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Two-Phase Liquid-Solid Hydrodynamics of Inclined Fluidized Beds

Huda Ridha[1*], Nhad K. Frhan Al-Abboodi[2]

[1] Veterinary Medicine College, Wasit University, 52001 Wasit, Iraq
[2] Mechanical Engineering Department, College of Engineering, Wasit University, 52001 Wasit, Iraq

[*] Correspondence: Huda Ridha (Hridha@uowassit.edu.iq)

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Abstract: Although many fluidized systems are not vertically oriented, little research has been done on fluidization within inclined channels. The fluidization of the gravitational force and the tensile force may be substantially opposing in the vertical system. The theory of gravitational field fluidization, which is related to industrial fluidization processes like coal gasification, iron ore reduction, and catalytic cracking and calls for the use of standing tubes or angled risers, has to be developed in order to encompass various orientations. Without underlying theories, engineers must rely on vertical fluidization equations to build these sloping systems. A significant barrier to improving the design and optimization of new solid circulation systems is the tendency of fluidization. Based on historical developments and theoretical progress, the study presents an overview of recent advancements of liquid-solid fluidized beds in inclined columns. The fluidized bed is investigated as a whole by looking at the governing factors.

Keywords: Liquid–solid substrates; Inclined fluidized bed; Particle diameter; Fluidization features; Length of the bed; Heat effect

1. Introduction

Solid-liquid substrates are adopted in many industrial applications, such as catalytic cracking, hydrometallurgical and ion exchange operations, particle classification, adsorption, crystallization, and precipitation. The size and density distribution are two important considerations in these applications. The design of these solid-liquid fluidized substrates with wide particle size and density distributions that regulate the volume of equipment based on the reaction phase requires an understanding of and ability to forecast substrate expansion, particle separation, and/or mixing. The flow of the solid and liquid phases is controlled by the spatial distribution of the solid phase, which indirectly influences the mixing rate, mass rate, and heat transfer.

Many important operations, such as the hydrogenation of coal for the production of oil, wastewater treatment, oil extraction procedures, sulfur treatment, and hydrocracking of oil sections, take place in vertical or inclined channels. The earlier studies on cylinder beds [1-4] concentrate on solid air in the big channel widths of two-phase flow. Despite its practical significance, fluidized beds in inclined pipes have only received a limited attention. These flows are crucial for oil drilling and pumping operations.

2. Hydro-Transport of Solid Particles

In recent years, oil fields have started drilling steep wells on a single platform that slope in many directions. Multiple sloping wells are often drilled at the same time. Odia et al. [5] tested substrates with horizontal angles between 45° and 90° and various kinds of powder. To forecast the pattern of a solid rotation, Hudson et al. [6] evaluated the pattern of maintenance and rotation of the liquid and solid phases on modest slopes that were just 10° from the vertical. Doron et al. and Ercolani et al. [7, 8] modeled sloping pipes and horizontal water transport, while Sarkar et al. [9] investigated pneumatic transfer.

According to Doron et al. [7], slope has a considerable impact even for very minor angles on the bed created at both ends of horizontal pipes as well as sloping pipes (up to 7°). Ercolani et al. [8] studied the process by which beds form in inclined pipeline sections: they looked at how elbow position relates to profiling formation, measured solid beds, and ascertained a solid bed's profile. The flow of solid particles through a tube that slopes downward to a receiver container was studied by Sarkar et al. [9] along with the effects of connecting pipe length on the slope angle and fluidizing bed speed of the solid particle flow. Assuming a smooth boundary condition for the channel wall, Hutter and Scheiwiller [10] led a numerical analysis of the acquired particle velocities and downward flow in an inclined channel.

Masliyah et al. [11] evaluated the increased separation of particles from suspensions in inclined pipes. The authors investigated the development of removing light and massive particles from suspensions using inclined channels. The researchers noticed that for a predetermined set of working conditions, the increase of a horizontal particle is represented by a larger degree of division. The liquid filtration through the particles was constrained by a 0.4-meter-long conduit that served as a sample channel. Results from other studies show that tube particle points have a considerable influence on fluid-particle intelligence results and stream features. In practical applications and industrial operations, fluidized beds in inclined pipes allow for higher solid circulation rates in the bed and less instability problems [12].

Yakubov et al. [13] carried out an experimental investigation to examine the fluidized bed dynamics in inclined pipes. As the pipe inclination angle varies, a significant shift in the fluidization parameters takes place. Figure 1 shows a schematic diagram of their experimental setup. Their experiment adopts a total of two glass columns with diameters of 2.58 cm and 2.78 cm, L/D ratios of 95 and 150, and inclination angles ranging from horizontal to vertical.

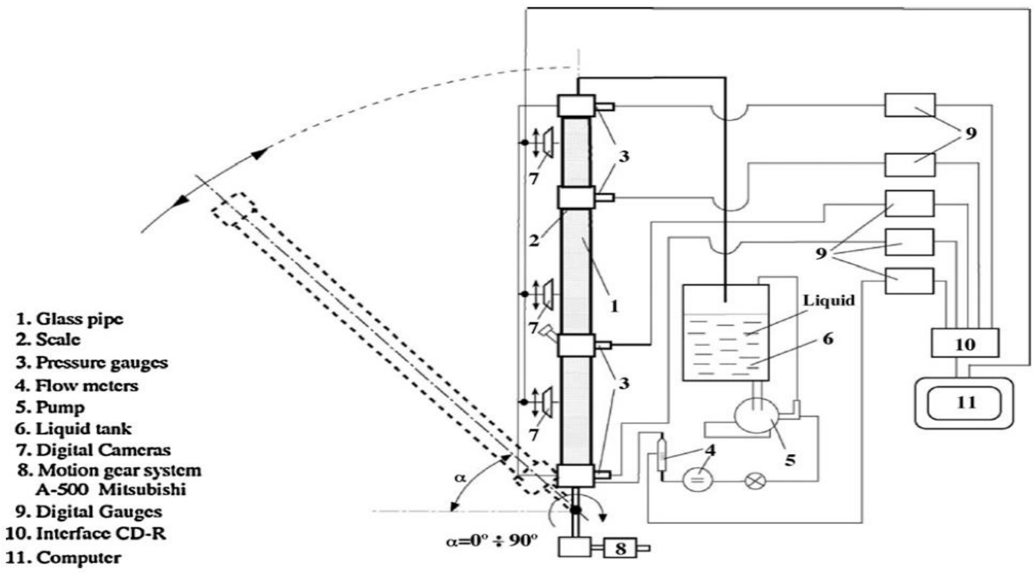


Figure 1. The long pipe of Yakubov et al.'s experiment [13]

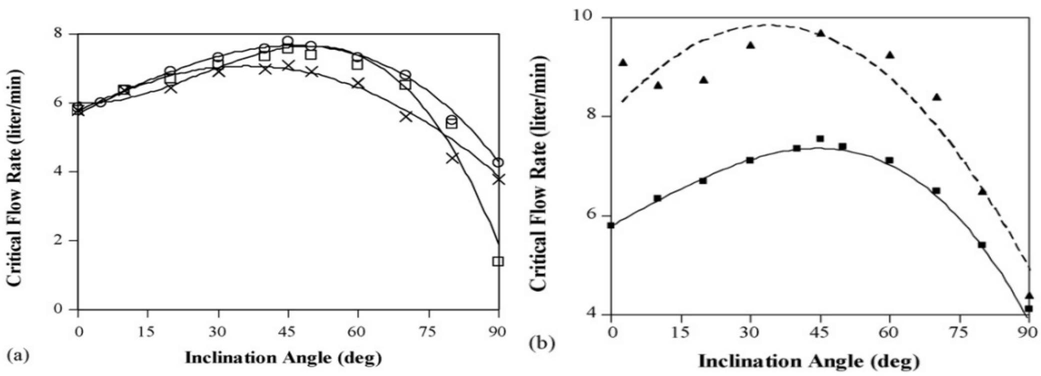


Figure 2. Critical flow rates for bed escaping by Yakubov et al. [13]

Yakubov et al. [13] demonstrated the significance of particle diameter and density in Figures 2(a) and (b). Figure 2(a) illustrates the critical flow rate d_b for bed escape for three different types of particles with the same density but varied sizes. For all diameters, critical flow rates are typically at their highest at an inclination of around 45°.

As seen in Figure 2(b), the flow rate rises with the inclination of the column as particles with various densities and almost identical diameters are gathered inside. Another finding is that at inclination angles of roughly 45°, the flow rate is at its maximum. With density, the critical flow rate increases dramatically for all inclination angles.

3. Particle Separation

Gravity partition, a physic division that deals with pollution, is widely used in the mining business. A Boycott impact was revealed as a result of an increase in the surface zone and the rate of corpuscles in an inclined tube, which is settling (U). This triggers an improvement in the performance of the Reflux Classifier [14-17]. Ponder [18] represented a kinematic model called PNK on particle transport in an inclined channel. Based on the PNK hypothesis, inclined channel tools have been investigated and used as the basis for the Reflux Classifier innovation to implement partitioning in a liquid-solid fluidized bed [19-21]. The Reflux Classifier was the name of the unused gravity partition device with a number of channels on a typical fluidized bed. The fluidization framework has long employed the influence of particle plates on particles [22].

Laskowski et al. developed the dimensional examination rule and an inclined channel [23]. On the flat, a particle point with 70 components was suggested. Based on Galvin et al.'s model with channel involvement, the Reflux Classifier technology enhancement used the RC to density-based particles partition [24]. Multiphase particles have been used in previous investigations. This discovery led to the study of particle partitioning in inclined channels [25]. The contact of the circle with the divider in the plane serves as an example of shear flow. King and Leighton [26] measured the inertial lift in a moving circle of a plate divided by the shear flow. The lift force was assigned based on particle width rather than particle span. The lift force was assigned according to the particle width, rather than the particle span, and the inertial lift was addressed straightforwardly in the hypothesis by Galvin and Liu [27]. Brownian dissemination combining elements and gravity settling were used to discover the particles transport; the results show that a precise depiction of the transport and the statement conduct of the particles were realized [28].

The liquid-solid fluidized bed involves complex basic physical instruments. Moreover, the particle shape, the liquid speed, and particle estimates are sensitive to the hydrodynamic strengths on a particle and the drag lift [29-32]. Zarghami et al. investigated the hydrodynamic forces in a particle near a divider using the grid Boltzmann approach [33]. Li et al. [34] proposed the hydrodynamic behavior of the liquid-solid fluidized bed coinciding with bed extension. Koerich et al. [35] predicted particle fluidization, established the effects of lift and drag force, and used a drag model to assess them.

He et al. [36] created a novel theoretical model to describe how particles dissociate in critical situations. This model takes into account the equipment parameters, Reynolds number, particle type, and terminal velocity of the particles. The penetration velocity of particles separated in inclined channels was predicted for various spacings using the established model. The authors have theoretically established the characteristics of single particle motion using the streamlined system depicted in Figure 3. where the X- and Y-axes represent a normal channel and a tangential channel, respectively. Their findings showed that when the Reynolds number was below 43, the innovative model was remarkably good at forecasting the surface velocity. Compared to a conventional practical model, the new approach produced significantly superior decisions. Their study provides theoretical and experimental underpinnings for the design of the inclined channel construction and operating parameters for industrial applications.

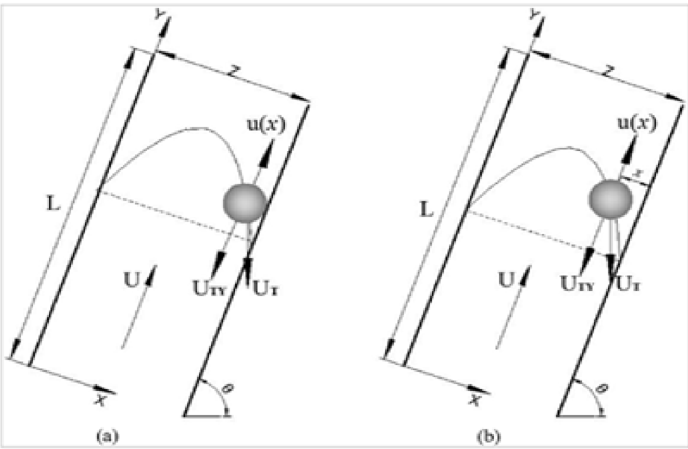
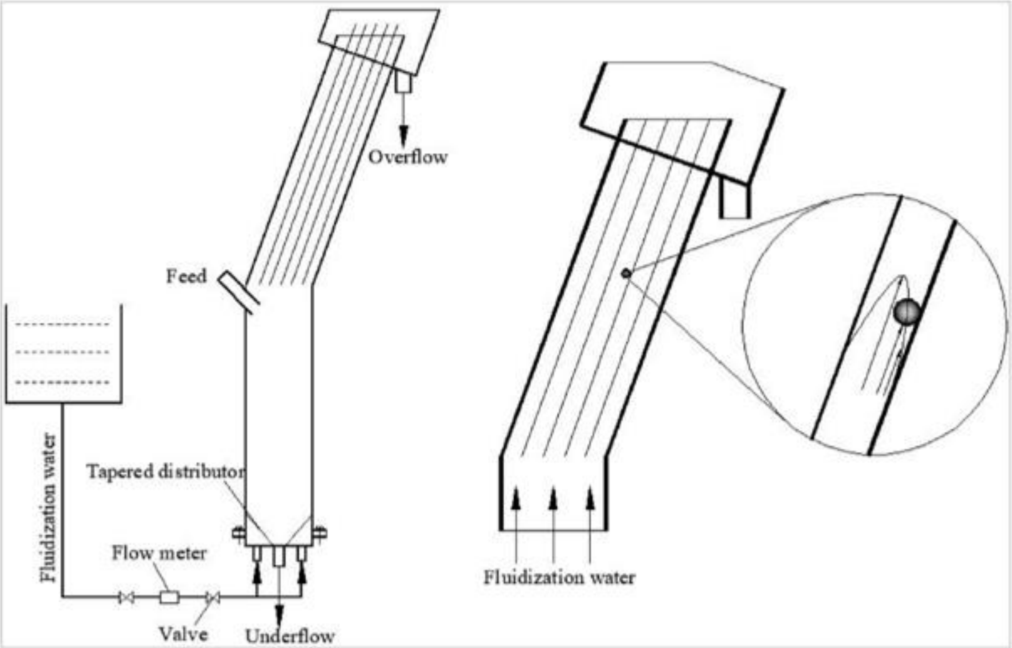
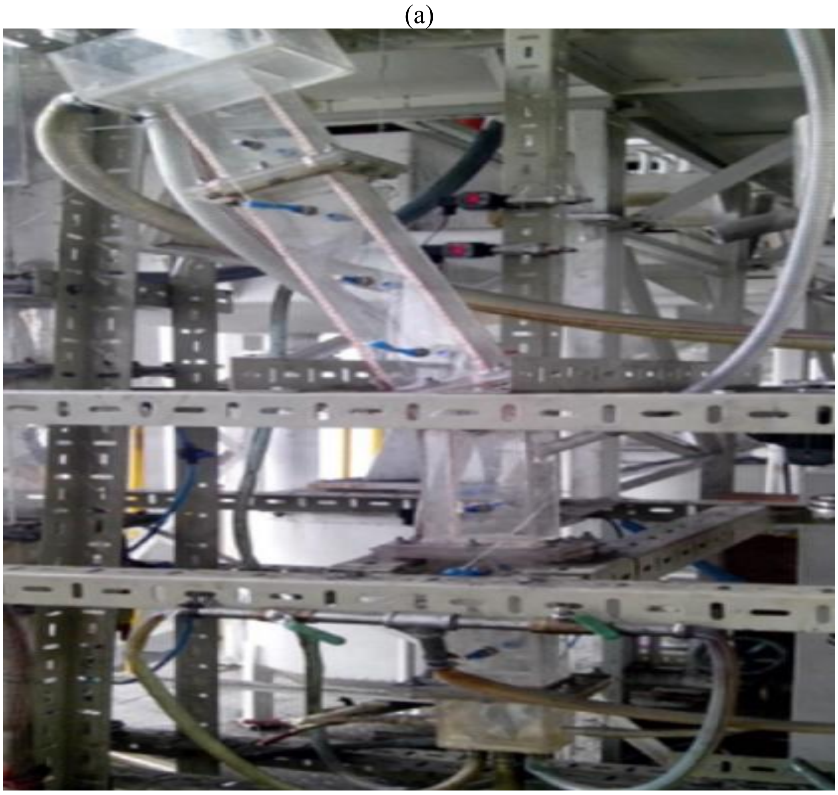


Figure 3. Particle velocities in inclined channels of He et al. [36]

Figure 4 illustrates an experimental system designed to verify the theoretical model. The inclined channels can be used with different spacing by adding or removing inclined plates.



(a)



(b)

Figure 4. Experimental system of He et al. [36]

4. Feature Motions

Reflux classifiers have been widely used to classify minerals using liquid-solid fluidized beds produced with particles [19]. The working liquid may be greatly expanded in conventional fluidized beds due to the particle plate's proximity. In fact, it may be enhanced more than the particle final rate. Many researchers have studied the p article plate effects on improving isolation competency using dimensional examination standards [37]. Iveson et al. [38] made the assumption that RC could desliming minerals with a measure range of 0.05 mm to 0.35 mm by partition method. A wide range of suspension concentrations can also be used to change the introduction of the plates at a given fluidization speed. As such, it is possible to significantly increase the throughput of the framework while maintaining the ability to handle strong particles. Extensive research has been done to comprehend the fundamental components. Galvin and Nguyentranlam [19] developed a kinematic demonstration consideration to assess the monodispersed suspension model, drawing on Ponder [39] and Nakamura [40]. Davis et al. [41] formulated a theory to explain how the particles are formed in weaker suspensions. Davis and Gecol [42] discovered the prerequisite for particles classification of suspensions particle settlers.

By merging the sediments committee, Doroodchi et al. [43] clarified the kinematic demonstration of his peers, and derived a practical representation in the inclined channel. Furthermore, the creators expanded the hypothetical system to show the fluidization and isolation of double suspensions. In any event, earlier research focused on sedimentation rather than specific particle movement behavior, without any explanation of binary strong one to increase separation efficiency [15]. The single-particle elements were shown by Li et al. [44] to relate to a single particle direction in an inclined channel. The particle concentration without any connection to actual generation is disregarded by the particle sedimentation restriction models, which consider the normal volume division of the inclined channel. This model examines the mechanics of particle sedimentation on the inclined plate bed in both binary- and mono-dispersed suspensions.

When employing plate fluidized beds, such as Reflux Classifier, it is preferable to separate or categorize the particles according to physical features, such as size and density (RC). The mechanics of the parallel inclined plate in a fluidized bed has been thoroughly reviewed. The inclined settler provided a more productive settling area, in accordance with the so-called Boycott influence, as opposed to a fluidized bed with deep particle categorization like a traditional settler [45]. Particles settle at varying speeds due to their different settling velocities; hence diluted suspensions are categorized using an inclined settler [41, 42]. Friedle et al. [46] calculated the pressure drop over fluidized beds can be derived from the gravtational field using a drag model. Wang et al. [47] and Hou and Williams [48] simulated the dynamics of a fluidized bed composed of a liquid and solid layer. Different parameters, such as particle density, equipment parameters, fluidization speed, and solid particle size distribution were found to affect the simulated trajectories of solid particles and the bed stability. Galvin and Nguyentranlam created a kinematic model in accordance with the available effective area for particle separation within inclined channels. Their kinematic model establishes advantages within liquid fluidized beds by relating concentrations to the length of suspension settling [49]. Hatami and Domairry [50] analyzed a spherical particle in Newtonian fluid media to derive the motion equation. With high precision in modeling particle motions, the differential transformation technique (Ms-DTM) was created to solve equations of particle motion on parabolic surfaces [51]. Different fluidization approaches have been identified for enhancing the fluidization effect. Among them, a new fluidization arrangement was found to reduce the turbulence in the fluidization water and increase separation effectiveness [15].

It was evident that RC particles are separated regardless of their size when the dependence on particle densities is increased and strong shear rates are coupled through closely spaced channels [52]. Doroodchi et al. also put forth a theoretical model for binary particle suspensions based on the flux balances between the liquid and solid components of an inclined channel [43]. RC successfully deslimed fine coal in the size ranges of + 0.35 - 0.05 mm, according to a pilot plant testing [38]. Researchers discovered that RC was successful in separating relatively coarse particles up to 8 mm in size [37]. Zigrang and Sylvester [53] proposed the terminal settling speed of particles, and Richardson and Zaki [54] suggested that the illegal settling terminal speed can be calculated by their equation. RC can separate the mineral sands at a ratio of about 200 [55]. Pulsed flow was used to successfully fluidize the fluidized bed [56], and flow pulsation was employed to effectively de-fluidize cohesive particles [57] and increase the separation efficiency of different particles [58].

Qi et al. examined the characteristics of the critical motion of monodisperse particle suspensions by adjusting the solid particle inventories and fluidization velocities to synchronize accurate passage through the inclined channel [59]. The authors derived the following equation using the particle critical trajectory model of monodisperse particle suspensions in an inclined channel:

$$\frac{U_L}{U_0} = sin\ \theta(1-\Phi_s)^n \cdot \left(\frac{L \cdot cos\ \theta}{k} + sin\ \theta\right) \tag{1}$$

Particle terminal speeds, inclined surface volume fractions, equipment parameters, and fluidization velocities are some of the modelled parameters. Fine particles are transported over greater distances in the inclined channels when fluidization water is used, as illustrated in Figure 5.

The particle liquid-solid fluidized bed has been broadly connected for grouping and partitioning in the coal and mineral processing. Over a typical liquid-solid fluidized bed, a modified fluidized bed (mFB), a generally modern system, is prepared with parallel particle plants. A sizable amount of effort has been put forward to evaluate the effects of inclined channels on the division of fluidized beds. It has been demonstrated that mFB can successfully achieve a broad run of concentrated suspensions at a particular fluidization speed for the water inside the channel

[19]. To clarify the largest separation of mono-disperse particle suspension, Galvin constructed a kinematic hypothetical demonstration based on the theories of Nakamura and Kuroda [39, 40]. By envisioning sedimentation as a fictitious process, Doroodchi et al. [43] illustrated the unchanging state interplay between fluidization and isolation in an inclined channel based on the premise of previous research, and examined the standards of gravity partition for the mFB at full scale and the concealment of the particle impacts detected inside the sharply separated inclined channels [52]. Davis and Gecol [42] established the strong particle coherence condition under the assumption that particles are isolated on an inclined channel. Iverson [60] investigated the benefits of desliming energy using particles that ranged in size from 0.07 to 0.2 mm.

Li et al. [44] created a particulate sediment demonstration based on the free terminal settling speed and fluidization shallow speed for amazingly moo concentrations within the mFB. The link between n and the Reynolds number of the particles [61] has been the subject of much investigation. The isolation and genuine surrender advantage of an RC are predicted by a generalized equation. The study found that the perspective percentage asymptotically confined one of the water powered capabilities of inclined channels [23]. Li et al. [62] investigated the inclined channel execution in relation to fine cinder development appearances in a liquid-Solid fluidized bed. The mFB was used to divide mineral sands more effectively, with a significant angular proportion of 200 [55]. By adding thick glycerin to the holdups, it was discovered that the mFB was effective at desliming coal with an estimate range from 2.0 to 0.25 mm [63].

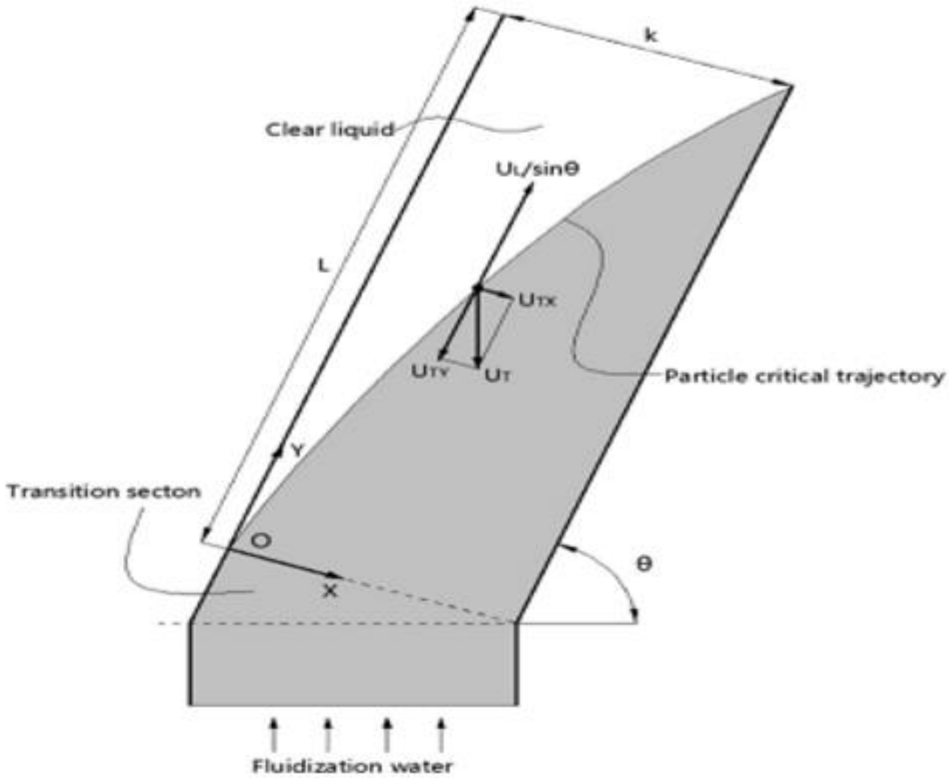


Figure 5. Particle trajectory in an inclined channel

5. Theoretical Methodology

The strong particles in the suspension have encountered a variety of complex forces, including gravitational, Magnus, drag, Saffman, and extra buoyancy. Two forces, namely, gravity and liquid shear, induced the lift force. In supply arrangement, a rather simple and accurate representation exhibits that, all fundamental strengths are taken into account by linking them to speed vectors, allowing us to analyze the movement features of particles according to their speed vectors.

The theoretical model has been simplified in the list that follows [64, 65]:

(1) Particle growth is not accompanied by fracture or distortion.

(2) Particles moving freely within the X and Y headings in the inclined channel.

(3) The fluid moves at a constant pace across the inclined channel.

The focused suspension permits a quick movement in the vertical channel from side to side and then into the inclined area at position ef. Particles are fluidized when they slide back to the vertical fluidized bed from the inclined channels where they were initially placed. The particles will reach the flow harbor once they have traveled along the inclined channel. Figure 6 and Figure 7 present a concise hypothetical framework for the investigation of molecular settlement. The hypothetical framework is operated by a device with a single vertical channel, a wand width that is easily interfaced to the width of k, a depth of z, and a tilt angle of θ.

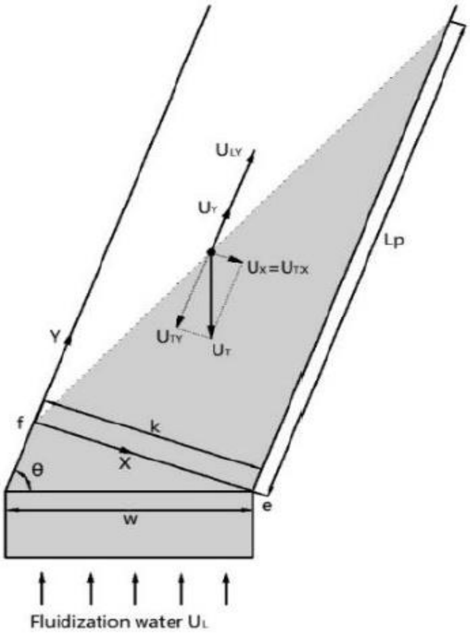


Figure 6. Mono-disperse of suspensions

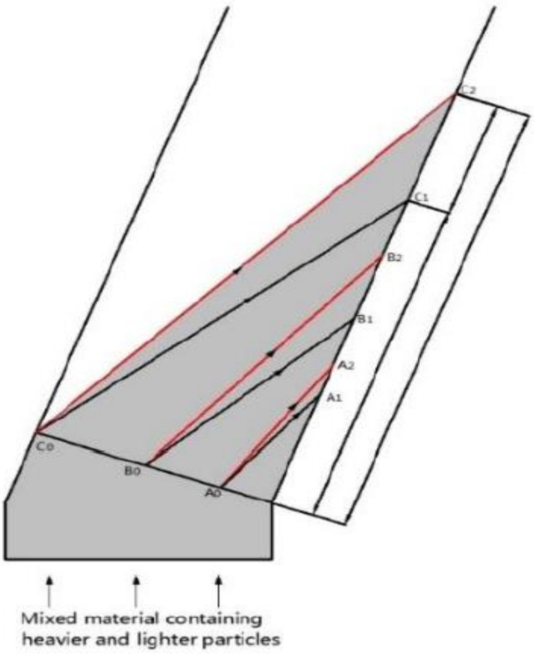


Figure 7. Bi-disperse suspensions

The movement of the particles within the inclined channel is examined, and settling is taken into consideration. In addition, the subscripts X and Y are taken into account. The subscripts X and Y stand for the conventional and digressive inclined channels with the conventional and divergent orientations, respectively. Following observational setup, Zaki described the relationship among monodisperse-condition to depict the relationship among particles, and Richardson created the following empirical equation [54]:

$$U_T = U_O(1 - \Phi_S)^n \tag{2}$$

where, U_0 is the free settling terminal speed; U_T is a measure of hindered settling by particle terminal velocity; Φ_S is the number of particles resulting from volume fraction; $(1-\Phi_S)^n$ is the hindering factor for settling; *n* is only the Reynolds number function (n~4.6 for particles with a low Reynolds value). Acrivos and Herbolzheimer [64] and Nir and Acrivos [66] measured the fluidization speed of the *n* channels. The superficial speed of fluidization is assumed to be uniform across the inclined channel. Within the channel, the fluidization superficial speed can be expressed as [43, 60]:

$$U_{LY} = U_L/sin\ \theta \tag{3}$$

During the settling of a highly concentrated suspension, particle–particle interactions are often examined by employing the empirical hindered settling function Eq. (2).

As a result, the X and Y velocities of the particles can be expressed respectively as follows:

$$U_{TX} = U_T \cdot cos\ \theta \tag{4}$$

$$U_{TY} = U_T \cdot sin\ \theta \tag{5}$$

Eq. (2) can be used to rewrite these velocities as:

$$U_X = U_{TX} = U_0(1-\Phi_S)^n \cdot cos\ \theta \tag{6}$$

$$U_Y = U_{LY} - U_{TY} = U_L/sin\ \theta - U_0(1-\Phi_S)^n \cdot sin\ \theta \tag{7}$$

Consider the case where particles enter the inclined channels at point f (*ef* = k). The particles travel a distance k along the X direction in the same amount of time as it travels a distance L_P along the Y direction relative to a vessel. Hence, the following equations can be derived [67]:

$$k/U_X = L_p/U_Y \tag{8}$$

$$k = w \cdot sin\ \theta \tag{9}$$

$$L_p = \frac{w}{cos\ \theta}\left(\frac{U_L}{U_0(1-\Phi_S)^n} - sin\ \theta^2\right) \tag{10}$$

$$L_p = \frac{w}{cos\ \theta}\left(\frac{a}{(1-\Phi_s)^n} - sin\ \theta^2\right) \tag{11}$$

If particles enter the inclined channel from the middle of line *ef*, there will be variation in the settling distance at position ef for a monodisperse suspension [67]:

$$0 \leq L_p \leq \frac{w}{cos\ \theta}\left(\frac{a}{(1-\Phi_S)^n} - sin\ \theta^2\right) \tag{12}$$

6. Heat Transfer in Fluidized Beds

The fluidized bed and well-warm exchange productivity in an isothermal environment with soaked objects provide significant advantages over conventional reactors. However, the accurate prediction of the warm exchange in a fluidized framework necessitates knowledge of a number of related connection variables, such as the fluidization vessel measurement, the liquid wholesaler's design, and the vessel internals [68, 69]. Heat exchange involves flooding vertical and horizontal tubes. Also, additional studies focusing on t how the fluidized bed's programs help the particle heat transfer surfaces [69-72] have produced contradictory results, as may be shown below.

According to Gelperin et al. [69], there was no calculable precise increase in the warm exchange coefficient with a change in the attach point, which is the region between the tube's midline and the direction of the wind current. The warm exchange coefficient had a minor tendency to lengthen the continuous transition to the vertical position. The largest warm exchange coefficient was taken into consideration for vertical tubes and was 5–6% higher. The coefficients looked to be 5-7% off from their warm exchange coefficient-speed band maximum in an uncorrelated manner.

The impact of inclination on the warm exchange features of finned and barred tube portions was also investigated by Genetti et al. [72]. When the tube was at a point of 45° to the vertical, the bed coefficient was proved valid through testing. Thus, coefficients were about to fall as the particle grew larger. A particle increased by 60% in the bed with a reduction of 32% from the value within the finned tube.

Baskakov et al. [71] assessed the temperature distribution in a warm exchange plate. The plate was warmed on one side and flooded at characteristic locations in a fluidized bed with a rectangular cross-section. They observed a considerable shift in the exchange coefficient's value, ranging from 200 W/m^2 c in the even position upstream to 450 W/m^2 c to a particle of 10 to the vertical. In the downstream position, the value decreased from 300 W/m^2 to 60 W/m^2.

Stojanovic et al. [73] explored how quickly fluidization affected the warm exchange between a rectangular fluidized bed and a cross-segment warm exchange tube. For all of the radiator particles, the warm exchange coefficients showed a comparative propensity to increase the fluidization speed. The exchange coefficient should be depicted at a particle point of 10-15; particle points beyond 60 have negligible effects on the warm exchange coefficient. In a study by Abid et al. [70], an immersion heat transfer tube was used to heat a fluidized bed of sand that was positioned at various inclinations to test the parameters of heat transfer, as shown in Figure 8. In the case of a heat transfer tube operating at an angle of inclination between 0 and 90, the average and maximum heat transfer coefficients were affected by the fluidizing velocity and particle size when taking into account particles with a diameter ranging from 150 to 350 m and a fluidizing velocity of 0.25 m/s. Over a variety of velocities and particle sizes, they investigated the average and maximum heat transfer coefficient. The experimental results show that, the angle of inclination close to the tube affected the bubble size and behavior, which decreased the coefficient of heat transfer for smaller particles. Heat transfer coefficients minimized at the inclination of 45° and increased with the growing inclination angle. The optimal angle was between 10 and 15° relative to the direction of the flow.

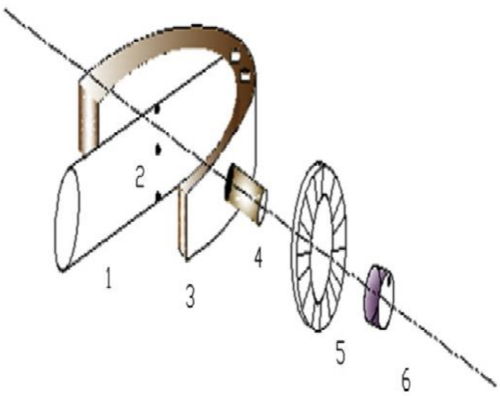


Figure 8. Inclination of the heater arrangement used by Abid et al. [70] (1) protractor disk; (2) metal shaft; (3) frame; (4) thermocouple junctions; (5) heater cylinder (6) pointer

7. CFD Analysis

Boycott effect has been proven to greatly increase the rate of particle sedimentation in an inclined channel [14]. Velocities and particle sizes have an impact on the average and maximum heat transfer coefficients of an inclined heat transfer tube [19]. Acrivos developed a number of theoretical physics studies [64, 74] and put out certain theories to gauge the relationship between particle sedimentation rate and effective sedimentation components. Many industrial processes, including water filtration [75] and wastewater treatment [76], use gravity settling to remove solid particles from liquid streams. The Boycott effect was used for particle classification in mineral processing in a liquid fluidized bed inclined plate classifier by Galvin et al. [16]. In comparison to the typical design, inclined plate liquid beds have operated at fluid speeds greater than the terminal speed of the particle, resulting in increased throughput. Particle sorting is made simpler using a reflux system, and the redesigned bed performs better at separation. Other researchers [16, 43, 77, 78] have attempted to thoroughly grasp the systems' overall functionality. In theoretical models [43, 78], lumped parameters are included to assess the system's hydrodynamic properties for suspension and sediment length. Liquid-solid two-phase flow has not yet been thoroughly studied at the particle scale. Experimental concentration approaches require relatively complex instrumentation and measuring techniques. The characteristics of a particle flow can be identified on a local scale using computational fluid dynamics (CFD). This numerical model has been adopted to emulate beds using both Eulerian-Lagrangian (E-L) and Eulerian-Eulerian (E-E) methods (E-E). The E-E technique is used when the solid and fluid phases are seen as interpenetrating continuum phases. The two approaches share the same governing equations. The predictions and experimental results of Doroodchi et al. [79] on inclined plates and solid suspensions were found to be in good accord.

Salem et al. [80] assessed the IPS hydraulic features involved a CFD simulation based on the E-E model. He discovered that CFD software is crucial to understanding the hydraulic performance of IPS. The solid phase treatment does not follow solid particles in altered beds with sloped channels, and the E-E technique does not reveal information at the particle level. Periodically, it is possible to learn more about each particle, such as its position, velocity, forces, and diffusivity. Peng et al. [81] examined the liquid-solid flow characteristics of a modified fluidized bed with inclined channels in great detail using a combined CFD-DEM model. The liquid-solid flow characteristics were carefully examined in a fluidized bed that had been modified to have inclined channels. The in-situ investigations by Doroodchi et al. [43] utilizing glass ballotini particles and water as the liquid phase exhibited the same physical characteristics as the simulation. As shown in Figure 9, the experimental bed size was reduced to give an appropriate turnaround time for simulations after each simulation in order to reduce calculation time. Figure 10 shows the various inclination angles of a fluidized modified bed. In this case, U_{sf} = 0.02 m/s. Figure 10 also provides a close-up view of solid flow vectors, where the flow vector is close to the joint position. When the inclination angle is changed, distinct differences in fluidization behavior are observed. With a greater sediment length, bed expansion height augments significantly as the inclination angle increases.

CFD was used by Ridha and Oleiwi [82] to analyze a fluidized bed in an inclined position. The initial water velocity, particle height, and degree of inclination were all modified. The volume fractions of the fluidization bed at 0.01 and 0.05 m/s speeds, with a 200°inclination and a 5 cm height, are shown in Figure 11. The bed height grew as water velocity increased within the 0.3m/s velocity range until reaching the peak at the water velocity of 0.01m/s. CFD was utilized to numerically validate the study results, and other experimental results were used to numerically validate the model. Their findings showed that solid particles in the pipe get more advanced as water velocity rises. Additionally, solid particles expanded less as the pipe's inclination increased.

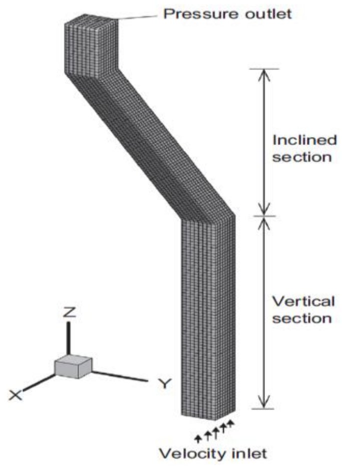


Figure 9. Modified fluidized bed domain, mesh, and boundary conditions utilized by Peng et al. [81]

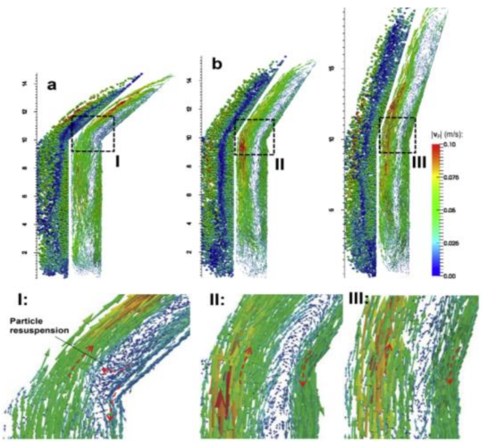
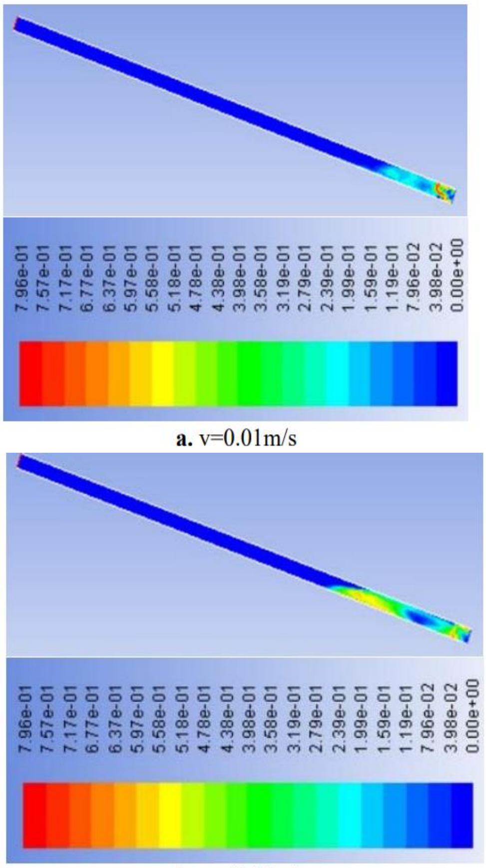


Figure 10. A solid distribution in an inclined fluidized bed with an inclination angle of 45, 60, and 75°, with fluidization velocity of U_{sf} = 0.02 m/s



a. v=0.01m/s

b. v=0.05m/s

Figure 11. Impact of the water superficial velocity on the solid volume fraction at 20° and 5 cm inclination by Ridha and Oleiwi [82]

The Eulerian approach deals with concentration of particles and calculates the overall dispersion and convection of a number of particles, whereas the Lagrangian approach works with individual particles and calculates the trajectory of each particle individually [83].

8. Conclusions

Based on theoretical advancements and historical developments, this paper offers a chronological summary of how liquid-solid fluidized beds have changed through time in inclined columns. In this article, the governing principles of the inclined fluidized bed are reviewed. The initial layer breaks up into a few subsidiary beds that generate a focal wave pattern during the liquefaction process in the inclined columns. Inclined tubes have the tendency to reduce instability concerns while increasing steel bed turnover [13].

In this work, the phrase "fluidized bed" refers to a vertical, inclined, or horizontal two-phase flow in which particles are trapped inside the system rather than being taken away with the fluid. Several improvements have been made in the interaction between affect factors and liquid-solid fluidization as well as in the design of equipment structure. Despite this, large-scale industrial applications for liquid-solid inclined fluidized beds are still far off. Liquid-solid inclined fluidized beds are being increasingly industrialized with the use of large-scale machinery. According to results of several industrial-scale experiments, this kind of equipment needs to have both its structural conditions and operating parameters optimized. However, there is not much fundamental theory on the subject. To control operation and improve fluidized bed conditions, it is crucial to analyze the technical parameters during equipment operation. An online data collecting system is urgently needed in this field. We anticipate that liquid-solid inclined fluidized beds will advance significantly across the board in the near future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Nomenclature

A	Volume fraction
B	Dimensionless heat source length
CP	Specific heat, J. kg^{-1}. K^{-1}
D	Diameter (m)
E	Rib height (m)
F	Force (N)
g	Gravitational acceleration, m.s^{-2}
k	Thermal conductivity, W.m^{-1}. K^{-1}
h	Heat transfer coefficient (w/m^2.K)
Nu	Local Nusselt number along the heat source
Pr	Prandtl number (μ Cp/k)
Re	Reynolds number (ρ u D/μ)
T	Temperature (K)
v	Velocity (m/s)
w	Duct width (m)
α	Thermal diffusivity, m^2. s^{-1}
β	Thermal expansion coefficient, K^{-1}
ϕ	Solid volume fraction
θ	Dimensionless temperature
μ	Dynamic viscosity, kg. m^{-1}. s^{-1}