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The effect of riser end geometry on gas-solid hydrodynamics in a CFB riser operating above fast fluidization regimes

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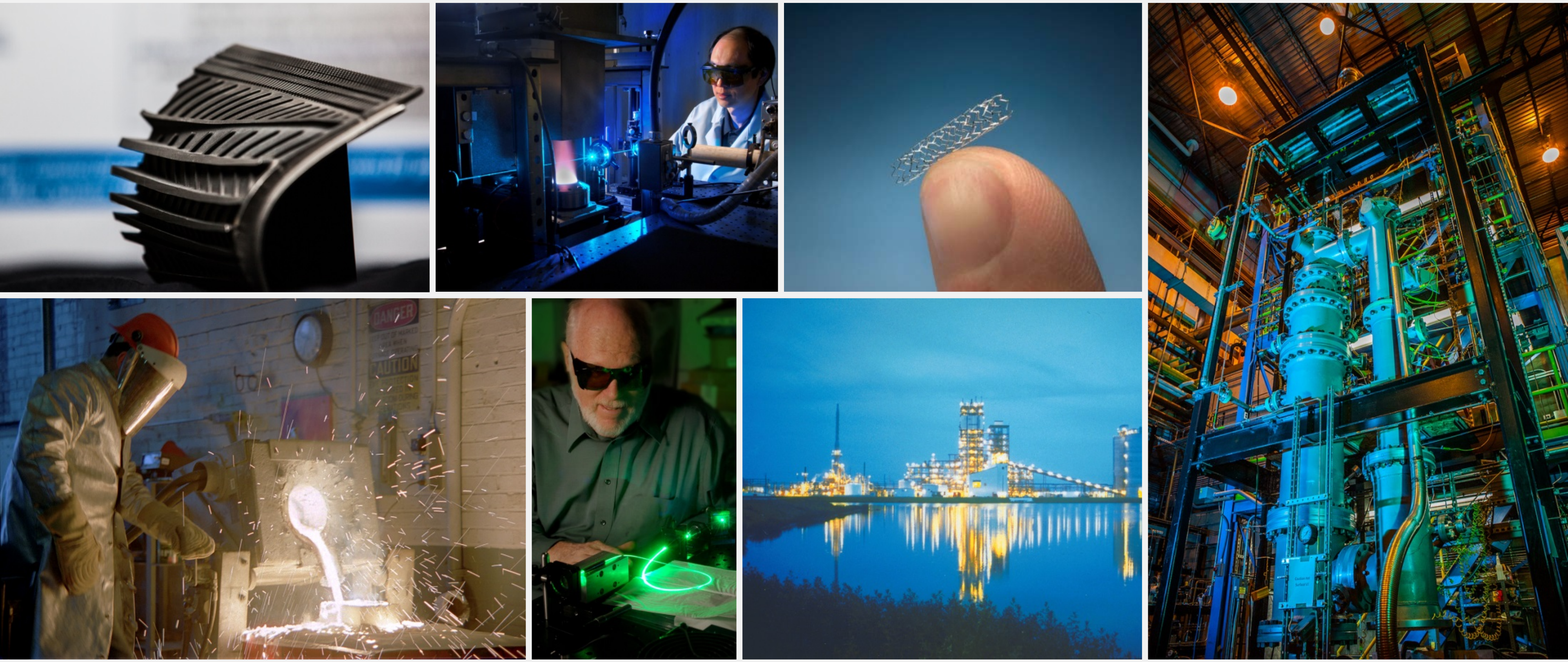

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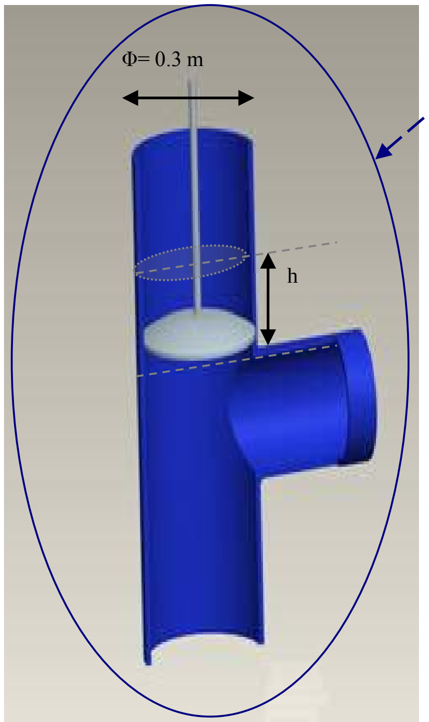
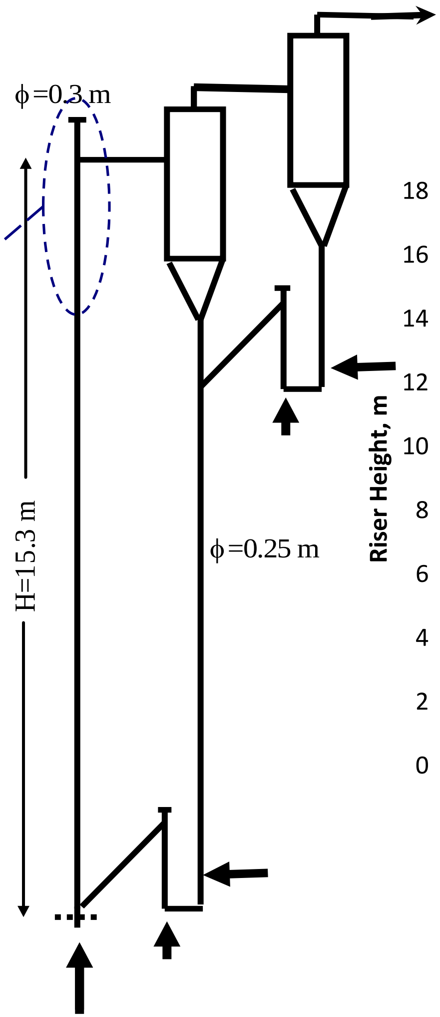
Larry Shadle, Ph.D.

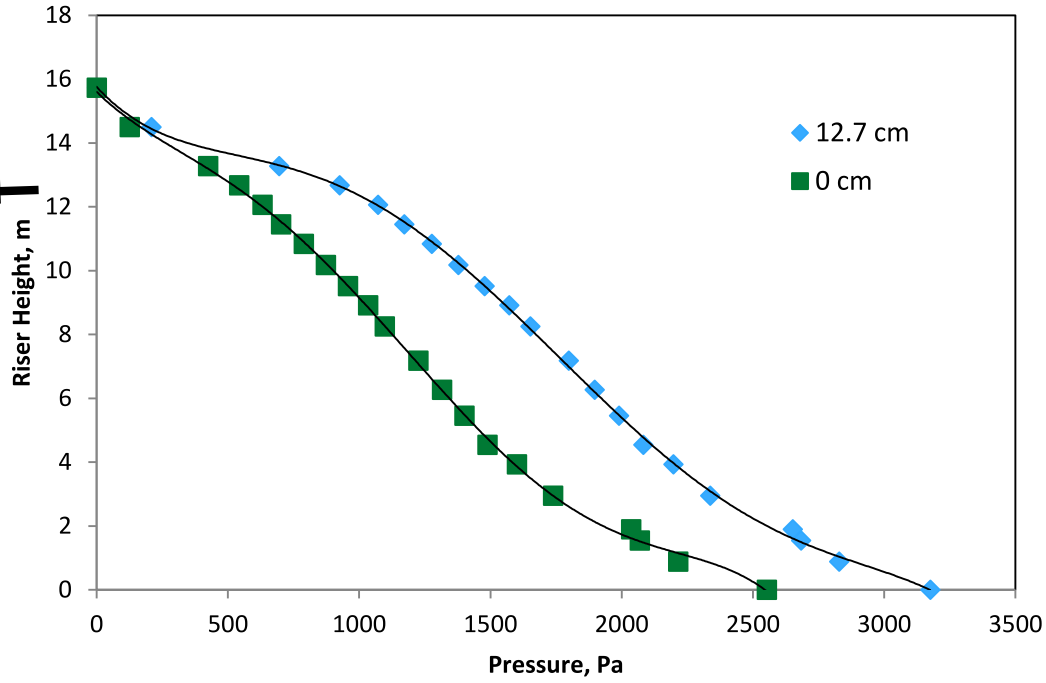
Fluidization XV

May 22-27, 2016

CFB Configuration Focus on Riser Outlet
Effect on riser P-profile







Literature on Riser End effects

- **Exit geometry has a clear effect on riser solids concentration profiles.**
- **The extent of exit effects can be related to riser diameter and particle terminal velocity.**
- **Smooth and abrupt exits**
  - Abrupt exits reflect particles back downwards along the riser walls.
  - smooth exits allow most up-flowing particles to exit riser.

Author	Riser cross section		Riser height (m)	G_s (kg/m^{2}s) & U_g (m/s)	Material & density (kg/m^3)	Particle size (mm)	Exit shape
	Diameter (m)	Rectangular (m x m)					
Brereton & Grace [3]	0.152	NA	9.3	9 to 116 & 3.7 to 9.2	Sand 2650	148	Abrupt Ts, rounded L
Harris et al. [4]	0.15	NA	0.83	1 to 5.5 & 1.3	FCC 1700	48	Mitered L, rounded L
Pugsley et al. [5]	0.1	NA	6	10 to 45 & 4 to 6	Sand 2500	220	Mitered L, rounded L
					FCC 2200	71	
	.2	NA	12		Sand 2500	230	Mitered L, rounded L
					FCC 1500	80	
Jin et al. [6]	.140	NA	11	30 to 180 & 1.3 to 10	FCC 1545	59	Abrupt T, angled L
					Silica-gel 711	165	
					Silica-gel 706	80	
					Sand 2672	37	
Senior [7]	0.152	NA	9.3	20 & 60 & 6.5 & 9.0	Glass beads 2470	230	Abrupt T, rounded L
						218	
						233	
					Sand 2600	160	
					Sand 3220	177	
					Sand 4420	148	

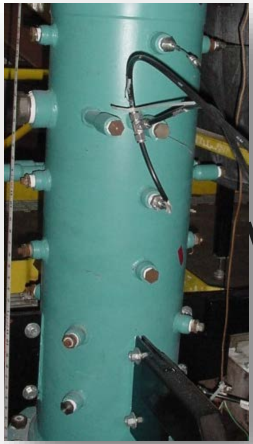
Literature on Riser End effects

- Solids back-mixing and length of exit effects decrease with increasing gas velocity.
- For a T-shaped exit geometry, the cavity between riser roof and exit stimulates internal recirculation of particles, resulting in increased bed density, decreased solids flux, and visual observation of cluster formation.

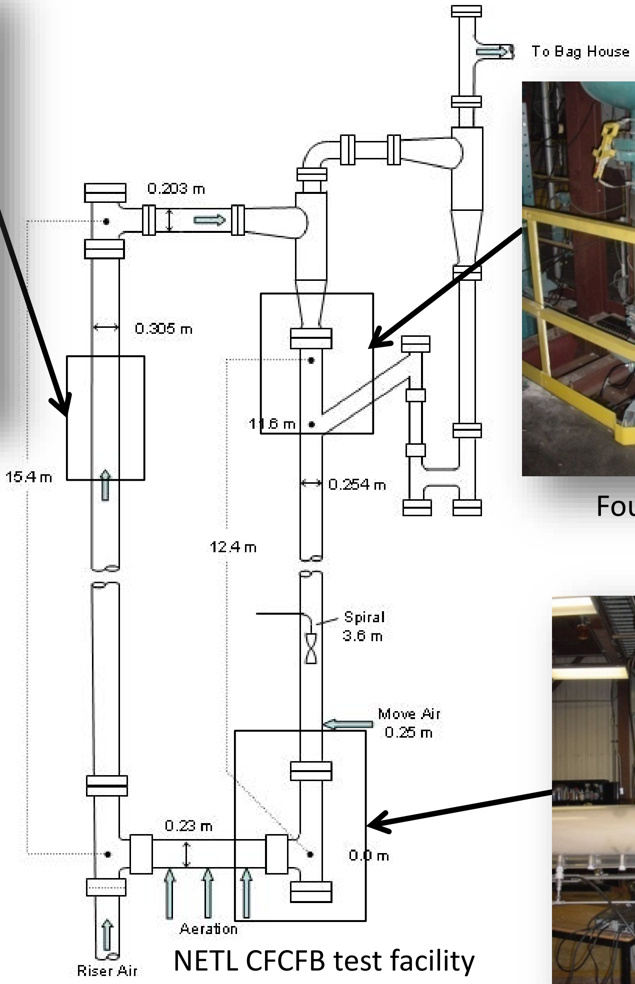
Author	Riser cross section		Riser height (m)	G_s (kg/m²s) & U_g (m/s)	Material & density (kg/m³)	Particle size (mm)	Exit shape
	Diameter (m)	Rectangular (m x m)					
Zheng & Zhang [8]	0.102	NA	5.25	4 to 13 & 5.2 to 6.2	Resin 1400	550	Abrupt T, mitered L, angled L
Zhang et al. [9]	NA	0.316 x .08	4	13 to 16 & 4.4 to 5	Sand 2600	175, 350	Abrupt T with varied heights, mitered L, angled L
Fan et al. [10]	0.102	NA	5.25	4.2 to 10.3 & 5.14	Resin 1400	500	Abrupt T, mitered L, angled L
Monazam et al. [11-12]	0.3	NA	15	6.9 to 12.8 & 6.4	Cork 189	812	Abrupt T
				19 to 77 & 5.35	Coke 1250	1250	
				43 to 282 & 7.7	Glass beads 2550	60	
Current Study	0.3	NA	15	18.4 to 163 & 4.35 to 7.7	Glass Beads 2550	66	Abrupt T with movable plunger
				47.2 & 6.85	Coke 1250	143	

Cold Flow Circulating Fluidized Bed (CFCFB) Facility

- 16 m height
- 0.3 m diameter riser
- 0.25 m diameter standpipe
- Some sections acrylic and some carbon steel
- Humidified riser air
- L-valve with sparger aeration along length
- Aeration at discrete points along standpipe
- Various ports allowing probe insertion (3/4” NPT)



Third floor



NETL CFCFB test facility

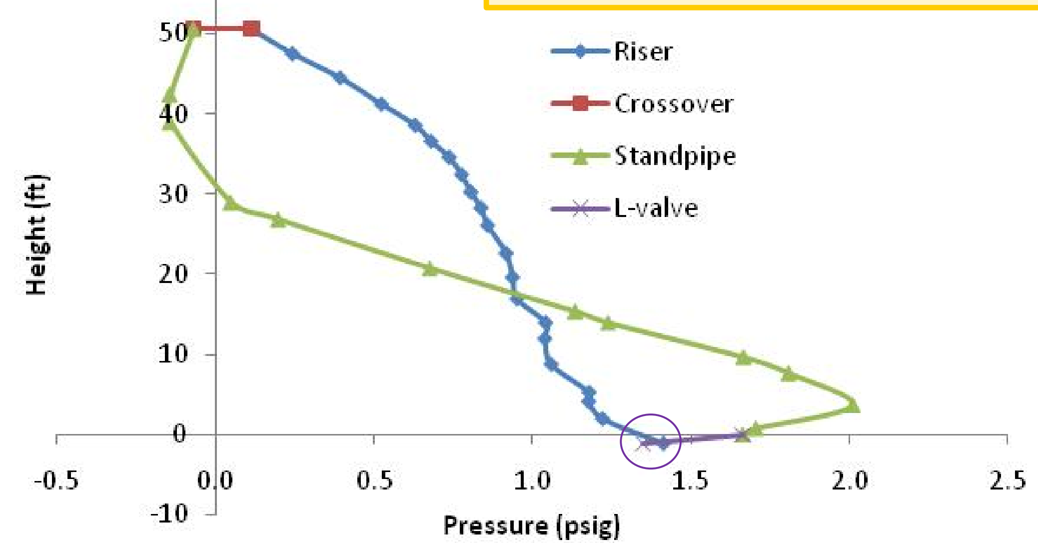
Fourth floor

Ground floor

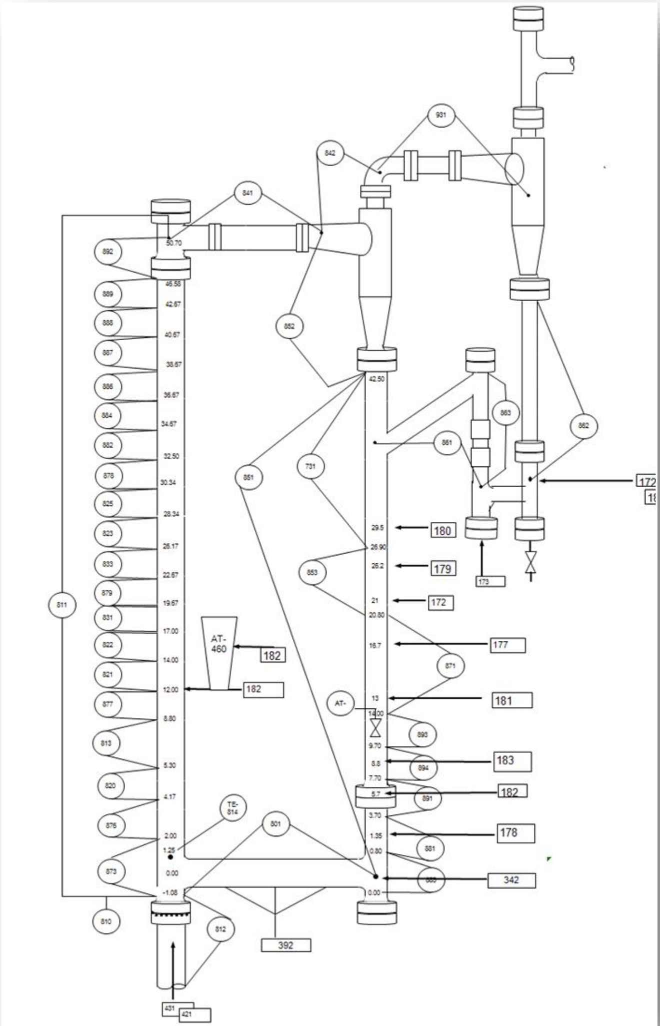
Low Frequency ΔP measurements

Pressure measurements @ 1 sample/s
Also averaged for 30 s and 5 min intervals

Riser ΔP @ 21 locations
Standpipe ΔP @ 9 locations
Other ΔP measurements :
- Crossover
- L-valve
- Cyclone



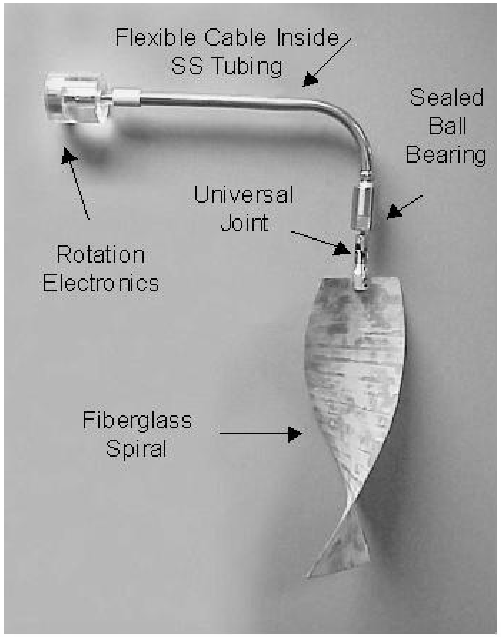
Typical pressure plot from the CFCFB

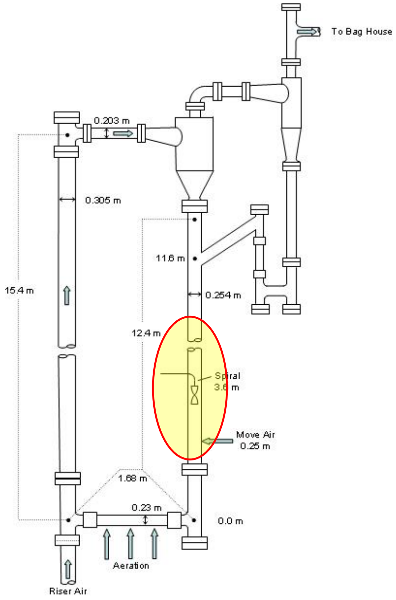


Pressure tap locations on the CFCFB

Solids circulation measurements
Developed at NETL

Spiral vane inserted in standpipe





Measured parameter:

Pulse/second

Constant parameters:

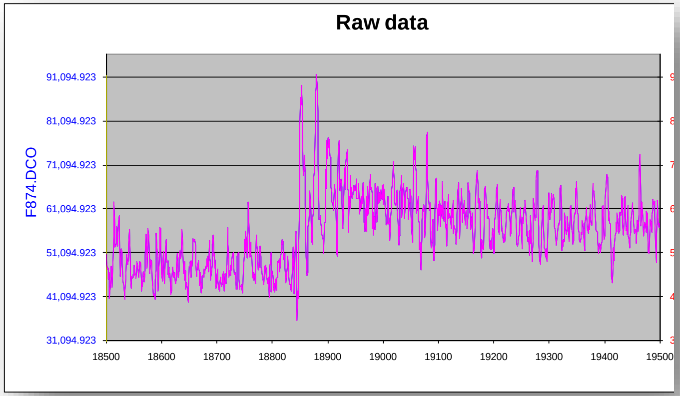
Length/Θ = 1.02 ft/180°

Θ/pulses = 360°/128

Area = 0.545 ft^2

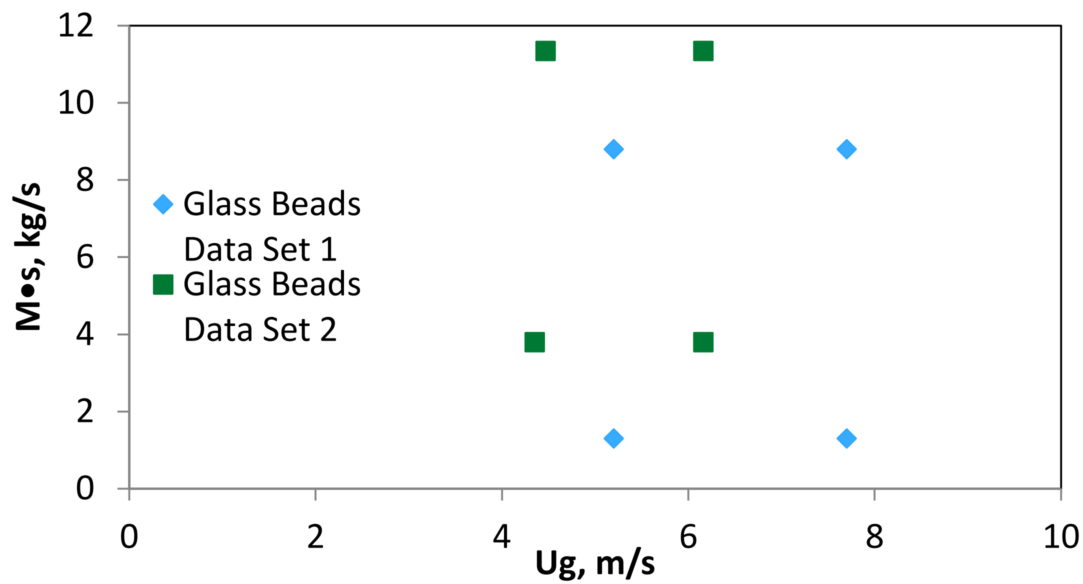
ρ_{bulk} = 35 lb/ft^3

$$\frac{length}{\theta} * \frac{\theta}{pulse} * \frac{Pulse}{second} * area * \rho_{bulk} = solids\ circ\ rate$$



Granular Materials - Test Matrix

Material	Coke	Glass Beads
Density (kg/m^3)	1250	2550
Particle Size (mm)	230	68
Sphericity	0.85	0.90
U_{tr1}	2.35	1.69
U_{tr2}	4.28	3.52
D/d_p	1325	5000
Ar	608	868
Geldart Group	B	A

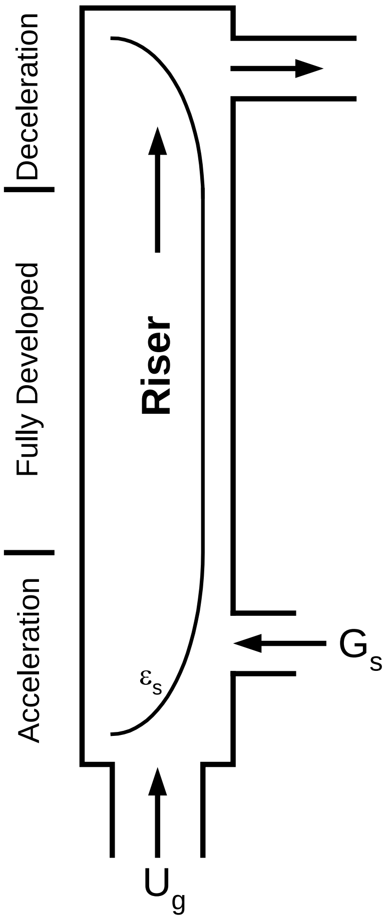


Material	Coke	Glass Beads
P (kPa)	109.7 to 116.7	102 to 140
$(\rho_s-\rho_g)/\rho_g$	1015 to 1079	1275 to 1643
ρ_g (kg/m^3)	1.30 to 21.38	1.48 to 1.90
Re	66 to 86	85 to 152
Fr	9.5 to 15.8	6.2 to 19.8
G_s/G_g	5.5 to 11.0	1.1 to 20.4
Configuration	Loop seal	L-valve

Hydrodynamics in Transport Regime

The hydrodynamics were analyzed from data taken above the transport velocity for a wide range of operating conditions.

- **The riser generally includes three distinct regions:**
  1) **Acceleration** zone where the solids accelerate upon entry into the riser and gas & solids are poorly distributed.
  2) **Fully developed** flow zone where the gas and solids distribution reach some steady state (constant void along this length of the riser).
  3) **Deceleration or exit** zone for CFB units equipped with an abrupt exit at the top of the riser.
- **The three sections of the riser were analyzed individually determining average voidage, pressure drops, and solid inventory as a function of axial location**.



Data Analysis: Riser End Effects

- **Voidage is inferred from pressure profile.**

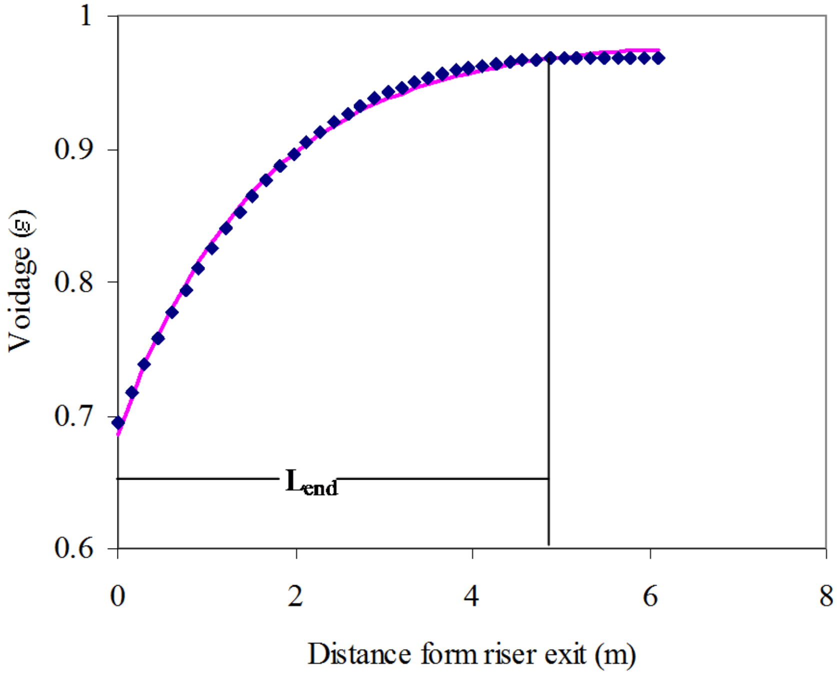
$$\frac{dP}{dz} = \rho_g (1-\varepsilon) g$$

- **Change in apparent voidage exponentially decays from Fully Developed region**

$$\frac{d\varepsilon_{L_{end}}}{dz} = k_{decay}(\varepsilon_{FD} - \varepsilon_{L_{end}})$$

- **Integrating directly**

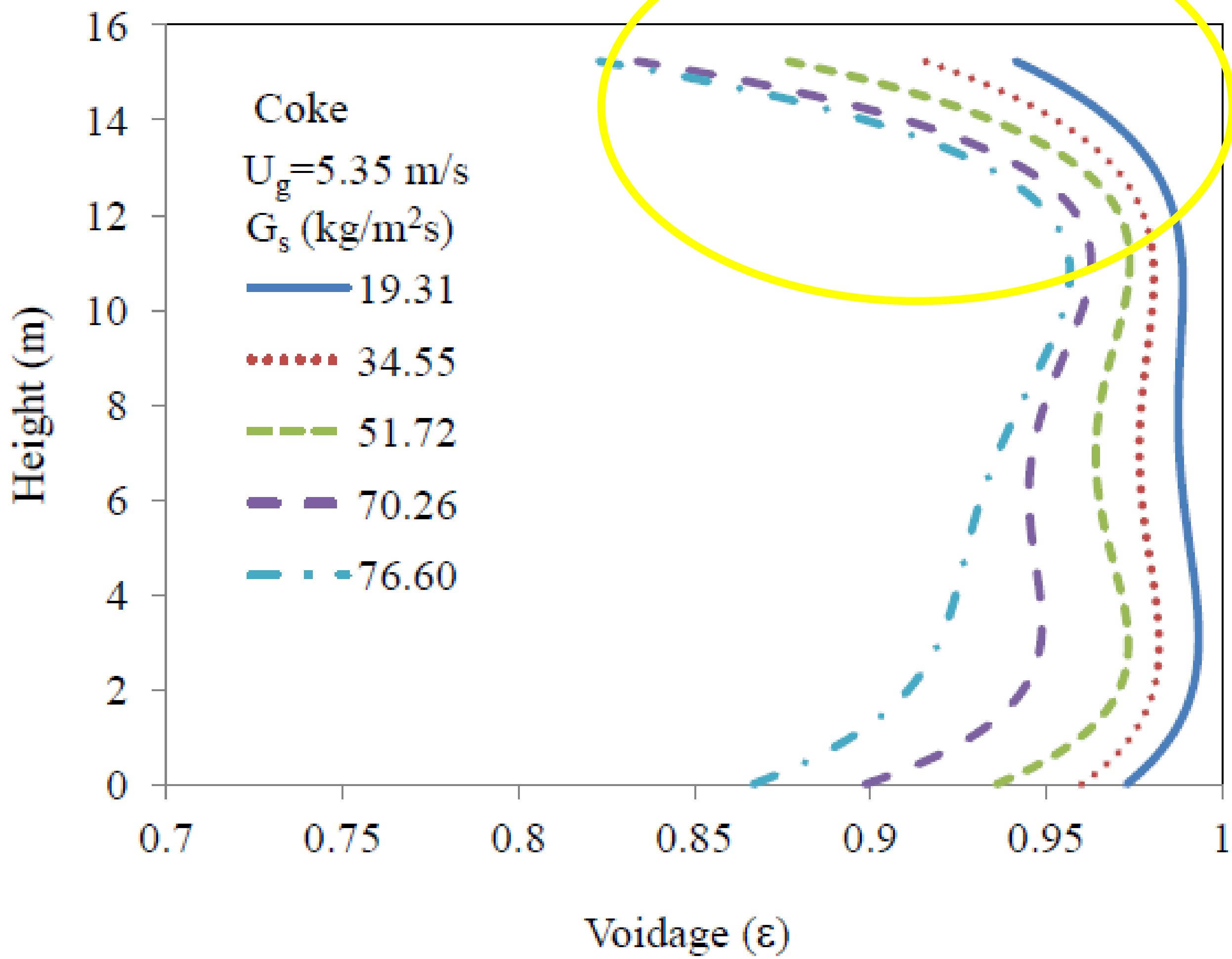
$$\frac{\varepsilon_{L_{end}} - \varepsilon_{FD}}{\varepsilon_{exit} - \varepsilon_{FD}} = e^{-K_{decay} z}$$



Monazam et al. (2016) Riser end-effects, submitted to Powder Technology

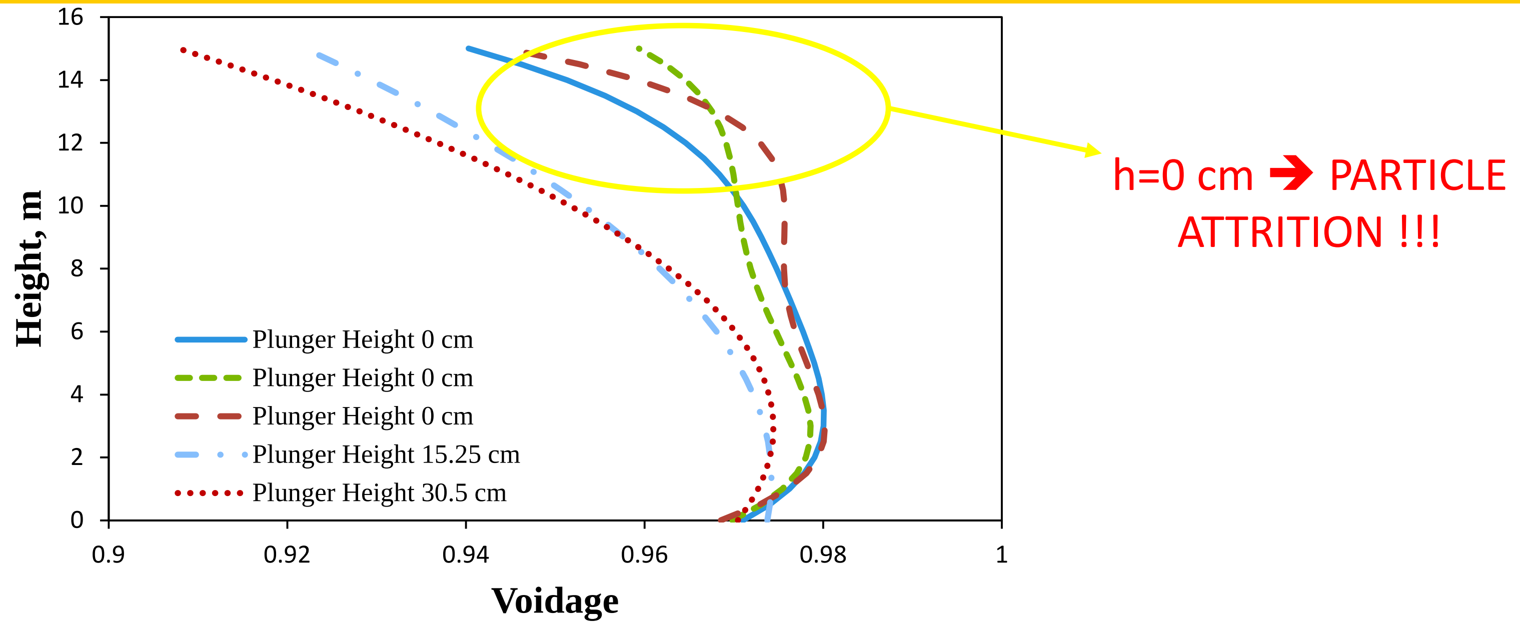
Monazam and Shadle (2008) Ind. Eng. Chem. Res., 47; p. 8423-8429.

Riser axial voidage varies with solids flux



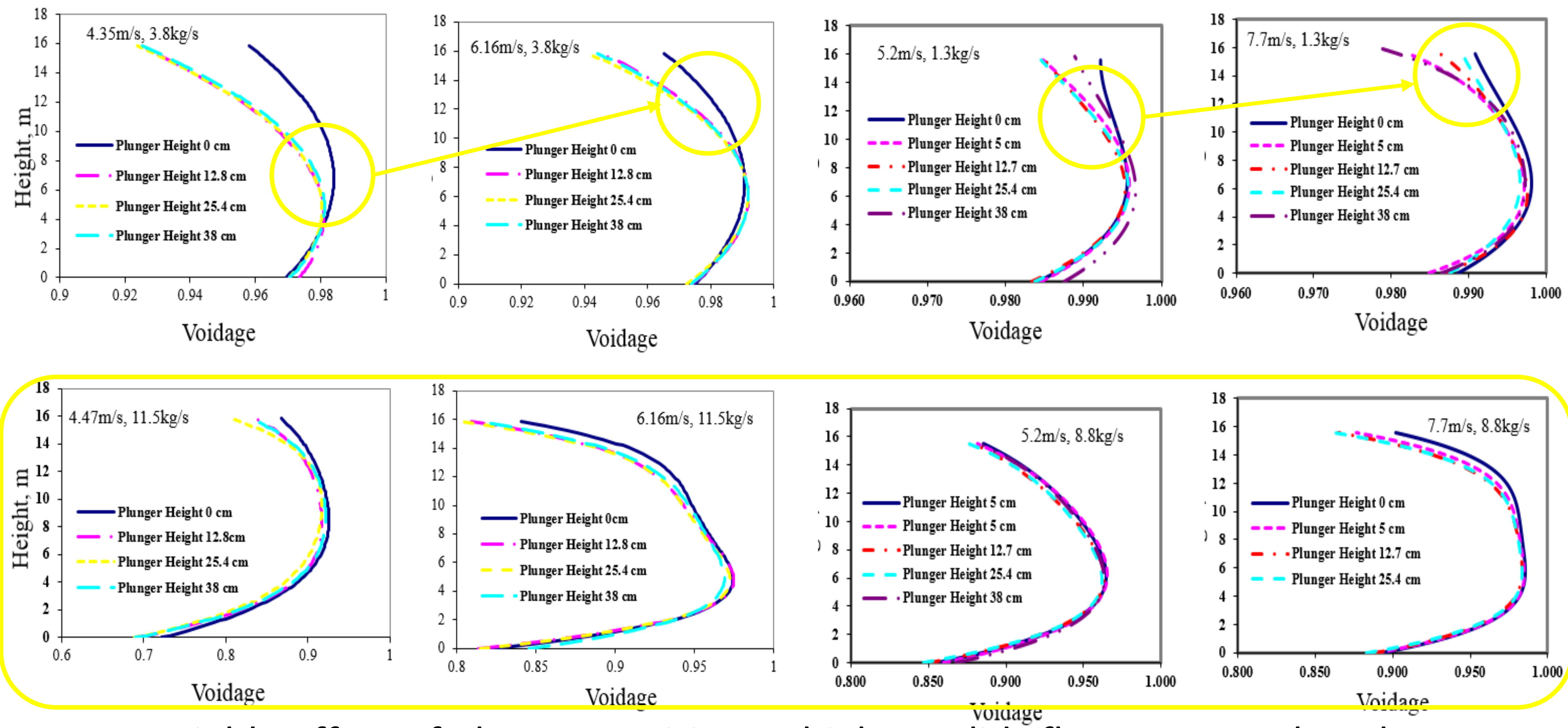
Effect of Length of Dead End Tee

U_g= 6.85 and m_s= 3.45 kg/s. coke



- Due to particle degradation, only 5 tests were conducted using Coke.
- All tests exhibited the "reverse-C" shape, as seen with the glass beads.
- Average voidage decreased when projected roof height changed from 0 cm to 15.25 cm above riser exit.
- Little to no appreciable change in voidage between projected roof heights of 15.25 cm and 30.5 cm.

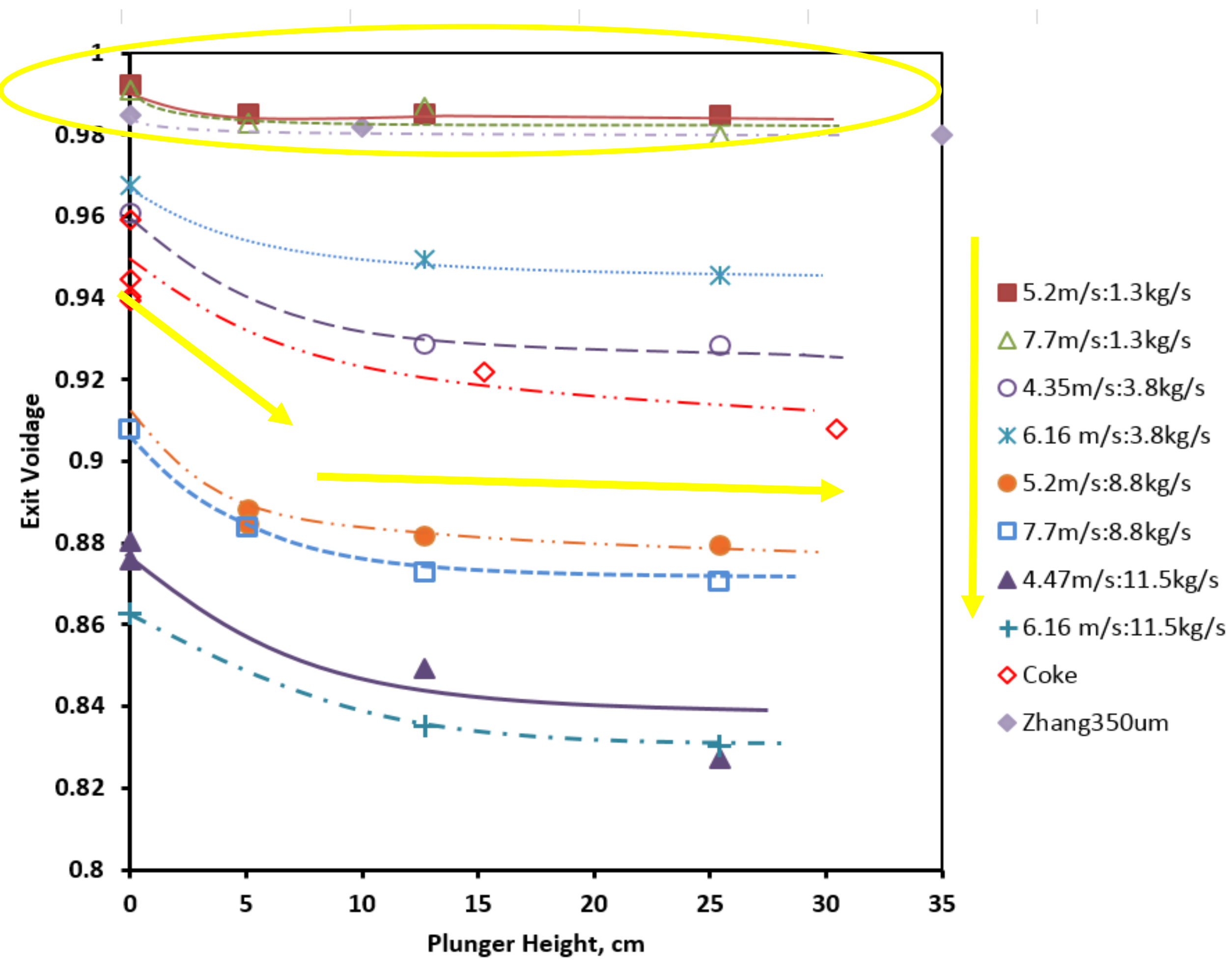
Effect of Riser Exit Geometry on Axial Voidage Profile (glass beads)



- No appreciable effect of plunger position at higher solids flux rates - Only at lower solids fluxes
- As U_g, increases: 1) Maximum value solid fraction decreases, 2) Length of end effects decreased, 3) Height of minimum solids fraction relatively unchanged.

Effect of the Length of the Dead End Tee

- Low solids flux cases exhibit little change in exit voidage.
- As solids flux increases, exit voidage decreases.
- In most cases, for a given solids flux, exit voidage decreases with increasing gas velocity.
- In each case, exit voidage reaches a minimum value at a given plunger height, above which there is little to no change in voidage.

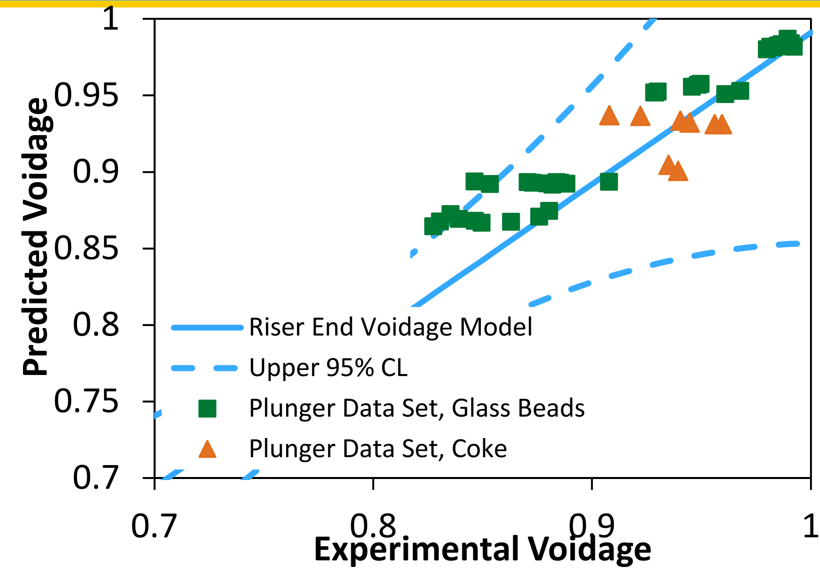


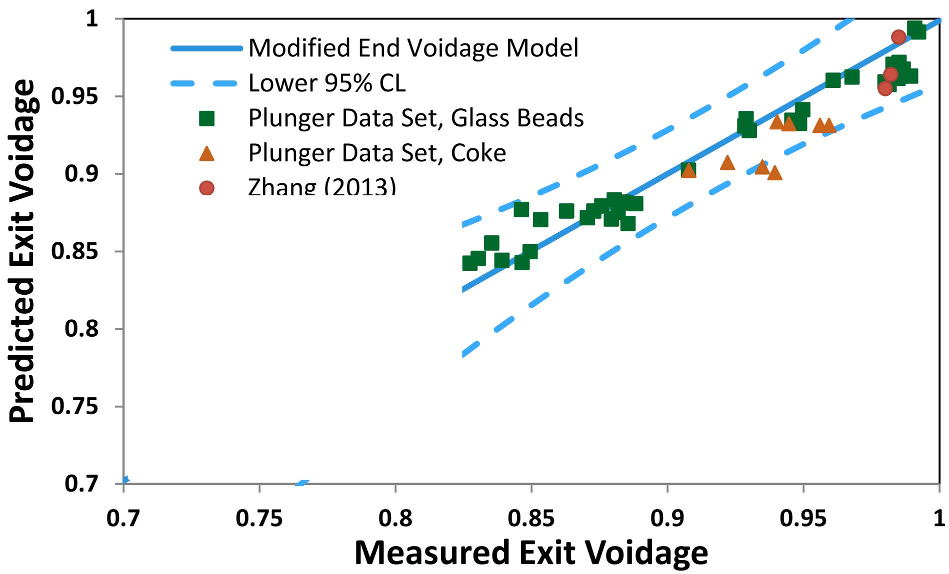
Adding correction for Riser Exit Geometry

Riser exit voidage:

$$\varepsilon_{exit} = 1.0 - (2.38\times10^{-3})\left(\frac{G_s}{\rho_g U_g}\right)^{0.917}\left(\frac{\rho_s-\rho_g}{\rho_g}\right)^{-1.041}\left(\frac{D}{d_p}\right)^{0.704}\left(\mathrm{Re}_g\right)^{0.901}$$

- No correction for variation in the projected height in dead end Tee
- Over-predictions of riser exit voidage.





$$\varepsilon'_{exit} = 1.01\left(\varepsilon_{exit} - 0.03\left(\frac{h}{D_C}\right)^{0.25}\right)$$

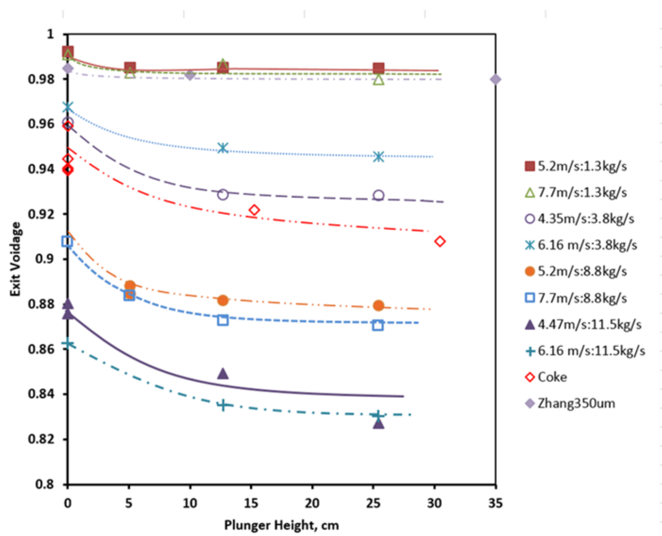
- Correction for the dimensionless dead end height
- Results in close match between experiments and model predictions, including those published by Zhang et al. (2013).

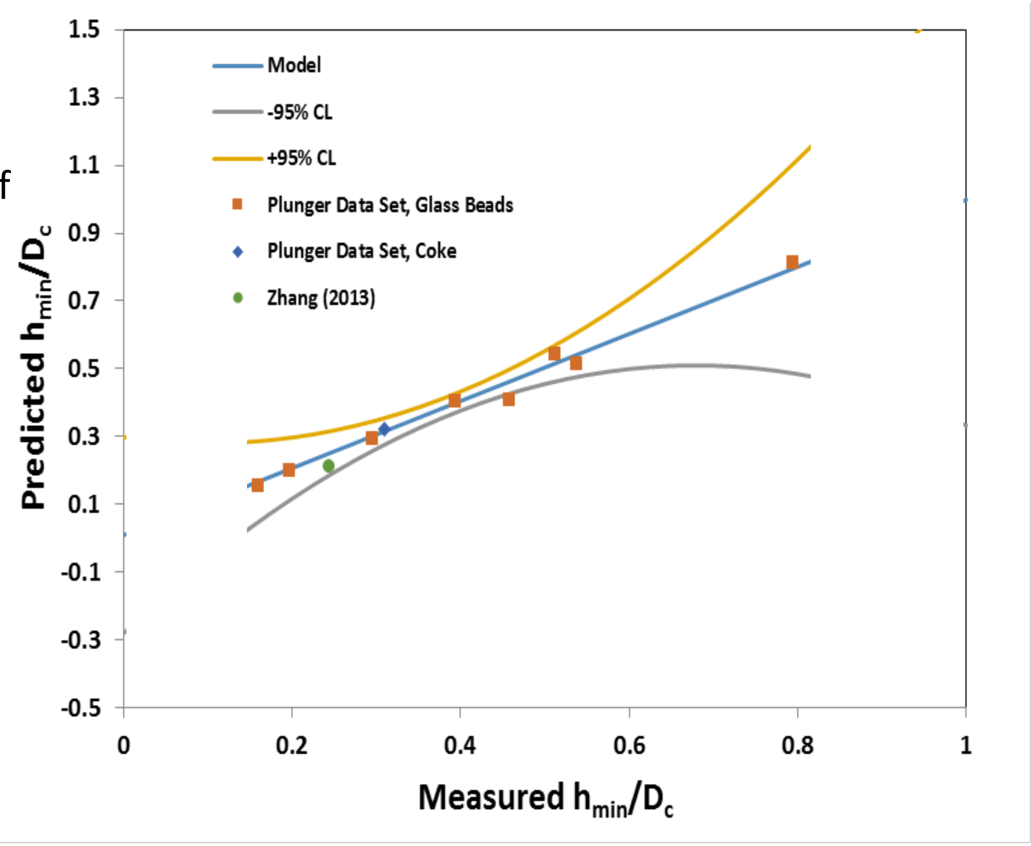
Estimation of Height of Minimum Exit Voidage

- Observed that there is a height at which the riser exit voidage asymptotically reaches a minimum value.
- This minimum height was obtained for each of the experiments to develop the following.

$$h_{min}/D_c = 0.215\left(\frac{G_s}{\rho_g U_g}\right)^{0.5}\left(\frac{U_g}{U_t}\right)^{-0.25}$$

The predictions match well, with 98.7% of the variance explained (R^2)





Summary

- **Investigated the Riser End effect in industrial scale CFB**
- **Observed dramatic particle attrition on particles when using an abrupt exit without cavity above riser outlet.**
- **Confirmed literature trends of reduced solids reflux into riser with shorter cavity above riser outlet.**
- **The Length of the effected region of the riser remained unchanged by the size of the cavity above the outlet.**
- **The exit voidage exponentially decreased and a correction for the effect was developed:**

$$\varepsilon'_{exit} = 1.01\left(\varepsilon_{exit} - 0.03\left(\frac{h}{D_C}\right)^{0.25}\right)$$

- **The height required for the riser outlet was directly proportional to the load ratio, ie.:**

$$h_{min}/D_c = 0.215\left(\frac{G_s}{\rho_g U_g}\right)^{0.5}\left(\frac{U_g}{U_t}\right)^{-0.25}$$

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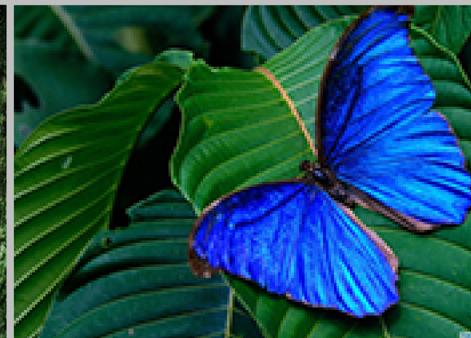
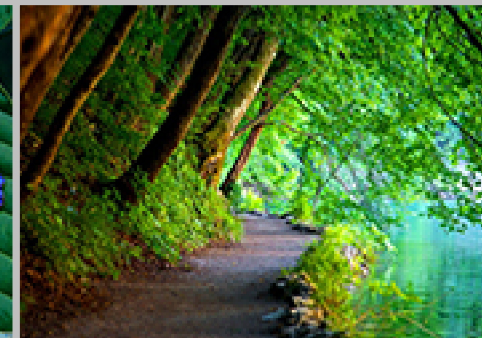

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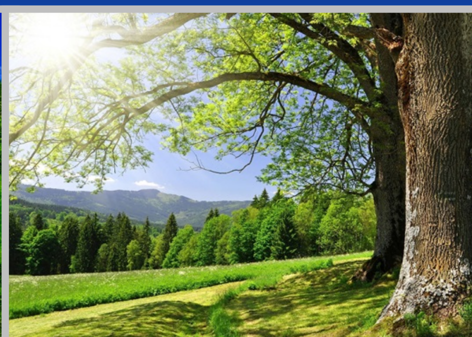

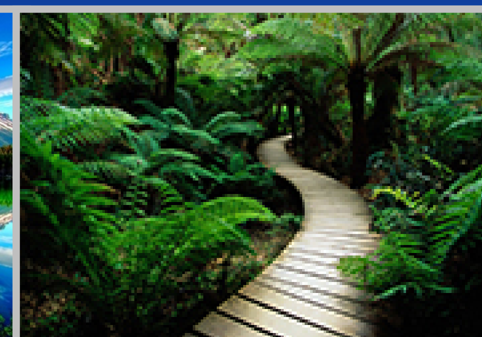

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