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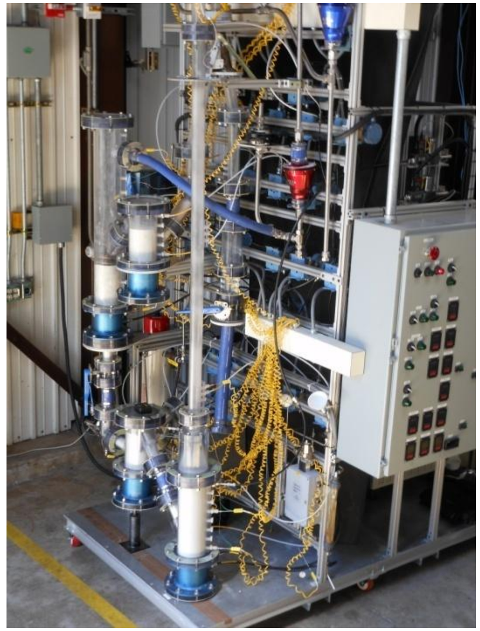

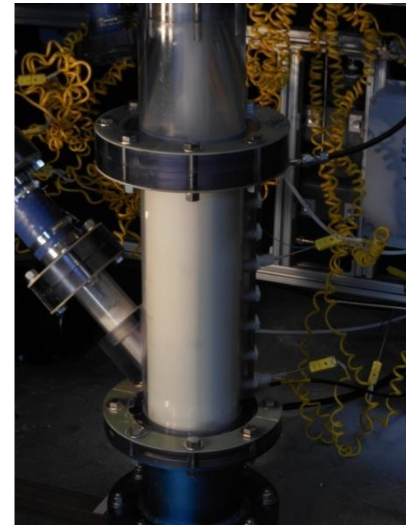

Development of a Circulating Fluidized Bed for Flue Gas Carbon Capture using Solid Sorbent

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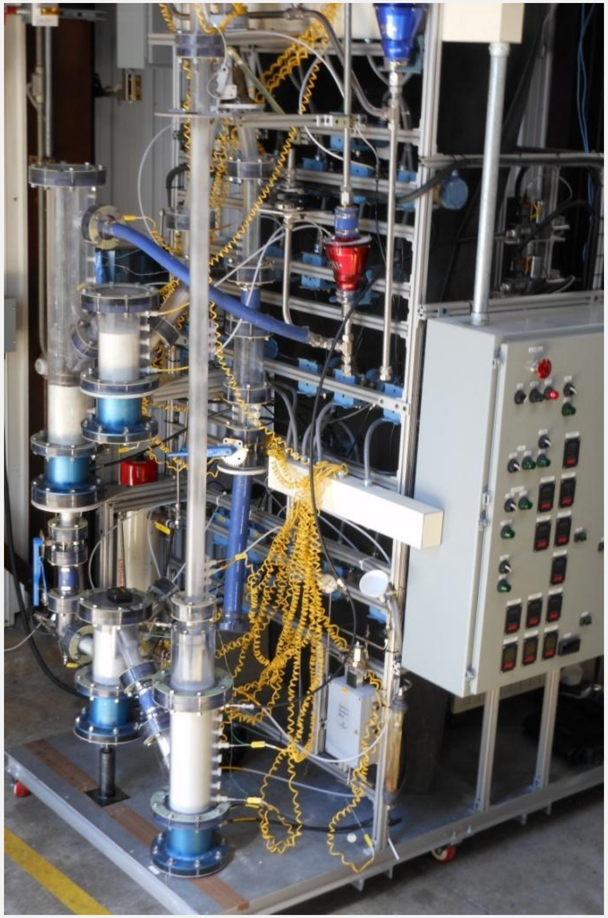
Overview

- A bench scale circulating fluidized bed system designated as the "Carbon Capture Unit" or "C2U" has been designed and built to evaluate the performance of sorbents on a solid substrate for removal of CO_2 from flue gases.



Program goals

- This project relates to the Existing Plants, Emissions and Capture (EPEC) Program within the Post-Combustion CO_2 Capture area and under the category of Solid Sorbents.
- Program goal: To develop fossil fuel conversion systems that can capture 90% CO_2 while keeping the increase in cost of energy service below 35%.*

** DOE/NETL Carbon Dioxide Capture and Storage R&D Roadmap, DOE/NETL Document, December 2010.*

Success criteria for sorbents: MATRIC* study

Initial performance:

30 – 50 % energy required for wet MEA process

Minimum Delta Loading:

3.0 gmol CO_2/kg sorbent

Temperature adsorption/desorption envelope:

40 – 110 C @ atm. press. with humidity

Stability, durability and performance:

Sorbent must maintain its adsorption/desorption capability in the presence of water and other flue gases and maintain structural integrity through multiple cycles.

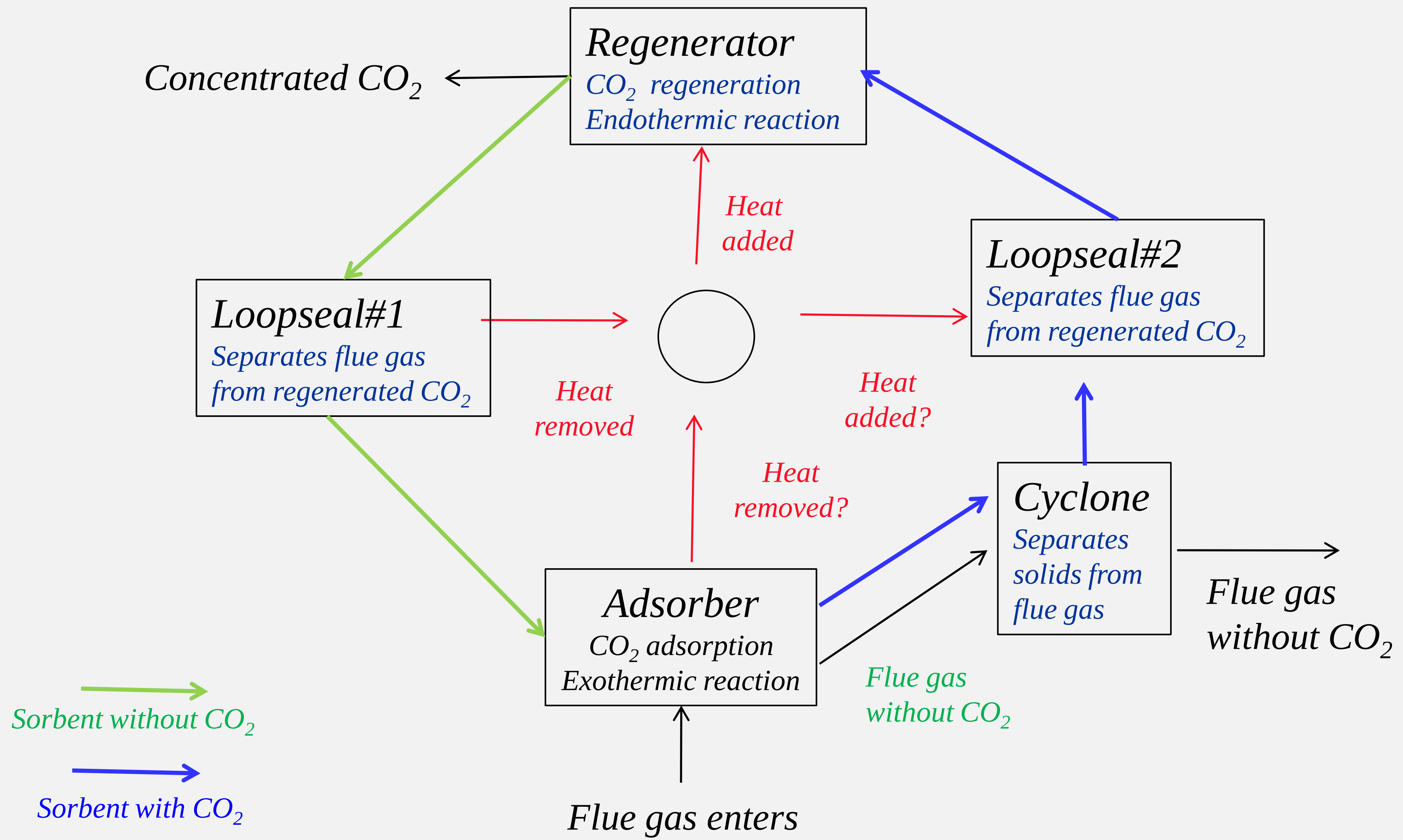
* **Mid-Atlantic Technology, Research and Innovation Center (MATRIC),** ***PROCESS ANALYSES AND R&D PLANS FORWARD FOR DRY-SORBENT-BASED PROCESSES FOR REMOVAL OF CO_2 FROM POWER PLANT FLUE GA*** S, July 19. 2006

Goals/objectives of C2U

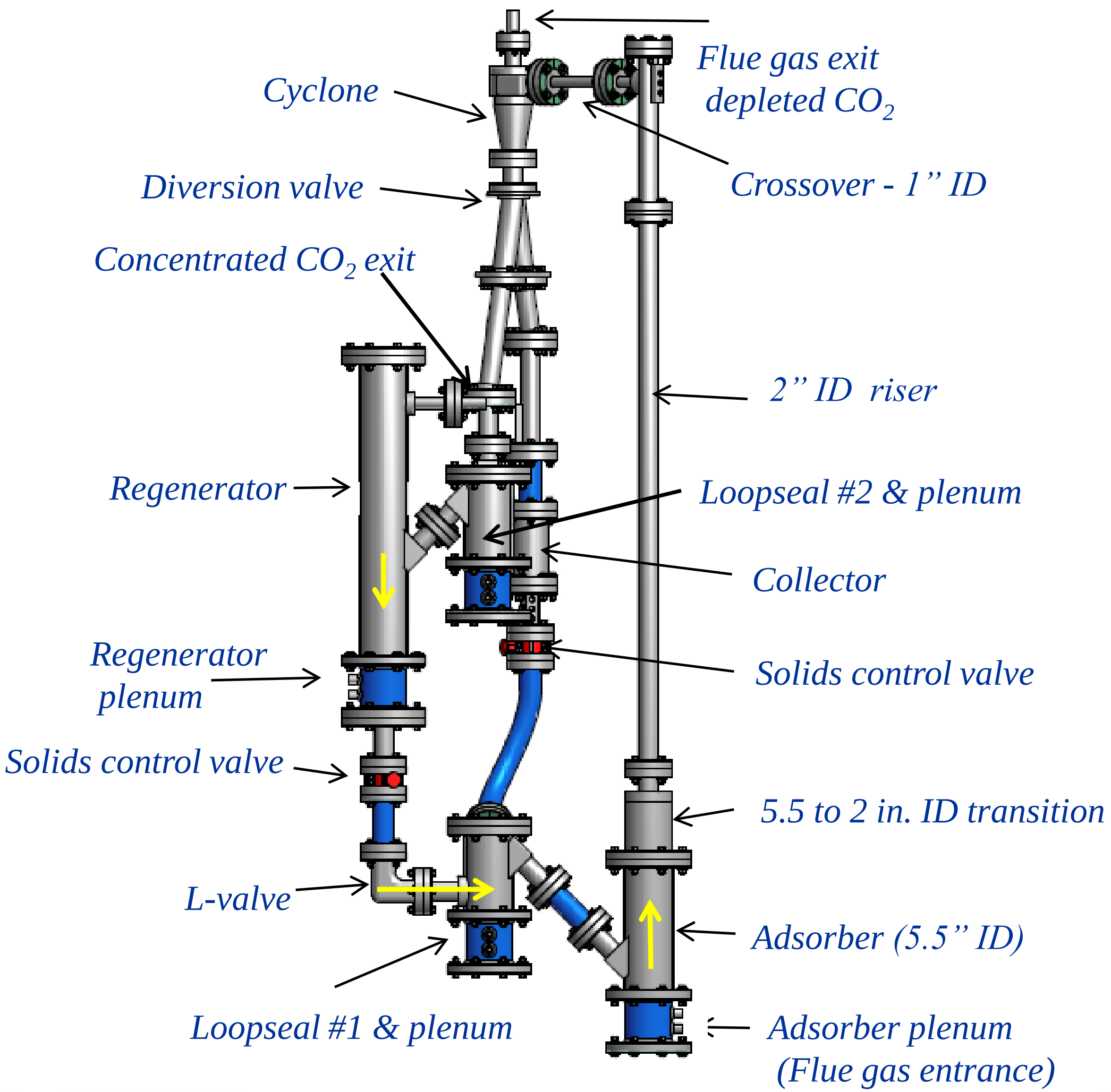
- **Flexible, inexpensive, small scale unit capable of validating CFD models including CO_2 adsorption and regeneration**

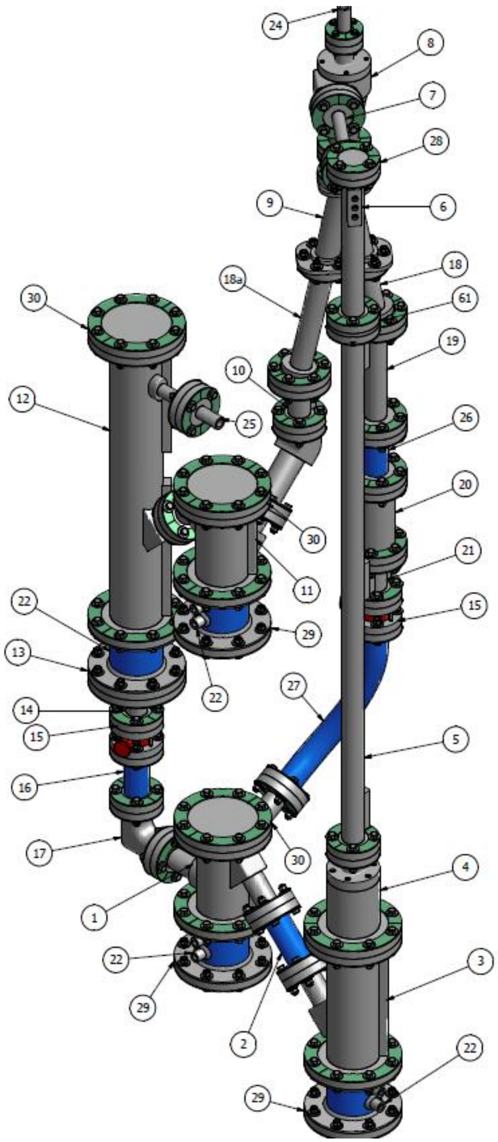
- **Desired Capabilities:**
  - Evaluate heat transfer modes
  - Define mass transfer limits
  - Map hydrodynamic parameters
  - Validate sorbent kinetics
  - Quantify desired CO_2 loading on sorbent
  - Evaluate ability to isolate processes
  - Control process variables, such as mixing, flue gas composition, residence times, etc.
  - Evaluate reactor performance

Conceptual design



C2U components





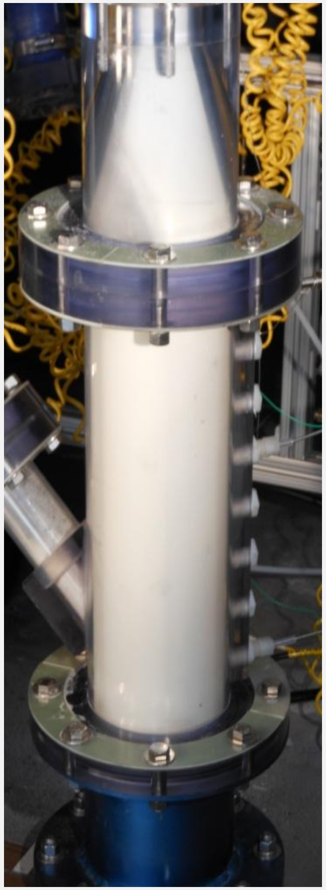
Design basis – Centerpoint of operation envelope

- **Sorbent**
  - Density: 2.0 g/cc
  - Diameter: 200 µm (Operation range : 70 to 400 µm)
  - Specific heat: 837 J/kg-K
  - Sorption capacity: 3.0 g-mol CO_2/kg sorbent
- **Flue gas composition**
  - Dry: 81.3 % N_2, 15.9 % CO_2, 2.8 % O_2, 0.0% H_2O
  - Wet: 68.1 % N_2, 13.5 % CO_2, 2.4 % O_2, 15.1% H_2O
- **Flue gas flow**
  - 3.5 x U_{mf} in adsorber without cooling coils (116 slpm)
  - CO_2 flow: 18.4 slpm (1.26 x 10^{-2} g-mol/s or 5.53x10^{-4} kg/s)
  - Equivalent to 5.0 kW (thermal) power plant. 1.75 kW with 35% efficiency

Design basis – Centerpoint of operation envelope

Adsorber – 5.5" (0.14 m) ID, 18" (0.45 m) height, polycarbonate

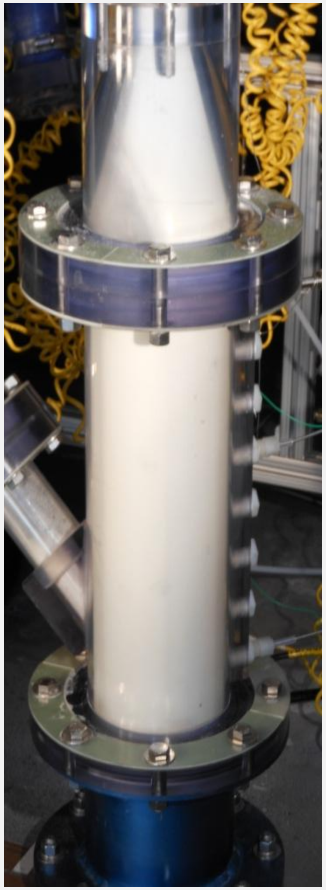
- **Sorbent circulation rate –with adsorber heat transfer**
  - CO_2 total flow: 5.53×10^{-4} kg/s (1.26×10^{-2} g-mol/s)
  - 90% CO_2 capture
  - Sorbent loading : 3.0 g-mol CO_2/kg sorbent
  - Circulation rate:
    - 0.9 *(1.26×10^{-2} g-mol/s)/ (3.0 g-mol CO_2/kg sorbent) = 3.77×10^{-3} kg/s (30 lb/hr)
- **Heat to be removed**
  - Heat of reaction
    - Adsorption heat of reaction ($\Delta H = 1.51 \times 10^{6}$ J/kg CO_2):
    - CO_2 total flow: 5.53×10^{-4} kg/s (1.26×10^{-2} g-mol/s)
    - 90% CO_2 capture
    - Heat produced: 1.51×10^{6} J/kg CO_2* 5.53×10^{-4} kg/s*0.9 = 752 J/s
  - Sorbent sensible heat
    - Allow sorbent ΔT = 30 C (Enter @ 50 C leave @ 80 C)
    - Sorbent specific heat 837 J/kg- C
    - $Q_{sorbent}$ = 0.9 *5.53×10^{-4} kg/s * 837 J/kg- C* 30 C = 95 J/s
    - Heat to be removed = 752 - 95 = 657 J/s



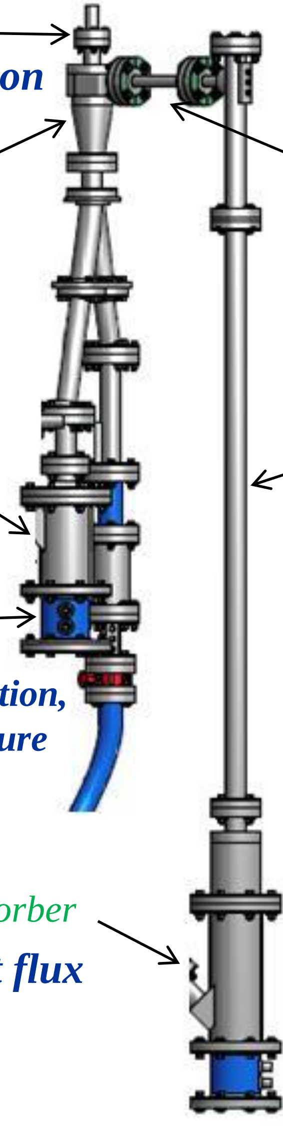
Design basis – Centerpoint of operation envelope

Adsorber – 5.5" (0.14 m) ID, 18" (0.45 m) height, polycarbonate

- **Required sorbent circulation rate - without adsorber heat transfer**
  - Heat produced by reaction 752 J/s
  - Sorbent circulation rate
    - Sorbent specific heat: 837 J/kg- C
    - Assume sorbent temp not permitted to exceed 80 C for adsorption, enters adsorber at 50 C (ΔT = 30 C)
    - Circulation rate: (752 J/s)/(30 C* 837 J/kg-K) = 3.0 x10^{-2} kg/s (237 lb/hr)
  - Sorbent loading
    - 0.9 *(1.26x10^{-2} g-mol/s)/3.0 x10^{-2} kg/s = 0.4 g-mol CO_2/kg sorbent
    - Some heat is removed by flue gas flow (approx. 10%) decreasing the required sorbent circulation rate calculated above



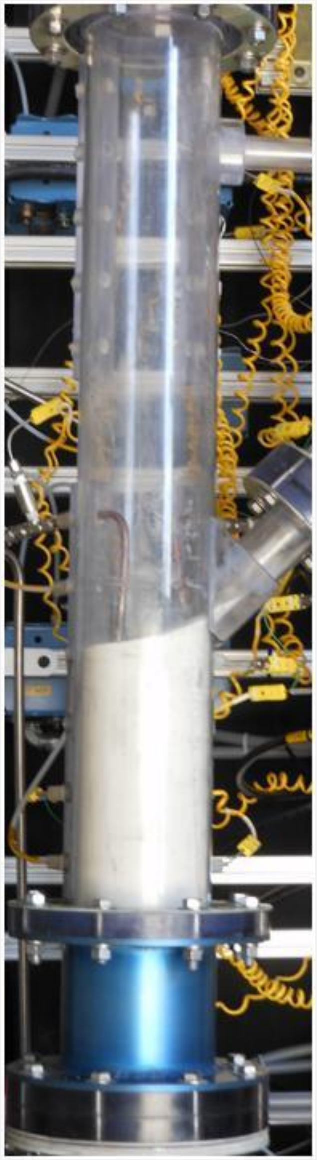
Measurements-Adsorber side



Regeneration

Regenerator – 5.5" (0.14 m) ID, 40" (0.45 m) height, polycarbonate with internal coils

- **Heat addition for 100 % CO_2 regeneration**
  - Reverse amine reaction - 752 J/s
  - Heat substrate from 80 to 100 C
    - Circulation rate: 3.77×10^{-3} kg/s $Q_{sorbent}$ = 63 J/s Total = 815 J/s
    - Circulation rate: 3.00×10^{-2} kg/s $Q_{sorbent}$ = 501 J/s Total = 1253 J/s



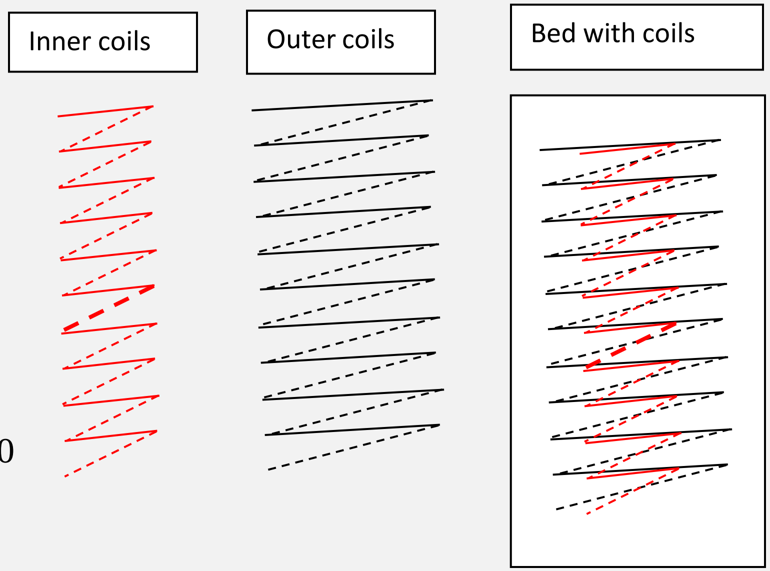
Heat transfer coils

Heat transfer within all reactors accomplished using two copper coils nested axisymmetrically.

Chilled water flows through the coils for cooling. Heat addition utilizes heated oil.

*Heat transfer coefficient is determined using correlation from *Vreedenburg 1958 for horizontal tubes in a bubbling bed*

$$\frac{h_c D_t}{k_g} = 0.66\,\mathrm{Pr}_g^{0.3}\left(\frac{\rho_s(1-\varepsilon)}{\rho_g \varepsilon}\right)^{0.44}\mathrm{Re}_D^{0.44} \quad \textit{when} \quad \frac{\rho_s}{\rho_g}\mathrm{Re}_p \le 2050$$



where

$$\mathrm{Re}_p = \frac{d_p \rho_g U_g}{\mu_g} \qquad \mathrm{Re}_D = \frac{D_t \rho_g U_g}{\mu_g}$$

*Handbook of Fluidization and Fluid Particle Systems (Yang) p. 263

Heat addition by coils in regenerator

Using values at right and Vreedenburg correlation the following heat transfer coefficients are determined:

Heat transfer coeff of outer tube (h) = 188.6 W/m²-K
hA_{outer} = 28.8W/K

Heat transfer coeff of inner tube (h) = 211.8W/m²-K
hA_{inner} = 17.52W/K

$U_g = 2 * U_{mf}$ = 0.064 m/s
ρ_{gas} = 1.28 kg/m3 @ operating pressure
μ_{gas} = 1.81x10-5 kg/m-s
k_{gas} = 2.58x10-2 W/m-K
Pr = 0.713
Void fraction = 0.516
Outer coil tube diameter = 1.27×10^{-2} m
Outer coil tube length = 3.83 m
Outer coil tube surface area = 0.229 m^2
Inner coil tube diameter = 9.67×10^{-3} m
Inner coil tube length = 2.55 m
Inner coil tube surface area = 0.116 m^2

Required Log Mean Temperature Difference

$$\Delta T = \frac{Q}{(hA)_{outer} + (hA)_{inner}}$$

For circulation rate 3.77×10^{-3} kg/s ΔT = 17.6 K since Q = 815 J/s

For circulation rate 3.00×10^{-2} kg/s ΔT = 27.0K since Q = 1253 J/s

Heat addition by coils in regenerator

Log mean temperature difference for a parallel flow heat exchanger

$$LMTD = \frac{\Delta T_{x=0} - \Delta T_{x=L}}{\ln\left(\Delta T_{x=0} / \Delta T_{x=L}\right)} = \frac{(T_{h,i} - T_{c,i}) - (T_{h,o} - T_{c,o})}{\ln\left[(T_{h,i} - T_{c,i})/(T_{h,o} - T_{c,o})\right]}$$

$T_{h,i}$ - *Temperature of oil at the inlet.*
$T_{c,i}$ - *Temperature of sorbent at the inlet.*
$T_{h,o}$ - *Temperature of oil at the outlet.*
$T_{c,o}$ - *Temperature of sorbent at the outlet.*

Increase sorbent temperature from 80 C ($T_{c,i}$) to 100 C ($T_{c,o}$) and add regeneration energy

Using heated oil @ 4.0 liter/min (7.33×10^{-2} kg/s) sp. ht. = 1910 J/kg-K
*ΔT_{oil} = Q/(mass flow *sp. ht.)*

Low circulation rate:
ΔT_{oil} = -5.8 C for LMTD - 17.6 C
Oil inlet temp = 113.6 C, Oil exit temp = 107.8 C - Using LMTD equation:

High circulation rate:
ΔT_{oil} = - 9.0 C for LMTD - 27.0 C – sorbent circ rate 3.00×10^{-2} kg/s
Oil inlet temp = 124.0 C, Oil exit temp = 115.0 C

Heat removal by coils in Loopseal #1

Decrease sorbent temperature from 80 C ($T_{h,i}$) to 50 C ($T_{h,o}$)

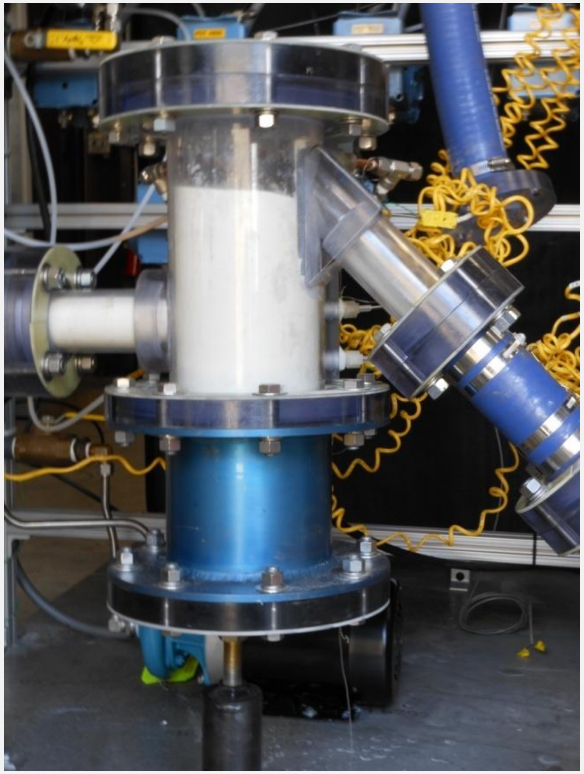
Heat transfer coeff of outer tube (h) = 214 W/m^2-K , hA_{outer} = 24.6 W/K,
Heat transfer coeff of inner tube (h) = 252 W/m^2-K , hA_{inner} = 14.5 W/K

$Q_{low\ circ}$ = 158 J/s , LMTD = 4.0 C , $Q_{high\ circ}$ = 1253 J/s, LMTD = 32.1 C

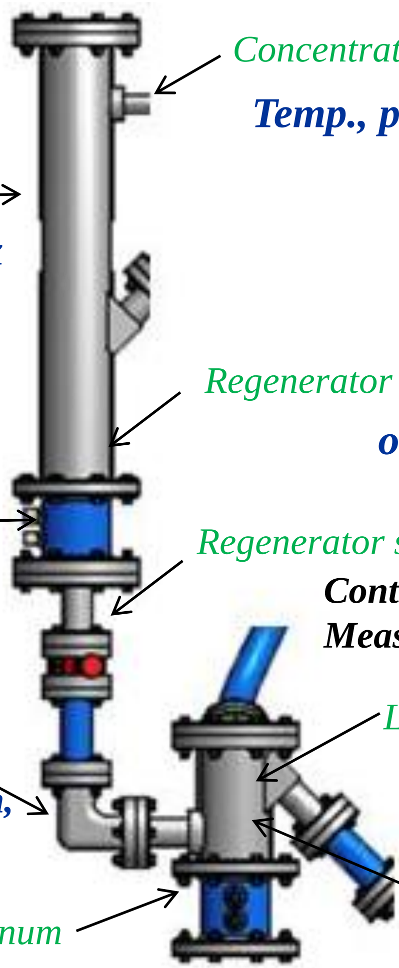
Using chilled water @ 4.0 liter/min ($6.67x10^{-2}$ kg/s)
sp. ht. = 4181J/kg-K
*ΔT_{water} = Q/(mass flow *sp. ht.)*

Low circulation rate:
ΔT_{water} = 0.6 C for LMTD - 4.0 C
Water inlet temp = 49.4 C,
water exit temp = 50.0 C

High circulation rate:
ΔT_{water} = 4.5 C for LMTD - 32.1 C
Water inlet temp = 33.2 C,
water exit temp = 37.7 C



Measurements- Regenerator side



Concentrated CO_2 exit

Temp., press., gas flow rate, composition

Regenerator

Δp, temp, wall heat flux

Regenerator heating coils

oil inlet & outlet temp, flow rate

Regenerator plenum

Control: ***Fluidizing gas flow and composition,***
Measure: ***Δp across distributor, temperature***

Regenerator standpipe

Control: ***Fluidizing gas flow and composition,***
Measure: ***Δp, temperature***

Loopseal #1

Δp, temp, wall heat flux

L-valve

Control: ***Fluidizing gas flow and composition,***
Measure: ***Δp, temperature***

Loopseal #1 cooling coils

water inlet & outlet temp, flow rate

Loopseal #1 plenum

Control: ***Fluidizing gas flow and composition,***
Measure: ***Δp across distributor, temperature***

Conclusions

The design meets the criteria previously expressed

- Flexible, inexpensive, small scale unit capable of validating CFD models including CO_2 adsorption and regeneration

- **Desired Capabilities:**
  - Evaluate heat transfer modes
  - Define mass transfer limits
  - Map hydrodynamic parameters
  - Validate sorbent kinetics
  - Quantify desired CO_2 loading on sorbent
  - Evaluate ability to isolate processes
  - Control process variables, such as mixing, flue gas composition, residence times, etc.
  - Evaluate reactor performance