AIChE ASME AIME IEEE ASCE

Carbon Management

# Analytical Temperature Modeling for Early Detection and Rate Estimation of $CO_2$ Wellbore Leakage

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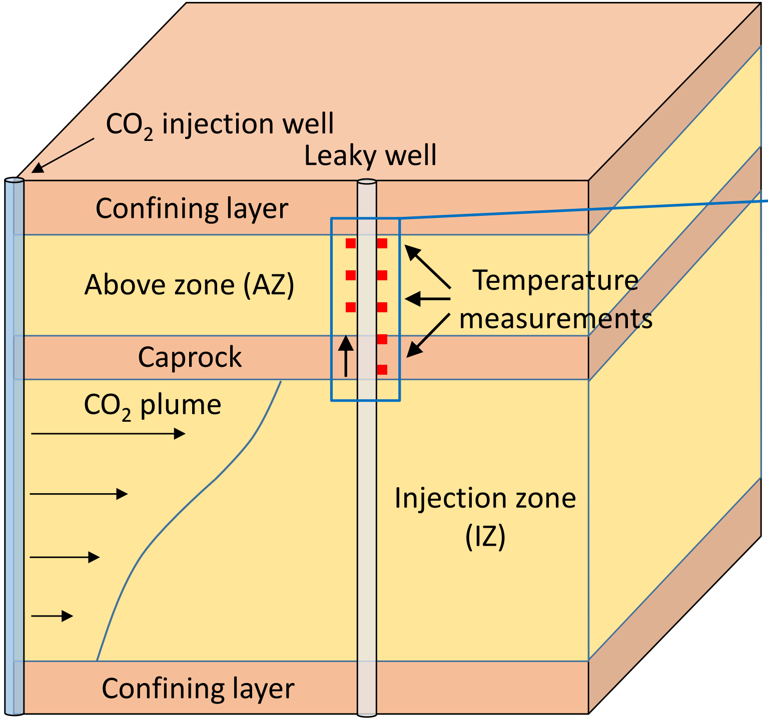
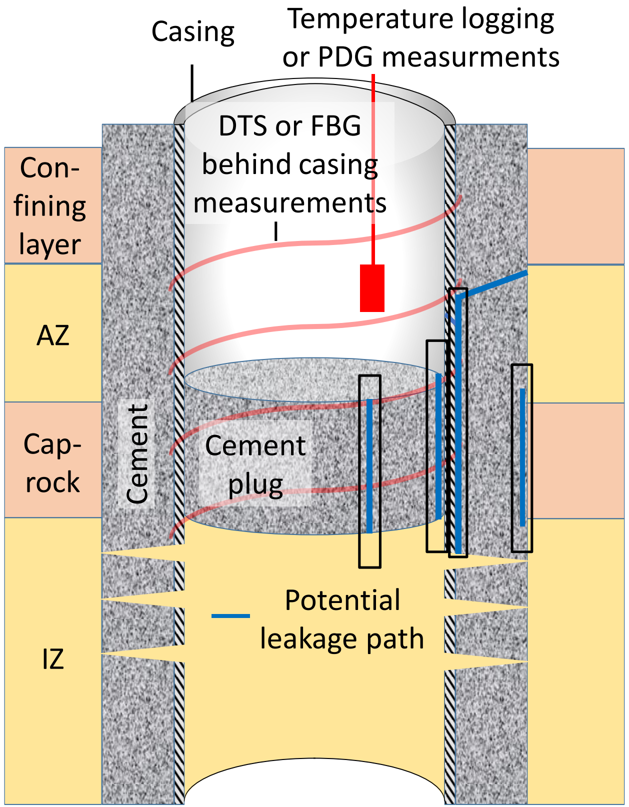
LSU

# Outline

- Model description and introduction
- Methodology
- Result and procedure
- Conclusion

# Model description



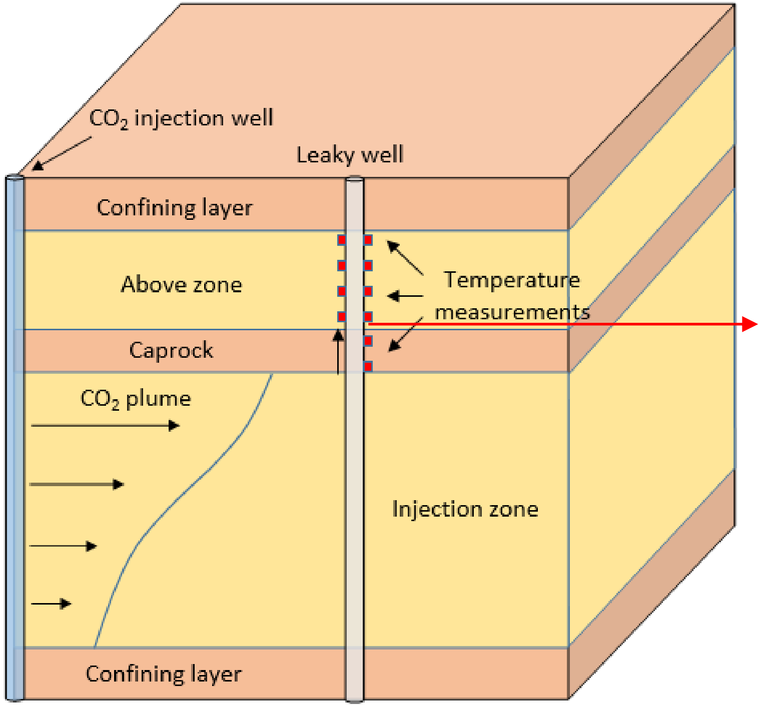



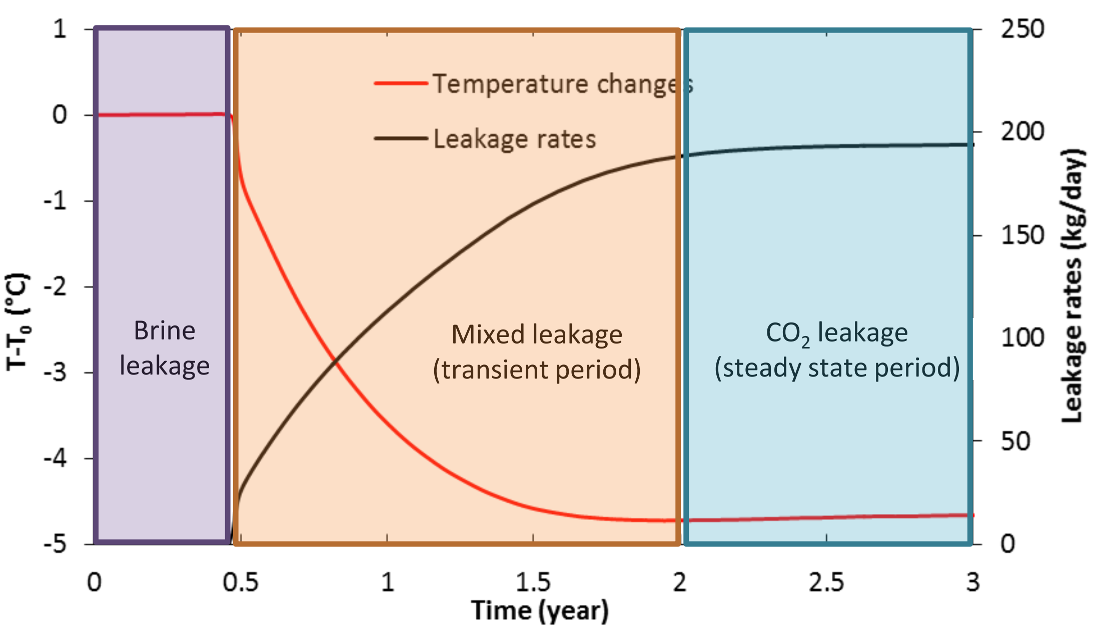

PDG: permanent downhole gauge

DTS: distributed temperature sensing

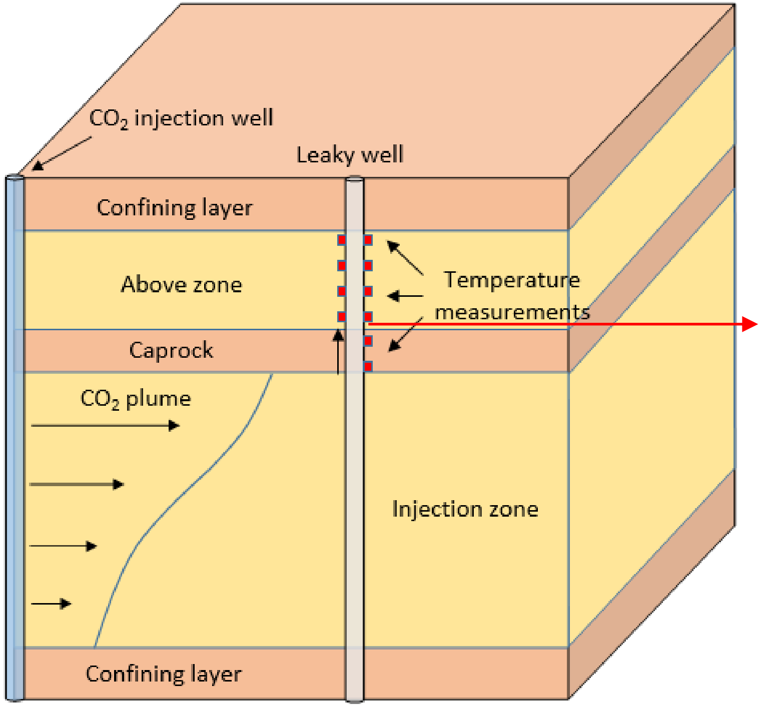
FBG: Fiber Bragg grating sensor

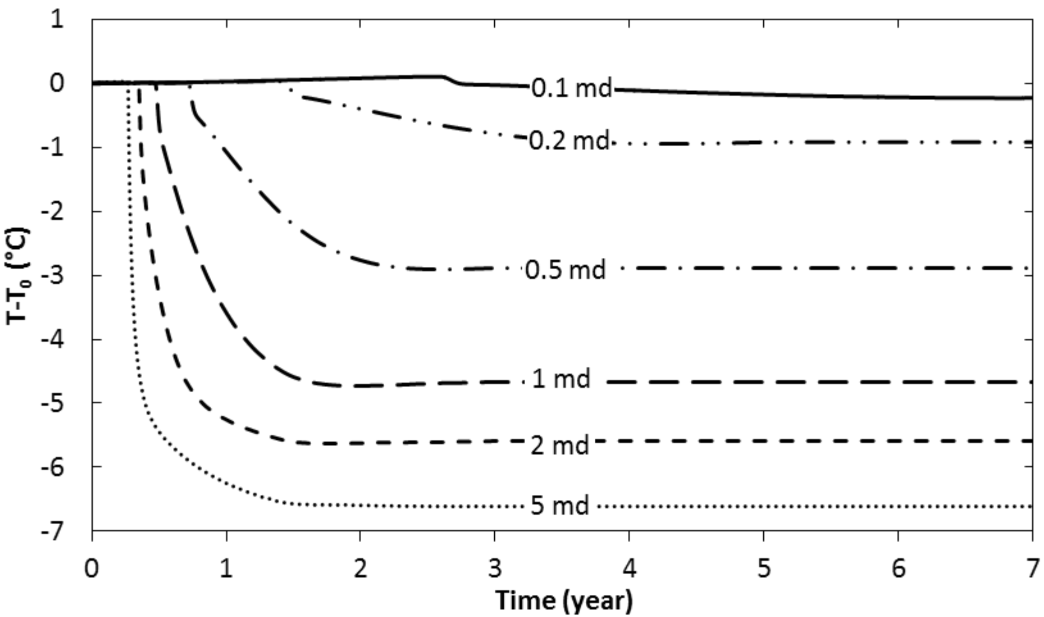
# Introduction - thermal behavior



# Introduction - permeability



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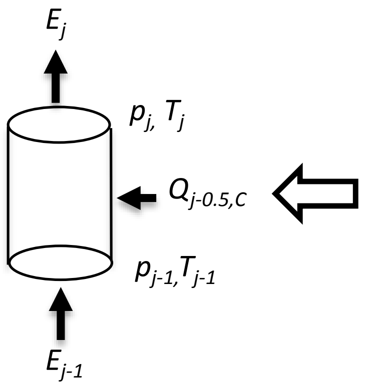
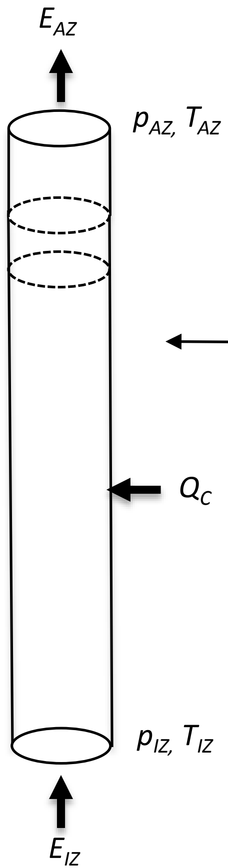
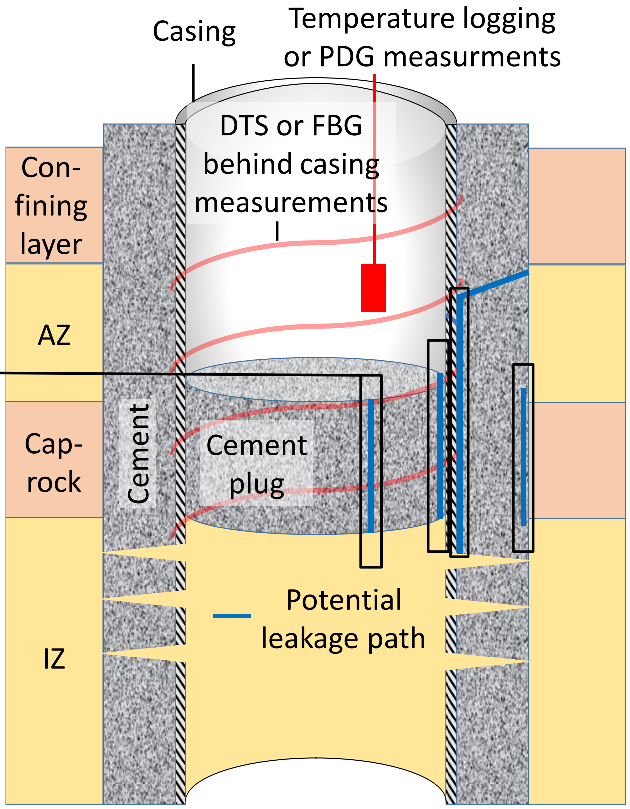
# Control volume




**Discretized**




**Integrated**



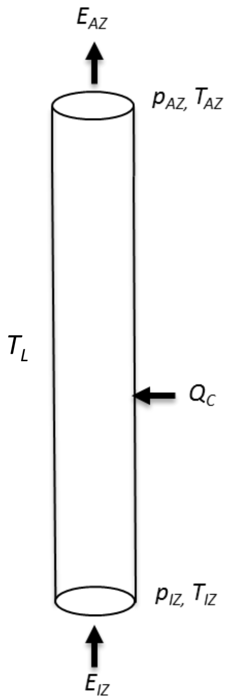

*E*: energy

*Q*: heat

*p*: pressure

*T*: temperature

# Energy balance




$$E_{AZ} - E_{IZ} = Q_C$$ (Steady state condition)

(Internal and potential energy)

$$m\left(\hat{H} + gz\right)_{AZ} - m\left(\hat{H} + gz\right)_{IZ} = Q_C$$

$$d\hat{H} = \left(\frac{\partial \hat{H}}{\partial p}\right)_T dp + \left(\frac{\partial \hat{H}}{\partial T}\right)_p dT = -\mu_{JT} c_p dp + c_p dT$$

$$\dot{Q}_c = \frac{2\pi HK\left(T_{i,L} - T_L\right)}{\ln\left[1 + \left(c - \frac{1}{a + \sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

$$\dot{m} c_p T_{AZ} - \dot{m} c_p T_{IZ} + \dot{m} gH = \dot{m} c_p \mu_{JT}\left(p_{AZ} - p_{IZ}\right) + \frac{2\pi HK\left(T_{i,L} - T_L\right)}{\ln\left[1 + \left(c - \frac{1}{a + \sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

$$\dot{m} = \frac{2\pi HK\left(T_{i,L} - T_L\right)}{\left[c_p \mu_{JT}\left(p_{IZ} - p_{AZ}\right) + c_p\left(T_{AZ} - T_{IZ}\right) + gH\right] \ln\left[1 + \left(c - \frac{1}{a + \sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

$\hat{H}$: enthalpy

$z$: height

$\mu_{JT}$: Joule-Thomson (JT) coefficient

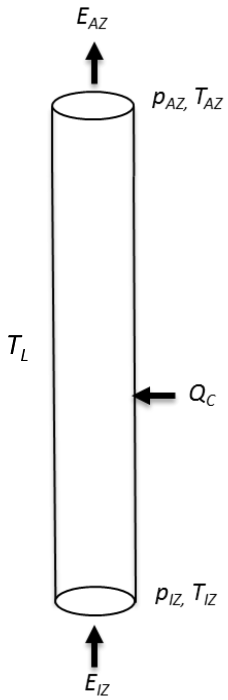
$c_p$: specific heat

$K$: conductivity

*a and c*: contants

$t_D$: dimensionless time for conduction

# Analytical approach




Convection

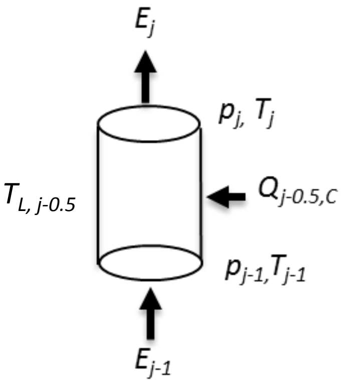
$$\dot{m} = \frac{1}{\left[c_p\mu_{JT}\left(p_{IZ}-p_{AZ}\right)+c_p\left(T_{AZ}-T_{IZ}\right)+gH\right]}\frac{2\pi HK\left(T_{i,L}-T_L\right)}{\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

Conduction

Joule-Thomson (JT) effect

Gravity effect

$$\dot{m}_j = \frac{2\pi h_j K_{j-0.5}\left(T_{i,j-0.5}-T_{j-0.5}\right)}{\left[c_j\mu_{JT,j-0.5}\left(p_{j-1}-p_j\right)+c_j\left(T_j-T_{j-1}\right)+gh_j\right]\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_{D,j}}}\right)\sqrt{t_{D,j}}\right]}$$



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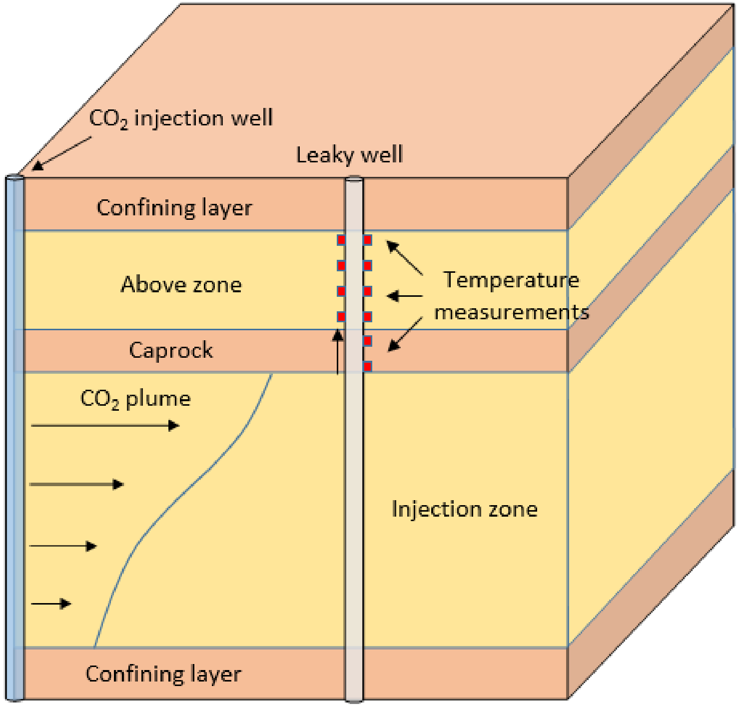
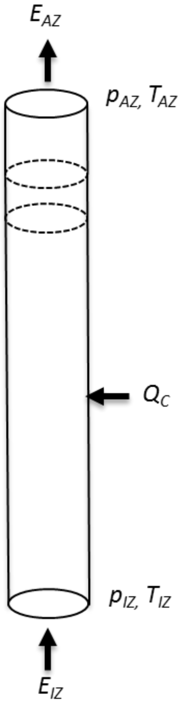
# Model and leakage properties

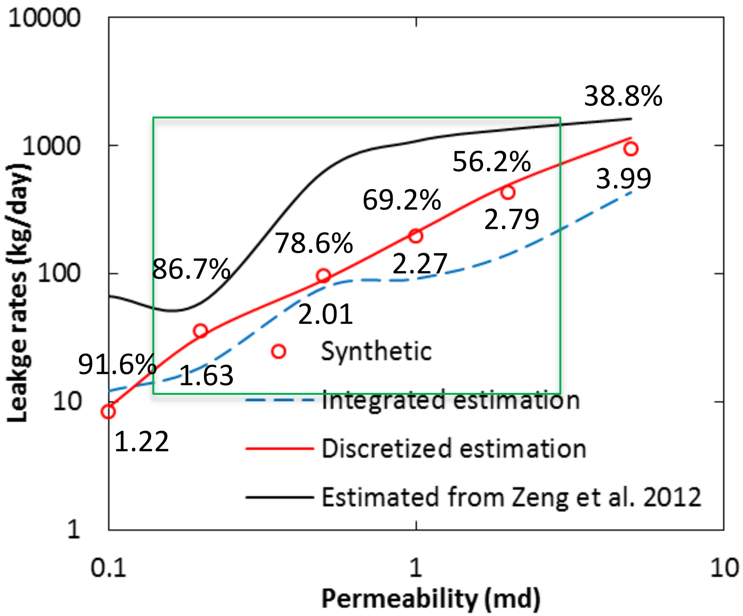


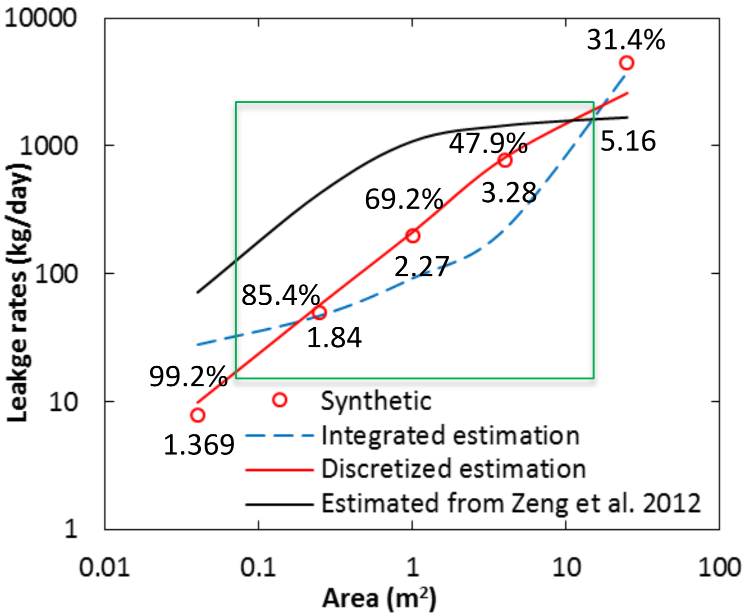

| Model properties | | Leakage properties | |
|---|---|---|---|
| Porosity (fraction) | 0.3 | Leak-injector distance (m) | 100 |
| Vertical permeability (md) | 10 | Leakage area ($m^2$) | 0.04-25 |
| Lateral permeability (md) | 100 | Leakage vertical permeability (md) | 0.1-5 |
| Initial temperature at IZ (degC) | 45 | Leakage rates (kg/day) | 8-2600 |
| Geothermal gradient (degC/m) | 0.03 | | |
| Injection pressure (MPa) | 13 | | |
| Initial pressure at IZ (MPa) | 8 | | |
| Caprock thickness (m) | 10 | | |
| IZ thickness (m) | 55 | | |
| Depth of IZ top (m) | 1000 | | |

Source: Mao, Y., Zeidouni, M., Askari, R., 2017. Effect of leakage pathway flow properties on thermal signal associated with the leakage from $CO_2$ storage zone. Greenh Gases 7, 512-529.

# Leakage rate estimation




*Scope: 1.5 – 3.5*

Source: Zeng, F.H., Zhao, G., Zhu, L.J., 2012. Detecting $CO_2$ leakage in vertical wellbore through temperature logging. Fuel 94, 374-385.

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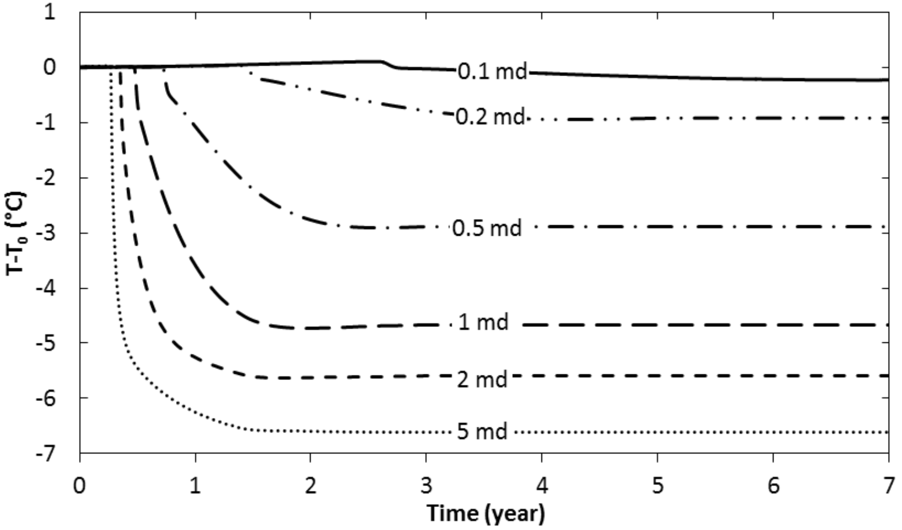
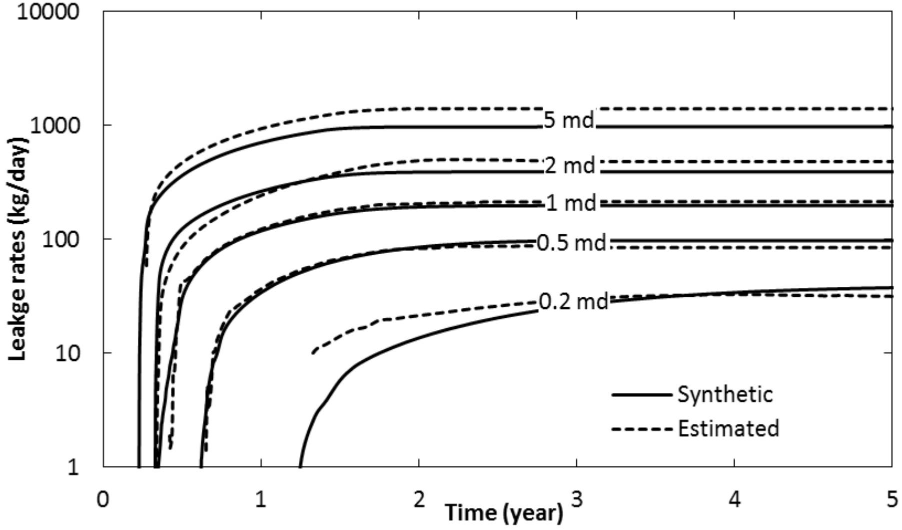
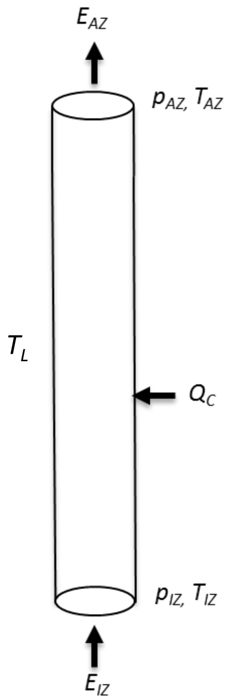
# Leakage rate estimation




# Scope of this approach




Convection

$$\dot{m} = \frac{1}{\left[c_p\mu_{JT}\left(p_{IZ}-p_{AZ}\right) + c_p\left(T_{AZ}-T_{IZ}\right) + gH\right]} \frac{2\pi HK\left(T_{i,L}-T_L\right)}{\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

Conduction

Joule-Thomson (JT) effect

~~Gravity effect~~

$$ratio = \frac{1}{\dot{m}c_p\mu_{JT}\left(p_{AZ}-p_{IZ}\right)} \frac{2\pi HK_r\left(T_L-T_{i,L}\right)}{\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right]}$$

⇩

$$N_{JT/cond} = \frac{\dot{m}c_p\mu_{JT}\Delta p}{KL\Delta T}$$

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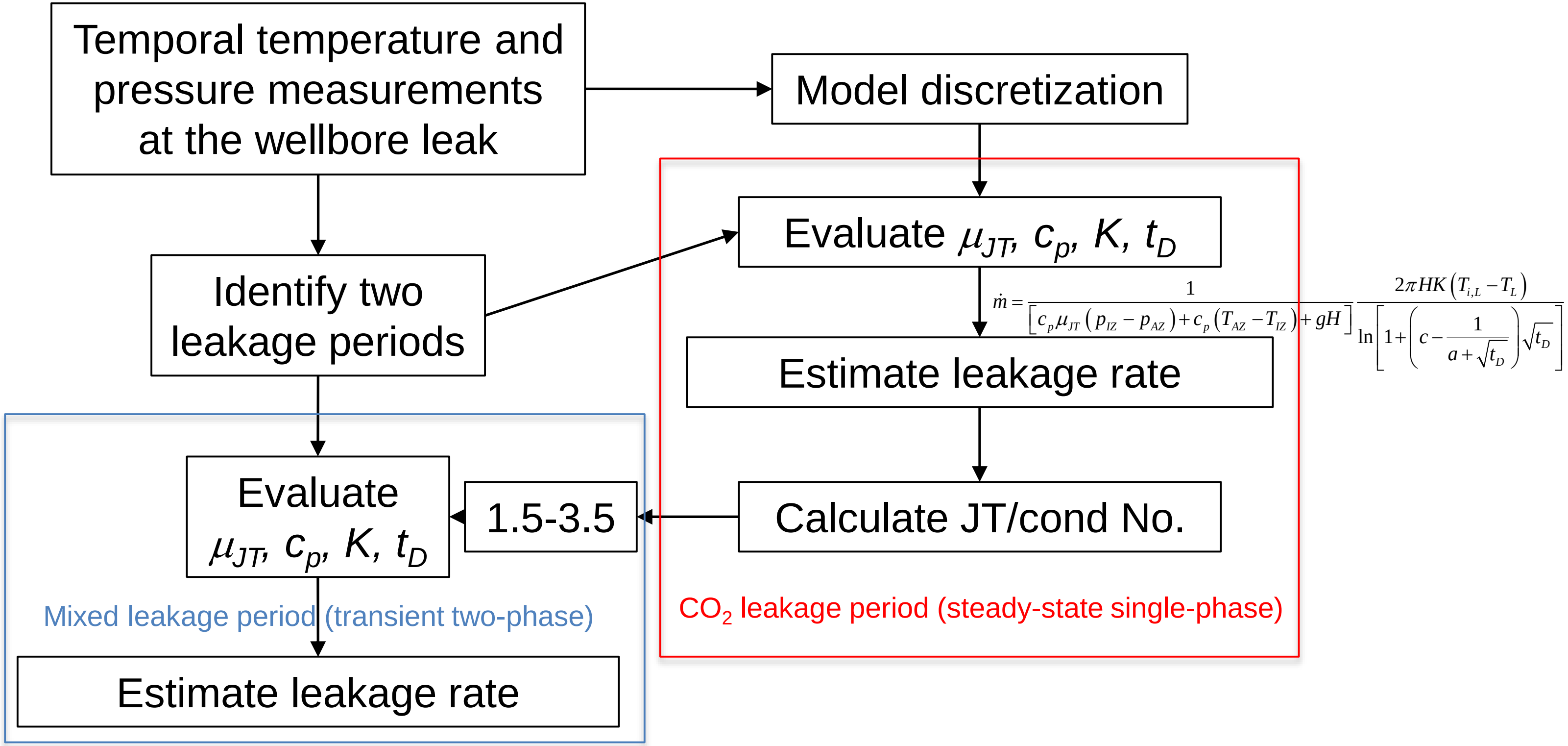
# Procedures


Temporal temperature and pressure measurements at the wellbore leak
Model discretization
Identify two leakage periods
Evaluate $\mu_{JT}$, $c_p$, $K$, $t_D$
$\dot{m} = \frac{1}{\left[c_p \mu_{JT}\left(p_{IZ} - p_{AZ}\right) + c_p\left(T_{AZ} - T_{IZ}\right) + gH\right]} \frac{2\pi HK\left(T_{i,L} - T_L\right)}{\ln\left[1 + \left(c - \frac{1}{a + \sqrt{t_D}}\right)\sqrt{t_D}\right]}$
Estimate leakage rate
Calculate JT/cond No.
$CO_2$ leakage period (steady-state single-phase)
1.5-3.5
Evaluate $\mu_{JT}$, $c_p$, $K$, $t_D$
Mixed leakage period (transient two-phase)
Estimate leakage rate

# Conclusions

- ✓ Thermal behaviors of wellbore leakage
- ✓ Analytical modeling of leakage rate
- ✓ Estimation validation for both periods
- ✓ Scope of this approach
- ✓ Practical procedures