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

DOE Project # DE0007531

Project Manager: Ms. Elaine Everitt

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Rice University

NETL CO_2 Capture Technology Meeting

June 24th, 2015

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)

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

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

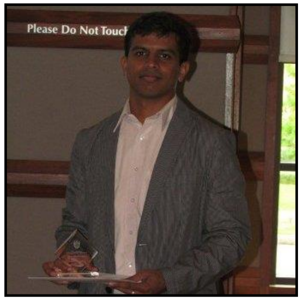
Zhen Wang
PhD, Thermal Power Engineering (ZJU, 2014)

Postdoctoral Associate

Mayank Gupta
PhD , Chemical Engineering (LSU, 2010)

Past Members

Colin Shaw
Undergraduate Chemical & Biomolecular Engineering



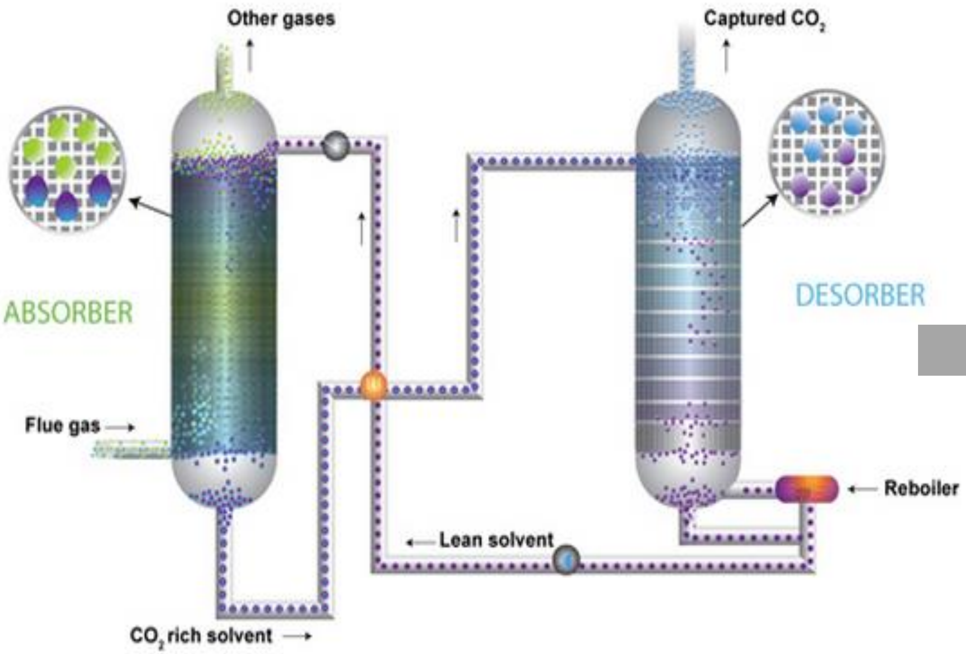
Sumedh Warudkar
PhD (April 2013)

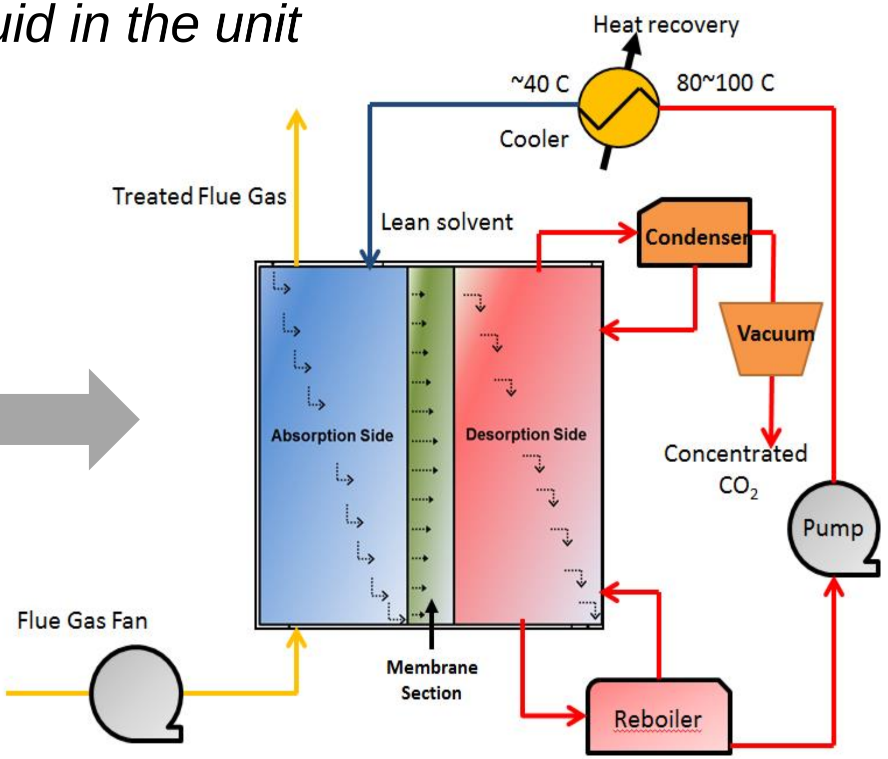
Jerimiah Forsythe
PhD, Chemistry (LSU, 2011)

Technical Approach

Major challenges:

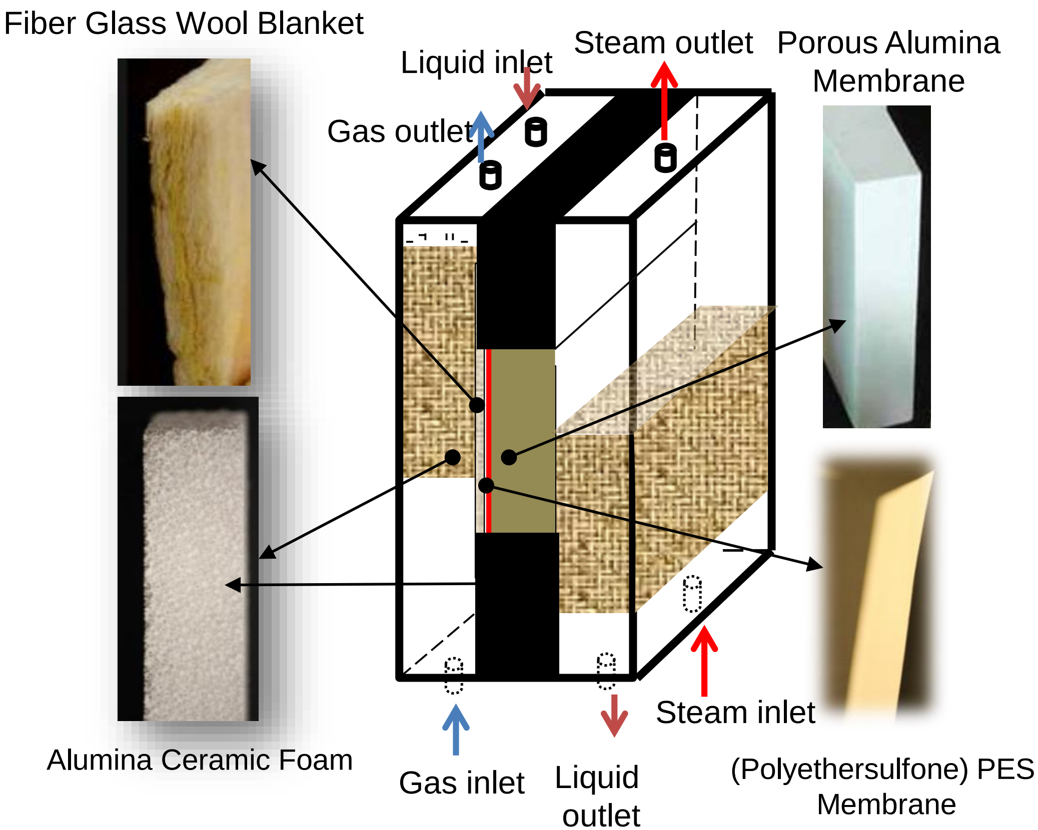
- ☐ *Selective permeation of the rich solvent through the membrane into the desorber*
- ☐ *How to facilitate the lateral flow of liquid in the unit*





A comparison of the conventional amine system with the proposed ‘combined’ process

Technical Approach



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*

Key milestones

- Completed
- In progress
- Not started

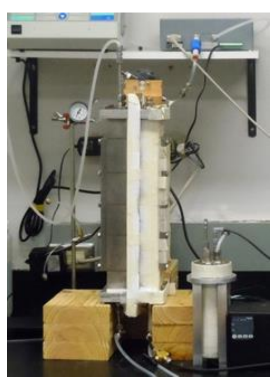
BP1:

Hydrodynamic and mass transfer studies of ceramic foam

10/2011-6/2012

BP2:

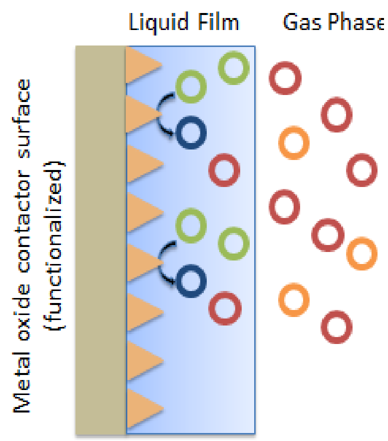
Lab-scale Prototype Design and Test



6/2012-4/2013

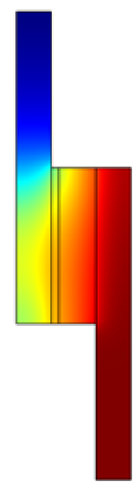
BP3:

Catalytic desorption of CO_2 using metal oxides



9/2012-12/2014

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



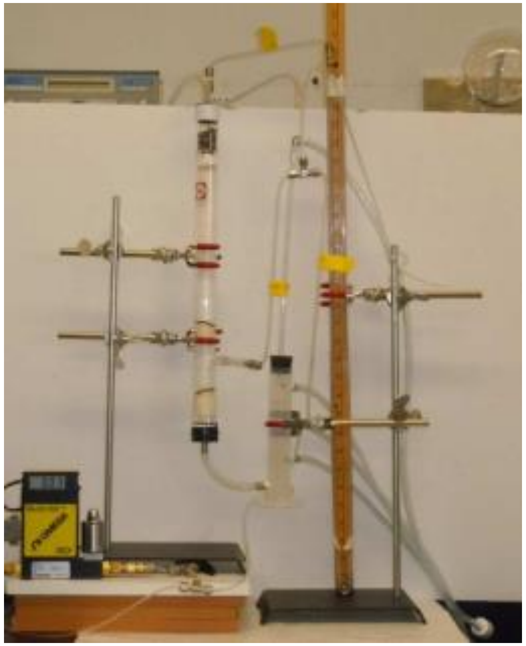
4/2014-10/2014

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

10/2014-3/2015

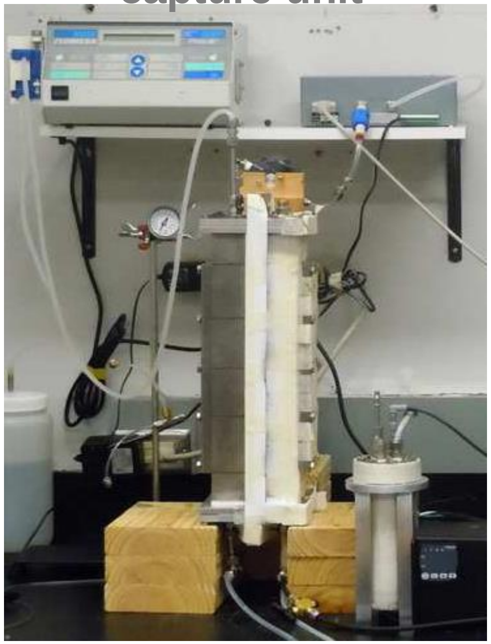
Testing Equipment Facilities

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

Lab-scale combined absorber/desorber CO_2 capture unit

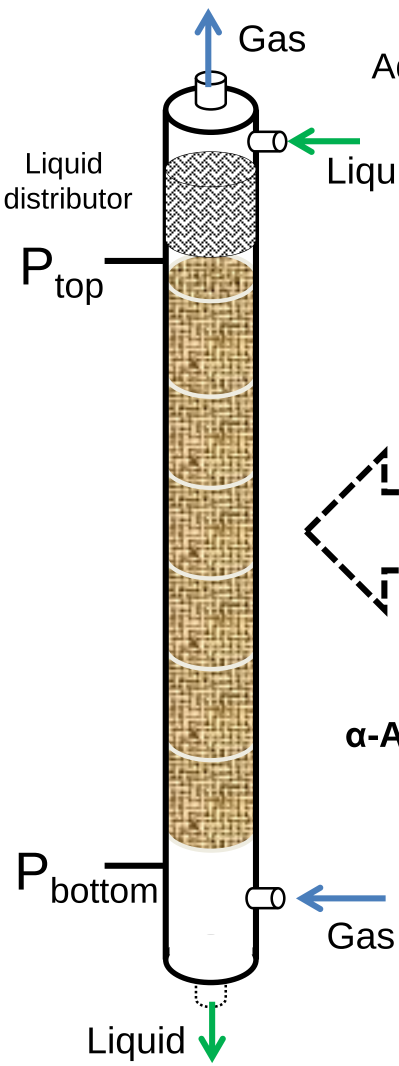


- Demonstrate the feasibility of the concept of a performing CO_2 absorption and stripping in a single integrated unit
- Parametric and optimization studies

Bubble reactor for catalysts screening tests

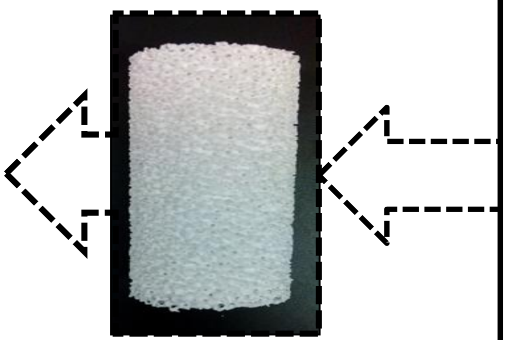
- Solid metal oxide catalysts screening test

Hydrodynamic and mass transfer studies:
1D ceramic foam column

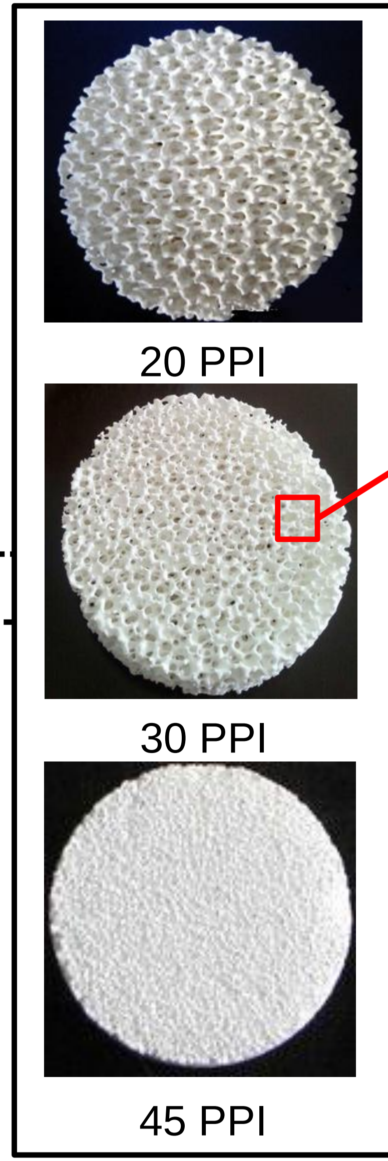


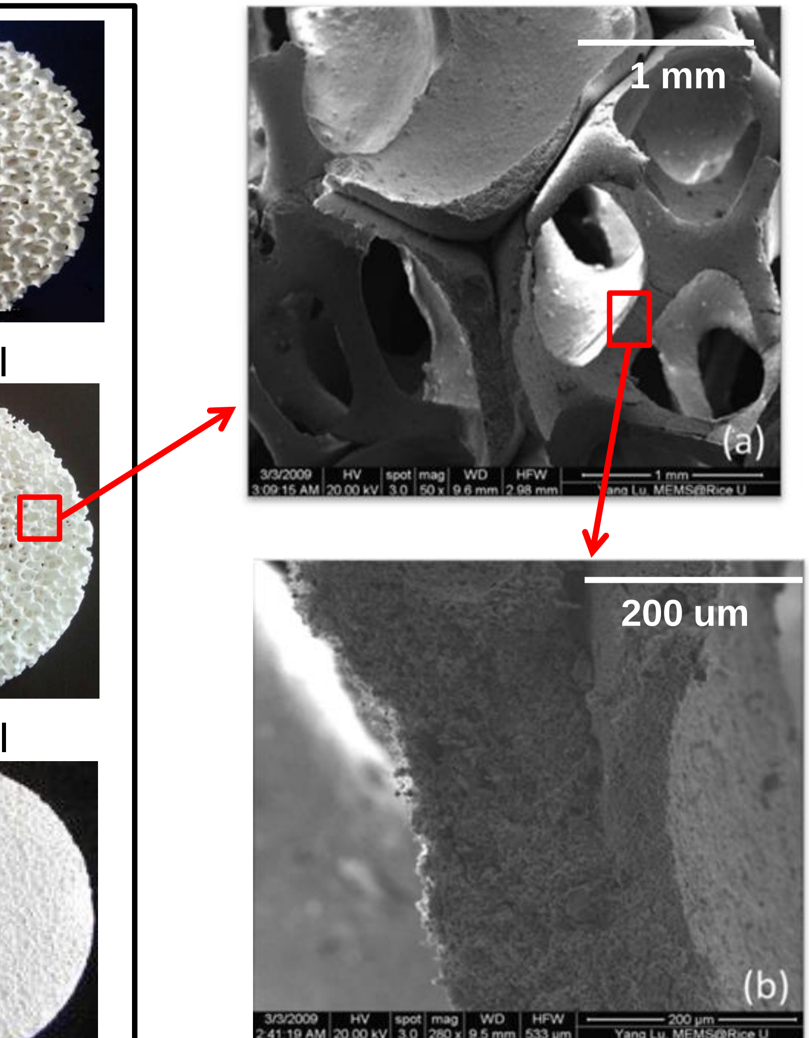
Absorbent:
Aqueous Diglycolamine (DGA) 30 wt%

Structure:



α-Al_2O_3 ceramic foam





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

Material Properties

Advantages of ceramic foam:

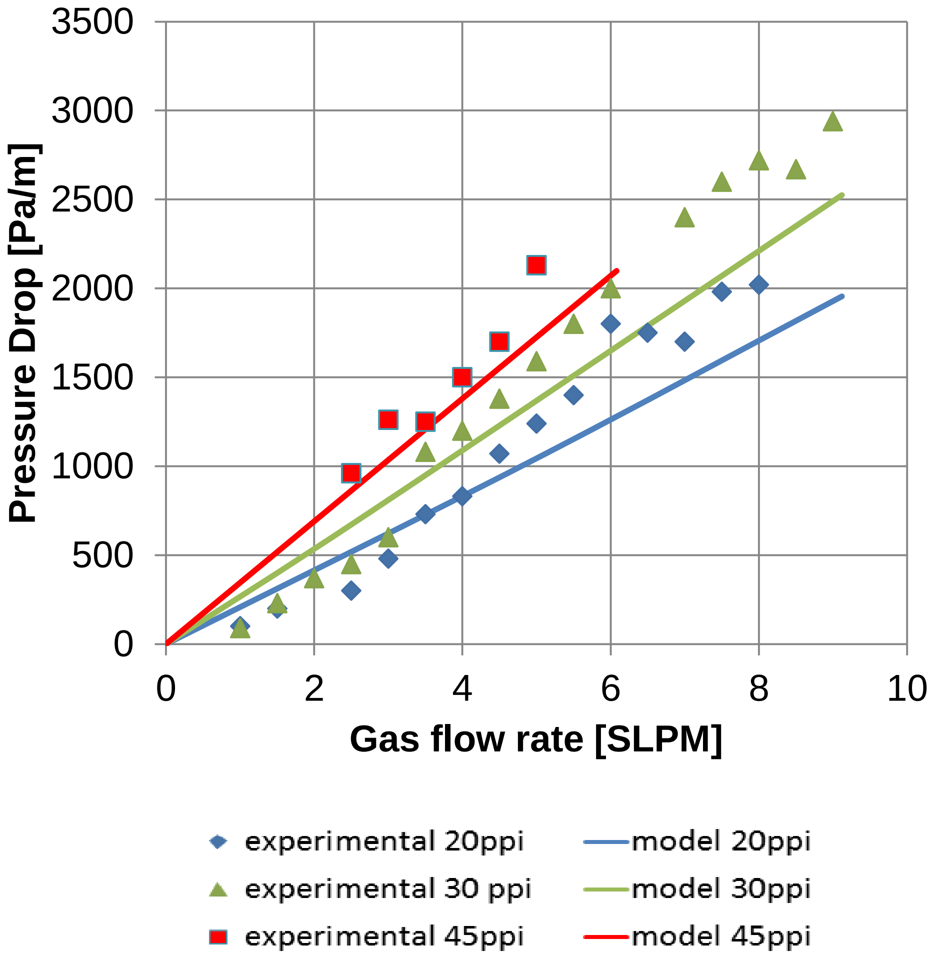
1) Low bulk density and pressure drop
2) Very high geometric surface area and macro-porosity (80%-90%)
3) Regulated pore-size and ease of reproducibility of structure
4) Low pressure drop
5) High structural uniformity

Packing Type	Structure	Porosity (%)	S (m^2/m^3)	Bulk density (g/cm^3)	Equivalent Pore diameter (mm)	Permeability (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}

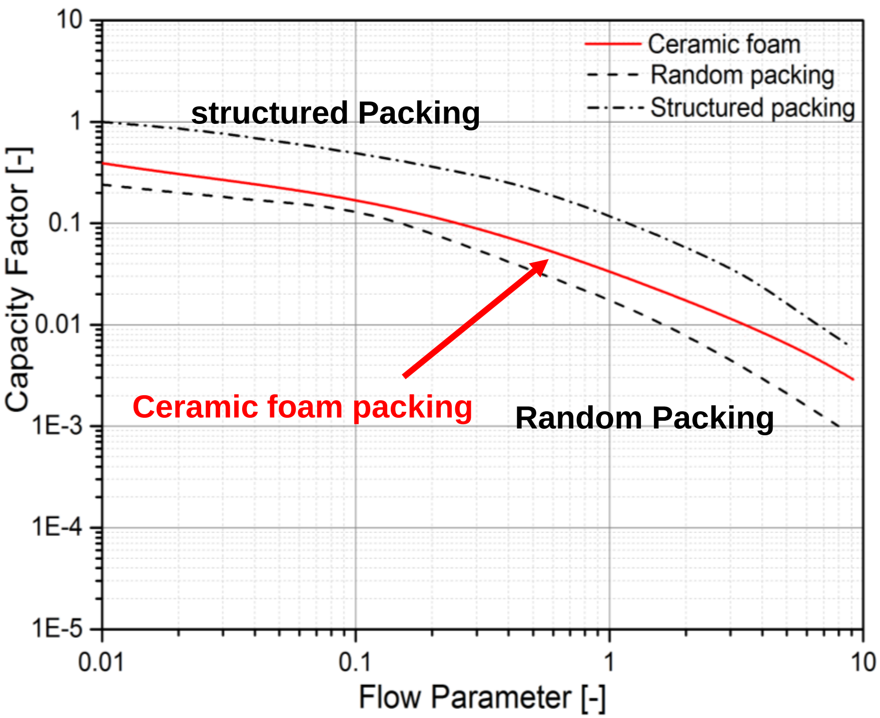
(a) PPI: Number of pores per linear inch length; (b) C.P.Stemmet,IChemE, 2006 (c) Jerzy Maćkowiak, IChemE, 2011 (d) www.**ask-chemicals**.com

(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



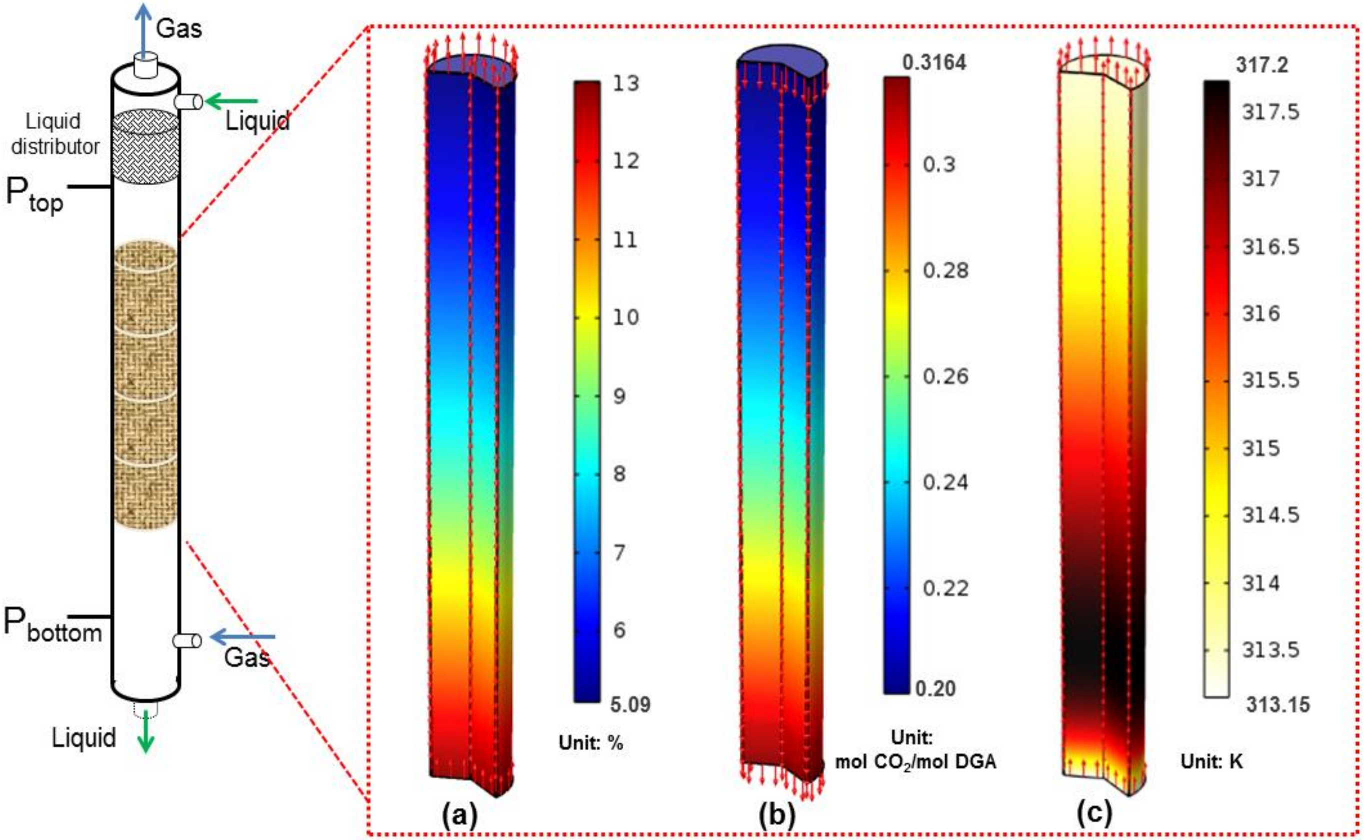
$$\text{flow parameter} = \left(\frac{L'}{G'}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$$

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

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

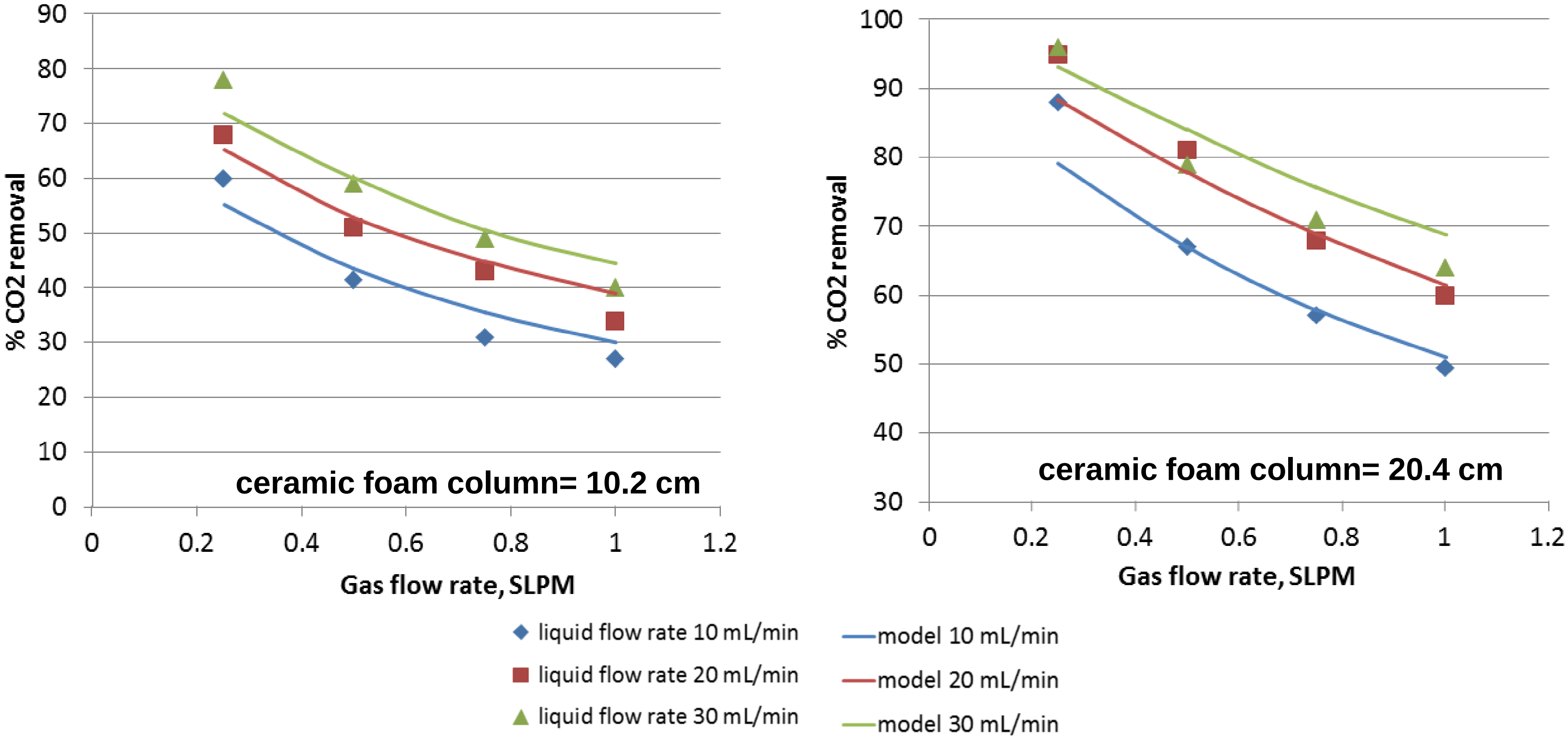
1-D model:
Simulation of CO_2 separation in ceramic foam column

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 solvent; gas phase: 13% CO_2/87% N_2; absorption temperature: 40 ^oC; lean loading: 0.2 mol CO_2/mol DGA

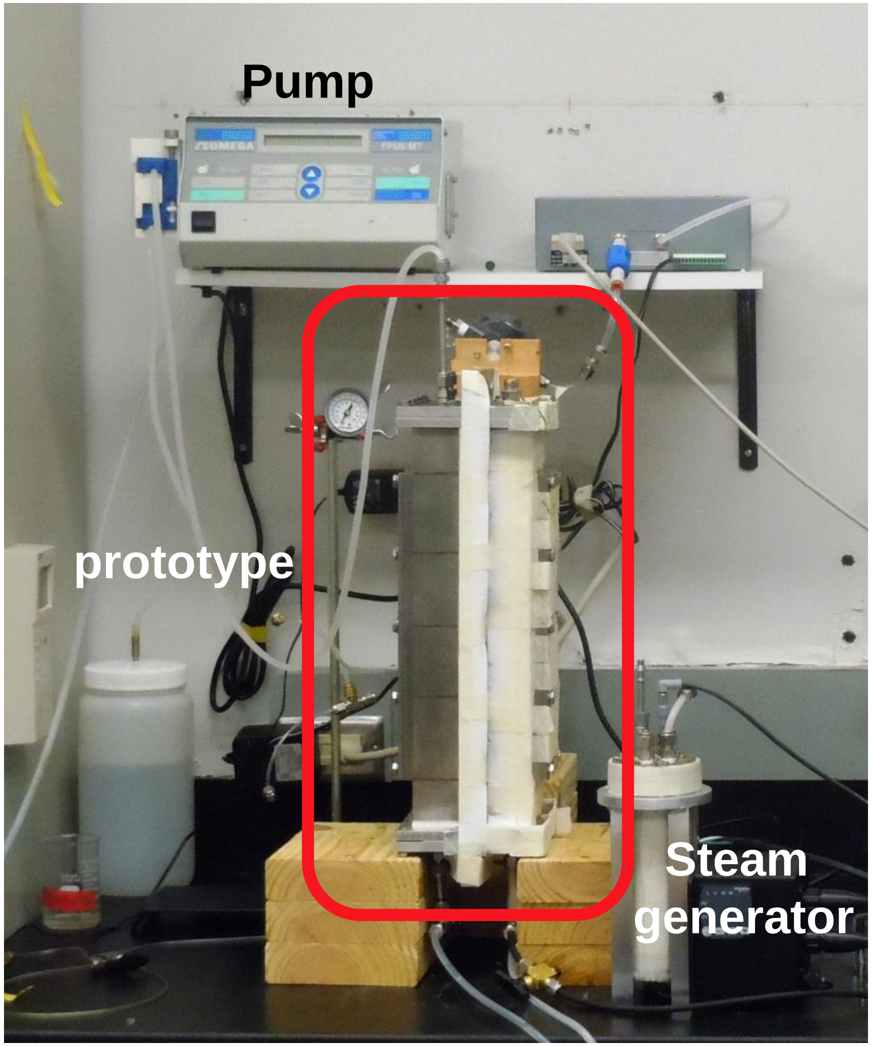
Experimental and Simulated CO_2 Removal Ratio
(ceramic foam column= 10.2 cm & 20.4 cm)

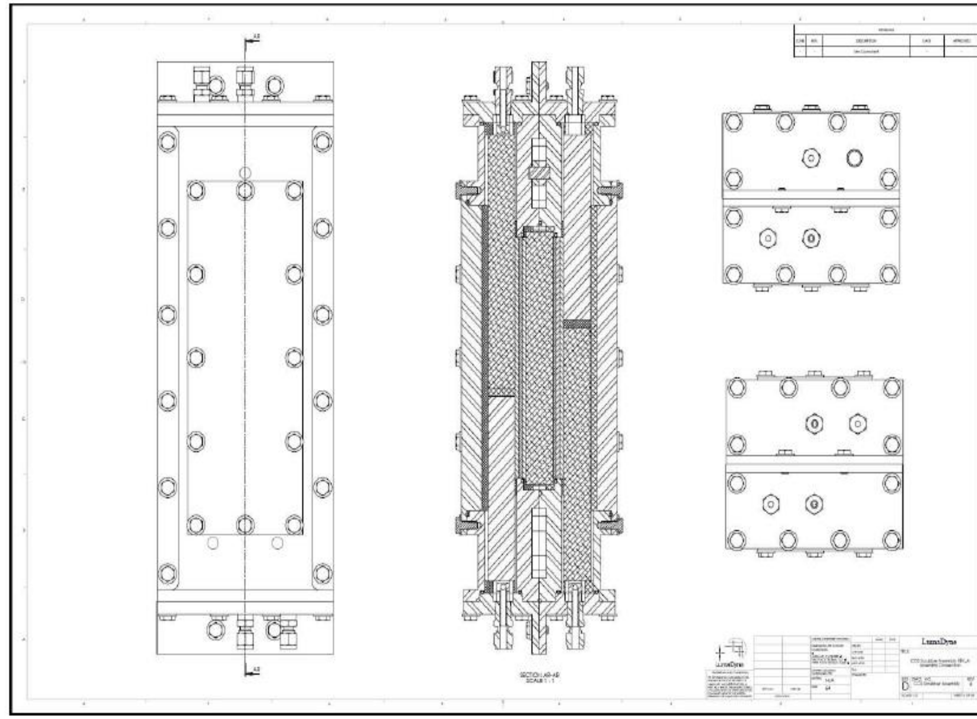


Experimental vs Modelling

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

Stainless steel prototype of Integrated CO_2 Absorber and Desorber Unit

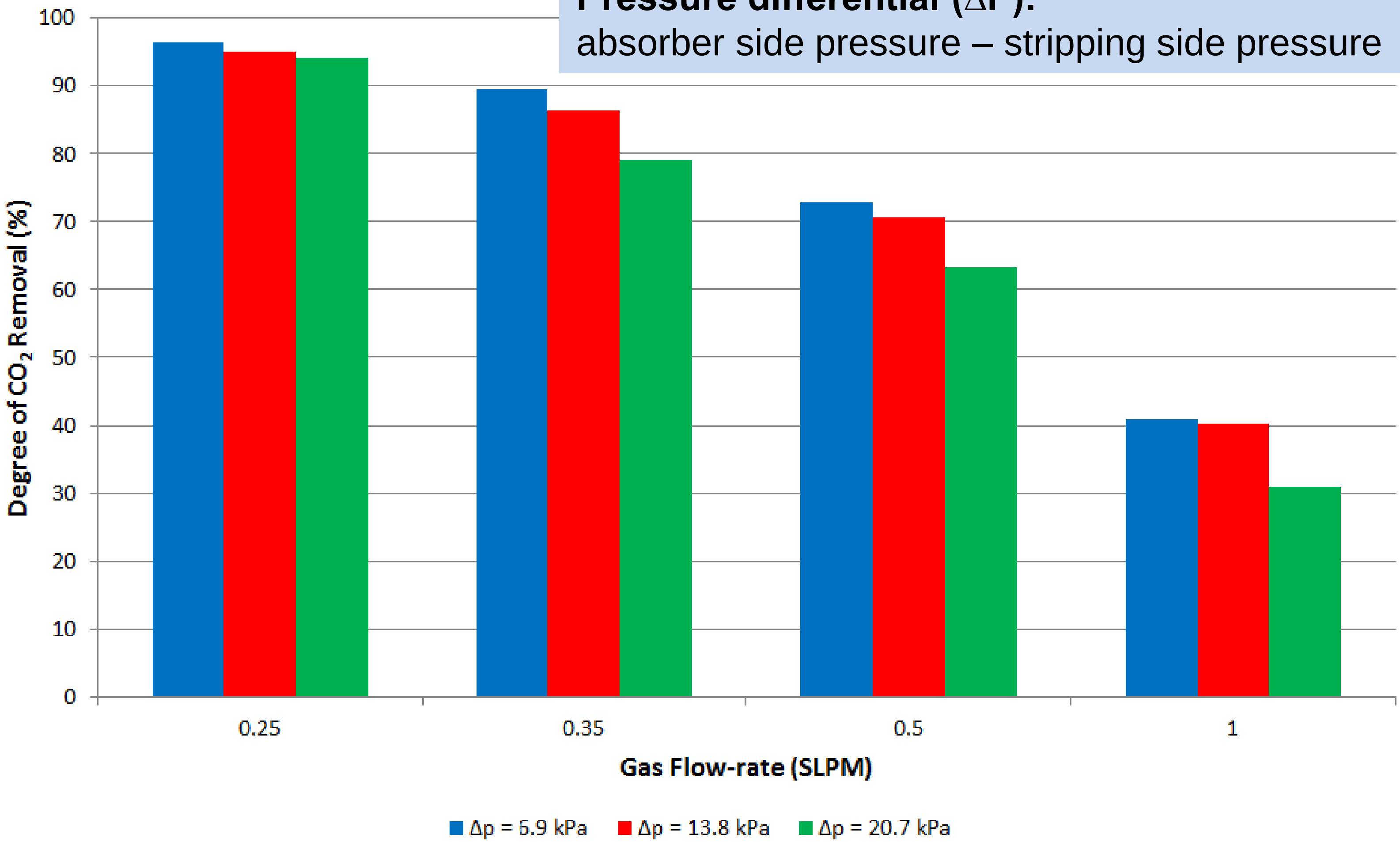




Experimental setup developed for the proof-of-concept demonstration

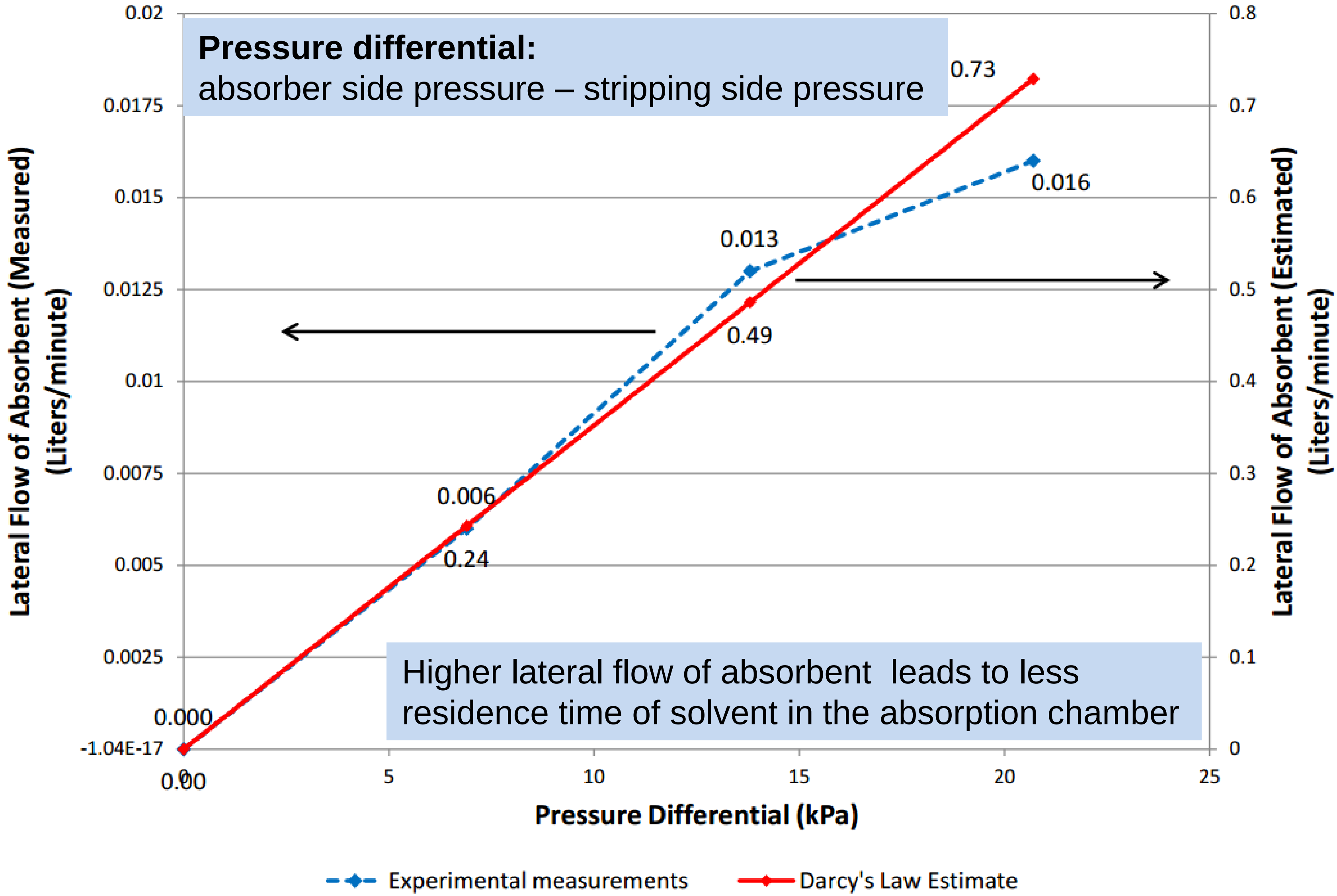
Combined Absorber and Stripper System: Degree of CO_2 Removal

Pressure differential (ΔP):
absorber side pressure – stripping side pressure



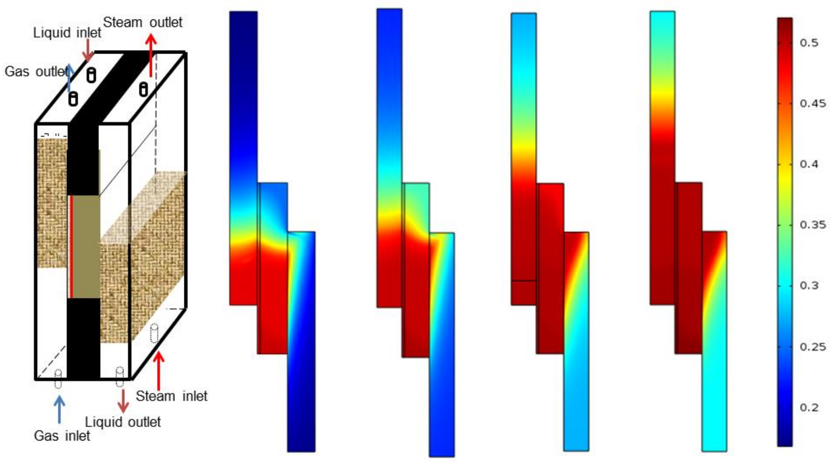
Degree of CO_2 removal at variable gas flow-rates and absorbent flow-rate of 0.01 liters per minute (LPM), (DGA solvent)

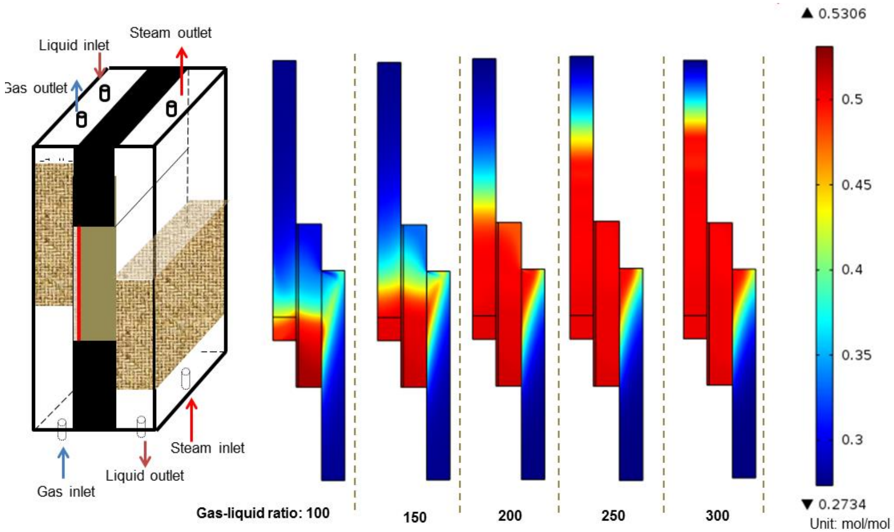
Combined Absorber and Stripper System: Lateral Flow of Absorbent



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.

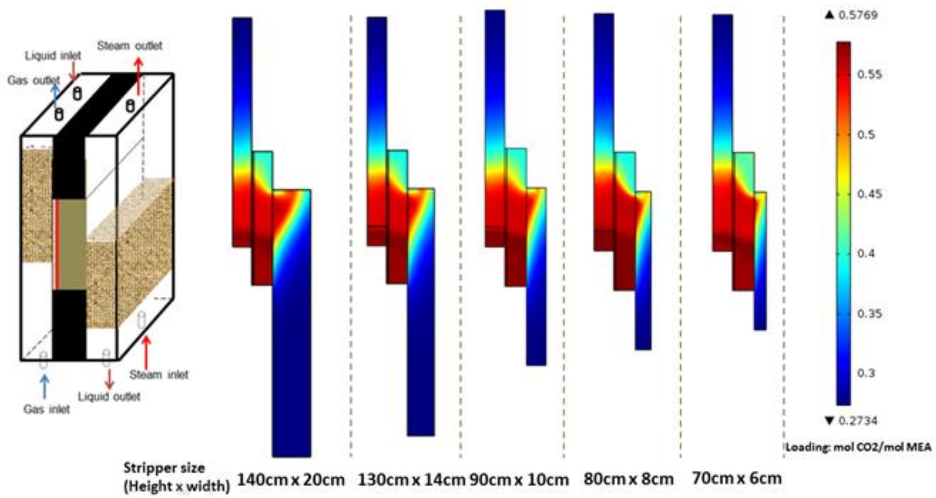
- ◻The CO_2 lean solvent loading (mol CO_2/mol MEA)

  The solvent CO_2 lean loading of 0.27 mol CO_2/mol MEA was recommended.

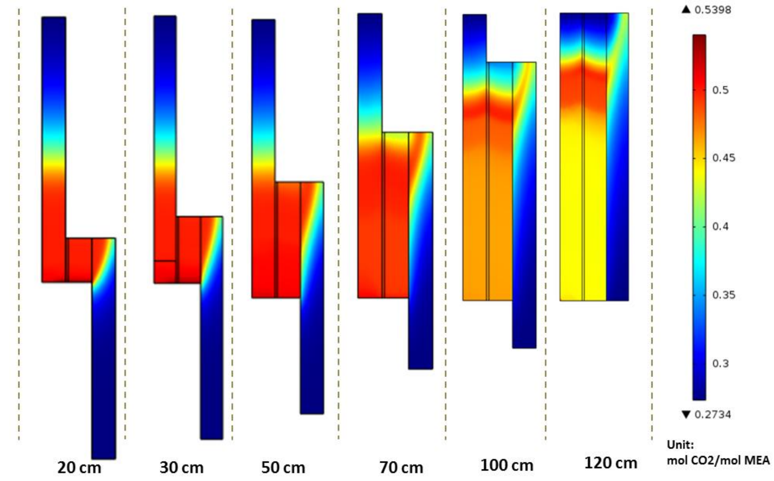
- ◻Stripper operating temperature

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

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

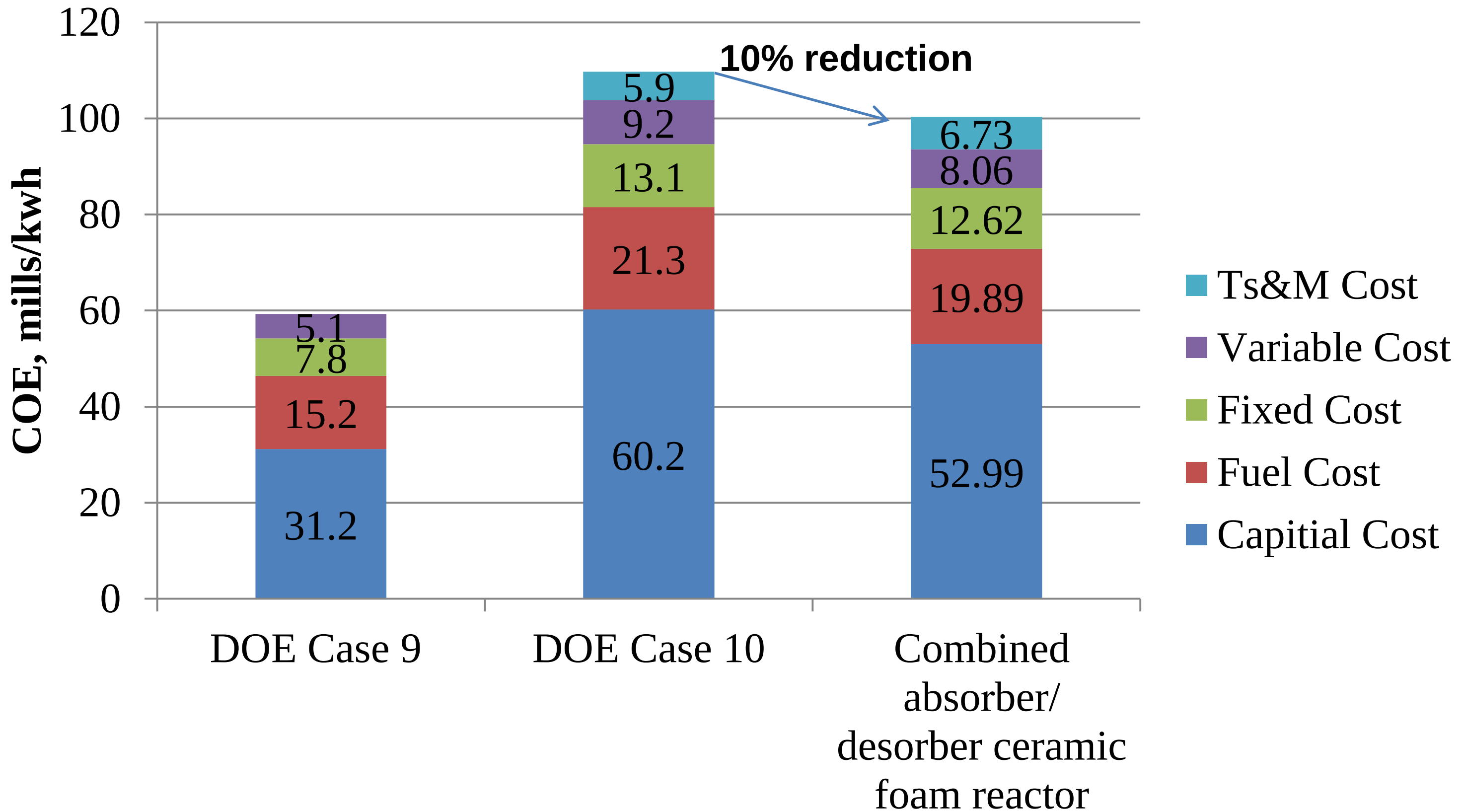
    Optimum absorber/stripper overlapping height is expected to be around half length of the absorber with lowest regeneration heat consumption and over 90% CO_2 removal efficiency
  - Membrane section thickness

    Optimal membrane section thickness is around 10 cm.

Techno-economic analysis (TEA) results

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

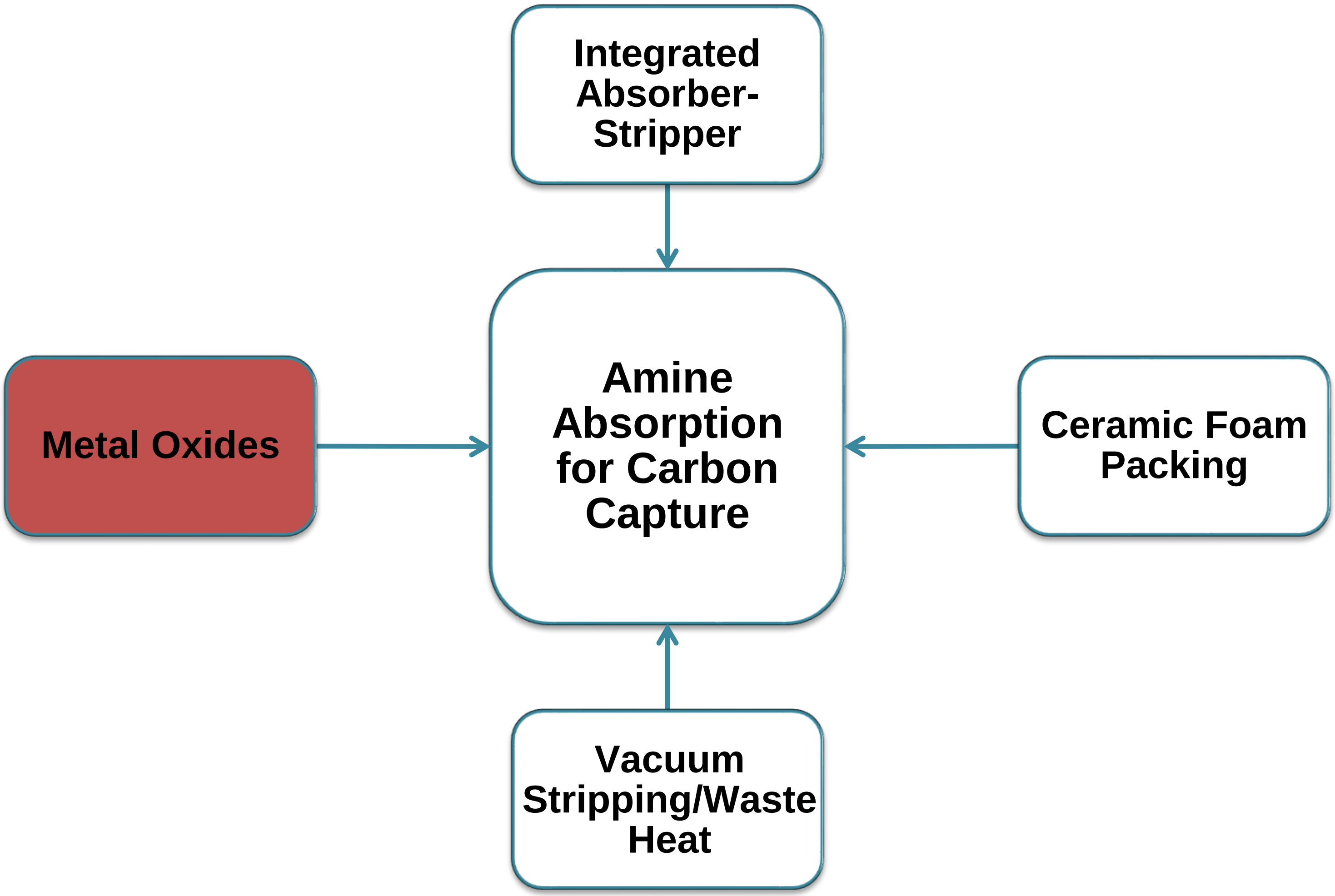
- Absorbent: 30 wt% MEA, lean loading 0.27 mol/mol
- Desorption temperature 100 °C
- All at 90% capture ratio
- CO_2 compression to 150 bar



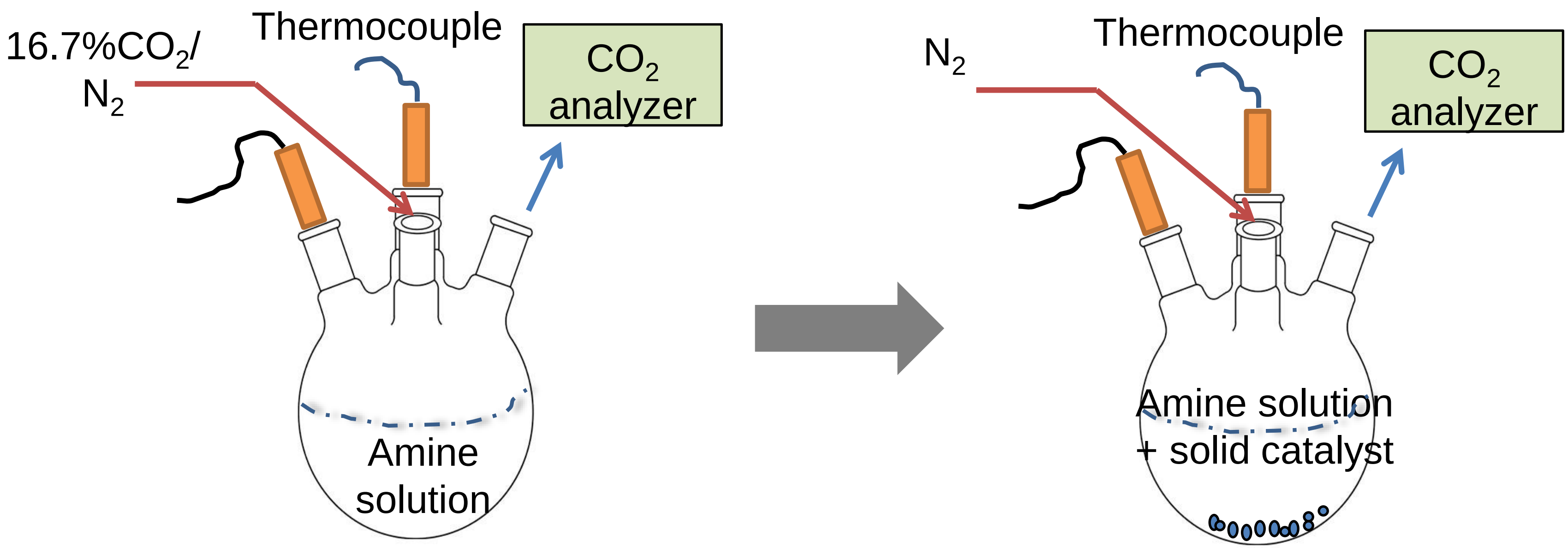
* In 2007 US$

Our Approach: Using Metal Oxides during Desorption

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



Experimental Setup

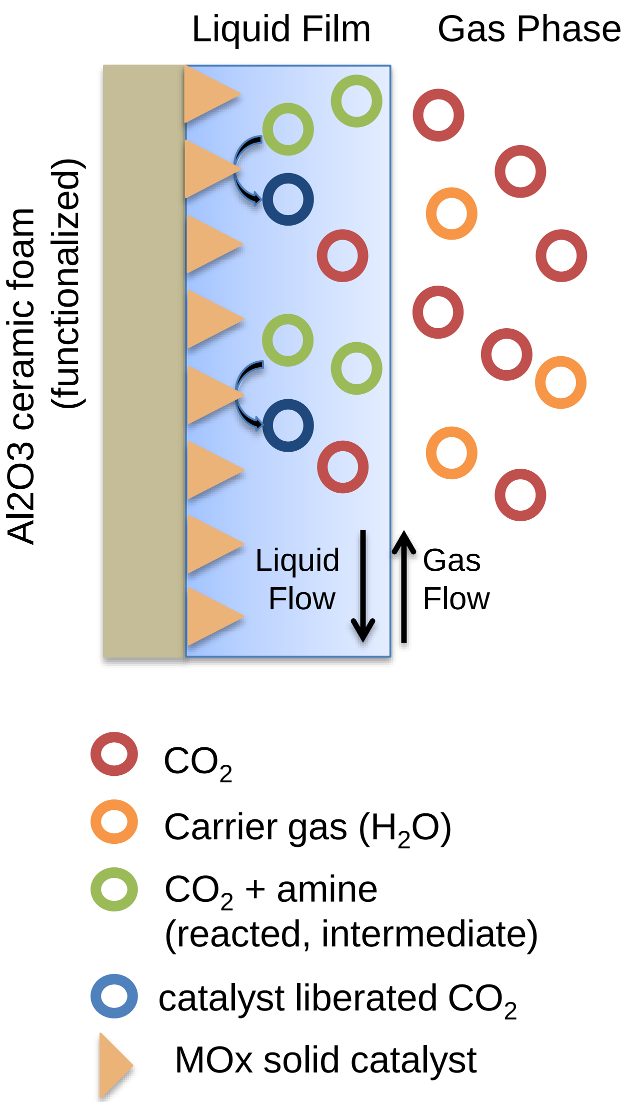


Absorption at 40±2ºC **Desorption at 90±7ºC**

- 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}

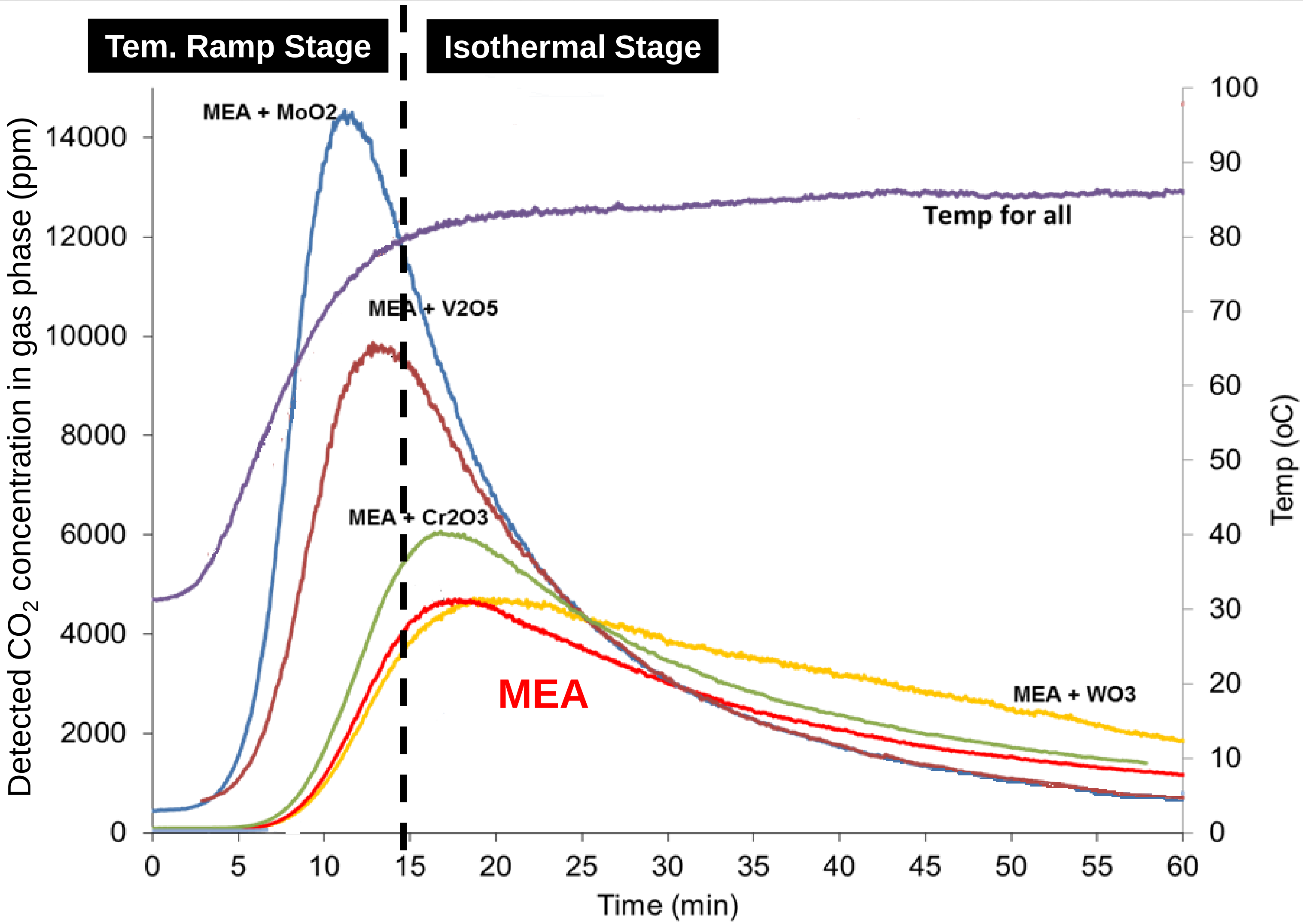
Solid Materials Tested

Desorber side

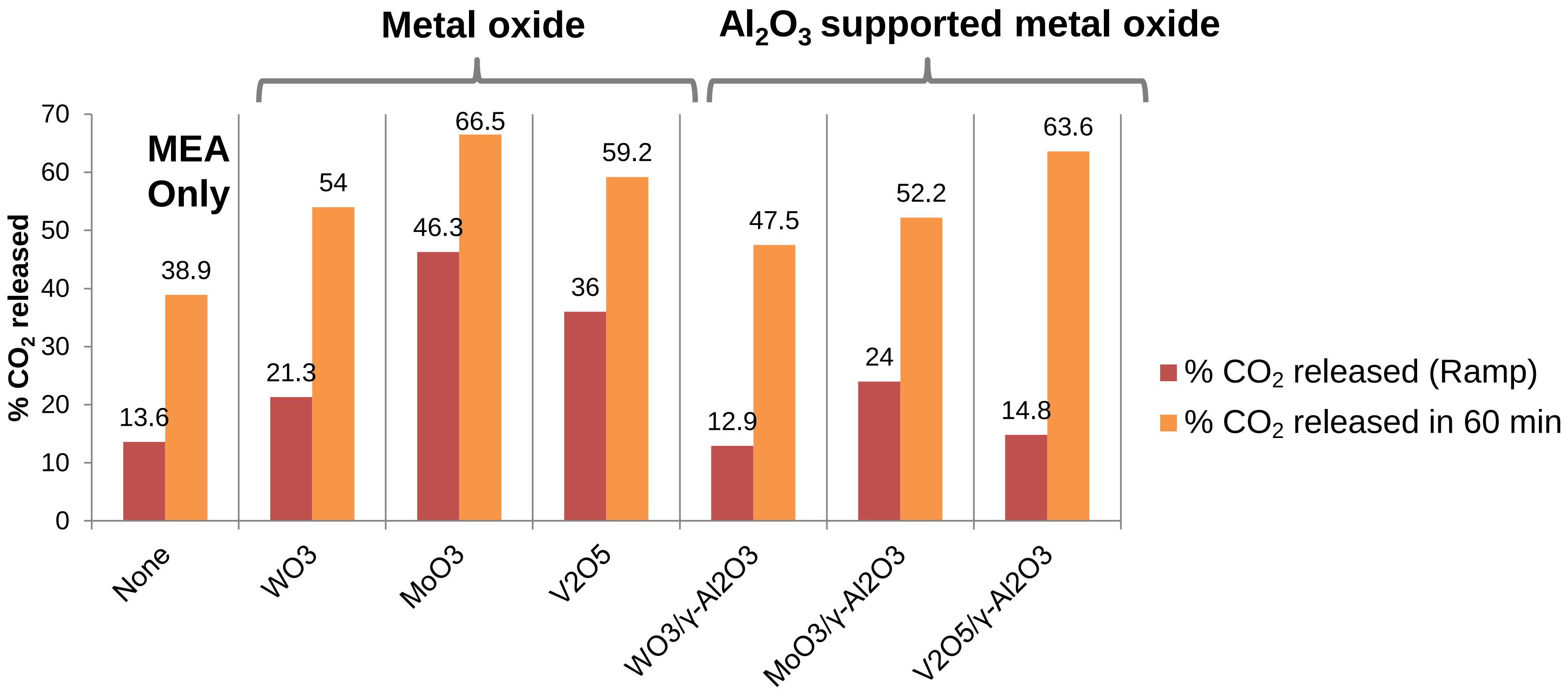


Material	IEP	Surface Area (m^2/g)	Surface Density (M-atoms/nm^2)	γ-Al_2O_3 supported catalyst
WO_3	0.3	1.2	--	--
V_2O_5	1-2	4.5	--	--
MoO_3	2.5	0.9	--	--
MgO	12-13	115.8	--	--
WO_3 (7.5 wt%) /γ-Al_2O_3	--	49.3	6.0	Yes
V_2O_5 (1.3 wt%)/γ-Al_2O_3	--	137.9	7.7	Yes
MoO_3 (4.2 wt%)/γ-Al_2O_3	--	80.0	7.1	Yes

Screening of Metal Oxides for CO_2 Desorption (MEA)



CO_2 catalytic desorption results



- All desorption at 85 ^oC, except V_2O_5 /γ-Al_2O_3 desorption at 91 ^oC
- 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% CO_2 desorption increment.

Summary and Conclusions

- **Combined absorber/desorber CO_2 separation process**
  - Hydrodynamic and mass transfer studies on 1D ceramic foam column
  - Demonstrate the feasibility of CO_2 capture in lab-scale "combined" unit
  - Successful development of 1D and 2D model to simulate CO_2 capture in "combined" system
  - Performed a sensitivity analysis and process optimization
- **Techno-economic analysis of combined absorber and desorber system**
  - 10% COE reduction compared with DOE case 10
- **Catalytic desorption of CO_2 using metal oxides**
  - Metal oxides represent a new approach to enhance CO_2 desorption and reduce the desorption temperature
  - Al_2O_3 supported catalysts are also available to catalyze CO_2 desorption

Acknowledgements

Personnel

- Ms. Elaine Everitt, DOE NETL
- Dr. Joe Powell, Chief Scientist at Shell Oil Company
- Dr. TS Ramakrishnan, Scientific Advisor at Schlumberger-Doll Research Center
- Hirasaki Group & Wong Group members at Rice University

Additional Funding Support

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- Schlumberger

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Schlumberger