CFD-DEM MODELLING OF CONICAL SPOUTED BED SOLAR RECEIVERS

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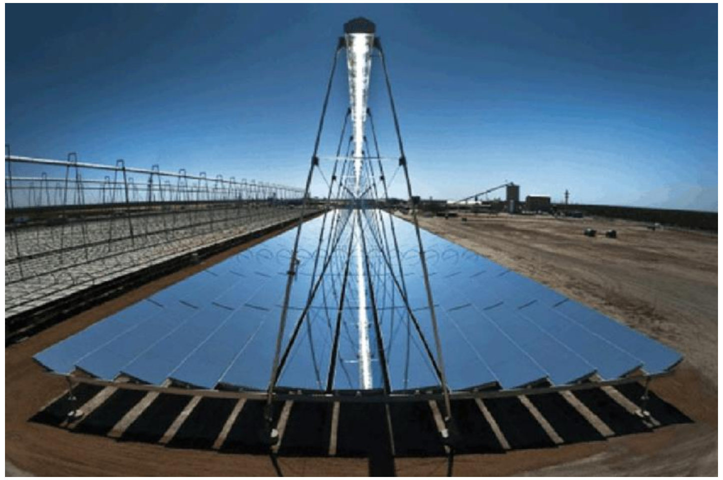
INTRODUCTION

Concentrated Solar Power Systems

- ✓ Aim to reduce CO_2 emissions
- ✓ Great interest for places where direct normal irradiation is over 2000 kWh / (m^2 year)
- ✓ Captures solar radiation in a heat transfer medium through the concentration of radiation by a series of mirrors

Figure 1: A CSP Plant [1].

TYPES OF CSP PLANTS



- Linear Reflector

- Solar Power Tower

- Parabolic Reflector

- Power Dish Collector

Figure 2: Types of CSP [1-4].

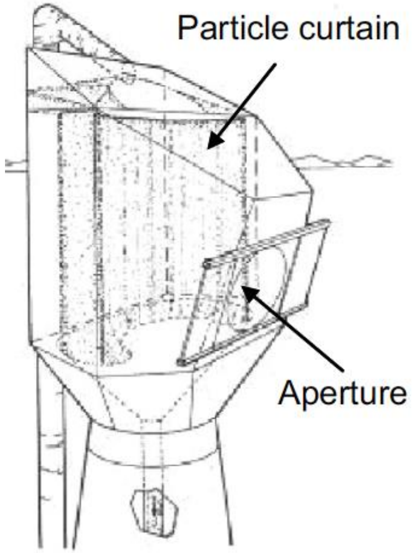
RECEIVER TYPES

Table 1 Receiver Types

RECEIVER TYPE	MOLTEN SALT	SOLID PARTICLE	GAS
Common Kinds	Carbonates Fluorides Chlorides	**Silica sand** **Ceramic particles**	Air CO_2 Helium
Working Temperature	500-565 ^oC	**> 700 ^oC**	> 700 ^oC
Advantages	•High heat capacity	**•High and wide operating T range** **•Direct use of TES medium** **•Stable chemical properties** **•Cheaper than other options**	•High operating temp.
Disadvantages	•Expensive •Decomposition, corrosion and efficiency reduction at high temp.	**•Attrition and erosion** **•Particle loss resulting in increase in heat loss** **•Additional energy requirement for fluidization**	•Poor thermal properties •Low heat transfer rates •Low receiver efficiency

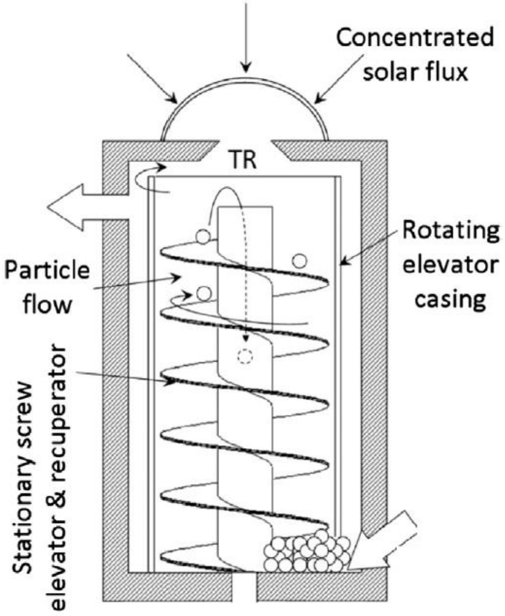
Solid Particle Receivers [6]

Free-Falling



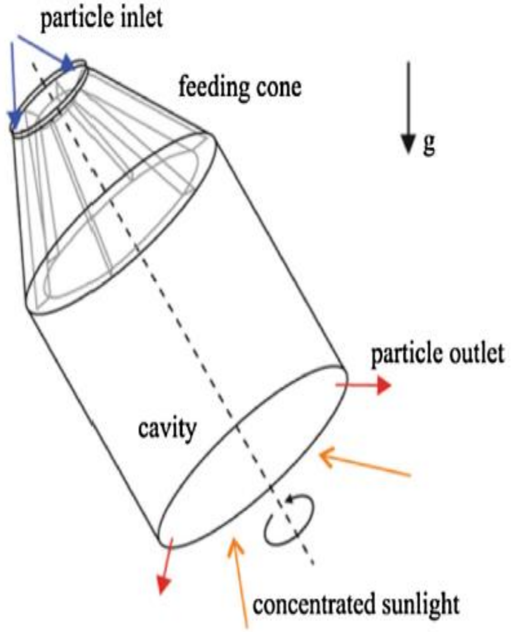
T_{outlet} > 700 °C

Obstructed



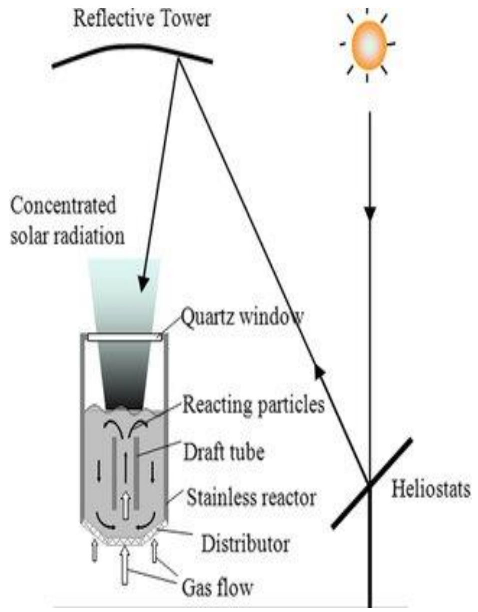
T_{outlet} > 700 °C

Rotating Kiln



T_{outlet} ~ 900 °C

Fluidized Bed /Spouted Bed [5]



T_{outlet} > 1000 °C

Spouted Beds

- Invented in 1954 by Gishler and Mathur as an alternative method of drying badly slugging fluidized bed
- Based on the movement of coarse particulate solids with fluid injection
- Advantageous for large and heavy particles (Geldart D) for which conventional fluidization requires high flow rate and pressure drop.

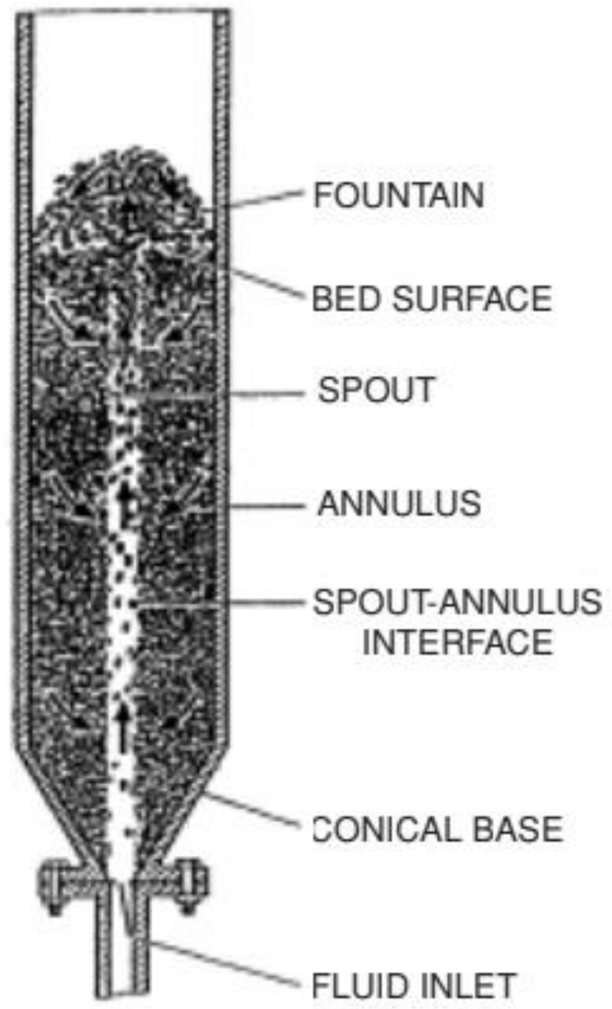


Figure 3: Schematic Diagram of Spouted Bed [7].

SPOUTED BEDS AS THERMAL RECEIVERS IN CSP SYSTEMS

Potential Advantages

- Can handle coarse and heavy particles typically used in CSP applications
- Can reach very high temperatures, $\mathbf{T_{outlet}} \sim \mathbf{1400}\ ^{o}C$

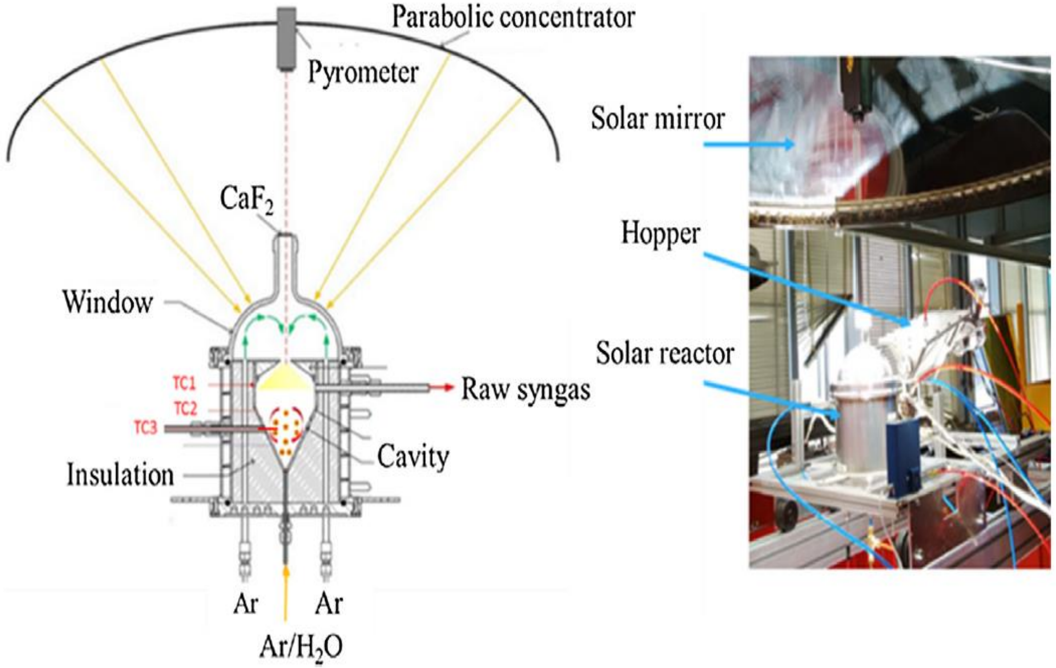


Figure 4: Solar Driven Spouted Bed [8].

Table 2 Properties of Solid Particles

MATERIAL	COMP.	PROPERTIES				ADVANTAGE	DISADVANTAGE
		DENSITY (kg/m^3)	SPESIFIC HEAT (J/kg-K)	Absorptance	Emissivity		
SILICA SAND	SiO_2	2100-2650	742-1175	0.44-0.66	0.59-0.9	Stable, abundant, low cost	Low solar absorptivity and conductivity
CERAMIC PROPPANTS	83% Al_2O_3 5% SiO_2 7% Fe_2O_3 4% TiO_2	**3560**	1275	0.934	0.843	High solar absorptivity, stable	Synthesized, higher cost
OLIVINE	48 % Mg, 42 % SiO_2 1.5-8 % Fe_2O_3 4-10.5% CaO	**2965-3165**	700-900		0.88-0.94	Uniform thermal expansion, Low cost, Found in large quantities in Turkey	Angular grain shape, Low sand reclamation rates [9]

OBJECTIVES

- Development of a CFD-DEM model for conical spouted beds operated with different energy storage particles (There is no specific study to model CSP systems using DEM although TFM studies exist),
- Comparison of the gas-solid flow modeling results with the in-house experimental data (particle velocity, solids concentration, pressure drop),
- Expanding the CFD-DEM model with thermal radiation model,
- Comparison of the thermal modeling results with the in-house experimental data (temperature distribution, charge and discharge times).

METHODOLOGY

- MFIX is an open-source Multiphase Flow solver and is **free to download and use**
- **3D Geometry** with **CGP-DEM** (**Course Grained Particle**) was used.
- For **small diameter/large number of particle** systems, conventional DEM requires large computational time.
- CGP method **reduces** computational time with grouping particles.
- An in-house post-processing code was developed in order to time-average and plot particle velocities, solid hold-up, and interstitial gas velocity profiles of specific regions.

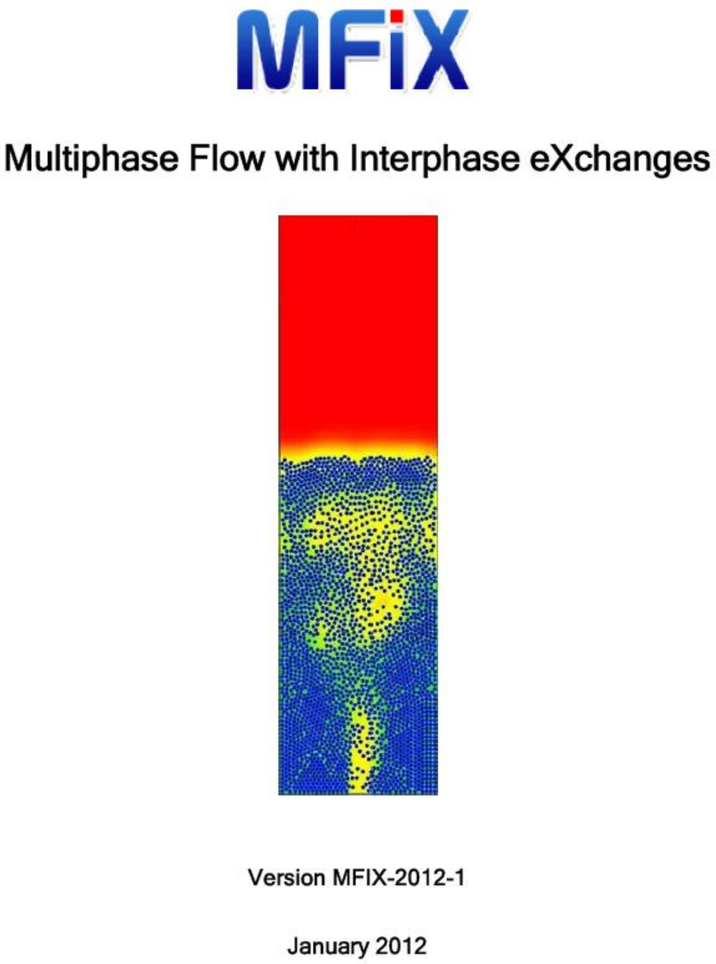


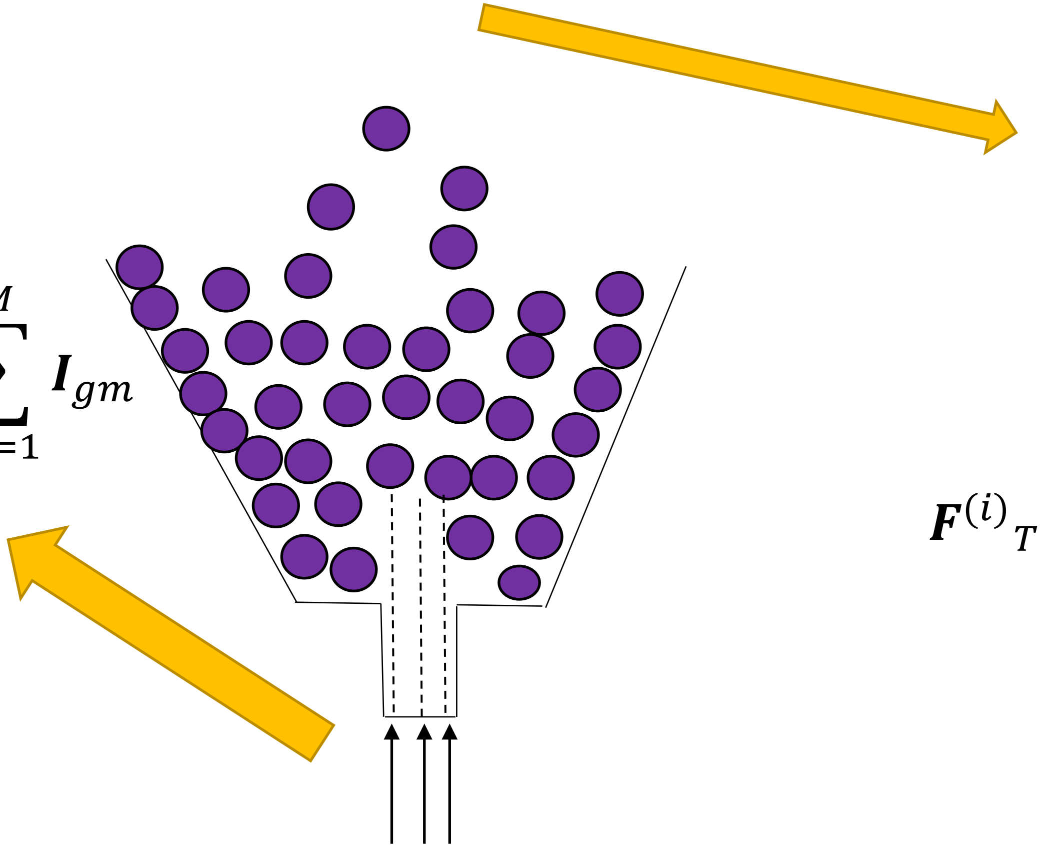
Figure 5: MFIX [10].

CFD-DEM EQUATIONS

Gas Phase

$$\frac{\partial(\epsilon_g \rho_g)}{\partial t} + \nabla \cdot (\epsilon_g\ \rho_g\ \boldsymbol{v_g}) = 0$$

$$\frac{D}{Dt}(\epsilon_g\ \rho_g\ \boldsymbol{v_g}) = \nabla \cdot \overline{\overline{S_g}} + \epsilon_g\ \rho_g - \sum_{m=1}^{M} \boldsymbol{I}_{gm}$$



Solid Phase

$$\frac{d\boldsymbol{X}^{(i)}(t)}{dt} = \boldsymbol{V}^{(i)}(t)$$

$$m^{(i)}\ \frac{d\boldsymbol{V}^{(i)}(t)}{dt} = \boldsymbol{F}^{(i)}{}_T$$

$$\boldsymbol{F}^{(i)}{}_T = m^{(i)}\mathbf{g} + \boldsymbol{F}^{(i\in k,m)}{}_D + \boldsymbol{F}^{(i)}{}_c$$

$$I^{(i)}\ \frac{d\boldsymbol{\omega}^{(i)}(t)}{dt} = \boldsymbol{T}^{(i)}$$

Figure 6: Application of CFD-DEM in a spouted bed.

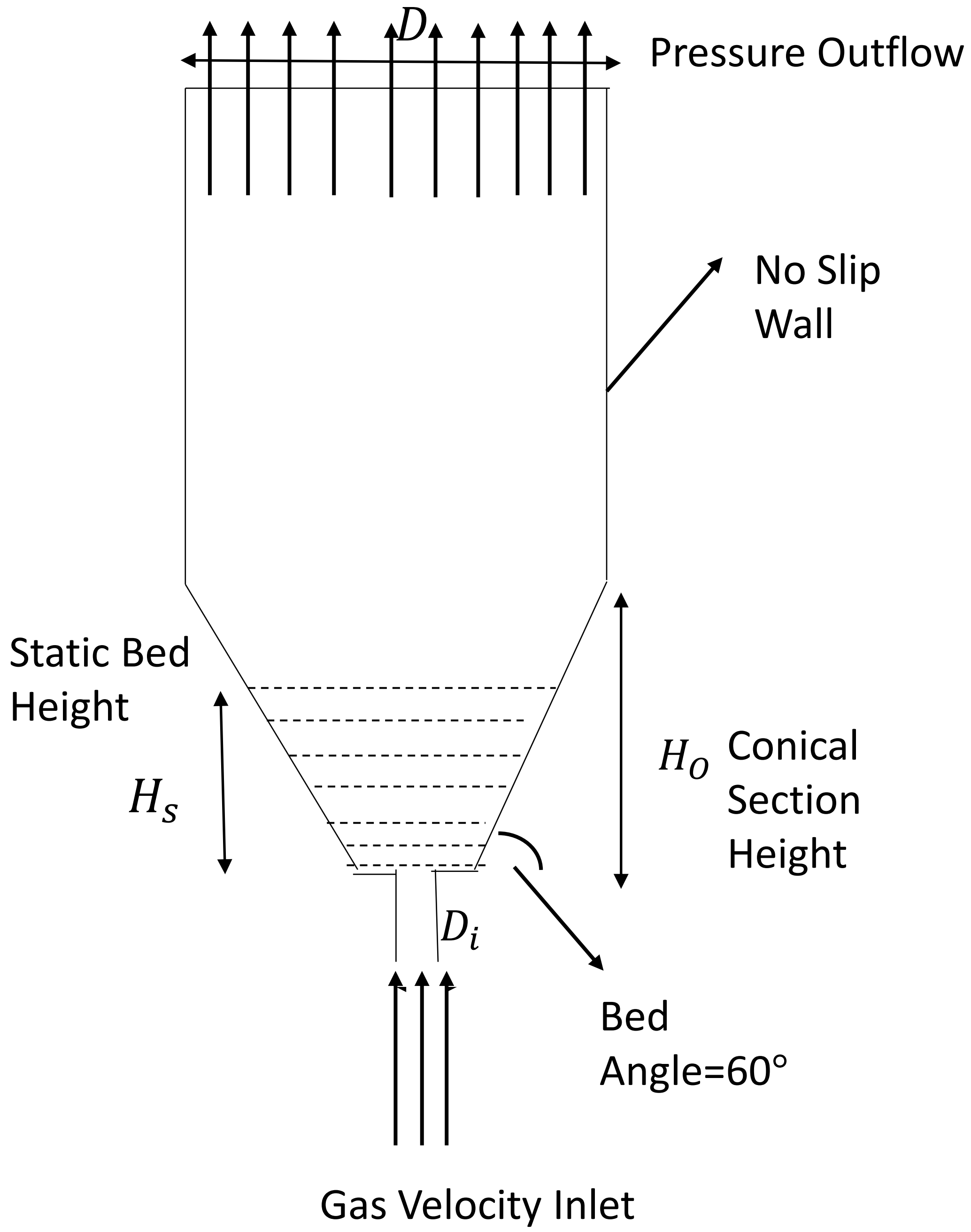


Figure 7: CFD Nomenclature.

Table 3 Boundary and Initial Conditions

Boundary and Initial Conditions	
Bed Material	Olivine
Inlet Gas Velocity	31.6 m/s
Gas Inlet Diameter	15 mm
Static Bed Height (H_s) and Conical Section Height (H_O)	100 mm and 108.25 mm
Measurement Height	70 mm (gas velocity)
Particle Mean Diameter	1.2 mm
Particle Density	$3080\ \frac{kg}{m^3}$
Gas (air) Density	$1.25\ \frac{kg}{m^3}$
Simulation Time	5 Seconds
Geometry Type	3D

MESH GENERATION

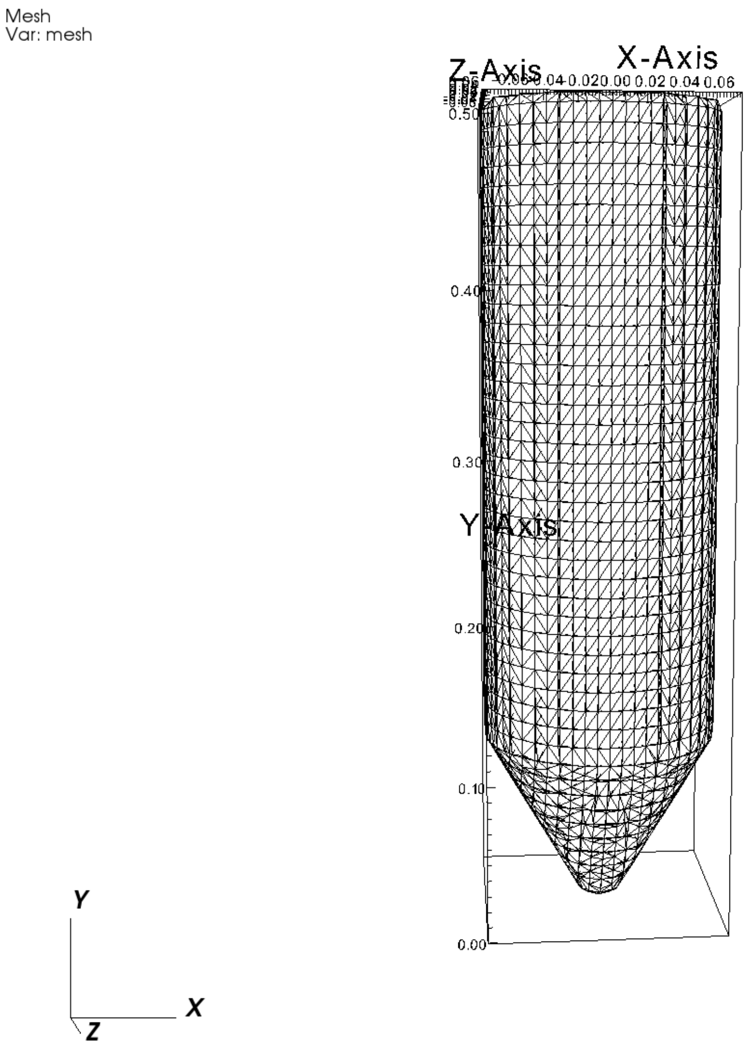


Figure 8: 3D Mesh Generation.

- **Structured Cells**
- **20 cells in x and z directions,45 cells in y direction**
- **Cell lengths are 7.5 mm in x and z directions,11.6 mm in y directions**

Table 4: Solution Cases

Solution Cases	CGP				
	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
Number of Cells	18,000				
Number of Particles (Real Case=4.01×10^5)	3.95×10^5	3.95×10^5	3.95×10^5	3.96×10^5	4.04×10^5
Drag Model	Gidaspow	Di Felice	Syamlal	Di Felice	Di Felice
Min. Spouting Velocity (m/s)	31.625 (1.15 Ums)				
Coarse Grained Particle Diameter (mm)	3	3	3	2	2.5
Real Particle Diameter (mm)	1.2	1.2	1.2	1.2	1.2
Particle Density $\frac{kg}{m^3}$	3080				
Spring Stiffness (k) (N/m)	1000				
Coulomb Friction	0.8				
Rolling Friction	0.03				
Spring tan/normal ratio	0.29				
Damping Ratio	0.5				
Resitution Coefficient	0.97				
Min. Fluid Volume Fraction	0.42				
Simulation Time	5 seconds				

DiFelice Gidaspow Syamlal O’brien

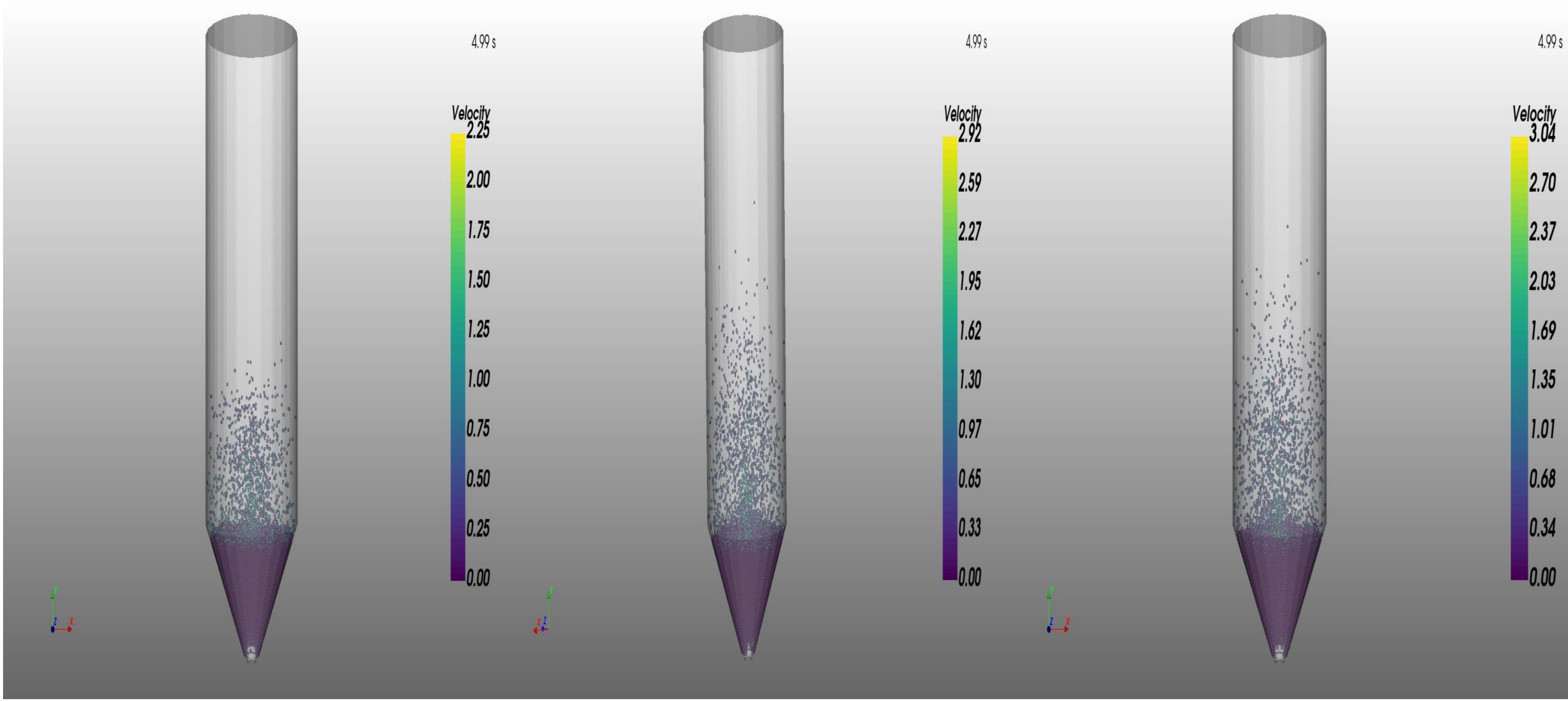


Figure 9: Last time step of 3 cases.

EXPERIMENTAL SETUP

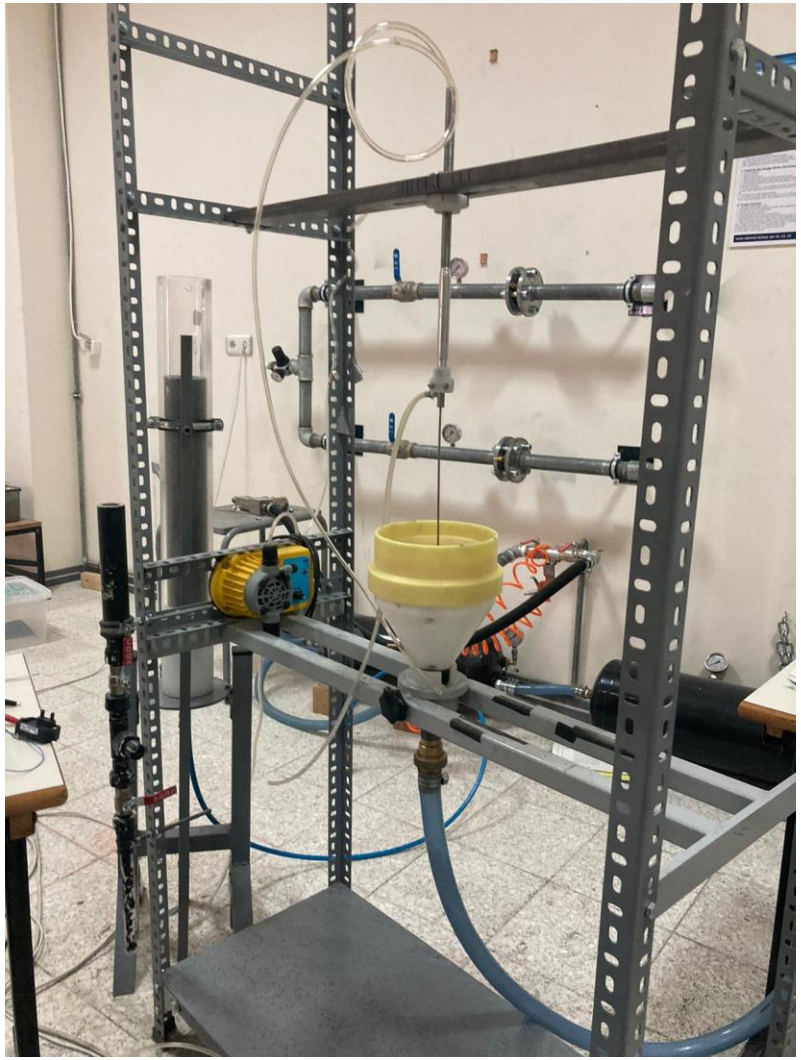


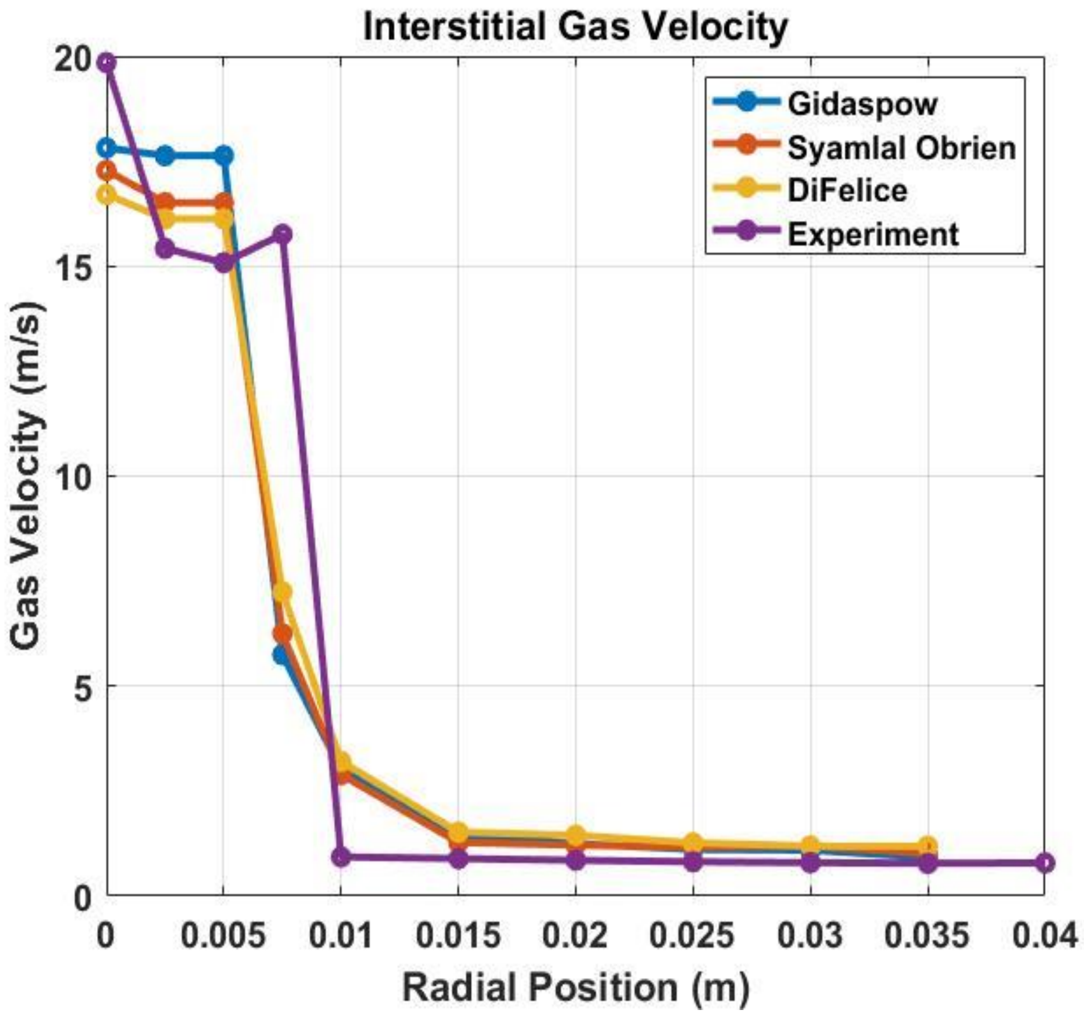
Figure 10: Experimental Set-Up

- The minimum spouting velocity, and pressure drop of olivine were measured by using a differential pressure transducer (Omega PX163-120BD5V).
- The gas velocity of olivine was measured by using a pitot tube and differential pressure transducer.
- The Pitot tube was recalibrated to measure the gas velocity of the annulus region.

For more detail, you can visit Ref. [1] which is completed in our lab.

Table 5: Bed Pressure Drop –

Solution Cases	CGP				
	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
Drag Model	Gidaspow	Di Felice	Syamlal	Di Felice	Di Felice
Bed Pressure Drop (Pascal)	831.24	740.49	758.75	745.02	745.53
Bed Pressure Drop (Pascal) Gorshtein [12]	1012	1012	1012	1012	1012
Bed Pressure Drop (Pascal) Olazar [11]	1047	1047	1047	1047	1047
Bed Pressure Drop (Pascal) Ref.[3]	981	981	981	981	981



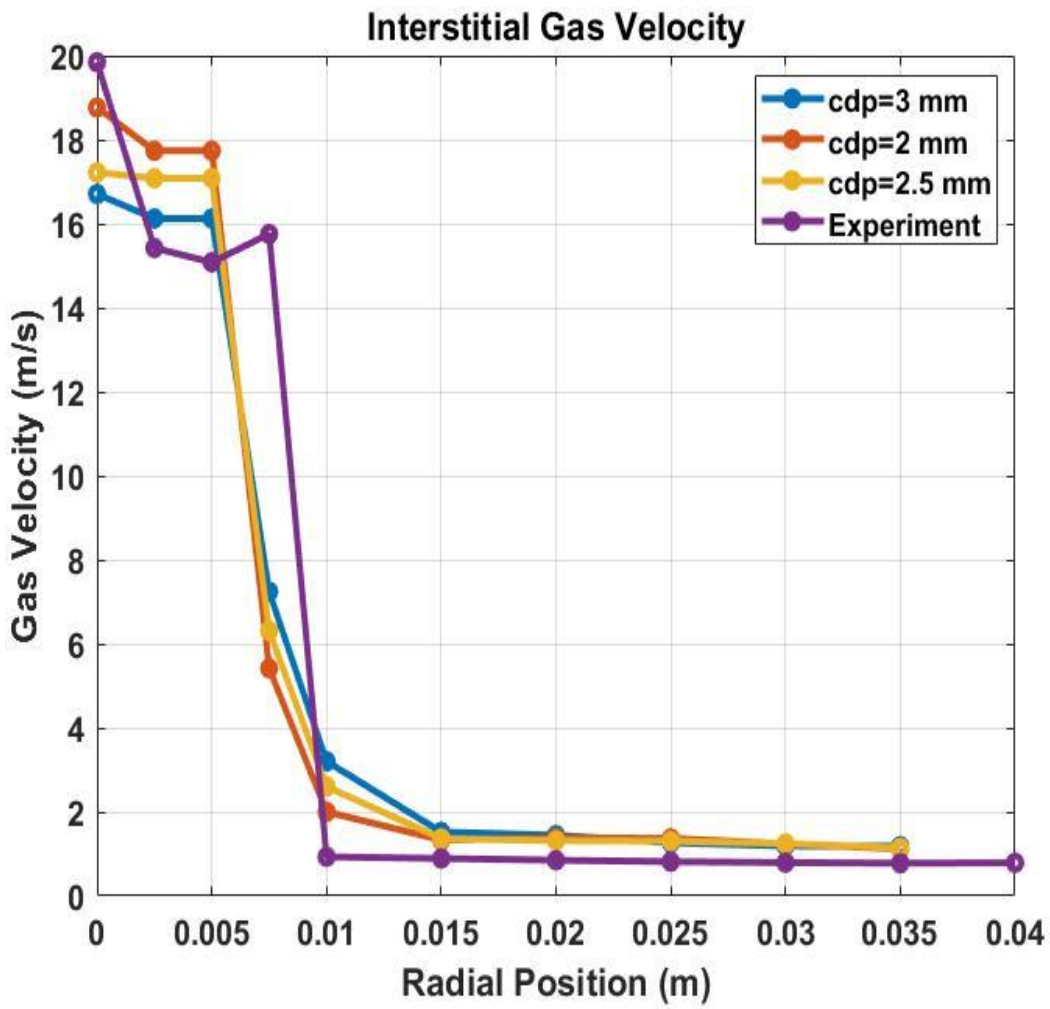
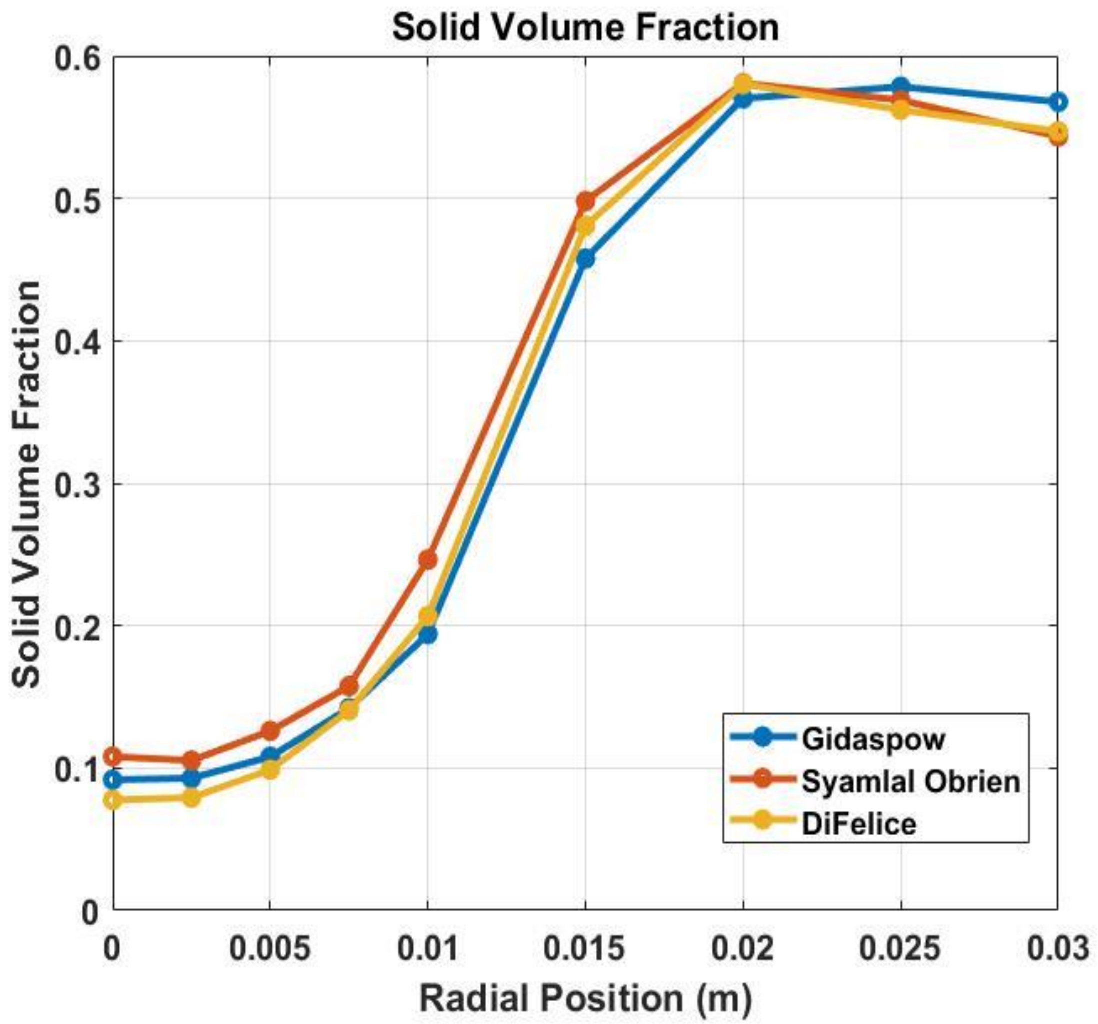


Figure 11: Interstitial Gas Velocity Comparison

a) Effect of drag models (cdp = 3mm)

b) Effect of coarse grained particle diameter. (Drag Model:DiFelice)



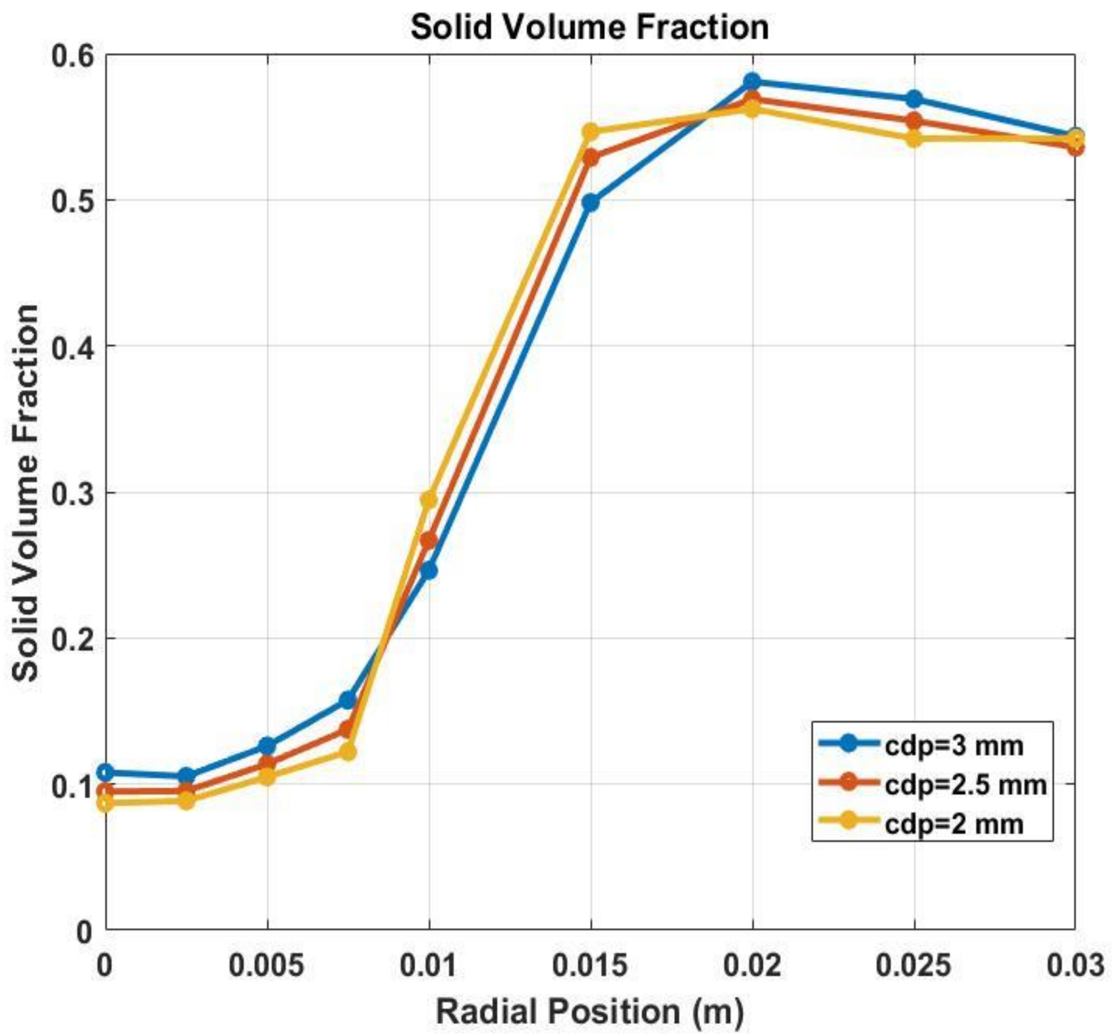


Figure 12: Solid Volume Fraction Comparison (Measurement Height=50 mm)

a) Effect of drag models **b)** Effect of coarse grained particle diameter.

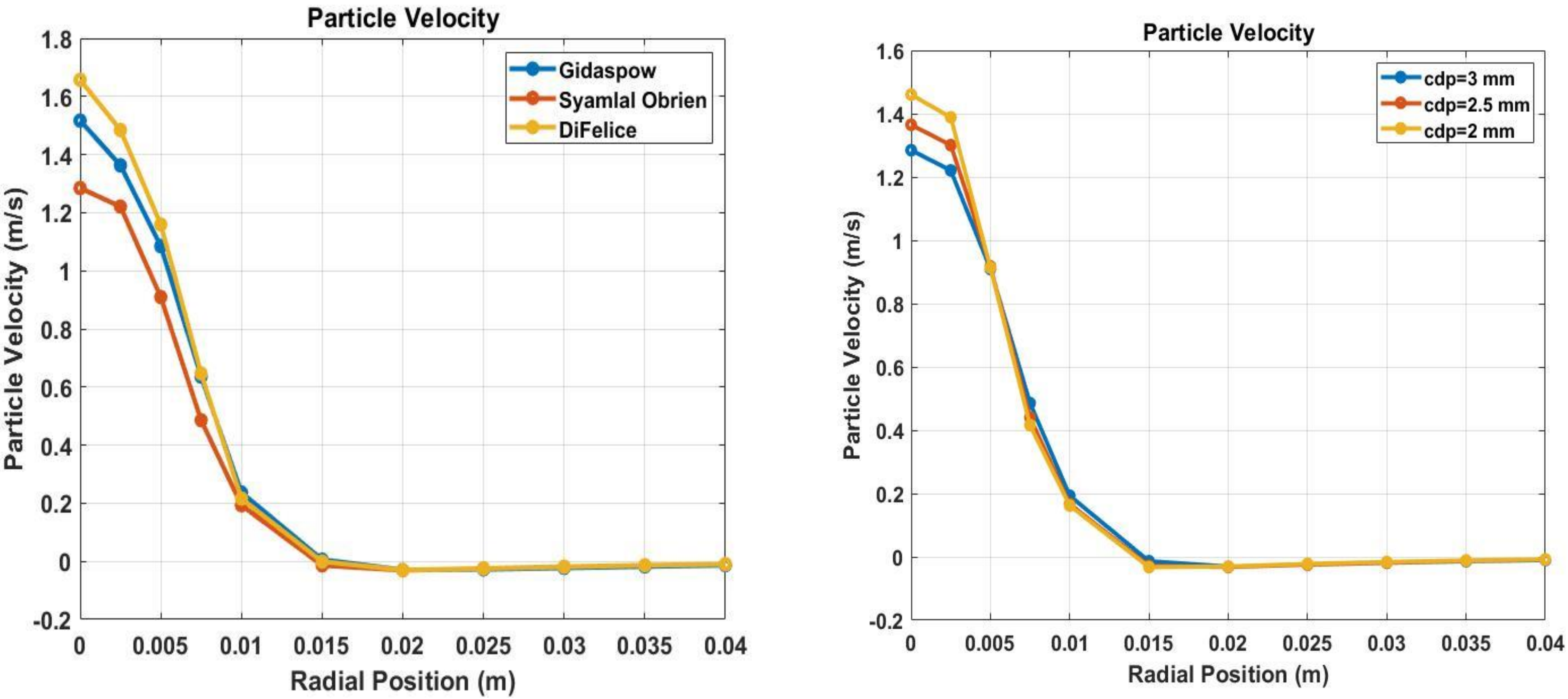


Figure 13: Particle Velocity Comparison (Measurement Height=50 mm)

a) Effect of drag models **b)** Effect of coarse grained particle diameter.

CONCLUSION

- A 3-D course grained CFD-DEM model was developed and implemented in MFIX for the simulation of spouted bed thermal receivers in CSP applications.
- Olivine as a potential candidate for bed material in CSP applications was used both in the experiments and simulations.
- CFD-DEM model captures the radial variation of the interstitial gas velocity successfully when compared to experimental measurements.
- Both the drag law and course grained particle diameter have affects on the interstitial gas velocity, particle velocity and solids volume in varying extents.
- Particle and interstitial gas velocity are affected by the drag law and course grained particle diameter especially in the spout region. The effects of these two parameters on the solids volume fraction are less pronounced.

FUTURE WORKS

- Particle velocity and solid volume fraction of olivine and other materials will be measured using an optical fiber probe. (previous experiments are available at Ref. [2])
- Real CSP conditions with incoming radiation will be simulated in order to obtain temperature distribution and energy storage capacity of the bed.

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SOME OF THE RELATED PUBLICATIONS COMPLETED IN HACETTEPE MPL

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Ref.[3] Golshan, S., Yaman, O., Koksal, M., Kulah, G., Zarghami, R., Mostoufi, N., "A New Correlation for Minimum Spouting Velocity for Conical Spouted Beds Operating with High Density Particles", *Experimental Thermal and Fluid Science,* v. 96, p. 358–370, 2018.

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ANY QUESTIONS ??

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