Study of Parameters Affecting Fluidization Process and their Effect on the Process of Fluidization in a Fluidized Bed Combustion Boiler

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Abstract:- Fluidized bed combustion is considered as one of the few key options to burn low grade fuels such as biomass and municipal waste. In Fluidized bed combustion, the fluidization process is very critical & behavior of fuel & air mix as a fluid is very significant for the combustion performance. A lot of research work has been conducted to investigate fluidization process &heat transfer characteristics of a typical fluidized bed furnace. This provides a useful start for understanding the furnace behavior in FBC boilers. This paper describes fuel particle relations to overall fluidization process with use of an experiment. Starting with a very brief review of the combustion process inside a fluidized bed boiler, paper elaborates on the concept of fluidization &its controlling parameters. With the help of this experimental set-up the paper throws light on the relations between fluidizing air velocity & particle size which contribute as a major factor in FBC furnace design.

Keywords:- *Fluidization, Computational Fluid Dynamics, Superficial velocity, Voidage, Porosity.*

I. INTRODUCTION

Fluidized bed combustion (FBC) technology is gaining utmost importance due to its ability to burn various low calorific fuels including biomass and municipal waste. The boiler has very controlled emissions thanks to its controlled combustion which eliminates NOX (i.e. Nitrogen Oxides) completely. FBC technology is ready to enter into the upper crest of supercritical range of boilers also.

Fluidization is a very interesting yet a very complicate process involving a mix of solid fuel particles along with combustion air. Unlike other combustion technologies, combustion inside FBC furnace is very sensible& changes with many parameters. These parameters could be fuel ingredients (such as moisture, ash), fuel density and particle size, air velocity, bed dynamicsand furnaceheat transfer etc. These parameters try to control combustion and fluidization process in their own ways.

Until 1987, main focus of FBC experiments was on particle velocities & particle concentrations. Since then numerical modellers are able to compare & evaluate their theoretical models with experimental studies. Study reports tell that the lower furnace portion is very sensitive to erosion during operation of an FBC boiler, as this lower regionis exposed to dense hot stream of fuel, limestone (as applicable) and sand etc. Todesign FBC boiler, thestudy on lower furnace portion is equally important.

The paper study considers proven literature as a basis &refers to the available CFD simulations for hydrodynamic characteristics of two phase flow. The experimental set-up used to conduct few trials, helps to develop relations between the fluidizing air velocity & fuel particle size in process of fluidization. However the paper do not study combustion but concentrates only on fluidization process.

A. Fluidized Bed Combustion

FBC uses pressurized furnace & circulates un-burnt particles again into the furnace (in case of CFBC). This improves combustion efficiency considerably. In general, for all Fluidized Bed Boilers, furnaceis a bed of hot sand, ash & fuel. The bed is maintained in a turbulent fluidized state by the primary air which is introduced through nozzles located at the bottom of the combustor. The large quantity of heat held by the bed functions as a thermal “flywheel”, keeping the temperature constant throughout the furnace & leveling out variations in fuel quality and moisture content. Low combustion temperature, low excess air & staged combustion provide means to minimize NOx generation in the flue gases. Also, SOx formation can be controlled by adding limestone in furnace to capture sulfur & hence requirement of FGDs. (Flue Gas Desulfurization) becomes obsolete. The operation characteristics of FBC promote total fuel flexibility.

B. Fluidization Phenomenon

If to be defined, fluidization is a two-phase process which induces an upward flow of a gas through a stacked height of solid particles. At high enough gas velocities, the gas / solids mass exhibits liquid like properties & hence termed as fluidized bed. On fluidizing, a bed of solid particles gets converted into an expanded, suspended mass which possess many properties of a liquid. For example, zero angle of repose, it seeks its own level, and assumes the shape of the containing vessel. Generally, particle size distribution is between 8 mm to 15 mm give best results with least formation of large bubbles. Large particles cause instability and result in slugging or massive surges& Small particles frequently, even though dry, act as if damp, forming agglomerates or fissures in the bed, or spouting. Adding finer sized particles to a coarse bed or coarser-sized particles to a bed of fines usually results in better fluidization.

If we go on increasing air flow rate continuously, the drag forces on the particles counterbalance the gravitational force. Due to this the solid particles remain suspended in air. The upward velocity of the gas is usually between 0.5 m/s to 6 m/s. This velocity is based upon the flow through the empty vessel and is referred to as the superficial velocity(Us).

Superficial Velocity (Us)

$$Us = \frac{Q}{A * 3600}$$

Where

Us = Superficial velocity (m/sec)

Q = Theoretical Air flow required (m3/hr)

A = Cross sectional area of furnace (m²)

As the gas velocity is increased, pressure drop increases until it equals the weight of the bed divided by the cross-sectional area. This velocity is called *minimum fluidizing velocity, (Umf).*

Minimum fluidisation velocity (Umf)

$$Umf = \frac{[(\rho P - \rho A)^{0.934}] * [g^{o.934}] * Dp^{1.8}}{[1110 * \mu^{0.87} \rho A^{20.066}]}$$

Where

Umf = Minimum fluidization velocity (m/sec)

g = Gravitational acceleration (m/sec²)

Dp = Average Particle size (in m)

µ = Viscosity of air (cp)

ρp = Density of fuel (Kg/m3)

ρA = Density of air (Kg/m3)

When this point is reached, the bed particles will expand uniformly until at some higher velocity gas bubbles will form *(minimum bubbling velocity, Umb)*.Minimum fluidizing velocity is a vital term used in fluid-bed calculations. It quantifies one of the particle properties. This gives a particle size that takes into account effects of size distribution and sphericity. The flow required to maintain a complete homogeneous bed of solids in which coarse or heavy particles will not segregate from the fluidized portion is very different from the minimum fluidizing velocity.

If the gas velocity is increased further, bed density will reduce &turbulence will increase. If bed is smaller is cross section, slugging will be observed due to increase in bubbles size greater than half of the bed cross-section. The increase is by vertical and lateral merging. Size increase is also due to the gas velocity increase.On further increase in gas velocity, bubbles start to disappear and streamers of solids and gas prevail, pressure fluctuations in the bed are greatly reduced. Further increase on velocity results in dilute-phase.

C. Other Equations Used

- *Calculations for Viodage (ε)*

Voidage can be defined as comparison of fuel mass with available volume in the furnace bed portion.

$$\in = \frac{M}{(\rho P * \rho A * A * H)}$$

Where

ε = Bed Voidage Fraction

M = Mass of fuel particles (in Kg)

H = Bed height (m)

Pressure drop thru bed plate

$$\Delta Pb = \frac{Vb^2 * \rho A}{0.64 * 2g}$$

Where

ΔPb = Pressure drop across bed plate (in mmwc.....converted from Kg/cm²)

Vb = Velocity thru bed nozzle (m/sec)

Total Pressure drop (ΔPt)

$$\Delta Pt = H * (1 - \in) * (\rho P - \rho A) * g$$

Where

ΔPt = Total Pressure drop (in mmwc.....converted from Kg/cm²)

D. Fluidized Bed Design

The fluidized bed is comprised of various parts such as Fluidized furnace, fuel feed & control system, fuel discharge & distribution system, air supply system & required amount of instrumentation.

The fluidization furnace consists of Fluidized-bed, bed height & Gas distributor or wind-box assembly. The volume above the bed is called the disengaging space. In boiler terms it is also called as bed height. Bed cross-sectional area is determined by the volumetric flow of air and the allowable or required air fluidizing velocity at operating conditions. Dimensions of the bed (cross-sectional area and height) decide maximum air flow required. It also depends up-on carry-over of solids. Bed height is worked based on various factors, like Air-contact time, *L*/*D* ratio constraints for air staging, Space required for In-Bed Heat exchangers & fuel particles retention time in furnace.

FBC boilers operate at elevated temperatures of the range 800 - 1000˚C. Of course, due to high temperature operation furnace is refractory-lined. The refractory serves two main purposes; it insulates the pressure parts from the elevated temperatures, and it protects the pressure parts from abrasion by the bed and particularly splashing fuel particles at bed top resulting from bursting bubbles.

Bed height is the distance between the top of the fluid bed and the end level of dense phase of fluidized mix. Two actions take place within the bed height: Mixing of fuel particles with air & burning of the fuel particles in the same suspended position after the start of combustion. During process of combustion, fuel particle burns & losses its mass. Due to loss of mass it moves vertically up. Bed temperature increases and it also expands vertically up. The wind-box assembly provides stage-wise progressive combustion & has a considerable effect on proper operation of the fluidized bed.

Bed temperature and heat transfer coefficient increases with increase in bed inventory and particle size.

Fluidized bed furnace can be distinguished into two zones as dense zone at bottom & dilute zone at top. The dense zone is the zone the fuel particles are fluidized by the primary air supply whereas the dilute zone is the region with decaying suspension density especially the upper portion of the furnace.

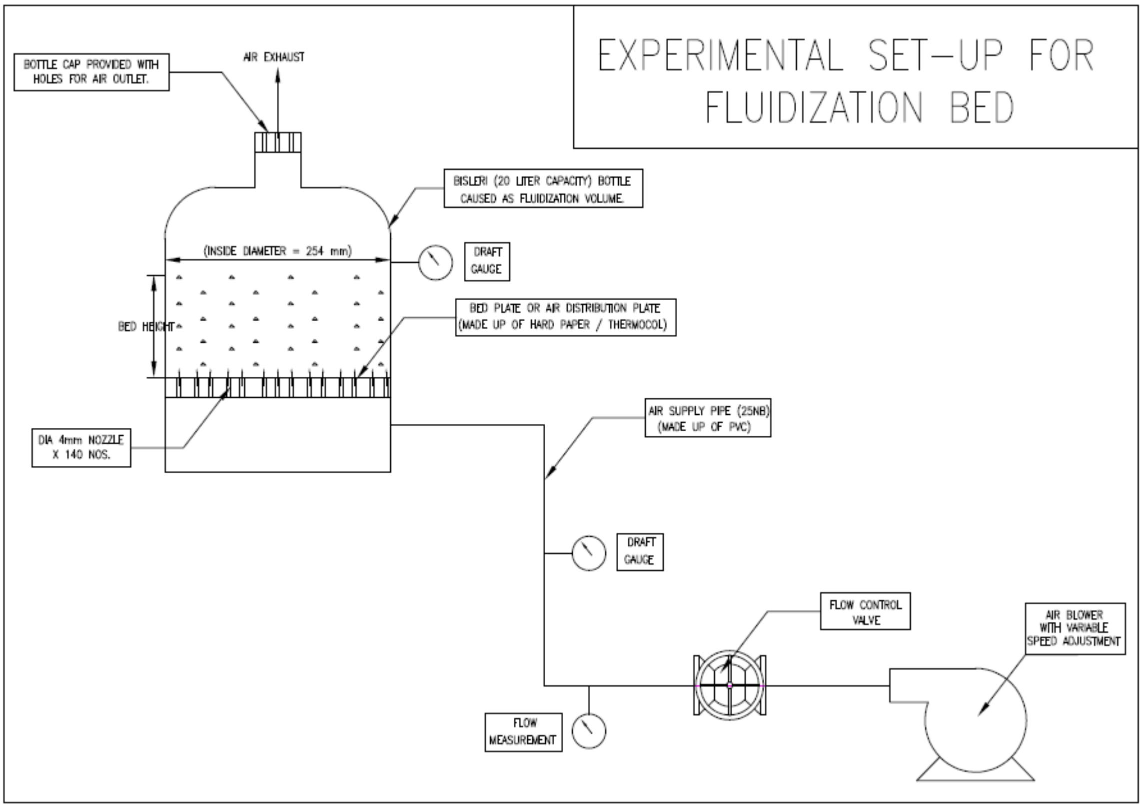
II. EXPERIMENTATION

A. Experimental Set-Up

Following figure shows a simple set-up for the experiment of fluidization. This involves a large volume to represent furnace made from a simple 20 litre mineral water tank (made up of PVC). This tank is transparent such that it will be easy to observe the fluidization process while trial. The volume at the bottom is attached with anair distribution plate. This plate is made up of wooden plate& is drilled with numerous equi-spaced holes based on hole size. An opening symbolizing chimney is available for air exit. Below air distribution plate, a small tank resembling wind-box is provided for air supply into the furnace & is supplied with a positive displacement blower & inlet duct (made up of a simple PVC pipe). The set-up is equipped with required instruments such as flow-measurement&draft gauges such that we can conduct number of trials & note down required parameters. Required size mesh-screens are used to ensure k fuel particle size as required & a weighbridge to get only required weight of the fuel.

Steady state experiments were conducted to examine relations between particle size, density, distribution area & fluidization air velocity. These experiments were conducted with variety of material such as coal, puffed rice&Ground nut huskso that variation in density also can be taken into consideration.

B. Schematic of Set-Up Arrangement



C. Sample Readings

- *Case showing variation in results with respect to air flow variation.*

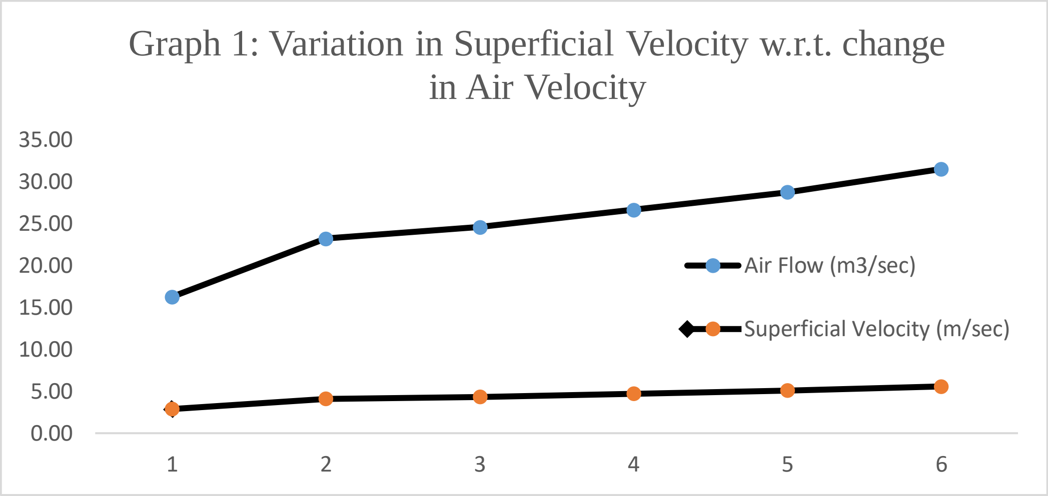
Fuel Specimen	Groundnut Husk					
Fuel particle size in mm	Below 10 mm					
Mass of fuel particles (grams)	100					
Density (Kg/m3)	228					
Air Density (kg/m3)	1.2					
Bed Plate Hole size (mm)	3					
Bed Plate Hole quantity	222					
Minimum fluidization velocity calculated (Umf in m/sec)	0.067					
Case	1	2	3	4	5	6
Air flow rate (Q in m3/hr)	16.28	23.21	24.59	26.67	28.75	31.52
Air velocity thru bed hole (m/sec)	2.88	4.11	4.35	4.72	5.09	5.58
Pressure drop (Δp) thru bed plate When bed is fluidized @ given flow rate (MMWC)	16.37	33.26	37.35	43.93	51.04	61.35
Actual pressure drop (MMWC)	28	53	58	66	70	78
Bed Height (mm)	200	250	270	300	330	380

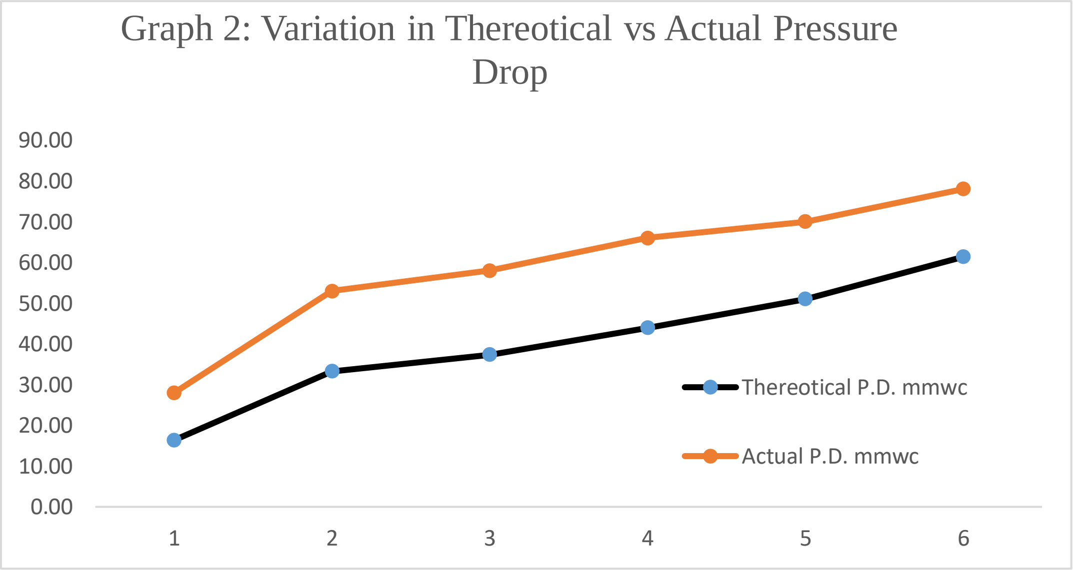
III. RESULTS AND DISCUSSION

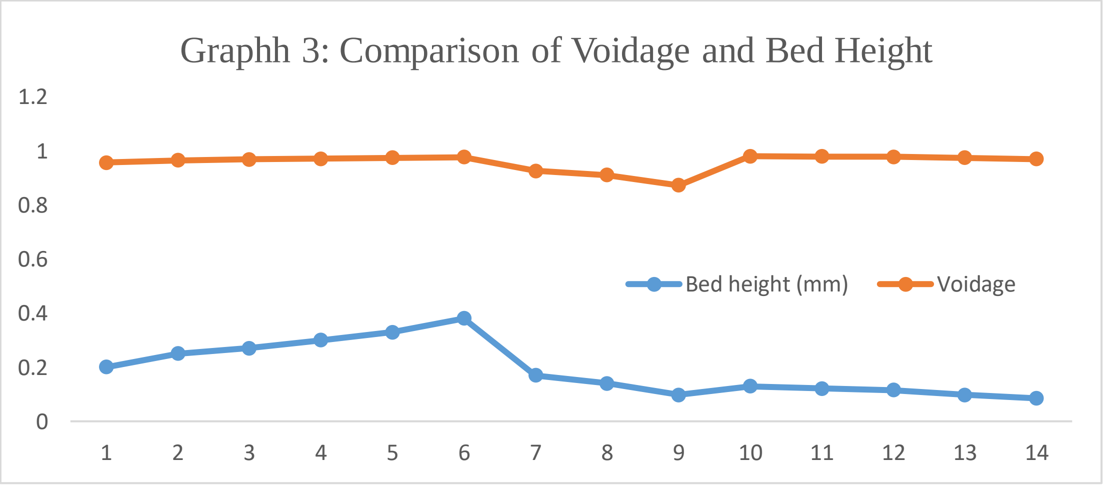
A. Observations:

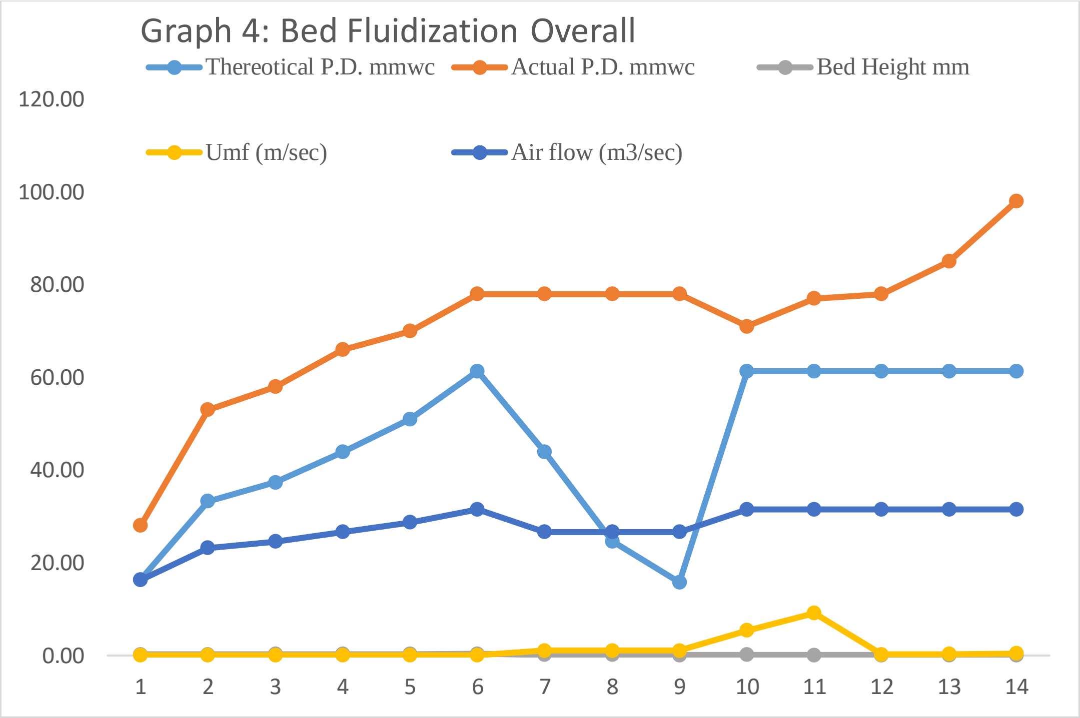
- The experimental set-up, particularly fluidized bed chamber is made by joining a wooden plate (i.e. Bed Plate) to vessels made of plastic fibre material. These joints may have few leakages minute in nature and difficult to trace and close with naked eye. This is causing an increase in actual air flow requirement compared to the theoretical. Also affecting extra pressure drop.
- Fuel feed is manual, from the top of the tank. Being manual, this feeding is not exactly uniform all over the cross-section.This is causingslight increase in actual air requirement for fluidization. Whereas in actual case fuel feed is by mechanical means, continuous, controlled and more uniform.
- The Bed-hole layout is not exactly symmetrical and has its own limits resulting in non-homogeneous air distribution. Thus, calls for extra fluidization air required. Fluidization too is not uniform throughout cross-section.
- If the particle size is increased for the same density, required air flow rate increases, with effective increase of fuel mass allowed. The ratios of increase are almost same.
- Actual pressure drop is more due to possible leakages, limitation of experimental set-up & due to limited accuracy of the measurement.
- Pressure drop increase is more dependent on-air flow than the particle size. Due to this actual pressure drop is higher compared to the theoretical as air flow required in actual case is high.
- Other parameter such as L/D ratio for the tank also has impact on pressure drop & air flow requirement which is not considered in the experiment.
- The experimental results match with the theoretical, with accuracy level of ±10 % which is even though not a very good accuracy but is sufficient to confirm the theoretical basis.
- There is no continuous bubble formation during the experimentation.

B. Discussion Based on Graphs Plotted









IV. VALIDATING EXPERIMENTAL SET-UP RESULTS WITH THE HELP OF CFD:

A. Objective:

It is very difficult to predict the boiler performance without using professional tools such as CFD (Computational Fluid Dynamics). Also, the simulation results obtained through CFD are tested with some experimental set-up or a test bed. CFD simulations are used to simulate two phase problems & predict heat transfer characteristics such as temperature, heat transfer coefficient & hydrodynamic characteristics such as pressure, velocity, volume fraction etc.

The main objective of doing CFD analysis is to confirm, cross-check or vet the experimental set-up readings. It gives a third eye look to evaluate our conclusions. The behavior in terms of pressure variation, velocity variation can be observed minutely, the trends could be found out and accordingly results can be compared. CFD is not expected to deliver 100% in terms of the output but it would be great even if it gives some improvements.

B. Boundary Conditions and Inputs For CFD Analysis:

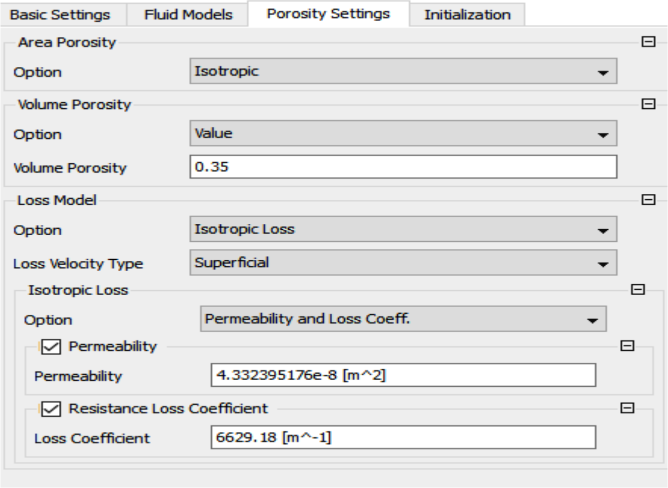
- CFD software used: ANSYS
- Software version: R15.0
- No dimensional deviation in experimental set up
- Fuel
- Considered Fuel: Coal
- Particle size considered: 8 mm and below
- Fuel mass considered: 3.95 kg
- Bed plate case considered: With 3mm hole size
- Bed height considered as 150 mm.
- Flue gas
- Density considered as 1.2 kg/m3
- Viscosity considered: 0.002 PaS
- Geometry meshing method used:
- Air domain: Tetragonal
- Coal Bed: Hexagonal
- Total nodes used: 10157
- Elements: 471154

Outlet: Open to atmosphere.

(Boundary conditions are applied to the computational model based on the data collected from the experiment.

Wall and thermal boundary conditions: The wall of the vessel was assigned constant temperature boundary condition. A Simple model was considered i.e. No erosion, cavitation etc. No slip boundary condition was assigned to the wall.

C. CFD Input Sheet:



Area Porosity
Option: Isotropic
Volume Porosity
Option: Value
Volume Porosity: 0.35
Loss Model
Option: Isotropic Loss
Loss Velocity Type: Superficial
Isotropic Loss
Option: Permeability and Loss Coeff.
☑ Permeability
Permeability: 4.332395176e-8 [m^2]
☑ Resistance Loss Coefficient
Loss Coefficient: 6629.18 [m^-1]

D. Assumptions in CFD Analysis:

- *Porosity:* Fluidizing air is flowing through the bulk of particles. The pressure drop across the fixed bed area is related to the particle size, particle shape, particle alignment and void fraction (or bulk porosity). This

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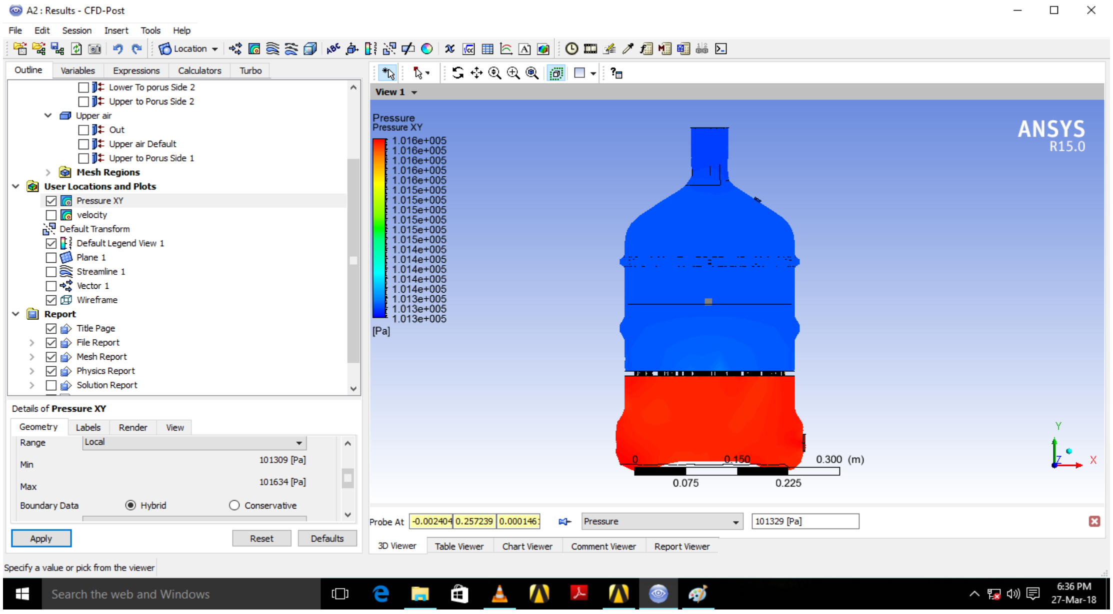
correlation between fluid velocity and the pressure drop per the length/height of bed was described by Ergun [5] in 1952

To resolve our problem in CFD simulation, the number of calculating node were reduced by considering the fixed bed as the porous volume. The holed sieve is considered as the porous wall. Important factors (viscous and inertia loss coefficient) and equivalent porosity of bulk are estimated from the pressure drop and air velocity of previous results. The overall objective of this study is to conduct simulation of the fluidization and air velocity profiles in the experimental set-up model by using ANSYS (FLUENT) software and to validate the results with the previous experiment.

	Calculations for porosity	
1	Vessel Dia (mm)	254
2	Bed height (mm)	150
3	Volume (m3)	0.007600612
4	Fuel density considered (kg/m3)	800
5	Fuel mass for the case study (kg)	3.95
6	Fuel volume for the case study (kg)	0.0049375
7	Porosity can be considered	0.350381275

E. CFD Results:

Below figure shows the pressure variation inside experimental set-up. wind box region below bed plate is more pressurized than the fluidization region above bed plate.



Details of **Pressure XY**

Range: Local

Min: 101309 [Pa]

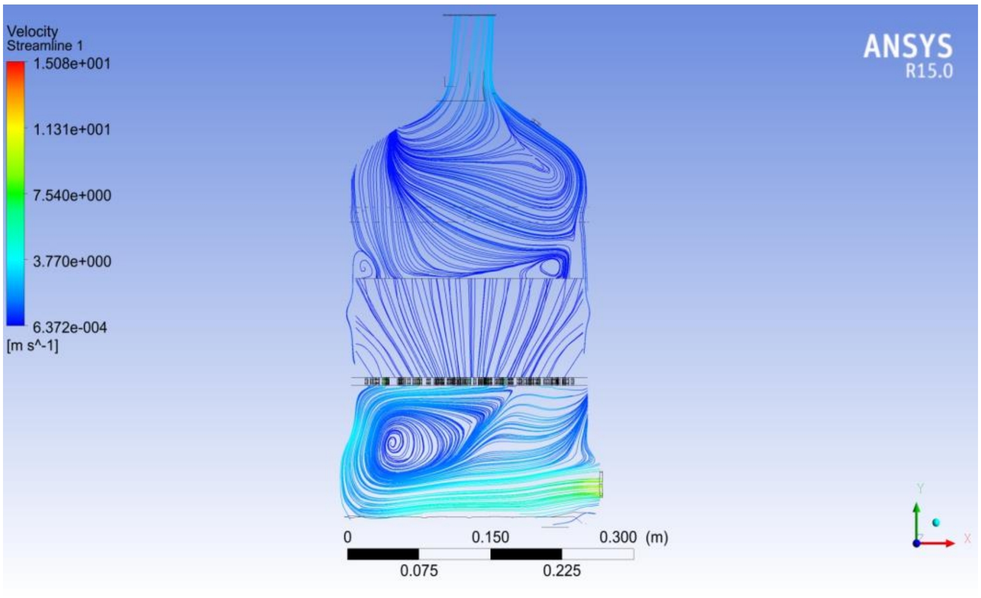
Max: 101634 [Pa]

Boundary Data: ● Hybrid ○ Conservative

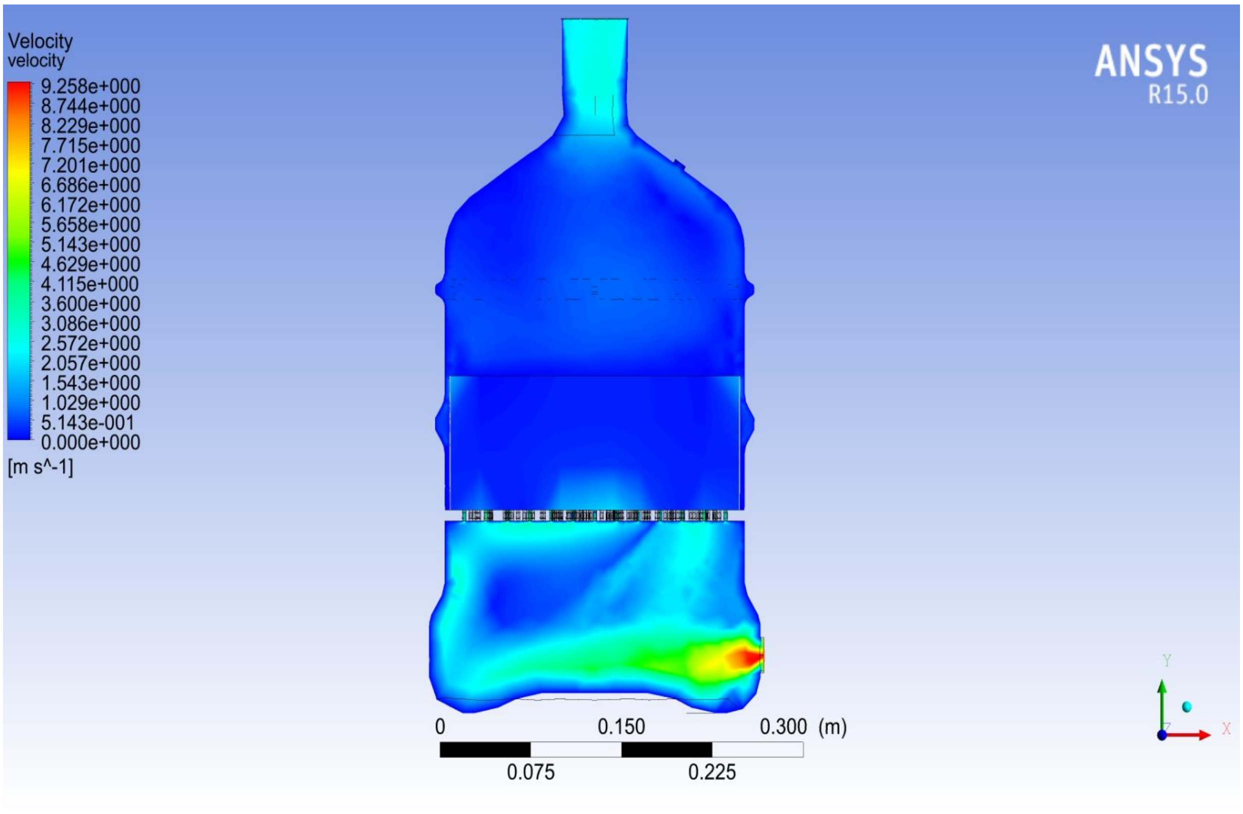
Probe At: -0.002404 0.257239 0.000146 Pressure 101329 [Pa]

Specify a value or pick from the viewer

Below figure shows the air velocity contour formed due to the air flow through various holes thru bed plate. It also shows the path followed by the air pathlines.



Following figure indicates air velocity pattern inside fluidization region. One can observe the changes in velocity starting from air entry into wind box to the air exit to atmosphere.



F. Differences and Reasons:

Following are the reasons for variation in results i.e. Practical vs CFD

- CFD does not account for any air loss due to leakages whereas in the experimental model there are some unavoidable losses due to leakages. (Mainly across bed plate joint)
- Particles considered in CFD are of exact 8 mm size whereas practically particle size is 8 mm and below. Even though sieve analysis is not done the average particle size is below 8 mm approximately 6-7 mm.
- Due to software limitation, CFD considered Fuel bed as a porous material with porosity as 0.35 with density as 800 kg/m3. Practically fuel bed does not have constant density and does not have constant height even. It varies with concentration of fuel particles against air flow and its velocity. This difference has triggered to major variation in the output.

- CFD has not considered blower, inlet pipe but has considered the model from inlet of windbox portion. This does not account for major variation but still fact is it overlooks the inlet portion of the experimental set-up.
- Accuracy of measurements in experimental set-up and CFD are largely different which also accounts for variation.

V. SUMMARY

From the CFD simulation of fluidization and comparing it with the results of experiment conducted; we can summarize few facts such as, fluidizing, converts the bed of fuel particles into an expanded, suspended masshaving many properties of a liquid. Compared to the smaller size particles, large particles cause more instability. If the variation in the particle size is too high, fluidization becomes difficult as we cannot predict the exact fluidization air requirement.

Also, with the variations in density & variations in particle size, we could find that bed height needs to be varied with change in density however for same density if particle size is changed, we need not change bed height. It will not result big impact on air requirement & pressure drops.

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