Dynamic Modeling of a Solid-Sorbent CO$_2$ Capture System

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OUTLINE

- Motivation
- Dynamic Model Development
- Results and Discussions
- Conclusions
MOTIVATION

- Under the auspices of US DOE’s Carbon Capture Simulation Initiative (CCSI), we are developing computational models of various post-combustion CO$_2$ capture technologies.

- As part of this project, our current focus is on the development of dynamic models and control systems for solid-sorbent CO$_2$ capture and compression system.
Optimized Process Developed using CCSI Toolset

Solid Sorbent: NETL 32D, a mesoporous amine-impregnated silica substrate

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<table>
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<tr>
<th>ADS-001A</th>
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<tr>
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<td>Bed Depth (m)</td>
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<td>Total HX Area (m²)</td>
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<td>Height (m)</td>
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<td>Total HX Area (m²)</td>
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<table>
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<th>MEA^{27} (Δ10°C HX)</th>
<th>MEA^{27} (Δ5°C HX)</th>
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<td>Q_Sen (GJ/tonne CO2)</td>
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Modeling Domain
Bubbling Fluidized Bed Model Development

- 1-D two-phase pressure-driven non-isothermal dynamic model of a solid-sorbent CO₂ capture in a two-stage bubbling fluidized bed reactor system.
- Models are flexible such that it can be used as an adsorber or regenerator.
- Embedded cooler/heater depending on the application.
- Flexible configuration- solids can enter/leave at/from the top or bottom.
- A 2-stage adsorption model with customized variables for uncertainty quantification capabilities has been developed.
Model Assumptions

1. Each BFB consists of bubble, emulsion and cloud-wake regions.
2. Bubble region is free of solids.
3. Constant average particle properties throughout the bed.
4. Adsorption-reaction takes place in solid-phase.
5. Solids leave at the top of the bed (Overflow-type configuration).
6. Transients of the immersed heat exchangers are neglected.

MODEL DEVELOPMENT

- Gaseous species: CO$_2$, N$_2$, H$_2$O
- Solid phase components: bicarbonate, carbamate, and physisorbed water.
- Transient species conservation and energy balance equations for both gas and solid phases in all three regions.

CONSERVATION EQUATIONS

Bubble Region :
Gaseous Components

\[
\frac{\partial (\delta_x \alpha_x AC_{b,j,x})}{\partial t} = -\frac{\partial (\gamma_{b,j} c_{b,x})}{\partial x} - \delta_x AK_{bc,j,x} (C_{b,j,x} - C_{c,j,x}) + K_{g,bulk,j,x}
\]

\[
\frac{\partial (C_{bt,x} A \delta_x C_{p,g,b,x} (T_{g,b,x} - T_{ref}))}{\partial t} = -\frac{\partial (G_{b,x} C_{p,g,b,x} (T_{g,b,x} - T_{ref}))}{\partial x} - A \delta_x H_{bc,x} (T_{g,b,x} - T_{g,c,x}) + H_{g,bulk,x}
\]

Cloud-wake Region :
Gaseous Components

\[
\frac{\partial (\delta_x \alpha_x AC_{c,j,x})}{\partial t} = \delta_x AK_{bc,j,x} (C_{b,j,x} - C_{c,j,x}) - \delta_x AK_{cs,j,x} (C_{c,j,x} - C_{s,j,x}) + \alpha_x \delta_x (1 - \varepsilon_{d,x}) A \rho_{g,c} c_{g,c,x}
\]

\[
\frac{\partial (C_{ct,x} A \alpha_x \delta_x \varepsilon_d C_{p,g,c,x} (T_{g,c,x} - T_{ref}))}{\partial t} = A \delta_x H_{bc,x} (T_{g,b,x} - T_{g,c,x}) - A \delta_x H_{cs,x} (T_{g,c,x} - T_{g,s,x})
\]

\[
- A \alpha_x \delta_x (1 - \varepsilon_{d,x}) \rho_s \alpha_p h_{p,x} (T_{g,c,x} - T_{c,c,x}) + \alpha_x \delta_x (1 - \varepsilon_{d,x}) A \sum_j \left( r_{g,c,j,x} C_{p,g,j,c,x} (T_{g,c,x} - T_{ref}) \right)
\]
CONSERVATION EQUATIONS

Cloud Wake Region:

Adsorbed Species

\[
\frac{\partial}{\partial t} \left( A \alpha_\infty \delta_x (1 - \varepsilon_{d,\infty}) \rho_s n_{c,i,x} \right) \\
= -A \frac{\partial}{\partial x} \left( J_{c,x} n_{c,i,x} \right) - K_{s,\text{bulk},x} - A \delta_x \rho_s K_{c_e,bs,x} (n_{c,i,x} - n_{e,i,x}) \\
+ A \alpha_\infty \delta_x (1 - \varepsilon_{d,\infty}) r_{s,c,i,x}
\]

\[
\frac{\partial}{\partial t} \left( A \alpha_\infty \delta_x (1 - \varepsilon_{d,\infty}) \rho_s C_p,s (T_{c,\text{ref}} - T_{\text{ref}}) \right) \\
= -A \frac{\partial}{\partial x} \left( J_{c,x} \left( C_p,s (T_{c,\text{ref}} - T_{\text{ref}}) + h_{ads,c,x} \right) \right) - H_{s,\text{bulk},x} \\
- A \delta_x \rho_s K_{c_e,bs,x} \left( C_p,s (T_{c,\text{ref}} - T_{\text{ref}}) + h_{ads,c,x} - (C_p,s (T_{e,\text{ref}} - T_{\text{ref}}) + h_{ads,e,x}) \right) \\
- \alpha_\infty \delta_x (1 - \varepsilon_{d,\infty}) A \sum_j r_{g,c,i,x} C_{p,g,j,c,x} (T_{g,\text{ref}} - T_{\text{ref}}) \\
+ A \alpha_\infty \delta_x (1 - \varepsilon_{d,\infty}) \rho_s a_p T_p (T_{g,c,x} - T_{c,c,x})
\]
Emulsion Region:

Gaseous Components

\[
\frac{\partial}{\partial t} \left( A(1 - \alpha_x \delta_x - \delta_x) \epsilon_d C_{e,j,x} \right) = \delta_x A K_{c,e,j,x} (C_{c,j,x} - C_{e,j,x}) - K_{g,bulk,j,x} + (1 - \alpha_x \delta_x - \delta_x)(1 - \epsilon_{d,x}) A r_{g,e,j,x}
\]

\[
\frac{\partial}{\partial t} \left( C_{e,t,x} A(1 - \alpha_x \delta_x - \delta_x) \epsilon_d C_{p,g,e,x} (T_{g,e,x} - T_{ref}) \right) = A \delta_x H_{c,e,x} (T_{g,e,x} - T_{g,e,x}) - H_{g,bulk,x} - A(1 - \alpha_x \delta_x - \delta_x)(1 - \epsilon_{d,x}) \rho_x \alpha_x h_{p,x} C_{p,g,e,x} (T_{g,e,x} - T_{ref}) + A(1 - \alpha_x \delta_x - \delta_x)(1 - \epsilon_{d,x}) \sum_j (r_{g,e,j,x} C_{p,g,j,x} (T_{g,e,x} - T_{ref}))
\]
CONSERVATION EQUATIONS CONTD.

Emulsion Region:

Adsorbed Species

\[ \frac{\partial}{\partial t} \left[ A(1 - \alpha_x \delta_x - \delta_x)(1 - \varepsilon_{d,x}) \rho_x n_{e,i,x} \right] \]
\[ = -A \frac{\partial}{\partial x} \left( J_{e,x} n_{e,i,x} \right) + K_{s,bulk,x} + A \delta_x \rho_x K_{c_e,bs,x} (n_{c,i,x} - n_{e,i,x}) + A(1 - \alpha_x \delta_x - \delta_x)(1 - \varepsilon_{d,x}) r_{s,e,i,x} \]

\[ \frac{\partial}{\partial t} \left[ A(1 - \alpha_x \delta_x - \delta_x)(1 - \varepsilon_{d,x}) \rho_x C_{p,s}(T_{s,e,x} - T_{ref}) \right] \]
\[ = -A \frac{\partial}{\partial x} \left( J_{e,x} (C_{p,s}(T_{s,e,x} - T_{ref}) + h_{ads,s,x}) \right) + H_{s,bulk,x} + A \delta_x \rho_x K_{c_e,bs,x} \left( C_{p,s}(T_{s,e,x} - T_{ref}) + h_{ads,s,x} - (C_{p,s}(T_{s,e,x} - T_{ref}) + h_{ads,s,x}) \right) - A(1 - \alpha_x \delta_x - \delta_x)(1 - \varepsilon_{d,x}) \sum_j \left( r_{g,e,i,x} C_{p,g,j,x} (T_{g,e,x} - T_{ref}) \right) + A(1 - \alpha_x \delta_x - \delta_x)(1 - \varepsilon_{d,x}) \rho_x \alpha_{p} h_{p,x}(T_{g,e,x} - T_{s,e,x}) + \pi d_{hx} h_{t,x} \Delta T_{hx,x} N_{hx} C_r \]
HYDRODYNAMIC MODEL

\[
\left( \sqrt{\frac{d_{b,u,x} - d_{b,e,x}}{d_{b,0} - d_{b,e,x}}} \right)^{1 - \frac{y_1}{y_{3,x}}} \left( \sqrt{\frac{d_{b,u,x} - y_{2,x}}{d_{b,0} - y_{2,x}}} \right)^{1 + \frac{y_1}{y_{3,x}}} = e^{-\left( \frac{0.3x}{D_t} \right)}
\]

where \( \gamma_1 = \frac{2.56 \times 10^{-2}}{v_{mf}} \sqrt{\frac{D_t}{g}} \) and \( \gamma_{3,x} = \sqrt{\gamma_1^2 + 4 \frac{d_{b,m,x}}{D_t}} \)

\[
d_{b,e,x} = \frac{D_t}{4} (\gamma_1 + \gamma_{3,x})^2
\]

\[
d_{b,m,x} = 2.59 g^{-0.2} \left( A_x \left[ v_{g,x} - v_{e,x} \right] \right)^{0.4}
\]

\[
d_{b,0} = 1.38 g^{-0.2} \left( a_o \left[ v_{g,0} - v_{e,0} \right] \right)^{0.4}
\]

\[
v_{b,x} = v_{g,x} - v_{mf} + 0.35 \sqrt{gD_t,h}
\]

\[
K_{bc,j,x} = 1.32 \times 4.5 \frac{v_{mf}}{d_{b,x}} + 5.85 \frac{D_{j,x}}{d_{b,x}}^{0.5} g^{-0.25} d_{b,x}^{5/4}
\]

\[
K_{ce,j,x} = 6.78 \sqrt{\frac{\tau_{d,x}^2 D_{j,x} v_{b,x}}{d_{b,x}^3}}
\]

Mori and Wen (1975)

Sit and Grace (1981)
**REACTION KINETICS**

\[ H_2O_{(g)} \leftrightarrow H_2O_{(phys)} \]

\[ 2R_2NH + CO_2,(g) \leftrightarrow R_2NH_2^+ + 2R_2NCO_2^- \]

\[ R_2NH + CO_2,(g) + H_2O_{(phys)} \leftrightarrow R_2NH_2^+ + HCO_3^- \]

\[ r_{1,r,i} = k_{1,r,i} \left( \frac{PC_{r,H_2O,i}}{C_{r,t,i}} - \frac{n_{r,H_2O,i}}{K_{1,r,i}} \right) \]

\[ r_{2,r,i} = k_{2,r,i} \left( 1 - 2 \frac{n_{r,carb,i}}{n_v} - \frac{n_{r,bicarb,i}}{n_v} \right) n_{r,H_2O,i} \frac{PC_{r,CO_2,i}}{C_{r,t,i}} - \left\{ \frac{n_{r,carb,i}}{n_v} + \frac{n_{r,bicarb,i}}{n_v} \right\} \frac{n_{r,bicarb,i}}{K_{2,r,i}} \]

\[ r_{3,r,i} = k_{3,r,i} \left( 1 - 2 \frac{n_{r,carb,i}}{n_v} - \frac{n_{r,bicarb,i}}{n_v} \right)^2 \frac{PC_{r,CO_2,i}}{C_{r,t,i}} - \left\{ \frac{n_{r,carb,i}}{n_v} + \frac{n_{r,bicarb,i}}{n_v} \right\} \frac{n_{r,carb,i}}{K_{3,r,i}} \]

*Lee et al. A model for the Adsorption Kinetics of CO₂ on Amine-Impregnated Mesoporous Sorbents in the Presence of Water, 28th International Pittsburgh Coal Conference 2011, Pittsburgh, PA, USA.*
Dynamic Model–Moving Bed Reactor

1-D two-phase pressure-driven non-isothermal dynamic model of a moving bed reactor mainly for the regenerator application.

Model Assumptions

- Vertical shell & tube type reactor
- Gas and solids flows are modeled by plug flow model with axial dispersion.
- Particles are uniformly dispersed through the reactor with constant voidage
- Particle attrition ignored
- Temperature is uniform within the particles

- Gaseous species: CO₂, N₂, H₂O
- Solid phase components: bicarbonate, carbamate, and physisorbed water.
Integrated pre and post-heat exchangers are considered for heat recovery.

Gas and solids flows are modeled by plug flow model with axial dispersion.

For pressure drop calculation, a modified Ergun equation by using the slip velocity between the solids and gas is used instead of the superficial fluid velocity.

Energy balance equations consider heat transfer between solid and gas and tube wall and the mixed phase.

Heat transfer coefficient between the mixed phase and the tube wall is calculated by a modified packet-renewal theory.

Bed hydrodynamics are described by analogy to fixed bed and fluidized bed systems.

Reaction kinetics are similar to the bubbling bed model.
Pneumatic Transport Modeling

- **Assumptions**
  - Isothermal
  - Ideal separation of gases and solids. Therefore, transport gas is free of solids after separation.
  - No mass transfer and reactions during the transport

- **Options considered for the transport medium**
  - Unclean flue gas from the adsorber inlet
  - Clean flue gas from the adsorber outlet
  - A recycling transport medium with makeup from the clean gas
  - $\text{CO}_2$ from the outlet of the regenerator

- **Calculation of the overall pressure drop in the vertical pipe**
  - Pressure drop due to gas acceleration
  - Pressure drop due to solids acceleration
  - Pressure drop due to gas to pipe friction
  - Pressure drop due to solids to pipe friction
  - Pressure drop due to static head of the solids
Pneumatic Transport Modeling: Regenerator to Adsorber

<table>
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<td>ΔP (bar)</td>
<td>0.56</td>
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<tr>
<td>Pipe Dia (m)</td>
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<tr>
<td>Pipe Length (m)</td>
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<tr>
<td>Load Ratio (S/G)</td>
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<tr>
<td>Choking Velocity (m/s)</td>
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<td>Superficial Velocity (m/s)</td>
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Pneumatic Transport Modeling: Adsorber to Regenerator

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<td>Pipe Length (m)</td>
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<td>Load Ratio (S/G)</td>
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<tr>
<td>Choking Velocity (m/s)</td>
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<tr>
<td>Superficial Velocity (m/s)</td>
<td>22.9</td>
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Dynamic model of a multi-stage integral gear compressor system with inter-stage coolers, knock-out drums, and TEG absorption system has been developed.

Performance curves obtained from a commercial vendor has been used for calculating off-design performance.
CO₂ Compression System Model

Dimensionless Exit Flow Coefficient

\[ \varphi_3 = \frac{\dot{V}_3}{\pi d_2 b_2 u_2} \]

\[ \dot{V}_3 = \dot{V}_s \frac{z_d T_d P_s}{P_d z_s T_s} \]

\[ T_d = T_s \left( \frac{P_d}{P_s} \right)^{\frac{k-1}{k\eta}} \]

Dimensionless Isentropic Head Coefficient

\[ \varphi_s = \frac{2y_s}{u_2^2} \]

\[ y_s = \text{Isentropic head} = z_s R T_s \left( \frac{P_d}{P_s} \right)^{\frac{k-1}{k}} - 1 \]

\[ \varphi_s = A \varphi_3^2 + B \varphi_3 + C \]
CO$_2$ Compressor Load Control

IGV Model

\[ y = ae^{bx} + ce^{dx} \]

Surge Detection and Control

\[ \frac{\partial}{\partial \dot{V}} \left( \frac{p_a}{p_s} \right) = 0 \]

\[ \frac{\partial \varphi_s}{\partial \varphi_3} = 0 \]

\[ PS = \frac{\varphi_{op} - \varphi^*_3}{\varphi^*_3} \]

Gain Scheduling Controller

\[ \sigma_\lambda(\xi) = \begin{cases} 
0 & \text{if } 0 \leq \xi \leq \lambda \\
\xi - \lambda & \text{if } \xi > \lambda
\end{cases} \]

\[ u(t) = k(t) y(t) + u_0 \]

\[ k(t) = \alpha \sigma_\lambda \left( |y(t)| \right) \]

\[ k(0) = k_0 \]
Modeling of Balance of the Plant

1. Pressure flow-network along with the control valves

2. Gas and Solid distributors

3. Downcomer and Exit-hopper

4. Other components such as flue-gas stack etc.

5. Pre-heater, post-heat exchanger, post-cooler, steam and BFW system for heat recovery
SOLUTION METHODOLOGY

- All models are set up in Aspen Custom Modeler
- The dynamic model is solved by using the Method of Lines
- ACM model is embedded in Simulink for LMPC implementation.
Bubbling Bed Model: Results from Single Stage

**Adsorber**

![Graph showing mole fraction and molar loading for H$_2$O and CO$_2$ in the Flue Gas Inlet and Outlet for Adsorber configuration.]

**Regenerator**

![Graph showing mole fraction and molar loading for H$_2$O and CO$_2$ in the Gas Inlet and Outlet for Regenerator configuration.]

![Graph showing solids overflow exit type configuration for Bic, Car, and H$_2$O.]

**Carbon Capture and Storage Initiative (CCSI)**

[Logos of West Virginia University and NETL]

U.S. Department of Energy
Moving Bed Regenerator: Results

- **Mole Fraction**
  - CO$_2$ and H$_2$O mole fraction changes across the bed.

- **Molar Loading (mol/kg solids)**
  - Bicarbonate (Bic), Carbonate (Car), and Water (H$_2$O) molar loadings vary along the solid inlet and outlet.

- **Solids Temperature (C)**
  - Temperature changes across the bed.

- **Gas Flow Rate (kmol/hr)**
  - Flow rate increases along the gas inlet and outlet.
CONTROLLER DESIGNS FOR MAINTAINING CO$_2$ CAPTURE – ADSORBER-ONLY (20% step increase in flue gas flowrate)

1. PID CONTROLLER

- PID controller for controlling CO$_2$ capture by manipulating the solid sorbent flowrate.
- Note the large undershoot and long settling time.

Configuration and Performance of the PID Controller
CONTROLLER DESIGN CONTD.

2. FEEDBACK-AUGMENTED FEEDFORWARD CONTROLLER

- Data for the process and disturbance models are generated by implementing step changes in the sorbent flowrate and the flue gas flowrate, respectively.

- Process and disturbance models are identified in MATLAB as first-order and pure-gain-plus-second–order models, respectively.

Comparison of the process model to the data from ACM®
**CONTROLLER DESIGN CONTD.**

2. FEEDBACK-AUGMENTED FEEDFORWARD CONTROLLER

- Note the smaller/shorter undershoot with large overshoot and settling time

Configuration and Performance of the Feedback-Augmented Feedforward Controller
CONTROLLER DESIGN CONT'D.

3. LINEAR MODEL PREDICTIVE CONTROLLER

Estimated using ARX on data set t

Discrete-time IDPOLY model: $A(q)y(t) = B(q)u(t) + e(t)$

$A(q) = 1 - 1.473 q^{-1} + 0.2636 q^{-2} + 0.2923 q^{-3} - 0.08314 q^{-4}$

$B_1(q) = -0.03877 q^{-1} + 0.1641 q^{-2} + 0.05974 q^{-3} - 0.1471 q^{-4}$

$B_2(q) = -4.348 q^{-1} + 0.03616 q^{-2} - 21.36 q^{-3} + 20.11 q^{-4}$

ARX model as the disturbance model
Simulink block diagram for LMPC implementation
3.1 Offset-free LMPC Using an Integrator

- Manipulated variable is sorbent flowrate.
- ACM model is embedded in SIMULINK for MPC implementation.
- 20% step increase in flue gas flowrate as disturbance.

![Configuration of LMPC with Additional Integrator](image-url)
3.2 Offset-free LMPC Using Unmeasured Disturbance

- Estimation of unmeasured disturbance using advanced Controllers of MPC toolbox in MATLAB®.
- The ACM model is embedded in SIMULINK for MPC implementation.
- 20% step increase in flue gas flowrate.
- Performance is satisfactory even for other disturbances.

Configuration and performance of LMPC with estimation of unmeasured disturbance
CONTROLLER PERFORMANCE COMPARISON

Control performances of LMPC-I and LMPC-II are superior to others

Control Performance Table

<table>
<thead>
<tr>
<th>CONTROLLER</th>
<th>IAE</th>
<th>ISE</th>
<th>ITAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) PID</td>
<td>0.8111</td>
<td>1.7551</td>
<td>1.12E-04</td>
</tr>
<tr>
<td>(2) FBAUGFF</td>
<td>0.4751</td>
<td>0.5502</td>
<td>6.60E-05</td>
</tr>
<tr>
<td>(3) LMPC-I</td>
<td>0.3913</td>
<td>0.6138</td>
<td>5.57E-05</td>
</tr>
<tr>
<td>(4) LMPC-II</td>
<td>0.4007</td>
<td>0.6386</td>
<td>6.30E-05</td>
</tr>
</tbody>
</table>
Control Configuration of the Regenerator System

Schematic of the ACM flow sheet of the moving bed regenerator with steam/BFW system
Integrated Adsorber-Regenerator Dynamic Model: PID Controller

Disturbance: 10% Ramp Increase in Flue Gas Flowrate
Integrated Adsorber-Regenerator Dynamic Model: PID Controller

Disturbance: 10% Ramp Increase in Flue Gas Flowrate
Pressure Dynamics in CO2 Compression System: 10% Ramp Change in flowrate
Power Dynamics in CO₂ Compression System: 10% Ramp Change in flowrate
CONCLUSIONS

1. One-dimensional, non-isothermal, pressure-driven dynamic models of a two-stage BFB adsorber-reactor, a moving bed regenerator, an integral gear CO$_2$ compression system along with the balance of the plant has been developed in ACM for solid-sorbent CO$_2$ capture.

2. For adsorber-only case, the performances of both LMPC strategies are satisfactory and superior to other control strategies.

3. The response of the coupled adsorber-regenerator system is slow and oscillatory due to interactions between the systems. Advanced control strategies should be considered for satisfying the overall CO$_2$ capture target over a period of time.
Acknowledgements:
- As part of the National Energy Technology Laboratory’s Regional University Alliance (NETL-RUA), a collaborative initiative of the NETL, this technical effort was performed under the RES contract DEFE0004000.

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Thank you
Table 1. Base case conditions.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Gas Conditions</th>
<th>Solid Conditions</th>
<th>HX Conditions</th>
<th>Fluid Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_t$</td>
<td>$G_{b,in}$</td>
<td>$F_{sorb,in}$</td>
<td>$F_{HX,in}$</td>
<td>216 kg/s</td>
</tr>
<tr>
<td>$L_b$</td>
<td>$T_{g,in}$</td>
<td>$T_{sorb,in}$</td>
<td>$P_{HX,in}$</td>
<td>101325 Pa</td>
</tr>
<tr>
<td>$d_{HX}$</td>
<td>$y_{g,CO_2,in}$</td>
<td>$n_{HCO_3,in}$</td>
<td>$T_{HX,in}$</td>
<td>305.65 K</td>
</tr>
<tr>
<td>$N_{HX}$</td>
<td>$y_{g,H_2O,in}$</td>
<td>$n_{H_2O,in}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_0$</td>
<td>$y_{g,N_2,in}$</td>
<td>$n_{NHCO_2,in}$</td>
<td>$P_{L_b}$</td>
<td>101325 Pa</td>
</tr>
</tbody>
</table>
Pneumatic Transport Modeling

Terminal Velocity of the particles:

\[ u_t = u_t^* \left( \frac{\mu_g (\rho_s - \rho_g) g}{\rho_g^2} \right)^{-1/3} \]

\[ u_t^* = \frac{1}{18} \frac{D_p^2}{D_p^*} \left( \frac{2.335 - 1.744 \varepsilon_{ch}}{(D_p^*)^{0.5}} \right) \]

\[ D_p^* = D_p \left( \frac{\rho_g (\rho_s - \rho_g) g/\mu_g^2}{\rho_g^2} \right)^{1/3} \]

Choking Velocity, Voidage at Choking, and Superficial Velocity

\[ G_s = \frac{F_s/3600}{\pi D^2/4} \]

\[ \frac{u_{ch} - u_t}{\varepsilon_{ch}} = \frac{G_s}{\rho_s (1 - \varepsilon_{ch})} \]

\[ \rho_g^{0.77} = 2250D \frac{((\varepsilon_{ch})^{-4.7} - 1)}{\left(\frac{u_{ch} - u_t}{\varepsilon_{ch}}\right)^2} \]

\[ u = 1.2u_{ch} \]
Pneumatic Transport Modeling

Load Ratio, Gas and Solid Velocities

\[ u_g = \frac{u}{\varepsilon_p} \]

\[ u_s = u_g - u_t \]

\[ G_s = \rho_s (1 - \varepsilon_p) u_s \]

\[ G_g = \rho_g \varepsilon_p u_g \]

Load Ratio = \( \frac{G_s}{G_g} \)

Reynold’s Number and Gas Friction Factor

\[ f_g = 0.079 Re^{-0.25} \]

\[ Re = \frac{Du \rho_g}{\mu_g} \]