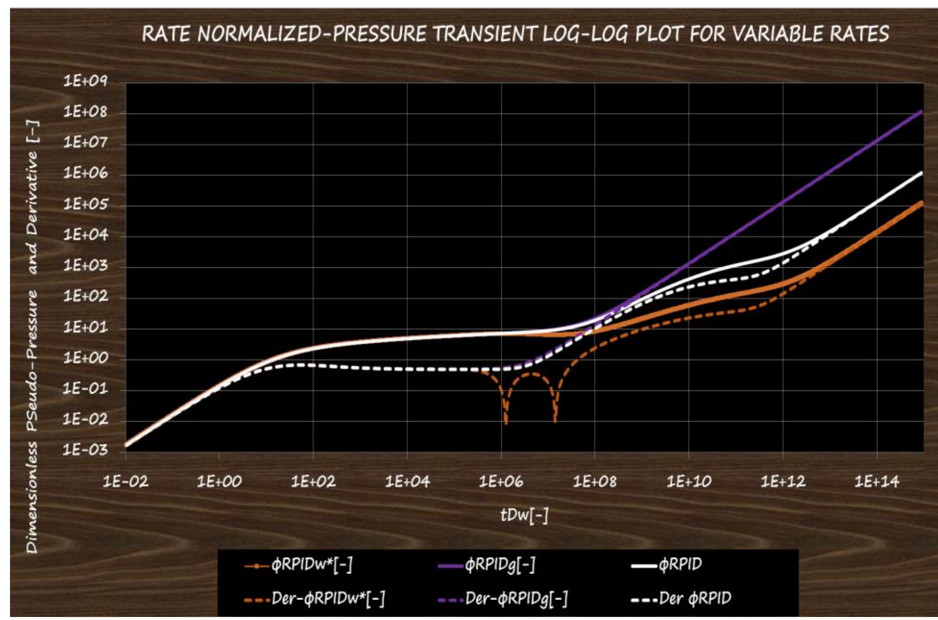
Results and Observations

Case 1 : Edge Aquifer- Normalization

OBC-Aquifer	NFB-Circular
Distance to Boundary; r_{eA} [m]	5000
CD[-]	10
ati/ag [-]	0.9
k[mD]	**1000**
kA[mD]	**1**
re[m]	500
r_w[m]	0.1



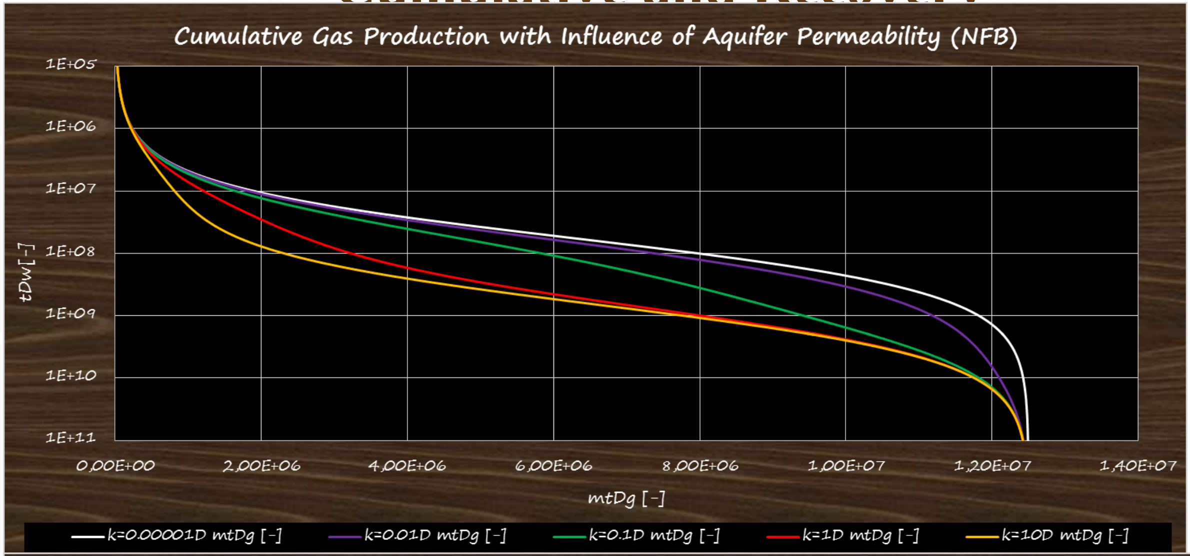


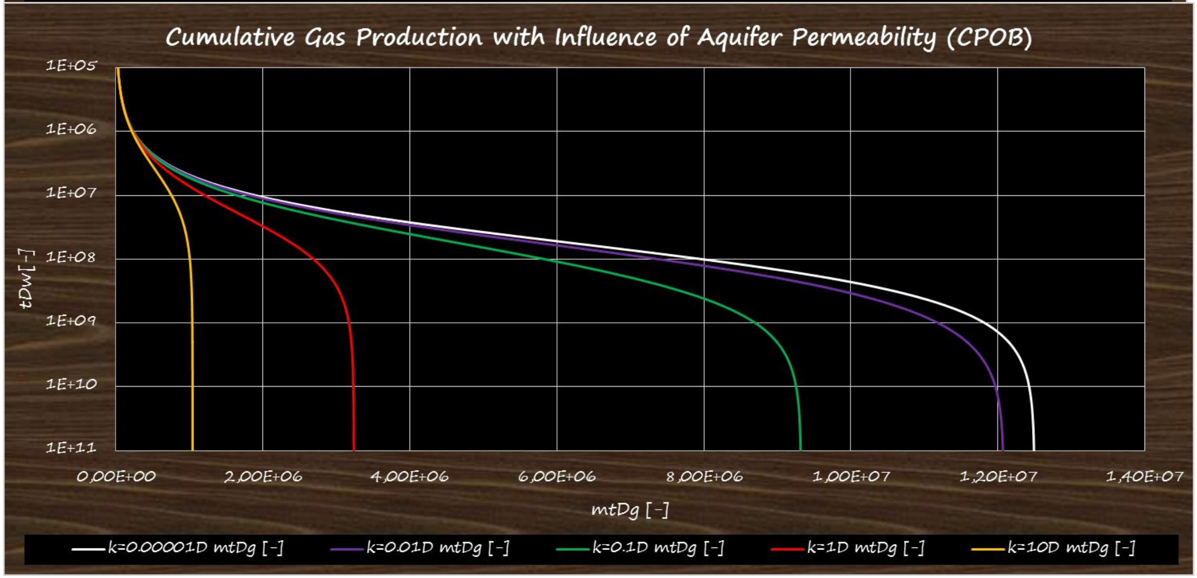


Results and Observations

Case 1 : Edge Aquifer- Cumulative and Recovery

Distance to Boundary; r_{eA} [m]	5000
CD[-]	10
re[m]	500
r_w[m]	0.1
ati/aw	1,00E-08
ati/ag	1,00E+00



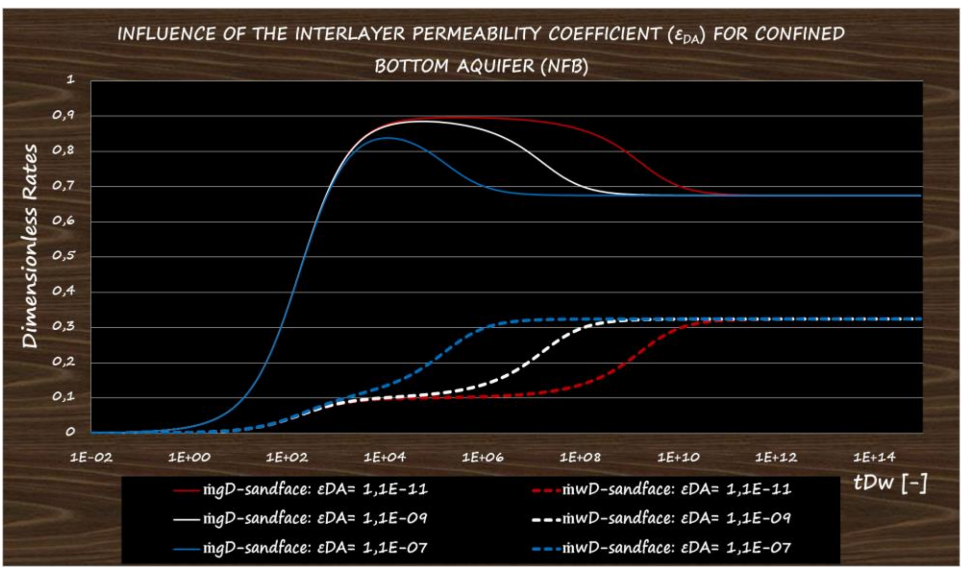


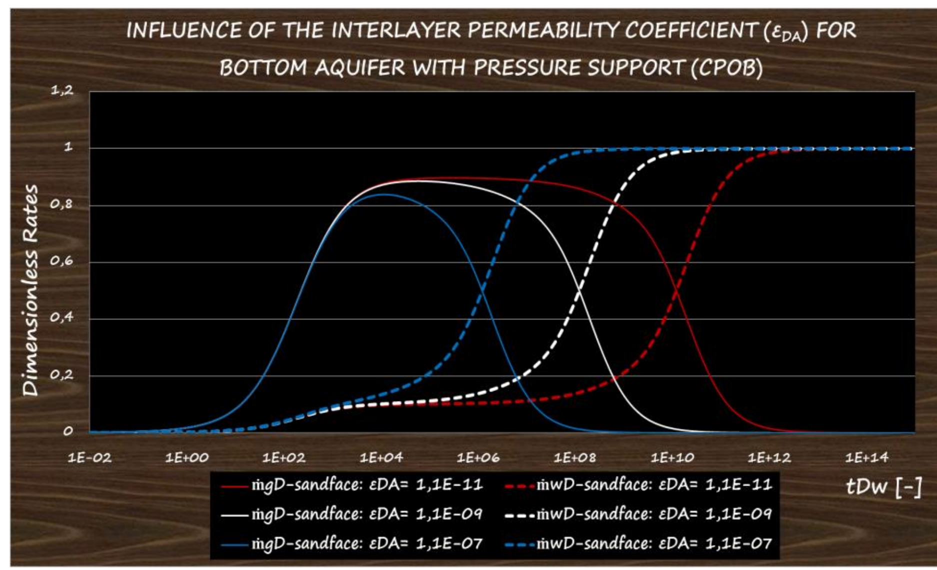
RESULTS AND OBSERVATIONS

Case 2 : Bottom Aquifer

OBC-Aquifer	NFB-Circular
Distance to Boundary; r_{eA} [m]	5000
CD[-]	10
ati/ag [-]	0.9
kA/k[-]	**1E-22**
re[m]	500
r_w[m]	0.1

h1[m]	10
kA,v[mD]	1,00E-02
h1/h [-]	0,333333333
εD	1,11111E-10

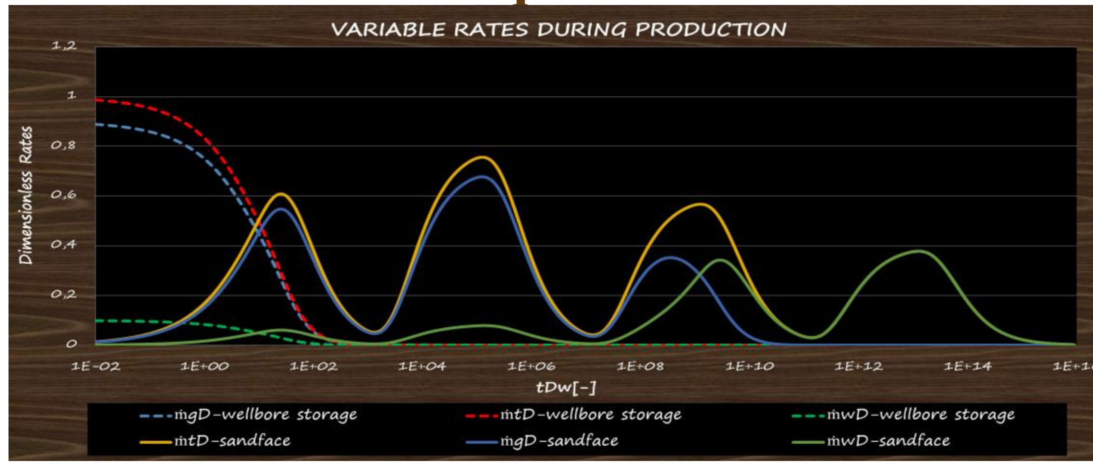


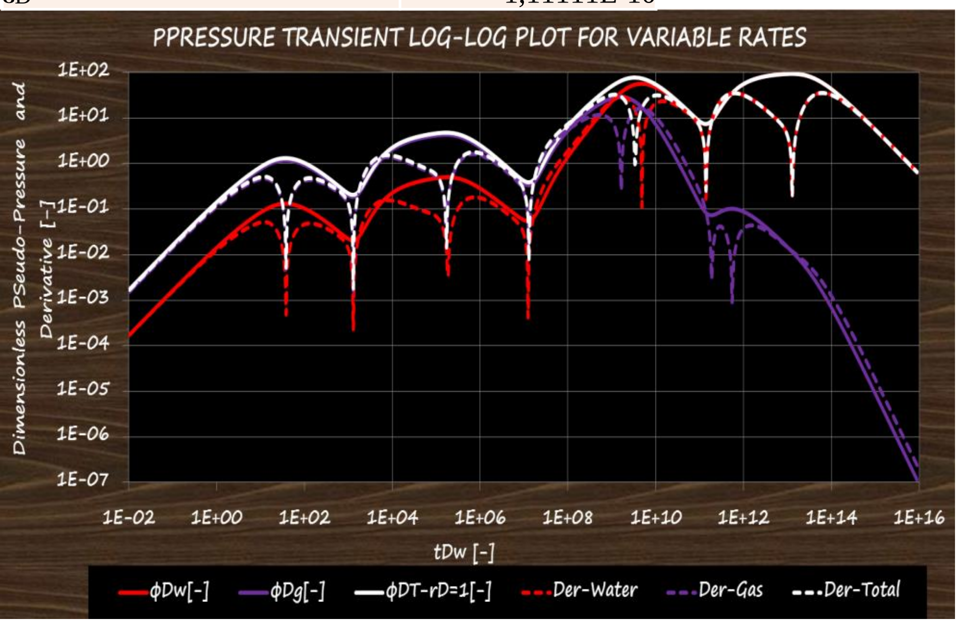


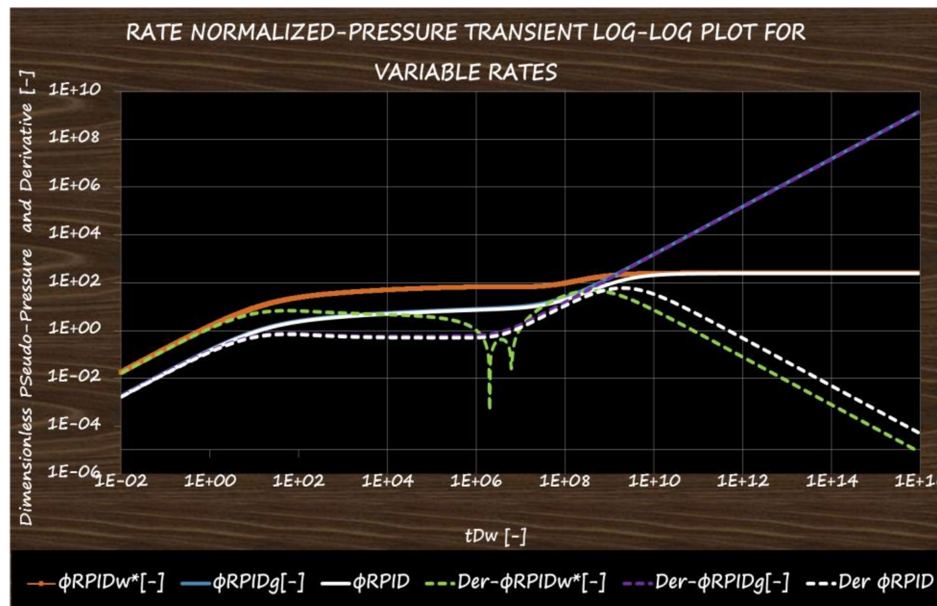
RESULTS AND OBSERVATIONS

Case 2 : Bottom Aquifer- Normalization

CD[-]	10
ati/ag [-]	0.9
k[mD]	**1000**
re[m]	500
r_w[m]	0.1
Bottom Aquifer Parameters	**CPOB-Linear**
h1[m]	10
kA,v[mD]	1,00E-02
h1/h [-]	0,333333333
εD	1,11111E-10



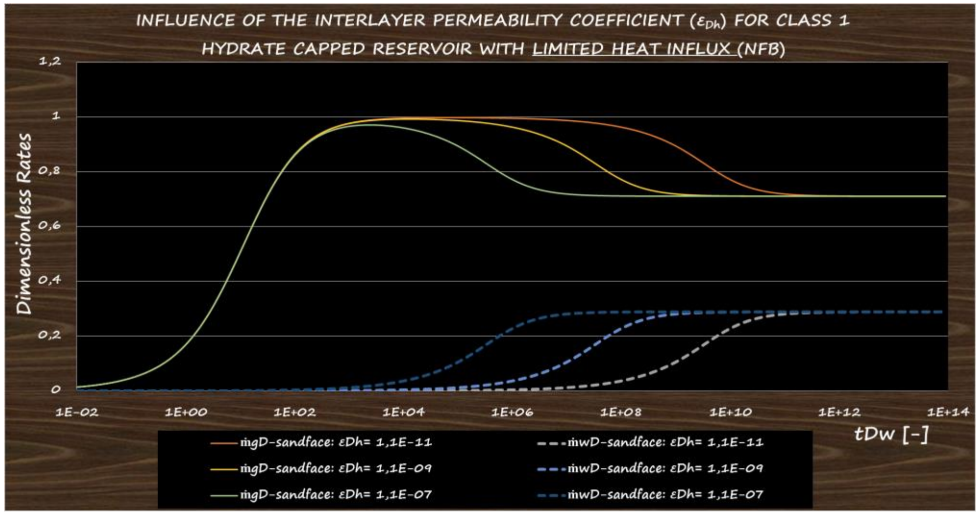


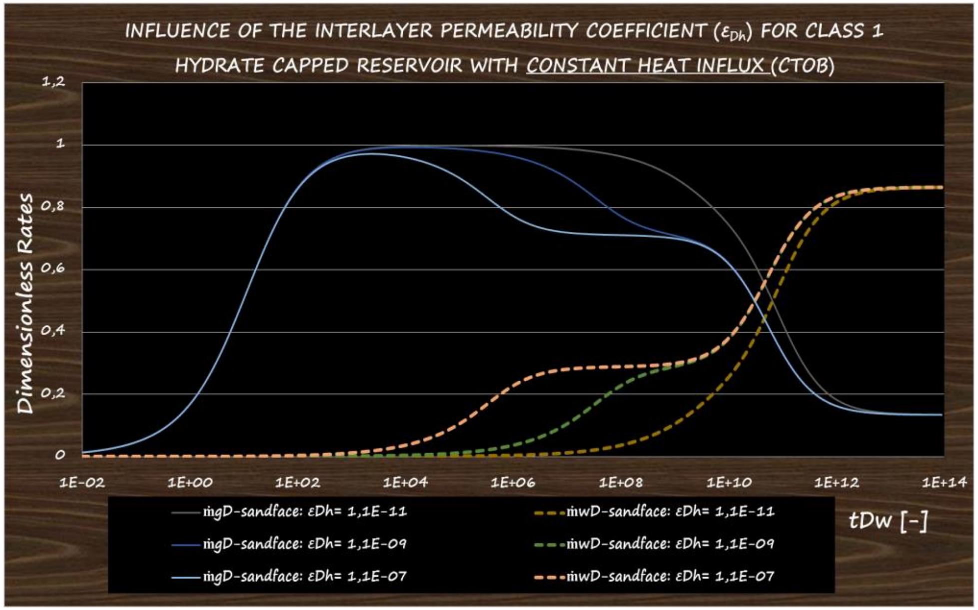


RESULTS AND OBSERVATIONS

Case 3 : Gas Hydrate –Class 1 (No Aquifer)

Dimensionless Wellbore Storage Coefficient; C_D [-]	10
k[mD]	1000
re[m]	500
r_w[m]	0,1
h2[m]	20
ati/aw	0,000000001
ati/ag	0,999999999
Caprock-Properties	NFB-Linear
H2[m]	200
λ [W/mK]	2
(λti/Sti)*[(cp*ρ)eff/λ]	1
h[m]	30
Hydrate Cap	
H1 [m]	15
dφ/dp [Kg/(m³*Pas)]	200000
hd[J/kg]	500000
dT/dp [K/Pa]	0,0000005
(λti/Sti)*[Sh/λh]	1
fwh=ṁw/ṁh [-]	0,865792994
fgh=ṁg/ṁh [-]	0,1341025

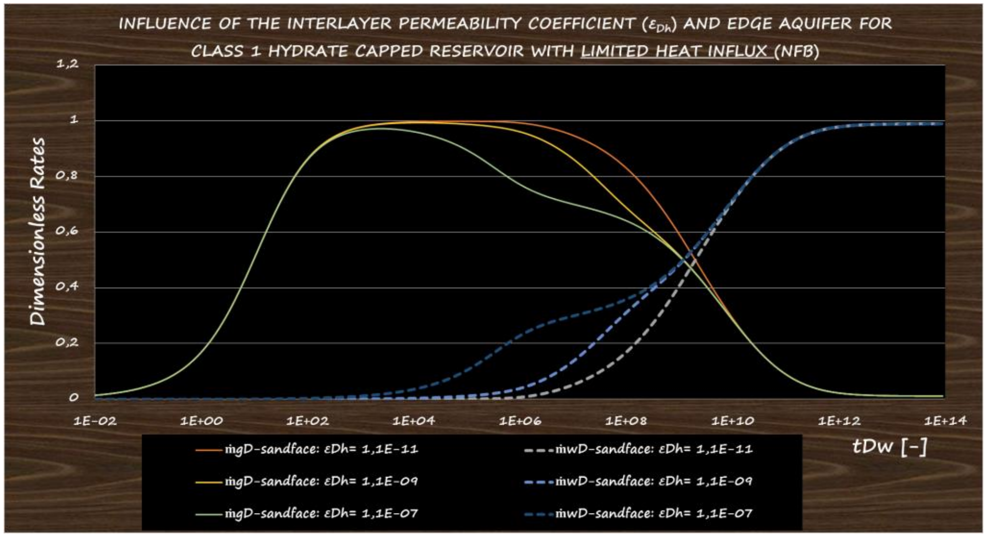


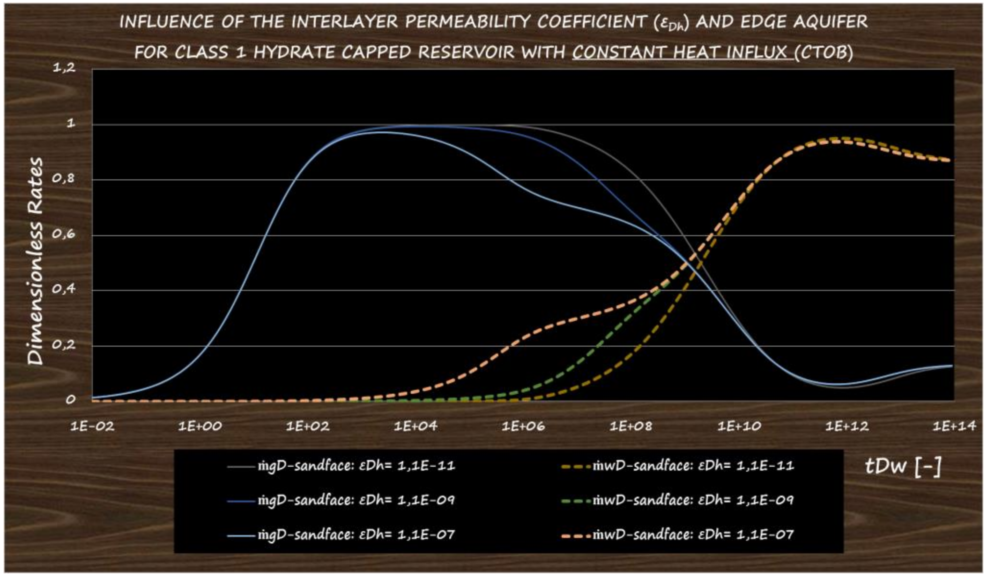


RESULTS AND OBSERVATIONS

Case 4 : Gas Hydrate –Class 1 (Edge Aquifer)

Edge OBC-Aquifer	NFB
Dimensionles Wellbore Storage Coefficient; C_D [-]	10
k[mD]	1000
reA[-]	5000
re[m]	500
r_w[m]	0,1
h2[m]	20
ati/aw	0,000000001
ati/ag	0,999999999
Caprock-Properties	NFB-Linear
H2[m]	200
λ [W/mK]	2
(λti/Sti)*[(cp*ρ)eff/λ]	1
h[m]	30
Hydrate Cap	
H1 [m]	15
dϕ/dp [Kg/(m³*Pas)]	200000
hd[J/kg]	500000
dT/dp [K/Pa]	0,0000005
(λti/Sti)*[Sh/λh]	1
fwh=ṁw/ṁh [-]	0,865792994
fgh=ṁg/ṁh [-]	0,1341025





Conclusions

- We have shown that estimates of water influx and breakthrough periods can be made using the multiphase pseudo-pressure.

- Though the pressure diffusivity of the hydrocarbon/hydrate reservoir were assumed constant, type curves can be generated to address these changes, especially during boundary dominated flow.

- For well test analysis, normalizing the multiphase data is very vital in reducing the fluctuations in the reservoir response.

- From the rate and pseudo-pressure transient models developed for each flowing phase, matching the rate and improving on rate decline analysis becomes easier.

- The rate normalized forms of pseudo-pressure and the pseudo-pressure normalized form of the cumulative rates are recommended for proper analysis as they provide a much smother plot and approach for analysis, which can further be used for material balance calculations and reserve estimation purposes.

THANK YOU

ANY QUESTIONS?

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