Hydrodynamic Study of Tapered Fluidized Bed and its Validation

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School of Chemical and Materials Engineering

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DEDICATION

"To my loving family, friends and teachers"

ACKNOWLEDGEMENTS

All praise is because of "ALLAH," the creator of this world, who gave us the capacity to enhance our knowledge and make ways for us to learn new skills for about the planet as a whole. Warmest welcomes to the supreme ruler of this world and the hereafter, "Prophet Mohammed (PBUH)," a source of knowledge and benefits for all of humanity.

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D_0 Bottom diameter of tapered fluidized bed.

D top surface diameter of taper bed

D_p Diameter of the particle

D_s Initial static height of the particle bed, m.

U_S Superficial velocity of fluidized bed

U_{mf} Minimum fluidization velocity.

G_f Mass velocity at fluidization condition.

G_{mf} mass velocity of fluid at minimum fluidization condition

Kgp interphase momentum exchange

d_{pm} particle diameter of binary mixture, m

dp particle diameter of lighter wight

d_{p0} particle diameter of heavy weight

H_s initial stagnant height of the particle bed,

ABSTRACT

This research examines the hydrodynamics study of tapered fluidized bed of sand particles using sand particles on the fluent versionV18.0 platform. The drag model reviewed are Gidaspow, Hulin-Gidaspow, Syamlal O Brain, Gilabaro. Comparison between experimental data and simulated results have been made in the recent study. The results show that gidaspow drag model show similarity with experimental data. The other applied drag model highly overestimated the gas-solid momentum exchange results. Modified drag model gidaspow was also applied in which the drag factor with 0.9 show some similarity with experimental data. The results were compared with experimental data. other than modified gidaspow results, the change in solid frictional viscosity from Schaffer model to Johnson et al also showed some similarity with experimental data. In order to predict bubble size, diameter its expansion ratio fraction of fluidized area and volume fraction of the particle using homogeneous and heterogeneous drag models was calculated and compared with the experimental findings. Also, the flow structure, heterogeneous and homogeneous was observed while applying different drag models. On the basis of dimensional analysis, various correlations have also been developed while considering the parameters such as geometry of tapered bed, diameter of the particle, static bed height, density of solid particles and gas and superficial velocity of the fluidizing medium.

Keywords: gas-solid fluidization, drag factor, two- fluid model, hybrid drag model, Tapered fluidized bed

CHAPTER 1: INTRODUCTION

1.1 Introduction of tapered fluidized bed

The process of Fluidization is defined as the fine particles of the solid are transformed into state of fluid by bringing them into in touch with solid and gas or either one. Practically the above-mentioned method of gas-solid contact very different characteristics that is concerned with the engineers dealing with fluidization process which utilizes this process and bring it in good use.

In the process of fluidization, the factors that influence the characteristics of fluidization of any process includes agglomeration, geometry of vessel, charges in system, gas inlet arrangement. The range of operating conditions and degree with which each particle fluidize in the process of fluidization vary from each other in each fluidization process.

1.2 Statement of problem

Tapered fluidized bed have gained significant attention across various industrial applications due to their efficient heat, mass transfer and mixing properties [1]. The design and operation of such reactors rely heavily on understanding the complex hydrodynamics within the bed. Tapered fluidized bed are also characterized by variation in cross sectional area along the bed height and have emerged as a promising configured tool that provide an advantage in terms of improving residence time distribution, enhanced solid mixing and reduced pressure drop as compared to conventional fluidized bed that are used in industries. However, despite their potential, a comprehensive understanding of hydrodynamic behavior and flow characteristics within tapered fluidized bed remain limited and hence a detailed study is required. This gap is addressed in this study by conduction a systematic investigation into hydrodynamic study of tapered fluidized bed focusing on flow patterns, gas-solid interactions and particle behavior. Also, a correct bed height is predicted by applying various homogeneous models in order to save computational time and cost.

To study the hydrodynamics of fluidized bed, different techniques and models have been used. The commonly used techniques are Eulerian-Eulerian approach and Eulerian-Lagnarian approach are used for the flow of solid gas solid modelling.in Eulerian-Lagranian approach solid phase is treated as divided entity while applying a discrete phase model while the eulerain-eulerian approach deals with interpenetrating continua for gas phase and solid phases which is known as two fluid model. Various different models such as KTGF (kinetic theory of granular flow) are also incorporated for the interaction of particle-particle in the process of fluidization.

The paraments present in two fluid model includes: drag force, virtual mass force and lift forces. According to the reports of sensitivity analysis which was done with the help of study of hydrodynamics of fluidized bed, among all the factors which are; temperature, pressure, restitution co-efficient, specularity coefficient and drag factors, drag force was having the greatest impact in comparison with other parameters. Drag force forms the basis of two fluid model as described by different drag models. [3]. On the basis of its significance, various drag models have been classified into homogeneous as well as heterogeneous drag models.

Well defined homogenous models of drag such as Gidaspow, Hulin Gidaspow, Syamlal-O'Brien, Wen and Yu were implied in order to inquire hydrodynamics of tapered fluidized bed by Two Fluid Model. The difference these drag models made on the hydrodynamics of fluidized bed were also studied later and results are then compared with experimental findings. Also, there impact is measured and compared on axial and lateral profile of the bed. heterogeneous model usually measures the bed angle, particle size, particle diameter, bed expansion ratio of the model. These parameters are not considered by homogeneous drag models. the bubbles in bed that changes the particle size diameter and particle ratio is usually examined under heterogeneous models.

1.3 Application of Tapered Fluidized Bed

In the fluidization process, tapered fluidized bed have been very useful as they provide large area which eases the particle distribution. The larger area from base to the top, along the bed height make sure that fluidization takes place efficiently leading to prevent the phenomena of entrainment and DE fluidization of minute particles leading to low rate of reaction and less amount of heat release during the process. Hence, we can prevent the high temperature zone around the area where distribution takes place.

Tapered fluidized bed has some unique hydrodynamics characteristics because of the presence of gradient of velocity along the height of the bed. tapered fluidized bed have numerous industrial applications such as;

a. Biofilm reaction that are Immobilized
b. In the process of burning of wasted particles or materials.
c. Covering of particles of nuclear plants.
d. Waste water biological treatment
e. Crystallization and roasting of sulfide ores
f. Polymerization of catalyst
g. Fluidization of cohesive powder
h. Liquefaction and gasification of coal

The study of hydrodynamics characteristics of fluidization encompasses two area;

a. solid-liquid systems
b. solid-Gas system

For fist type, liquid solid, the hydrodynamic characteristics of tapered fluidized bed that is the fixed bed has been elaborated by [4] as he has explained in his theory of bubble less fluidizations.. [5] has also systematically discussed the change in pattern of flow regimes that is when the bouncy force acting on the particle much lesser less than the gravitational force acting on the particle in the process of fluidization, hence the bed remain static which leads to fixed bed regime

In the application of fluidized bed in various industries, different kind of flow regime may occur on the basis of particle size, particle diameter and bed expansion ratio. Mixing of particles present in the fluidized bed Fluidization process forms bubbles, which move the material of the bed from the bottom to the top of the bed, leads to mixing of particles in the fluidized bed. Just like with gas bubbles in liquids, particles travel upward in the bubble wakes, which are the material that follows the bubble; however, the wakes are often smaller in fluidization. Due to "gulf streaming" in the bed, there may be another, possibly much larger, flow. If the bubble density is significantly higher in one area of the cross-section than another—for example, because of poor gas distribution or, in large beds, because of bubble concentration in the middle of the cross-section due to coalescence—material between the bubbles may be carried upward in this area, resulting in a compensatory downflow in areas with low bubbling.

. Nevertheless, to calculate or predict the characteristic of fluidization for partially flow regimes it is difficult.it might be easy theoretically as compared to practically. [1]. All these studies that were discussed above are the basis of an idealized fluidized system that is defined by Peng [6], that is according to the following assumptions which are given below;

a. there should be uniformity at any point of cross-section in the radial direction of fluid of the conical bed.
b. For the fluid which is present in liquid phase, there should be no back mixing.
c. The fore of friction between the wall and fluid particles is negligible.

Considering the gas–solid systems flow for conical spouted beds, [7] different flow patterns were observed these regimes were named as partial flow regime, bubble flow regime and fully fluidized regime.in the bubbling flow regime, the movement of bubbles takes place from the bottom section of the bed to the top section. Another flow regime that has not been discussed extensively in the literature gulf streaming, also occurs in the process of fluidization when there in uneven distribution of density of bubbles in the fluidized column. However, these all regimes are presented by empirical correlations served.

While we use the tapered or conical fluidized bed of various particles whether we consider Geldard A, B, C particles using a conical bed with three different cones including Geld art-D powder, fluidization properties were examined in three controls: fixed bed, partial fluidize d bed and fully fluidized bed. Purpose:

· To determine the flow rate of solid or gas tapered fluidized bed
· To derive the ideal conditions described by of Peng and Fan [7]
· To discuss the application of relationship report
· To discuss the general characteristics in the process of fluidization.

1.4 Factors that Affect the Quality of Fluidization:

Given below are the factors that greatly affect the degree of fluidization process:

1) **Inlet of fluid:** The design should be in that manner so that the fluid which enter is distributed overall throughout the bed.
2) **Fluid flow rate**: fluid flow rate should be maintained in such a manner that it shouldn't be so high that channeling occurs and its shouldn't be so low that solids are not kept in suspension.
3) **Bed height:** In order to obtain good fluidization, the greater bed the is necessary element the more difficult is to obtained.
4) **Particle size**: it is much easy to have a good quality of fluidization process with which the particles having a greater range than to have fluidization with uniform size of particles
5) **Densities of gas, liquid, and solid:** For fluidization to occur smoothly, the relative densities Of the substances such as liquid, solid and gas be near to one another.

- **Internals of the Bed:** the following are the purposes that the bed internals provide during the fluidization process: In order to stop bubble sizes from growing
- To stop fluid and solid materials from moving laterally.
- To stop slugs from forming
- To stop fine particle elutriation

1.5 Structure of Tapered Fluidized Bed:

Tapered fluidized beds, distinguished by their conical shape, offer unique advantages in various chemical processes. Their structure is characterized by a gradual increase or decrease in cross-sectional area along the bed height, driven by specific design and process requirements. Let's delve into the key components and functionalities of this configuration:

- **Geometrical Configuration:**

  Tapered fluidized beds exhibit a conical shape, with the cross-sectional area either expanding or contracting as you move upward or downward along the bed. This tapering provides specific flow characteristics that can be advantageous for certain processes.

- **Bed Zones:**

  There are following bed zones in the tapered fluidized bed:

  Bed Zone: This lower portion of the bed serves as the primary reaction or process area. It accommodates the majority of solid particles and experiences the most intense fluidization.

  Freeboard Zone: Located above the bed zone, this region is marked by lower solid concentrations and higher gas velocities. This zone allows for efficient gas-solid separation, promoting gas expansion and disengagement from the solids.

  Transition Zone: This intermediate zone bridges the bed zone and freeboard zone, seamlessly transitioning the bed's cross-sectional area. It plays a vital role in regulating gas-solid interactions and flow dynamics .

Gas Distribution System: To ensure uniform fluidization and mixing of gas and solid particles, tapered fluidized beds often incorporate strategically placed gas distribution systems. These systems guarantee optimal gas injection and distribution across the entire bed cross-section..

- **Solid Circulation**: The unique tapered geometry influences the circulation of solid particles within the bed. The upward flow of gas and gravitational forces interact with the conical shape, leading to variations in solid circulation patterns along the bed's height. This dynamic flow pattern can be tailored to optimize certain process parameters.
- **Reactor Configuration**: Tapered fluidized bed provide flexibility in design in order to meet the varying applications requirements. They can operate independently as rectors or complement larger system like chemical reactors and gasifiers. The tapered structure of fluidized beds maximizes gas-solid contact, improves mixing, and enhances heat transfer, leading to optimal process outcomes. The tapered geometry offers advantages over traditional fluidized beds, including improved residence time distribution, better solids mixing, and reduced pressure drop.

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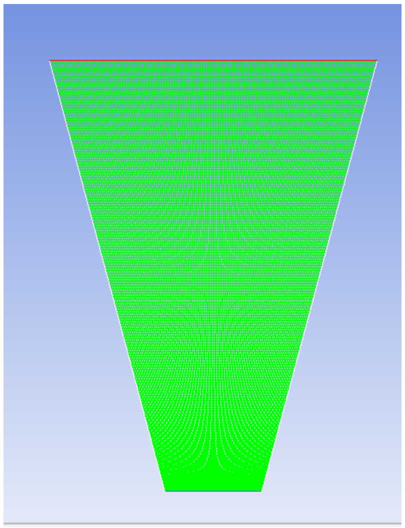

Figure 1. 1: Mesh of Tapered fluidized bed

1.6 The Phenomena of Fluidization

The fluidization process involves the transformation of a bed of solid particles into a fluid-like state when a fluid (usually a gas) passes through it. Several key phenomena characterize the fluidization process which includes, initiation of fluidization, formation of bubbles, expansion of bed, uniformity of fluidization, transition of fluid from laminar to turbulent and behavior of particles of gas-solid flow in tapered fluidized bed.

In the beginning, when the fluid velocity is low, the solid particles in the bed are closely packed, and gap in between is filled by the fluid. A critical value known as the minimum fluidization velocity is reached by the fluid velocity as it rises. This is the moment at which the particles become suspended and the bed begins to behave like a fluid because the drag force of the fluid balances the gravity force upon them.

The formation of fluidized gas bubbles inside the bed occurs when the fluid velocity rises above the minimum fluidization velocity. These bubbles contain suspended solid particles as they ascend through the bed. The bed contents are mixed and homogenized in part by the creation and movement of bubbles.

The void age, or volume of void spaces between the particles, increases during fluidization, causing the bed to expand. The upward fluid flow and the buoyancy impact on the suspended particles cause this expansion. Particle size, bed shape, and fluid velocity are some of the variables that affect how much the bed expands. [11] The solid particles and fluidizing gas are distributed uniformly throughout a well-fluidized bed. For effective mixing, heat transport, and chemical reactions inside the bed, this homogeneity is necessary. One of the main goals in the construction and use of fluidized bed systems is to achieve and maintain uniform fluidization.

A steady, homogeneous fluidization may give way to turbulent fluidization in the fluidized bed at increasing fluid velocities. Turbulent fluidization causes the bed to show more mixing and particle agitation, as well as more chaotic flow patterns. Increased pressure drop and particle attrition are potential side effects of turbulent fluidization, which can potentially improve mass transfer rates and heat transfer coefficients. Solid particles in the fluidized bed interact with the fluid flow in diverse ways, such as through drag forces, buoyancy, and collisions with other particles. The fluidized bed system's performance is greatly impacted by the interactions that control particle behavior, including circulation, segregation, and dispersion.

Understanding these phenomena is essential for optimizing the design and operation of fluidized bed reactors in various industrial processes, including chemical synthesis, combustion, drying, and particle coating. Effective control of fluidization behavior allows for improved process efficiency, pro Whenever we pass fluid (either gas or solid) at a less rate of flow through the bed of whether liquid or gas, then it first enters into the empty spaces that is between the layers of stationary particles which creates the fixed bed .by increasing the flow rate of the fluid, the fluid particle gets separated and the fluid starts to flow within the areas of the phases that were created and then it’s also starts vibrating .

by increasing the flow rate of the liquid, few particles of gas or liquid begins to vibrate leading to separation of the particles while moving in the limited area of the bed.at the greater or higher velocities the particles leads to expansion of the bed and the pressure drops throughout the bed increases significantly.. When the velocity is reached at its critical point, the pressure drop also starts to reach at its higher point, and the particles begins to suspend in the upward direction of flow whether in liquid phase or in gas phase. At this juncture, the particles which are present below the top area that is the base of fluidized bed, begin to fluidize, and fluidization expands from the bottom up, causing a sharp decrease in pressure drop.

The fluidization process starts whenever the exertion of force by medium of fluidization excels the force exerted by weight of the particle., and then it subtracts the force of adjacent particles but that is in the vertical direction of the force of compression. In this state, the pressure drop through any segment of the bed approximately equals the combined weight of fluid and particles in that segment.

The fluidized bed is considerably fluidized in maximum or at minimum fluidization rates. Assuming negligible friction between particles and bed walls, lateral fluid velocity is minimal and can be disregarded. Vertical fluid velocity is evenly distributed across the cross-sectional area.

Gas-solid systems typically exhibit distinct behavior. Beyond minimum fluidization, increasing the flow rate leads to large instabilities, including gas-bubbling behaviors bubbling and channeling even higher flow rates, agitation intensifies, causing vigorous solid movement. Causing vigorous solid movement.

Notably, the fluidized bed after the formation of peaks at the critical velocity don’t show expansion beyond the point of minimum fluidization velocity. such kind of beds are typically called aggregative fluidized bed and they characterized in the basis of their heterogeneity.

the general scheme of the hydrodynamic properties of the tapered bearing is shown in Figure 2 b elow. As the gas velocity Ug0 increases, the ΔPt O∨AΔ line of the total pressure drop clearly sho ws that it changes along the B ~ C bed fluidization. The stages are as follows: 1st stage O ~ A: Si

From the beginning of the process Ug0 is at lower point of the fluidized bed. From, the point of the stagnation pressure of the particle bed remains constant from the beginning. It is also seen tha t the total pressure increases to a maximum in the liquid phase. This phenomenon is similar to th e liquidsolid conical bed discussed in [9], and the flow state is also called stable bed. The gas vel ocity appearing as point A in Figure 1.2 is called theUmf minimum fluidization velocity Umf. Ph ase A ~. B: Where Ug0 is greater than Umf as shown in the figure below - Pt decreases by increasing U_{g0} there is no change in the constant height of the tapered fluidized bed or the conical bed. The height of the bed remains fixed by increasing the initial velocity Ug0nof the bed and the height of the bed remains constant of tapered fluidized bed with the decrease of Pt. The same result has been observed for petroleum products by [14] and for liquid systems by [9]. Here the flow is called a part of the fluidized bed. In Fig. 2, when Ug0 reaches Ums, the over all voltage drop characteristics is different from the two levels that are mentioned above. Phase B~C: When Ugo is greater than Ums as the figure above depicts Pt remains almost constant as shown in the figure below. At that point of the fluidization, the tapered bed having angles 5.61,6.47 and 9.52 receives the flow, foam and jet fluidization. At that point the properties of fluidization of gas-solid may vary from liquid solid fluidization as given be literature [11] flow regime during fluidization.

Experimental Phenomena and Flow Regime of Tapered Fluidized Bed:

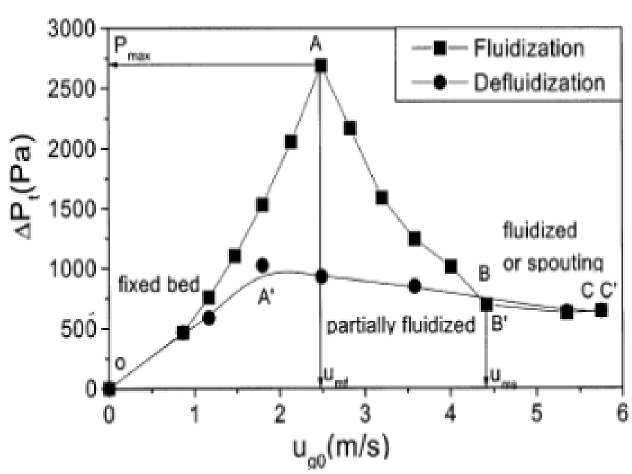

Figure 1. 2: Superficial velocity of gas showing effect on total pressure drop [14]

1.7 Importance of studying the hydrodynamics of Tapered Fluidized Bed:

Studying the hydrodynamics of fluidized beds is crucial for several reasons such as:

1. In optimizing efficiency of the process
2. In scaling up design and process
3. Making predictive modelling
4. Mitigating of Operational Issues
5. Studying Environmental Impact

Optimizing fluidized bed reactors for a variety of industrial processes is made easier by an understanding of hydrodynamics. Engineers can optimize mixing, heat transfer, and mass transfer inside the bed, which will increase process efficiency and productivity, by examining aspects such as gas distribution, flow patterns, and particle behavior. The behavior of fluidized beds at various scales can be understood by hydrodynamic investigations. The ability to build fluidized bed reactors that satisfy production needs while minimizing energy consumption and optimizing throughout the process is crucial for scaling up lab-scale processes to industrial levels. A thorough grasp of fluidized bed hydrodynamics is necessary for accurate fluidized bed behavior prediction. Instead of spending money and time on expensive and time-consuming experimental trials, engineers can simulate and forecast fluidized bed performance under various operating conditions by creating and testing computational models based on hydrodynamic principles. In [15]

Particle attrition, aggregation, and channeling in fluidized beds are examples of possible operational difficulties that can be found with the aid of hydrodynamic research. Engineers can reduce the consequences of these problems and guarantee steady, dependable operation by identifying the underlying causes of the problems and implementing design changes or process controls. In procedures like particle coating, drying, and catalytic reactions, hydrodynamic studies are essential for guaranteeing product quality and consistency. Manufacturers may achieve homogeneous particle coating, effective drying, and consistent reaction rates by managing the fluidized bed hydrodynamics, which results in low variability and high-quality goods. Also, in order to understand the phenomena of fluidization it is necessary to study its impacts on environment to minimize it and then ensuring the safety of the operations. For example, by the optimization of process of combustion, harmful gases and carbon dioxide and pollutants can be reduced into the atmosphere. fluidized bed combustors can be optimized in such a way that they can emit less amount of Sulphur and nitrogen oxides. Hence its investigation of hydrodynamics of fluidized bed can help in DE fluidization and entrainment of particles so that its implementation can be done on appropriate safety measures.

In summary, studying the hydrodynamics of fluidized beds is critical for optimizing process efficiency, scaling up and designing reactors, developing predictive models, mitigating operational issues, ensuring product quality and consistency, and minimizing environmental impact and safety risks.

The drag force term, which is the result of the momentum exchange coefficient and slip velocity, provides an explanation of the gas-solid interactions in the current study.
.In the ANSYSY fluent various drag models are present for the study of gas solid interaction by two fluid model. Drag model such as Gidaspow [16],Syamlal-O'Brien ([17],Wen and Yu [18],Hulin-Gidaspow [19],Gilbaro [20] are available in ANSYS for calculating momentum exchange coefficient. Several drag models, including gidaspow, Hulin-gidaspow, wen and Yu, Gilbaro and Syamlal, and Obrien, have been used to analyze the gas-solid momentum transmission term.

CHAPTER 2: LITERATURE REVIEW

Mostly research on gassolid fluidization behavior is for the right cylindrical or columnar flui dized bed, and walls are usually inclined in tapered fluidized bed or column bed. The existence of the velocity gradient in the axial direction leads to the unique hydrodyn amic properties of the conical fluidized bed. Due to this feature, conical fluidized bed is wide ly used in wastewater treatment, immobilized biofilm reaction, waste incineration, nuclear fu el particle coating, crystallization, coal gasification and liquefaction and sulfur ore roasting, f ood, etc. It is widely used in many industrial processes including It is also used in the fluidiza tion of large products and can be used in exothermic reactions [21]. The advantages of the co nical fluidized bed also include smooth operation without instability during the exothermic p hase associated with pressure changes and also allow mixing. Despite its quality and perform ance, no general studies have been published in many documents to understand its special pr operties such as minimum fluidization rate and maximum loss. To ascertain the variables influencing the minimum fluidization rate and maximum loss, researchers released a study. A few results are limited to normal items. Previously published work on conical fluidi zed beds includes bed pressure loss calculations, flow rates, initial fluidization conditions, vo id age particle distribution, calculation of bed expansion of particles and for the development of loss model so that the mathematical modeling can be done distribution, of the maximum loss model for initial fluidization conditions in a conical fluidized bed. The friction between the particles and the wall is ignored in the model that was created, which is based on Ergun's equation. Theoretical models were also created for gas-solid systems in conical vessels, specifically for creating fluidization velocity having very less velocity of fluidization and pressure drop in a bed where bed is packed and particles are spherical in shape. Unrestricted and random particle movement takes place in a tapered bed with less back mixing because of the inclined walls. has also contrasted the results of their experiments with the figures computed utilizing the created models that were based on Ergun's equation and it leads to neglecting the friction between the particle and the wall.

y [14] [22] [13] [2]. Numerous things are revealed to us by the Ergun equation. Given a fluid velocity, it indicates the pressure drop along the packed bed's length. It also indicates that the length of the bed, the packing density, the fluid viscosity, and the packing size all affect the pressure drop.

The hydrodynamic properties of fluidization in a conical bed were then thoroughly examined in paper [4]], which also provided a theoretical model based on theory that predicted the largest loss at the lowest fluidization rate.

Dynamic energy balance. [16] However, the testing was done only on the surface of the sphe re and not on other parts of the object. [23] and [3] developed the gassolid conical fluidized b ed model consisting of two types of particles which are coarse spherical and particles of fine size the model that was developed on the basis of research of Peng and Fang. But also, they do not focus on the drop of pressure caused by dynamic changes in the bed Conical fluidized bed reactors have also been researched using temperature wall measurements and static pressure.[24] and a model to determine the bed height has been proposed [7] have effectively employed conical or tapered fluidized bed tapered in chemical reactions [4] and have suggested using the beds for sulfide ore roasting and biological reactions. The study conducted by Kumar et al. [1981] [20]and Yogesh Chandra [1981] on the hydrodynamics of tapered fluidized bed by the use of particles of single size.

Conical fluidized beds also have numerousattractive properties, including the ability to proce ss different materials and properties [25] and achieve various combinations [26]. Immobilize d biofilm reaction, waste incineration, nuclear fuel particle coating, crystallization, coal gasifi cation and liquefaction as well as roasting sulfur ore. It's interesting to note that conical sections are frequently included in the manufacturing of industrial fluidized beds [27].

On the other hand, application of conical fluidized beds appears to be more advanced than us Knowledge of their basic behavior. Several previous studies on tapered fluidized bed includes

The study of shock in a fixed bed and fluidized bed in a conical vessel, flow regime, primary process of fluidization, void age distribution, expansion of bed and mixing of various particles. [13]

Whenever the material of the column of the fluidized bed is at the point of dynamic equillibrium a fluidized bed is formed to resist and buoyancy is applied against gravity, thus pulling the particles downward [31] and [32]. that force of drag at any point in the tapered bed is constant with particles of uniform size, whereas its speed reduces in the upward direction when it is along with superficial velocity which is reduced in the same direction.

The particles present at the bottom of the bed will therefore fluidize more quickly than the particles at the top of the fluidized bed as a result of increasing the rate of the gas-solid flow. They will exhibit unchanging behaviors. T [33]. The phenomenon referred to as partial fluidization bears some resemblance to the phenomenon known as tapered fluidized bed. The majority of published research on tapering fluidized beds has dealt with flow regimes and the early stages of fluidization, with very little on the hydrodynamic properties of these beds. [34] have also talked about the partial fluidization regime of flow in a tapered bed of gas-solid. [6] has provided descriptions that clarify how the change in flow pattern of gas-solid tapered bed change.

The forces that are acting on the bed of particle are dynamic and can be used to forecast the initial state of process of fluidization taking place in a conical bed. For gas-solid tapered beds, [12], [35], and [36] used this strategy. For liquid-solid tapered beds, [36] did the same. However, in forecasting the initial state of fluidizing process and the corresponding decline in maximum pressure, none of this research considered the phenomenon of partial fluidization.

Conical bed fluidization is also widely used in many industrial processes such as wastewater treatment [37], coating of nuclear fuel, crystallization of sulfur ores, gasification and liquefac tion of coal and roasting. It works well without stability, for example with minor changes (Ri dgway, 1965), and also allows combinations (Babu et al., 1973, [30]. More methods, includin g the use of splits, streaming, and vibration in multiple systems. To solve the warping proble m of air mattresses (level room) has been suggested from time to time. Using a tapered beari ng instead of a traditional cylindrical bearing is another technique to solve this problem in oil -fluid systems. It was observed that improved quality of mixing and better quality of fluidization can be obtained with the help of tapered or conical bed fluidizers. [22].in order to make sure the smoothness and stability of the fluidizer, small particles must be used on a frequent basis due to the gradual loss in clarity of big fluid velocity caused by the upstream cross-sectional area. According to Singh et al. (1992), back mixing is decreased in the conical bed because of the angle, which causes random and uncontrolled particle movement. The topic of oil-liquid in tapered bearings is not well studied, despite the fact that some information about it does exist.

Despite its quality and usefulness, there are not many studies published in the literature to un derstand some important issues, especially the changing bed. Some of the previous research i ncludes measurement of bed pressure drop [38], flow control, primary water flow, non-distribution and bed calculation.

The previous mentioned research also developed the relationship between particles that are either spherical or non-spherical for the spherical volume in the taper tubes of the column for the production of gas excluding the density of material and medium of fluidization. [6]proposed an analytical method to predict bed expansion and shock in conical fluidized beds. [9]conducted research on the taper fluidizing bed and suggested a model that uses static pressure and wall temperature measurement to determine the height of the bed.

Fluidization process in cylindrical towers is widely used in industrial processes. However, un der many operating conditions the size of the product is often uneven or may be reduced due to chemical reactions such as combustion, gasification or corrosion. In cylindrical beds, the r eduction in size causes penetration, limitation of operating speed, and other disadvantages us ually associated with beds, such as slowing down and non-uniform fluidization. These disadvantages can be overcome by using a conical bed for fluidization. This is because the apparent velocity of the liquid gradually decreases as the cross-sectional area increases with height. Conical fluidized beds are widely used in many industrie s, including wastewater treatment, chemical biofilm, waste incineration, nuclear fuel particle coating, crystallization, coal gasification and liquefaction, roasting of sulfur ores, and food pr ocessing. These beds can be used for exothermic reactions as well as for the hydration of mat erials with wide particle size distributions. The tapered bearing also reduces material backmi xing. There are four categories in which the multiphase flow of fluid can be classified. These are as follows;

- Liquid-gas medium,
- Solid-gas medium,
- solid-liquid fluidization
- three phases of liquid flowrate

The terminology that was used in the process flow of fluidization “gas-solid flows" and that refers to the meaning “suspension of solid particles” [11]. Among the various items in this area are bubbling/circulating fluidized beds and pneumatic conveyance.in the same way in heavy machinery in industries such as ball mills, hoppers, mixers, grinders and chutes where the flow is granular, it is of great importance.

The technological component of the US chemical industry is projected to be worth $61 billion. Specifically, the conversion of gas products is crucial in numerous significant sectors, ranging from dryers and electric bed machines to pneumatic classifiers, dryers, and coaters. The density of the powder structure often plays a significant role in plant operation issues, as powder flow can result in back fluidization and channeling in the combustion/feed system. Forty prosperous American and Canadian businesses were the subject of a six-year investigation by the RAND Corporation. According to their research, about 80% of plants have trouble solving problems. when a result, numerous issues arise when the powder's stickiness spreads to various areas.

he movement and characteristics of liquid products remain poorly understood despite recent advances. As a result, a connection must be created in order to compute the two crucial parameters of steady and regular water parameters: the minimum fluidization rate and the maximum drop in the conical fluidized bed. For regular and disordered petroleum products, covering all parameters such particle diameter, density, cone shape, porosity, and sphericity, an empirical dimensionless correlation was created in this work to forecast the minimum fluidization rate and maximum loss. But the height of the bed also affects how the shock works. The novel model's appropriateness was evaluated against previously published models.

Recent years have seen a significant increase in interest in liquid and solid fluidization due to its wide range of industrial applications, including water treatment, hydrometallurgy, food technology, pharmaceutical granulation, semiconductor chlorination, and biochemical processing [1,2]. (LSFBs) offer a number of advantages, such as well-mixing, a high fluid/solid relative velocity, a large contacting surface area, and a high heat transfer rate system [3]. In addition, fluidization is the process of allowing liquid to flow upward, turning solid particles into liquids. It has appeared as though solid particles suspended in water have "fluidized" [4,5,6]. LSFBs are vital and efficient process tools that maintain a uniform particle distribution at high fluid velocities. Typically, the flow system is identified as the homogeneous regime. The characteristics of flow of particles of fluidized bed has been examined by various investigators such as Farkas coloni(2019) [40], Liu et al. (2019): [41], Lev et al. (2014): [27] [42].

They had done their investigation by conducting experimental and computational studies in order to examined the hydrodynamics study of tapered fluidized bed. their studies focusing on calculating the factors that affect the characteristics of particles and their flow regime. Such factors include: velocity of solid particles, velocity of solid volume fraction of particles, bed bubbles gap and bed expansion ratio. They study that was done by Schaffer and Liu et al. encompasses the study of taper in and taper out risers of tapered fluidized bed so that hydrodynamic characteristics can be studied and efficiency can be improved. [28]. similarly various heterogenous models were also incorporated to study the bubble size and bubble diameter and to investigate its effect on the hydrodynamics of fluidized bed. Hydrodynamics study of tapered fluidized bed under various conditions were done by Yang ET al. [29].their deduced results were helpful in studying the various flow regimes that were developed by the formation of bubbles of different diameter or due to the formation of turbulence that occurs in the tapered fluidized bed.

A tapered fluidized bed reactor device has been developed by Scott et al. [5] for aqueous bioprocess. For mono component particles, Pitt et al. [6] investigated the hydraulic pressure loss and enlarged bed height at various apex angles. Peng and Fan [7] were the first to use varied tapering angles of the bed to investigate distinct flow regimes in tapered beds at varying fluidizing liquid flow rates. They also created hydrodynamic characteristics equations based on many hypotheses. When studying the liquid-solid fluidization of binary mixtures, Pruden and Epstein [8] discovered that layer inversion will happen at a threshold liquid velocity where the bulk bed density of both nanocomponent beds is the same.

Additionally, Yang et al. (2018): [44] and associates studied the hydrodynamics of tapered fluidized beds under various operating conditions using computational fluid dynamics (CFD) simulations. Their research shed important light on the distribution of particles in the bed, pressure drop characteristics, and flow regime transitions.

The literature claims that at low velocities, liquid solid fluidized bed (LSFB) systems are frequently regarded as homogeneous not heterogeneous. However, at higher gas velocities considerable heterogeneous particle–fluid patterns were detected and local voids were observed in the studies with calcite grains at very low fluid velocities. Peng et al. [13] examined the particle's fluidization behaviors and hydrodynamic characteristics using a two-phase Eulerian–Eulerian model (kinetic theory of granular flow). By contrasting simulation and actual data regarding the expansion degree of low and high density, the CFD model was validated.

for the gasification of biomass in different industrial applications, different studies were carried out by Li et al. (2022). [25].He adopted a pragmatic approach in order to optimize the designing of tapered fluidized bed. His research encompasses the area where the efficiency of gas-solid contact and rate of heat transfer can be enhanced by taking the help of geometric modifications and operational parameter adjustments.in a nut shell his studies focus on the importance of studying the characteristics of tapered fluidized bed for the optimization of performance of reactor, increasing its mixing efficiency and improving process stability across various industrial applications for achieving good results .Continued research in this field is essential for increasing our understanding of tapered fluidized bed behavior and developing innovative solutions which leads to advancement for energy conversion, chemical synthesis, and environmental remediation processes. [2]

CHAPTER 3: MODELLING TECHNIQUES

3.1 CFD theoretical frame work and modelling techniques

There are different methods in theoretical frame framework of computational fluid dynamic. As computers become more powerful, the discipline of computational fluid dynamics (CFD) is in creasingly becoming numerically applicable to modeling wave energy transfer behavior (WECs). In summary, CFD can be used to study the design of a particular WEC, conduct parametric studi es to improve its performance, and study wave loads to characterize its life in the ocean of clouds Given sufficient computing power, CFD can simulate the performance ofWEC arrays. The follo wing systems: Partial Differential Equations (PDE). Classicallythese equations are continuity eq uations as well as the wellknown NavierStokes equations. To complete the mathematical model, initial conditions must be satisfied along with internal. To complete the mathematical model, init ial conditions must be satisfied along with internal and external conditions. Generally speaking, methods describing partial differential equations cannot be solved analytically, so approximate s olutions are obtained by numerical algorithms (called solvers) used on digital computers. These s olutions are essentially discrete points in the calculation and deal with variables (pressure, speed, etc.) at different times during the simulation. In principle, the solution to a particular problem ca n be found in space and time depending on the accuracy of the algorithm or decision process.

3.2 Principal of Tapered fluidized bed

The fluidization properties of the conical fluidized bed depend on the reactor cone angle, distribu tor top angle, particle density and static bed height. Although studies on the fluid properties of co nical reactors have been published, there are not many studies on the effects of conical distributo rs with different top angles on the performance of conical fluidized bed reactors. The dependence of the minimum fluidization rate and the reactor cone angle as well as the cone distributor peak angle is also plotted. It is seen that the minimum fluidization rate (Umf) increases with the increa se of the upper flow rate (α) and reactor cone angle (β). It is also seen that bed expansion decreas es with increasing top angle and reactor cone angle for bed materials. Established relationships w ere tested for evidence; The mean and standard deviation of the relationships were 1% and 29%, respectively.

3.3 Working Principal of Tapered Fluidization

A fluidized bed involves solid particles (typically a granular material) that are suspended and mixed with a mixture gas or liquid flow in such aa behavior that it behaves like a fluid. The bed appears to be bubbling and swirling, with the solid particles exhibiting fluid-like behavior, such as mobility and a lack of distinct boundaries

The key working principles of tapered fluidized beds are given below:

Fluidization process: The process starts with a bed of solid particles placed having a container or chamber. A fluidizing medium, usually a gas (e.g., air or nitrogen) or a liquid (e.g., water), is introduced from the bottom of the bed. As the fluidizing medium flows upward through the bed, it imparts enough energy to the solid particles to overcome gravity, causing them to become suspended and exhibit fluid-like properties.

Minimum Fluidization Velocity (U_{mf}): Below a certain gas velocity called the Minimum Fluidization Velocity (U_{mf}, the particles settle and form a packed bed. At (U_{mf}, the particles start to become suspended and gently fluidized.

Bubbling and Turbulent Fluidization: As the gas velocity increases beyond (U_{mf}, the bed enters a bubbling fluidization regime, characterized by the formation of bubbles that rise through the bed. At higher velocities, it transitions into a turbulent fluidization regime, where intense mixing and bubbling occur.

Uniform Mixing and Heat Transfer: Fluidized beds provide excellent mixing of solid particles with the fluidizing medium, leading to uniform temperature and concentration distributions. This uniformity enhances heat transfer and mass transfer, making fluidized beds ideal for various chemical reactions and heat exchange processes.

3.4 Components in a Tapered fluidized bed system:

A typical fluidized bed system consists of the following components that are mentioned as follows:

1. Bed Composition: This is the substance that is not fluidized within the bed. Sand in a heat exchanger, catalyst particles in a chemical reactor, or any other granular substance appropriate for the planned operation can be used as substitutes.

2. Medium of fluidization: A liquid (such as water) or a gas (such as nitrogen or air) can be used as the fluidizing medium. It is added from the bed's bottom and is in charge of causing the solid particles to become suspended and more fluid.

3. Distribution of particle phenomena: The component at the bottom of the fluidized bed known as the distributor is responsible for distributing the fluidizing medium uniformly throughout the bed's cross-section. It could be made up of perforated plates or nozzles.

4. Gas/Liquid Inlet: This is the point where the fluidizing medium is introduced into the bed.

5. Outlet: The outlet allows the fluidizing medium and any products or particles to exit the bed.

6. Heat Exchanger or Reactor: The fluidized bed reactor or heat exchanger is the main processing unit where chemical reactions, heat transfer, or other processes occur.

3.5 Advantages of Tapered Fluidized Beds

- Perfect temperature distribution and mixing.
- High mass transport and heat rates
.
- Enhanced reaction kinetics, making them suitable for catalytic reactions.
- Good control over process parameters.
- Reduced emissions in combustion processes due to lower combustion temperatures.
- Used in water treatment process
- Crystallization of sulfide ore

- Polymerization of catalyst

3.6 Disadvantages and Challenges

- Design and operation can be complex and require careful consideration of parameters like particle size and gas velocity.
- Abrasion and attrition of particles can lead to equipment wear.
- Potential for elutriation (particle entrainment) in high gas velocity conditions.
- Temperature control and maintenance can be challenging.

3.7 Geldard's Classification of particles

Geldard's classification distinguishes four main groups of solid particles is mentioned below:

1. Group A: Geldard Group A particles are fine and cohesive powders that tend to agglomerate when fluidized. They exhibit poor fluidization behavior and can lead to bed DE fluidization due to excessive particle-particle interactions. Examples of Group A particles include fine clays and cohesive powders.
2. Group B: Group B particles are non-cohesive and exhibit good fluidization characteristics. They maintain stable fluidization even at high gas velocities. Sand and most commonly used catalyst particles in fluidized bed reactors fall into this category.
3. Group C: Group C particles are characterized by their fine size and the tendency to form bubbles in the bed. These bubbles can lead to non-uniform fluidization and mixing. Examples of Group C particles include fine powders like alumina.
4. Group D: Geldard Group D particles are coarse and non-cohesive. They have limited fluidization potential and tend to behave as static beds, only showing minimal expansion. Grains, granules, and certain ores are typical examples of Group D particles.

3.8 Fluidization Regimes

Gas-solid fluidized beds can exist in different fluidization regimes, namely:

- **Minimum Fluidization Velocity ((U_{mf})**: The gas velocity at which the bed initiates fluidization.
- **Partly Fluidized Bed**: Occurs at velocities just above **(U_{mf}**where the bed is partially fluidized, and some particles remain stationary.
- **Turbulent Fluidization**: At higher velocities, the bed transitions into a state of turbulent fluidization characterized by vigorous mixing and bed expansion.

Understanding these regimes and Geldard's classification is necessary for designing and operating fluidized bed reactors effectively.

3.8.1 Fundamentals of Computational Fluid Dynamics:

In CFD various set of methods are used in order to solve the complex equations.it first helps us in making a computational model of the research area that is under consideration.it the uses various methods such as: Finite volume method, Finite element method and Finite difference method in order to solve the various differential equations by dividing it into nodes and then and solving problem within domain.

3.8.2 Introduction to CFD

Computational Fluid Dynamics (CFD) is a powerful tool for simulating fluid flow and heat transfer phenomena within gas-solid fluidized beds. CFD allows engineers and researchers to gain insights into the complex interactions between gas and solid particles, aiding in the design and optimization of fluidized bed processes. The fundamentals of CFD are rooted in the Navier-Stokes equations, which describe fluid flow behavior.

3.8.3 Governing Equations

The Navier-Stokes equations, comprising the continuity equation and the momentum equation, are central to CFD simulations. These equations govern the conservation of mass and momentum within a fluid domain. Additionally, the energy equation accounts for heat transfer processes. Researchers commonly employ numerical methods like finite difference, finite element, or finite volume methods to discretize and solve these equations. The governing and constitutive equations are given in tables Table 1 and table 2 respectively.

Table 3. 1:Governing equations used in CFD

Governing Equations	**Mathematical Form of Equation**
Conservation of Mass equation of gas-solids phases	$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g \vec{u}_g\right) = 0$ Eq-1 $\frac{\partial(\alpha_s \rho_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s \vec{u}_s) = 0$ Eq-2 $\alpha_g + \alpha_s = 1$ Eq-3
Momentum conservation equations of gas and solids phases	$\frac{\partial(\alpha_g \rho_g \vec{u}_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g \vec{u}_g \vec{u}_g\right) = \nabla \cdot \left(\bar{\bar{\tau}}_g\right) - \alpha_g \nabla P - \beta\left(\overrightarrow{u_g}\overrightarrow{u_s}\right) + \alpha_g \rho_g g$ Eq-4 $\frac{\partial(\alpha_s \rho_s \vec{u}_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s \vec{u}_s \vec{u}_s) = \nabla \cdot \left(\bar{\bar{\tau}}_g\right) - \alpha_s \nabla P - \beta\left(\overrightarrow{u_g}\overrightarrow{u_s}\right) + \alpha_s \rho_s g$ Eq-5
Granular Temperature	$\Theta = \frac{1}{3} u'^2$ Eq-6
Equation of conservation of solids fluctuating energy	$\frac{3}{2}\left(\frac{\partial(\alpha_s \rho_s \Theta)}{\partial t} + \nabla \cdot (\alpha_s \rho_s \vec{u}_s \Theta)\right) = \left(-P_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \vec{u}_s - \nabla \cdot q - \gamma - J$ Eq-7

Table 3. 2:Constitutive Equations used in CFD

Equations	**Mathematical expressions**
Stress tensor in the gas phase (Lun et al)	$\bar{\tau}_{g} = \alpha_{g}\left[\left(\xi_{g} - \frac{2}{3}\mu_{g}\right)(\nabla \cdot \vec{u}_{g})I + \mu_{g}\left((\nabla\vec{u}_{g}) + (\nabla\vec{u}_{g})^{T}\right)\right]$
Stress tensor for solid phase (Lunet al.)	$\bar{\bar{\tau}}_{s} = -\alpha_{s}\left[\left(\xi_{s} - \frac{2}{3}\mu_{s}\right)(\nabla \cdot \vec{u}_{s})\bar{\bar{I}} + \mu_{s}\left((\nabla\vec{u}_{s}) + (\nabla\vec{u}_{s})^{T}\right)\right]$
Solids pressure (Lun et al)	$P_{s} = \alpha_{s}\rho_{s}\Theta + 2g_{0}\alpha_{s}^{2}\rho_{s}\Theta(1 + e_{s})$
Solids shear viscosity	$\mu_{s} = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr}$
Collisional viscosity (Gidaspow et al)	$\mu_{s,\text{ col}} = \frac{4}{5}\alpha_{s}\rho_{s}d_{s}g_{0}(1 + e_{s})\sqrt{\frac{\Theta}{\pi}}$
Kinetic viscosity (Gidaspow et al)	$\mu_{s,kin} = \frac{10}{96}\sqrt{\Theta\pi}\frac{\rho_{s}d_{s}}{(1 + e_{s})\alpha_{s}g_{0}}\left[1 + \frac{4}{5}g_{0}\alpha_{s}(1 + e_{s})\right]^{2}$
Kinetic viscosity (Syamlal et al)	$\mu_{s,k\text{ in}} = \frac{\alpha_{s}\rho_{s}d_{s}\sqrt{\theta\pi}}{6(3 - e_{s})}\left[1 + \frac{2\sim}{5}g_{0}\sim\alpha_{s}\sim(1 + e_{s})(3e_{s} - 1)\right]$
Frictional viscosity (Schaeffer et al)	$\mu_{s.ff} = \frac{P_{s}\sin\phi}{2\sqrt{l_{2p}}}$
Frictional viscosity (Johnson et al)	$P_{\text{friction}} = Fr\frac{(\alpha_{s} - \alpha_{s,\min})^{n}}{(\alpha_{s,\max} - \alpha_{s})^{p}}$

bulk viscosity of solid particles (Lun et al)	$\xi_s = \frac{4}{3}\alpha_s \rho_s d_s g_0 (1 + e_s)\sqrt{\frac{\theta}{\pi}}$
Function of radial distribution (Lun et al.)	$g_0 = \left[1 - \left(\frac{\alpha_s}{\alpha_{\sin}}\right)^{1/4}\right]^{-2}$
Dissipation of energy in collisions (Lun et al)	$\gamma_s = 4(1 - e_s^2)\alpha_s^2 \rho_s g_0 \Theta\left(\frac{4}{d_e}\sqrt{\frac{\Theta}{\pi}}\right)$

3.8.4 Modelling of Gas-Solid Flows

The below section of chapter discusses modeling of gas-solid beds.it included Eulerin, Eulerian approach and two fluid modeling approach. the Eulerian-Eulerian approach, in Eulerian -Eulerian model, we treat the phases as continuous fluids because we believe they are mixed on length scales smaller than what we want to resolve. Everywhere inside the flow domain, both phases coexist. The volume fraction indicates the percentage of volume that a phase occupies. The term "interpenetrating continua" refers to this idea. Because conservation equations for mass, momentum, and energy are resolved for every phase, the Eulerian-Eulerian model is frequently used to describe this.

Two-Fluid Model:

The TFM is widely used in commercial codes, such as those used in the oil and gas sector or in more modern versions of generic simulation software like ANSYS Fluent and CFX. By treating phases as interpenetrating continua [26], the method works by solving the continuity equations for each phase over a fixed, or Eulerian, numerical domain. Weighted continuity equations can be used to express this [18] the Two-Fluid Model (TFM), and related concepts like drag modeling and the Kinetic Theory of Granular Flow (KTGF).

Eulerian-Eulerian Approach:

In the gas and solid phase, The Eulerian-Eulerian approach treats them as interpenetrating continua, each having its set of conservation equations. This approach includes:

- The gas phase is described by the Navier-Stokes equations (continuity, momentum, and energy equations) as discussed earlier.
- The solid phase is described similarly, considering its own density, velocity, and energy equations.

The interaction between the gas and solid phases is represented through various modeling techniques, such as drag models and interphase heat transfer models. These models account for the forces and heat transfer between the two phases. Key points to consider in the Eulerian-Eulerian approach include:

- **Interphase Drag**: The drag force exerted by the solid particles on the gas phase and vice versa is crucial for accurate modeling. Various drag models like the drag coefficient and friction factor models can be employed.
- **Interphase Heat Transfer**: Heat transfer between the gas and solid phases is vital in capturing temperature distribution within the fluidized bed. This is especially important when studying reactions involving solid particles.

3.8.5 Two-Fluid Model (TFM):

The Two-Fluid Model (TFM) is a widely used approach for simulating gas-solid flows in fluidized beds. It considers two interpenetrating continua: the gas phase and the solid phase. In TFM:

- Each phase has its own set of conservation equations, including continuity, momentum, and energy equations.
- The phases are coupled through source terms in the momentum and energy equations, representing drag forces and heat transfer.

Key features of TFM include:

- **Volume Fractions**: TFM employs volume fractions to represent the fraction of each phase in a given control volume. These fractions are used to calculate mass and momentum exchange terms.
- **Drag Models**: TFM often uses empirical drag models to describe the interaction between the gas and solid phases. Common drag models include the Schiller-Naumann and Gidaspow models.
- **Heat Transfer Models**: Heat transfer between phases is represented using heat transfer coefficients that account for conduction and convection between gas and solid phases.

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3.8.6 Drag Models

When it comes to fluidized bed CFD models, it is crucial to clarify how particles interact and how momentum moves between different phases. Drag models encompass this interaction, especially between particles and the continuous gas phase, and several models have been specifically constructed for this purpose. These models accurately represent the momentum transfer between the phases, with drag being identified as a key element in the momentum equation of the granular phase. The choice of drag model has a significant impact on the dynamics of the granular phase and may be observed in the anticipated bed expansion and particle concentration in the sections of the bed that are highly populated. The equations essential to the drag models used in this investigation are presented in the next section.

Gidaspow

By the combination of Ergun equation and wen and Yu drag model, we obtain the drag model named ‘gidaspow” [26]. The interphase momentum exchange coefficient, K_{gp} present in this drag

Drag model gidaspow is given below:

Ergun equation:

$$K_{\mathrm{gp-\,Ergun}} = 150\frac{\varepsilon_{\mathrm{p}}\left(1-\varepsilon_{\mathrm{g}}\right)\mu_{\mathrm{g}}}{\varepsilon_{\mathrm{g}} d_{\mathrm{p}}^{2}} + 1.75\frac{\rho_{\mathrm{g}}\left|\boldsymbol{v}_{\mathrm{p}}-\boldsymbol{v}_{\mathrm{g}}\right|}{d_{\mathrm{p}}}, \varepsilon_{\mathrm{g}} \leq 0.80$$

Wen-Yu model:

$$K_{\mathrm{gp}-WenYu} = \frac{3}{4} C_{\mathrm{d}} \frac{\varepsilon_{\mathrm{p}}\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}\left|\boldsymbol{v}_{\mathrm{p}}-\boldsymbol{v}_{\mathrm{g}}\right|}{d_{\mathrm{p}}} \varepsilon_{\mathrm{g}}^{-2.65},\ \varepsilon_{\mathrm{g}} > 0.80$$

where the drag coefficient is Cd and the slip velocity is |vp_-vg |. The definition of the drag coefficient Cd is as follows:

$$C_{\mathrm{d}} = \begin{cases} \dfrac{24}{\varepsilon_{\mathrm{g}R} Re_{\mathrm{p}}}\left[1+0.15\left(\varepsilon_{\mathrm{g}R} Re_{\mathrm{p}}\right)^{0.687}\right] & ,\mathrm{Re}_{\mathrm{p}} < 1000 \\ 0.44, & Re_{\mathrm{p}} \geq 1000 \end{cases}$$

Syamlal-O'Brien model

This model's foundation is the terminal velocity of the particles in fluidized or settling beds, which is determined by equations based on the solid volume percentage and relative Reynolds number. The interphase momentum exchange coefficient, Kgp, for this drag model is defined as follows.:

$$K_{\text{gp- Syamlal-O,Brien}} = \frac{3\varepsilon_{\mathrm{p}}\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}}{4v_{\mathbf{r},\mathrm{p}}^{2}d_{\mathrm{p}}}C_{\mathrm{d}}\left(\frac{Re_{\mathrm{p}}}{v_{\mathbf{r},\mathbf{p}}}\right)\left|v_{\mathbf{p}}-v_{\mathrm{g}}\right|$$

$$v_{\mathbf{r},\mathbf{p}} = 0.5\left(A-0.06\mathrm{Re}_{\mathrm{p}}+\sqrt{\left(0.06\mathrm{Re}_{\mathrm{p}}\right)^{2}+0.12\mathrm{Re}_{\mathrm{p}}(2B-A)+A^{2}}\right)$$

with $A=\varepsilon_{\mathrm{g}}^{4.14}$ and $B=0.8\varepsilon_{\mathrm{g}}^{1.28}$ for $\varepsilon_{\mathrm{g}}\le 0.85$ and $B=\varepsilon_{\mathrm{g}}^{2.56}$ for $\varepsilon_{\mathrm{g}}>0.85$.

The constitutive equations for the solid stress tensor $(\boldsymbol{\tau}_{\mathbf{p}})$ in the TFM are modeled with the KTGF [27].

$$\boldsymbol{\tau}_{\mathbf{p}} = -p_{\mathrm{p}}\boldsymbol{I}+\varepsilon_{\mathrm{p}}\mu_{\mathrm{p}}\left(\nabla\boldsymbol{v}_{\mathbf{p}}+\nabla\boldsymbol{v}_{\mathbf{p}}{}^{T}\right)+\varepsilon_{\mathrm{p}}\left(\lambda_{\mathrm{p}}-\frac{2}{3}\mu_{\mathrm{p}}\right)\nabla\cdot\boldsymbol{v}_{\mathbf{p}}\boldsymbol{I}$$

Wen-Yu model

The interphase momentum exchange coefficient, K_{gp} in the Wen-Yu model is defined as follows [28]:

$$K_{\text{gp- WenYu}} = \frac{3}{4}C_{\mathrm{d}}\frac{\varepsilon_{\mathrm{p}}\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}\left|\boldsymbol{v}_{\mathrm{p}}-\boldsymbol{v}_{\mathrm{g}}\right|}{d_{\mathrm{p}}}\varepsilon_{\mathrm{g}}^{-2.65}$$

where C_d is the drag coefficient which can be defined as follows:

$$C_{\mathrm{d}} = \frac{24}{\varepsilon_{\mathrm{g}}Re_{\mathrm{p}}}\left[1+0.15\left(\varepsilon_{\mathrm{g}}Re_{\mathrm{p}}\right)^{0.687}\right]$$

3.8.7 Kinetic Theory of Granular flow (KTGF)

Many fluids hydrodynamic data that are difficult to get with current measurement devices can be obtained through the use of the computational fluid dynamics (CFD) approach. The two-fluid model (TFM) in CFD modeling considers the liquid and solid phases to be continuous and completely interpenetrating within one another. The kinetic theory of granular flow, or KTGF, is a common approach used to define particulate flow stresses. this approach is the extension of the classical kinetic theory of gases to dense particle flows. This theory introduced the idea of granular temperature to characterize the fluctuation energy of particles. As a result, the TFM-KTGF model can forecast the behavior of particle flow. Many research has demonstrated that the KTGF technique can be used to mimic fluidized beds. it is already known the Boltzmann equation serves as the basis for the kinetic theory of molecular gases' prediction of the transport coefficients. The kinetic theory fills in the gaps between the microscopic principles and the macroscopic principles by evaluating the distribution functions and the transport coefficients using the Chapman-Enskog technique, Grad expansion, and polynomials expansion. Characteristics of gas molecules [3, 4]. The granular hydrodynamic equations produced by the kinetic theory of granular gases accurately explain the dynamics of granular flows, despite the fact that applying kinetic theory to granular gases presents a number of challenges, such as the lack of scale separation and long-range correlations [5].

CHAPTER 4: PRACTICAL FRAMEWORK

4.1 Systematic analysis

The section of this thesis discusses the approach to research and framework used to answer the study questions and objectives. This chapter underlines the systematic procedures and tools utilized for data collection, data analysis, and the interpretation of findings. The chosen methodology is grounded in established research principles and aligns with the nature of the study, ensuring the reliability, validity, and generalizability of the results. Additionally, potential limitations related to the research are discussed. By meticulously detailing the methodology, this chapter aims to provide a transparent and replicable foundation for the investigation, allowing readers to understand the methods utilized and the rationale behind their selection.

For this part of thesis data comprising CFD simulations were carried out and validated with experimental data after validation a detailed parametric analysis on Tapered fluidized bed was done. adopted also, the correct bed height was predicted and other parameter were also examined such as, particle density, drag scaling factor, restitution coefficient, specularity coefficient, and mesh size on solid volume fraction.

4.2 Experimental Observation and data collection

A detailed parametric analysis was carried out in order to check the effect of input parameters on the axial solid volume fraction, after each simulation data was generated and extracted from ANSYS FLUENT.

Data was collected in following steps: -

- First of all, the CFD case was validated with experimental data
- . Then a parametric analysis was carried out
- After each simulation carried out in FLUENT data was extracted
- A total of 2500 datapoints were generated via CFD.

- Height, width, velocity, particle diameter, initial bed height, solid fraction, particle density, drag, scaling factor, restitution coefficient, specularity coefficient, frictional viscosity, granular viscosity, radial pressure, solid pressure and mesh size were used as input parameters and Solid Volume fraction was used as output parameter

The results were extracted using ANSYS fluent and experimental data points were collected using GET DATA DIGITIZER software. The obtained results were then compared with experimental findings. The results were shaped into graphical format using ORIGIN PRO Max software different drag models were implied to match the results with experimental data, additionally drag constant factors were also implied to get the desired results.

CHAPTER 5: RESULT AND DISCUSSION

5.1 Simulation setup:

For studying the governing equations that are used in computational fluid dynamics, the equations are first of all solved in the software ANSYS Fluent 18.0 including the phase-coupled governing algorithm that is built in the ANSYS software. A function that is defined by user named “user defined functions” combines the two model: hybrid drag model and two fluid model. In the Ansys FLUNT software the convective terms and the transient terms were divided by QUICK and first order schemes respectively. The grid size of 5mm was selected and step time of 0.005seconds was employed was selected. All the simulation cases were running for the duration of 20 seconds and were ran in an unsteady manner. Data statistics were collected for the time period of 10-20 seconds. Data sampling for time statistics were collected after initial 10s of simulation. steady state was also achieved after 10 seconds of every simulation. **Table 3** shows the simulation parameters that were used in conducting the simulation case studies using different drag models.

Table 5. 1:Variables of input and simulations

Parameters	**values**
Length of column base (m)	0.19
Column height(m)	0.9
Taper angle of the bed	15
Gas viscosity	1.7894×10^{-5}
Initial packing fraction $\boldsymbol{\varepsilon_{so}}$(-)	0.6
Friction packing limit $\boldsymbol{\varepsilon_s}$	0.5
Restitution coefficient	0.9
Maximum packing limit	0.65
Bed taper angle	15
length of column base$\boldsymbol{L^0}$(m)	0.19
Length at the top of column $\boldsymbol{L_0}$(m)	0.709
Gas void age at minimum fluidizing. ($\boldsymbol{\varepsilon_{mf}}$)	0.45
Minimum fluidization velocity,$\boldsymbol{U_{mf}}$(m/s)	0.059

5.2 Numerical model selection:

Numerical model that has been employed in the study of hydrodynamics of tapered fluidized bed is Eulerian-Eulerain approach. This approach deals both the gas and liquid phase as interpenetrating continua while solving set of Navier strokes equation for each phase. The following section presents the set of governing equations, constitutive relations, simulation setup and initial and boundary conditions.

Governing equations;

The gas solid interactions in the present study are explained though the drag force term which is the product of momentum exchange co-efficient and slip velocity. In the ANSYSY fluent various drag models are present for the study of gas solid interaction by two fluid model. Drag model such as Gidaspow [16],Syamlal-O’Brien ([17],Wen and Yu [18],Hulin-Gidaspow [19],Gilbaro [20] are available in ANSYS for calculating momentum exchange coefficient. various drag models such as gidaspow, Hulin-gidaspow, wen and Yu, gilbaro and syamlal, Obrien. Have been applied along with the drag constant modification factor.

5.3 Drag force correction

Drag model are tailored for gas solid fluidization for the study of hydrodynamics of tapered fluidized bed. There are few limitations that are attached to drag model.to overcome those limitations Mckeen and Pugsley [47] introduced empirical drag correction method for the scaling of standard gidaspow drag. For this purpose, the study of Mckeen and Pugsley targets to scale the drag model gidaspow by multiplying it with certain drag correction factor. For scaling down the standard drag model, the selected correction factor should be less than 1. In the presented study, the drag model gidaspow had been scaled down with the help of multiplying with the drag factor 0.4,0.7,0.8 and 0.9.

5.4 Multifluid model:

Energy minimization multiscale modelling (EMMS) has also implied in the study of gas -solid fluidization.

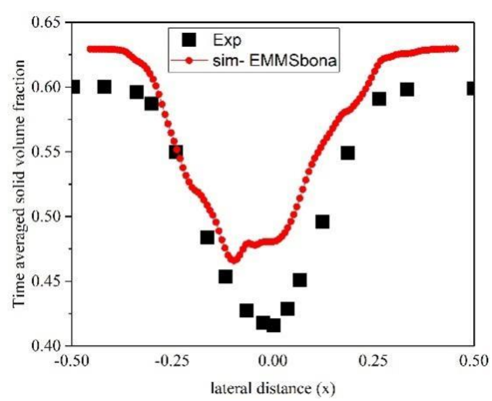


Figure 5. 1:Radial profile obtained from heterogenous drag model EMMSBona at the bed height of 0.18

Fig 1. radial profile obtained from heterogenous drag model EMMSBona at the bed height of 0.18

The results of the Fig 1 show the similarity of the simulation results with experimental data at one end of the wall while it shows discrepancy at the core region. A higher solid volume fraction profile is obtained at the other end of the wall leading to over-prediction of bed height.

5.5 Geometry and mesh independence study for mesh selection:

A coarse mesh with a uniform size of 5 mm is applied to all cases. Simulation results are affected by grid configuration and size of mesh. Prior to performing the CFD simulations a grid independence study was conducted over five grid resolutions. five types of first layer grid thickness of different ranges 3mm,4mm,5mm.6mm and 7mm were selected.

Thus, five meshes coarse to dense were generated to ensure that simulation results were sufficiently grid independent. The simulation employed a total of 118126 mesh elements and the mesh of the first layer of grid thickness, x=y=0.05, taking computing efficiency into consideration.

The mesh consists of structured quadrilateral elements. The meshing methodology adopted ensured capturing the complexities associated with the geometry within reasonable amount of time. Five sets of mesh size were employed that increases the mesh sensitivity range and helps determine the mesh independence resolution more accurately.

Table 5. 2:Characteristics of Mesh Sizes used in simulation

Mesh sizes	**Type of mesh**	**No. of cells**	**No. of nodes**
7mm	Fine	10266	10472
6mm	Mid-fine	14076	14317
5mm	Medium	20252	20541
4mm	coarse	31464	31824
3mm	Standard	56028	56508

5.6 Material Properties and initial and boundary conditions:

The study comprises the multiphase flow involving gas as primary phase and solid sand particles as secondary phase. The table given below gives the summary of the parameters of materials used in simulation.

Table 5. 3:Material Properties

Variables of material properties	**Given values**
Solid	Sand particles
Gas	air
Size of particle d_p(µm)	231
Gas density pg (Kg/m3)	1.325
Density of solid particle ps(kg/m3)	2500
Viscosity of used gas ug (kg/ms)	1.8794×110^{-5}

5.7 Initial and boundary conditions;

With a solid volume fraction of 0.6, the initial height of the tapered fluidized bed is 0.3 meters. At the fluidized bed's intake and outflow, the gas velocity and ambient conditions are the same for the gas phase. In the same manner, conditions for no-slip and partial slip (Φ = 0.5) were provided at the walls for the gas and solid phases, respectively. The solid phase boundary condition at the walls l has been used to represent the particle-wall interaction [48]. A quick overview of the boundary condition employed in the simulation setup is provided in Table 6 below.

Table 5. 4:Boundary Conditions

Description	Type	Comments
inlet	Velocity inlet	Uniform distribution for gas and solid phase
outlet	Pressure outlet	Atmospheric
wall	Stationary wall	For the gas phase there must be no-slip condition Rate of shear stress must be zero for solid phase.

A coarse mesh with a uniform size of 5 mm is applied to all cases. Simulation results are affected by grid configuration and size of mesh. Prior to performing the CFD simulations a grid independence study was conducted over five grid resolutions. five types of first layer grid thickness of different ranges 3mm,4mm,5mm.6mm and 7mm were selected.

Thus, five meshes coarse to dense were generated to ensure that simulation results were sufficiently grid independent. Considering computational efficiency, the mesh of first layer of grid thickness x=y=0.05 and the total 118126 mesh elements was used for simulation.

The mesh consists of structured quadrilateral elements. The meshing methodology adopted ensured capturing the complexities associated with the geometry within reasonable amount of time. Five sets of mesh size were employed that increases the mesh sensitivity range and helps determine the mesh independence resolution more accurately.

Table 5. 5:Characteristics of mesh sizes used in simulation

Mesh sizes	**Type of mesh**	**No. of cells**	**No. of nodes**
7mm	Fine	10266	10472
6mm	Mid-fine	14076	14317
5mm	Medium	20252	20541
4mm	coarse	31464	31824
3mm	Standard	56028	56508

5.8 Radial profile of grid independence study:

This section of study presents the radial profile of grid independence study at the bed height of 0.18 and 0.27 respectively. Fig 2 illustrates comparison of experimental and simulations of various radial fraction profile. Mesh experimental results mesh size at the height of 0.18

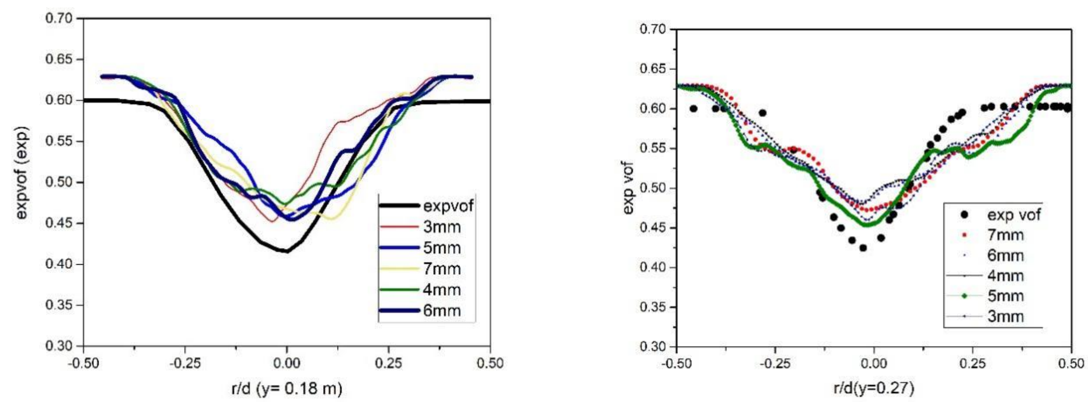


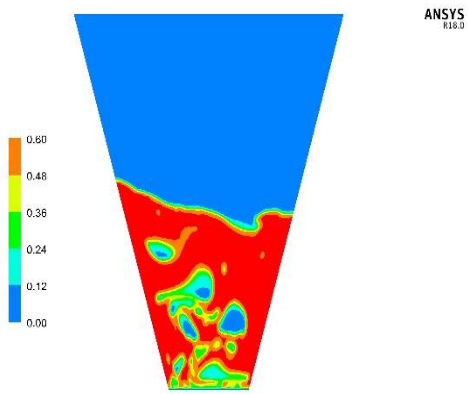
Figure 5. 2:. Averaged radial solid volume fraction profiles of grid independence study at the height of 0.18 and 0.27

The experiment reveals uniform profiles near the walls and in the central region. The radial profile of mesh size of 5mm show similarity with experimental data near the walls while it shows variation from the core.

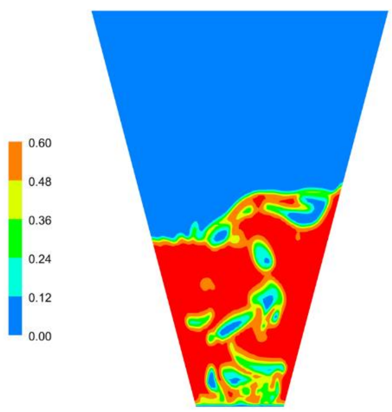
The mesh size of 3mm,4mm,6mm and 7 mm predicts the higher radial solid volume fraction than the experimental data. 5mm mesh size at the height of 0.27 show more similarity with experimental at the core while it shows deviation at one end of the column wall.

5.9 Contours of mesh independence study:

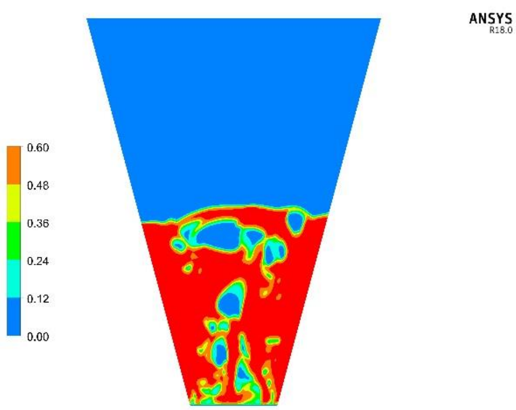
Contours of mesh independence was extracted from ANSYS 18.0 after meshing and grid independence test for tapered fluidized bed. Figure 3 illustrates the contours of grid independence of mesh size 3mm,4mm,5mm,6mm and 7mm. The bubble diameter is observed more is case of mesh size 4mm and 5mm while greater turbulence was seen at the base of the bed with mesh size of 5mm.the solid hold up is asymmetrical at the surface with the mesh size of 7mm. while with the mesh size of 5mm the bubbles penetrate at the bottom with larger diameter.



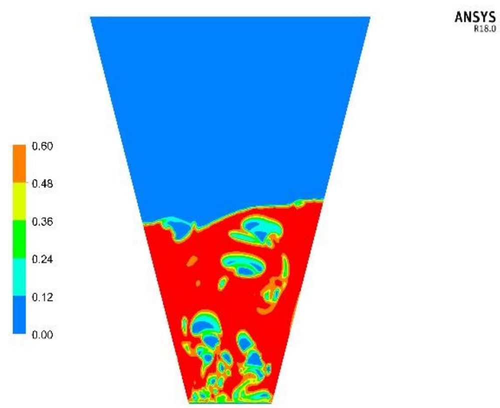
Gidaspow 6mm



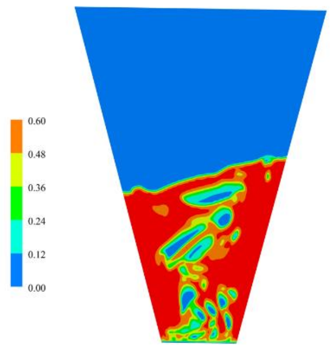
Gidaspow 7mm



Gidaspow 4mm



gidaspow 3mm



Gidaspow 5mm

Figure 5. 3:Contours of solid volume fraction of mesh independence study of mesh size 6mm(a),7mm(b),4mm(c),3mm(c) and 5mm(d)

5.10 Lateral profiles of various drag forces:

After extracting the lateral profiles of grid independence study, the lateral profiles for various drag force were obtained at the 20th second of every simulation. the lateral profiles were obtained at the height of 0.18 and 0.27 and results were compared with experimental data.**Fig.3(b)** illustrates the lateral profiles of drag force compared with experimental data at the bed height of 0.18. drag model Gidaspow predicts results closer to experiments near the walls but over predict from the core region. Similarly drag force Symalal o brain predicts results exactly near the walls while it over predicts results more than gidaspow and other drags from the middle region. Gilbaro and wen and Yu over predicts simulation results indicating the formation of larger bubbles in the fluidized bed.

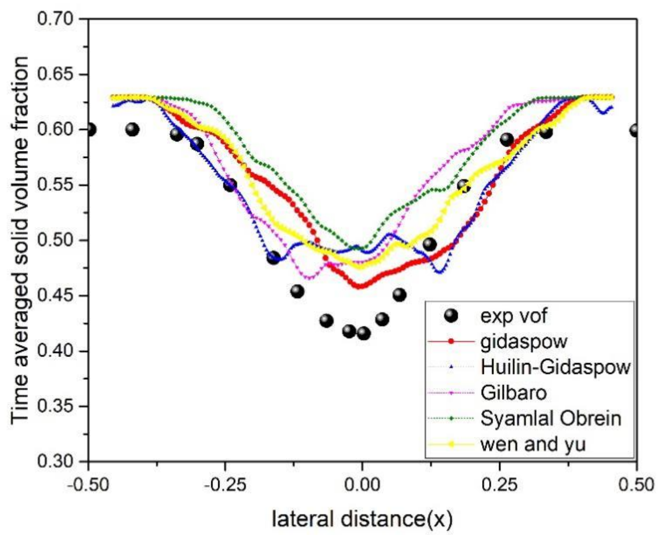


Figure 5. 4:Lateral profile at the bed height of 0.18 of various drag models

5.11 Lateral profile at the height of 0.27 of various drag models:

The lateral profile of drag force have been illustrated in the Fig 4. It gives the lateral profile at the bed height of 0.27. it is clear from the below figure that gidaspow drag model predicts results closer to experimental data near the walls of the bed, while it shows variation from the center region. This might be due to turbulence or formation of bubbles making it a dense region.

Results of drag force Hulin-Gidaspow shows significantly lower radial profile than the experimental results. This discrepancy is attributed to the model neglecting the impact of heterogeneous structures, resulting in an overestimation of drag force and bed height.

The simulation results of the drag force Gilbaro shows some similarity with the wall at the initial and final points. while it shows significantly above radial profile from the central region of the column. Due to formation of bubbles with large diameter at the central surface of the bed, it overpredicts the bed height as shown in the contours mentions in following section.

SyamlalO'Brein predicts the bed height somewhere close to experimental data near the walls while showing discrepancy at the central region.

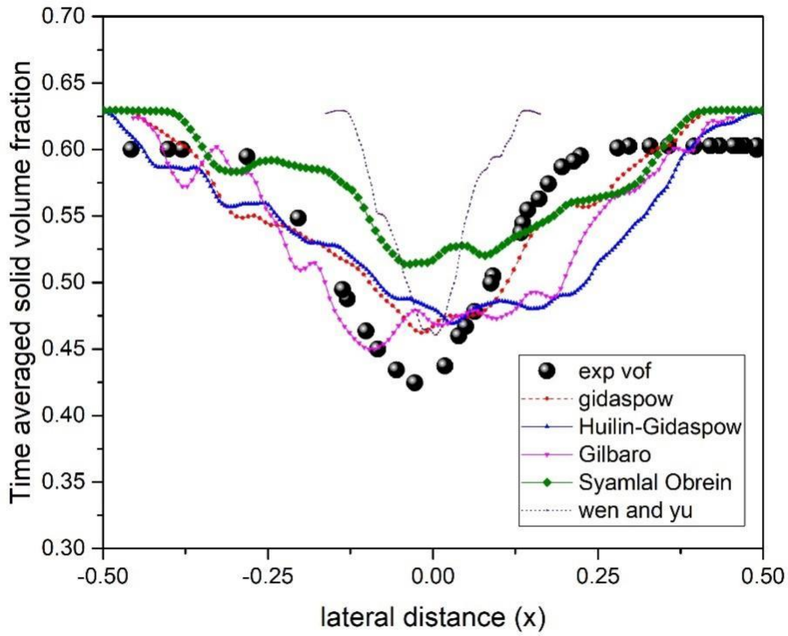


Figure 5. 5: Lateral profile predicted from Gidaspow, Hulin gidaspow, Gilbaro, Syamlal O'Brien and wen and Yu at the bed height of 0.276

5.12 Contours of drag forces:

In this section contours of drag forces have been discussed after extracting the radial profiles at the bed height of 0.18 and 0.27. Fig. 5 presents qualitative outcomes through instantaneous solid volume fraction snapshots obtained from default drag models i.e, gidaspow (a), Hulin gidaspow(b), gilbaro(c), Syamlal O brain and Wen and Yu(e).

The contours obtained from gidaspow predicts the elongated bubbles in the central region of the bed. heterogeneous flow structure is also observed at the base of the bed.

The contours obtained from Hulin gidaspow drag model predicts bubbles of les diameter as compared to default gidaspow drag model. turbulence was observed over the bed surface while dense concentration of bubbles was observed at the bed surface.

The contours of drag model gilbaro predicts a uniform formation of bubbles at the central region of the bed. Bubbles of smaller diameter are seen at the base of the column while elongated bubbles are seen on the top surface of the bed.

A Heterogeneous flow structure was observed in case of simulation case with drag model syamlal O'Brien. Bubbles of very small size with less quantity was seen in the central region of the bed while it predicts the similar dense structure with gidaspow, Hulin-gidaspow and Gilbaro drag models.

In case of applying the drag model Wen and Yu, it can be observed from its contours that very less bubble formation can be seen at the base and surface of the bed. Elongated bubbles can be observed at the central surface of the bed leading to over prediction of correct bed height

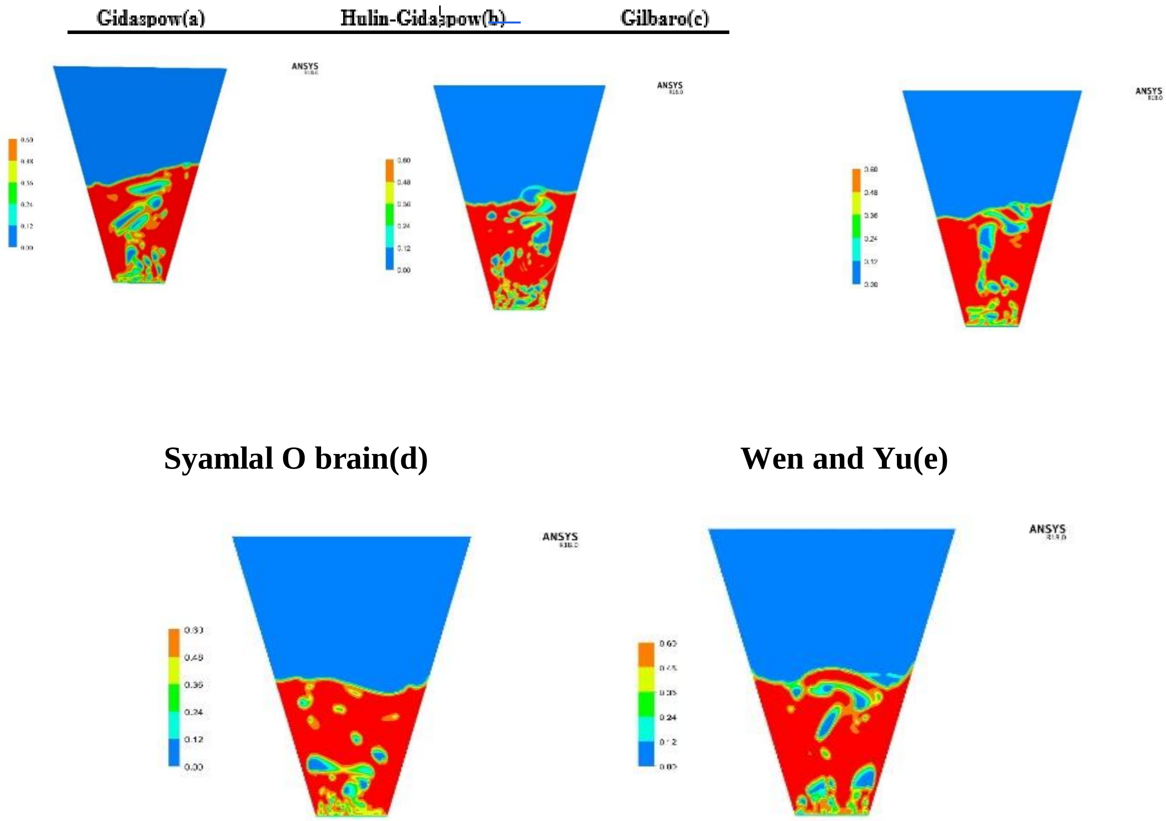


Figure 5. 6: Solid volume fraction contours at the 20th second simulation predicted from Gidaspow(a), Huilin-Gidasopow(b), Gilbaro(c), Syamlal O'Brien(d) and Wen and Yu(e)

5.13 Corrected drag factor lateral profile at the bed height of 0.18:

The corrected drag factor was implied in case of simulation with drag model gidaspow. A fine tuning was done by modifying gidaspow drag model as it yields result closer to experiment. Fig 6gives the result of gidaspow drag model with applied drag factor of 0.4,0.7.0.8 and 0.9 at the bed height of 0.18. [49]

It is clear from the figure that gidaspow drag model with drag modification factor of 0.9 gives result close to experimental data while other show deviation. Near the walls it shows the similarity with experimental data while it shows variation at the central region.

The drag model with factor 0.4 shows higher radial profile thus overpredicting the bed height.

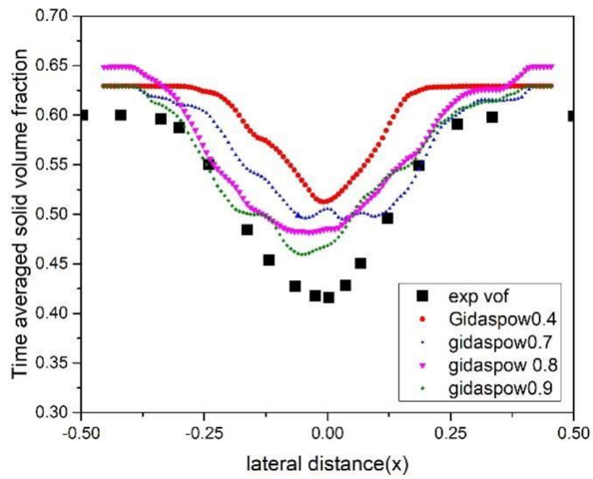


Figure 5. 7: Lateral profile predicted from Gidaspow,0.4, gidaspow0.7, Gidaspow0.8, Gidaspow0.9 at the bed height of 0.18.

5.14 Lateral profiles of drag correction factor at bed height 0.27:

The corrected gidaspow drag model results were compared with experimental data at the bed height of 0.27. none of the results shows similarity with experimental data. The results of gidaspow drag factor 0.4 shows much higher profile of solid volume fraction. [50]While the results of gidaspow with drag factor 0.8 and 0.9 shows near results at one end of the bed wall while at the other end they depict lower radial profiles as compared to experimental data.

The simulation results of gidaspow 0.7 shows similarity with experimental data at the initial and final stage of the wall but shows discrepancy at the central region of the bed.

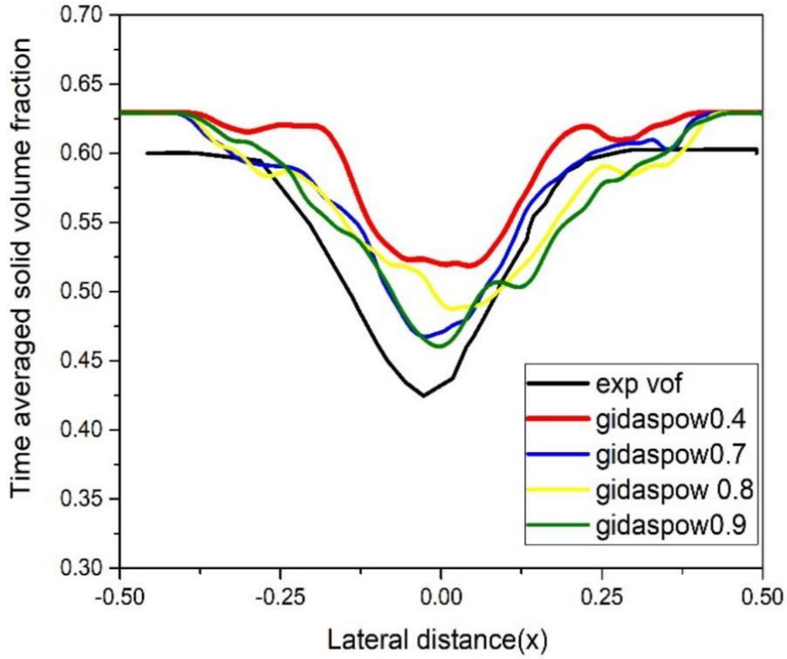


Figure 5. 8:. lateral distance at the bed height of 0.27 of grad model gidaspow with drag correction factor 0.4,0.7,0.8,0.

5.15 Gidaspow changed packing limit:

This section discusses the results of simulation case in which drag model gidaspow was implied. frictional packing limit was changed to 0.5 and maximum packing limit was kept 0.65.in rest of the simulation cases it was kept 0.63. mesh size of 5mm was selected and time step size of 0.0005s was kept. results of the radial profile were obtained at the bed height of 0.18 and 0. 27m.The results were obtained at the 20th second time. [51].As shown in the figure 8 given below with the changed packing limit of gidaspow, the results show bit similarity near the walls of the fluidized bed with the bed height of 0.27. Due to turbulence regime, it shows higher profile from experimental data at the center of the bed.

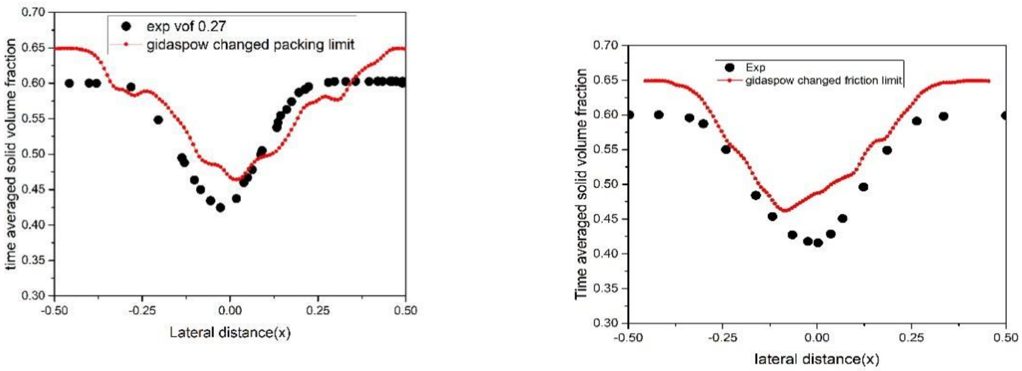


Figure 5. 9: Radial profile with default gidaspow and changed packing limit at the bed height of 0.18 and 0.27 respectively

5.16 Gidaspow changed packing limit with 30 seconds simulations:

With the changed packing limit from 0.63 to 0.5 and maximum packing limit to 0.65, the simulation case was ran for another 10 seconds. Results of radial profile at the bed height of 0.18 and 0.27 were obtained at the 30th second time.

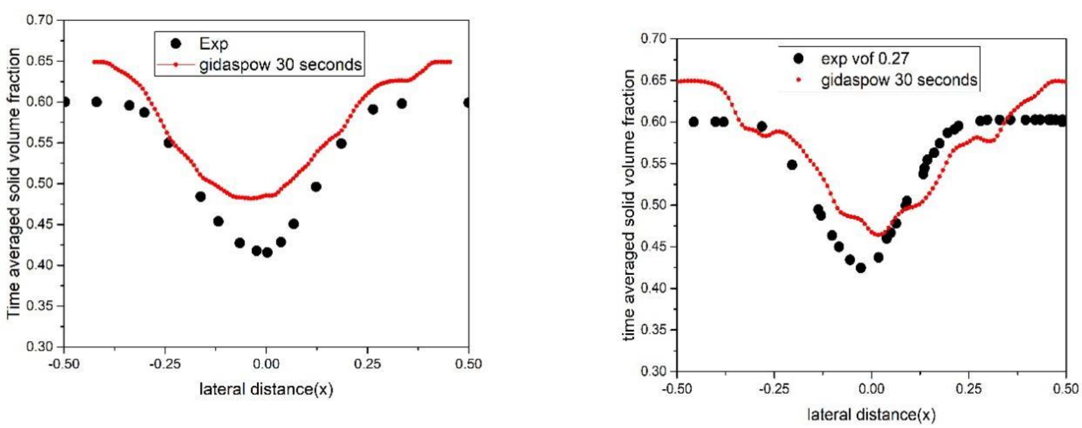


Figure 5. 10: Radial profile of default gidaspow for 30th second simulation

5.17 Change of solid frictional viscosity from Schaffer to Johnson-et-al:

The solid frictional viscosity was changed from Schaffer model [52] to Johnson-et-al [53].the simulation case was ran for 20 seconds. Time step size of 0.005s was selected with a volume fraction of 0.5. radial profiles were obtained at the bed height of 0.18 and 0.27.

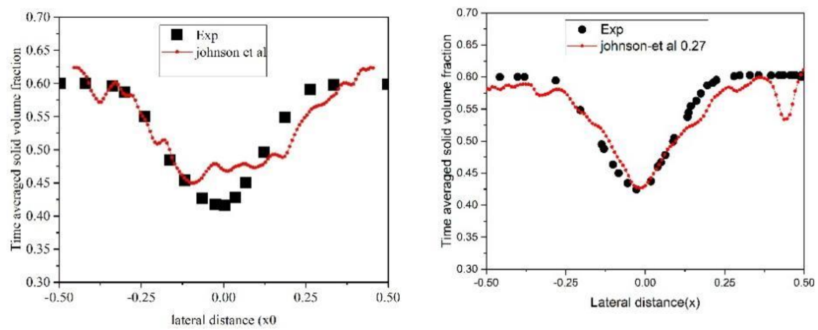
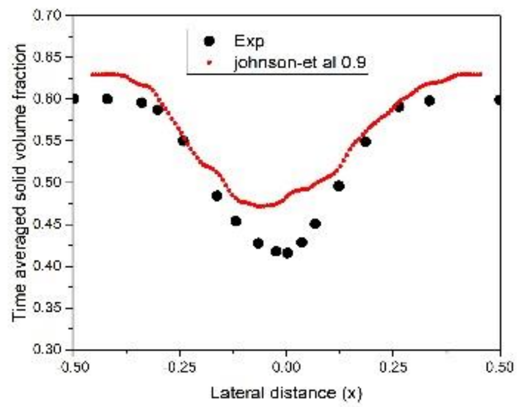


Figure 5. 11: Radial profiles predicted from Johnson-et-al at the bed height of 0.18 and 0.27

5.18 Applying drag constant of 0.9 and 0.95 with solid frictional viscosity Johnson-et-al:

In this simulation case, Johnson-et-al [53]solid frictional viscosity model was employed. The efficacy of empirical method was investigated for over-predicting the bed height. Drag constant of 0.9 and 0.95 was employed for the bed height of 0.18 and 0.27.



(a)

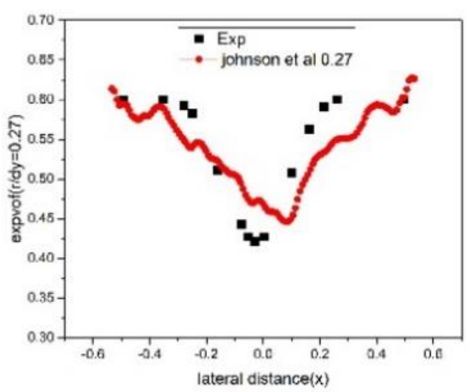


Figure 5. 12: Radial profiles predicted from Johnson-et-al at the bed height of 0.18 and 0.27

Fig 5.12. shows the contours of solid volume fraction while applying the solid frictional viscosity model Johnson-et-al [48] with a drag factor of 0.9.at the bed height of 0.18, it predicts results close to experiment near the walls of the fluidized bed. while it shows deviation at the central region. At the bed height of 0.27, it shows lower radial profile at one end of the wall predicting the entrainment of solid particle in the bed expanded region.

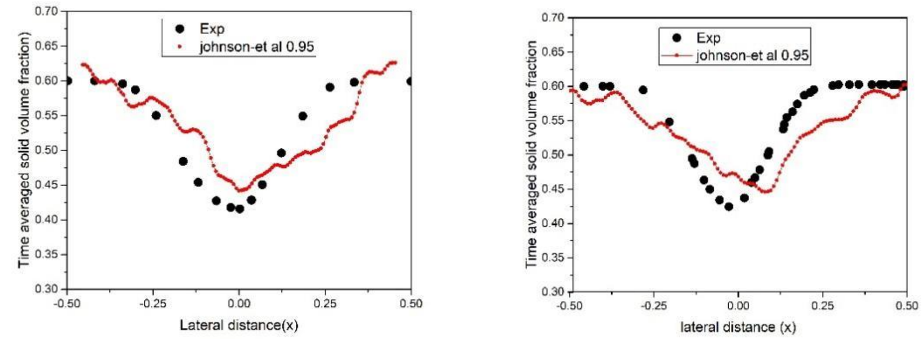


Figure 5. 13: Radial profile at the bed height of 0.18 and 0.27 with drag factor 0.95 and applied solid frictional viscosity Johnson et al

The above fig 5.13 gives the radial profile results while applying the drag factor of 0.95 with solid frictional viscosity Johnson -et-al model.at the bed height of 0.18 it shows deviation from the experimental data .at the bed core region it shows less deviation. Both the profiles predict lower radial profile at one end of model owing to the reason that it neglects the heterogenous flow structures due to which they overpredict bed height.

5.19 CFD results and discussion:

In the present study, the hydrodynamics study of tapered fluidized bed using ANSYS Fluent and the finding were compared with experimental results. The various drag models were implied such as gidaspow, Hulin-Gidaspow, Syamlal O Brien. Drag models with drag modification factor of 0.7,0.8 an d0.9 was also implied. A heterogenous model was also presented which show large deviation from experimental results.by applying the homogeneous drag model Gidaspow the obtained results were closer to experimental data. It takes into account the gradual rise in drag force brought on by the bubble's formation and motion, as well as the seamless transition of the momentum exchange coefficient from the dense phase to the bubble phase. Unlike most heterogeneous drag models, it additionally takes into account the bubble size increase along the elevation in its bubble-based drag formulation. The change in Solid frictional viscosity from Schaffer to john son at al [32] also leads to similar results Fig 11. shows the contours of solid volume fraction while applying the solid frictional viscosity model Johnson-et-al [48] with a drag factor of 0.9.at the bed height of 0.18, it predicts results close to experiment near the walls of the fluidized bed. while it shows deviation at the central region. At the bed height of 0.27, it shows lower radial profile at one end of the wall predicting the entrainment of solid particle in the bed expanded region.

CHAPTER 6: CONCLUSION

In conclusion, this study addresses the intimidating challenges of predicting hydrodynamics of Tapered fluidized bed and validating it with experimental results. Our investigation comprehensively examined the impact of various parameters, which includes prediction of correct bed height, width, velocity, particle diameter, initial height, solid fraction, particle density, drag scaling factor, restitution coefficient, specularity coefficient, and mesh size on solid volume fraction. IN addition to that, a modified drag model and a hybrid drag model was also introduced to examine the above-mentioned factors of the tapered fluidized bed. Notably, our findings also highlight the efficacy of the scaling factor as a robust technique for incorporating interparticle forces, particularly in the context of predicting correct bed height. Hence, modified drag models were implied along with various drag models to predict the correct bed height and resonate with experimental results showed gidaspow and modified gidaspow with drag constant 0.9 show similarity with experimental results.

REFERENCES

[1] D. L. O. Kunii, fluidization engineering, boston : butterworth-Heineman, 1991.

[2] M. Adnan, "Validation and sensiof a tapered fluidized bedtivity analysis of an Eulerian Eulerian Two fluid model (TFM)," *powder tachnology,* pp. 490-518.

[3] C. Loha, "Assessement of drag models in simulating bubbling flyidized bed hydrodynamics," *chemical engineering,Sci,* pp. 400-4, 2012.

[4] Y.Peng.L.T.Fan, "hydrodynamic characteristics of flyidization in liquid-solid tapered bed,Chemical engineering science," vol. 3, no. 2227-2229, 1997.

[5] N. .. Tekin.topl, Vols. 1784-1792, 1960.

[6] K. monograpg, "1993," *study of flow regimes in the process of flyudization,* pp. 30-40, 1998.

[7] Y. k. R. 5, no. 202-204.

[8] L. .. .peng, "dtermination of bed height of tapered fluidized bed," 1997.

[9] A. G. I. Mukhlonov, "Hydraulic resistance of a fluidized bed in a cyclone spherical partivclesChem eng," *Chem eng,* 1998.

[10] Nishi, "Incipient fluidization of gas-solid conical fluidized bed," *chemical engineering,* 1998.

[11] J. 9lenongrad), "fluidization of coarse particles of gas solid flyidized bed," 991.

[12] G. e. al, "flyidization of coarse particles of gas-solid fluidization," *Chemical Engineering Science,* pp. 60-70, 991.

[13] S. J. .. A. M. Olazar .M.J.Fan, *Eng Chemical,* pp. 57-90, 1997.

[14] A.E.GOSHERIN.I.P Mukhlenov, "hydraulic resistence of flyidized bed in a cyclone without grate ,critica; gas rate corresponding to jet formation," *chemical engineering,* 1997.

[15] Biswal, "correlations for the fluctuation ratio in a packed bed for sherical and non sherical particles," *Chemical Engg,* 1991.

[16] e. a. gidaspow, Hydrodynamics of circulating fluidized bed: kinectic theory approach., chicago: illinious instituite of Tech, 1991.

[17] s. m. brein, "Computer simulations of bubbles in a fluidized bed," 1989.

[18] C. Wen, Mechanics of fluidization, Chem.Eng.Prog100-111, 1966.

[19] L. Huilin, Hydrodynamics of binary fluidization in a riser: CFD Simulation using two grannular temperatures, chemical Engineering Science 58,3777-3792, 2003.

[20] L.-F. F. Gilbaro, Generalized friction factor and drag co-efficient correlations for flyuid-particle interactions., Chemical Engineering Science 40,1817 1823, 1985.

[21] s. OBrain, "drag models for hydrodynamic study of flidization," *chemical engineering,* pp. 300-400, 1987.

[22] T. K.C Biswal, "Prediction of minimum Flyuidization velocity for gas solid fluidization of regular particles in conical vessels," p. 224, 1984.

[23] J. e. al.Shan.Wang, "flyidization of gas solid particles," pp. 267-300, 1994.

[24] D. .J.G.Pieters.K.Dewettinck, "Expanded bed height determination in a tapered fluidized bed," *Journal of food engineering,* 2000.

[25] S. a. Hancher, *chemical engineering,* 1976.

[26] b. e. al, "dertermination of bed height of tapered fluidized bed and studying its hydrodynamics," pp. 330-271, 1973.

[27] M. .. A. .. A. I. .. Chem, "study of tapered beds," vol. 3, 1992.

[28] K. a. Farkas, "incipient flyidization condition for a tapered fluidized bed," *journal of food engineering,* p. 330, 1998.

[29] HSu, "prediction of minimum flyidization velocity in a conical vessel," *chemical engineering,* 1978.

[30] M. a. Sato, "expanded bed height determination in flluidized bed," pp. 89-100, 1991.

[31] W. a. Kwauk, "study of hydrodynamics of flyidized bed in conical bed," *chemical engineering,* 1984.

[32] D. a. Harrison, "Prediction of pressure drop of conical fluidized bed for spherical particles," 1971.

[33] Levery.Shagn, "study of tapered fluidized ned," *chemical engineeering,* 1991.

[34] T. a. Kawamuna, "flow regimes of tapered flyidized bed in column," *chemical ENGG,* 1997.

[35] Nishi, "study of hydrodynamics characyeristics of flyidized bed," *chemical engineering,* pp. 300-400, 1998.

[36] S. e. al, "study of flyidization cxharacteristics of iron ore fines," *chemical engg,* 1993.

[37] S. n. Hancher, "prediction of pressure drop of conical and fixed bed," *chemical Engg,* 1994.

[38] K. a. farkas, "flow regimes and incipient condition of fluidization,voidate distribution and bed expansion calculations," 1973.

[39] gidapow, "study of hydrodynamics of flyidized bed," pp. 330-400, 1991.

[40] Z. etal, "to investigate the hydrodynamics of tapered flyidized bed focusing on the imapct of gas distributors".

[41] liue, "study the hydrodynamic characteristics of taper in and taper out risers," *chem eng,* pp. 56-90, 2019.

[42] L. a. al, "study of hetrogeneous drag model incorporating variations in bubble size," 2014.

[43] Chen, "influence of tapered bed geomerty on gas-solid flow patterns," *Chem Engg,* 2020.

[44] Yang, "study the hydrodynamic of lfuidized bed under different operating conditions," *chem Engg,* pp. 300-400, 2018.

[45] W. e. al, "particle size distribution on the effect of hydrodynaics charrateristics of fluidized bed," *Chem engg,* 1998.

[46] L. e. al, "parametric study to optimize the deige of taperec fluidized bed," 2021.

[47] P. Mckeen T., "Simulation and experimental validation of a freely bubbling bed of FCC caralyst," Vols. 129,139-152, 2003.

[48] P. johnson, Frictional-collisional constituitive relations for grannular materials,with application to plane shearingJ.fluid mech179, 1987.

[49] S. C. Mori, "Estimation of Bubble Diameter in Gas Solid fluidization," *chemical engineering,* vol. 7, 2003.

[50] L. Jiang, Assesement of drag model in simulating bubbling fluidized bed hydrodynamics,FLYID MECHANICS, chem ENG, 1997.

[51] S. Liyam, "Hydrodynamic modelling of gas-solid fluidizaton on energy minimization model," *powder technology,* vol. 5, pp. 305-301, 2009.

[52] D. Schaeffer, "Instability in the evolution equations descrining incompressible granular flow.J.Differ.EQU 66,19-50," 1987.

[53] .. Johnson, "Frictional-Collisional constituitive relations for granular materials," Vols. J.Fluid Mech.176,67-93, 1987.

[54] D. Thomas, "hydromachanical simulation of bubbling fluidized bed using an extended buble based EMMS model," *powder tachnology*, pp. 361-381, 2017.