Combined Pressure and Temperature Contrast and Surface-enhanced Separation of Carbon-dioxide for Post-combustion Carbon Capture

DOE Project # DE0007531

Project Manager: Isaac "Andy" Aurelio

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Rice University

Wrap Up Meeting and Site Visit for DE-FE0007531 - March 24, 2016

Outline

- Project Overview
- Project Budget
- Project objectives and technical approach
- Hydrodynamic and mass transfer studies on ceramic foam
- CO_2 capture demonstration in bench-scale combined absorber/ desorber reactor
- Process simulation of gas/liquid flow and reaction in integrated CO_2 absorber/desorber
- Catalytic desorption of CO_2 using metal oxides
- Technical and economic feasibility study
- Summary and Conclusions

Project Overview

- Project funding under DOE agreement – DE-FE0007531
- Total project cost - $960,811 over three years. Federal share: $768, 647 | Non-federal share: $192,164

Budget Period Object Class Category	Budget Period 1 (10.01.11 – 09.30.12)	Budget Period 2 (10.01.12 – 12.31.13)	Budget Period 3 Revised (01.01.14 – 12.31.15)	Total
Federal Share	$243,621	$327,568	$197,458	$768,647
Non-Federal Share	$89,473	$51,348	$51,343	$192,164
Total	$333,094	$378,916	$248,801	$960,811

- Contract awarded executed October 2011
- **Project duration**: 10/2011 – 3/2015 (asked for non-cost extension to 12/2015, due to early technical difficulties, change in personnel last year and gap in funding between BP2 and BP3)

Project Team

Project Director

Michael Wong
Professor in Chemical & Biomolecular Engineering & Chemistry

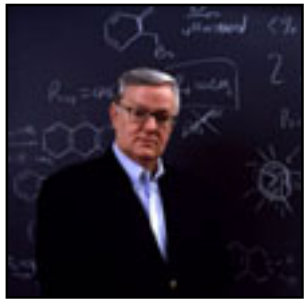
Co-Project Investigator

George Hirasaki
A J. Hartsook Professor in Chemical & Biomolecular Engineering

Co-Project Investigator

Kenneth Cox
Professor-in-practice in Chemical and Biomolecular Engineering

Co-Project Investigator



Edward Billups
Professor in Chemistry

Postdoctoral Associate

Zhen Wang
PhD, Thermal Power Engineering (ZJU, 2014)

Postdoctoral Associate

Mayank Gupta
PhD , Chemical Engineering (LSU, 2010)

Past Members

Colin Shaw
Undergraduate
Chemical & Biomolecular Engineering

Sumedh Warudkar
PhD (April 2013)

Jerimiah Forsythe
PhD, Chemistry (LSU, 2011)

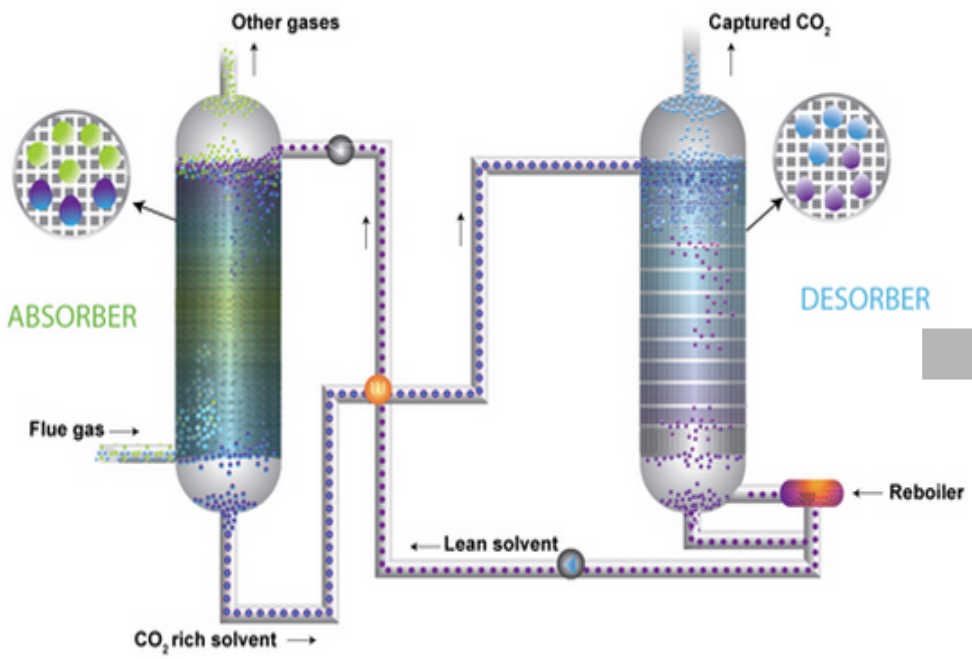
Objectives

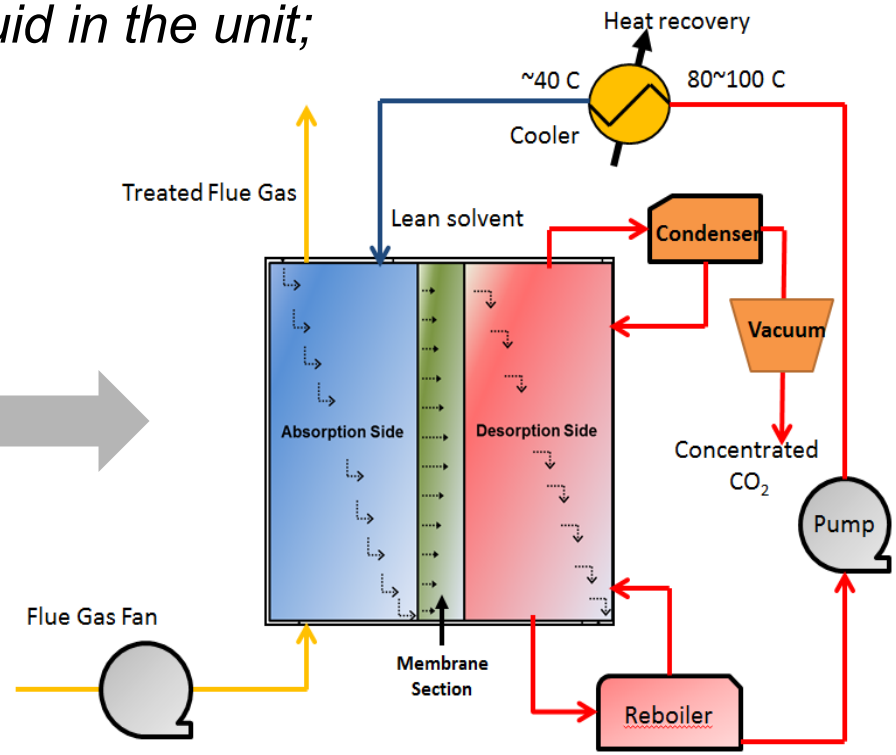
- Develop a new CO_2 capture process that uses a single integrated unit that combines both the absorber and desorber columns;
- Develop a rigorous model to simulate the CO_2 separation in integrated absorber and desorber unit, to test different configurations, and to optimize the operating condition and process;
- Reduce energy requirement by lowering the desorption temperature with the addition of metal oxide catalysts.
- Use waste heat for absorbent regeneration instead of low-pressure steam by operating the desorber section of the integrated unit under vacuum;

Technical Approach

Major challenges:

- *Selective permeation of the rich solvent through the membrane into the desorber;*
- *How to facilitate the lateral flow of liquid in the unit;*

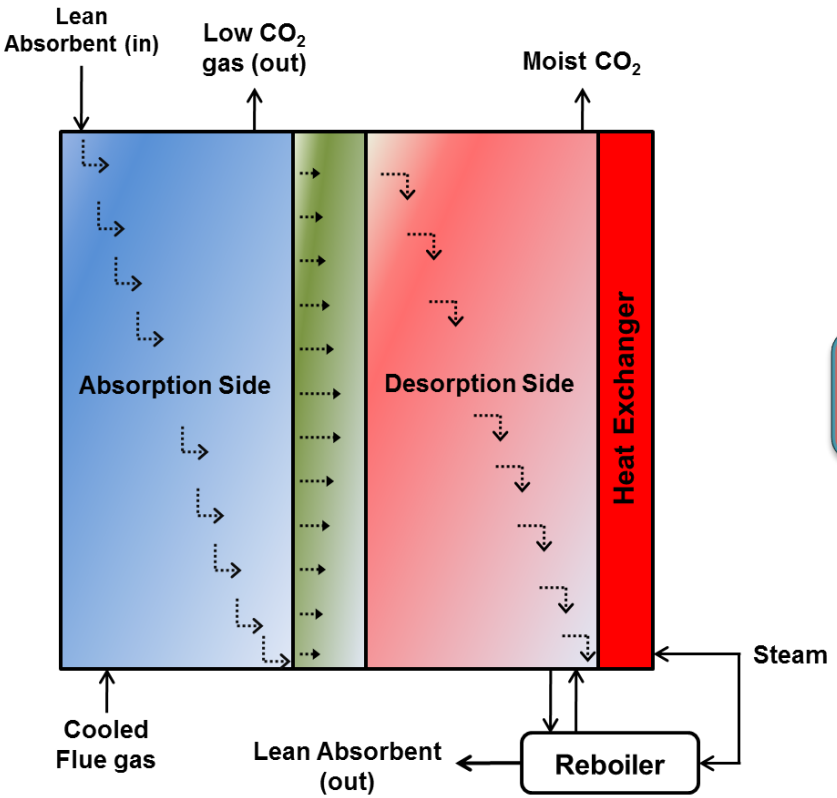


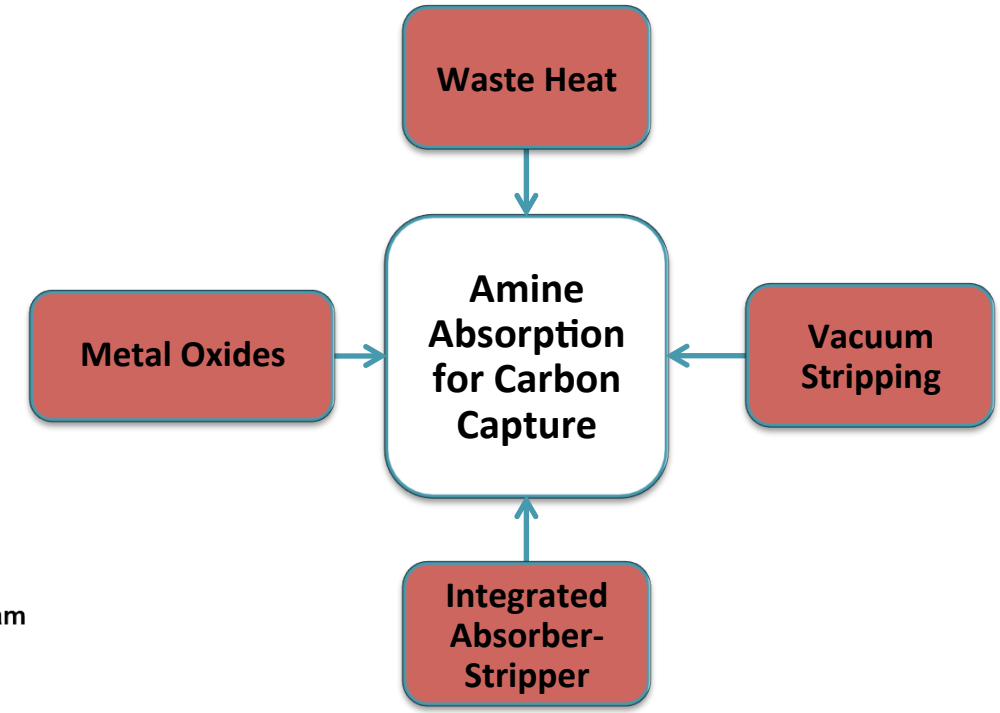


A comparison of the conventional amine system with the proposed 'combined' process

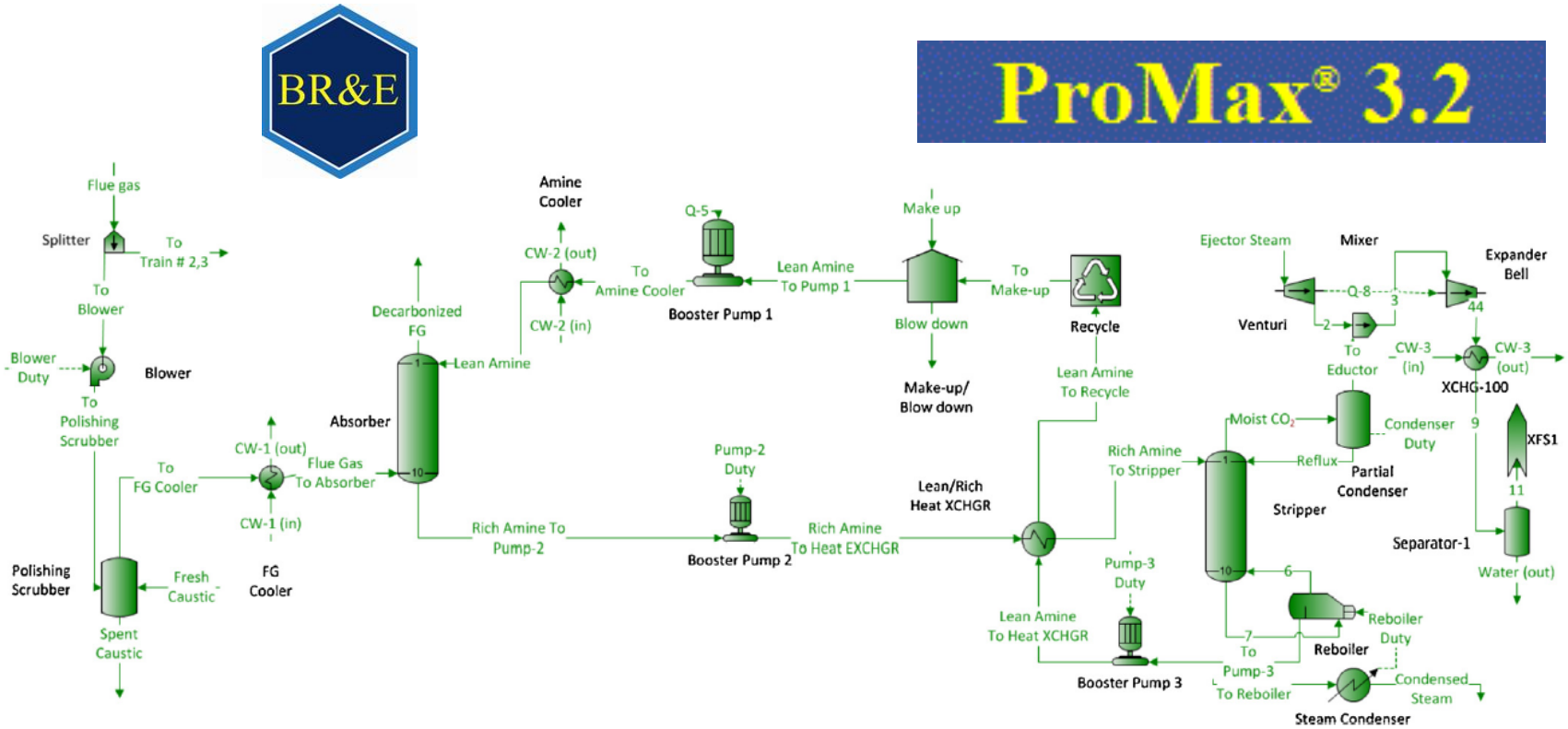
Technical Approach

COMBINED PRESSURE, TEMPERATURE CONTRAST, AND SURFACE-ENHANCED SEPARATION OF CO_2





Why vacuum stripping?

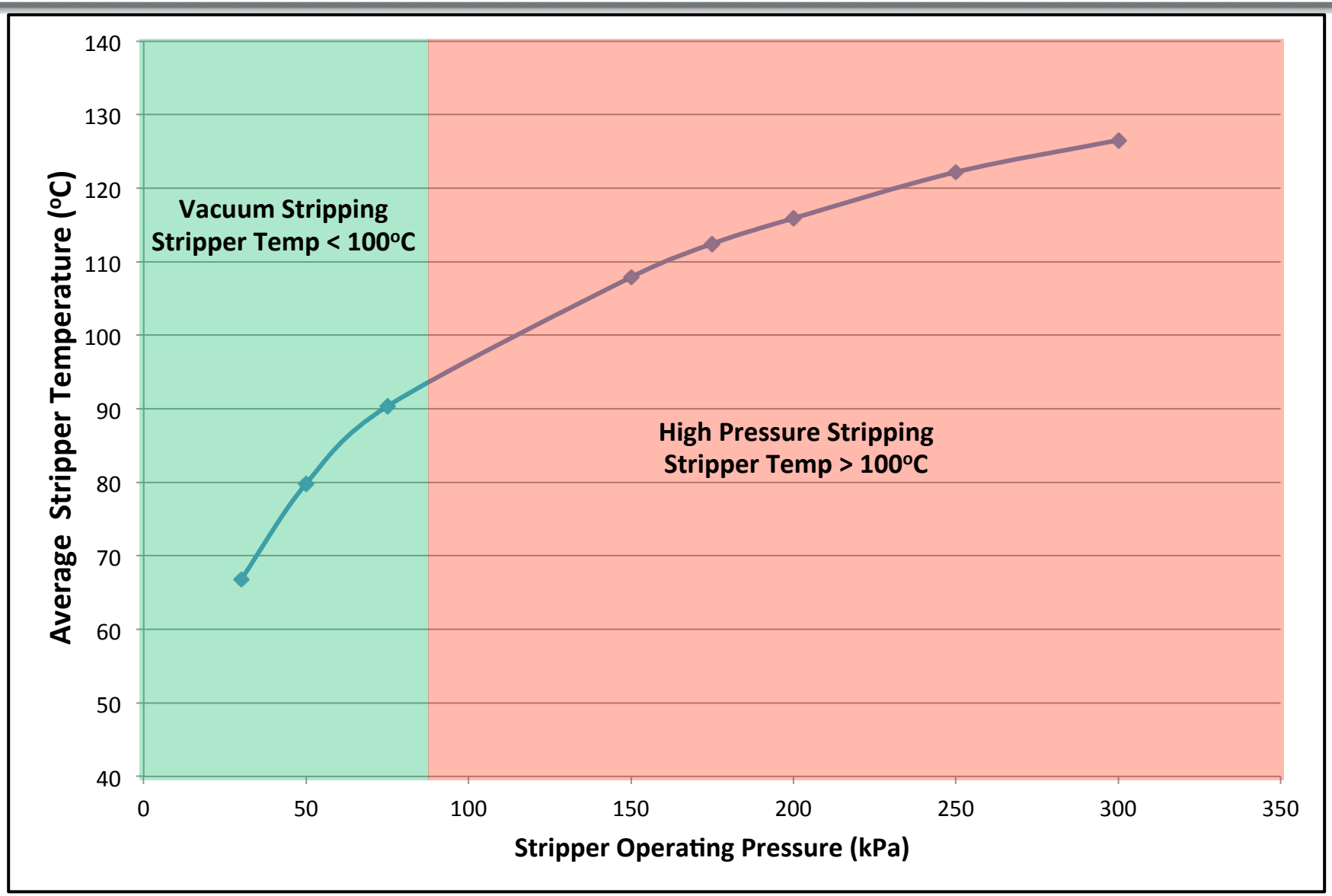


Flow-sheet used in ProMax® for amine absorption process

1) Typical 400 MW power plant
2) 90% of CO2 must be captured and compressed
3) All amines are studied at the typical concentrations that they are used at in commercial practice
4) The maximum CO2 loading of amine solutions is 0.4 moles-CO2/mole-amine

Stripper Operating Conditions

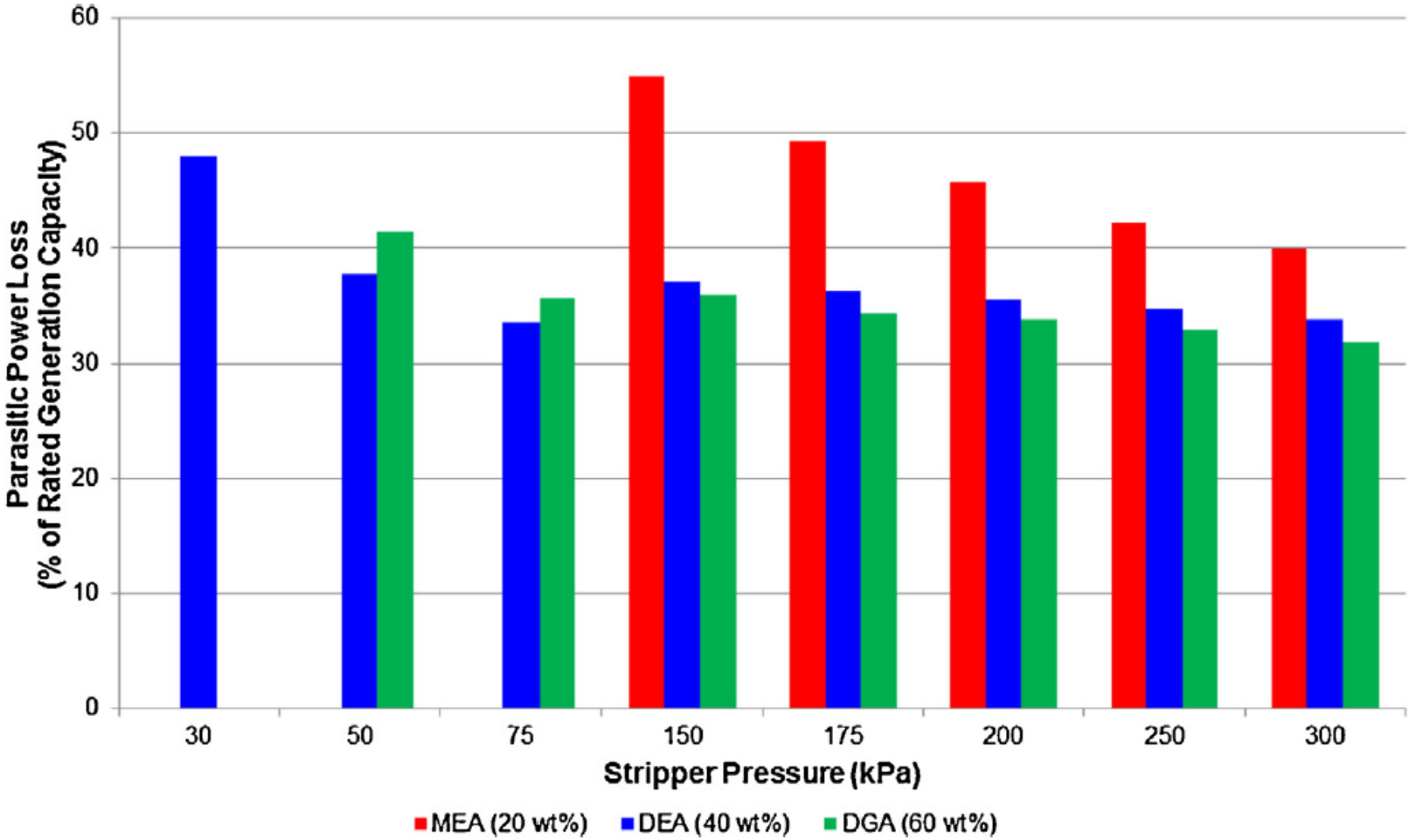
Correlation between Pressure & Temperature



Dependence of stripper operating temperature on operating pressure (DEA 40 wt%)

Parasitic Power Loss for different pressure stripper

Waste Heat Source Unavailable



Parasitic losses due to carbon capture system at reference power plant

Key milestones

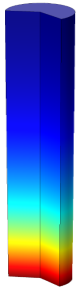
Completed

In progress

Not started

BP1:

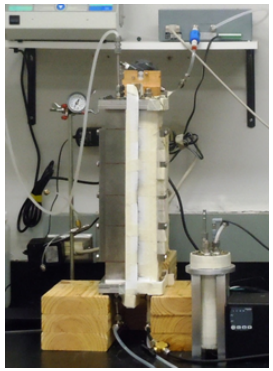
Hydrodynamic and mass transfer studies of ceramic foam



10/2011-6/2012

BP2:

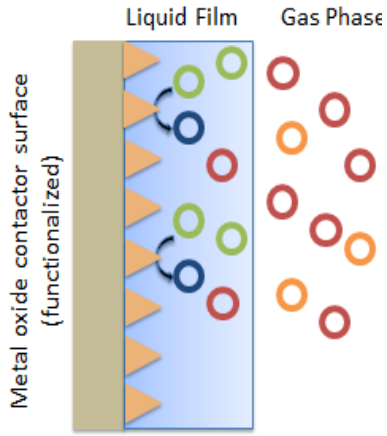
bench-scale Prototype Design and Test



6/2012-4/2013

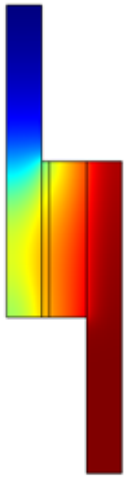
BP3:

Catalytic desorption of CO_2 using metal oxides



9/2012-12/2014

Process modeling and simulation (1D model and 2D model)



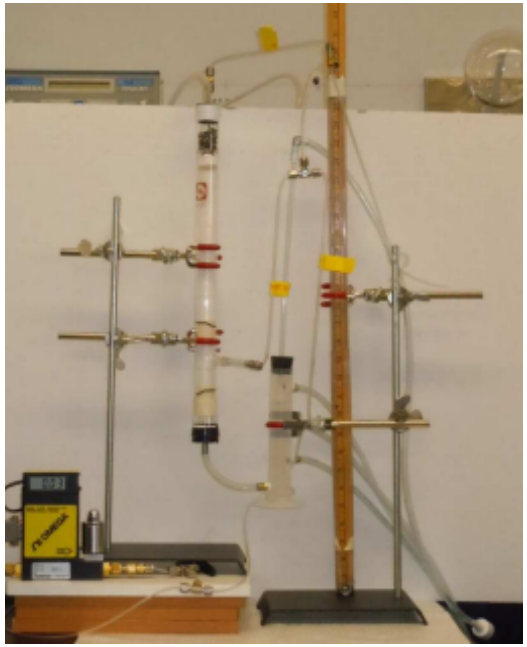
4/2014-12/2014

Technical and Economic Feasibility Study; Technology EH&S Risk Assessment

1/2015-12/2015

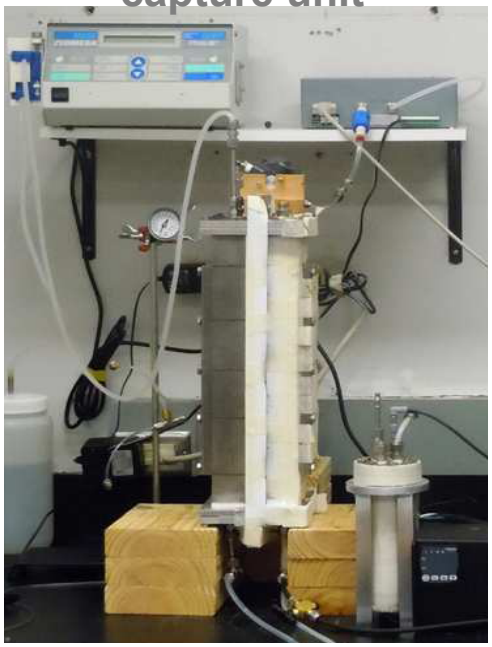
Testing Equipment Facilities

1-D ceramic foam column for CO_2 separation



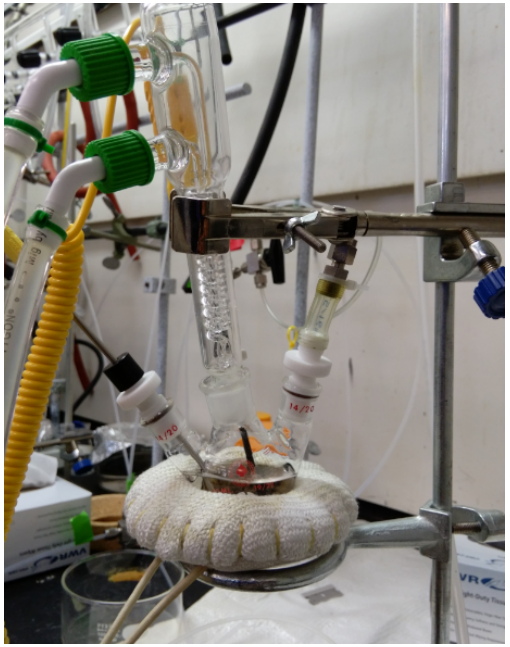
- Hydrodynamic study: flooding and pressure measurement
- To study the heat and mass transfer characteristics of the ceramic foam;
- CO_2 absorption performance in ceramic foam column;

Bench-scale combined absorber/desorber CO2 capture unit



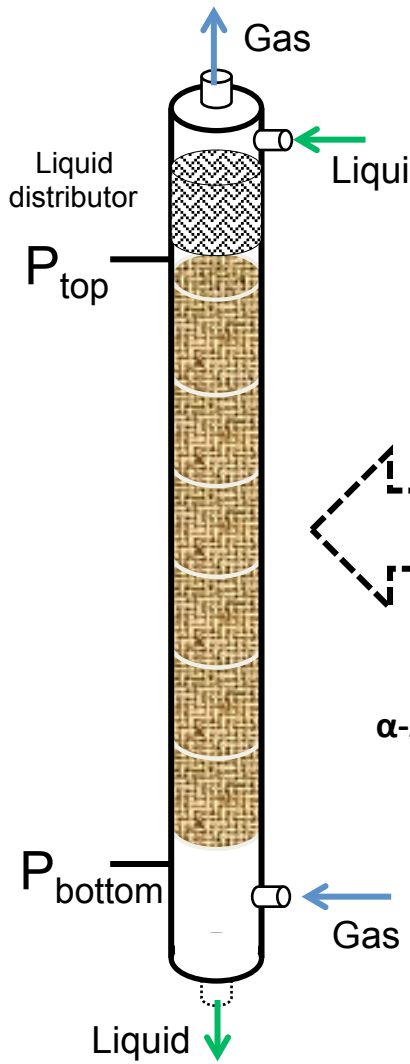
- Demonstrate the feasibility of the concept of a performing CO_2 absorption and stripping in a single integrated unit;
- Parametric and optimization studies.

Bubble reactor for catalysts screening tests



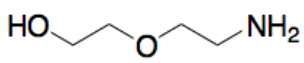
- Solid metal oxide catalysts screening test

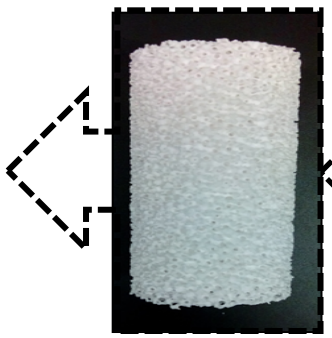
Hydrodynamic and mass transfer studies:
1D ceramic foam column



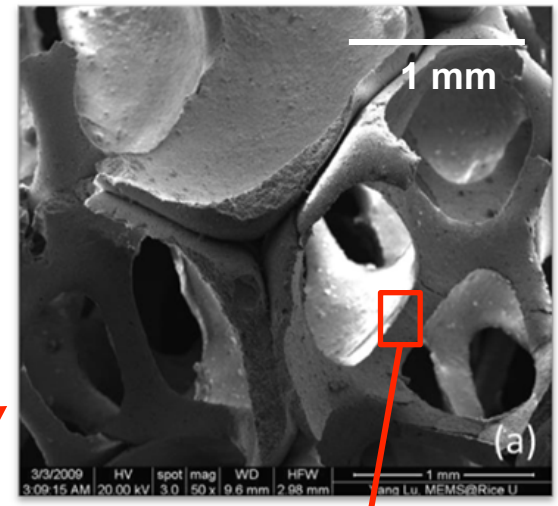
Absorbent:
Aqueous Diglycolamine (DGA) 30 wt%

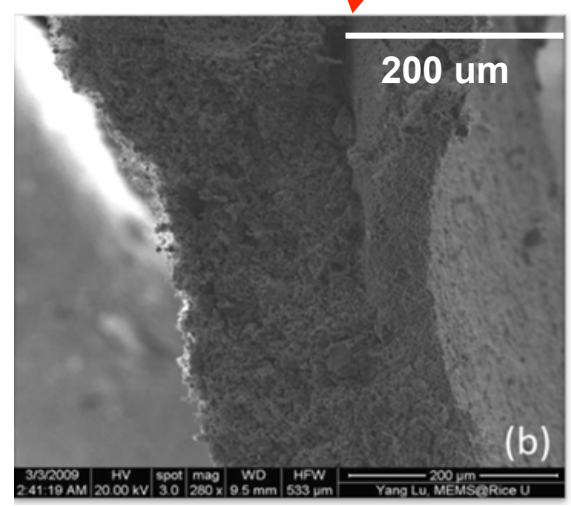
Structure:





α-Al_2O_3 ceramic foam





Scanning Electron Micrographs of Ceramic Foam : (a) 50x (b) 280x

Material Properties

Advantages of ceramic foam:

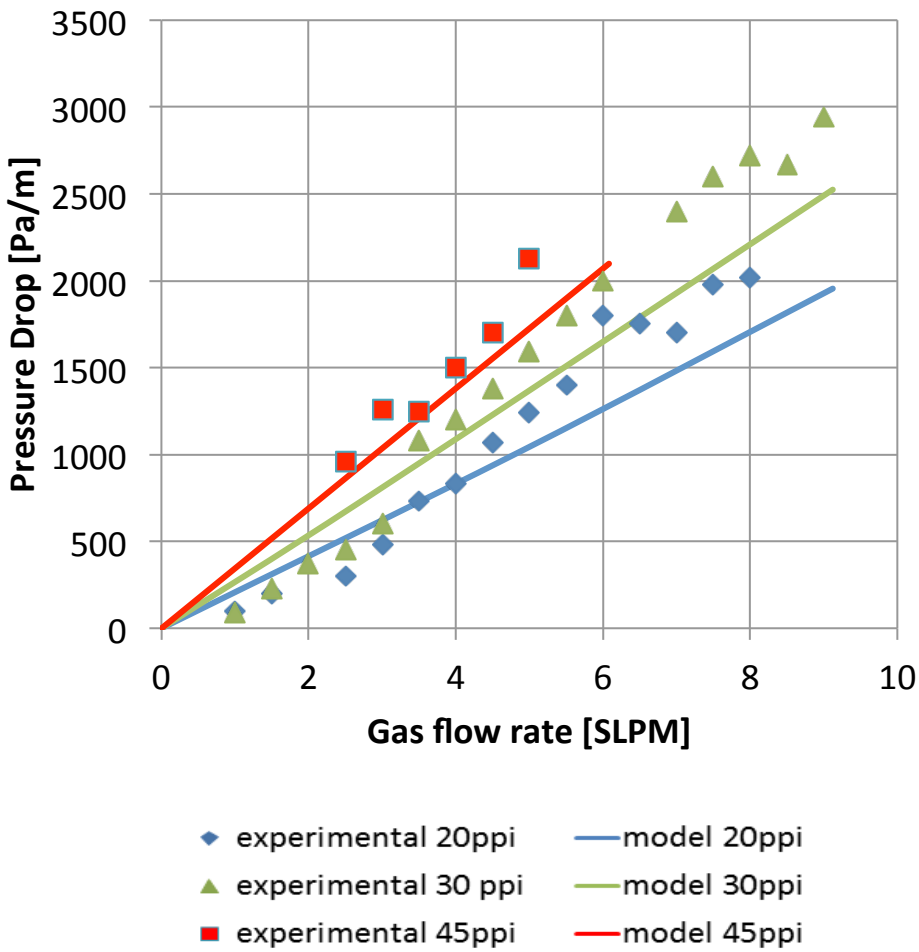
1) Low bulk density and pressure drop
2) Very high geometric surface area and macro-porosity (80%-90%)
3) Regulated pore-size and ease of reproducibility of structure
4) Low pressure drop 5)High structural uniformity

Packing Type	Structure	Porosity (%)	S (m^2/m^3)	Bulk density (g/cm^3)	Equivalent Pore diameter (mm)	Permeability[e] (m^2)
α-Al_2O_3 Ceramic Foam	20-PPI[a]	85	700[b]	0.60[d]	1.28	8.0×10^{-9}
	30-PPI	85	900[b]	0.65[d]	1.00	7.3×10^{-9}
	45-PPI	84	1400[b]	0.71[d]	0.60	6.2×10^{-9}
Random Packing[c]	Raschig Ring	62.6	239	0.58[e]	1.50	3.87×10^{-8}
	Pall Ring	94.2	232	0.48[e]	2.50	3.53×10^{-7}

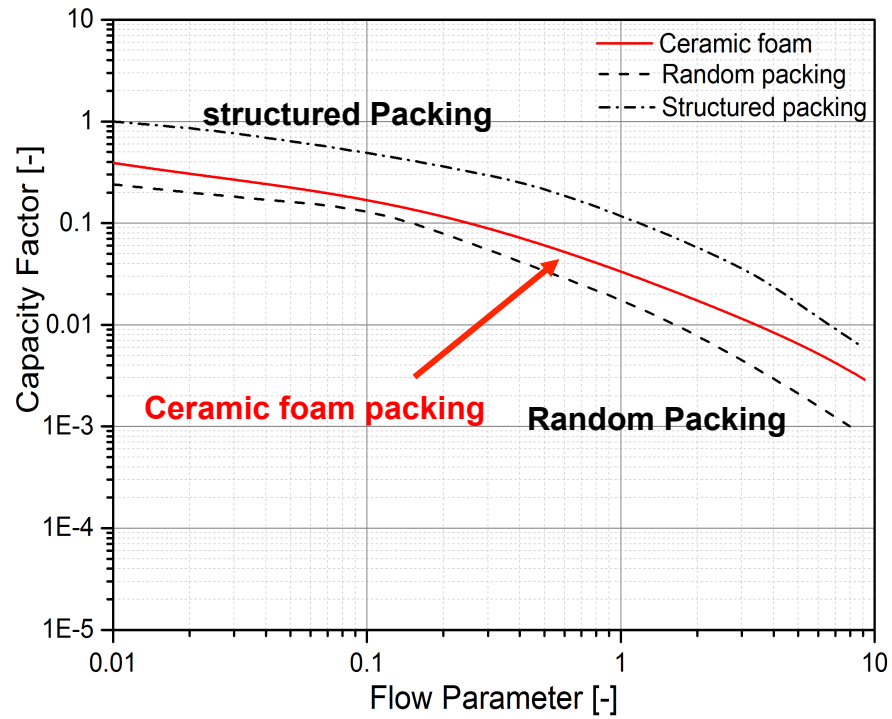
(a) PPI: Number of pores per linear inch length; (b) C.P.Stemmet,IChemE, 2006 (c) Jerzy Maćkowiak, IChemE, 2011 (d) www.**ask-chemicals**.com

(e) http://www.tower-packing.com (f) permeability of packing was calculated by $k = \frac{3\phi d_e^2}{50}$

Pressure drop and flooding:
ceramic foams



Measured and predicted pressure drop of different type ceramic foams
Packing Height: 30.5 cm; Liquid phase: water @25 °C
Gas Phase: air; Liquid flow rate 50 mL/min

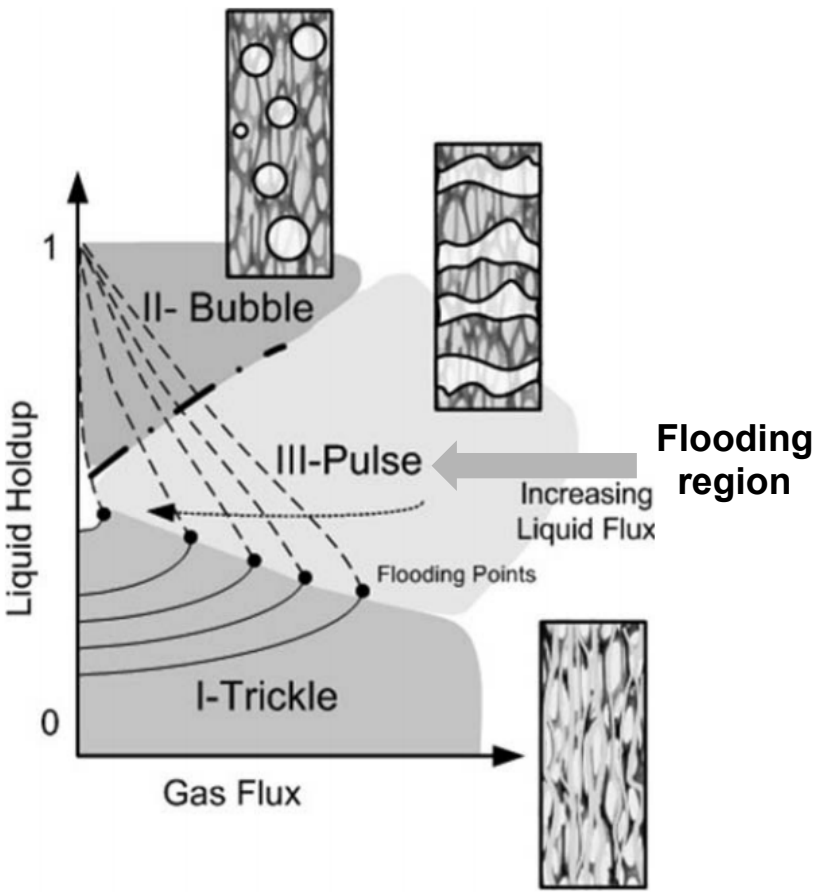


$$\text{flow parameter} = \left(\frac{L'}{G'}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$$

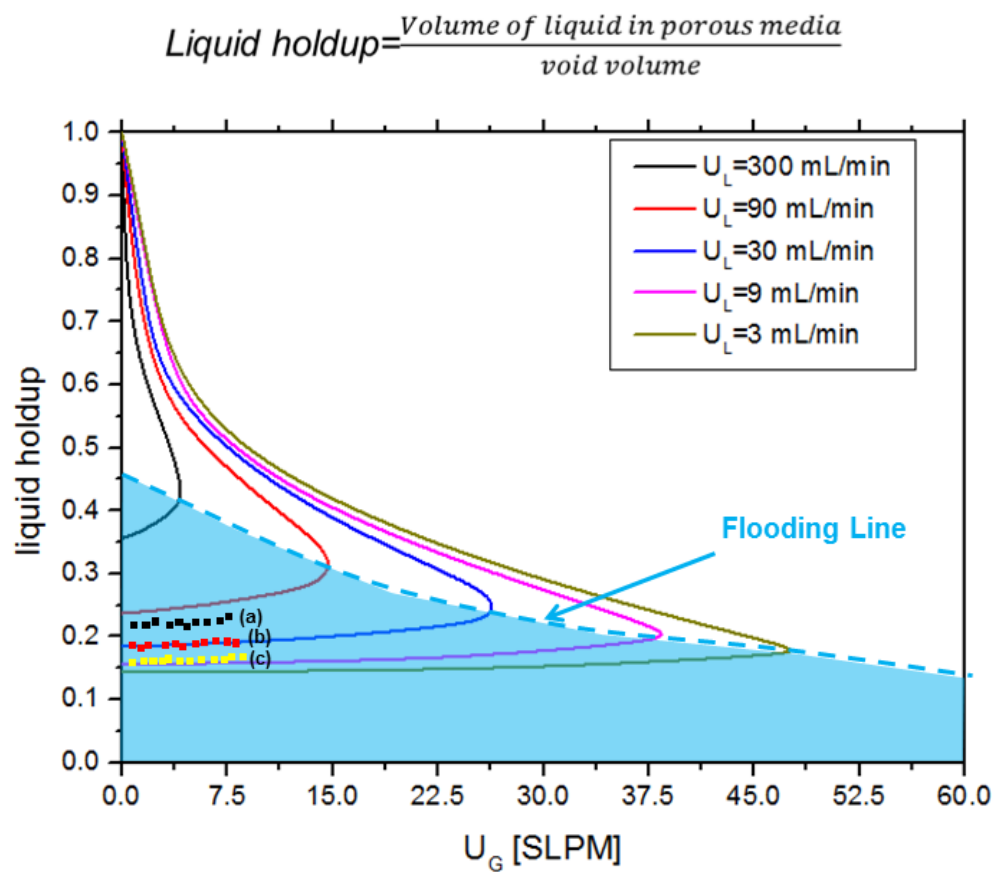
$$\text{capacity factor} = \frac{G'^2 F_P \mu_L^{0.2} \xi^2}{\rho_G \rho_L g}$$

Comparison of floodings for different packings in generalized pressure drop correlation (GPDC)chart

Flooding Point Prediction



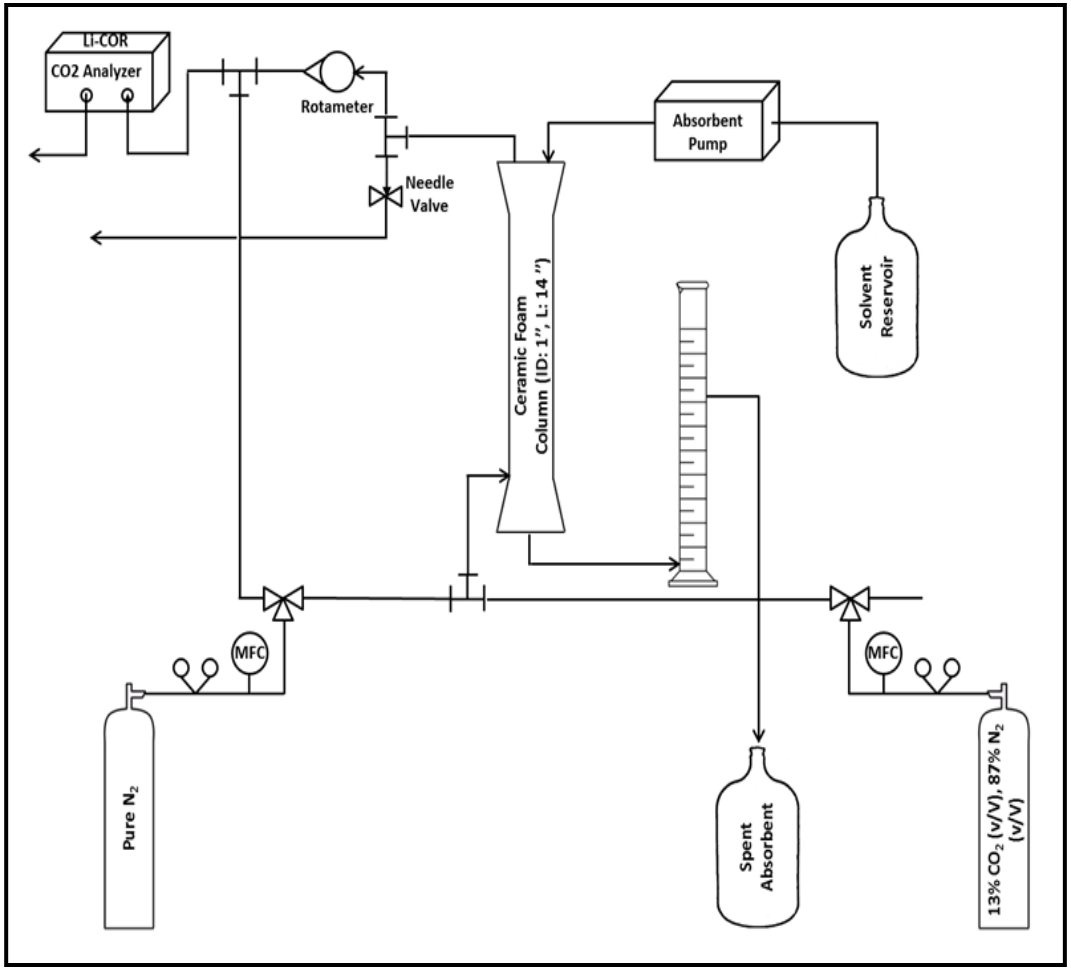
Typical flow regime for different gas and liquid Reynolds numbers. (Stemmet et al. 2005)



Figures: predicted flooding line for 20 PPI ceramic foam :

20-PPI ceramic foam; Packing Height: 30.5 cm; Liquid phase: water @25C; Gas Phase: air

CO_2 Absorption in ceramic foam column:
Experimental Setup-1D



Absorbent:
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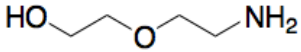
Structure:

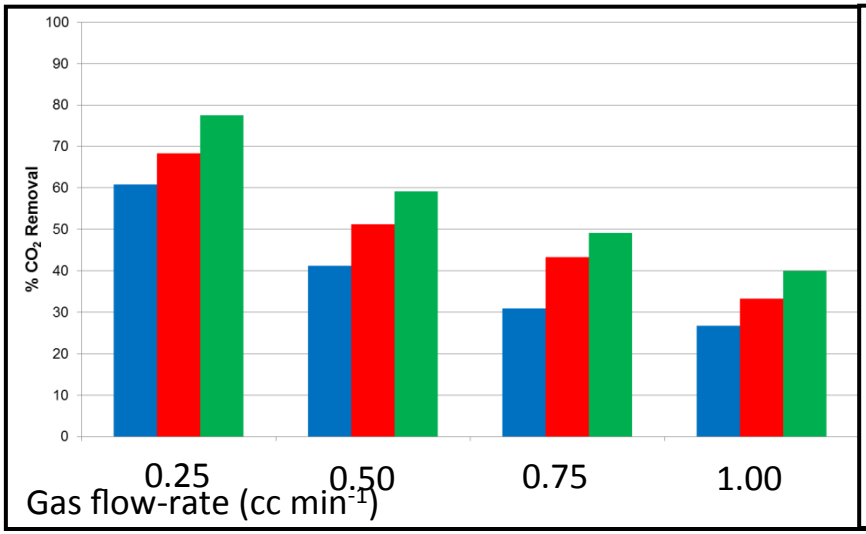


Operating conditions:
Inlet CO_2 concentration: 13 v/v%
Absorption temperature: 25 °C
Ceramic foam: 20-PPI

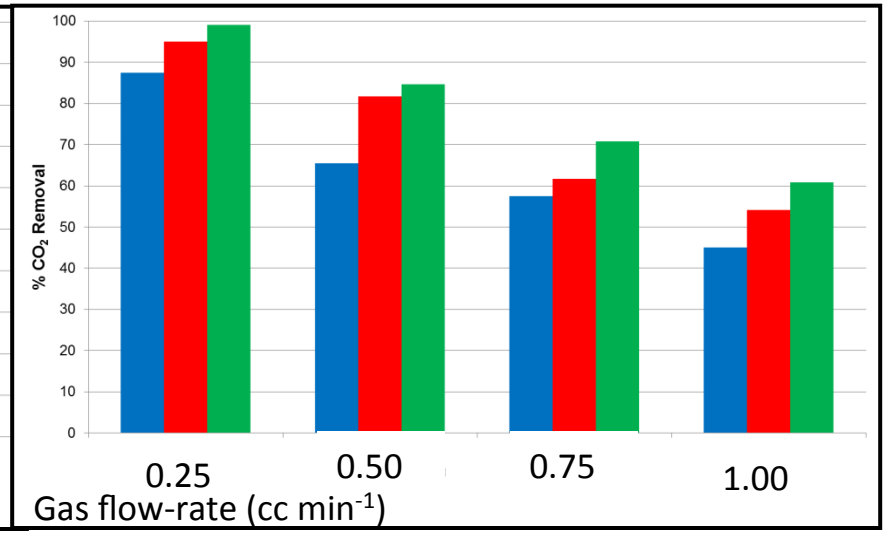
Degree of CO_2 Removal

Dependence on the Height of Ceramic Foam Packing

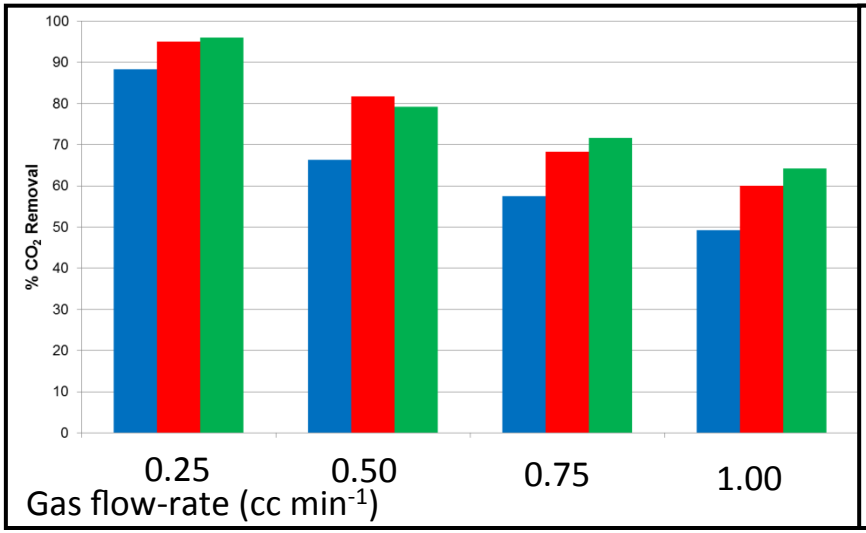
Height of ceramic foam packing: 10.1 cm



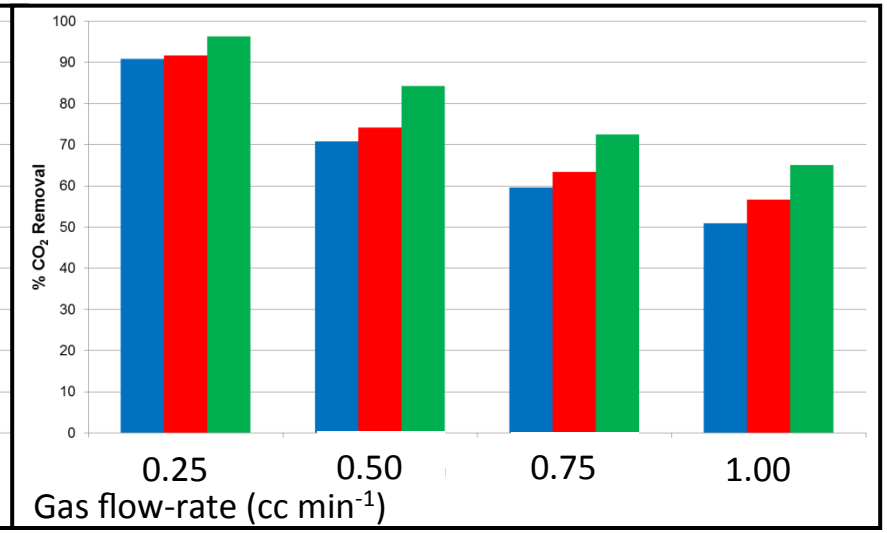
Height of ceramic foam packing: 15.2 cm



Height of ceramic foam packing: 20.3 cm



Height of ceramic foam packing: 25.4 cm



Liquid Flow:

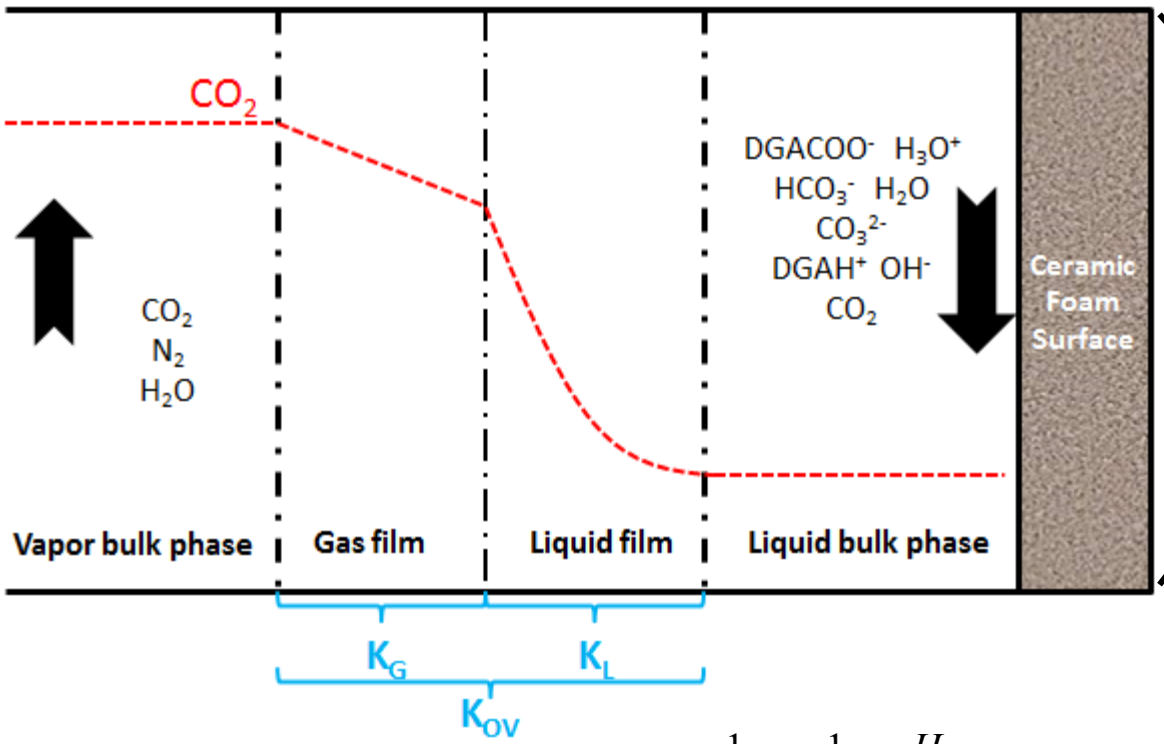
10 (cc/min)

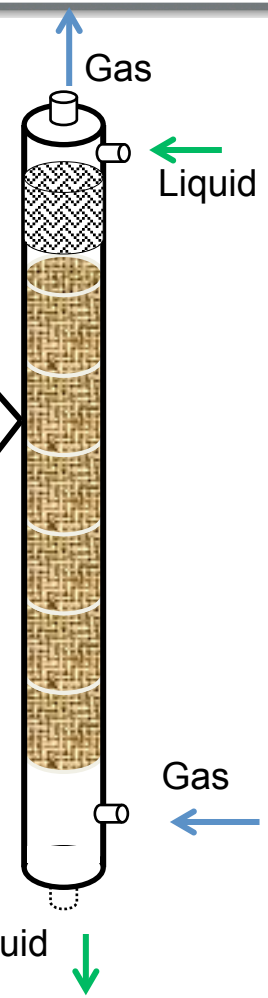
20 (cc/min)

30 (cc/min)

CO_2 absorption mass transfer model

☐ Two-film theory model





Overall mass transfer coefficient (K_{OV}) $$\frac{1}{K_{ov}} = \frac{1}{K_G} + \frac{H}{K_L}$$

Gas phase mass transfer coefficient (K_G) $$\frac{K_G de}{D_{CO_2,G}} = 0.054\left(\frac{\mu_G}{\rho_g D_{Gi}}\right)^{0.333}\left(\frac{\rho_g U_G de}{\mu_G(1-\varepsilon)}\right)^{0.8}$$ (ref.1)

Liquid phase mass transfer coefficient (K_L) $$K_L = \sqrt{1 + \frac{k_{obs} C_{DGA,L} D_{CO2,L}}{K_{L,0}^{\ 2}}}$$

1) Rocha, J. A.; Bravo, J. L.; Fair, J. R. *Ind. Eng. Chem. Res.* **1996**

CO_2 Reaction model

Main Kinetic Reactions

$$CO_2 + OH^- \rightarrow HCO_3^-$$

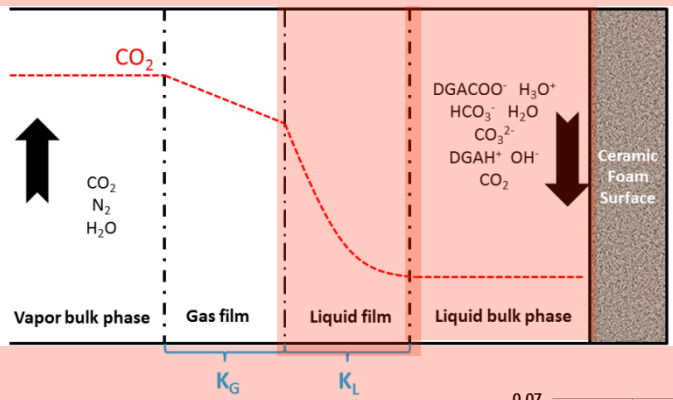
$$HCO_3^- \rightarrow CO_2 + OH^-$$

(Reaction can be ignored due to very low OH- concentration compared to DGA)

$$DGA + CO_2 + H_2O \rightarrow DGACOO^- + H_3O^+$$

$$DGACOO^- + H_3O^+ \rightarrow DGA + H_2O + CO_2$$

$$R_{CO2-DGA} = 5.98\times10^{18} e^{-\frac{66162}{RT}} [DGA][CO_2] - 2.45\times10^{31} e^{-\frac{114140}{RT}} [DGACOO^-][H_3O^+]$$



Equilibrium Reactions

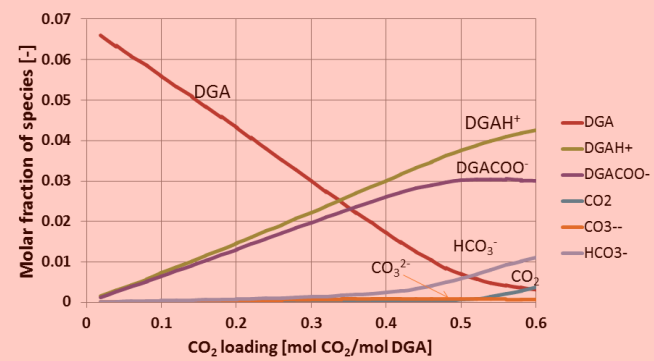
$$DGAH^+ + H_2O \leftrightarrow DGA + H_3O^+$$

$$2H_2O \leftrightarrow H_3O^+ + OH^-$$

$$CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^-$$

$$HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{-2}$$

$$DGACOO^- + H_2O \leftrightarrow DGA + HCO_3^-$$



Molar concentration of chemical species in 30 wt% DGA at 90C

1) Mohammed Al-Juaied; Gary T. Rochelle, Ind. Eng. Chem. Res. **2006;** **2)** ASPEN plus® V7.2. Burlington: Aspen Technology: **2010**

Model Equations

- **Continuity and momentum equations**

$$\nabla \cdot \rho_G U_G = 0 \quad \nabla \cdot \rho_L U_L = 0$$ Continuity equation

$$-\nabla \cdot p_G - \frac{\mu_G}{k_{rg} k} U_G + \rho_G g \nabla D = 0$$ For gas phase

$$-\nabla \cdot p_L - \frac{\mu_L}{k_{rw} k} U_L + \rho_L g \nabla D = 0$$ For liquid phase

$$P_G - P_L = P_c(S_L)$$

- **Mass Transportation equations**

$$\nabla \cdot (-D_{CO_2,G} \nabla C_{CO_2,G} + C_{CO_2,G} U_G) = -K_{ov} a_{eff} [\frac{C_{CO_2,G}}{H_i} - C_{CO_2,\mathrm{L}}]$$ CO_2 in liquid phase

$$\nabla \cdot (-D_{CO_2,\mathrm{L}} \nabla C_{CO_2,\mathrm{L}} + C_{CO_2,\mathrm{L}} U_L) = K_{ov} a_{eff} [\frac{C_{CO2,G}}{H_i} - C_{CO2,L}] - R_{CO2-DGA}$$ CO_2 in liquid phase

$$\nabla \cdot (-D_{\mathrm{DGA,L}} \nabla C_{\mathrm{DGA,L}} + C_{\mathrm{DGA,L}} U_L) = -2R_{CO2-DGA}$$ DGA in liquid phase

- **Energy equations**

$$\rho_L C_{p,L} U_L g \nabla T_L = \nabla g (\lambda_L \nabla T_L) + \mathrm{Q_L}$$ For liquid phase

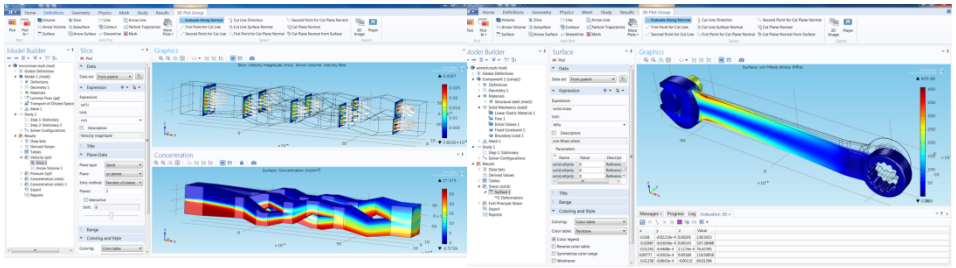
$$\rho_G C_{p,\mathrm{G}} U_G g \nabla T_G = \nabla g (\lambda_G \nabla T_G) + \mathrm{Q_G}$$ For gas phase

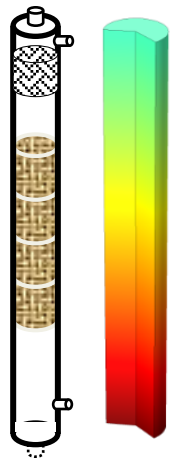
$$0 = \nabla g (\lambda_{eq} \nabla T_S) + \mathrm{Q_S}$$ For solid ceramic foam

COMSOL Multiphysics®

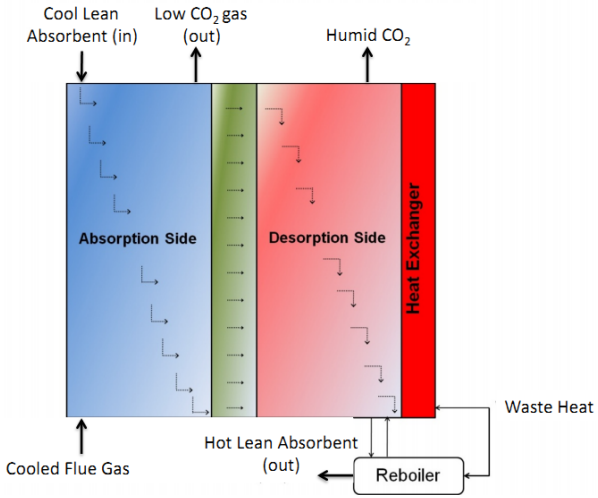
- Chemical Species Transport
  - Surface Reactions (chsr)
  - Transport of Diluted Species (chds)
  - Transport of Concentrated Species (chcs)
  - Nernst-Planck Equations (chnp)
  - Solute Transport (esst)
  - Species Transport in Porous Media (chpm)
  - Reaction Engineering (re)
  - Reacting Flow
  - Reacting Flow in Porous Media
- Fluid Flow
  - Single-Phase Flow
    - Laminar Flow (spf)
  - Porous Media and Subsurface Flow
    - Brinkman Equations (br)
    - Darcy's Law (dl)
    - Free and Porous Media Flow (fp)
- Heat Transfer
  - Heat Transfer in Solids (ht)
  - Heat Transfer in Fluids (ht)
  - Heat Transfer in Porous Media (ht)
  - Electromagnetic Heating
    - Joule Heating (jh)

- COMSOL Multiphysics® is a general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems.





1-D model

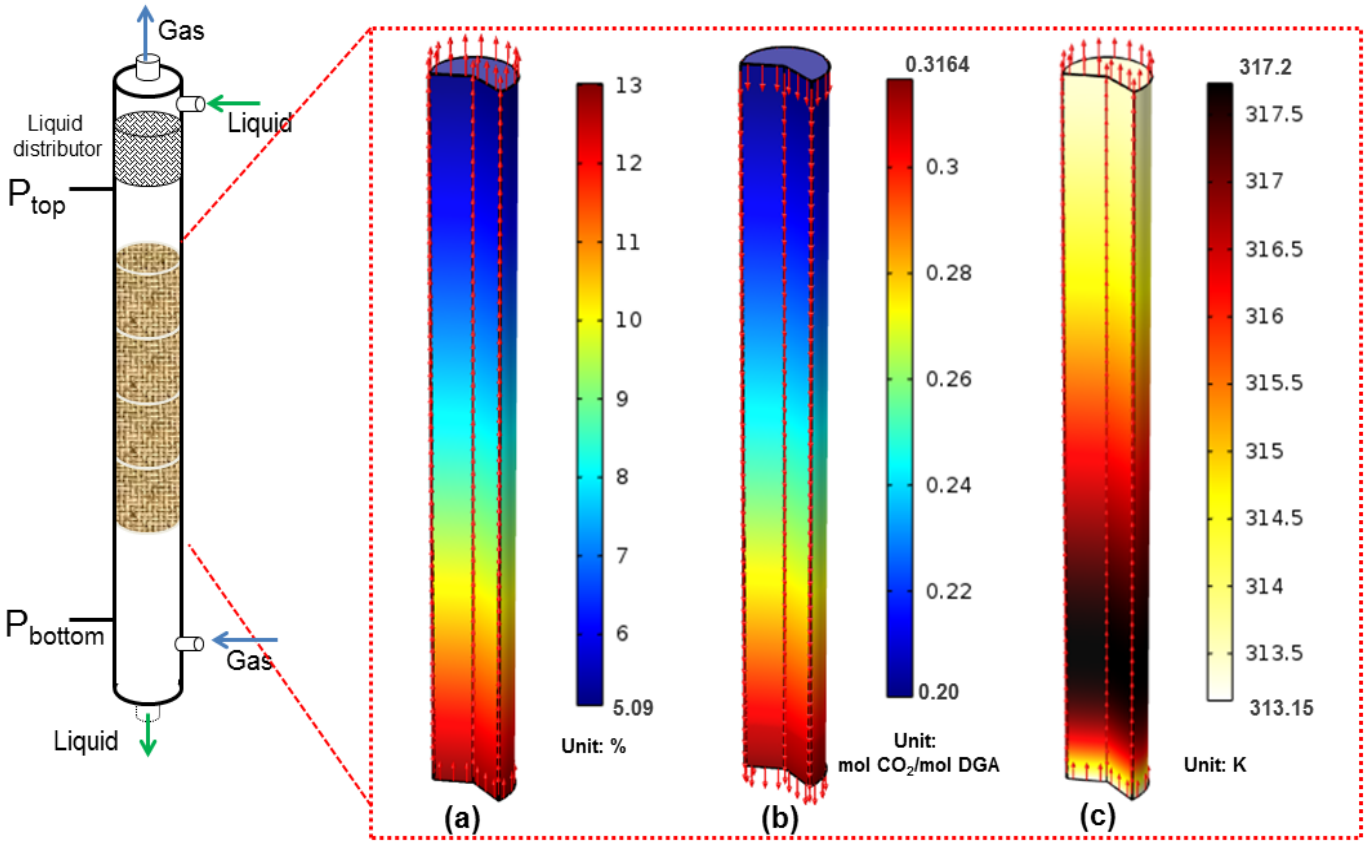


2-D model

1-D model:

Simulation of CO2 separation in ceramic foam column

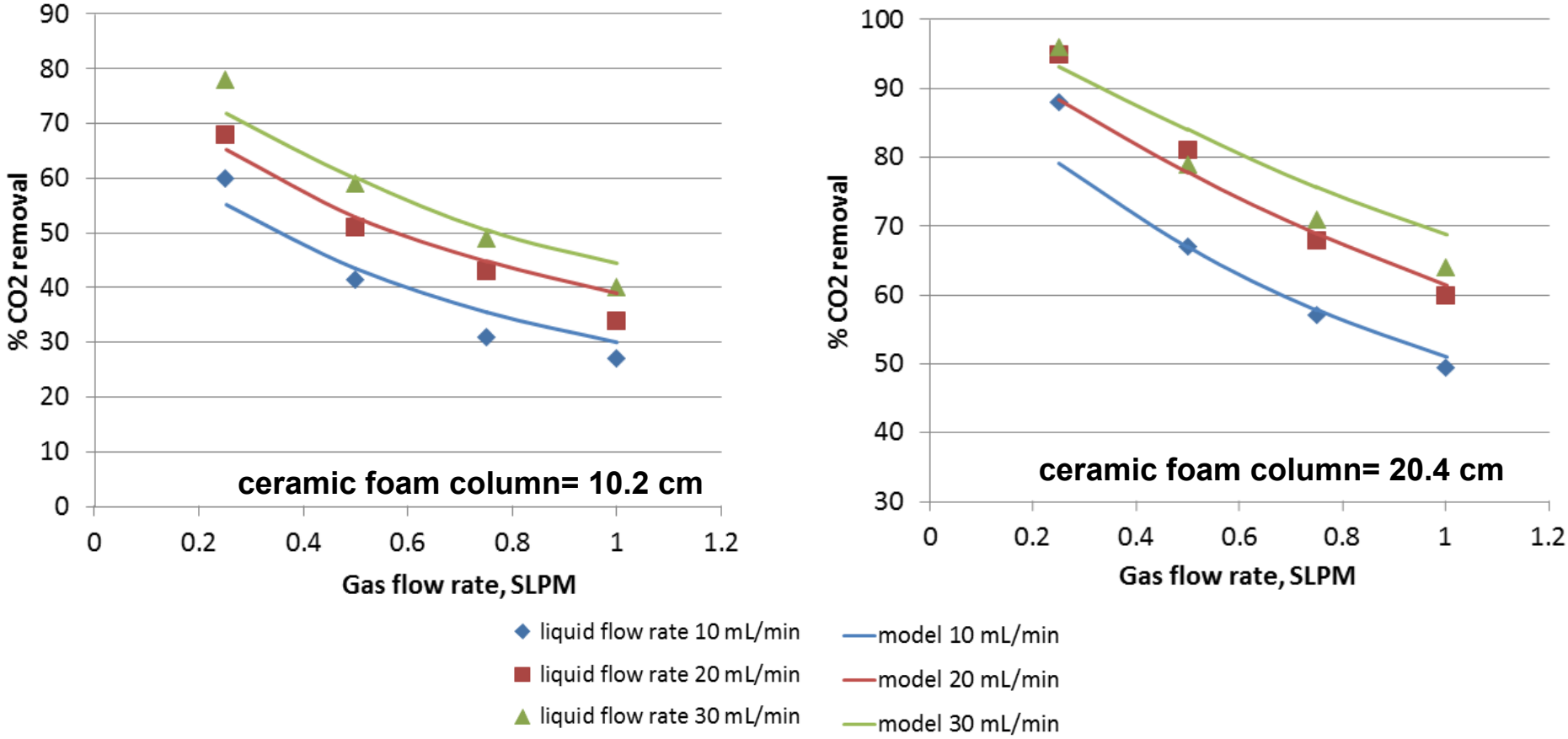
Representation of simulated CO_2 concentration, CO_2 loading and temperature distribution along column



ceramic foam height: 25.4 cm; ceramic foam type: 20 PPI; gas flow velocity: 0.01 m/s; liquid flow velocity: 0.01 cm/s; liquid phase: 30% DGA sovlent; gas phase: 13% CO_2/87% N_2; absorption temperature: 40°C; lean loading: 0.2 mol CO_2/mol DGA

Experimental and Simulated CO_2 Removal Ratio

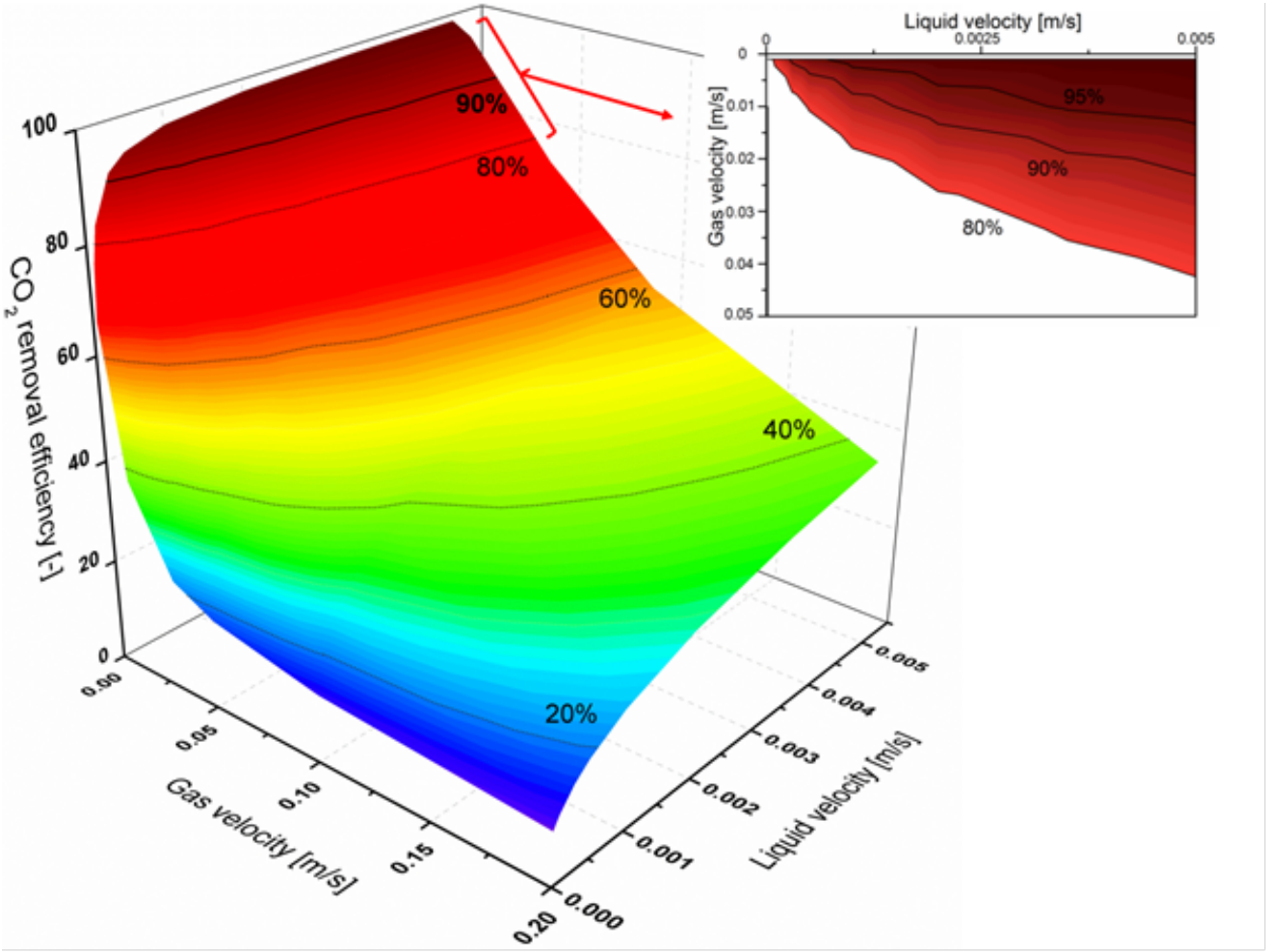
(ceramic foam column= 10.2 cm & 20.4 cm)



Experimental vs Modelling

Liquid phase: 30% DGA, Gas phase: 13% CO_2/87% N_2; Temperature: 25 ℃

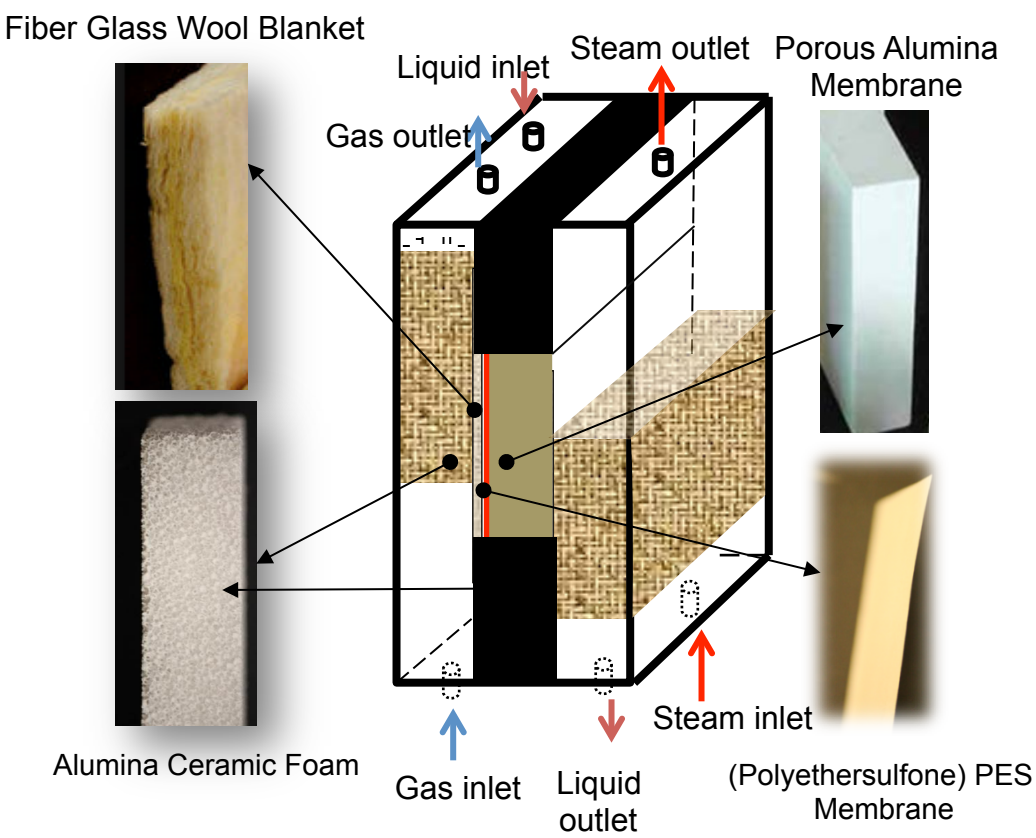
Simulated CO_2 removal efficiencies as the function of liquid velocity and gas velocity



(Inset: gas and liquid velocities yielding >80 % CO_2 removal efficiency)

Operating conditions: ceramic foam height: 25.4 cm; ceramic foam type: 20 PPI; liquid phase: 30% DGA solvent; gas phase: 13% CO_2/87% N_2; absorption temperature: 40°C; lean loading: 0.2 mol CO_2/mol DGA.

Technical Approach



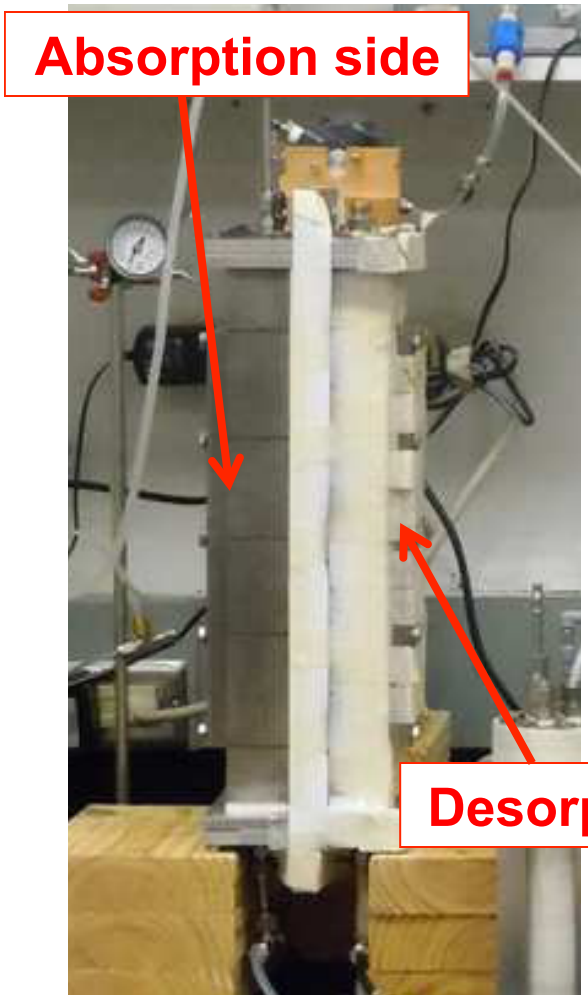
Key point:

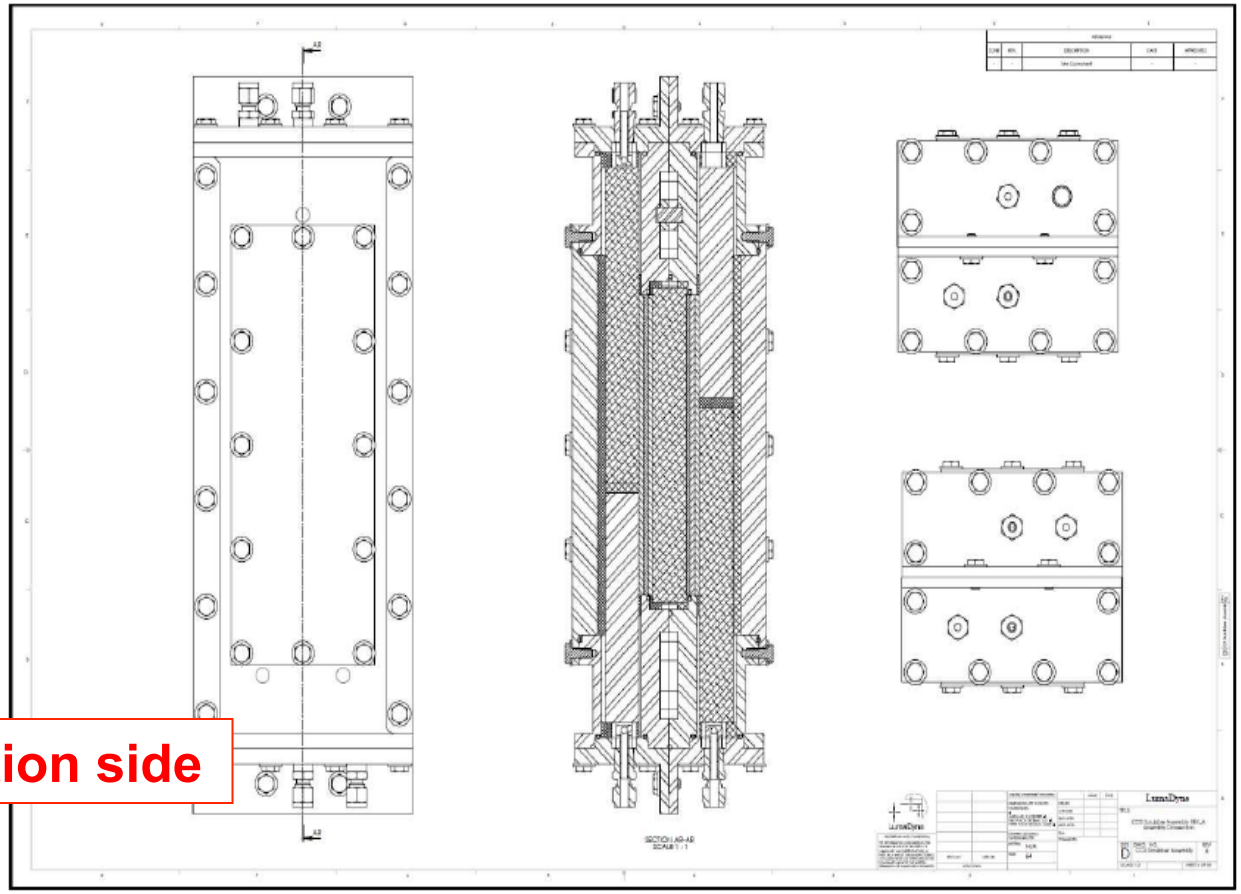
- ***Hydrophilic membrane (capillarity)***
- ***Ceramic foam packing***
- ***Pressure control in each side***

Advantages:

- ***Reduction of space requirement and capital cost*** *due to integration of absorber and desorber sections into a single unit;*
- ***Favorable characteristics for mass transfer*** *because ceramic foam gas-liquid contactors have large geometric surface areas;*
- ***Cost saving and less energy requirement*** *due to catalytic low-temperature desorption:*
  - *Metal oxide catalyzes the desorption of CO_2*
  - *Moderate vacuum helps desorption to be carried out at reduced temperatures*

Stainless steel prototype of Integrated CO_2 Absorber and Desorber Unit



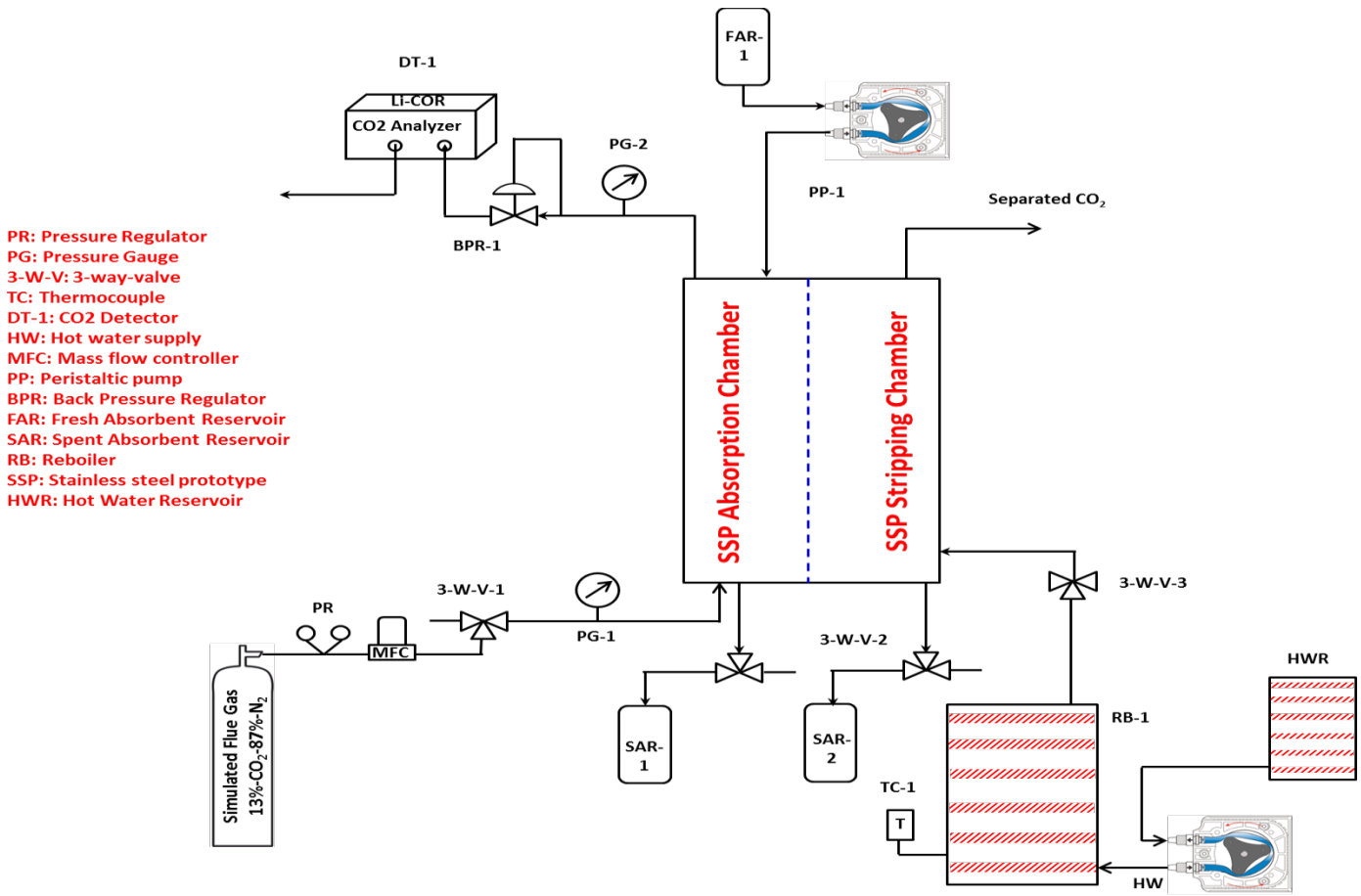


Experimental setup developed for the proof-of-concept demonstration

Material Properties of alumina membrane and polymer (PES) membrane

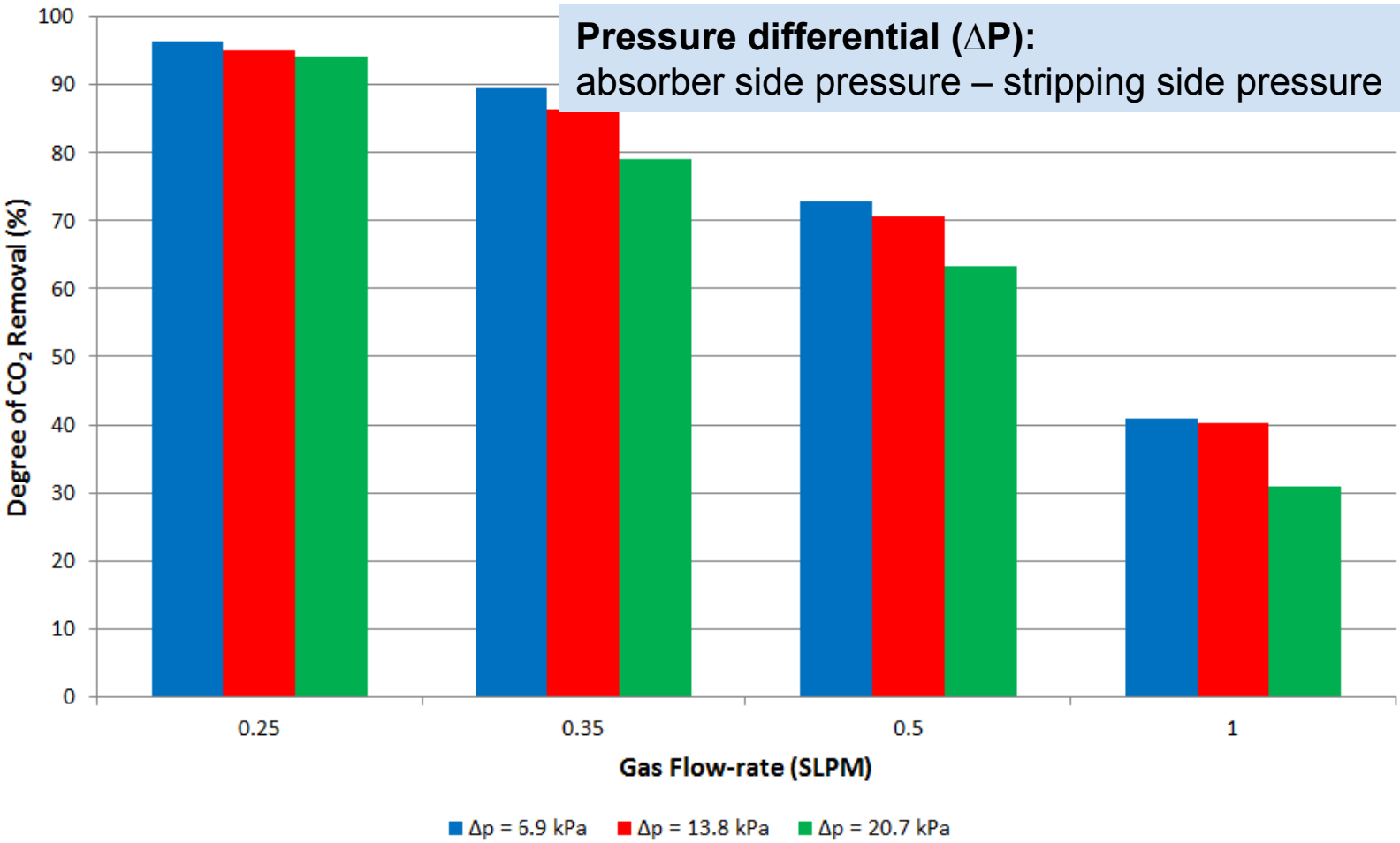
Porous Alumina Membrane	
Material	99.5 % (α-Al_2O_3)
Supplier	Refractron Inc., USA
Dimensions	12'' x 6 '' x 1''
Mean pore-size	19.3 um
Permeability & Gas Entry Pressure	5.37 x 10^{-12} m^2| 0.8 psi (with water)
Gas-Liquid Separator Polymer Membrane	
Material	Polyethersulfone (Hydrophilic)
Supplier	Pall LifeSciences Corporation, USA
Dimensions	8'' x 8''
Mean pore-size	0.8 um
Permeability & Gas Entry Pressure	0.32–1.52 10^{-12} m^2 | 15-31 psi (with water)

Experimental setup developed for the proof-of-concept demonstration



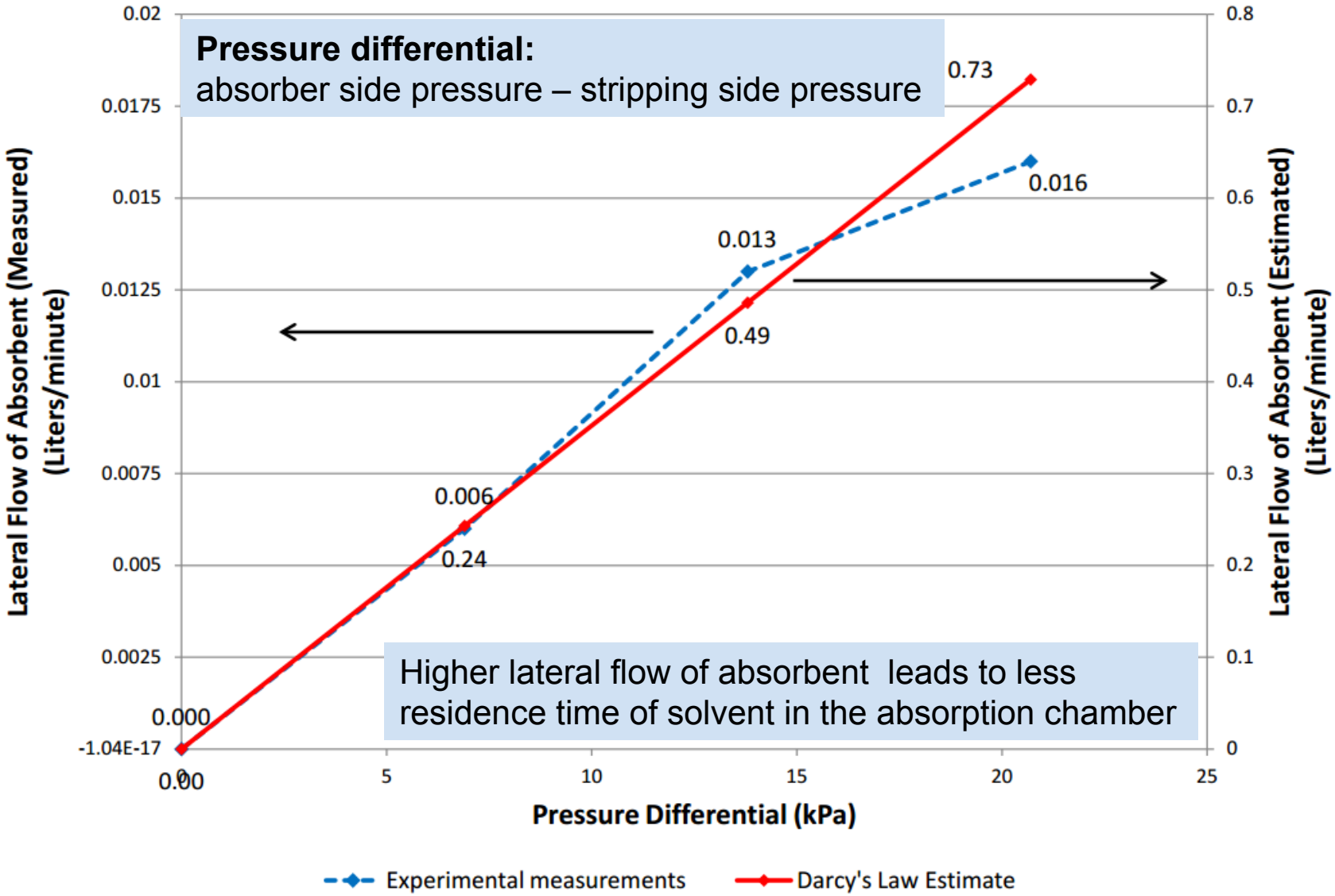
Schematic representation of the experimental setup developed for the proof-of-concept demonstration

Combined Absorber and Stripper System:
Degree of CO_2 Removal

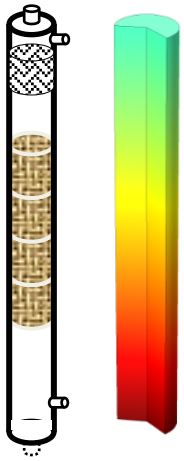


Degree of CO_2 removal at variable gas flow-rates and absorbent flow-rate of 0.01 liters per minute (LPM), (DGA solvent)

Combined Absorber and Stripper System:
Lateral Flow of Absorbent

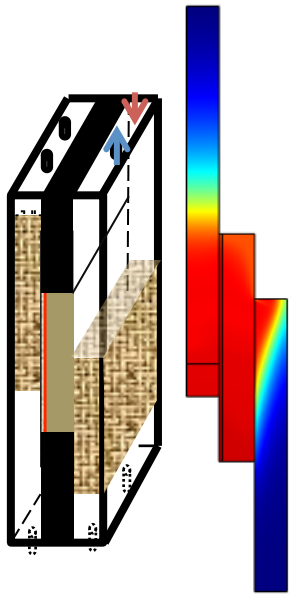


Modelling of CO_2 capture in integrated ceramic foam reactor



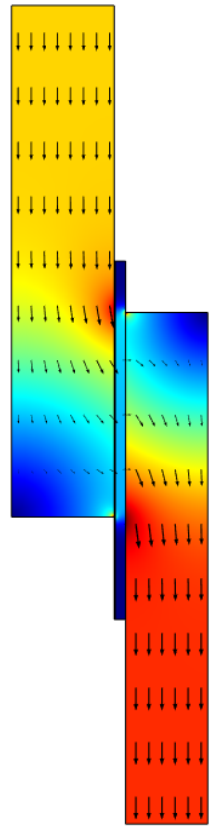
1-D model

■Pressure drop, flooding prediction
■CO_2 absorption performance prediction and validation



2-D model: Large-Scale
Size (abs): 120 cm x 10 cm

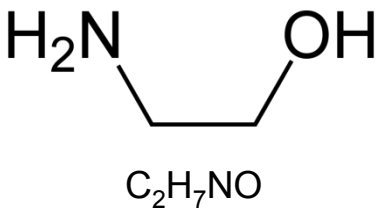
■Parametric and optimization studies (operating & geometric parameters)
■ Optimum process and geometric specifications determined

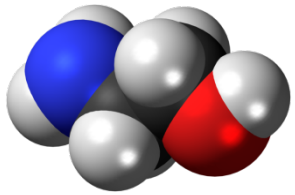


2-D model: Commercial-Scale
Size (abs): 5 m x 1m

2D model-Parametric study

- A parametric study of the technical performance based on 30wt.% monoethanolamine(MEA) studied by simulation



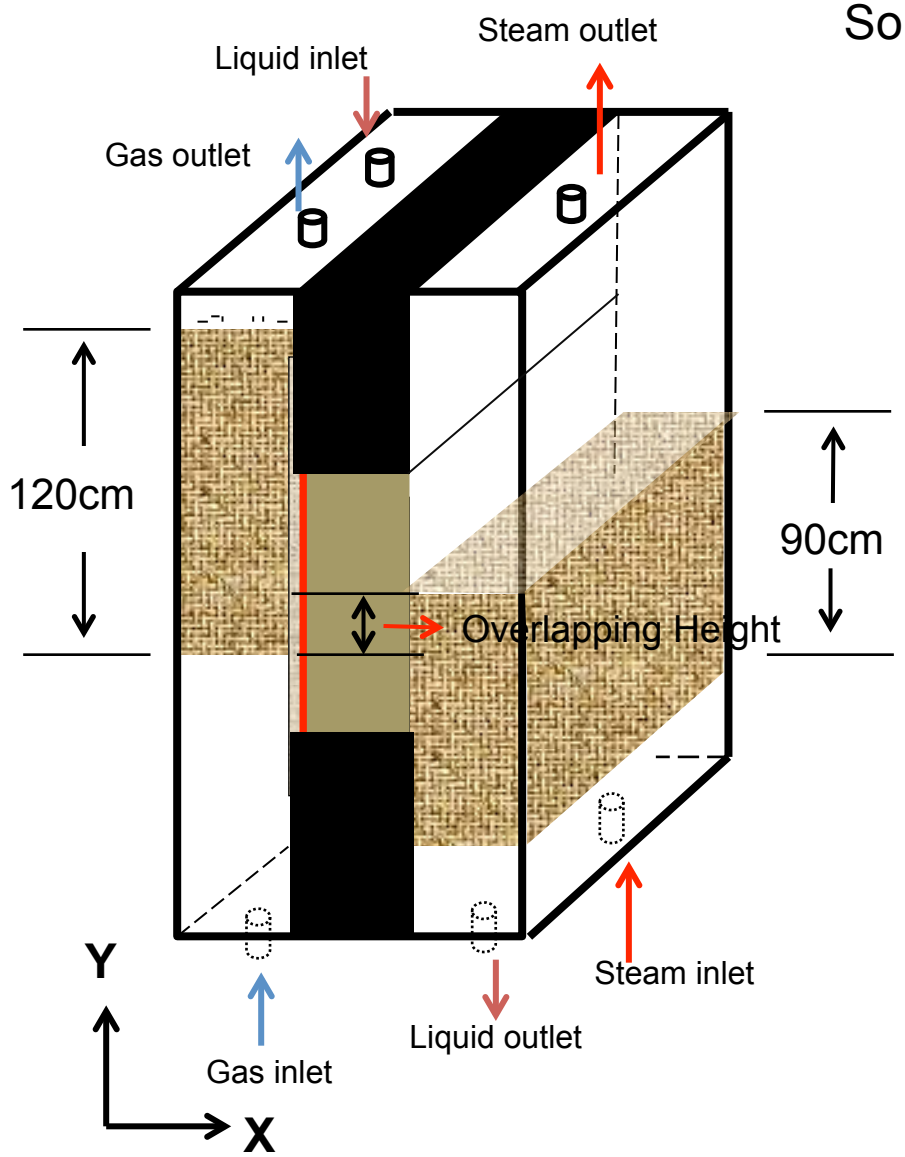


- Most common used absorbent for acid gas scrubbing;
- Suggested as base case absorbent by DOE

- Starting from the baseline case, the process operating and geometric parameters will be varied as an initial step towards an optimization of the process.

- Two performance indicators were used to investigate the effect of the parameters:
  - CO_2 removal efficiency in absorber (target is 90%)
  - The thermal energy required in the stripper(MJ energy/ton CO_2 removed)

2-D model: Baseline case for parametric study



Some key parameters for absorber/striper size and operating condition in this model

Operating conditions:

Liquid: 30 wt% MEA
Gas: 13% CO_2/87% N_2
Gas flow inlet velocity: 0.1 m/s
G/L ratio:200
Gas and liquid inlet temperature: 25 C
CO_2 lean loading: 0.27 mol CO2/mol MEA
Stripping temperature: 373 K

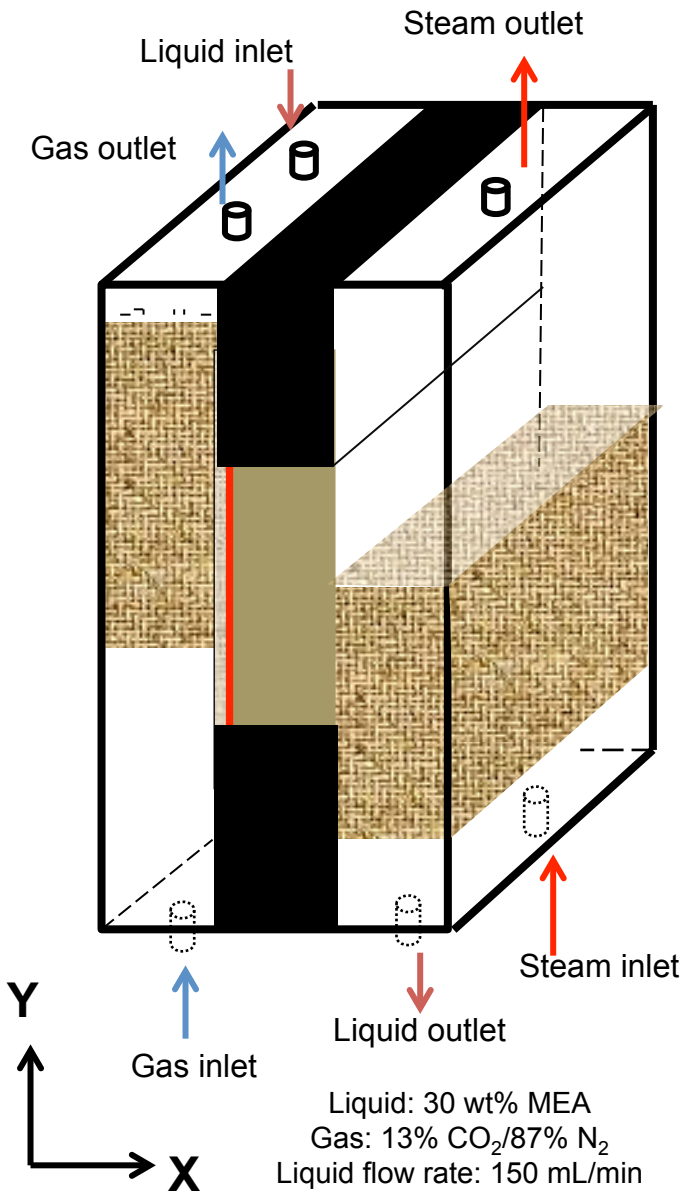
Geometric parameters:

Absorber Height: 120 cm
Absorber width: 10 cm
Membrane width: 10 cm
Stripper Height: 90 cm
Absorber/stripper overlapping Height:30 cm

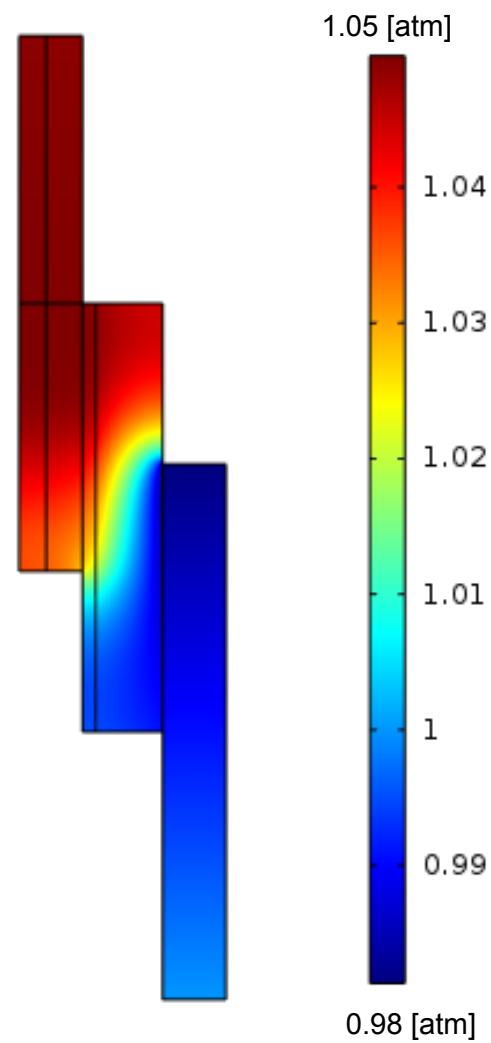
2D model-Parametric study

- **The main process operating parameters include :**
  - Gas flow rate to Liquid flow rate ratio (G/L)
    - G/L ratio changed from 100 to 300.
  - The CO_2 lean solvent loading (mol CO_2/mol MEA)
    - (0.17, 0.22, 0.27, 0.31)
  - Stripper operating temperature
    - (80 C, 90 C, 100 C, 110 C, 120 C)
- **The main geometric parameters include:**
  - Size of stripper section(140 cm×20 cm, 130 cm×14 cm, 90 cm×10 cm, 80 cm×8 cm, 70 cm×6 cm);
  - Membrane section thickness (2.5 cm, 5 cm, 7.5 cm, and 10 cm);
  - Absorber/stripper overlapping height (20 cm, 30 cm, 50 cm, 70 cm, 100 cm and 120 cm)

2D modeling - pressure profiles

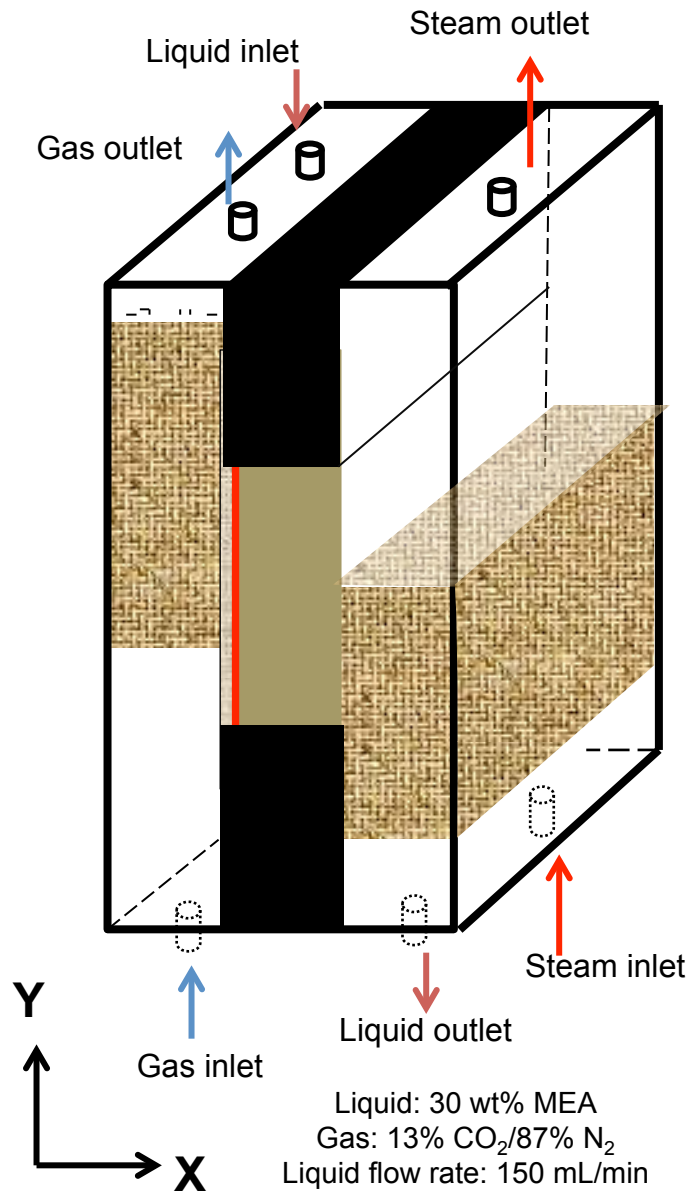


Liquid: 30 wt% MEA
Gas: 13% CO_2/87% N_2
Liquid flow rate: 150 mL/min
Gas flow rate: 15 SLPM

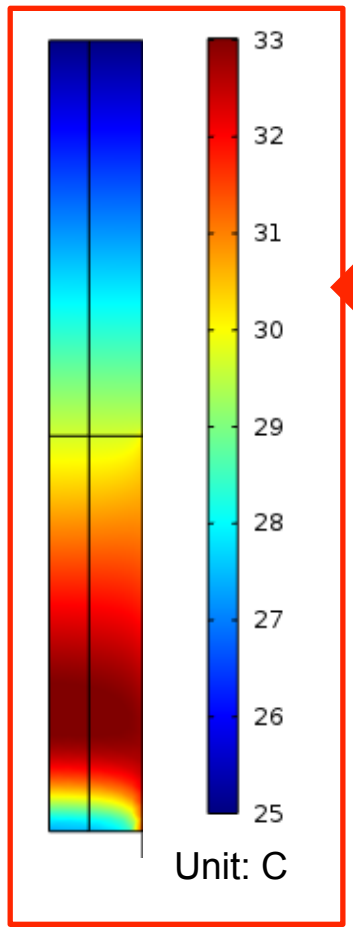


Liquid phase pressure profile

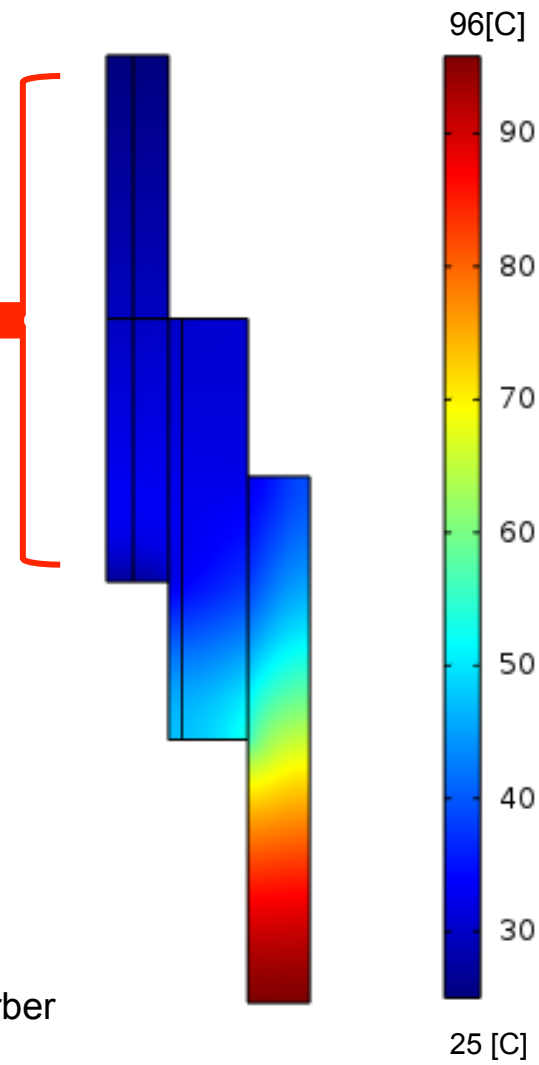
2D modeling - temperature profiles



Liquid: 30 wt% MEA
Gas: 13% CO_2/87% N_2
Liquid flow rate: 150 mL/min
Gas flow rate: 15 SLPM

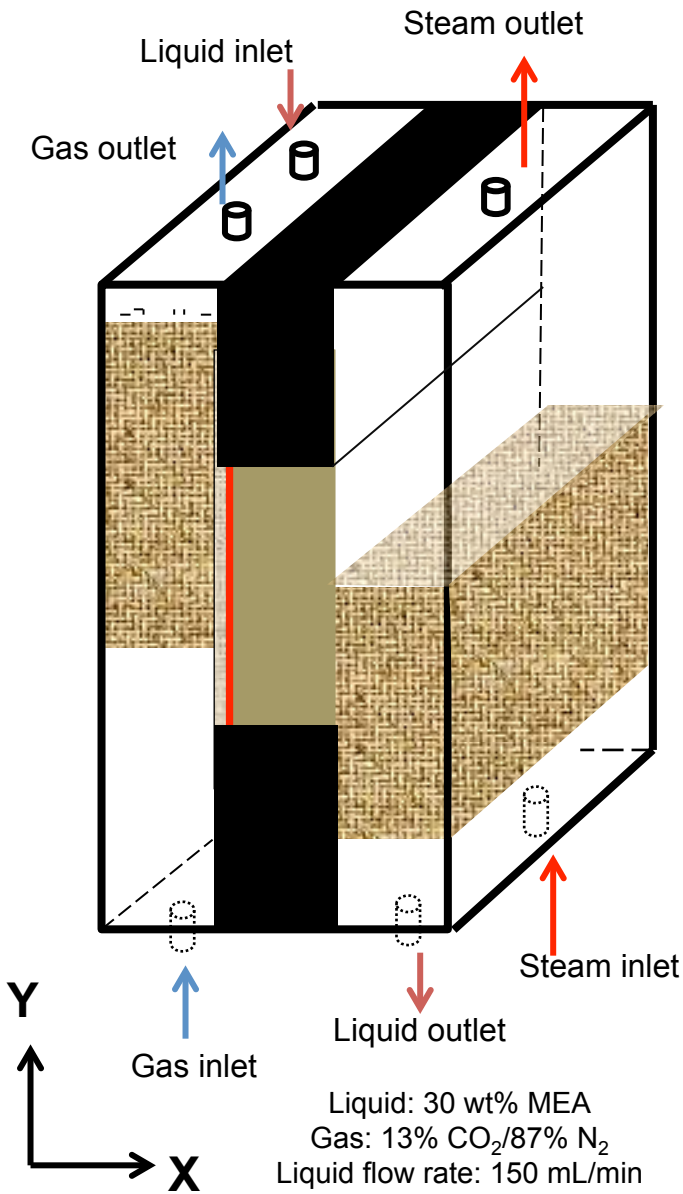


Temperature profile of absorber (liquid phase)

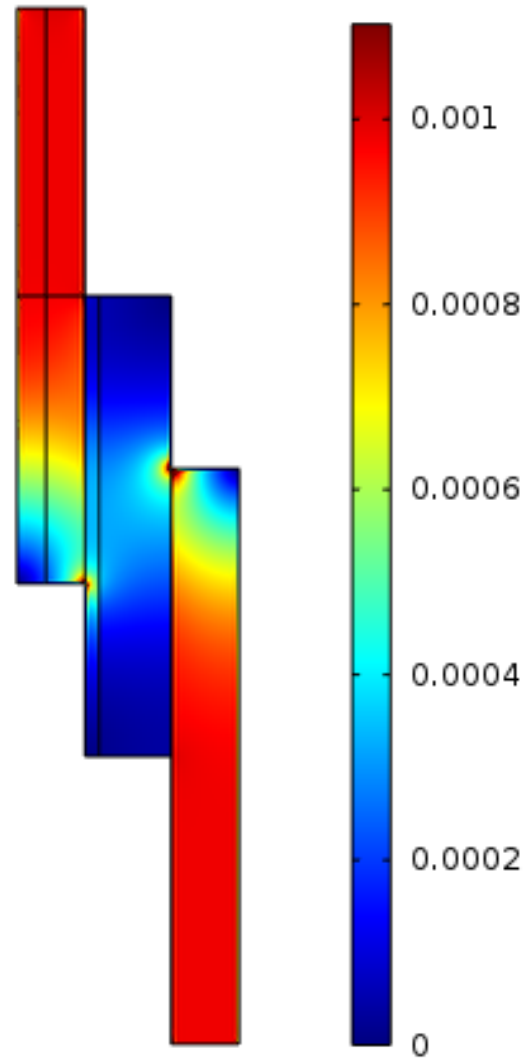


Temperature profile (liquid phase)

2D modeling – velocity profiles



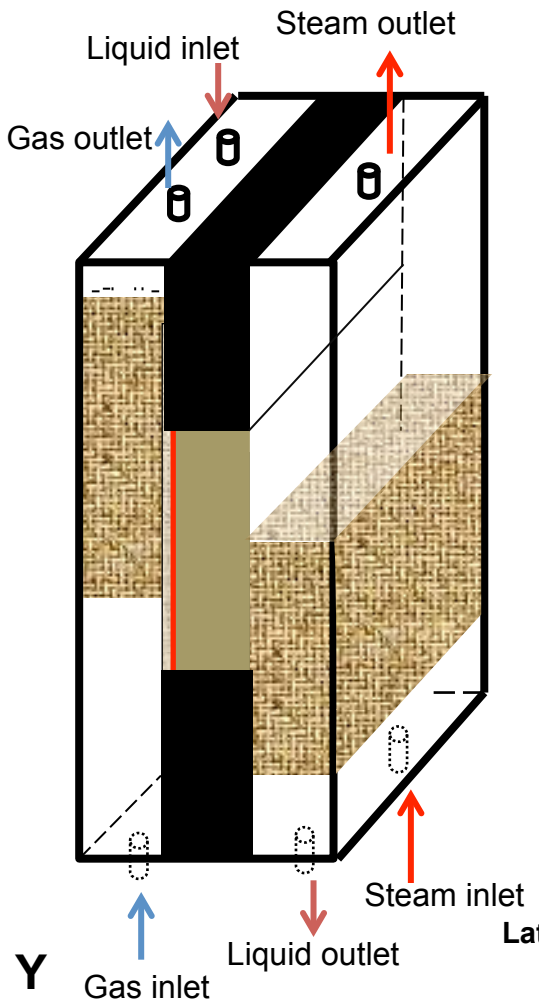
Liquid: 30 wt% MEA
Gas: 13% CO_2/87% N_2
Liquid flow rate: 150 mL/min
Gas flow rate: 15 SLPM

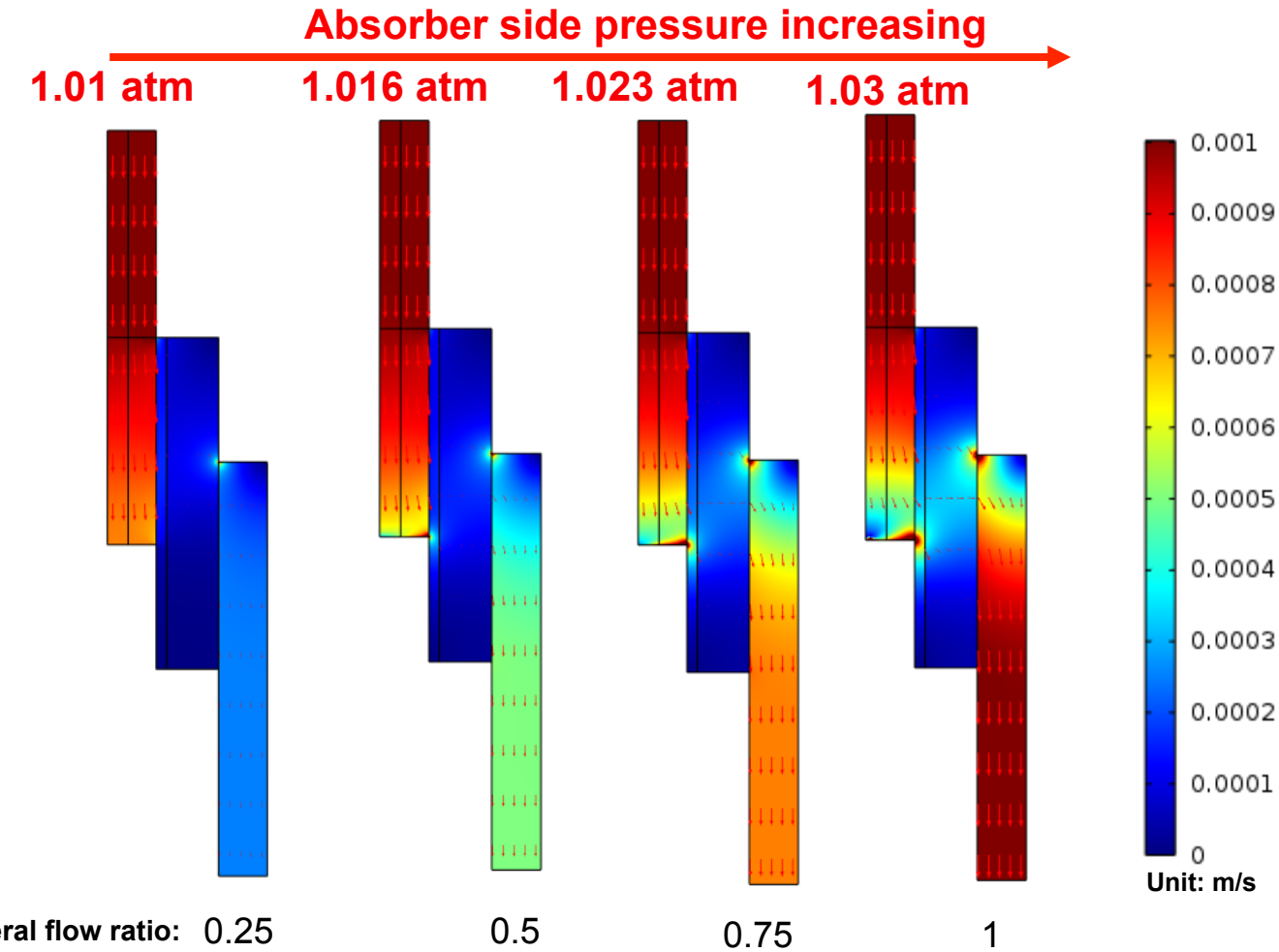


Unit: m/s

Liquid phase velocity magnitude [m/s]

2D model： Liquid velocity profile with increasing absorber sider pressure





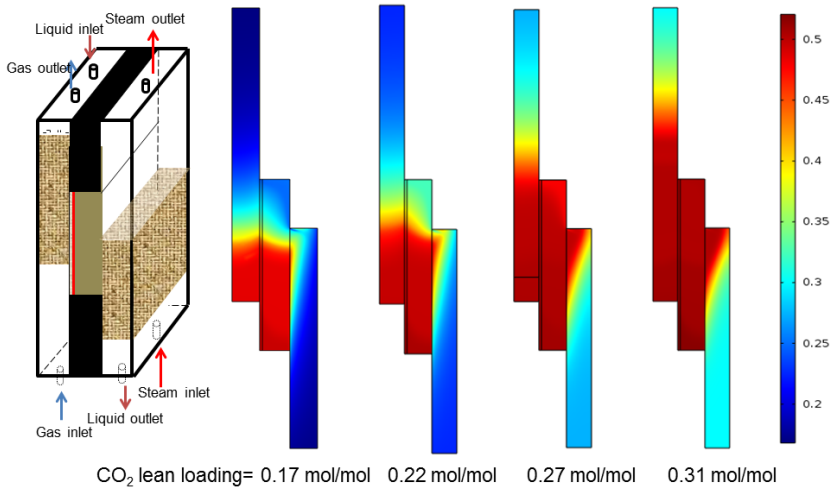
Change of lateral flow ratio and liquid velocity profile with increasing absorber sider pressure

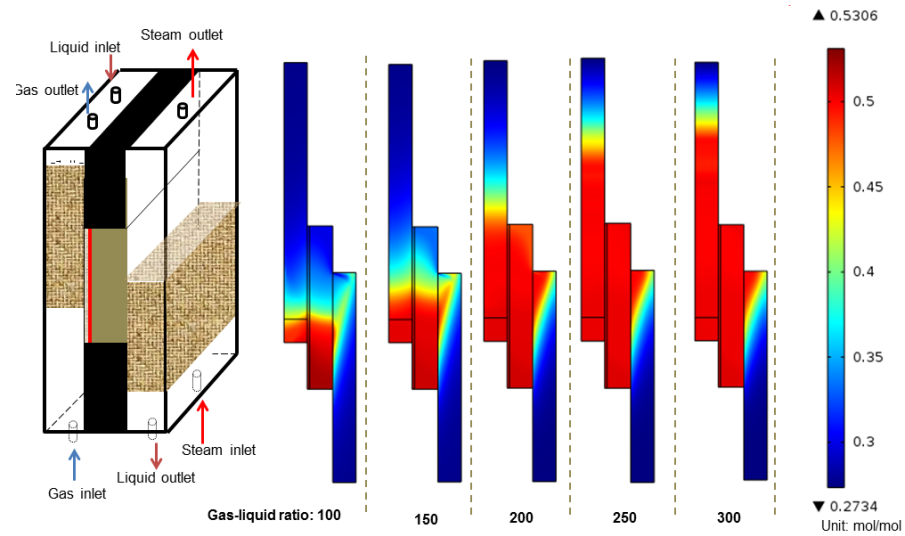
Liquid: water
Gas: air
Liquid flow rate: 1E-3 m/s
Gas flow rate: 0.1m/s

$$\text{Lateral flow ratio} = \frac{\text{Lateral flow rate}}{\text{Total flow rate}}$$

2-D model for combined abs/des system:

Process optimization and parametric study





- **The main process operating parameters include:**
  - Gas flow rate to Liquid flow rate ratio (G/L)

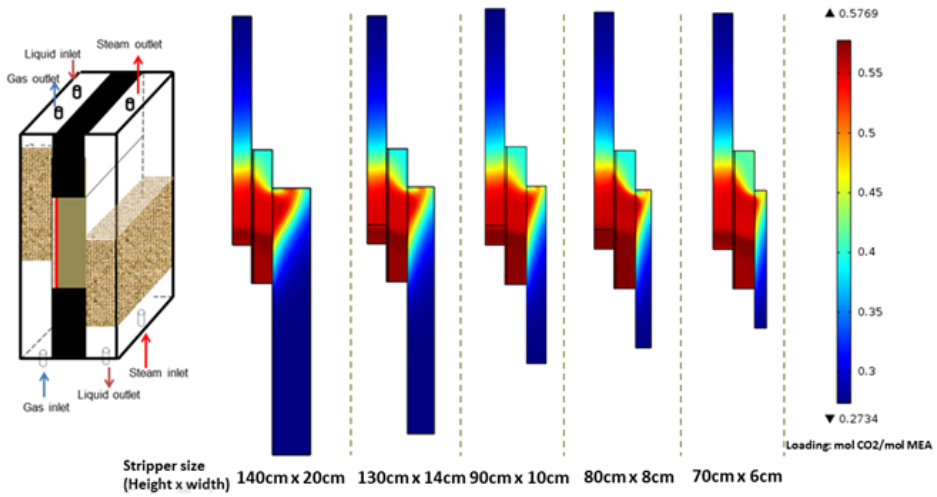
    G/L ratio of 200 was recommended to be operated due to minimal regeneration heat consumption.
  - The CO_2 lean solvent loading (mol CO_2/mol MEA)

    The solvent CO_2 lean loading of 0.27 mol CO_2/mol MEA was recommended.
  - Stripper operating temperature

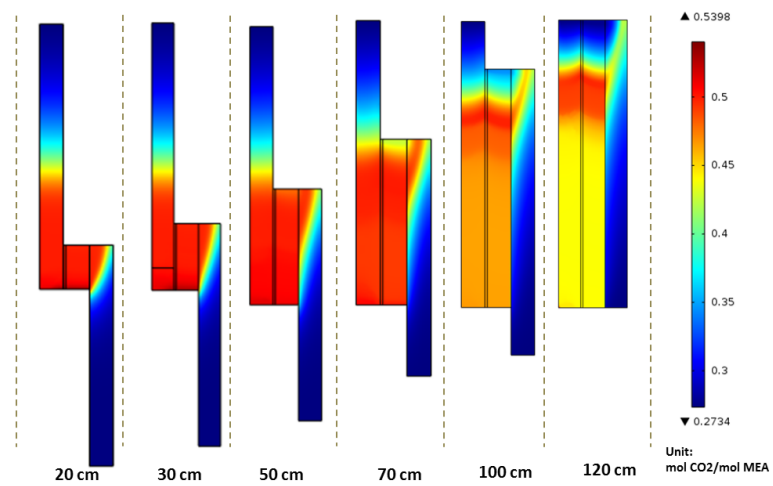
    The lowest regeneration heat consumption is found as stripping temperature was 100 C

2-D model for combined abs/des system:

Configuration optimization and parametric study



Simulated CO_2 loading profile with stripper chamber size

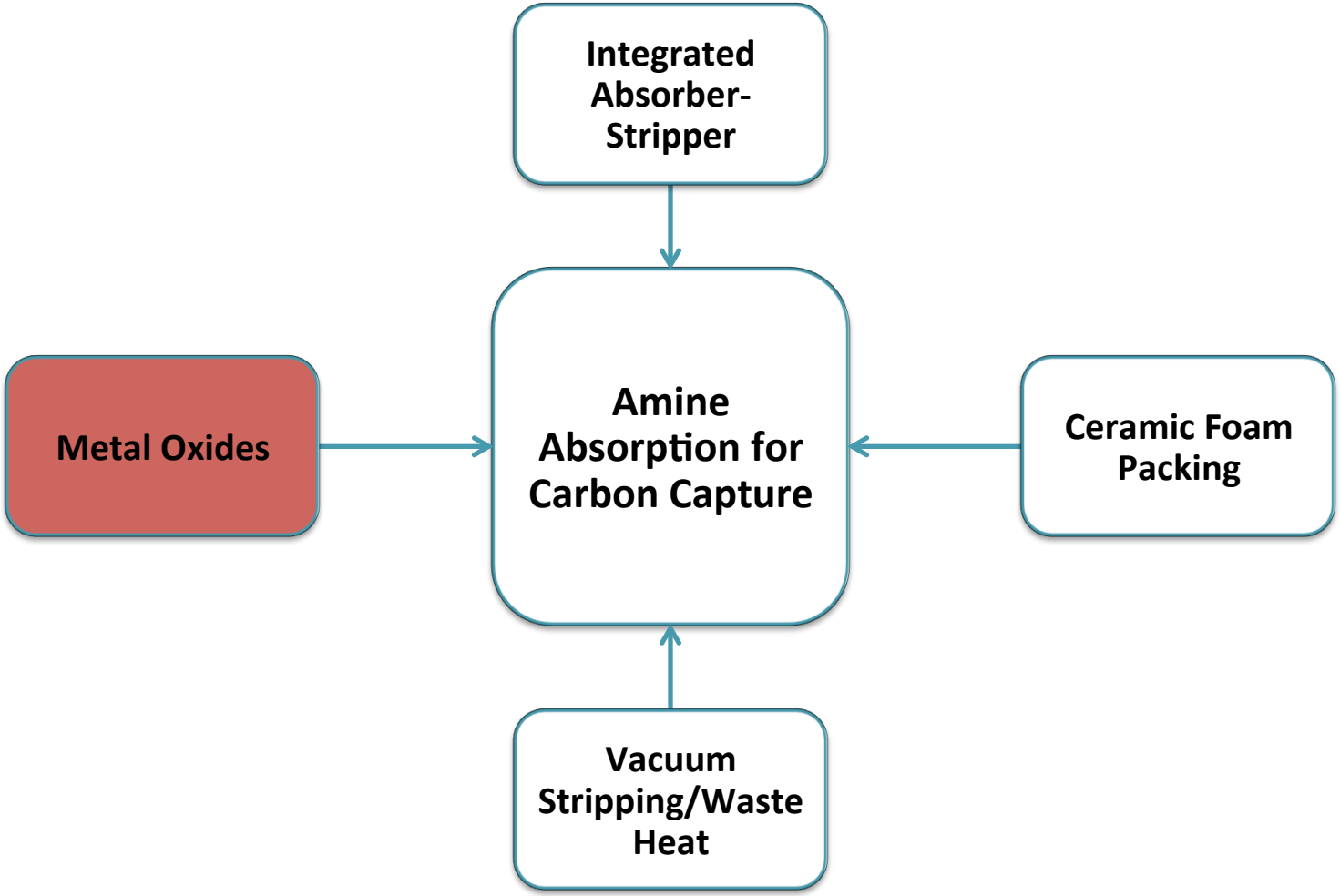


Simulated CO_2 loading profile with abs/des overlapping height

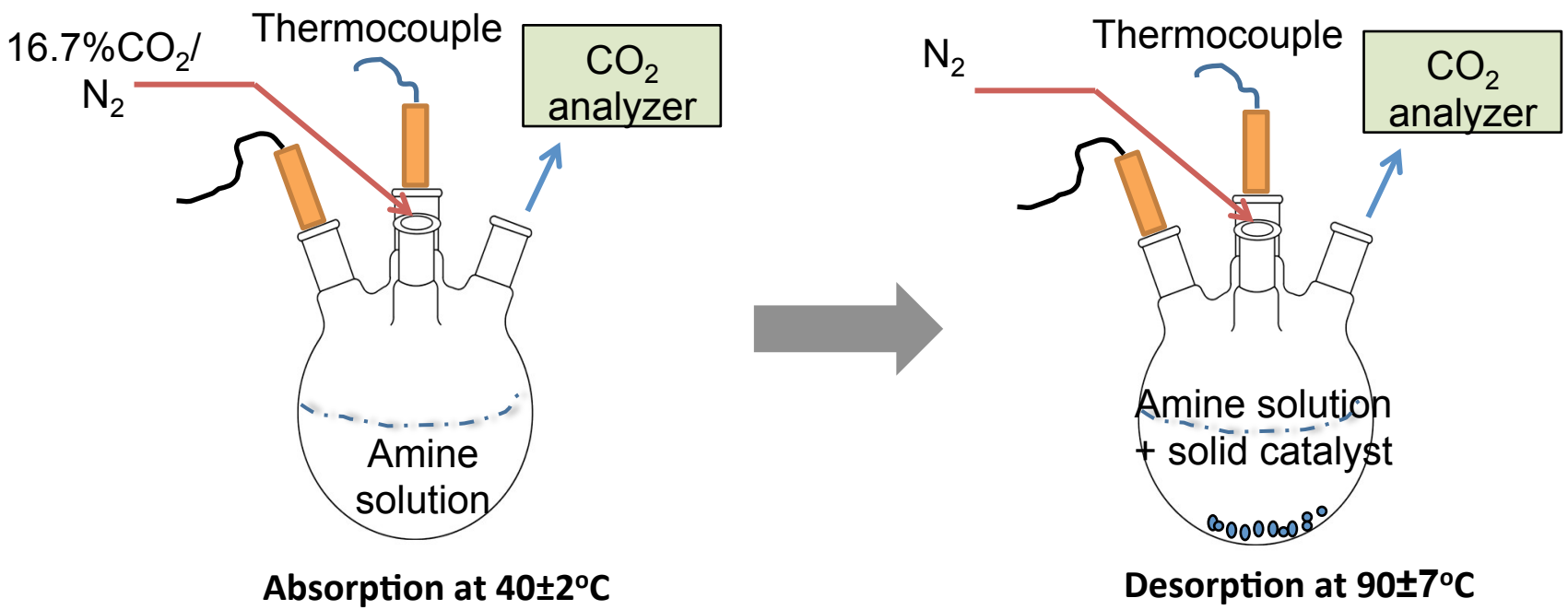
- **The main geometric parameters include:**
  - Stripper chamber size
    0.8 x size of absorber
  - Absorber and desorber overlapping height
    Optimum absorber/stripper overlapping height is expected to be around half length of the absorber with lowest regeneration heat consumption and over 90% CO_2 removal efficiency
  - Membrane section thickness
    Optimal membrane section thickness is around10 cm.

Our Approach:
Using Metal Oxides during Desorption

COMBINED PRESSURE, TEMPERATURE CONTRAST, AND SURFACE-ENHANCED SEPARATION OF CO_2



Experimental Setup

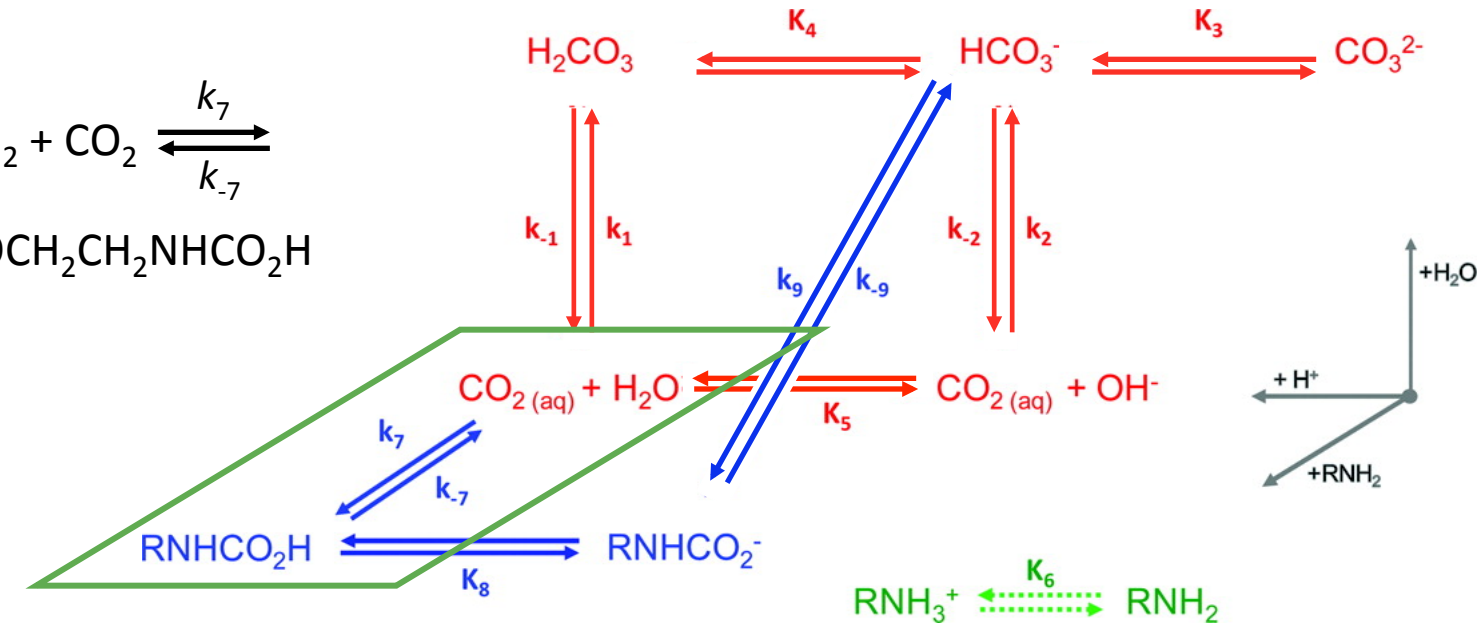


- 15 mL of an amine solution (3M MEA) pre-loaded
- To each solution, 1.5 g of MO_x powder added, 15 min equilibration
- N_2 bubbling through solution at 800 mL min^{-1}, temperature from 40 °C to 86 °C at 10 °C min^{-1}

Reactions between amine, CO_2, and bicarbonate

For MEA:

$$HOCH_2CH_2NH_2 + CO_2 \underset{k_{-7}}{\overset{k_7}{\rightleftharpoons}} HOCH_2CH_2NHCO_2H$$



		$k_7 = 5.8 \times 10^{10}\ e^{(-4872/T)}$ ($M^{-1}\ s^{-1}$)	$k_{-7} = 1.0 \times 10^{13}\ e^{(-7583/T)}$ (s^{-1})	Calculated Equilibrium K_7
Absorber	30 °C	6.0×10^3	136	44
	70 °C	~3.9×10^4	~2.5×10^3	~16

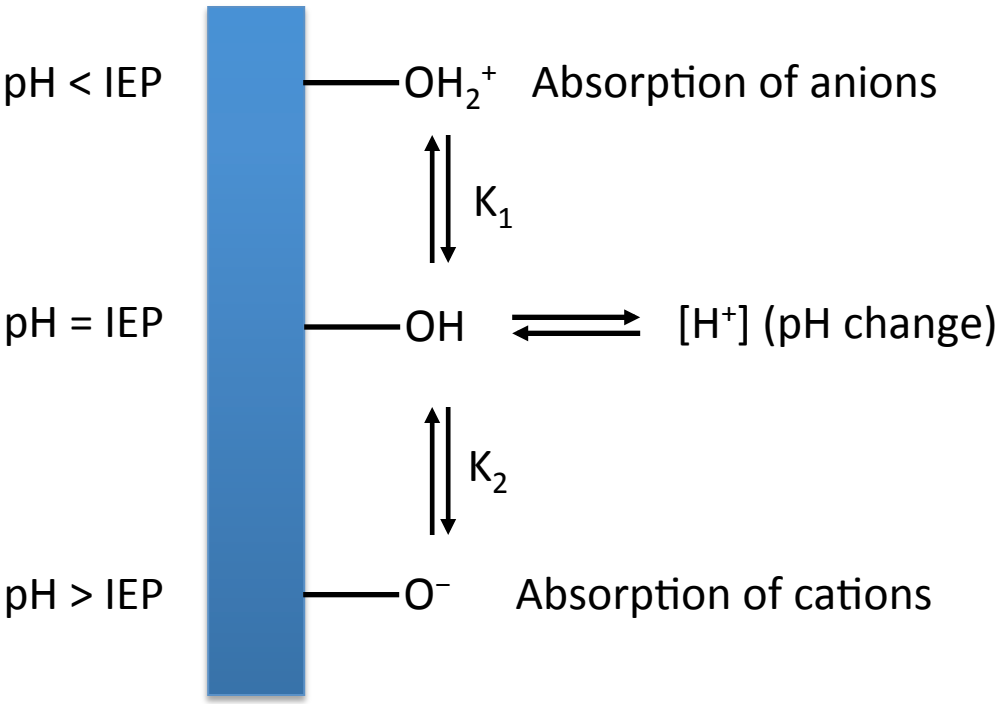
Conway, W. et al. *J. Phys. Chem. A* **2011**, *115*, 14340.

Consider Acidity of Substrate Surface on CO_2 Desorption

Others have demonstrated ability of acids to liberate CO_2 from carbamates

It is not very practical to add aqueous acid to the desorber (separation issues)

However, metal oxide surfaces can function as an acid/base from the view of isoelectric points (IEP) (aka Brønsted acids/bases):

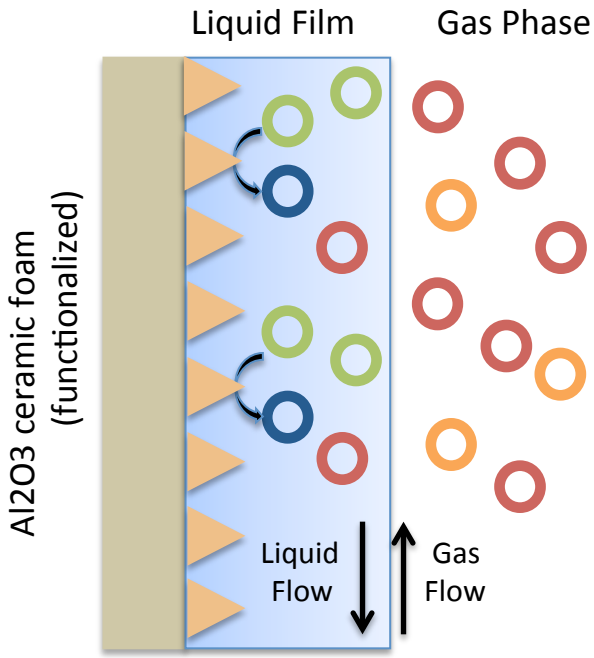


Metal Oxide:	$pH_{25\,°C}$ of IEP at 25 °C
WO_3	0.2 – 0.5
SiO_2	1.7 – 3.5
γ-Al_2O_3	7 - 8
α-Al_2O_3	8 - 9
ZnO	9.5
NiO	10 – 11

Kosmulski, M. "Chemical Properties of Material Surfaces", Marcel Dekker, 2001.

Solid Materials Tested

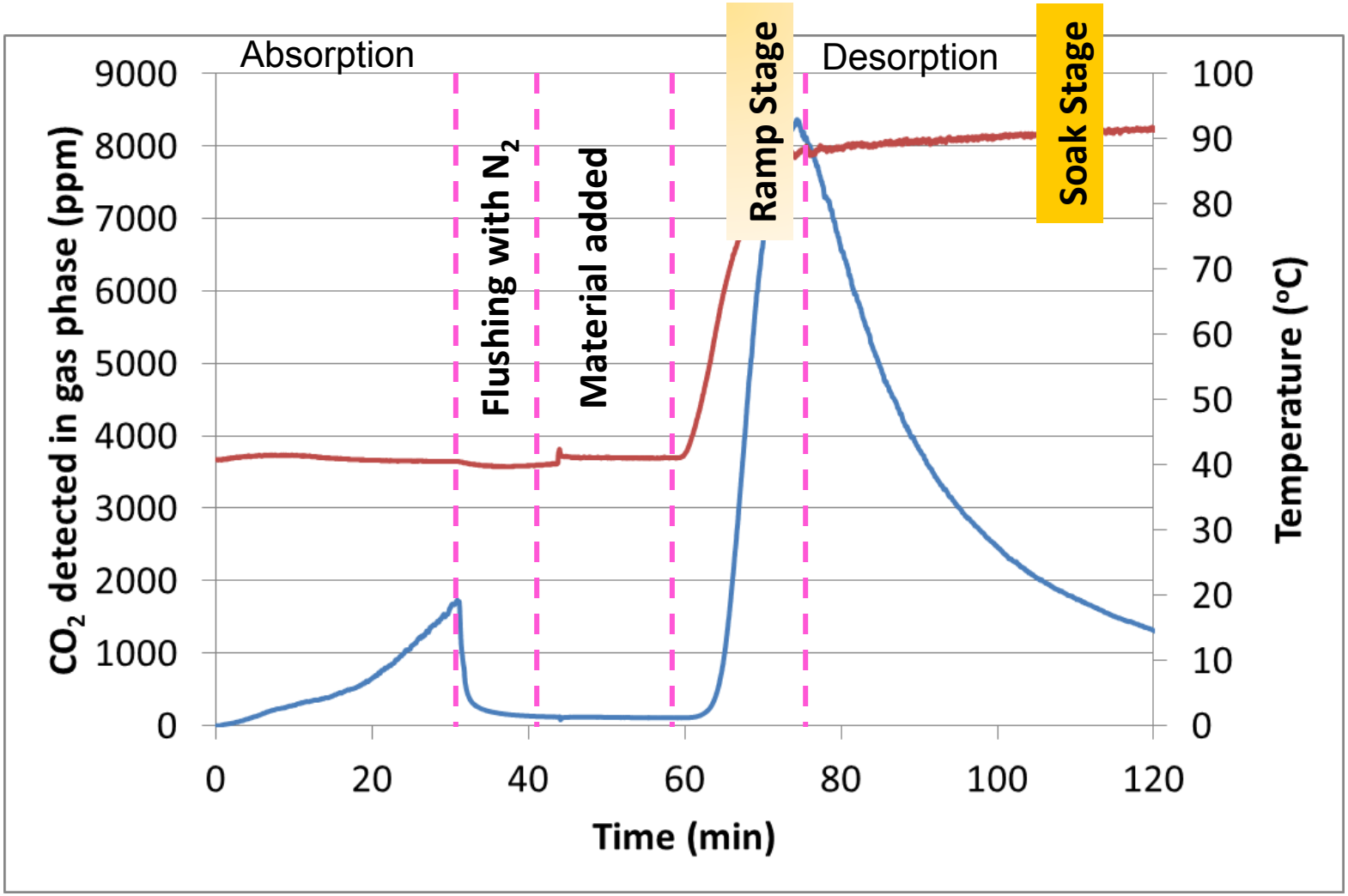
Desorber side



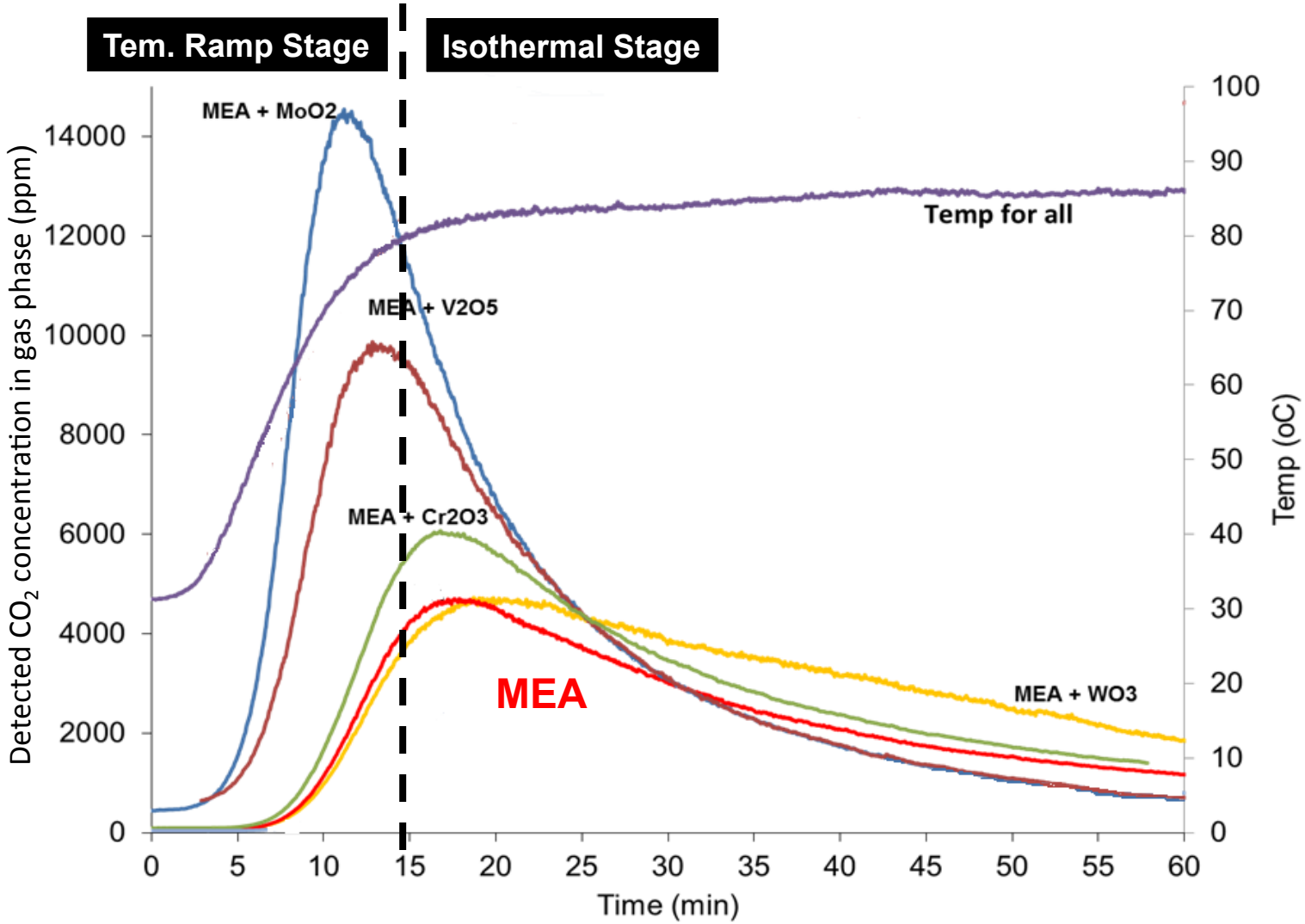
- CO_2
- Carrier gas (H_2O)
- CO_2 + amine (reacted, intermediate)
- catalyst liberated CO_2
- MOx solid catalyst

Material	IEP	Surface Area (m^2/g)	Surface Density (M-atoms/ nm^2)	γ-Al_2O_3 supported catalyst
WO_3	0.3	1.2	--	--
V_2O_5	1-2	4.5	--	--
MoO_3	2.5	0.9	--	--
MgO	12-13	115.8	--	--
WO_3 (7.5 wt%) /γ-Al_2O_3	--	49.3	6.0	Yes
V_2O_5 (1.3 wt%)/γ-Al_2O_3	--	137.9	7.7	Yes
MoO_3 (4.2 wt%)/γ-Al_2O_3	--	80.0	7.1	Yes

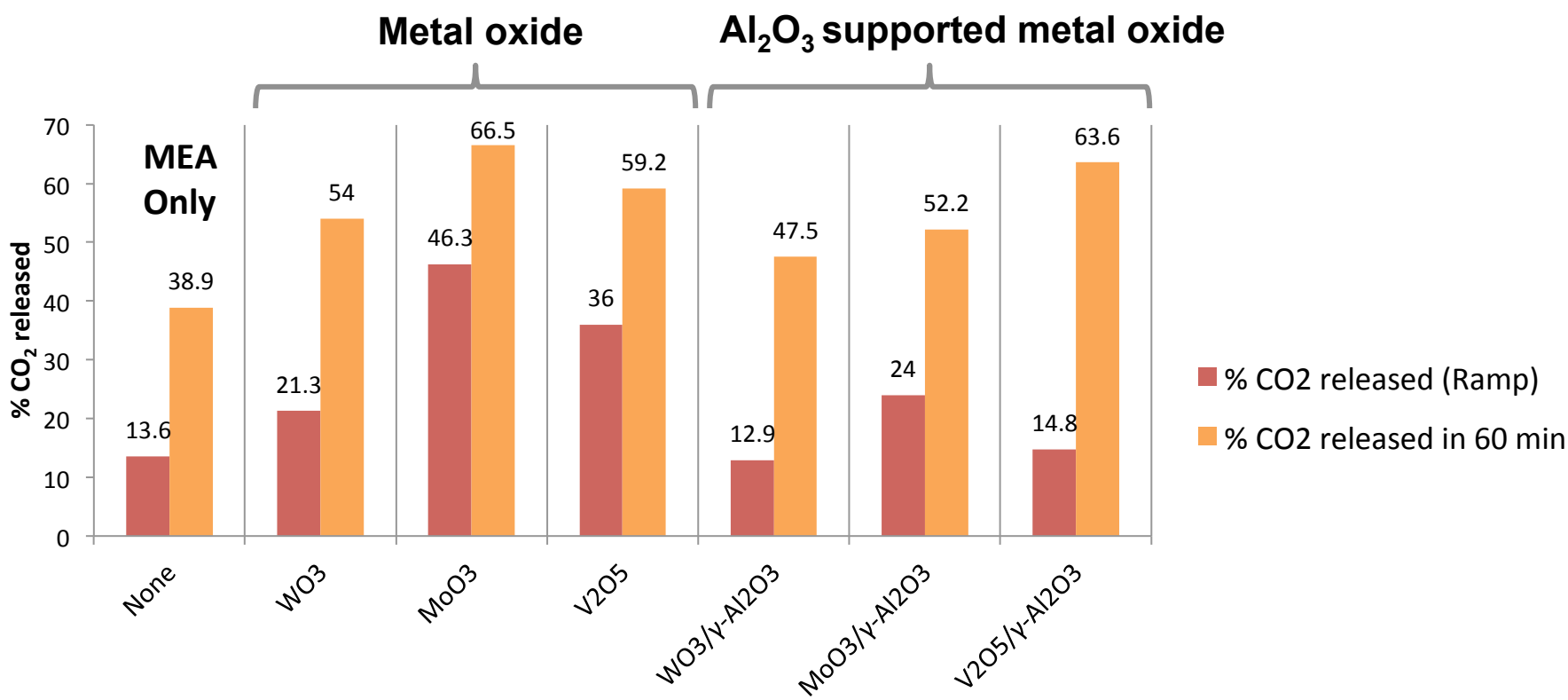
Example of CO_2 Experiment



Screening of Metal Oxides for CO_2 Desorption (MEA)



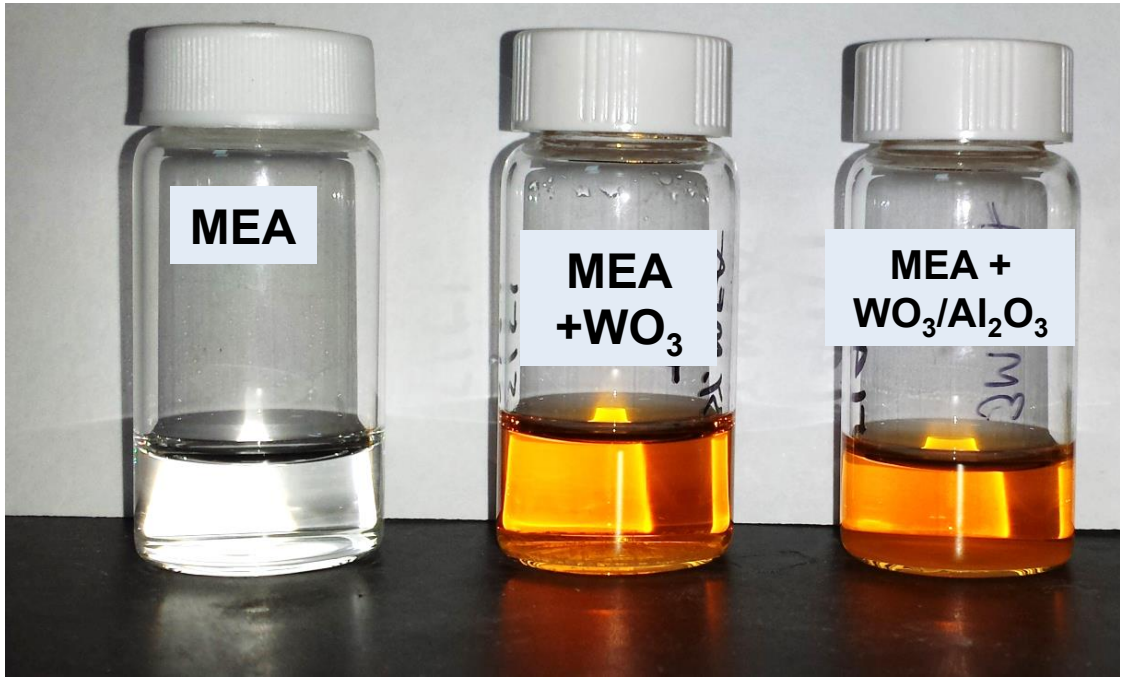
CO_2 catalytic desorption results



- All desorption at 85 ^{o}C, except V_2O_5 /γ-Al_2O_3 desorption at 91 ^{o}C
- Metal oxide only catalysts enhance CO_2 release up to 70%;
- Catalytic activities of metal oxide will be partially lost if supported by Al_2O_3 , but still have up to 40% CO2 desorption increment.

Material Stability Results

Post-reaction

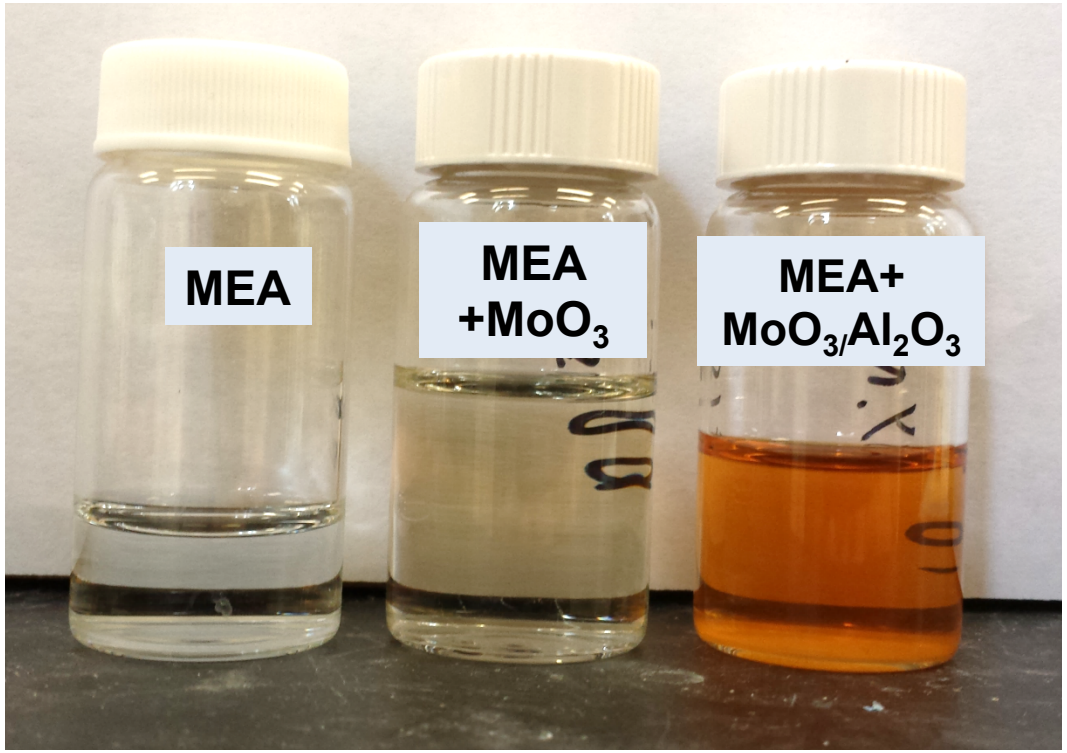


Amount of W dissolved (%)	53	24

- Dissolution is likely due to the formation of a reaction between WO_3 and MEA
- No dissolution of Al_2O_3
- Al_2O_3 helps reducing the dissolution of catalyst significantly

Material Stability Results

Post-reaction

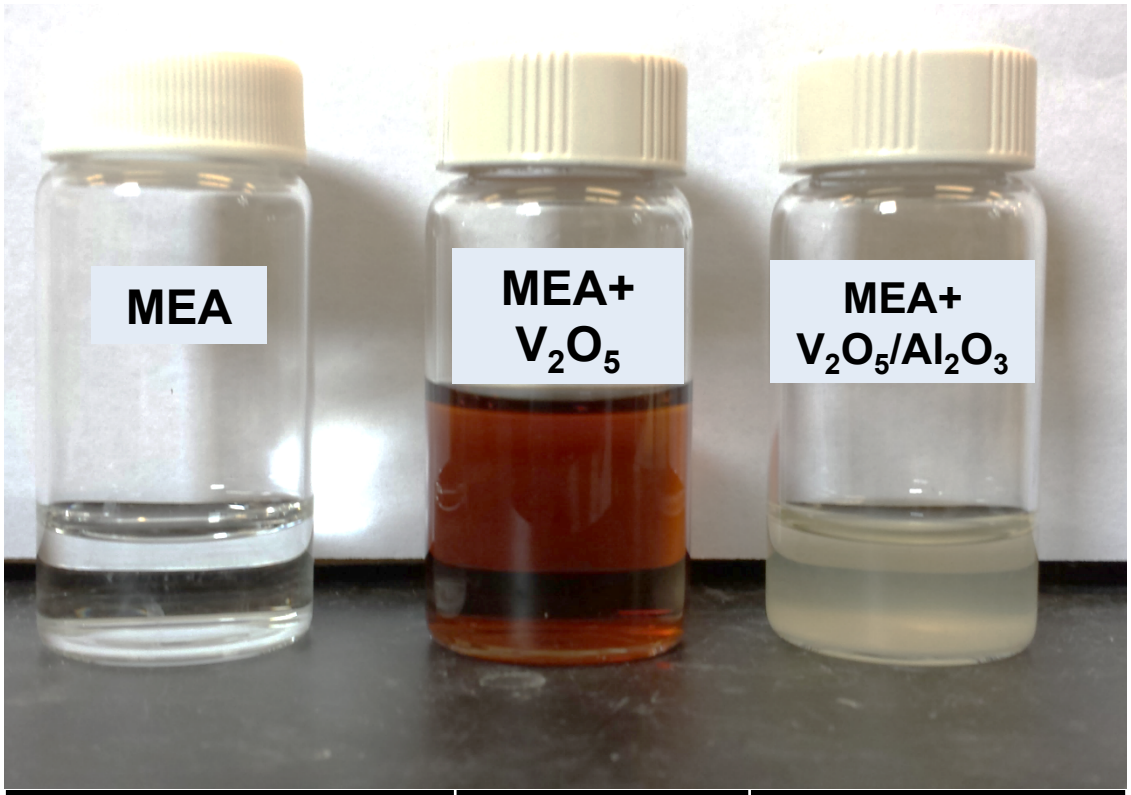


Amount of Mo dissolved (%)	96	68

- Al_2O_3 helps reducing the dissolution of MoO_3

Material Stability Results

Post-reaction



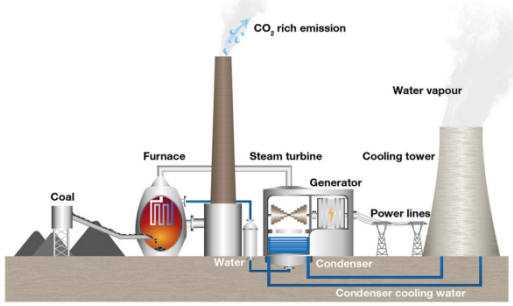
Amount of V dissolved (%)	88	79

- Marginal reduction in dissolution of V_2O_5

Techno-economic feasibility study

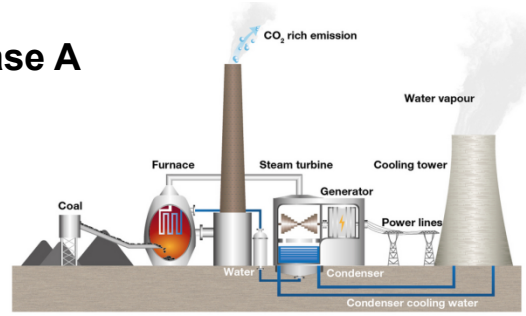
Baseline (cases studied)

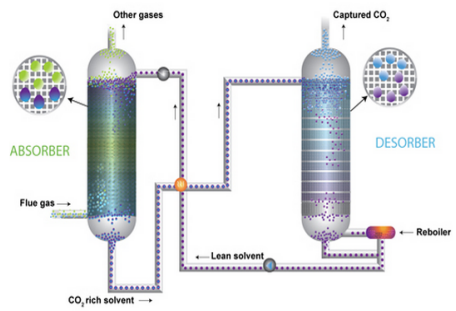
- **Reference Case**



Reference case *without CO2 capture is a subcritical PC power plant with a nominal net output of 550 MWe and a single reheat 16.5 MPa/566C/566C*

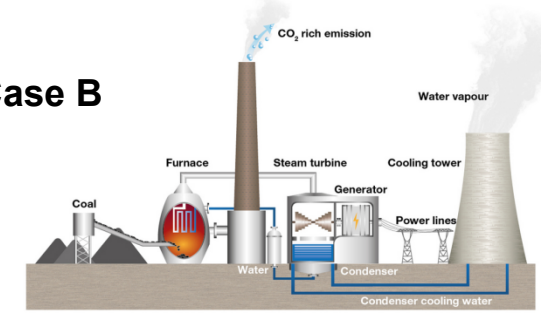
- **Case A**

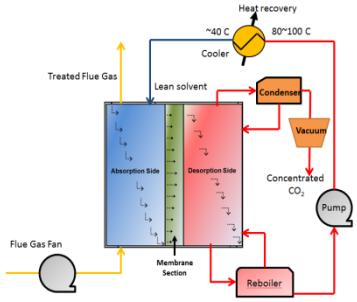




Fluor Econamine CO_2 capture *process (conventional amine-based CO_2 capture)*

- **Case B**





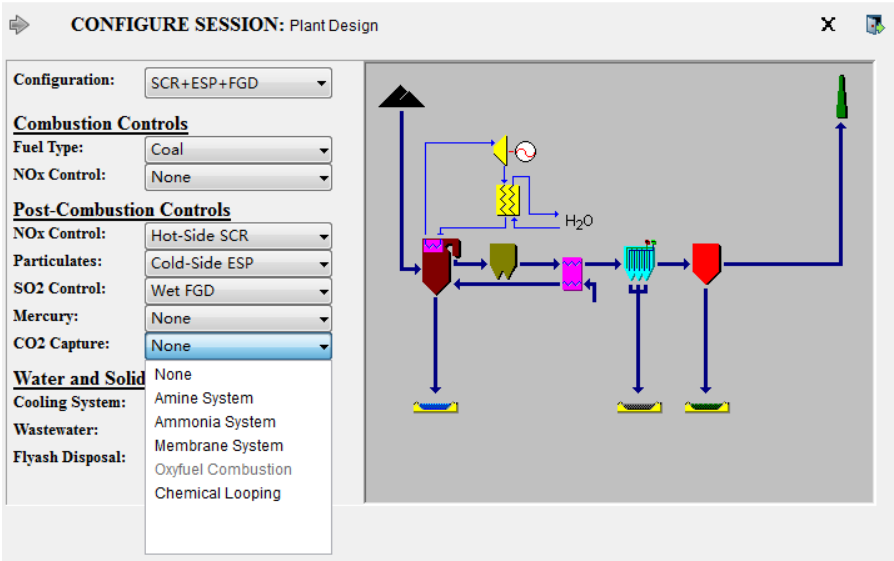
Rice University ***integrated absorber/desorber*** *CO_2 capture process,*

Tech-economic analysis method

IECM software http://www.cmu.edu/epp/iecm/

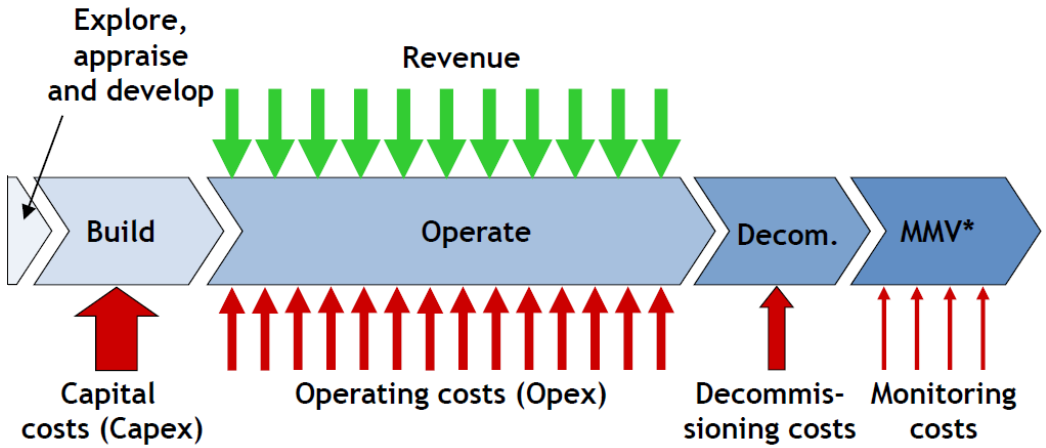
- A computer-modeling program that performs a systematic cost and performance analyses of emission control equipment at coal-fired power plants.
- Developed by CMU and Department of Engineering & Public Policy (EPP)

Integrated Environmental Control Model



Tech-economic analysis method

- Self-developed Tech-economic analysis model
  - Cash flow analysis



Components of CCS cash flow

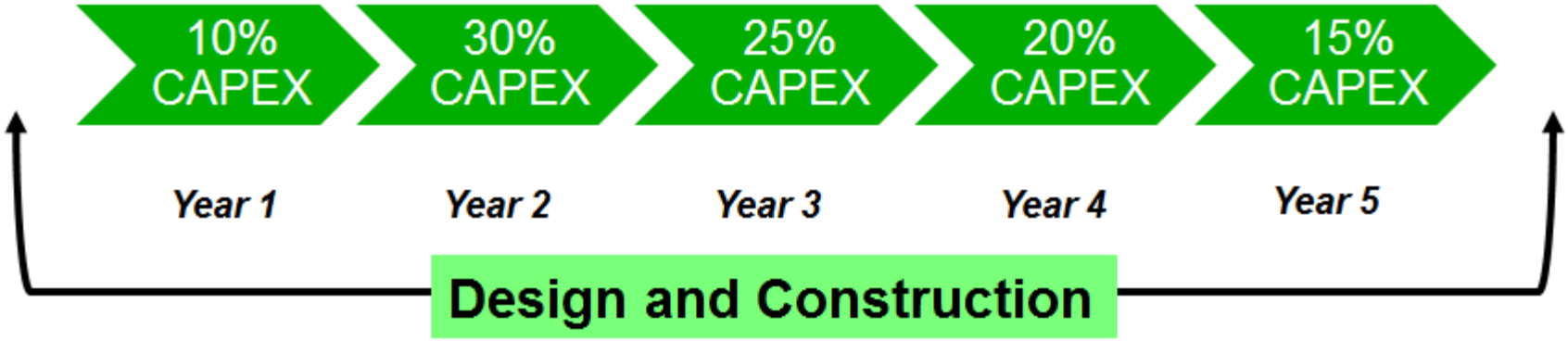
  - Present value

Discount Rate: d%

$$\text{Present Value} = \frac{\$ \text{ in year } n}{(1+d\%)^n}$$

Techno-economical baseline

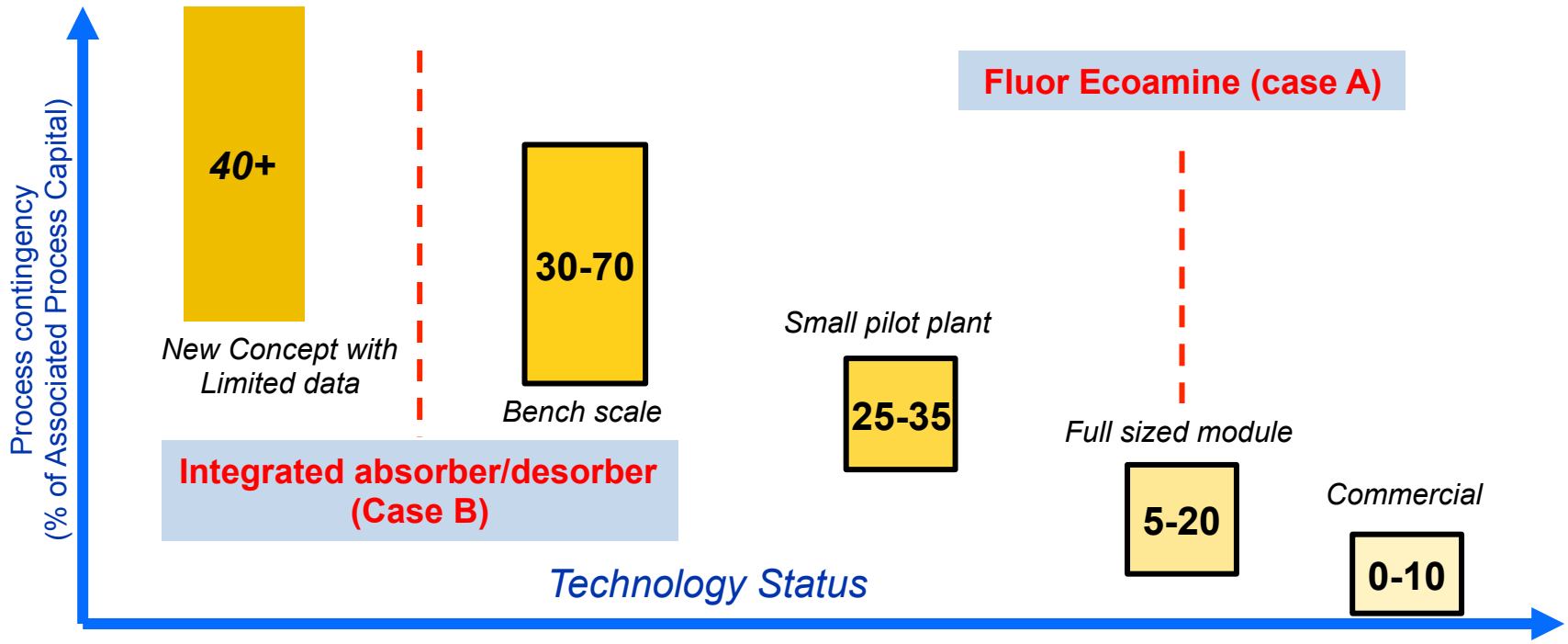
- Total design and construction period is 5.0 years
- As suggested by the guideline of technical-economic analysis (TEA) in DOE report, subcritical PC cases have been evaluated with the following investment profiles:



- Project life and startup date
  - This is **30** years for the subcritical PC cases. The project is assumed to start operation in **2012.**

Techno-economical baseline

- Load factor (Capacity factor)
  - As suggested by DOE, the default load factors for power plant is assumed to be **85%** during the operating years.
- Discount rate
  - use a **11%** nominal discount rate (suggested by DOE).
- Contingency (AACE Guidelines)



Techno-economic analysis validation

Comparison of Plant Performance Summary (Case A)

POWER SUMMARY (Gross Power at Generator Terminals, kWe)			
METHOD	**Calculated**	**IECM***	**DOE**
Steam Turbine Power	672,700	672,700	672,700
TOTAL (STEAM TURBINE) POWER, kWe	672,700	672,700	672,700
AUXILIARY LOAD SUMMARY, kWe			
Base Plant Use	21,630	22,470	/
SCR Use	4,880	4,522	/
TSP Use	2,130	2,698	/
FGD Use	6,720	5,390	/
Mercury Control Use	200	240	/
Cooling Tower Use	18,200	21,120	/
CO2 capture Use	68,230	67,100	71,190
TOTAL AUXILIARIES, kWe	121,990	123,500	122,740

Note:

1)Case A *(DOE Subcritical PC plant with amine CO2 capture).In this case, the subcritical PC plant with a nominal net output of 550 MWe, with a single reheat 16.5 MPa/566℃/566℃ cycle.*

2) IECM *software(Integrated Environmental Control Model)*

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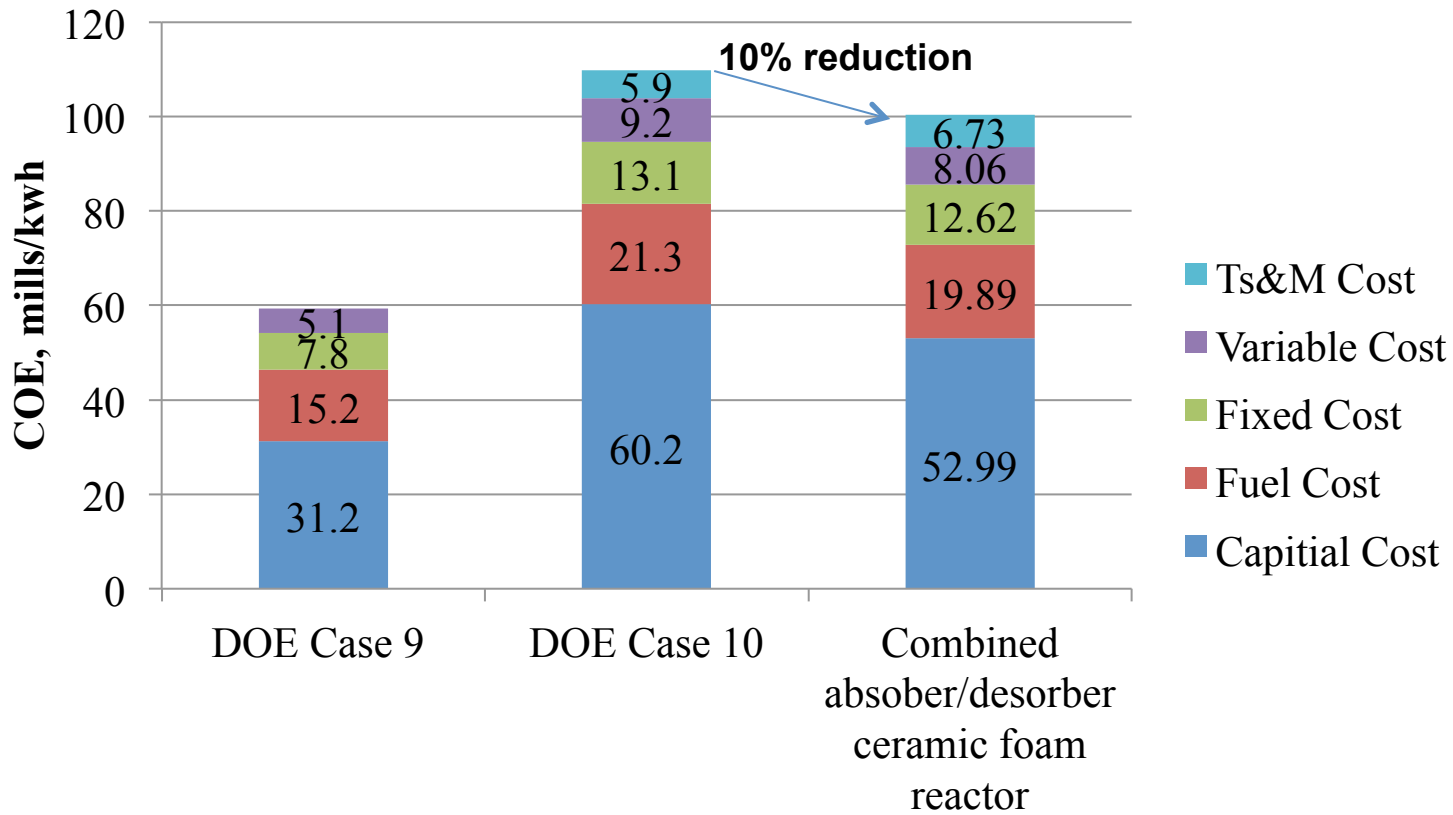
2) IECM *software(Integrated Environmental Control Model)*

Techno-economic analysis (TEA) results

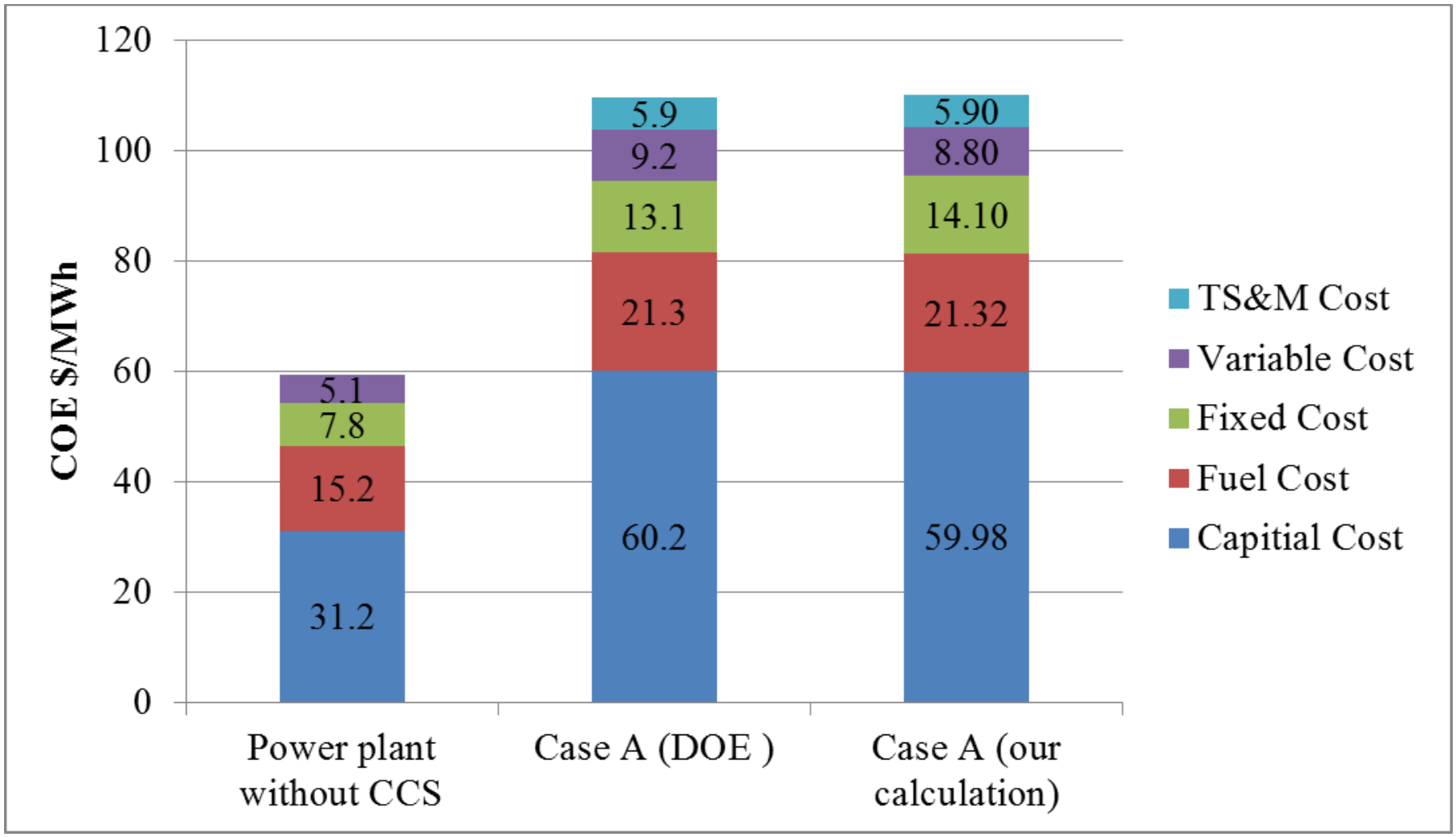
Scale-up "combined" system to commercial scale by 2D modeling

- Absorbent: 30 wt% MEA, lean loading 0.27 mol/mol;
- Desorption temperature100 C;
- All at 90% capture ratio;
- CO_2 compression to 150 bar

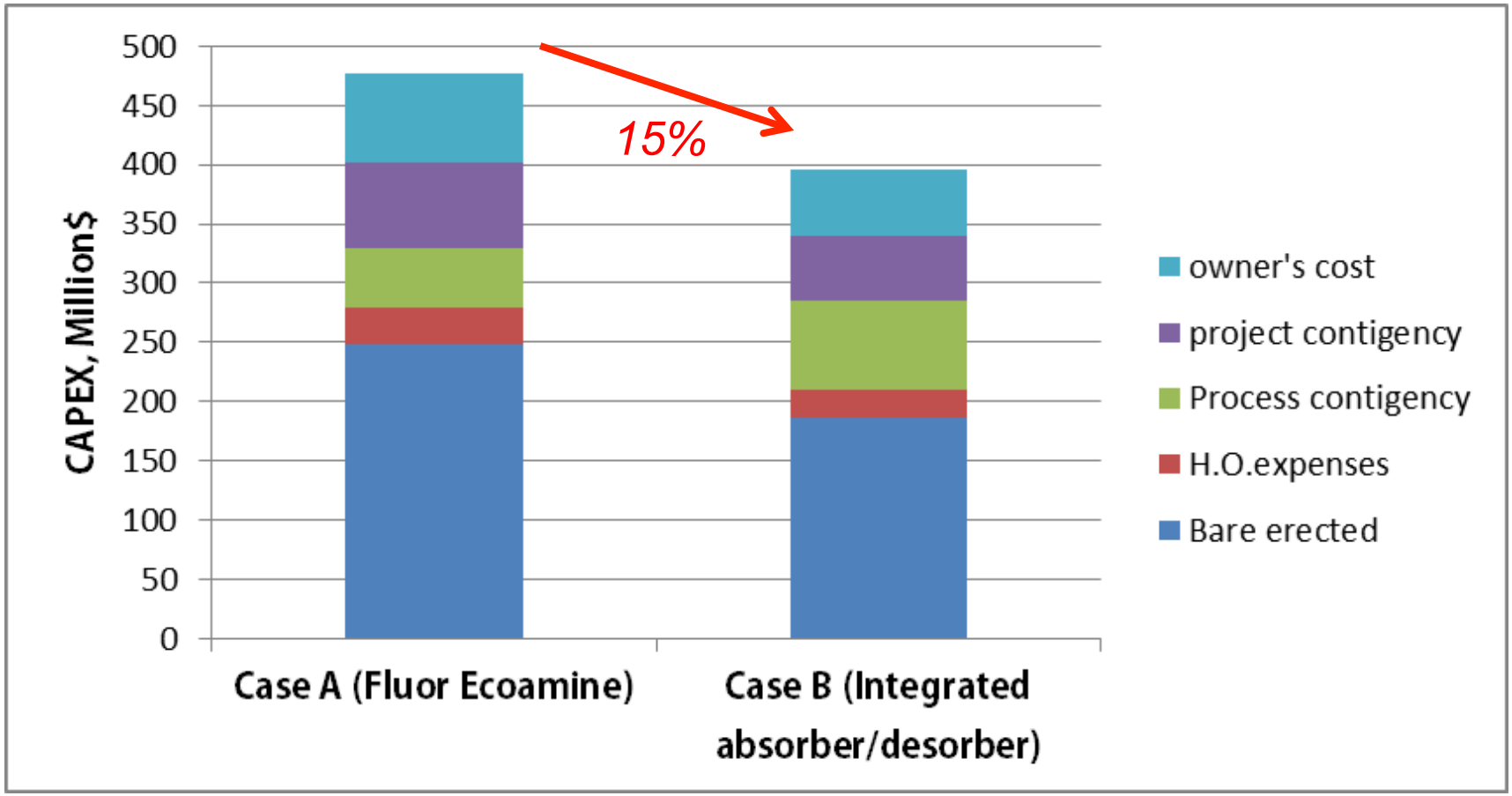


* In 2007 US$

Techno-economic analysis validation

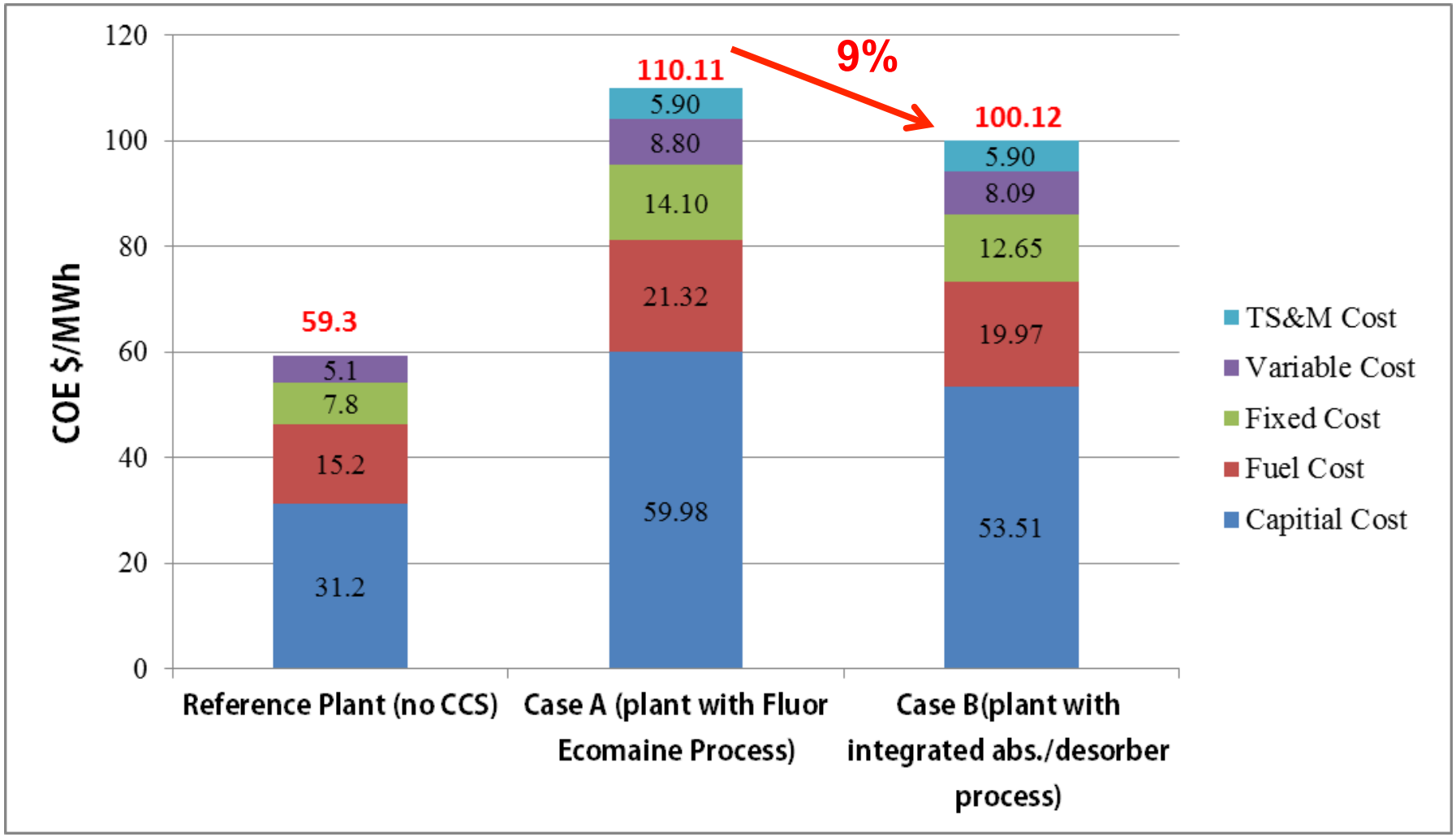


CCS plant CAPEX comparison: case A and B



(ceramic foam price: $2780/m^{3}catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18 /ton, waste heat availability: 0%)

COE comparison

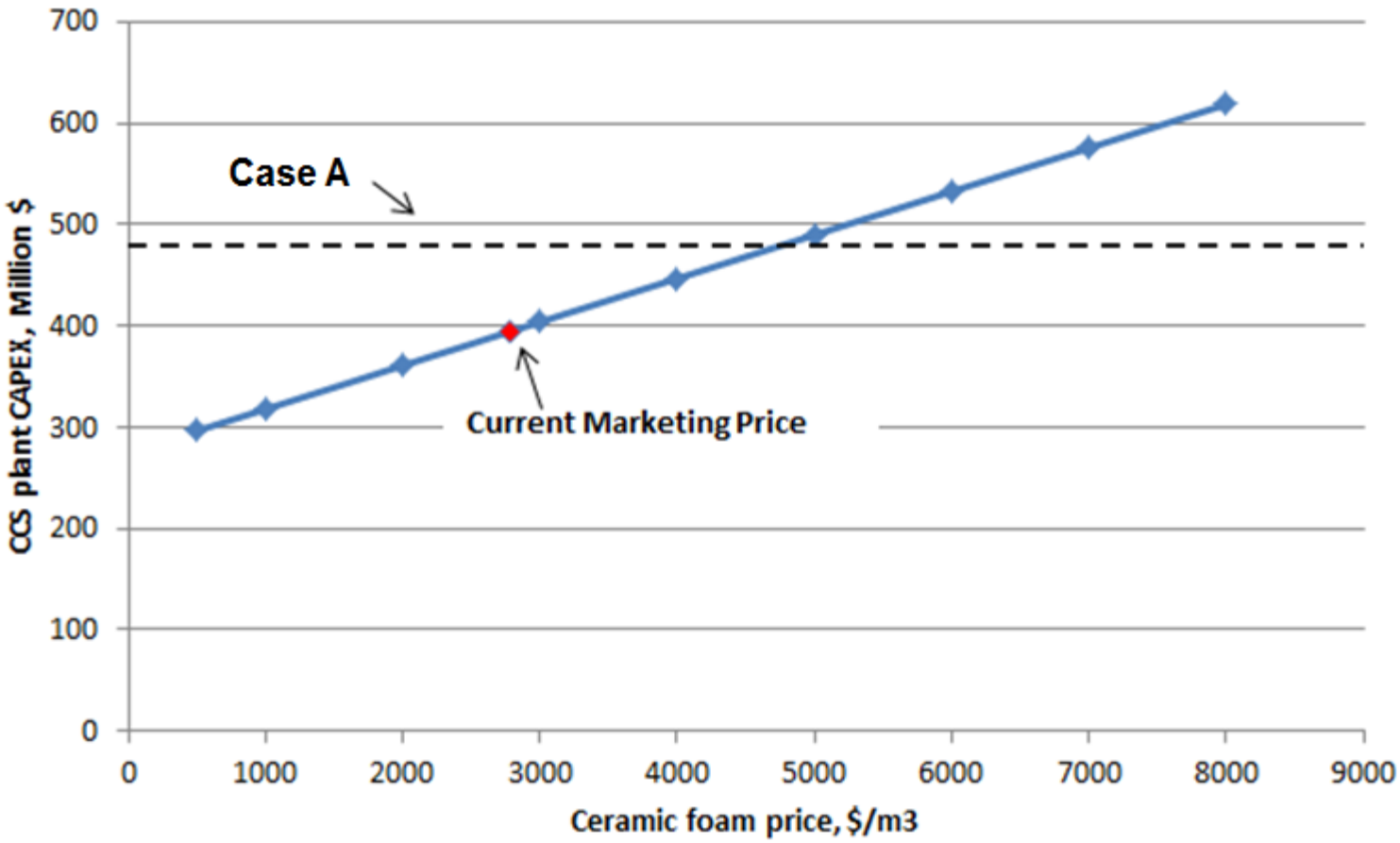


(ceramic foam price: $2780/m^{3}catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18 /ton, waste heat availability: 0%)

Cost sensitivity studies

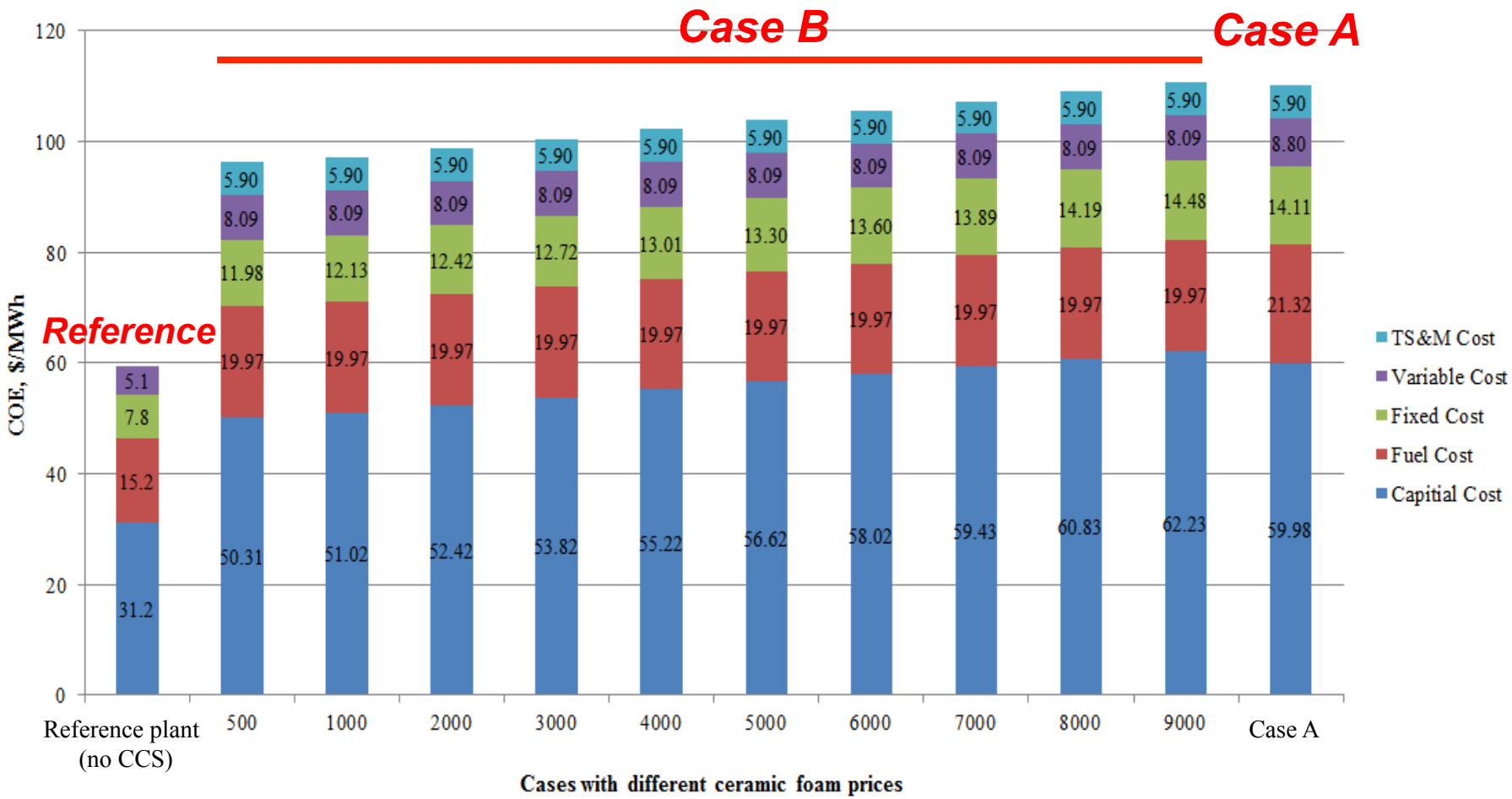
- Some key parameters and operating factors affecting the capital cost or operating cost of integrated absorber/desorber CO_2 capture plant
  - *Ceramic foam price*
  - *Catalyst price*
  - *Catalyst performance*
  - *Waste heat availability*
  - *Longevity of catalytic ceramic foam*
  - *Capacity factor*
  - *Coal price*
  - *Project lifetime*

1) Ceramic foam price



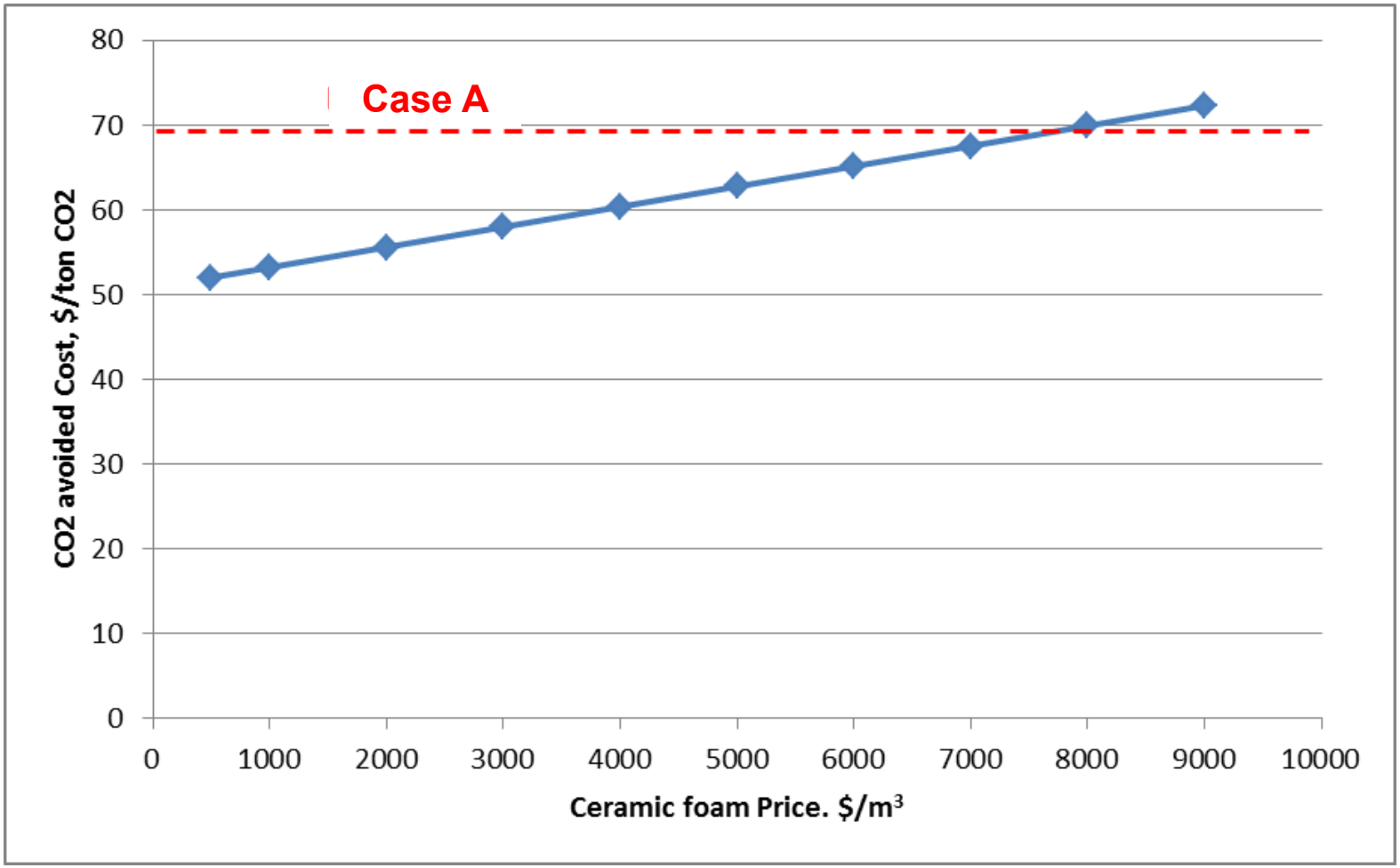
CCS plant CAPEX sensitivity to ceramic foam price (catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18 / ton, waste heat availability: 0%)

1) Ceramic foam price



COE sensitivity to ceramic foam price (catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18/ton, waste heat availability: 0%)

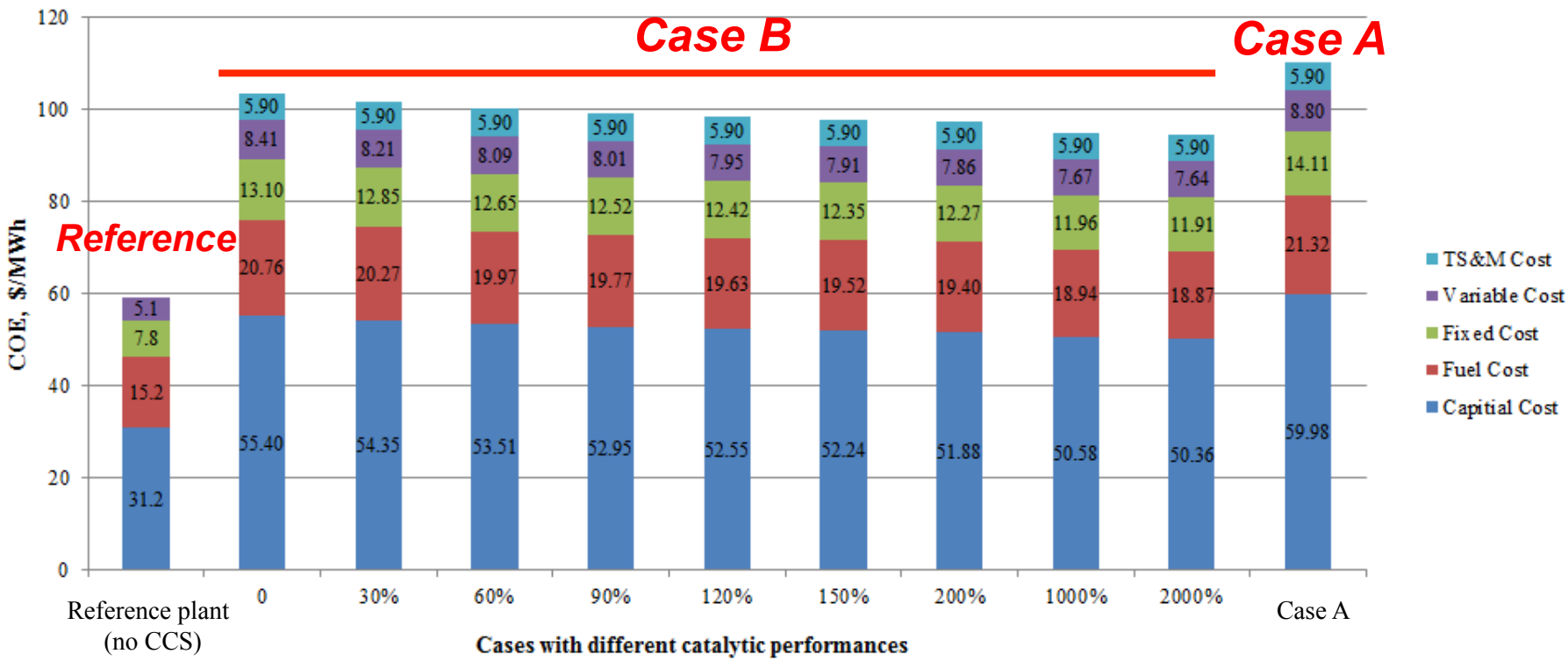
1) Ceramic foam price



The influence of ceramic foam price on CO_2 avoided cost (catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18/ton, waste heat availability: 0%)

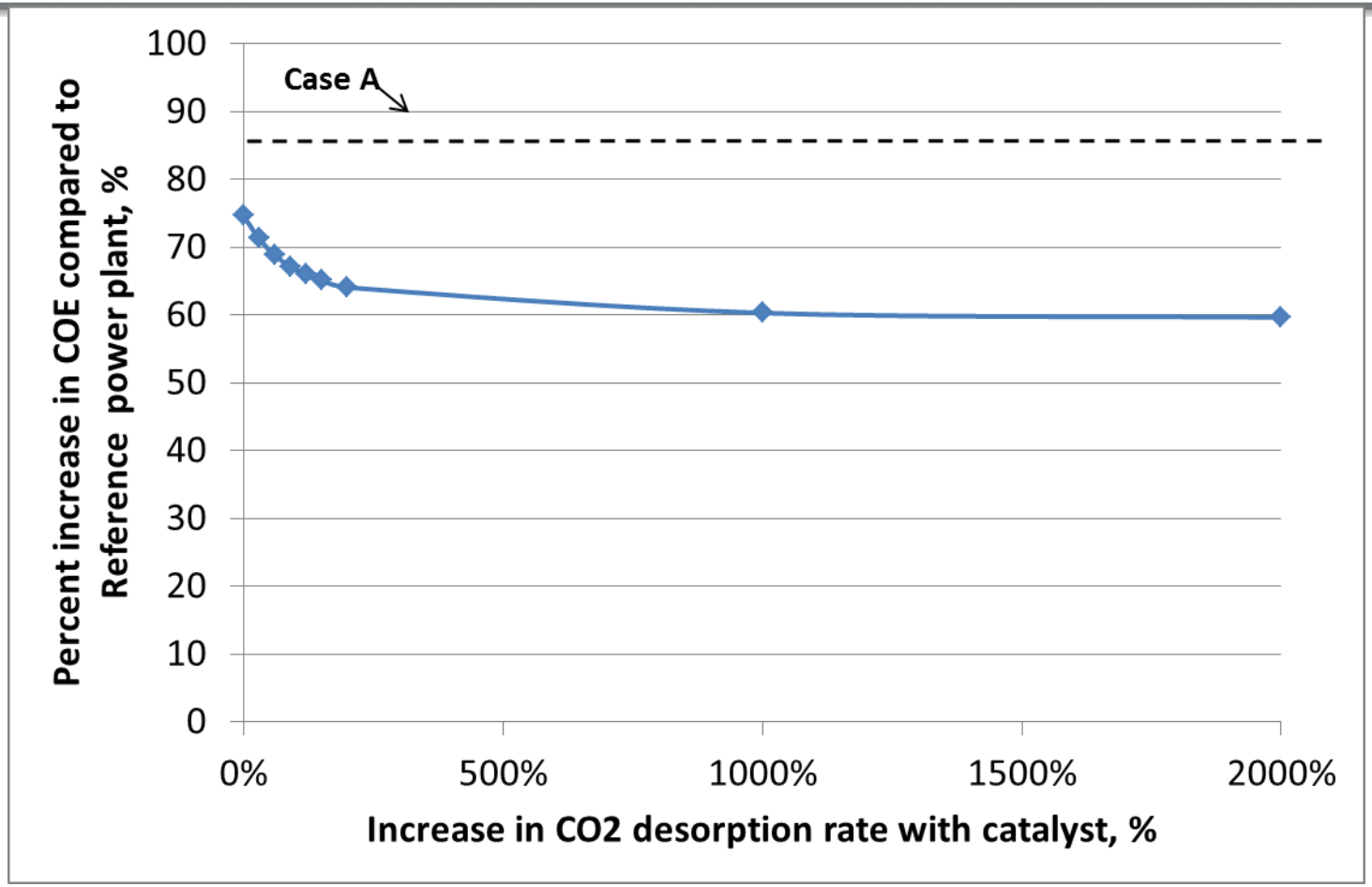
2) Catalyst performance sensitivity

- Catalyst performance is quantitatively described as the percent increase in CO_2 desorption rate compared to non-catalyst case, from 0% to 2000% in this study



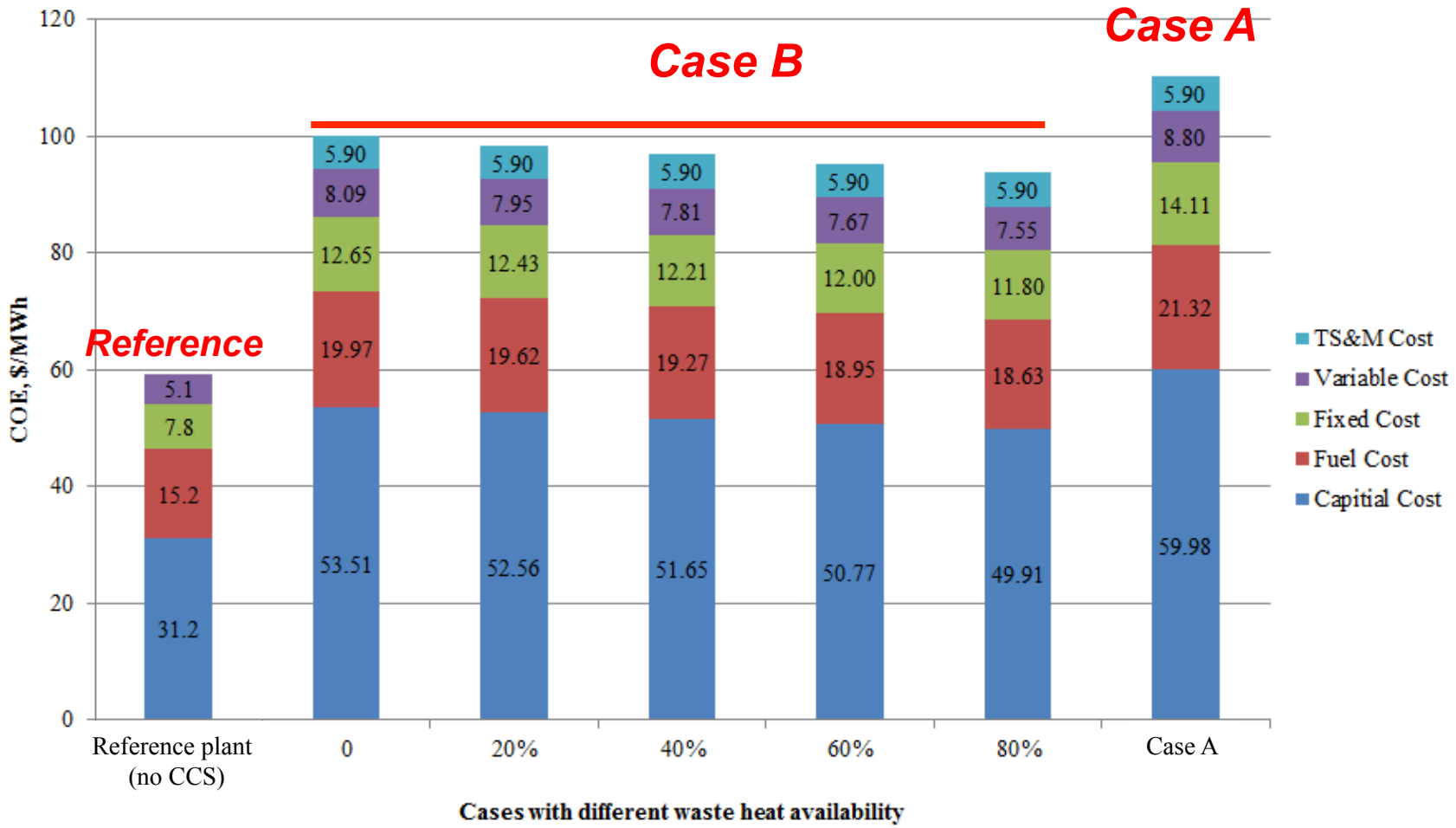
COE sensitivity to catalyst performance (ceramic foam price: $2780/m^3, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18/ton, waste heat availability: 0%)

2) Catalyst performance sensitivity



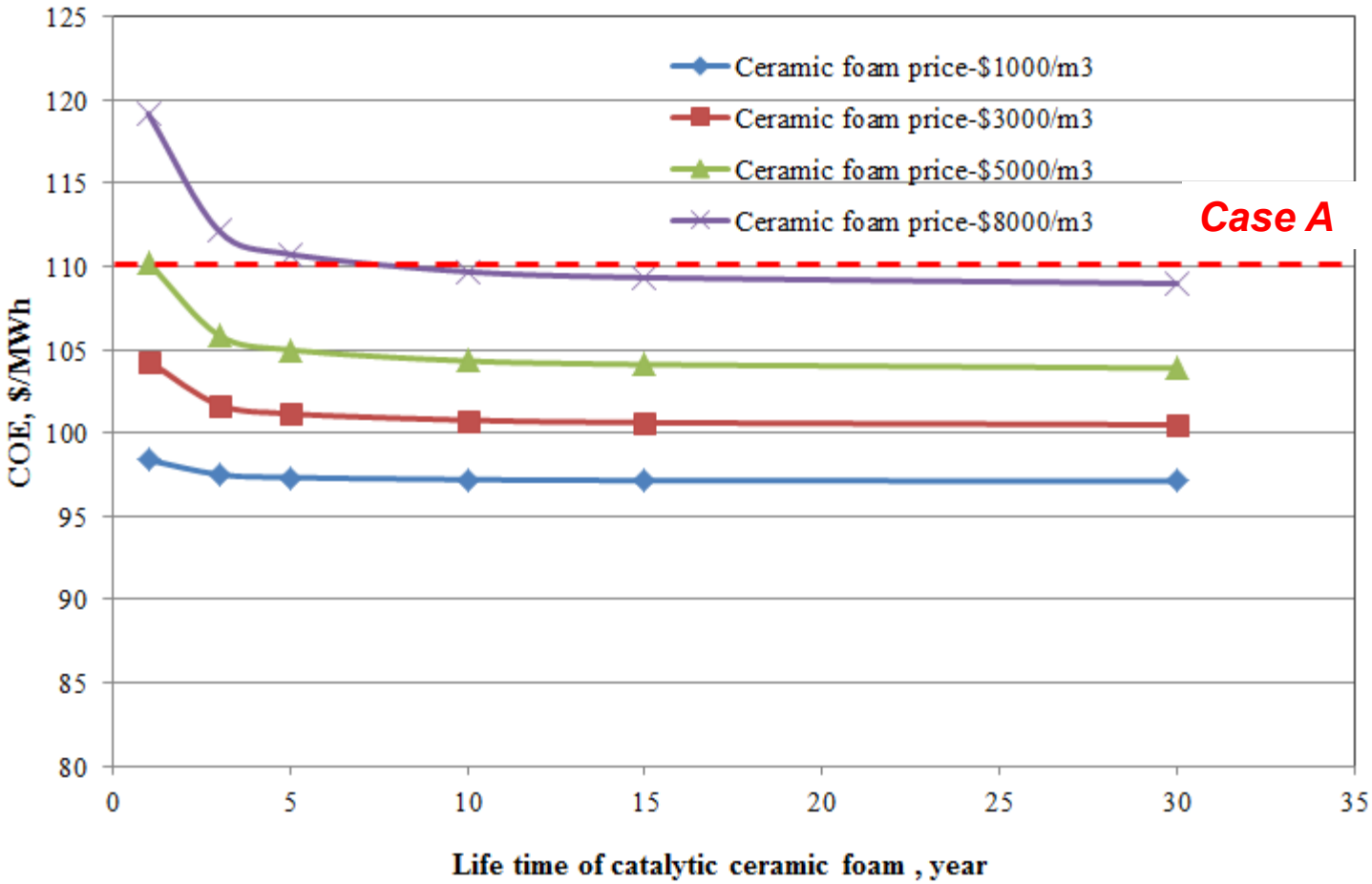
Increase in COE with different catalytic performances (ceramic foam price: $2780/ m^3, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18/ton, waste heat availability: 0%)

3) Waste heat availability



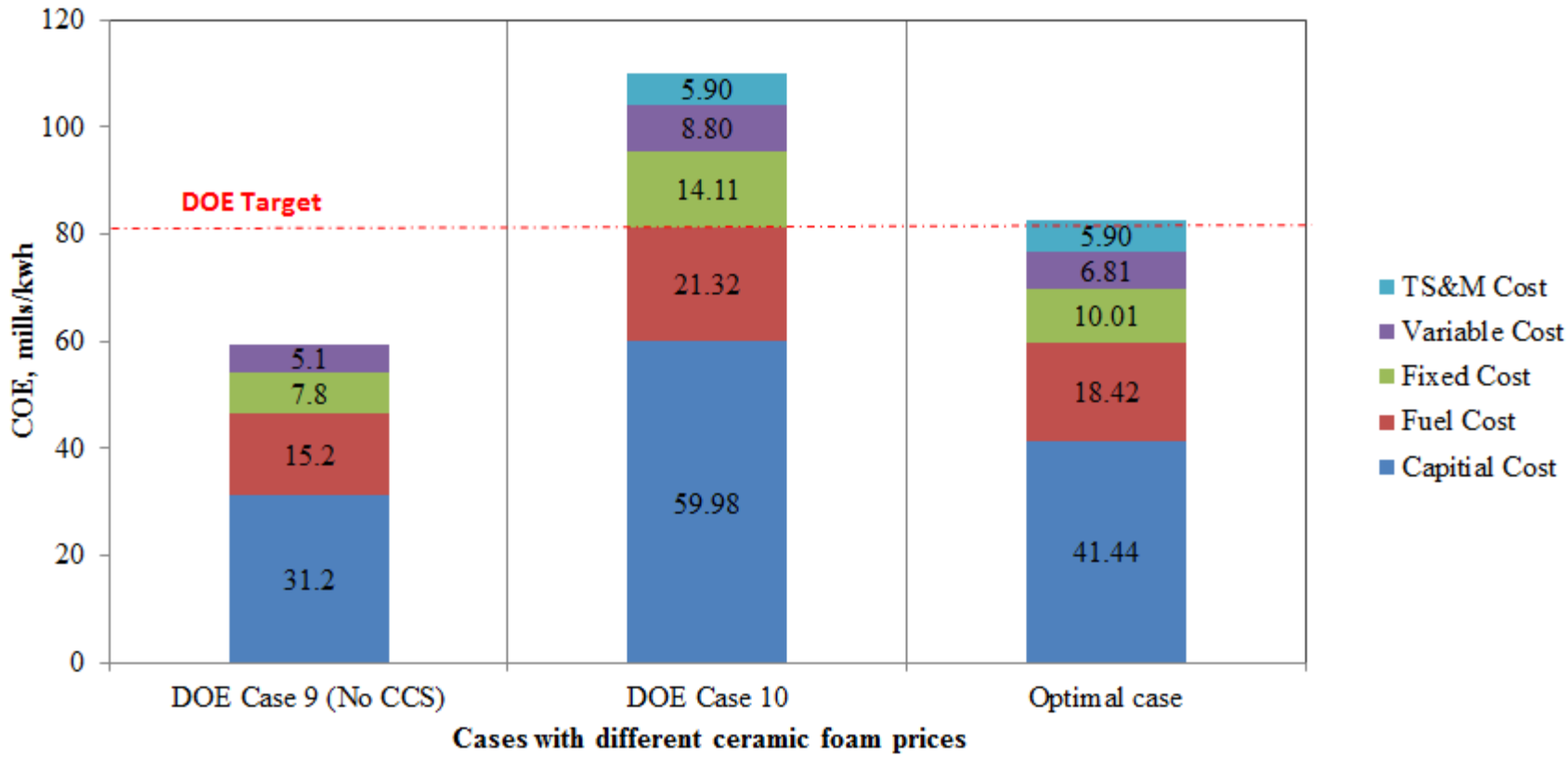
COE sensitivity to waste heat availability (ceramic foam price: $2780/m^3, catalytic performance: 60%, catalyst longevity: 30 years, capacity factor: 85%, coal cost: $38.18/ton)

4) Longevity of catalytic ceramic foam



COE sensitivity to the lifetime of catalytic ceramic foam (catalytic performance: 60%, capacity factor: 85%, coal cost: $38.18/ton, waste heat availability: 0%)

Optimal case of integrated absorber/desorber CO_2 capture



(ceramic foam price: \$500/m^3, catalytic performance: 200%, catalyst longevity: 30 years, capacity factor: 95%, waste heat availability: 90%, coal price: \$38.18/ton)

Summary and Conclusions

- **Hydrodynamic and mass transfer studies on ceramic foam**
  - Hydrodynamic and mass transfer studies on 1D ceramic foam column
  - Ceramic foams allowed for higher flow rates of gas and liquid to be used before flooding occurred, compared to random packings.
  - >90% CO_2 removal ratio can be reached in ceramic foam column
- **Combined absorber/desorber CO_2 separation process**
  - Demonstrate the feasibility of CO2 capture in lab-scale "combined" unit
  - More than 90% CO_2 removal can be achieved using the combined absorber/stripper configuration.
  - Successful development of a 2-D model to simulate CO2 capture in "combined" system
  - Performed a sensitivity analysis and process optimization

Summary and Conclusions

- **Catalytic desorption of CO_2 using metal oxides**
  - Metal oxides represent a new approach to enhance CO2 desorption and reduce the desorption temperature
  - Al2O3 supported catalysts are also available to catalyze CO2 desorption
  - γ-Al_2O_3 can help in mitigating the leaching problem of metal oxides in absorbent
- **Techno-economic analysis of combined absorber and desorber system**
  - Integrated abs./des. technology enable to reduce the capital cost of CCS and COE compared to conventional amine-based technology
  - Integrated absorber/desorber CO_2 capture shows a higher net plant efficiency of 30.10%, than conventional Fluor Econamine CO_2 capture (27.01%).
  - $82/MWh of COE can be achieved with using integrated absorber & desorber CO_2 capture technology, which is very close to DOE's target that no more than a 35% increase in COE with CCS.

Acknowledgements

Personnel

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- Schlumberger