NATURAL RESOURCES CANADA - INVENTIVE BY NATURE

Basic Reactor Design of CanmetENERGY's Pilot- Scale Pressurized Chemical Looping Conversion

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Fluidization XVI

Guilin, China

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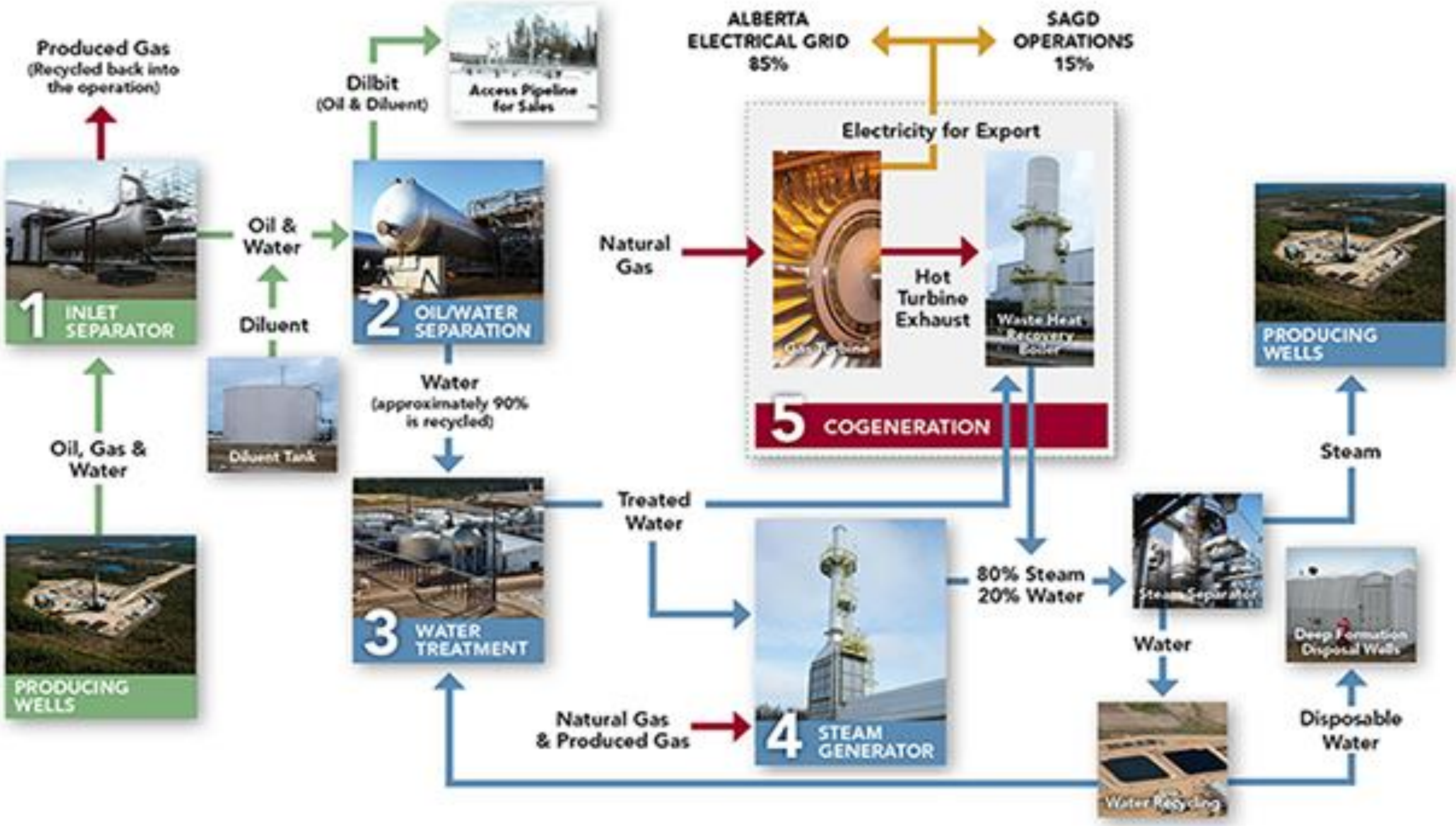
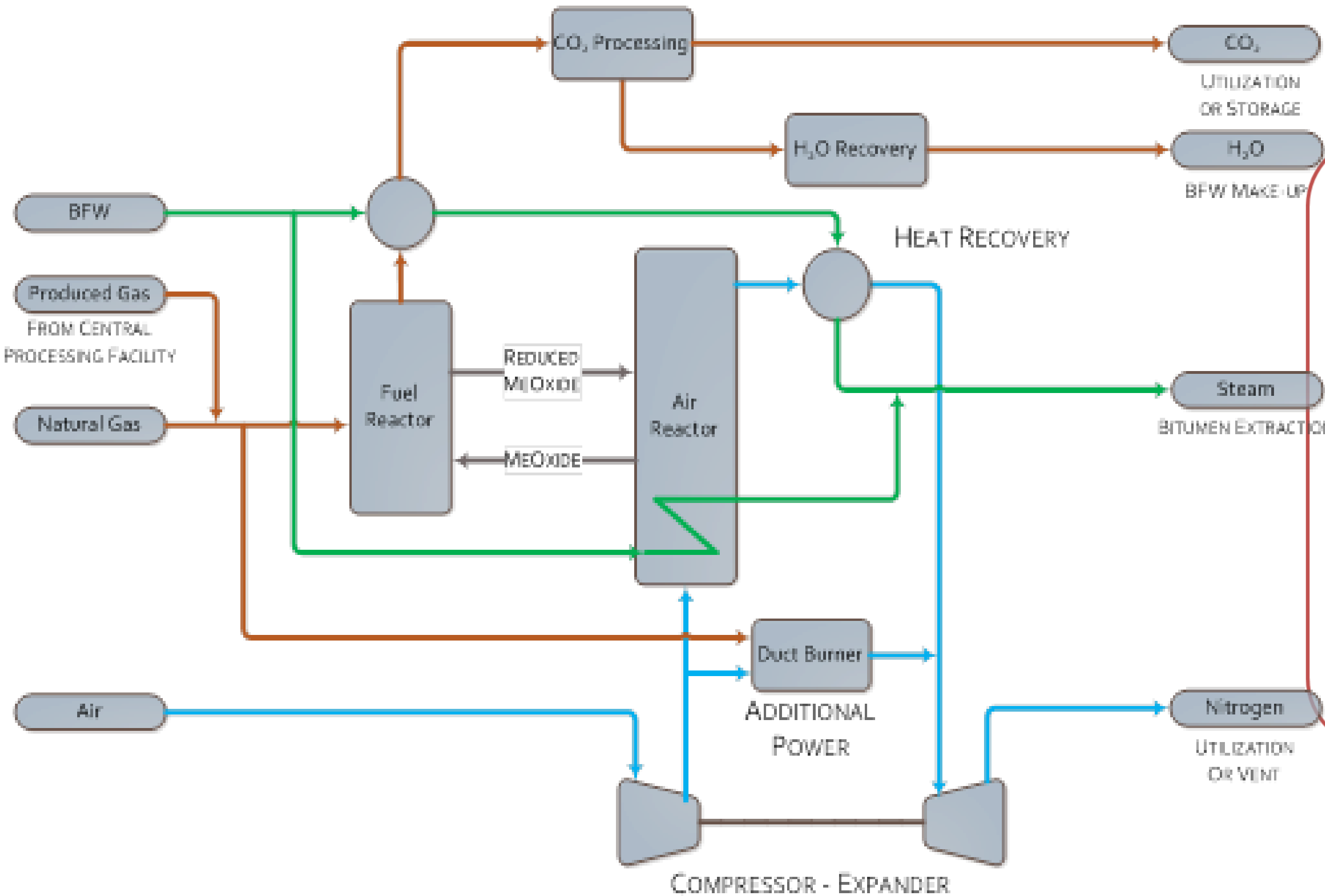
Oil-sands Upgrading Process



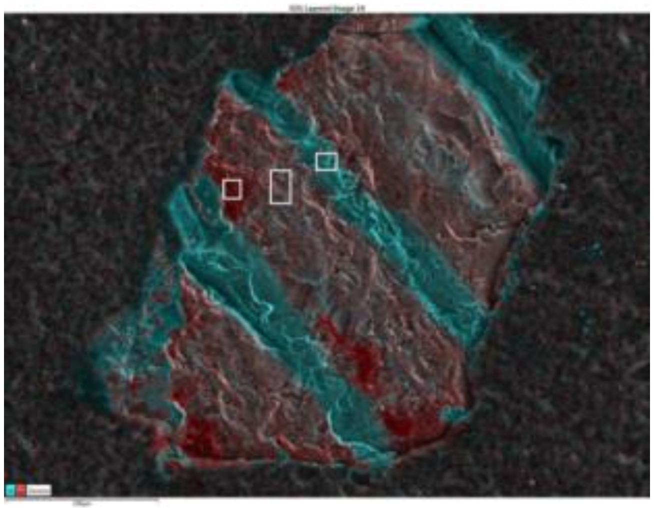
Pressurized CLC For Bitumen Extraction



Why Pressurized CLC?
Higher gas-solid reaction rates
Low cost, non-toxic oxygen carriers
Increased heat transfer rate
Effective use of latent heat
Compact, modular design
Cheaper downstream processing

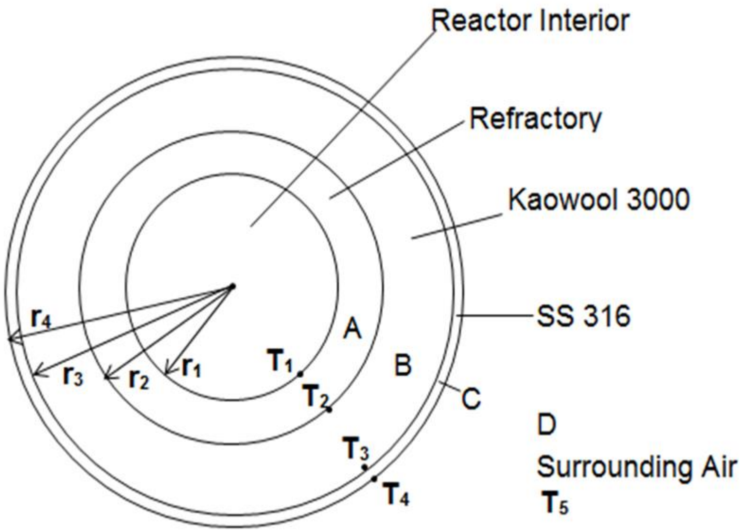
Pressurized CLC Process Benefits

- Advantages of PCLC:
  - 100% CO_2 capture, no SO_x or NO_x emissions **and** clean water generation
  - Separation of steam and CO_2 products – greater flexibility
  - Pressurized operation increases efficiency and reduces capital expenditures – increased reactivity, reduced equipment size, recovery of latent heat
  - Shop built and transportable CCS technology
- Ilmenite ore as the oxygen carrier:
  - Low cost, abundant, and commercially available
  - Spent carrier is potentially a valuable by-product for the titanium industry – upgrading

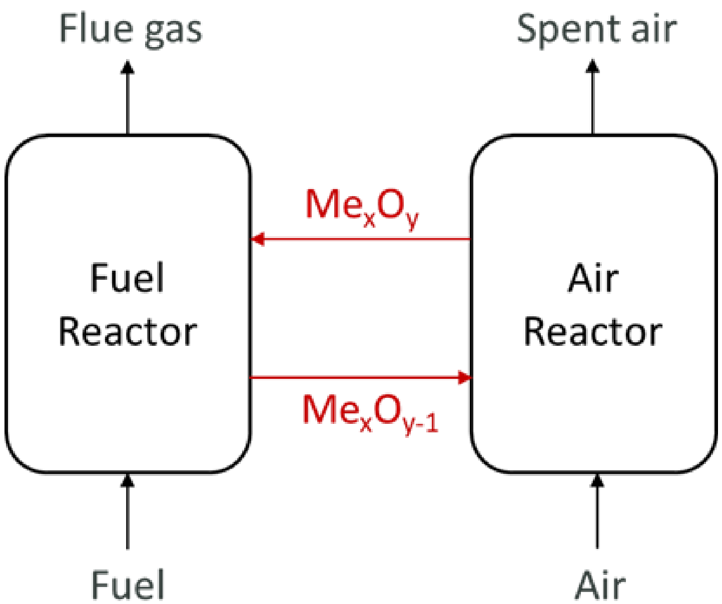


Objectives

- Define battery limits and size of major equipment.
- Determine the optimal inner and outer diameters of the fuel reactor, the air reactor bottom and the air reactor riser based on:
- Maintaining the fluidized bed operation in the desired fluidization regime.
- Minimizing the heat loss through the reactor walls.
- Measurement of the U_{mf} and bubble size under elevated pressures



Gas and Particle Properties



Air and NG properties			Ilmenite particle properties		
ρ_{air}	2.0	kg/m3	ρ_I	4400	kg/m3
μ_{air}	6.2×10^{-5}	Pa	D_{p_I}	1.47×10^{-4}	m
ρ_{NG}	2.6	kg/m3	ϕ_I	0.75	-
μ_{NG}	4.1×10^{-5}	Pa	ε	0.05	-

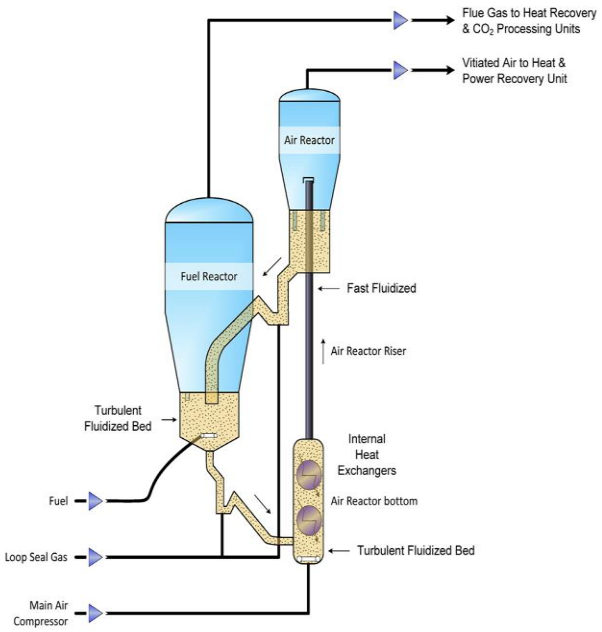
Determining the Fluidization Regime

- Air reactor bottom and fuel reactor: Turbulent regime

  The turbulent regime is desired in fluidized beds in which a gas-solid chemical reaction is taking place which promotes good solid mixing and heat transfer rates.

- Air reactor riser: Fast fluidization regime

  The fast fluidization regime is desired in risers of circulating fluidized beds in which solids are carried over the top of the column and enter a cyclone for separation from the gas.



Air Reactor:		**Check:**
Riser	Fast Fluidizing (u_{tr})	$u_{tr} < u_{top} < u_{dpc}$
Bottom	Turbulent (u_c)	$u_c < u_{bottom} < u_{tr}$
Fuel Reactor:		
Top	Turbulent (u_c)	$u_c < u_{top} < u_{tr}$
Bottom	Turbulent (u_c)	$u_c < u_{bottom} < u_{tr}$

Fluidization Case Study

- To examine the optimal inner diameter (ID) of each the FR, AR, and riser to operate in the required fluidization regime for the widest range of operating conditions.
- To be flexible in operating pressure, temperature, and thermal input (TI). Therefore, the FR, AR, and riser ID's should be chosen such that the desired flow regime is attained for the widest range of each.

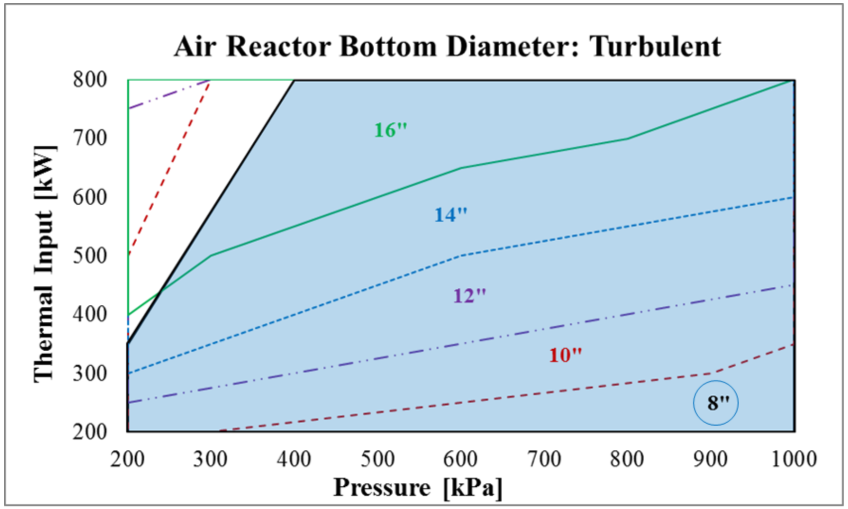
Range of variables considered in the fluidization case study

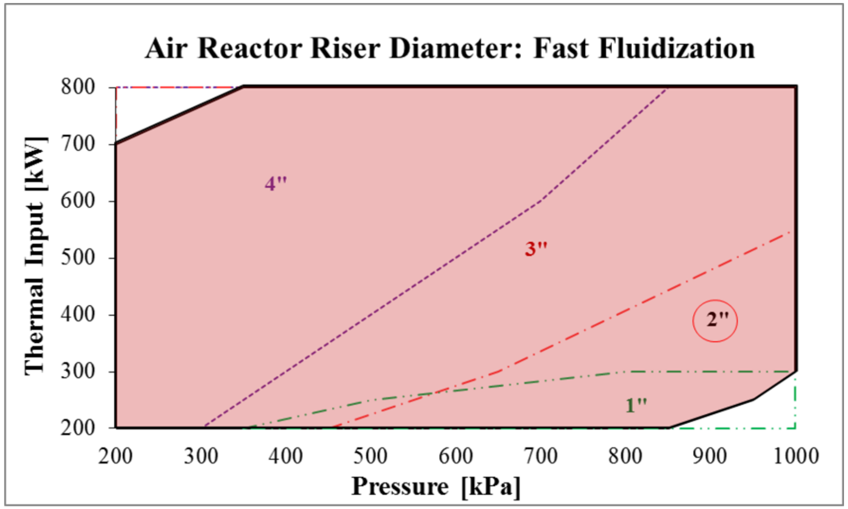
Variable	Range considered
Pressure (kPa)	200 - 1000
TI (kWth)	200 - 800
FR ID (cm)	10.2 - 40.6
AR ID (cm)	10.2 - 40.6
Riser ID (cm)	2.5 - 10.2

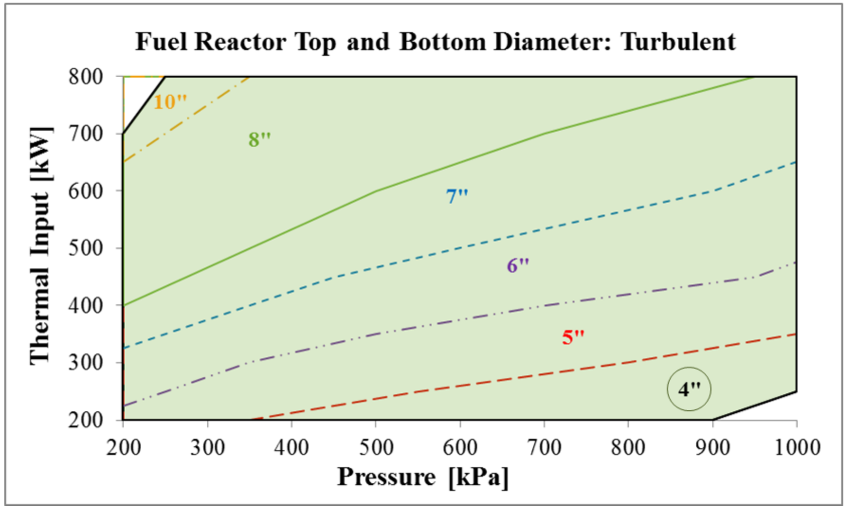
Calculation Methodology

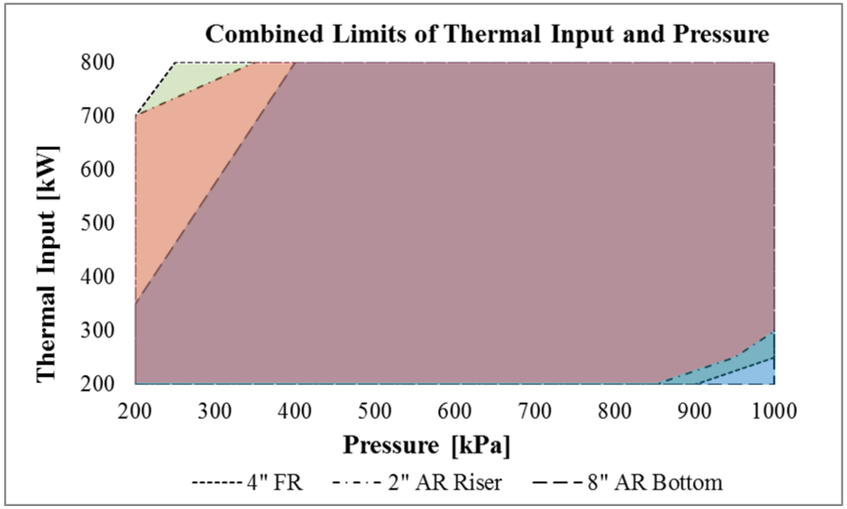
- In this study, the following estimation is used (Bi, Grace and Zhu 1995)
- $u_{c,tr} = Re_{c,tr} \frac{\mu_g}{\rho_g d_p}$
- $Re_c = 0.565 Ar^{0.461}$; $Re_{tr} = 1.53 Ar^{0.5}$
- $Ar = \frac{g\rho_g(\rho_p - \rho_g)d_p^3}{\mu_g^2}$
- The onset velocity is based on the bed voidance (ε), settling velocity (V_s), and net particle circulation flux (G_s) (Kim, et al. 2004)
- $u_{dpc} = 1160\varepsilon V_s \left[\frac{G_s}{\rho_p(1-\varepsilon)V_s}\right]^{-0.9} Ar^{-0.2}$
- $V_s = \frac{g(\rho_p - \rho_g)D_p^2}{18\mu_g}$; $G_s = \frac{\dot{m}_p}{\pi\left(\frac{D}{2}\right)^2}$
- $u_{FR,AR,riser} = \frac{\dot{V}_{NG,air}}{\frac{\pi}{4}D_{FR,AR,riser}{}^2}$

Recommended Inner Diameter



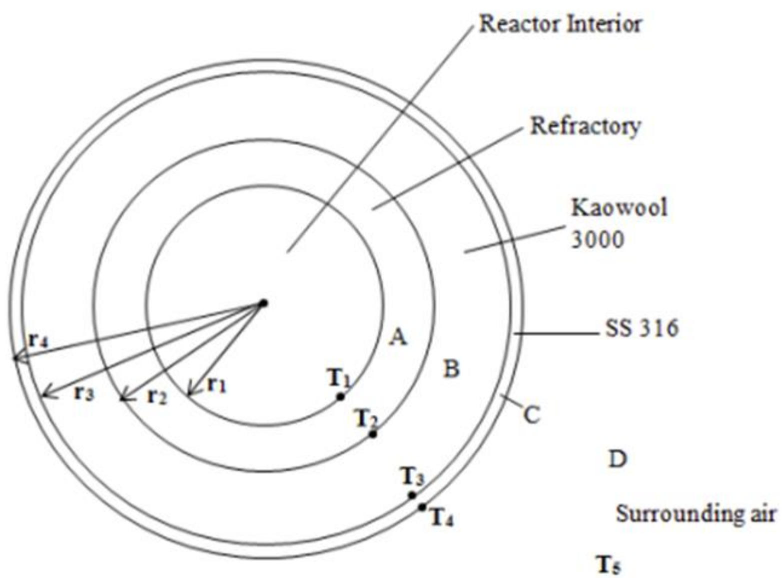






HX case study to determine OD

- To investigate the choice of reactor outer-diameter (OD) and the thickness of each layer of insulation surrounding the reactor sections such that heat-loss is sufficiently minimized without requiring costly over-insulation.
- Each reactor section (FR, AR, and riser) will be insulated with three layers:
  - refractory to withstand the high temperatures of reaction,
  - Kaowool 3000 to act as a strong insulator, and
  - a stainless-stee



Radial cross section of insulation and support layers surrounding the FR, AR, and riser

Heat Flux Equation

- The heat-flux through a cylindrical wall exposed to air is described by (Mills 1999):

- $\dot{Q} = \frac{2\pi k_A L(T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)} = \frac{2\pi k_B L(T_2 - T_3)}{\ln\left(\frac{r_3}{r_2}\right)} = \frac{2\pi k_C L(T_3 - T_4)}{\ln\left(\frac{r_4}{r_3}\right)} = \mathrm{h_c A(T_4 - T_5)}$

Where

$\dot{Q}$ is the heat flux in *W*,

k is the material thermal conductivity in *W/mK,*

L is the height of the reactor in *m*,

T is the wall temperature in $^{\circ}$ *C* or *K*,

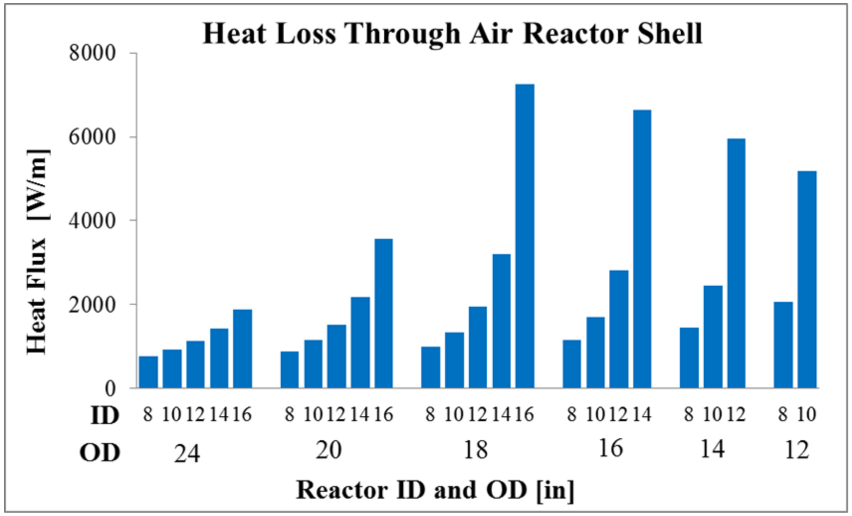
r is the radius in *m,*

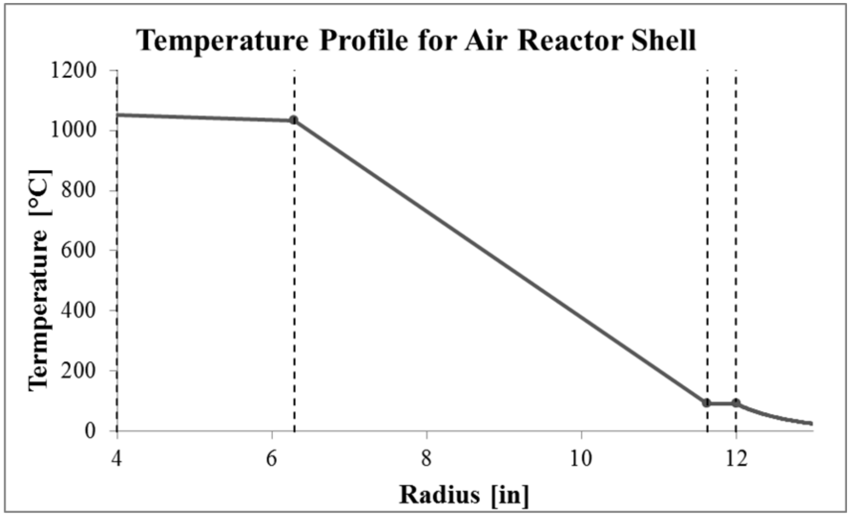
h_c is the convective heat transfer coefficient and *A* is the reactor surface area exposed to air.

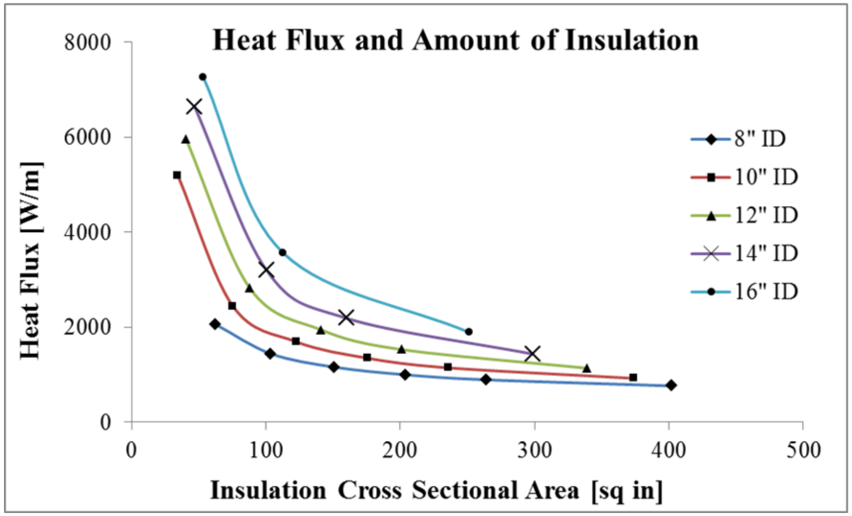
Calculation Assumptions

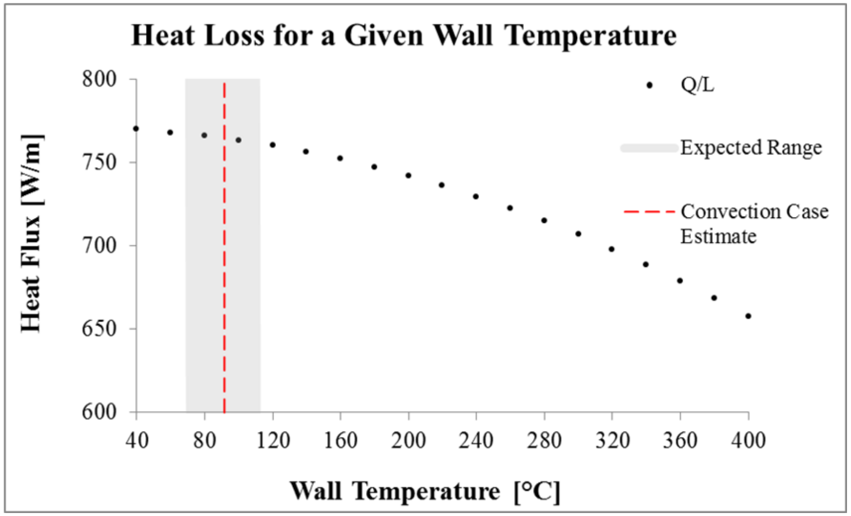
- The following assumptions are made for evaluation of conduction through the walls (middle three terms in Equation):
  - Conduction through air is negligible
  - Conditions are at steady-state
  - Conduction is in the one-dimensional radial direction
  - Contact resistance is negligible
  - Thermal conductivities within one material are uniform throughout the material
- The following assumptions are made for to evaluate convection from the outer-shell to the surrounding air (final term in Equation):
  - Curvature effects are negligible
  - The boundary layer for natural convection begins at the bottom of the cylinder
  - Forced flow over the cylinder is negligible
  - Air behaves as an ideal gas

Recommended Outer Diameter









Recommendation

- Air reactor bottom and fuel reactor: Turbulent regime

  The turbulent regime is desired in fluidized beds in which a gas-solid chemical reaction is taking place which promotes good solid mixing and heat transfer rates.

- Air reactor riser: Fast fluidization regime

  The fast fluidization regime is desired in risers of circulating fluidized beds in which solids are carried over the top of the column and enter a cyclone for separation from the gas.

Reactor Section	**Fluidization Regime**	**Recommended inner diameter**	**Recommended outer diameter**
Air reactor bottom	Turbulent	8”	24”
Air reactor riser	Fast fluidizing	2”	8”
Fuel reactor	Turbulent	4”	24”

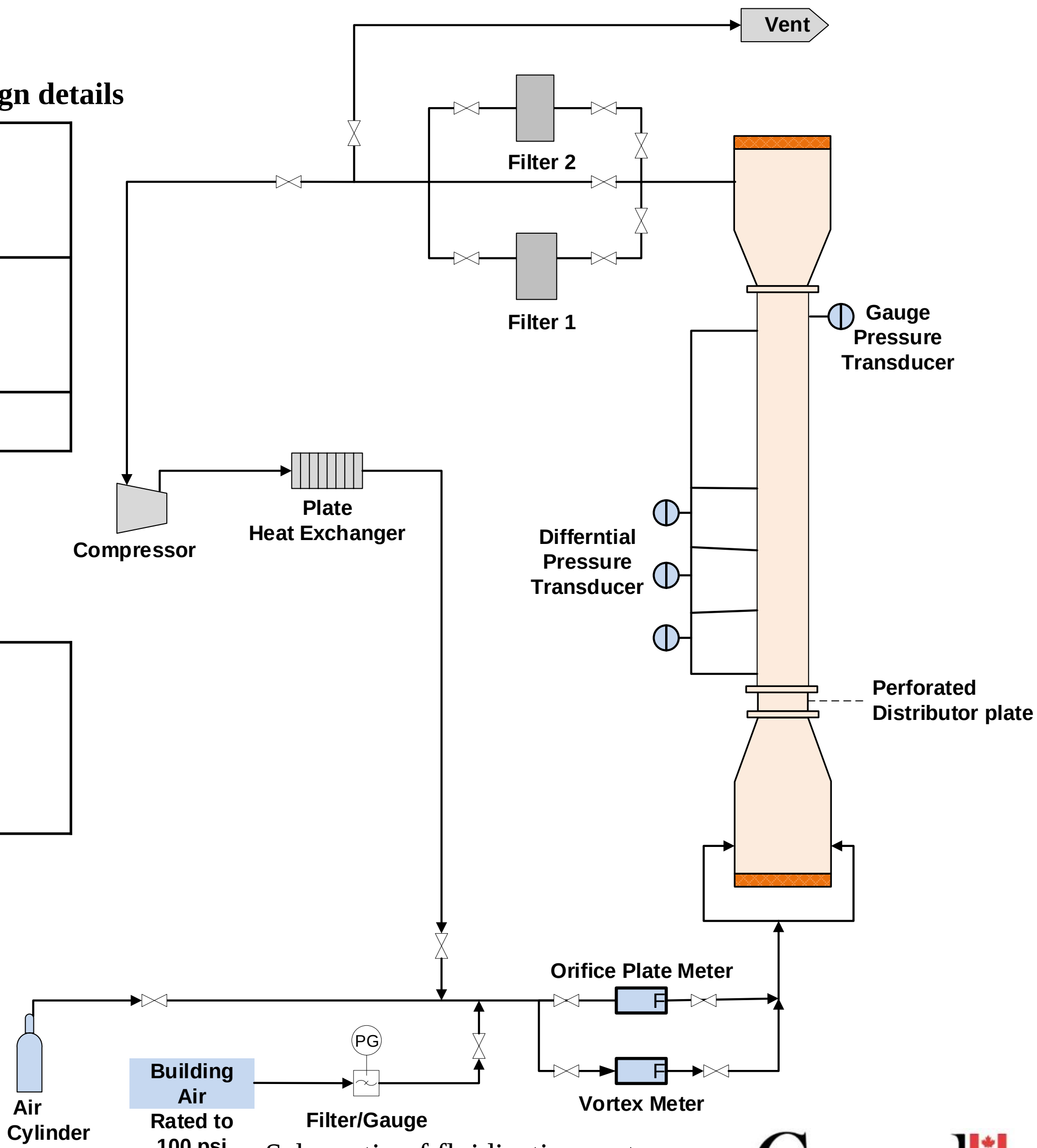
Pressurized Fluidization Facility at uOttawa

Table 1: Operating conditions and fluidization column design details

Column Diameter (m)	0.15 (6 inches)
Fluidization Section Height (m)	3
Column Material	Stainless Steel
Gas Velocity (U/U_{mf})	**< 5.0**
Gas Pressure (bara)	**1-20**
Gas Temperature (°C)	24 ± 1
Inert Bed Static Height (m)	0.50

Table 2: Particle properties

Ilmenite Particles	
Density (kg/m³)	4700
Size distribution (um)	155, 255, 368, 512

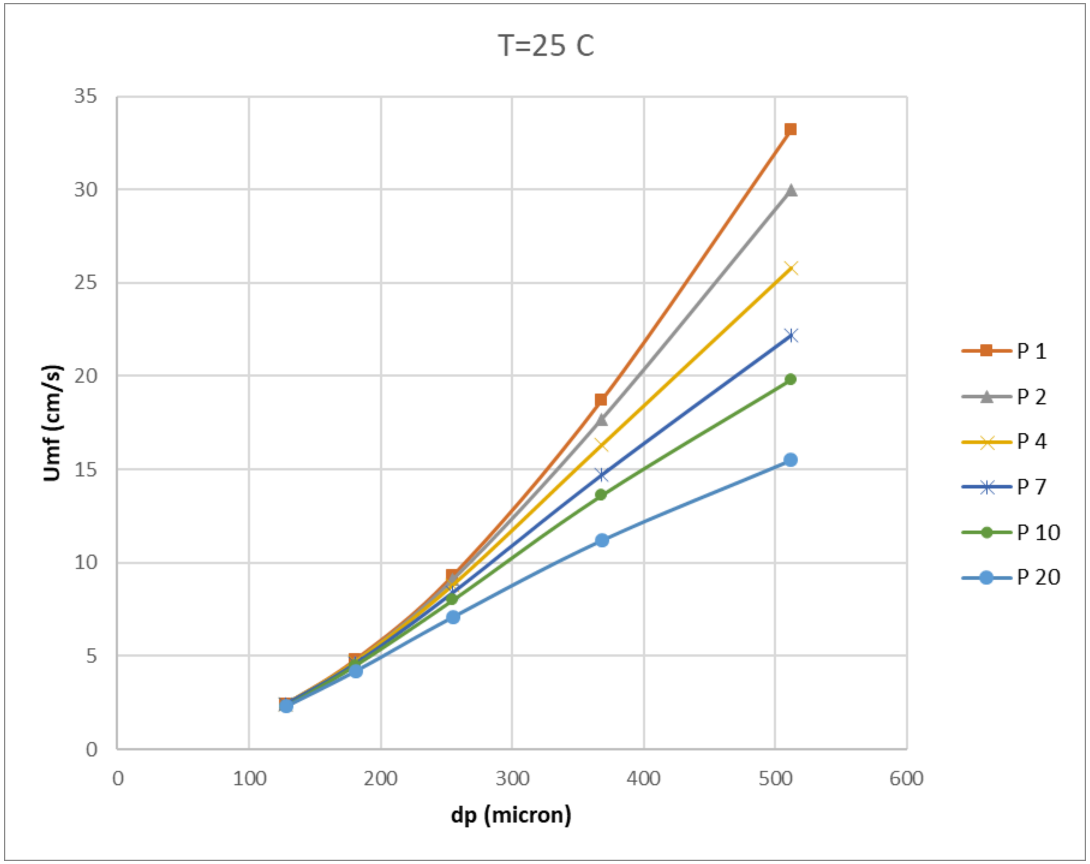


Schematic of fluidization system.

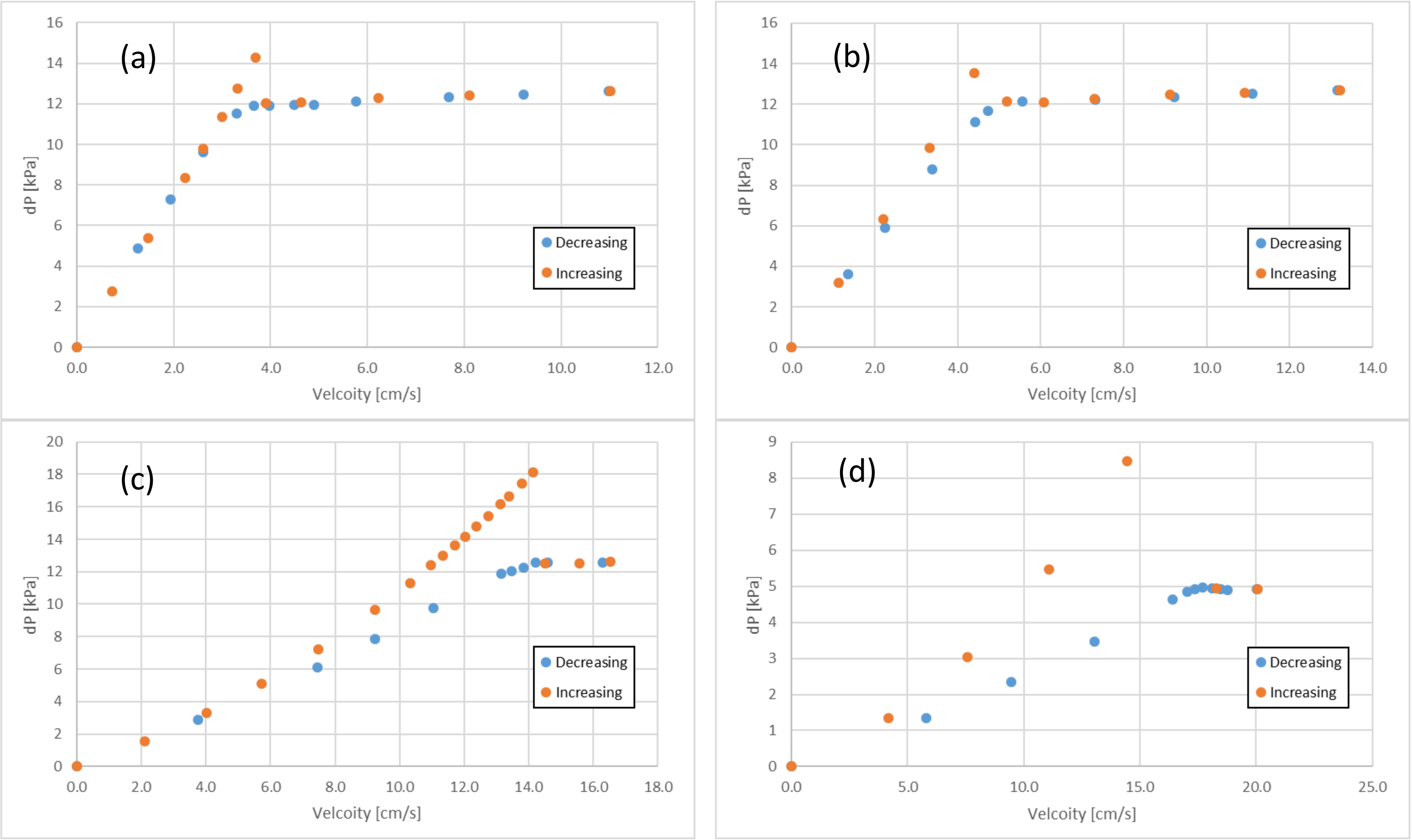
Facility Photos

Calculations based on Wen and Yu

Experimental data			
Cold flow reactor			
umf ≈	11.5	cm/s	
dp,average	300	micron	
Best Correlation to fit data is	**Wen and Yu**		
C1	33.7		
C2	0.0408		
umf	12.7	cm/s	



Recordings for Different Sizes @ 7bar

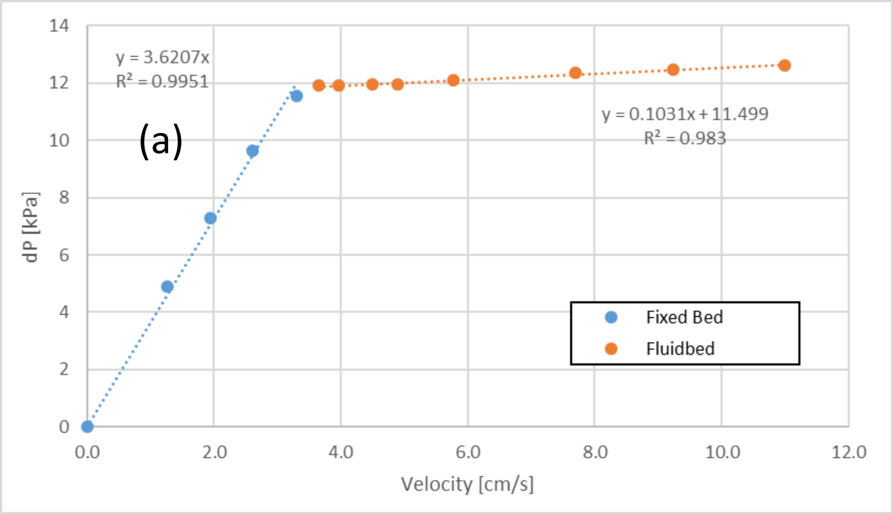


a=155, b=255, c=368, d=512 µm

Recording data for different sizes @ 7bar

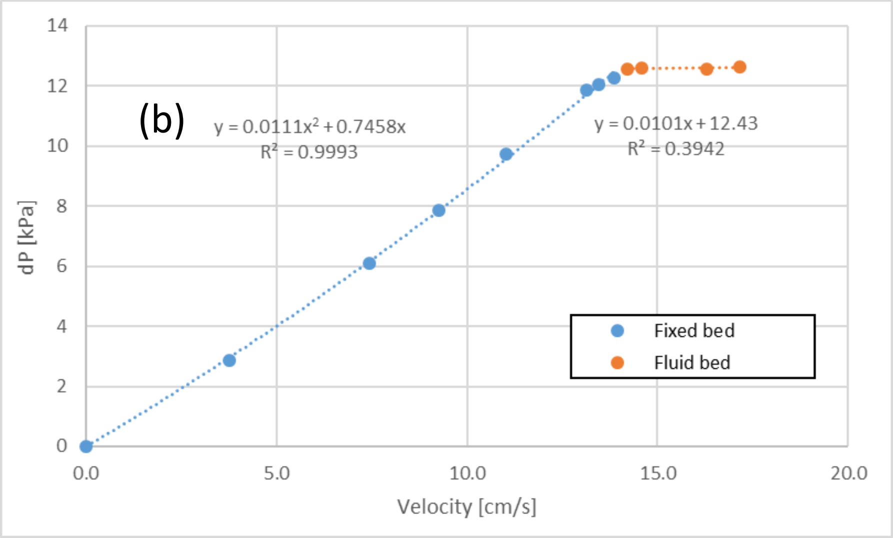
Test Summary

Test No.	4
Date	4/26/2019
Particle Size	155um
Bed Mass	25kg
Pressure	7bar
Gas Density	8.18kg/m3
Predicted Umf	3.5cm/s
Experimental Umf	3.3cm/s
Delta Z	0.31m
Experimental Emf	0.53



Test Summary

Test No.	2
Date	4/24/2019
Particle Size	368um
Bed Mass	25kg
Pressure	7bar
Gas Density	8.18kg/m3
Predicted Umf	14.7cm/s
Experimental Umf	14.0cm/s
Delta Z	0.31m
Experimental Emf	0.51



a=155, b=368 µm

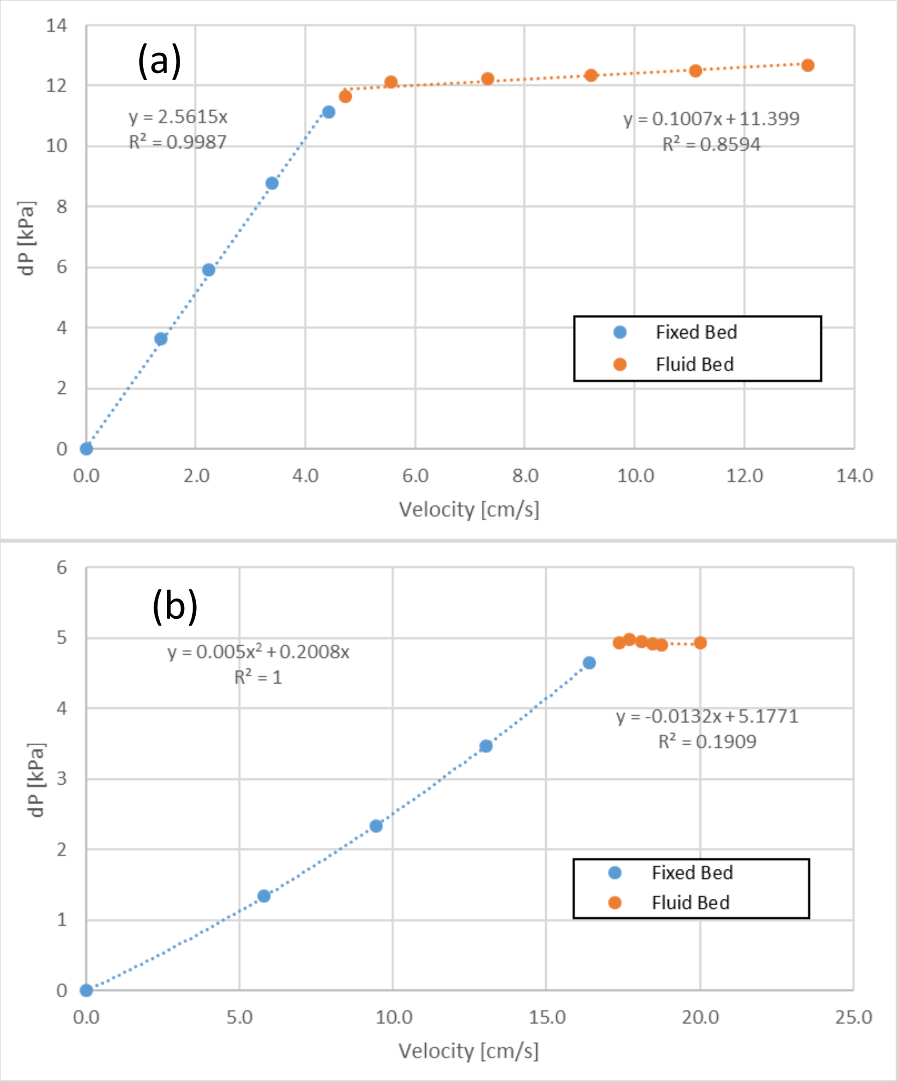
Recording data for different sizes @ 7bar

Test Summary

Test No.	1
Date	5/7/2019
Particle Size	255um
Bed Mass	25kg
Pressure	7bar
Gas Density	8.18kg/m3
Predicted Umf	8.4cm/s
Experimental Umf	4.6cm/s
Delta Z	0.31m
Experimental Emf	1.00

Test Summary

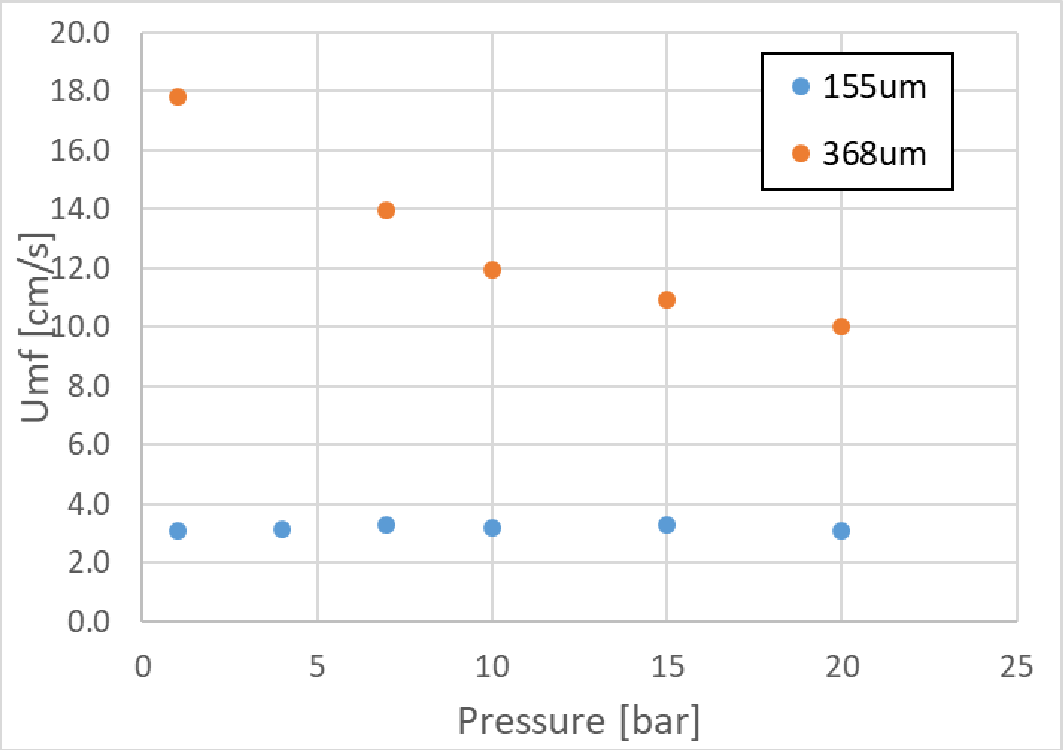
Test No.	3
Date	4/24/2019
Particle Size	512um
Bed Mass	20kg
Pressure	7bar
Gas Density	8.18kg/m3
Predicted Umf	22.2cm/s
Experimental Umf	17.2cm/s
Delta Z	0.31m
Experimental Emf	N/A



a=255, b=512 µm

Comparisons

	Umf, cm/s			
	155, µm		368 µm	
P, bar	pred	exper	pred	exper
1	3.6	3.1	18.7	17.8
4	3.55	3.2	16.3	
7	3.5	3.3	14.7	13.9
10	3.4	3.2	13.6	12
15	3.3	3.3	12.4	10.9
20	3.25	3.1	11.2	10



ε_{mf} = 0.49-0.56

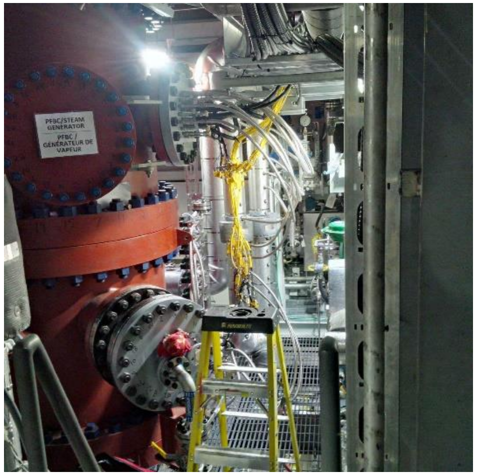
$$d_{B,\Delta P} \propto \frac{\sigma_{\Delta P}}{\rho_p g(1-\varepsilon_{mf})}$$

= 1.57 – 2.13 cm, at low bed

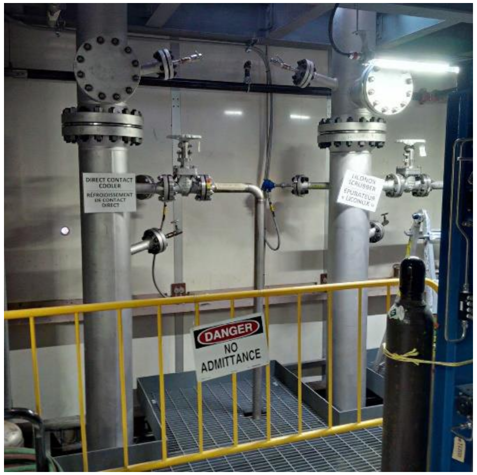
= 2.15– 2.42 cm, at full bed

Pressurized CLC Current Status

- SAGD performance assessments complete
  - Optimum pressure: 4 to 7 bar(g)
  - Reduced NG and BFW make-up demands
  - Published in IJGGC
  - Presented at the Suncor Academic Forum
- Economic optimization is on-going
  - Pressurized operation reduces both CAPEX and OPEX
  - Initial results presented at the 5th Annual CLC conference
  - Currently using Aspen In-Plant Cost Estimator
  - Invited to submit TEA information to both COSIA and Suncor
- 0.6 MW_{th} PCLC pilot-plant
  - Basic engineering nearly complete
  - Experimental trials expected in 2020



CLC vessel (above), CO_2 processing (below)



Conclusions

- Based on the result which operates in the turbulent regime for the most combinations of thermal input and pressure, the fuel reactor top and bottom inner diameter is recommended to be between 4-5 inches.
- It is recommended that the inner diameter of the air reactor riser be between 2-3 inches to ensure fluidization in the fast fluidizing regime for the most combinations of thermal input and pressure. The air reactor bottom between 8-12 inches to ensure fluidization in the turbulent regime.
- The air reactor bottom and the fuel reactor shells could be retrofitted using existing reactor shells of 24 inch outer diameter. It is recommended that the air reactor riser outer diameter be 8 inches to provide minimal heat loss without exceeding the amount of insulation required.
- The measurements of U_{mf}, ε_{mf}, and the bubble sizes are required for designing the pressurized FB reactors appropriately.