Carbon Dioxide Capture with Solid Carbonate Sorbents in a Fluidized Bed Riser and Regeneration in a Reduced Pressure Downer

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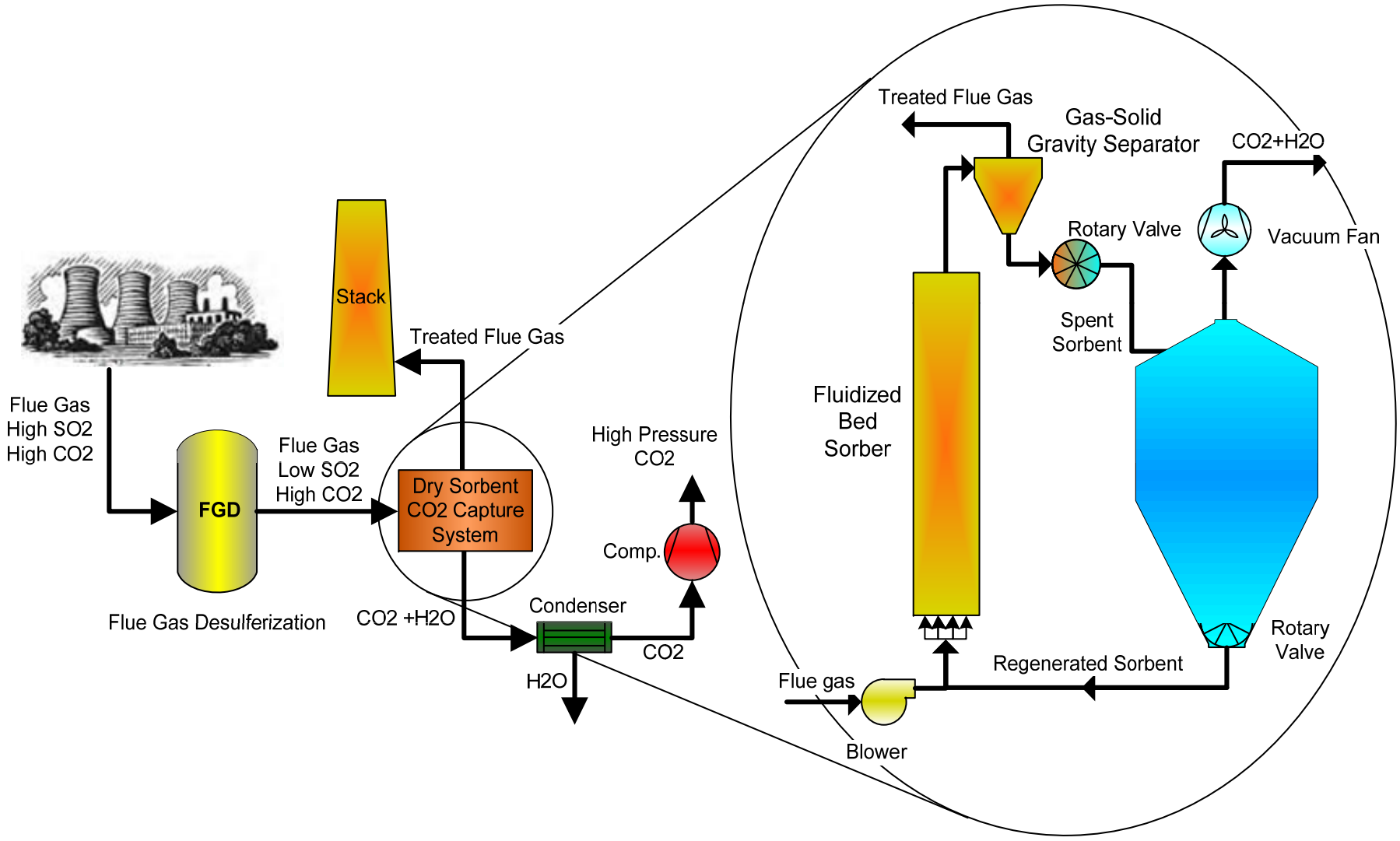
CO2 Capture Process



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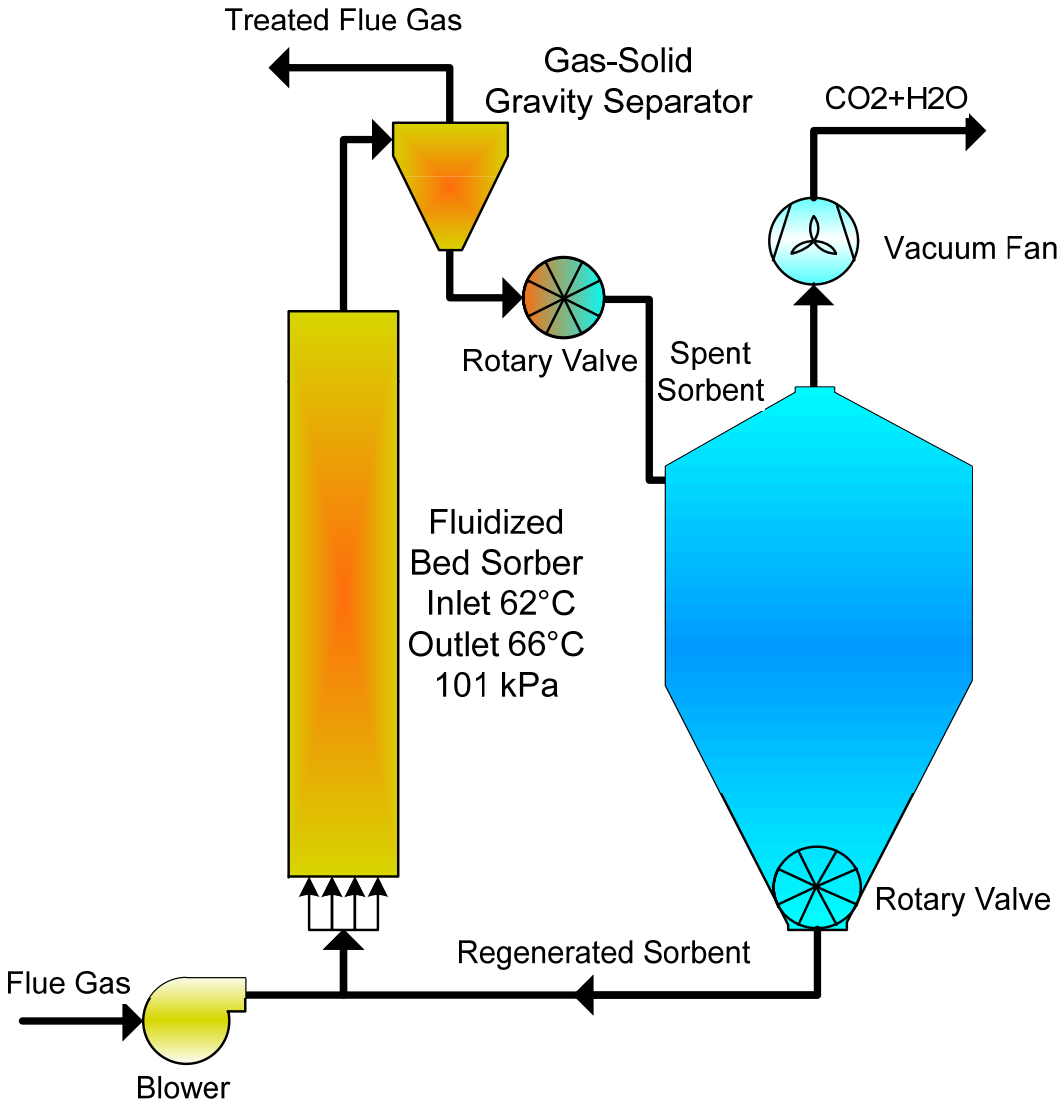
Concept of Dry Sorbent Fluidized Bed

Schematic Diagram



Sorption Section
(Atmospheric Pressure)

- ➔ CO_2 sorption reaction:

$Na_2CO_3\,(s) + CO_2(g) + H_2O(g) \leftrightarrow 2NaHCO_3(s)$

- ➔ CO_2 absorption is *exothermic*;
- ➔ Sorption inlet temperature ≈ 62 ºC
- ➔ Sorption outlet temperature ≈ 66 ºC

Desorption Section
(Reduced Pressure)

- ➔ Sorbent regeneration:

$2NaHCO_3(s) \leftrightarrow Na_2CO_3(s) + CO_2(g) + H_2O(g)$

- ➔ CO2 desorption is *endothermic*;
- ➔ Desorption temperature ≈ 62-66 ºC
- ➔ Desorption Pressure ≈ 1 kPa

Compact Fluidized Bed Sorber With Reduced Pressure Downer Regenerator

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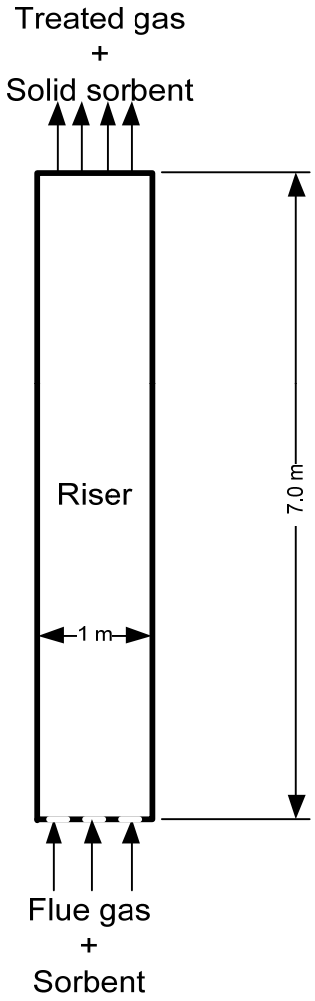
Fluidized Bed Sorber

Sorber Riser Simulation Conditions



Riser eliminating undesirable core annular regime occurred in the CFB

Conditions

Gas phase		
	-Ug	1.0 m/s
Solids phase		
	- Dp	500 μm
	- Density	500 kg/m3
	- Gs	48 kg/m2s
Inlet conditions		
	- CO_2 mole fraction	0.15
	- H_2O mole fraction	0.15
	- Air mole fraction (O_2+N_2)	0.7
Operating Temperature		335 K

Kinetic rate expression

Na2CO3 (s) + CO2(g) + H2O(g) ↔ 2NaHCO3(s)

$$r_{sorption} = k_{reaction}(C_{CO_2,eq} - C_{CO_2})\ (C_{H_2O,eq} - C_{H_2O})$$

Geometry, sorption rate and inlet conditions for CO2 removal from flue gases

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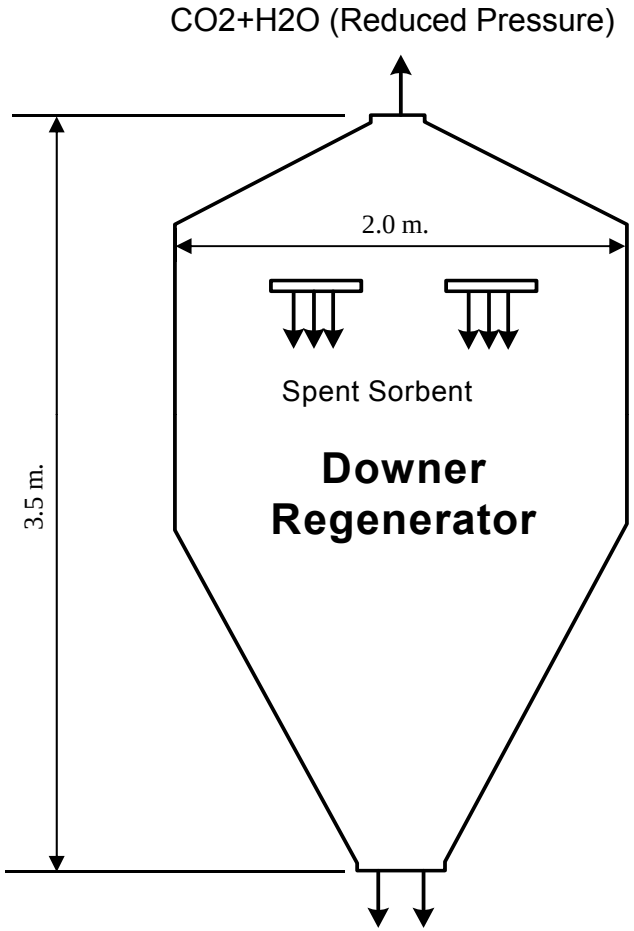
Downer Regenerator



Reduced Pressure
Downer Sorbent Regenerator

Conditions

Gas phase

	-Ug	-0.2 m/s
	-Us	-0.2 m/s

Solids phase

	- Dp	500 μm
	- Density	500 kg/m3
	- Gs	48 kg/m2s

Inlet conditions (Sorbent)

	- NaHCO3 mole fraction	(from riser outlet)
	- Na2CO3 mole fraction	(from riser outlet)

Operating Temperature	335-338 K
Operating Pressure	1 kPa

Kinetic Rate Expression

2NaHCO3(s) ↔ Na2CO3(s) + CO2(g) + H2O(g)

$$r_{regen} = k_{reaction}(C_{CO_2,eq} - C_{CO_2})\ (C_{H_2O,eq} - C_{H_2O})$$

Geometry, sorption rate and inlet conditions for CO2 removal from flue gases

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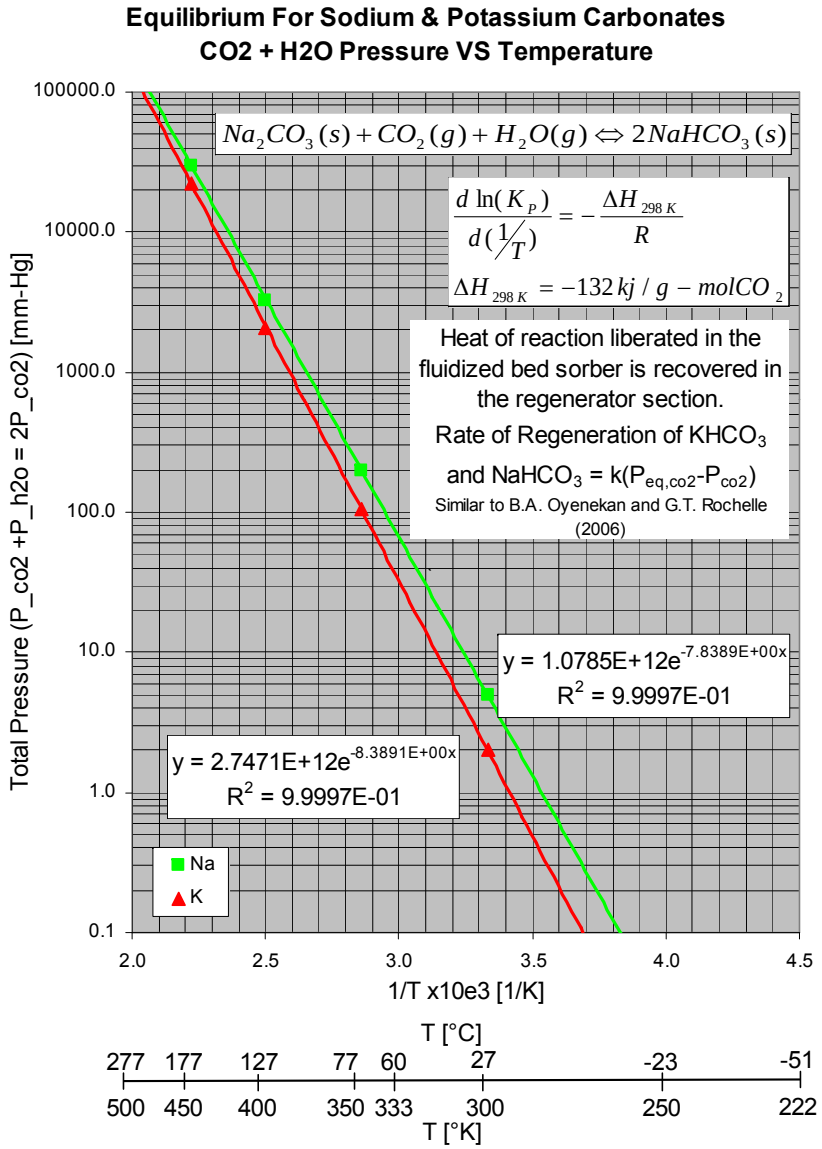
Reaction Model



Sorption Reaction

Na2CO3(s) + CO2(g) + H2O(g) ↔ 2NaHCO3(s)

$$r_{sorption} = -k_{reaction}(C_{CO_2,eq} - C_{CO_2})\ (C_{H_2O,eq} - C_{H_2O})$$

$$P_{CO_2,eq} = 1.0785\times10^{12}\left[\exp(\frac{-7.83893\times10^3}{T})\right]$$

$$k_{reaction} = 55.0\exp(\frac{3609}{RT})$$

Desorption Reaction

2NaHCO3(s) ↔ Na2CO3(s) + CO2(g) + H2O(g)

$$r_{regen} = k_{reaction}(C_{CO_2,eq} - C_{CO_2})\ (C_{H_2O,eq} - C_{H_2O})$$

$$P_{CO_2,eq} = 1.0785\times10^{12}\left[\exp(\frac{-7.83893\times10^3}{T})\right]$$

$$k_{reaction} = 55.0\exp(\frac{3609}{RT})$$

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Energy of Separation

Thermodynamics

From Availability Balance on the system[4]

$$TdS_{mixture} = v_{mixture}dP$$ **= work of separation (By Vacuum Fan)**

$$S_{mixture} = -R\sum_{i=1}^{n} x_i \ln x_i$$ **= Entropy changes due to composition**

Energy of Combustion

➔Combustion Energy ≈ **372** kJ/ g-mol-CO2

➔The minimum energy for separation of CO2 from flue gases, **7.3** KJ/g-mol-CO2[2]

Energy Consumption for Dry Sorbent System

➔Blower (Parasitic loss) ≈ **2** kJ/ g-mol-CO2

➔Vacuum Fan (Separation work) ≈ **23** kJ/ g-mol-CO2

➔Total Energy ≈ **27** kJ/g-mol-CO2

Energy Consumption for Amine Solvent [1][3]

➔Energy for separation of CO2 **= 43** kJ/ g-mol-CO2

➔Sorber consumes about 7% of combustion energy / g-mol-CO2.

➔Amine Solvent consumes about 11% of combustion energy / g-mol-CO2.

➔Sorber consumes only 62% of energy required by Amine Solvent technology.

References:
1.) Babatunde A. O. and Rochelle, G.T., Ind. Eng. Chem., 2006, 45, 2457-2464
2.) Oyenekan, B.A. Modeling of Strippers for CO2 Capture by Aqueous Amines, University of Texas at Austin Ph.D, 2007.
3.) Rochelle, G.T., Amine scrubbing for CO2 capture, SCIENCE 325 (2009) 1652-1654
4.) R.E. Fitzmorris and R. S. H. MAH, AIChE Journal, Vol. 26, No. 2, March, 1980, 265-273

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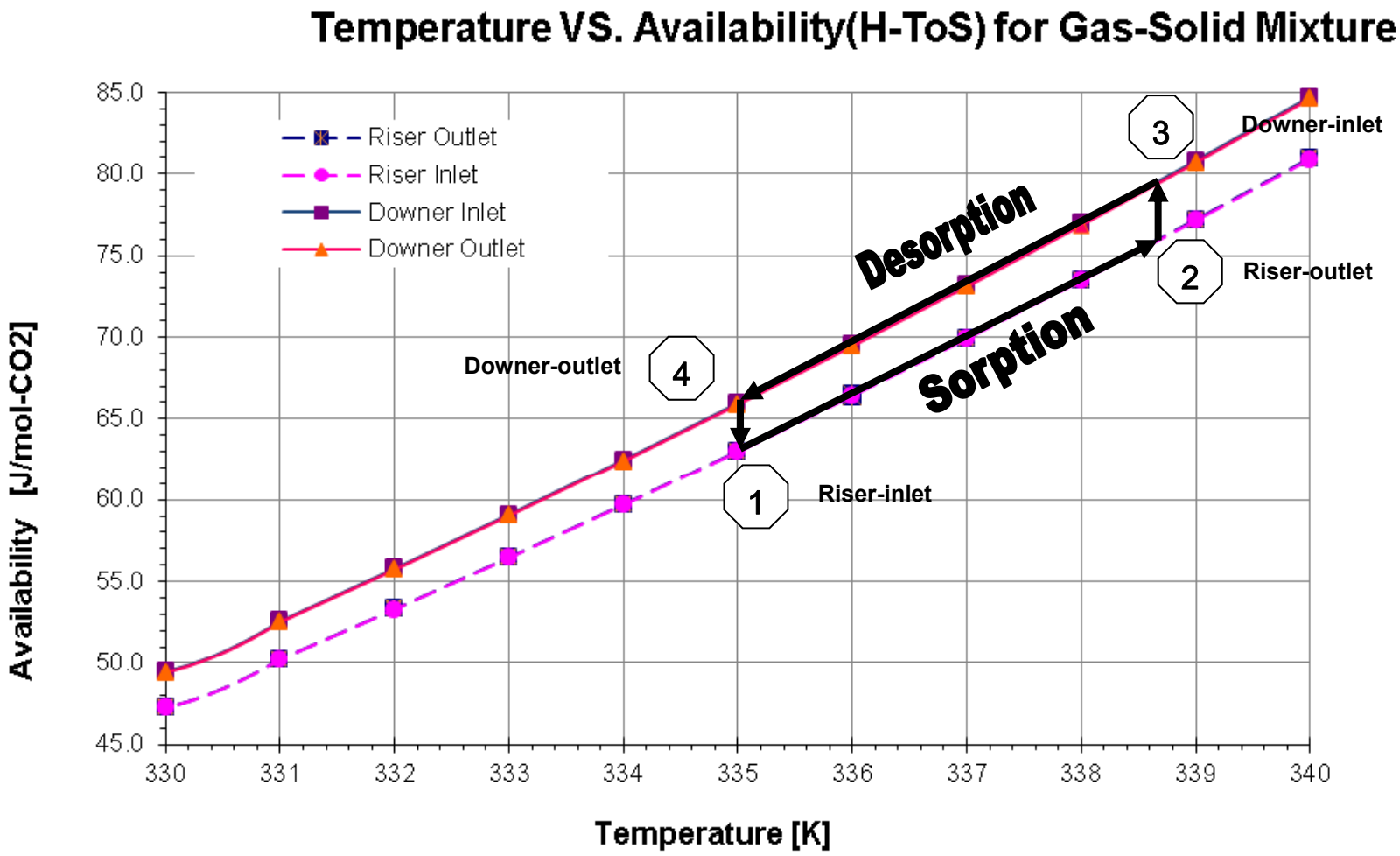
CO2 Capture Process



Availability analysis for the Sorber and Regenerator CO_2 capture process

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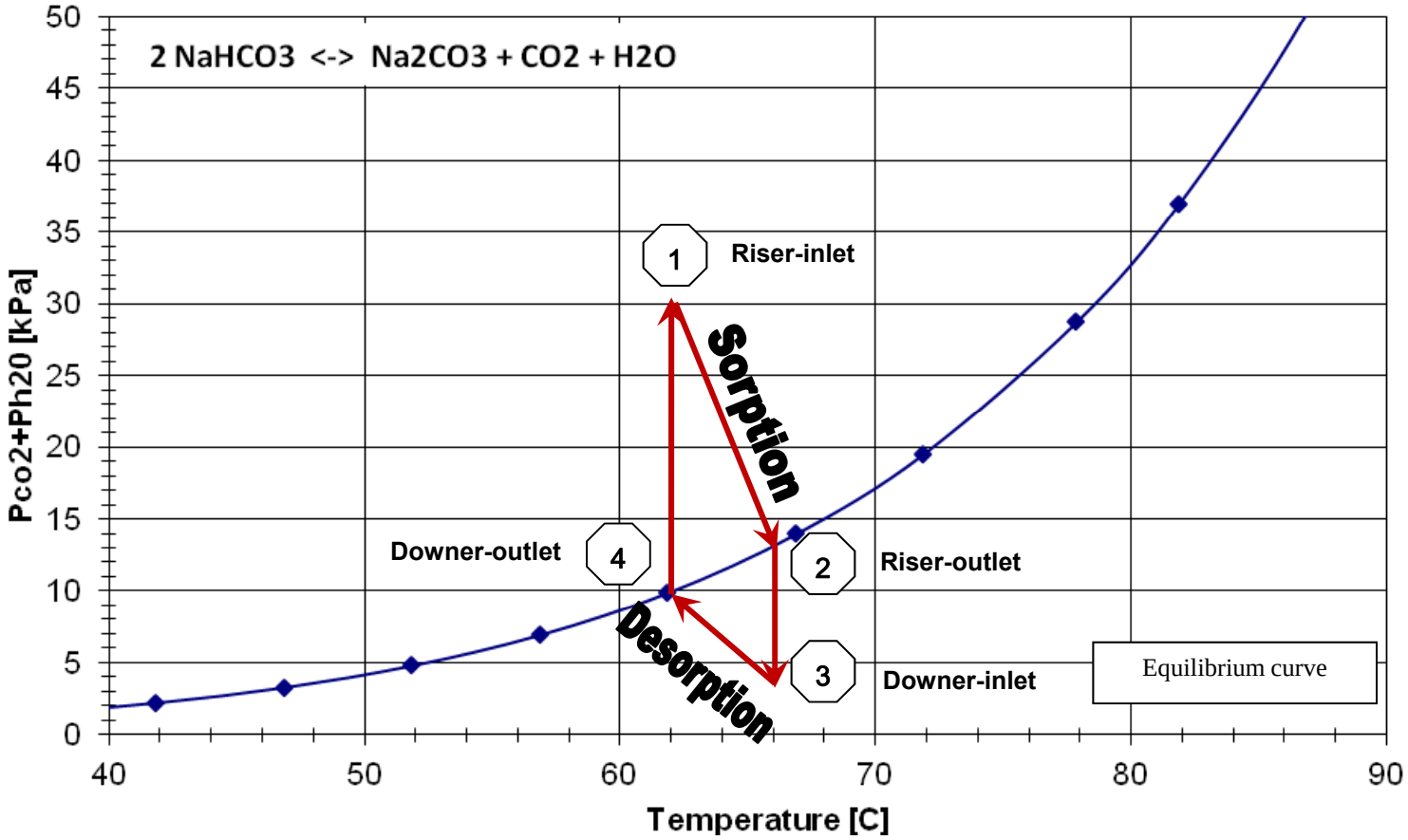
CO2 Capture Process

Sorber –Regenerator CO_2 Capture fluidized bed process.

Temperature and partial pressure equilibrium curve for Sodium Carbonate/Bicarbonate



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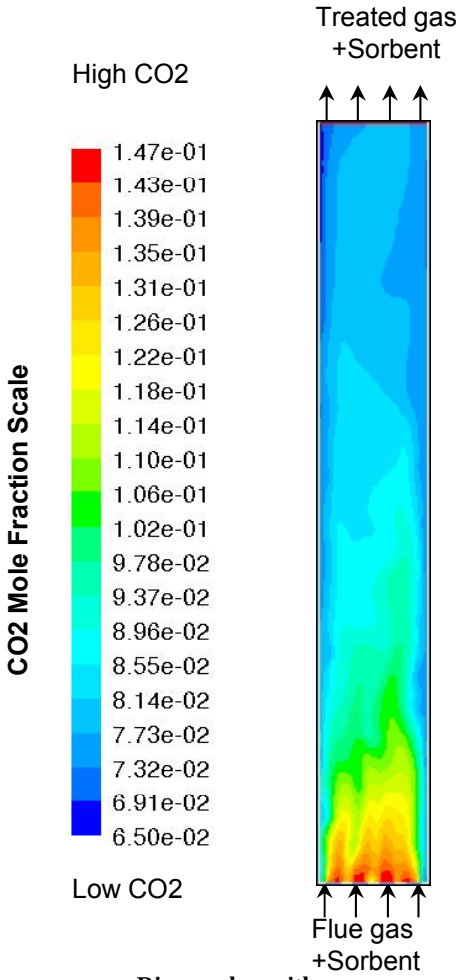
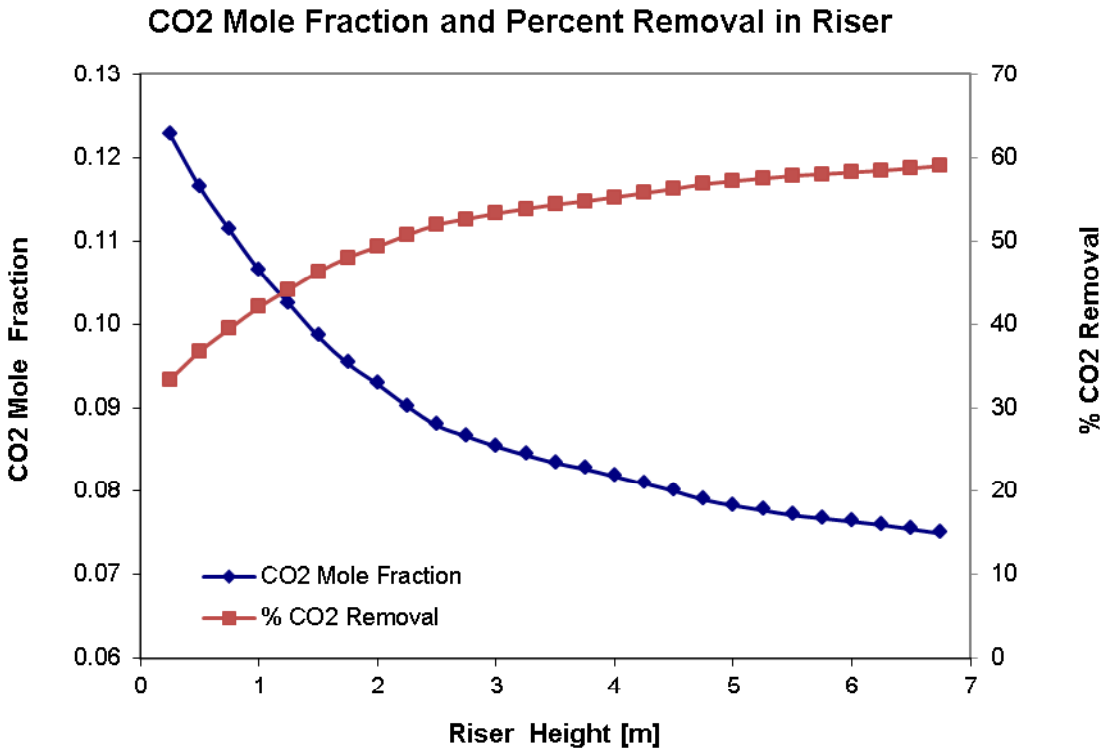
Simulation Results

CO2 Removal Efficiency



Riser sorber with no core-annular flow



CO_2 absorption in the riser.

The red color in the figure on the left represents the inlet CO_2 concentration of 23.7 wt %.
The figure of the right shows that nearly 60% of the CO_2 is removed in the 3 m. high riser compared with a 55% removal for the 3 m height.

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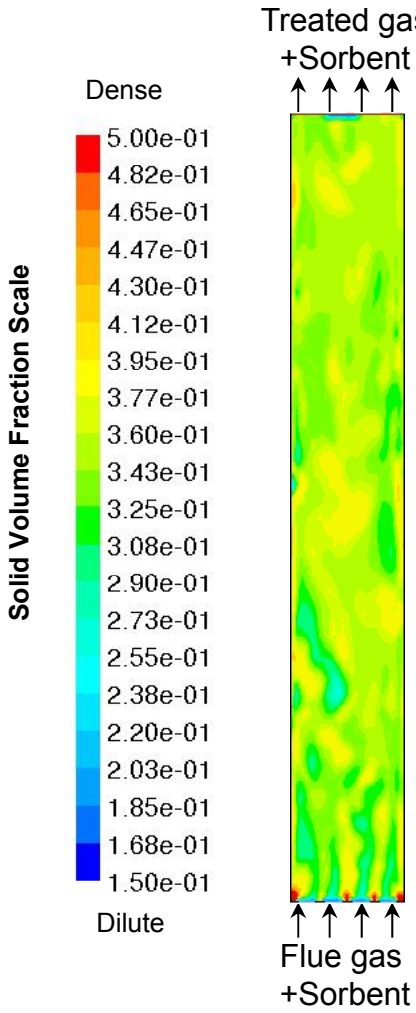
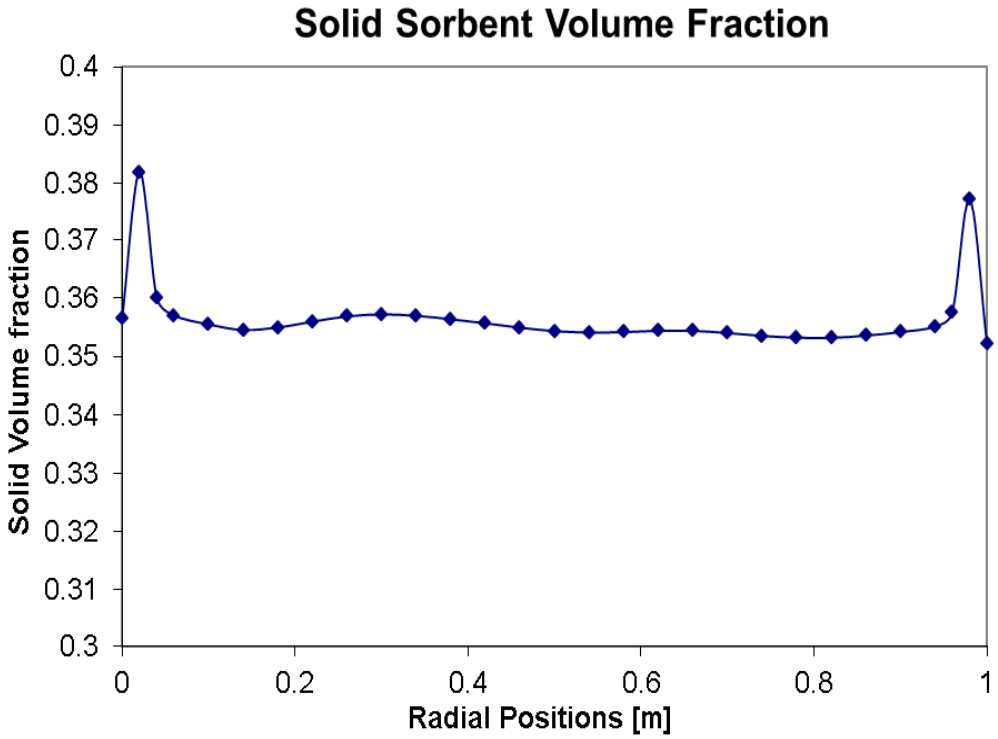
Fluidized Bed Sorber

Solid Volume Fraction - Riser



(A) Solid sorbent volume fractions for the riser with no core annular regime



(B) Time-averaged Solid sorbent volume fractions for the riser at 6m height

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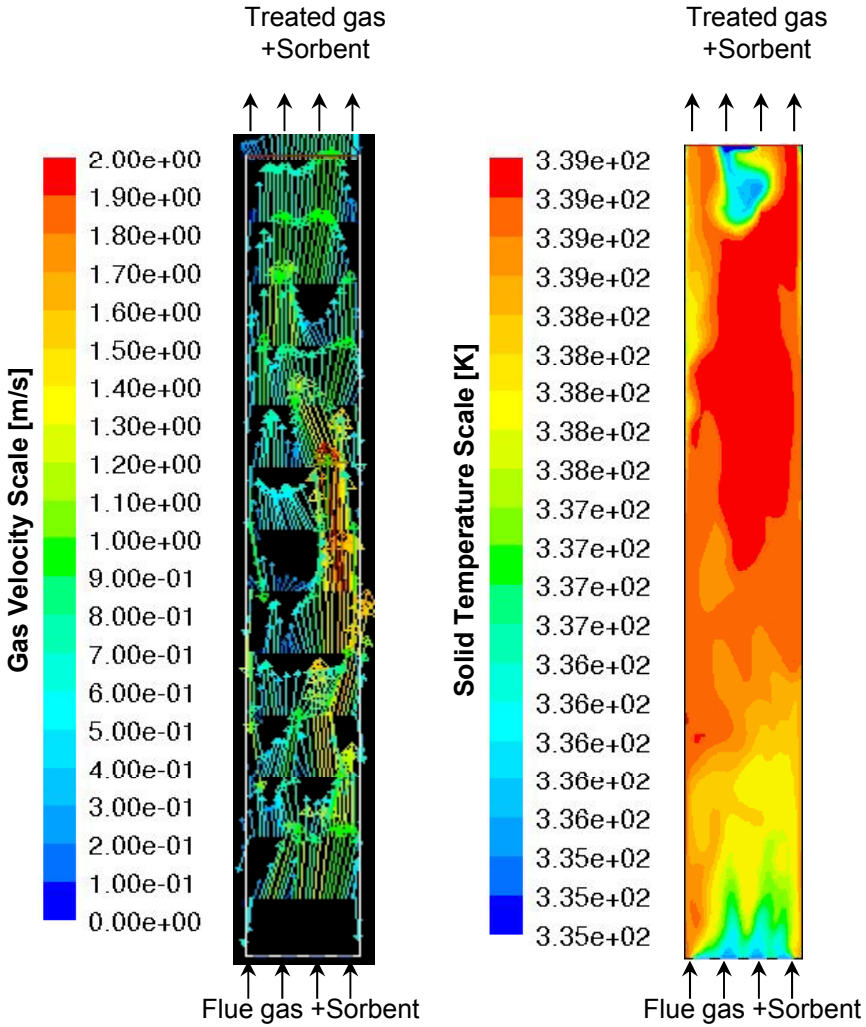
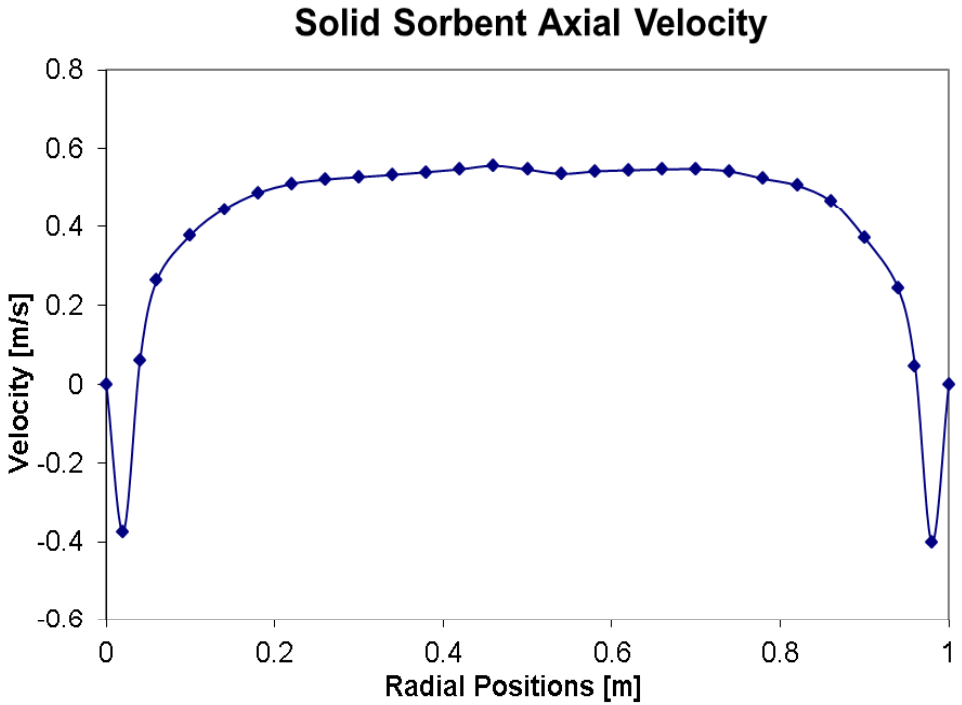
Fluidized Bed Sorber

Velocity Profile and Solid Temperature



(A) Gas velocity vector and Solid temperture for the riser with no core annular regime



(B) Time-averaged axial solid velocity in the riser.

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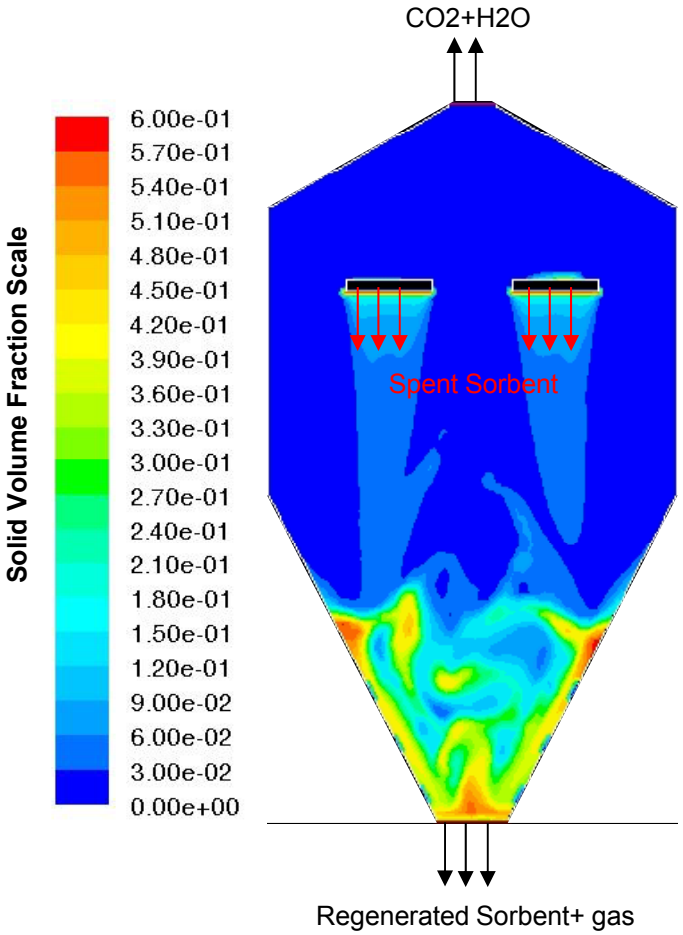
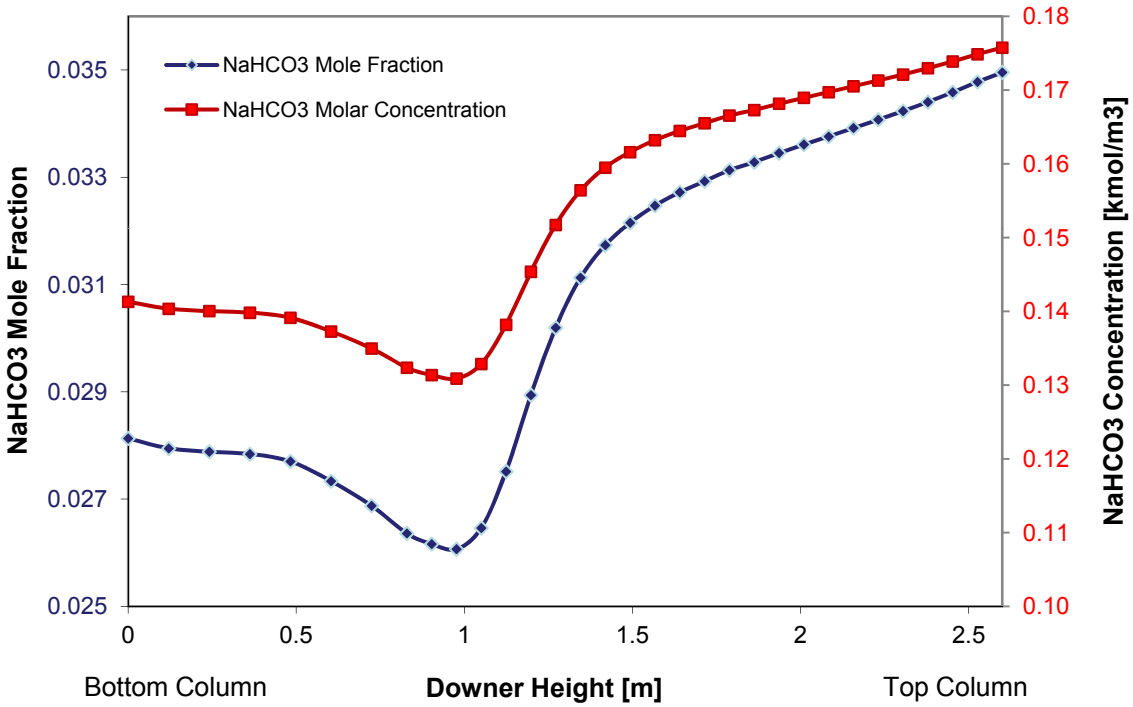
Simulation Results

Sorbent Regeneration Downer



Sorbent Volume Fraction



Time average Concentration of CO_2 and NaHCO3 mass fraction during desorption at the center line of reduced pressure downer regenerator.

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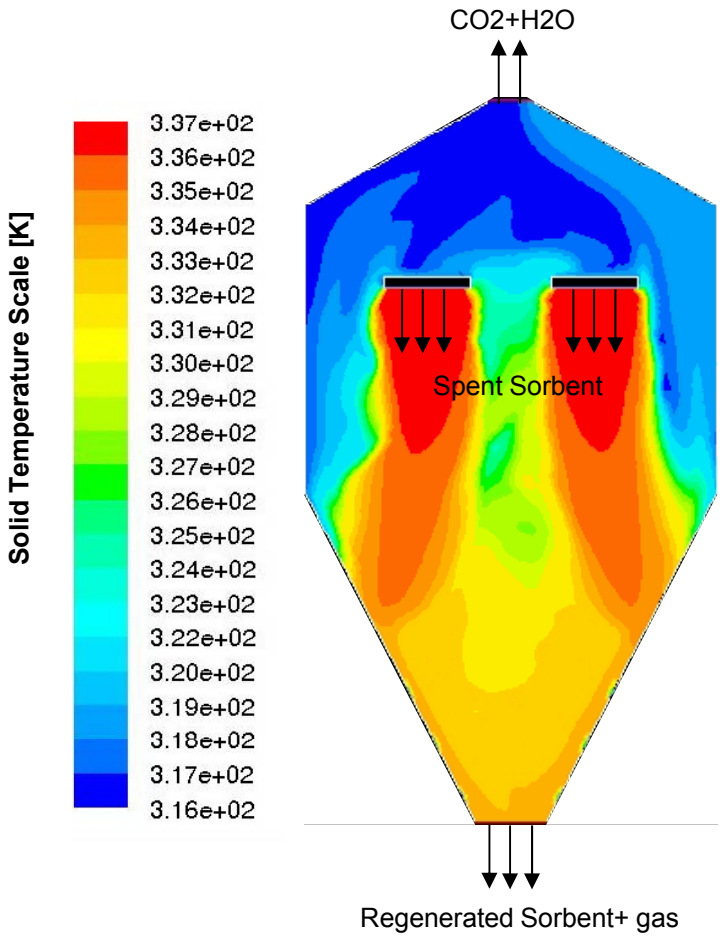
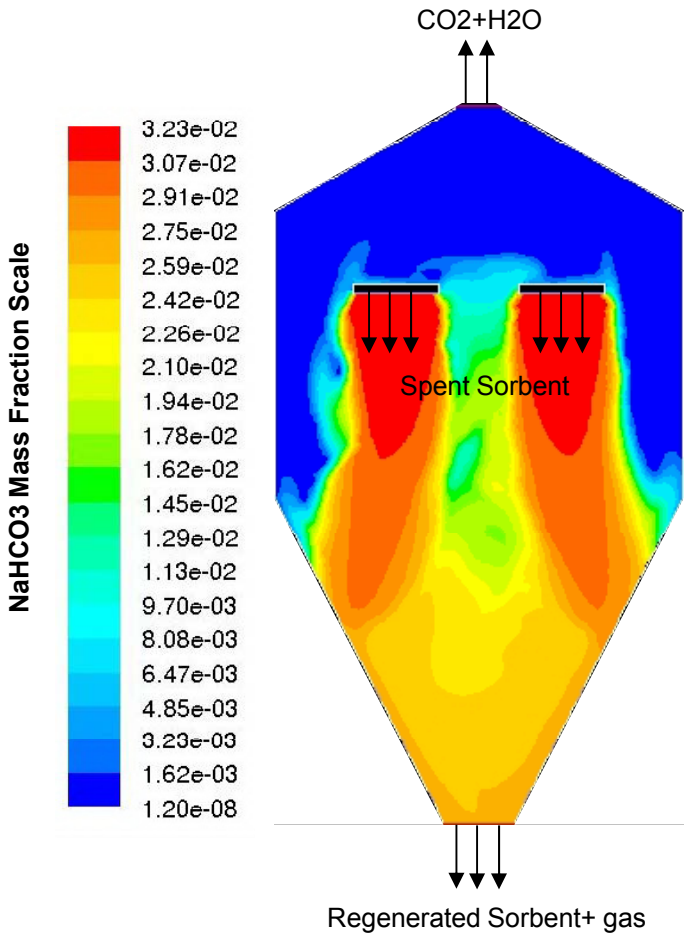
Simulation Results

Sorbent Regeneration Downer



Solid Temperature (K)



Mass Fraction of $NaHCO_3$

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Conclusions

Dry Sorbent Riser-Downer System

- A fluidized bed riser and reduced pressure regeneration downer process was designed using multiphase CFD for removing CO_2 from flue gas. 60% of the CO_2 is removed in a 7m high sorber. A second stage is needed for higher CO_2 removal.

- 88% of the heat liberated in the sorber is recovered in the downer regenerator. The loss in thermodynamic availability is only 1.5 kJ/gmol-CO_2.

- The work input for the flue gas blower is 2.1 kJ/gmol-CO_2 and 23.3 kJ/gmol-CO_2 for the vacuum fan which operated at 1 kPa suction pressure versus the combustion energy for carbon of 372 kJ/gmol-CO_2. Operating the vacuum fan at 5 kPa will reduce the energy input to 12.2 kJ/gmol-CO_2.

- 500 micron sorbent particles were used rather than the 75 micron sorbent manufactured by RTI. The large sorbent particle size allows better settling in the downer.

- The multiple jet inlets and the large sorbent particles in the riser eliminate the undesirable core-annular regime.