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Hydrodynamics and CFD Modeling of Food Materials using Circulating Fluidized Bed

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Abstract : Hydrodynamics plays an important role in defining the performance of circulating fluidized bed as a reactor. Hence, the present work, focus to study the hydrodynamic characteristics of food materials such as Poppy Seeds, Mustard, Semolina and Millet in circulating fluidized bed. The effects of axial variation of pressure with gas flow rate and solid circulation rate have been analyzed. Computational fluid dynamics simulations were performed using commercial computational fluid dynamics package. Simulations were done for the axial and radial variations of pressure drop with gas flow rate and packing height for poppy seeds. The experimental and simulations results were compared and found to be satisfactory.
Keywords : Circulating fluidized bed, Food Materials, Hydrodynamics, CFD modeling.

1. Introduction

Circulating Fluidized Bed is considered as alternatives for conventional fluidized bed because of their apparent intrinsic advantages, including short and controllable residence time for the gas and solids, high turn down ratios, flexibility, good heat and mass transfer and uniform temperature distribution. The behavior of CFB differs from a conventional fluidized bed, because of absence of bubbles and entrained flow of solids. Solid particles are widely used in chemical industries, in operations as mineral processing, pharmaceutical production, food processing and energy related processes, ore reduction and waste incineration. Circulating fluidized beds finds applications in calcination of aluminium hydroxide to high grade alumina, coal combustion and catalytic process such as fluid catalytic cracking and Fischer-Tropsch synthesis. It is also used for drying food grains and other granular materials, production Maleic anhydride, Alkylate and in Biochemical Industries.

Hydrodynamic aspects of circulating fluidized bed with perforated plate type of internals with different free area was studied, and it was found that 45% free area gives uniform solids concentration and pressure drop, also an increase in the plate free area increases the solids holdup in the modified CFB [1]. Internals can also be placed to optimize gas-solid flow in a CFB, the larger upper internal and a smaller lower internal provides uniform concentration and strong intensity of turbulence, internals are also needed in the corners to force the flow in the corners out in to the center [2]. The internals can reduce radial non-uniformity and solids are evenly distributed in radial direction. Under high superficial velocity and low solid circulation rate, more dilute flow is observed in the wall region than in the core region [3]. The hydrodynamics of circulating fluidized beds with risers of different shape and size was studied [4] and it was found that changing the solid properties affects the extent of the dense region and the dilute region voidage oscillations are strongly reduced.

Three different types of inlet configurations were investigated and found to have profound effect on the radial profiles of solid velocity and volume fractions even in the top section of riser which has been generally described as the fully developed region and believed to be immune to any entry effect[5]. A new approach was found [6] to specify the inlet boundary conditions for CFD modeling of hydrodynamic behavior of a CFB riser. The inlet boundary conditions plays an important role in simulating the hydrodynamics and flow structures in the CFB riser, both experimental and numerical results illustrate a clear core-annulus structure in the CFB riser under all operating conditions. Higher air velocity results in lower solids volume under the same solid circulation rate and higher solid circulation rate results in higher solids volume fraction under the same air velocity.

A two-dimensional transient eulerian model [7] was developed and combined with the kinetic theory of granular flow to obtain the hydrodynamic and chemical reaction behaviours in tapered circulating fluidized bed reactor risers. The tapered-in riser increases the solid particle residence time and gives more uniform temperature distribution while the tapered-out riser improves the system turbulence or mixing. The same effect was also observed in the study of the circulating fluidized bed reactor riser geometries on chemical reaction rates by using CFD simulations [8]. A multifled eulerian model was developed which incorporates the kinetic theory for solid particles to simulate the gas-solid flow, the momentum exchange co-efficient was calculated using Gidaspow drag model [9].

Hence, the objective of the present work is to study hydrodynamic aspects of food materials in the riser of a CFB covering wide range of operating conditions. Also to simulation the axial and radial variations of pressure drop on gas flow rate and packing height.

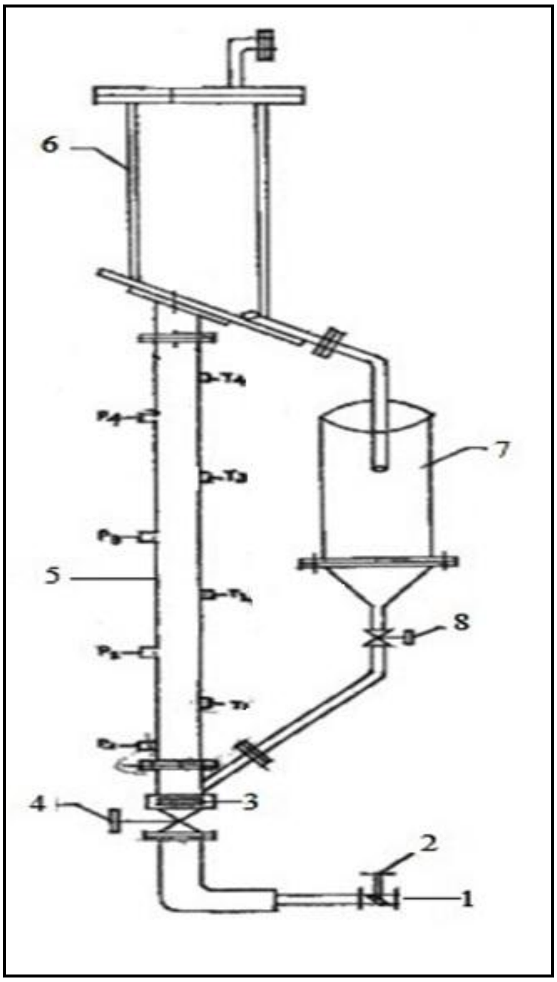
2. Experimental Set - UP:

The plexiglass column of 1600mm height and 50mm diameter consists of a riser, which has a provision for continuous feeding of the solids at a controlled rate from the hopper. Gas-solid separator is provided at the top of the riser to separate solids and gas. Air for fluidization is supplied through blower at the bottom of the column. Pressure tapings were located at the riser column and the pressure measurements were made through inclined manometer. The pressure tapings are located at 10cm, 30cm, 50cm, 70cm, 90cm and 110cm from the riser bottom respectively. RTD sensors were used to measure temperature and ball valves were provided at the solids feed point to measure solid circulation rate in the riser.

2.1 Computational Fluid Dynamics :

Computational fluid dynamics is a computer based mathematical modeling tool that incorporates the solution of the fundamental equations of fluid flow, the Navier-Stokes equation and other allied equations. CFD incorporates empirical models for modeling turbulence based experimentation as well as the solution of heat, mass and other transport and field equations. CFD is now widely accepted and validated engineering tool for industrial applications. The Fluent CFD code is the most widely used and popular software in the world.

In principle, experimental data are considered more precise; however, in many cases, conducting complete measurements is expensive and difficult. Experimentally lacking of a thorough quantitative understanding of the hydrodynamics in the fluidization process, CFD is thus considered a comparatively more powerful, less expensive, and more convenient tool for predicting the hydrodynamic behaviour of CFB's. With the growth of high performance computers and advances in numerical techniques and algorithms, CFD analysis of multiphase systems has grown over the past years and is anticipated to become a strong tool in the design and improvement of CFB units.



1 Air Inlet
2 Butterfly Valve
3 Distributor Plate
4 Ball Valve (50mm)
5 Riser (ID=50mm, h=1600mm)
6 Gas Solid Separator
7 Solid Hopper
8 Ball Valve (25mm)

Fig. 1 Schematic Diagram of Circulating Fluidized Bed

2.2 Modeling Description

An Eulerian-Eulerian model with the kinetic theory of granular flow was used to model the hydrodynamics of the gas-solid flow in the riser section of the CFB unit. The governing equations are given below. The continuity equation for the gas and solid phases are given in the following equations:

$$\frac{\partial}{\partial t}(\propto_g \rho_g) + \nabla.(\alpha_g \rho_g \vartheta_g) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\propto_s \rho_s) + \nabla.(\alpha_s \rho_s \vartheta_s) = 0 \qquad (2)$$

In these equations parameters $\propto_i$, ρ_i and ϑ_i represent the volume fraction, density and velocity of phase i, respectively.

Following are the momentum conservation equations for gas and solid phases :

$$\frac{\partial}{\partial t}(\propto_g \rho_g \vartheta_g) + \nabla.(\alpha_g \rho_g \vartheta_g \vartheta_g) = -\propto_g \nabla p + \nabla.\tau_g + \alpha_g \rho_g g + \beta(\vartheta_s - \vartheta_g) \qquad (3)$$

$$\frac{\partial}{\partial t}(\propto_s \rho_s \vartheta_s) + \nabla.(\alpha_s \rho_s \vartheta_s \vartheta_s) = -\propto_s \nabla p - \nabla p_s + \nabla.\tau_s + \alpha_s \rho_s g + \beta(\vartheta_g - \vartheta_s) \qquad (4)$$

In these equations β represents the interphase momentum exchange coefficient, which has the same value in both equations and τ_i stands for the stress tensors for the gas and solids phases.

2.3 Boundary Conditions :

To carry out the numerical simulations, the boundary conditions at the inlet and outlet of a CFB riser has been specified. The profiles of the solids volume fraction and velocities for both phases has been specified for the boundary conditions at the inlet. Regarding the boundary conditions at the outlet, the fully developed exit conditions are employed for both phases, since the riser is long enough.

3. Results and Discussions

3.1 Determination of Transport Velocity

It has been observed from Fig 2 – 6, that the time required for emptying of solid particles decreases with increase in velocity. As the velocity increases the bed could be emptied in a short period of time due to sharp increase of particle carryover in the absence of solid recycle [10]. The properties and obtained transport velocities of food materials used is represented in Table 1.

Table 1 - Properties of Food Materials Used

Food Material	Diameter (mm)	Density (Kg/m^3)	U_{tr} (m/s)
Poppy Seeds	0.425	558.3	5.39
Mustard Type I	1.70	1014	4.2
Mustrad Type II	1.40	1014	4.56
Semolina	0.3	705.87	3.55
Millet	1.40	845.35	4.5

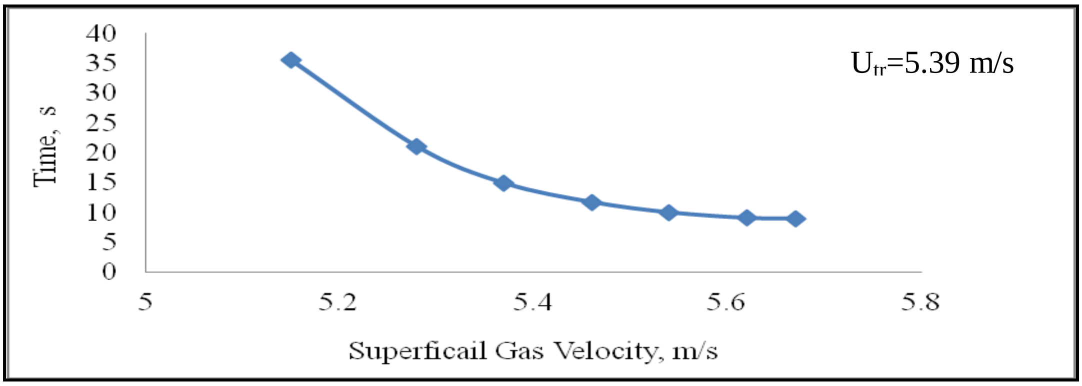


Fig 2 - Estimation of U_{tr} (Poppy Seeds)

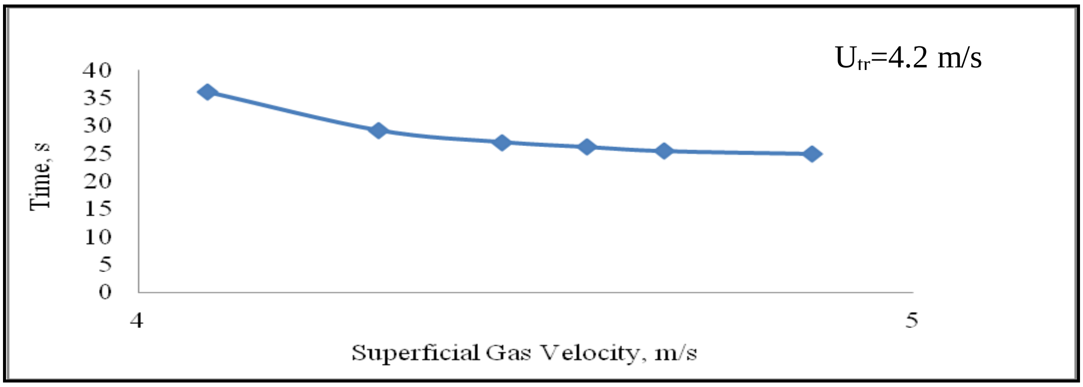


Fig 3 - Estimation of U_{tr} (Mustard Type I)

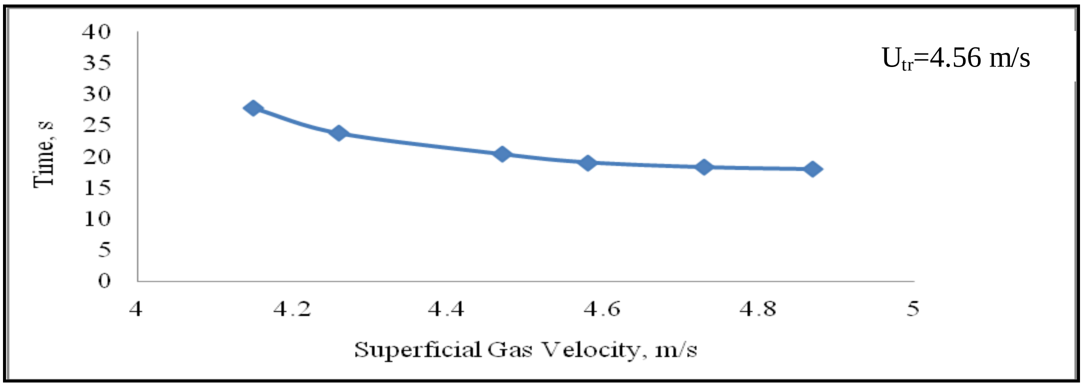


Fig 4 - Estimation of U_{tr}(Mustard Type II)

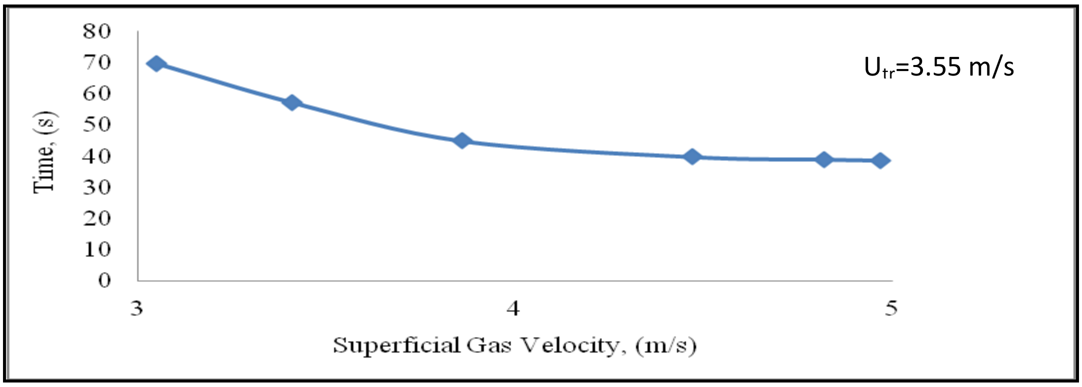


Fig 5 - Estimation of U_{tr} (Semolina)

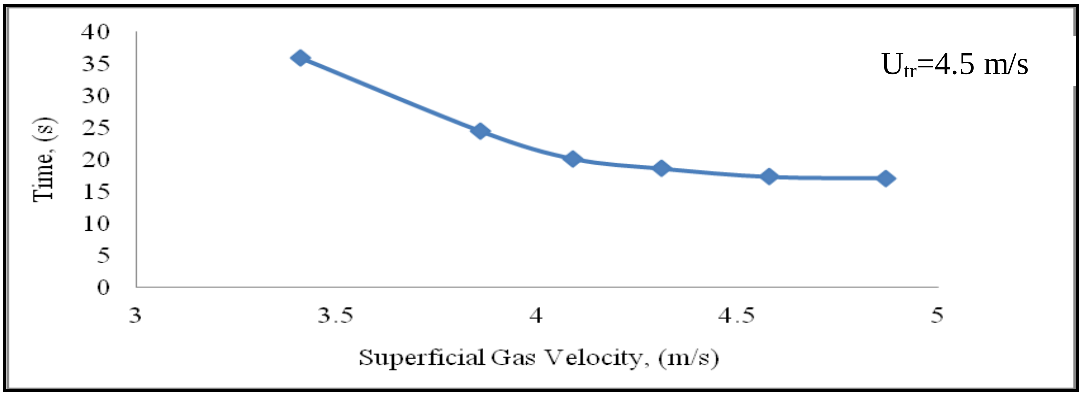


Fig 6 - Estimation of U_{tr} (Millet)

3.2 Axial Variation of Pressure Drop with Gas Flow Rate

The axial variation of pressure drop with different gas flow rate for various food materials is shown in Fig 7 -11. It has been seen from the figures that the pressure drop decreases along the length of the riser. The pressure drop is more at the lower part of the riser, while the pressure drop is less at the upper part of the riser. Also, the pressure drop increases with gas flow rate along the length of the riser [11]. It has been observed that the pressure drop decreases from bottom to top of the riser for all food materials used.

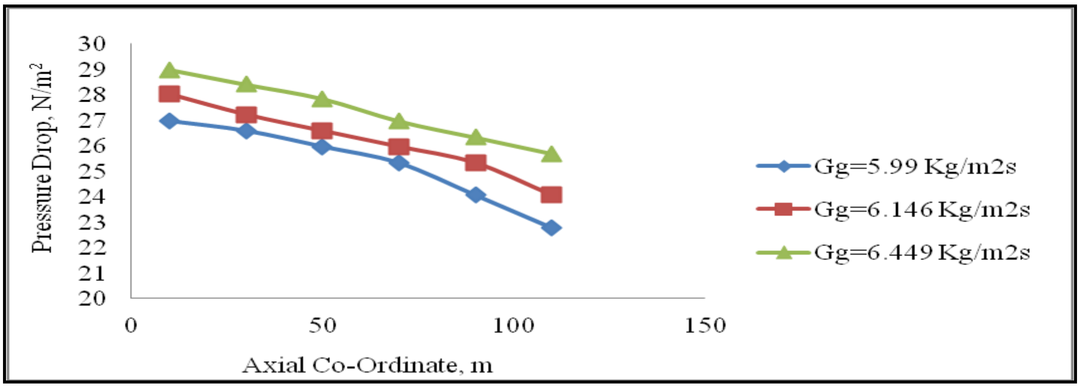


Fig 7 - Axial Variation of Pressure with Gg (Poppy Seeds)

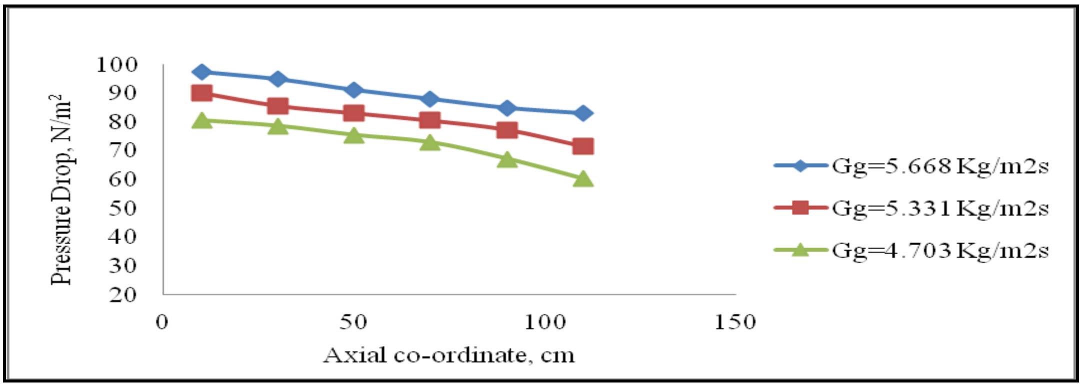


Fig 8 - Axial Variation of Pressure with Gg (Mustard Type I)

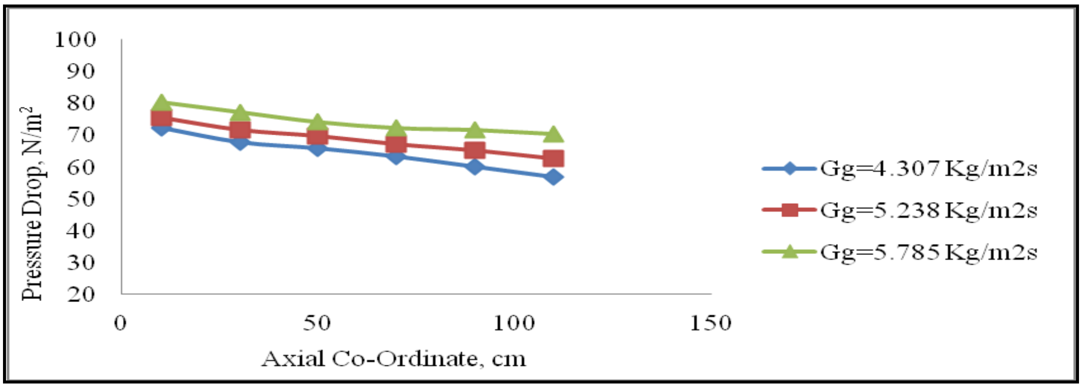


Fig 9 - Axial Variation of Pressure with Gg (Mustard Type II)

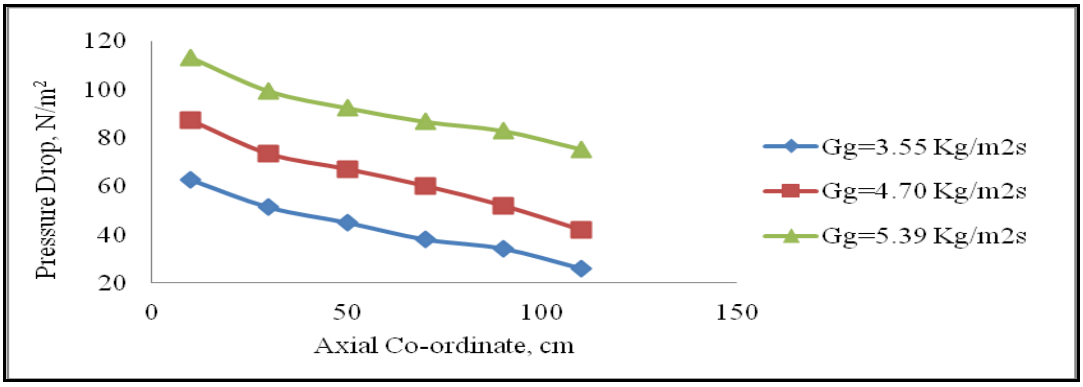


Fig 10 - Axial Variation of Pressure with Gg (Semolina)

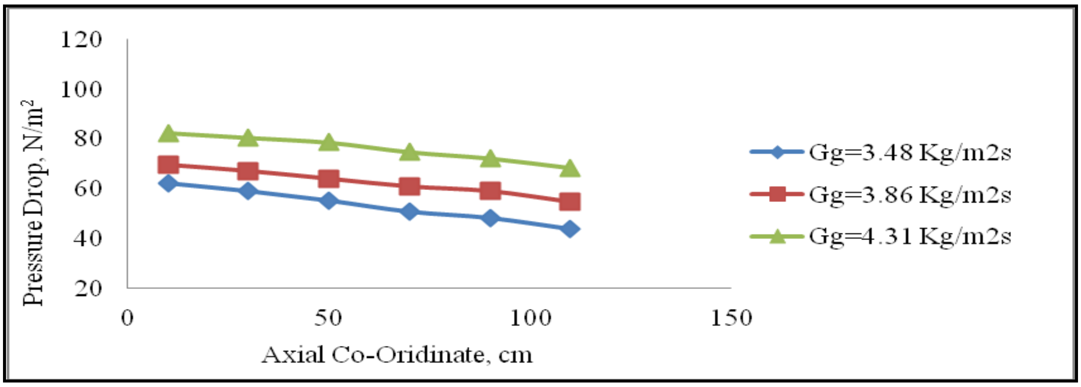


Fig 11 - Axial Variation of Pressure with Gg (Millet)

3.3 Axial Variation of Pressure Drop with Solid Circulation Rate

The lower part of the riser is the region of higher holdup with high solids concentration while the upper part of the riser is the region of lower holdup with low solids concentration. The axial variation of pressure drop with different solid circulation rate is shown in Fig 12 - 16. The initial portion corresponding to the lower portion of the riser is the region of higher solids holdup where the pressure is high, and the final portion, corresponding to the upper portion of the riser is the region of lower solids holdup where the pressure is low.

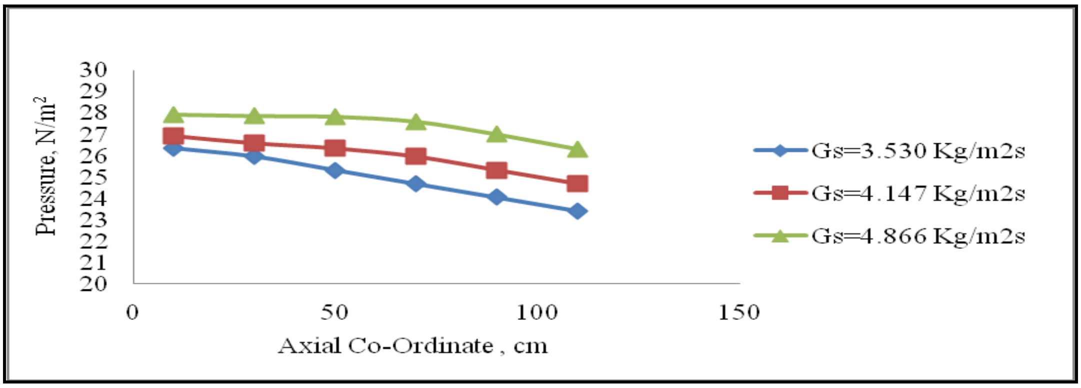


Fig 12 - Axial Variation of Pressure Drop with Gs (Poppy Seeds)

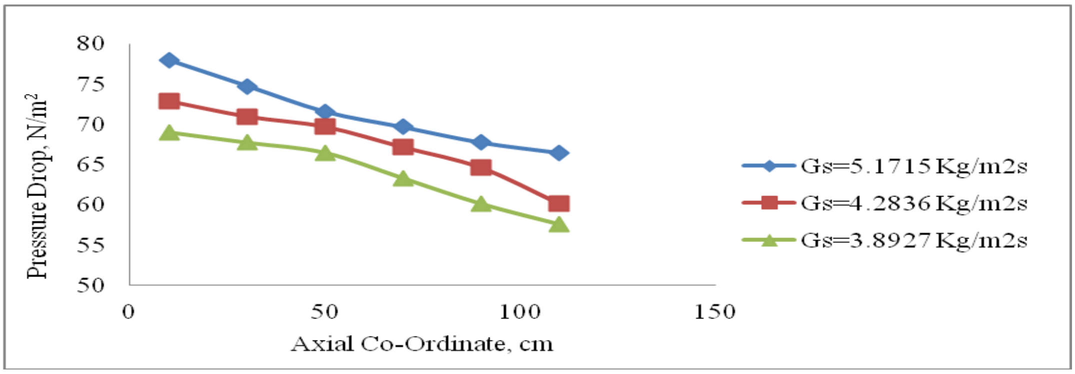


Fig 13 - Axial Variation of Pressure Drop with Gs (Mustard Type I)

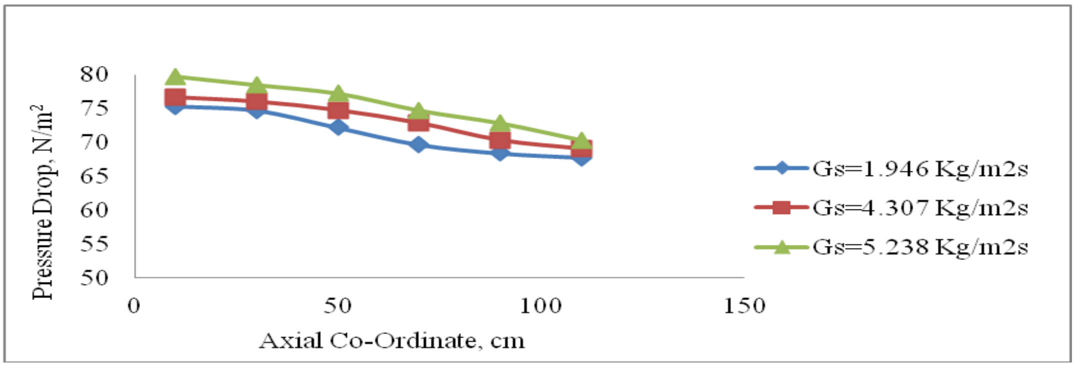


Fig 14 - Axial Variation of Pressure Drop with Gs (Mustard Type II)

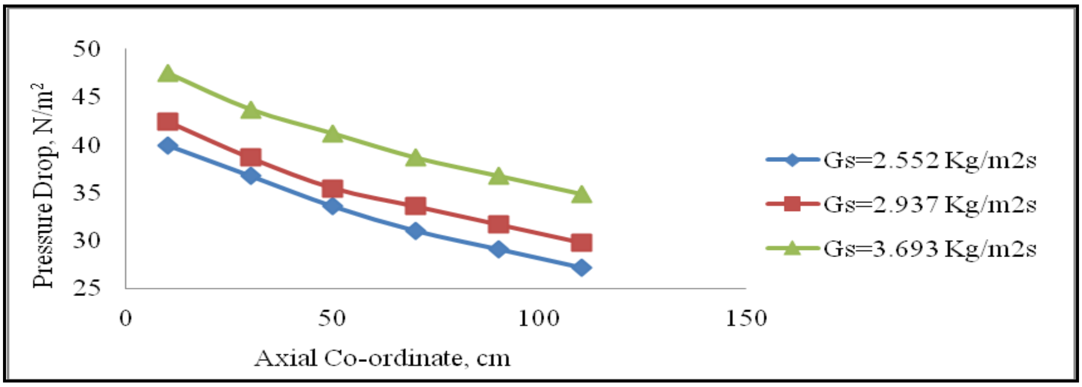


Fig 15 - Axial Variation of Pressure Drop with Gs (Semolina)

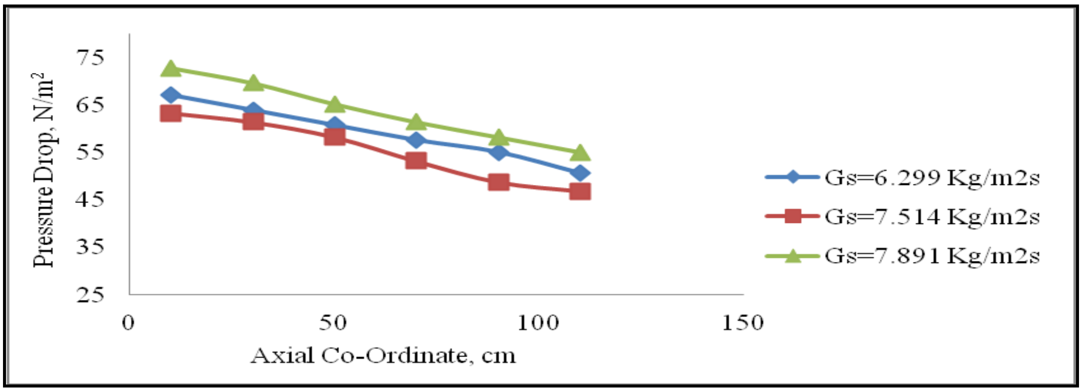


Fig 16 - Axial Variation of Pressure Drop with Gs (Millet)

3.4 Axial Variation of Pressure Drop with Gas Flow Rate and Solid Circulation Rate

The effect of pressure drop with gas flow rate and solid circulation rate for different food materials is shown in Fig 17 – 21. It is observed that the pressure drop increases with solid circulation rate. At low solids rate, the pressure drop increases slowly, corresponding to pneumatic transport, and at high solids rate, it approaches an asymptotic value corresponding to conventional fluidization. Also, the pressure drop decreases with increase in gas velocity for a given solids rate. It has been observed that the pressure drop increases with solid circulation rate and gas flow rate but decreases with gas velocity. The same behaviour is observed for all food materials.

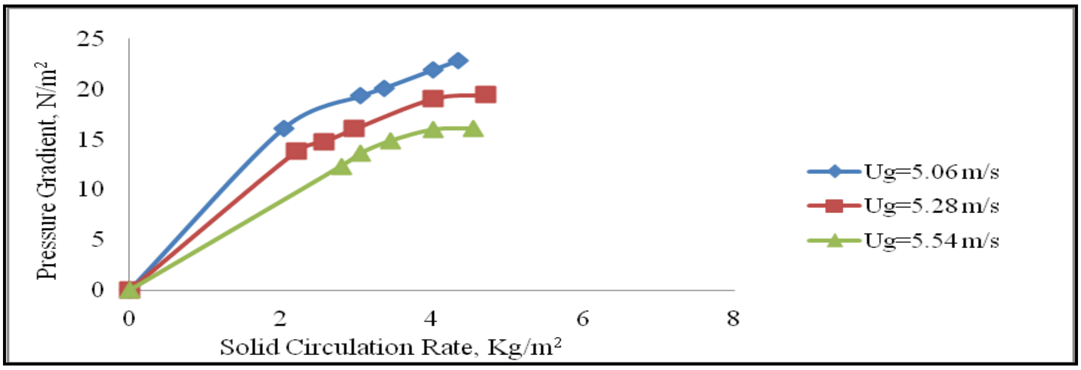


Fig 17 - Axial Variation of Pressure Drop with Gs and Gg (Poppy Seeds)

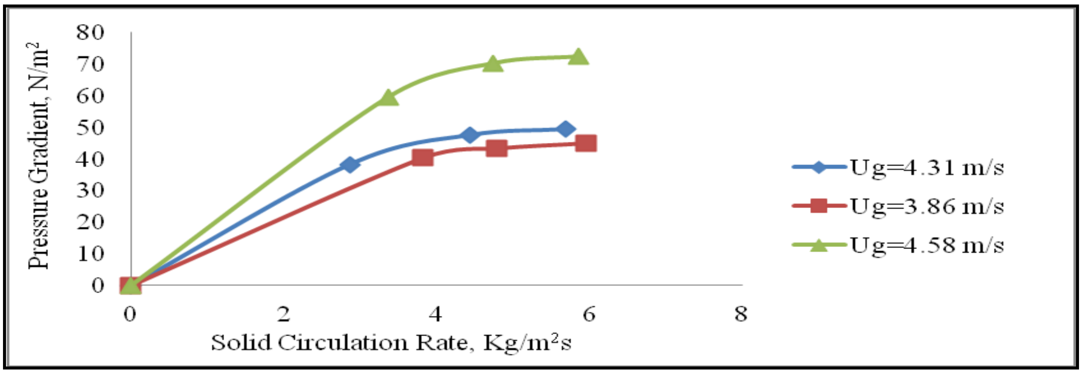


Fig 18 - Axial Variation of Pressure Drop with Gs and Gg (Mustard Type I)

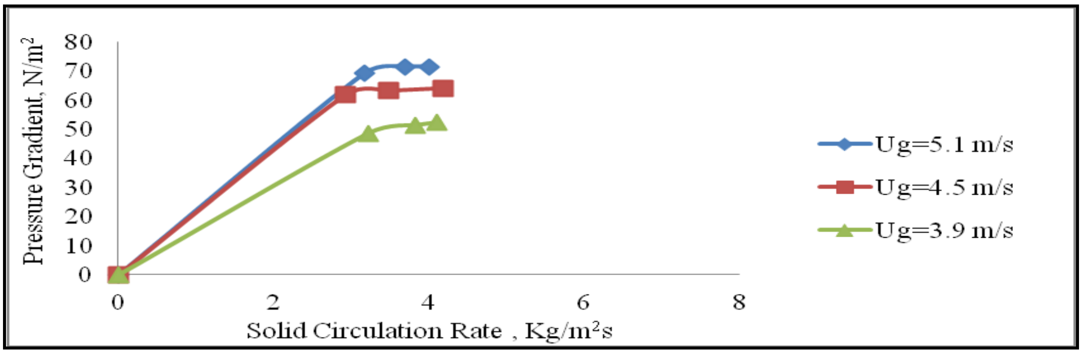


Fig 19 - Axial Variation of Pressure Drop with Gs and Gg (Mustard Type II)

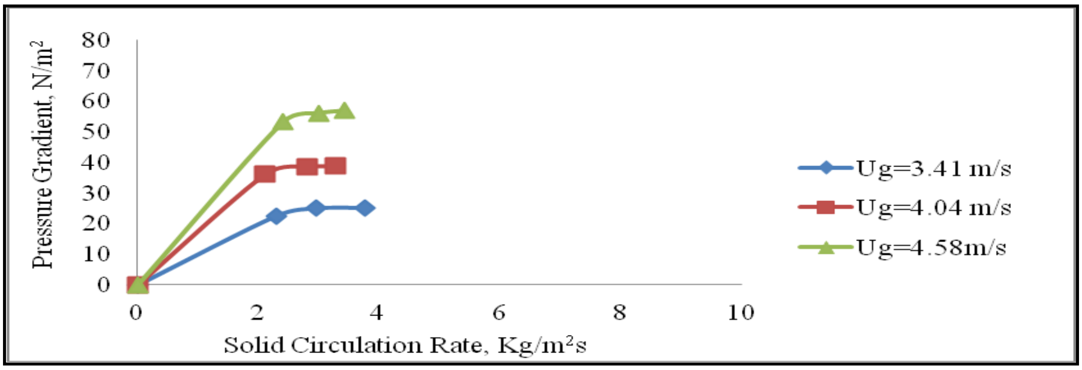


Fig - 20 Axial Variation of Pressure Drop with Gs and Gg (Semolina)

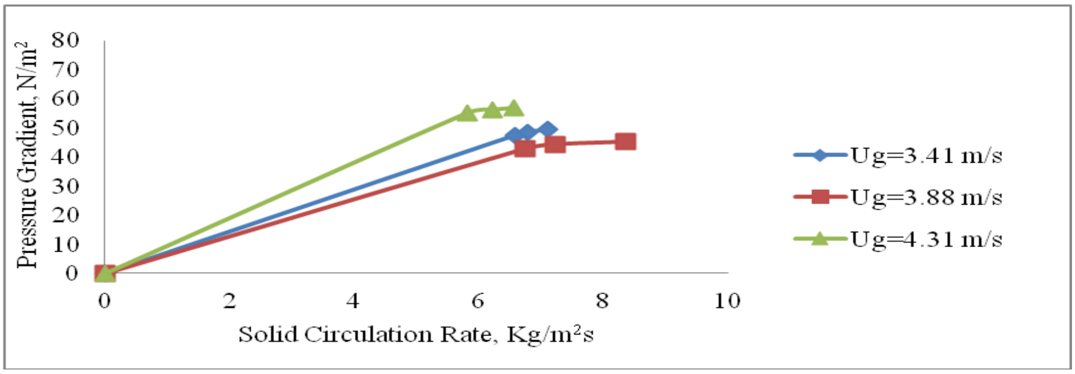


Fig 21- Axial Variation of Pressure Drop with Gs and Gg (Millet)

3.5 Modeling

The symmetric model is employed to simulate the flow in a CFB riser the boundary conditions at the inlet and outlet of a CFB riser has been specified. The mesh formulation is generated using Ansys Workbench. The mesh size given was 0.001. The mesh file is exported to fluent. The profiles of the solids volume fraction and velocities for both phases has been specified for the boundary conditions at the inlet. Regarding the boundary conditions at the outlet, the fully developed exit conditions are employed for both phases, since the riser is long enough. The Eulerian-Euleraian model is employed to simulate the results. The residual graph obtained as a result of 4000 iterations for poppy seed with gas flow rate 5.994 m/s is shown in Fig 22.

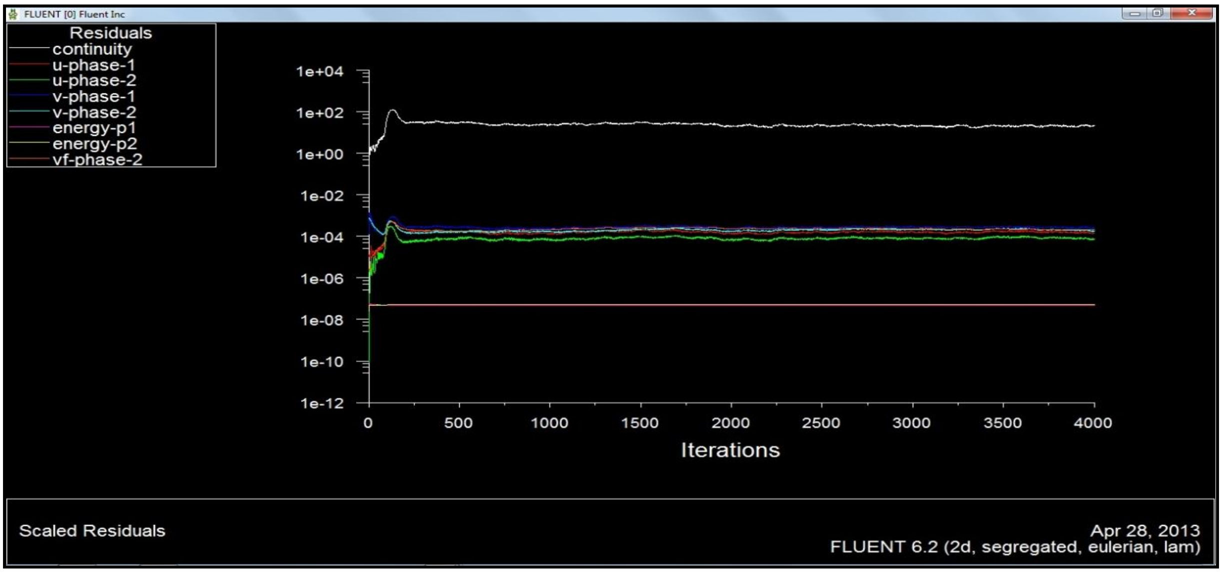


Fig 22 - Residual Plot for poppy seeds with Gg=5.994 Kg/m2s

The contour plot obtained for the axial variation of pressure along the riser at various velocities for poppy seeds were shown in Fig 23. It has been observed that the pressure drop decreases along the length of the riser.

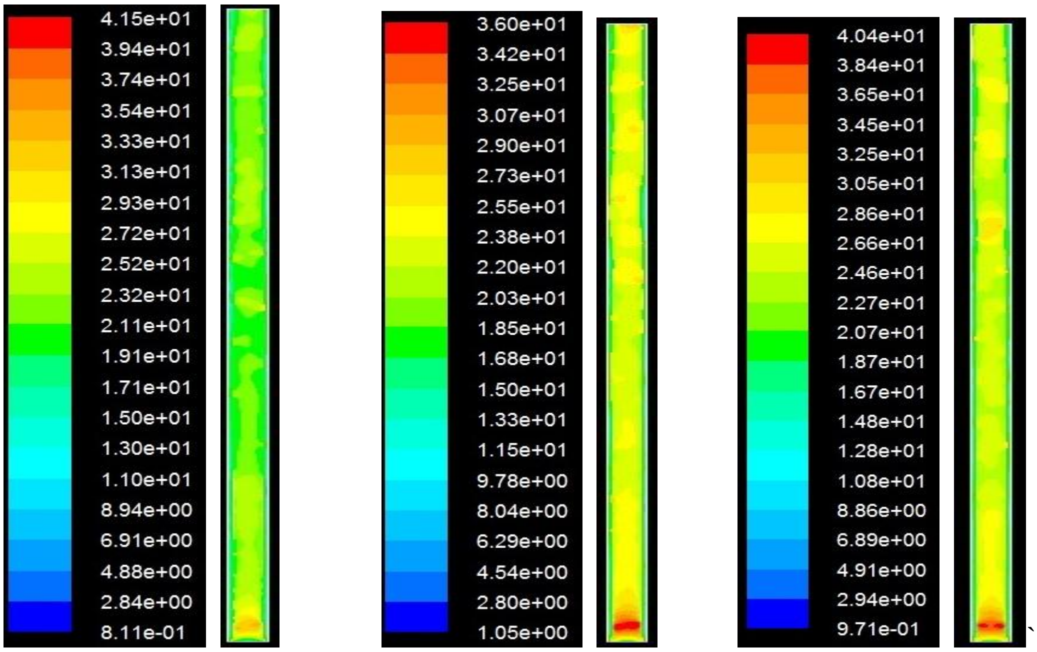


Fig 23 : Contour plot obtained for the axial variation of pressure along the riser at various velocities for poppy seeds

3.5.1 Variation of Pressure Drop with Packing Height

The variation of pressure drop with packing height has been simulated and the contour plot is shown in Fig 24. The packing height is changed as 0.5, 0.54 and 0.58 with a constant gas flow rate of 5.54 m/s.

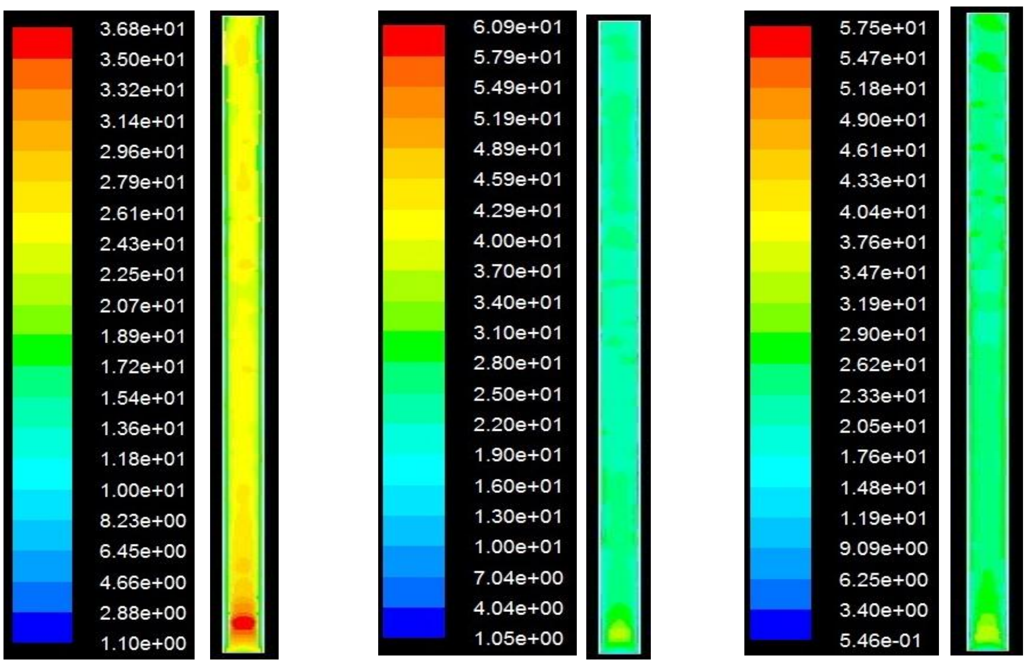


Fig 24 - Contour Plot Showing Axial Variation of Pressure for Poppy Seeds with different Packing Height

3.6 Comparison of Experimental and Simulation Results

The comparison of experimental and simulation results for variation of pressure with various gas flow rates for poppy seeds is shown in Fig 25-27. It has been observed that the deviation between the experimental and simulated results are within the range of 7 to 9.5%.

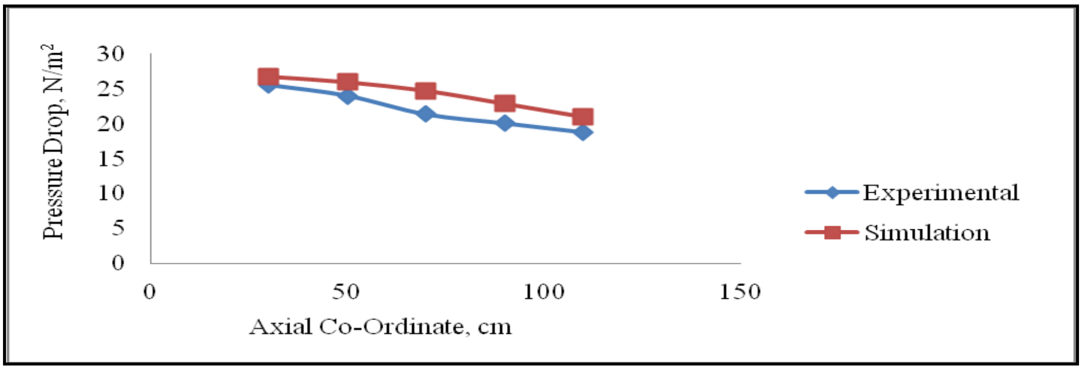


Fig 25 - Comparison of Experimental and Simulation results for Poppy Seeds with Gg= 5.995 Kg/m^{2}s

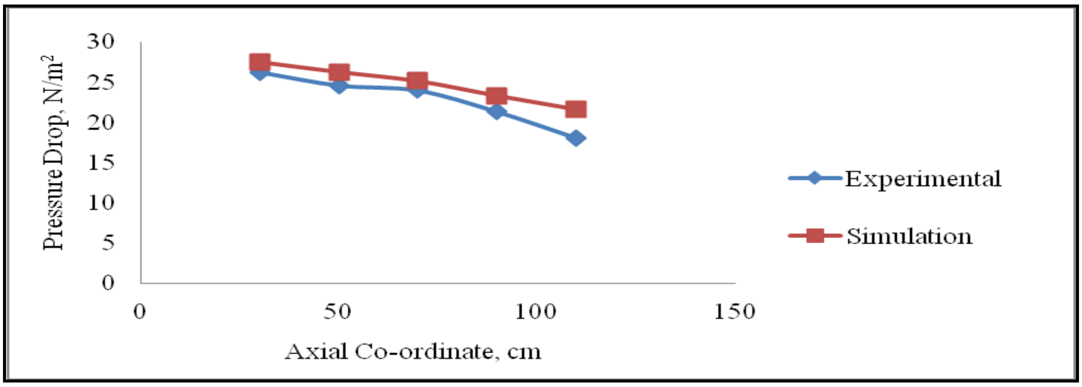


Fig 26 - Comparison of Experimental and Simulation results for Poppy Seeds with Gg= 6.146 Kg/m^{2}s

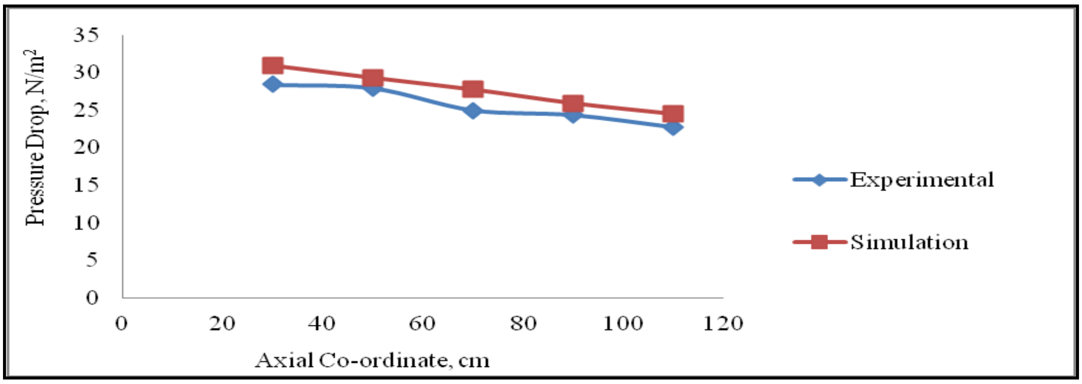


Fig 27 - Comparison of Experimental and Simulation results for Poppy Seeds with Gas Flow Rate 6.449 Kg/m^{2}s

4. Conclusion

A systematic work was carried out to study the hydrodynamic aspects of food materials such as poppy seeds, mustard, semolina and millet in circulating fluidized bed. The effects of various operating parameters such as axial variation of pressure drop with gas flow rate and solid circulation rate, effect of voidage with gas velocity and the effect of power with pressure drop has been studied. The pressure drop increases with gas flow rate and solid circulation rate along the length of the riser. It has been observed that to reduce the homogeneity of solids concentration horizontal perforated plates can be placed along the length of the riser. The same observations were made for all the food materials used in this study. The axial and radial variations of pressure drop for different gas flow rates and packing height have been simulated. The simulated results were found to be similar to that of experimental results and the deviation is in between 7 to 9.5%.

Nomenclature :

CFB – Circulating Fluidized Bed
CFD – Computational Fluid Dynamics

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