SPE International
Society of Petroleum Engineers

SPE workshop

Gas Field Development and Production – State of Play

15 – 16 January 2024 | BANGKOK, THAILAND

Analytical Model for Well Injectivity Prediction on CO_2 Injection in Heterogeneous Reservoirs

Siti Rohaida Mohd Shafian[1], Nazliah Nazma Bt Zulkifli[1], M Iqbal Mahamad Amir[1], Pavel Bedrikovetski[2]

[1]PETRONAS

[2]The University of Adelaide

Outline

- Overview – Carbon capture and storage (CCS)
- Factor causes CO_2 injectivity declines
- Development of analytical model – workflow
- Expression of well impedance during CO_2 injections
- New analytical formulae for well impedance
- Results
- Summary
- Conclusions
- Acknowledgements

Positioning to future new normal, refresh Technology Agenda is imminent to deliver MFT 50.30.0 and supporting future growth areas for PETRONAS

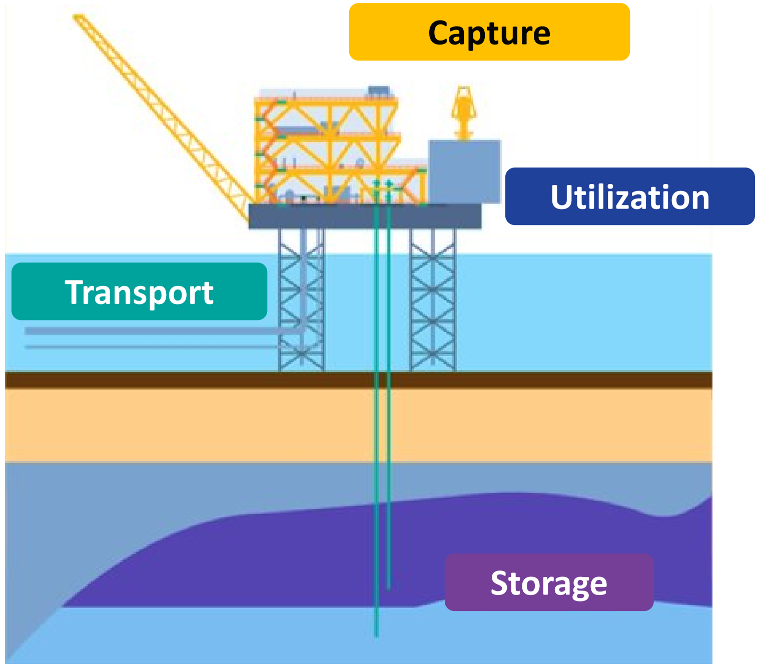
PETRONAS Technology Agenda

Value
50% improvement in cash flow from operations by **2025**

Growth
30% revenue by **2030** from new non-traditional business to complement growth in existing core

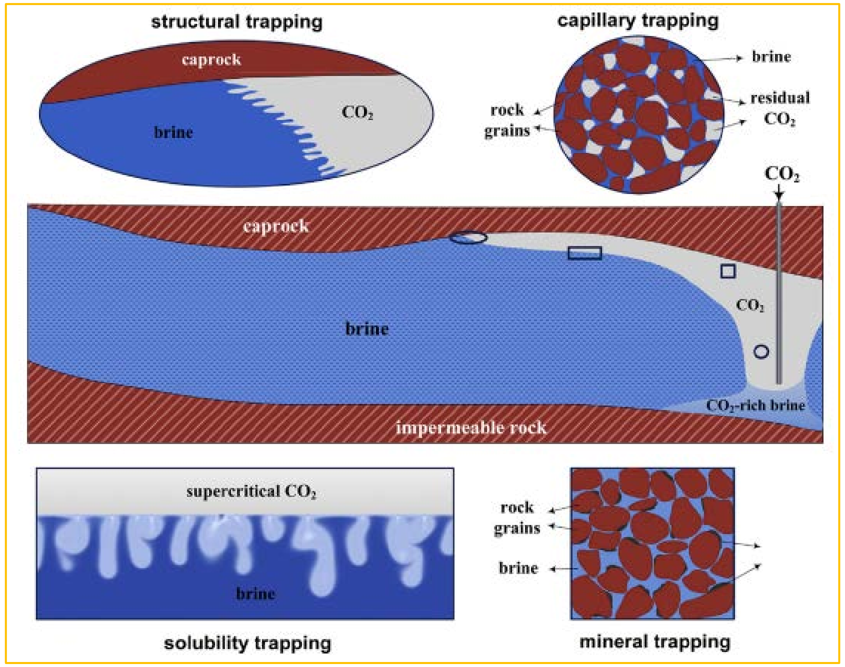
Sustainability
Net Zero carbon emissions by **2050** with positive social impact and adherence to business ethics and corporate governance

- Hydrogen
- CCUS
- Advanced Materials
- Subsea Factory
- Specialty Chemicals
- Renewables
- Fluid Technology Solutions



Overview - Carbon capture and storage (CCS)

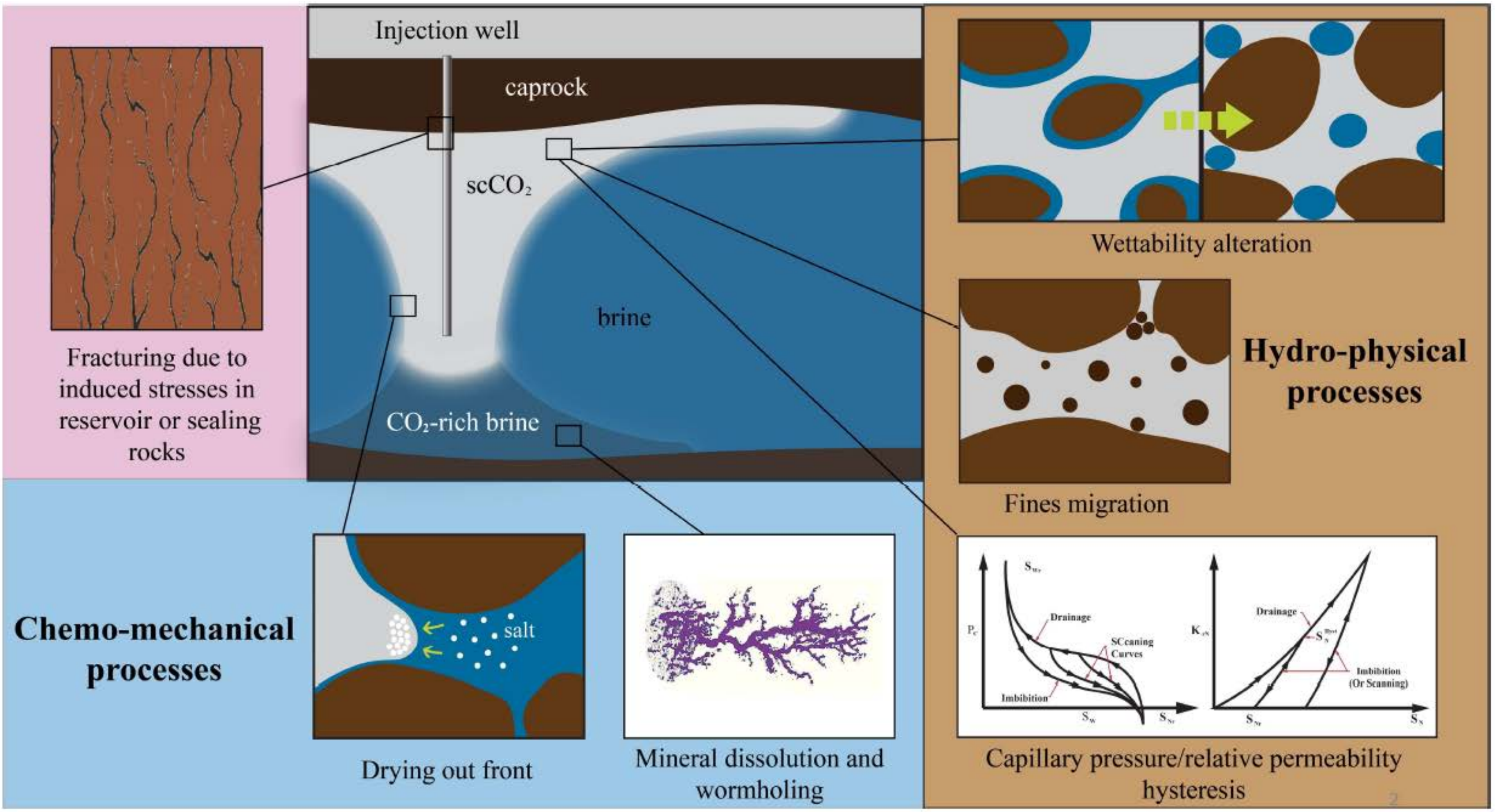
- CCS - process that involves capturing the CO2 at its source & storing it permanently subsurface
- PETRONAS is currently embarking an opportunity for CO2 storage at oil & gas reservoir and deep saline aquifer for short- and long-term geo-sequestration
- However, CO_2 storage into aquifers has greater complexity, as it causes various hydro-physical, chemical, and geomechanical interactions that affect the injectivity of wellbores



CO2 trapping mechanism

Ref. Hasan et al. 2021,

Factor causes CO_2 injectivity declines



Lost of seal/caprock integrity

Salt precipitation by Joule-Thompson (JT) cooling down and water evaporation into CO_2

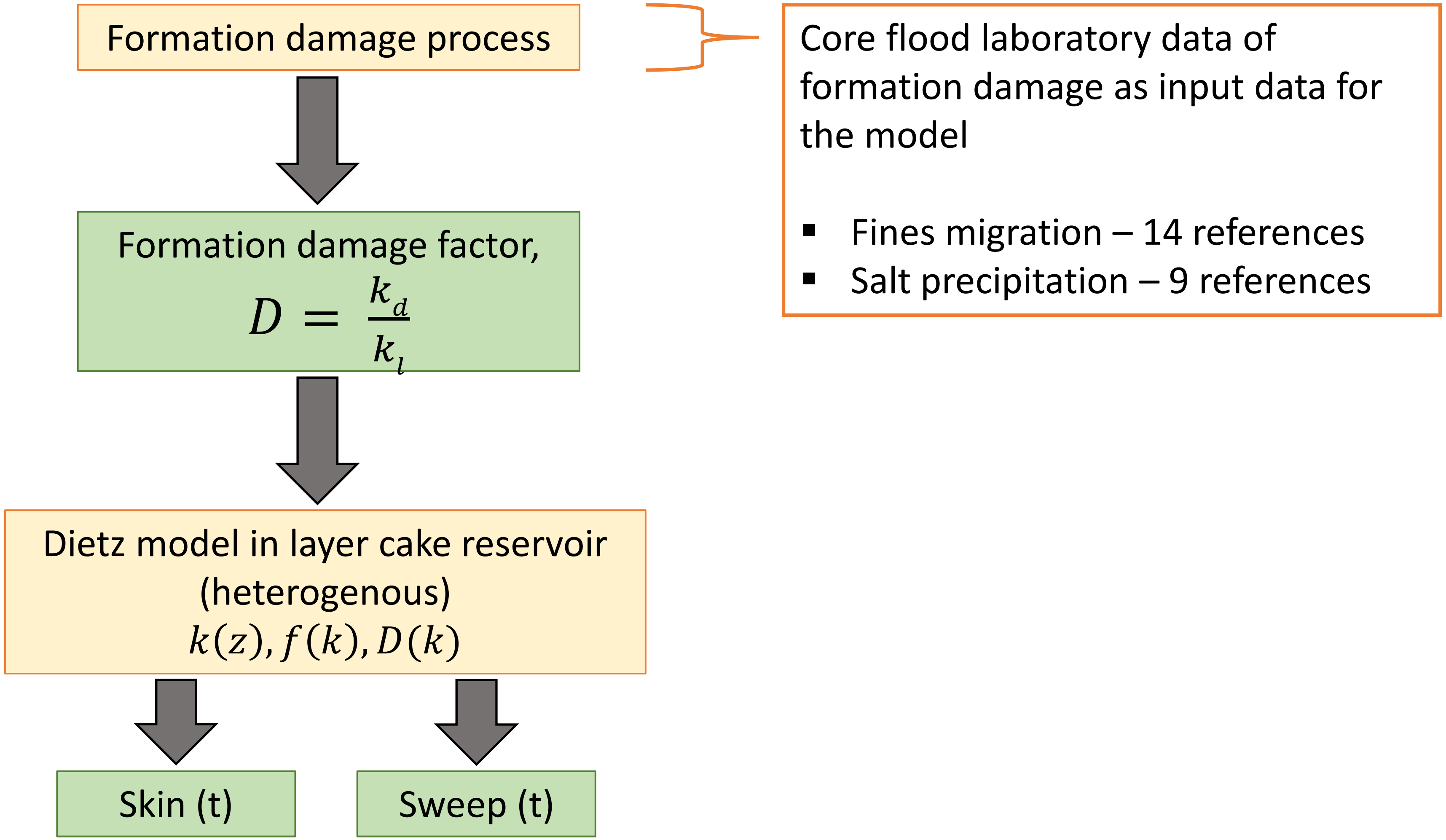
Wettability alteration

Fines mobilization and migration by water evaporation into CO_2

Effects of water-CO_2 wettability on relative permeability and capillary pressure

Dissolution of rock in carbonic acid with release of solid particles

Workflow for Development of analytical model



Formation damage process

Formation damage factor,

$$D = \frac{k_d}{k_l}$$

Dietz model in layer cake reservoir (heterogenous)

$$k(z), f(k), D(k)$$

Skin (t)

Sweep (t)

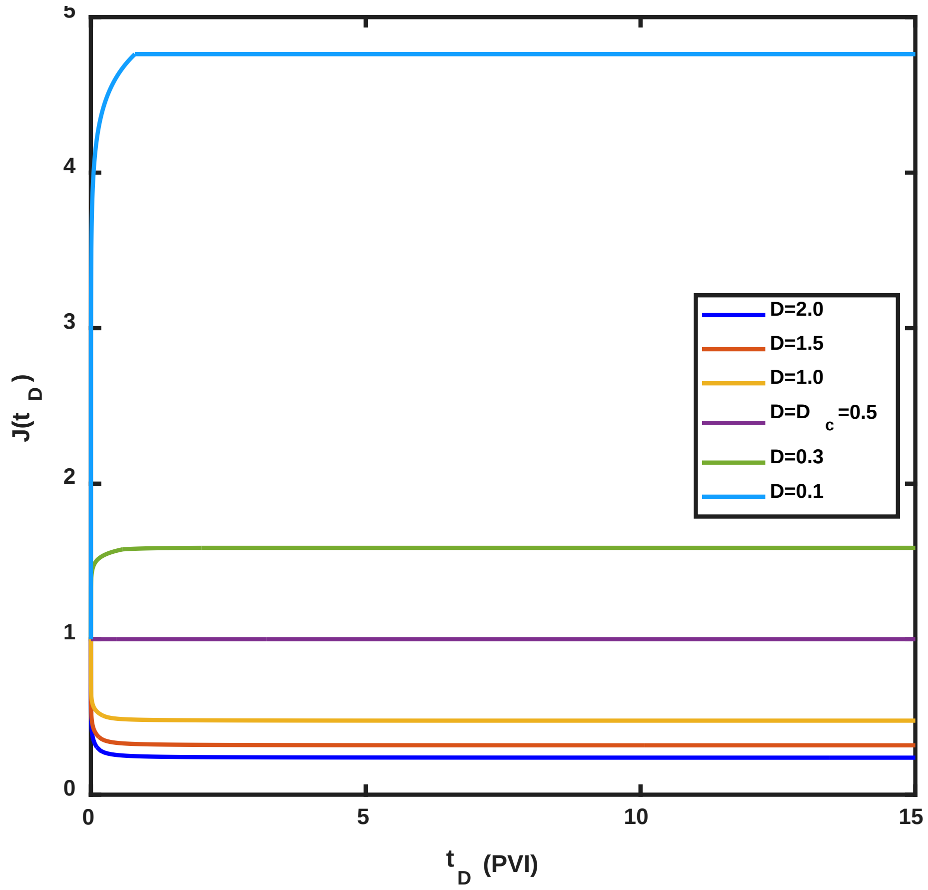
Core flood laboratory data of formation damage as input data for the model

- Fines migration – 14 references
- Salt precipitation – 9 references

Expression of well impedance during CO_2 injections

Formation damage governing equations

$$J\left(t_D\right)=\frac{II\left(t_D=0\right)}{II\left(t_D\right)}=\frac{q\left(t_D=0\right)}{\Delta p\left(t_D=0\right)}\frac{\Delta p\left(t_D\right)}{q\left(t_D\right)}$$



Well impedance versus dimensionless time at different damage ratios for c=0.5 in power-law profile

New analytical formulae for well impedance

$$J(t)=\begin{cases}\dfrac{\mu_g \ln\left(\dfrac{D_i t + x_w}{x_w}\right)}{\mu_w k_{rgwi} D < k >} + \displaystyle\int_{s_{wi}}^{s_f} \frac{f''(s)}{\left(f'(s)+\frac{x_w}{t}\right)\Lambda(s)} ds - \frac{\ln\left(D_f t + x_w\right)}{< k >} & 0 < t < \dfrac{1-x_w}{D_f} \\ \dfrac{\mu_g \ln\left(\dfrac{D_i t + x_w}{x_w}\right)}{\mu_w k_{rgwi} D < k >} + \displaystyle\int_{s_{wi}}^{s_t} \frac{f''(s)}{\left(f'(s)+\frac{x_w}{t}\right)\Lambda(s)} ds & \dfrac{1-x_w}{D_f} < t < \dfrac{1-x_w}{D_i} \\ -\dfrac{\mu_g \ln(x_w)}{\mu_w k_{rgwi} D < k >} & \dfrac{1-x_w}{D_i} < t < \infty \end{cases}$$

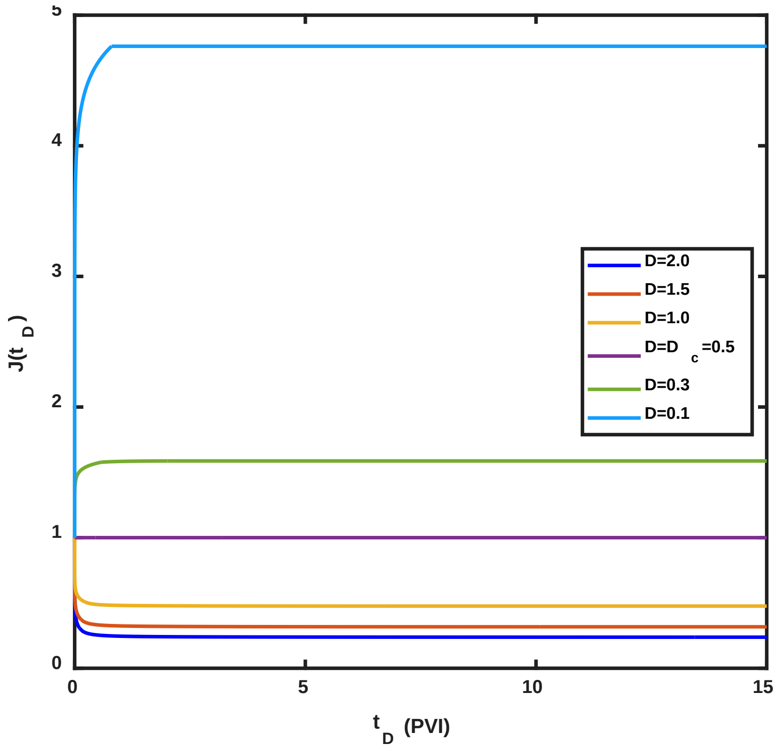
The impedance, J is determined by pressure losses

(i) near to well (early time)
(ii) in mixture zone(after breakthrough)
(iii) in water zone (late time)

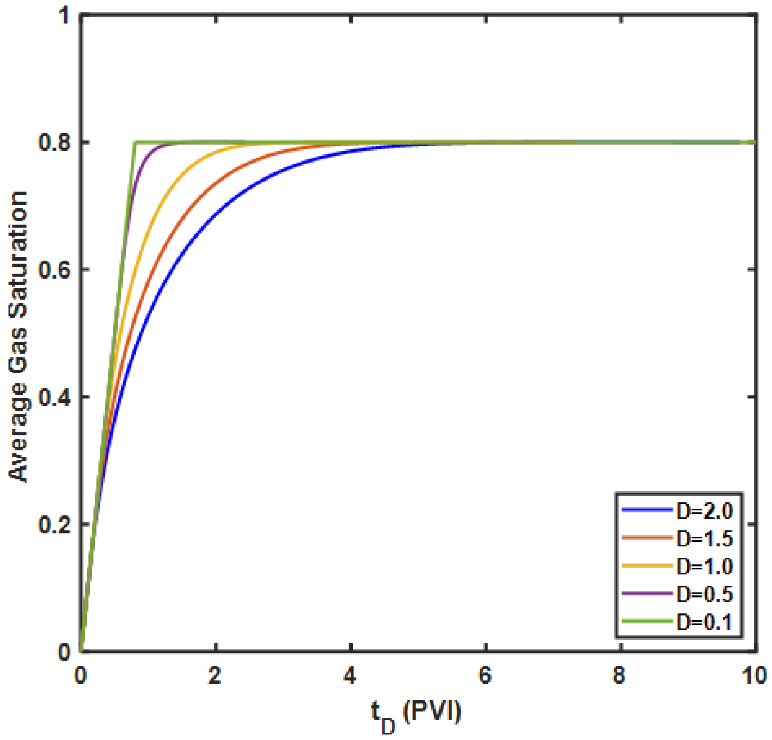
Field data: k(z) or g(k) – permeability distribution; CO_2 and water viscosities;
Lab data: D is the ratio between the damaged and initial permeabilities

Introduced analytical model for 2 phase flow with formation damage

Sweep coefficient evolution



Well impedance versus dimensionless time at different damage ratios for c=0.5 in power-law profile



The higher is the induced formation damage, D the higher the well impedance,J and skin factor, S of the injection well, and the higher the sweep coefficient

Society of Petroleum Engineers

Results (1/2)

Application of analytical modelling for sweep efficiency and well index calculation

Case study Field LW

Field overview

- Shallow offshore (60 m water depth)
- Depleted gas reservoir with weak aquifer support (21 production wells)
- Reservoir gas – 13% CO_2
- Depositional environment – shallow marine clastic

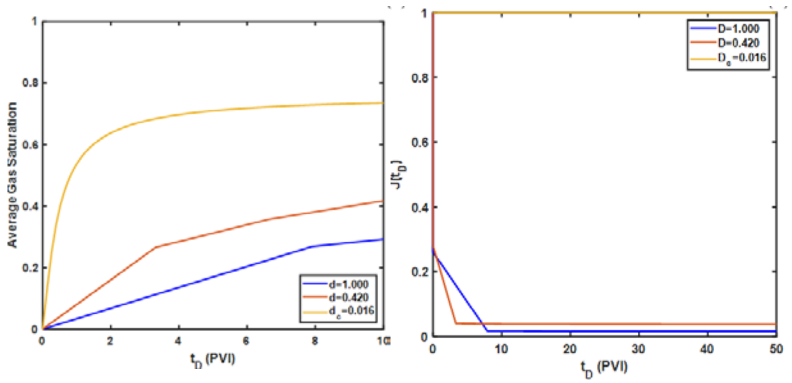
Reservoirs	**E-20/25**	**E-40/45/50**	**D-32/36**
Reservoir temperature (^{o}F)	235	250-260	214
Latest average reservoir pressure (psia)	600	800	700
Statistical parameters for permeability histograms			
Minimum	0	0	0
Maximum	2450	995	4000
Mean	72.30	64.28	320.18
Standard Deviation	235.15	116.89	504.80
Skewness	8.69	3.71	2.42
Kurtosis	86.87	20.28	8.89

Results (2/2)

Application of analytical modelling for sweep efficiency and well index calculation

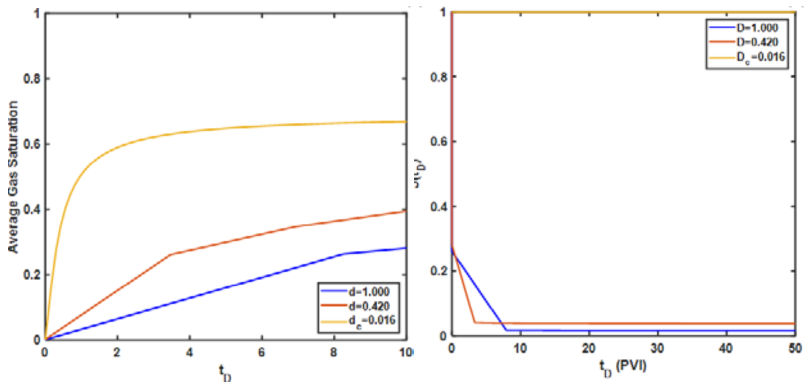
Well impedance versus dimensionless time when damage factor changes from 1 to critical value 0.016

E-20/25



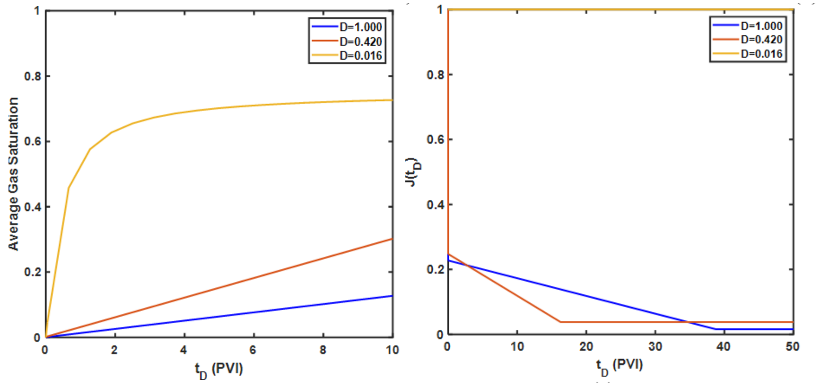
Sweep increases from 3 % to 53% and impedance increases from 0.23 to 1

E-40/45/50



Sweep increases from 7% to 50% and impedance increases from 0.20 to 1

D-32/36



Sweep increases from 1% to 52% and impedance increases from 0.22 to 1

Summary

- The analytical model allows derivation of the explicit formulae for well impedance / skin factor and sweep coefficient evolution during formation damage accumulation induced by CO_2 injection
- The higher is the induced formation damage, the higher the well impedance and skin factor of the injection well, and the higher the sweep coefficient due to creation of additional hydraulic resistance to the injected gas. So, formation damage increases gas storage capacity of the geological formation

Conclusion

The analytical model for CO_2 injection in heterogenous with inter-layer communications for prediction of well injectivity and the reservoir sweep efficiency will guide the decision making for an effective CCS projects because formation damage not only makes it difficult to inject, at the same time increases the storage capacity

Acknowledgements

PETRONAS Research Sdn Bhd

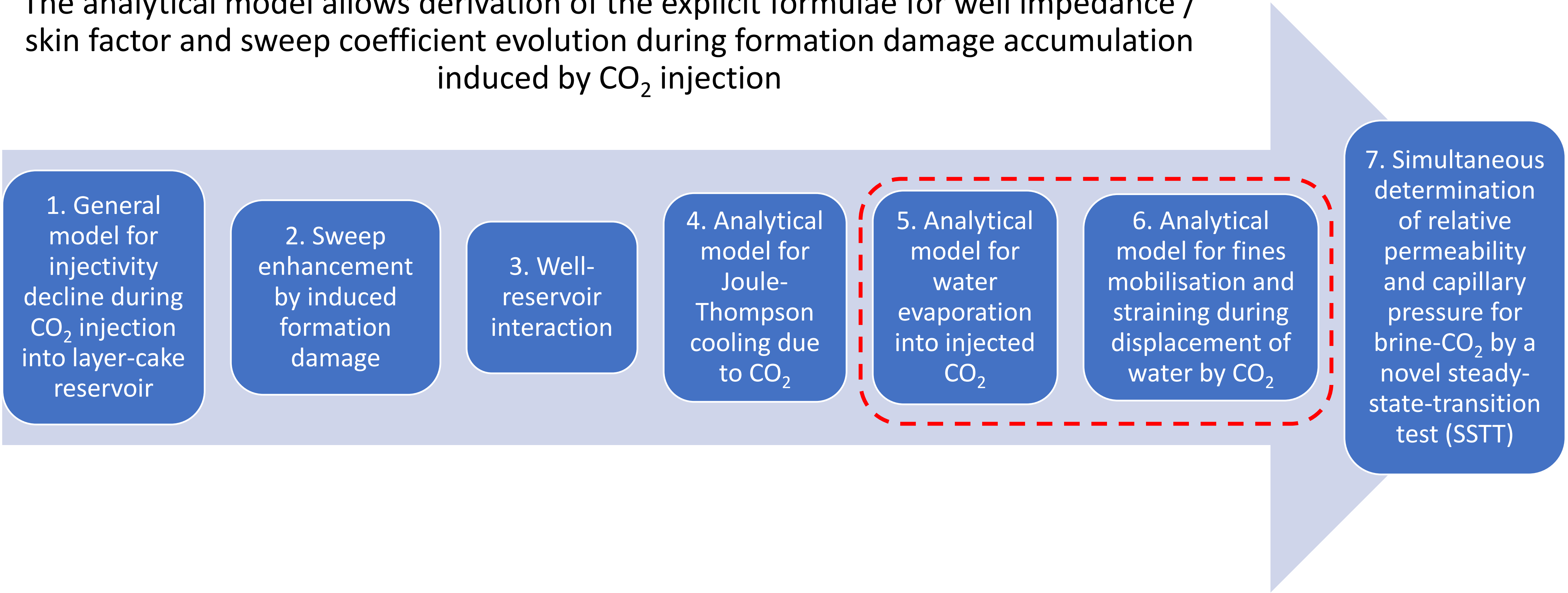
PETRONAS Carigali Sdn Bhd

The University of Adelaide

THANK YOU

Development of analytical model - general

The analytical model allows derivation of the explicit formulae for well impedance / skin factor and sweep coefficient evolution during formation damage accumulation induced by CO_2 injection



1. General model for injectivity decline during CO_2 injection into layer-cake reservoir
2. Sweep enhancement by induced formation damage
3. Well-reservoir interaction
4. Analytical model for Joule-Thompson cooling due to CO_2
5. Analytical model for water evaporation into injected CO_2
6. Analytical model for fines mobilisation and straining during displacement of water by CO_2
7. Simultaneous determination of relative permeability and capillary pressure for brine-CO_2 by a novel steady-state-transition test (SSTT)