A Study on the Hydrodynamic Behavior of a Slot-Rectangular Spouted Bed using CFD

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A Study on the Hydrodynamic Behavior of a Slot-Rectangular Spouted Bed using CFD

by

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A THESIS
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ABSTRACT

Spouted beds are widely used as gas-solid contactors in various physical and chemical processes. In order to improve the design of spouted beds for efficient gas-solid contact, a better understanding of the complex flow field of granular solids is required. The recognition of flow regimes is also very important in the application of spouted beds.

In this thesis, numerical modeling using FLUENT 6.3 commercial software was utilized to study the flow in a slot-rectangular spouted bed. Two-phase gas-solid flows in the bed were simulated with the computational fluid dynamics (CFD) technique using the two-phase Eulerian-Eulerian granular model. Two-dimensional computer simulations were performed to investigate the effects of physical parameters on the hydrodynamic behavior of slot-rectangular spouted beds. The fountain height and pressure drop were evaluated for various superficial gas velocities, bed heights, and solid particle sizes. The numerical results of the fountain height were in good agreement with the experimental data reported elsewhere.

The numerical simulations were applied to predict different flow regimes and construct flow regime maps. The constructed flow regime map for a bed containing solid particles with a diameter of 1.44 mm was in good agreement with an experimental map previously reported elsewhere. With this successful numerical mapping, a flow regime map for particles with a diameter of 3.77 mm was constructed for various superficial gas velocities and static bed heights. The map was composed of six distinct flow patterns, i.e., fixed bed, internal jet, jet-in-fluidized-bed, spouting, incoherent spouting, and slugging. The slugging flow regime occurred at large values for the static bed height and air inlet velocity, while the spouting regime arose by increasing the air inlet velocity at low values of static bed height. Unlike the spouting regime, large pressure drop fluctuations were observed in the incoherent spouting regime.

Keywords: Spouted bed, slot-rectangular, flow regime, multiphase, two-dimensional, Hydrodynamics, CFD.
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DEDICATION

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

Latin Letters

\( C_D \) Drag coefficient, dimensionless
\( d_s \) Diameter of solid particle, m
\( e \) Restitution coefficient of solid phase, dimensionless
\( \ddot{g} \) Gravitational acceleration, m/s\(^2\)
\( g_0 \) General radial distribution function, dimensionless
\( H_b \) Static bed height, m
\( \bar{I} \) Unit tensor
\( K_{sg} \) Gas-solid momentum exchange coefficient, kg/(s.m\(^3\))
\( k_{\theta_s} \) Conductivity of granular temperature, kg/(m.s)
\( P \) Pressure, Pa
\( P_s \) Solid pressure, Pa
\( \Delta P \) Pressure drop, Pa
\( \nabla, q_s \) Diffusive flux of fluctuating energy, kg/(s\(^3\).m)
\( Re \) Reynolds number, dimensionless
\( T \) Time, s
\( \Delta t \) Time interval, s
\( U \) Superficial gas velocity, m/s
\( \vec{v} \) Velocity vector, m/s

Greek letters

\( \alpha \) Width of the column at the upper section, m
\( \beta \) Angel of internal friction, °
\( \gamma \) Width of the column at the lower section, m
\( \gamma_{\theta_s} \) Dissipation of granular temperature, kg/(m.s\(^3\))
\( \delta \) Height of the column, m
\( \nabla \) Del operator
\( \varepsilon \) Volume fraction, dimensionless
\( \varepsilon_{s, max} \) Maximum solid packing, dimensionless

\( \eta \) Bulk viscosity, kg/(m.s)

\( \theta \) Internal angle of the lower section, degree

\( \theta_s \) Granular temperature, m\(^2\)/s\(^2\)

\( \lambda \) Air entry slot width, m

\( \mu \) Viscosity, kg/(m.s)

\( \rho \) Density, kg/m\(^3\)

\( \tau_w \) Wall tension, Pa

\( \tau \) Stress-strain tensor, Pa

**Subscripts**

\( g \) Gas

\( ms \) Minimum spouting

\( s \) Solid

**Abbreviations**

2D Two dimensional

3D Three dimensional

CFD Computational Fluid Dynamics

FB Fixed bed flow

IJ Internal jet flow

IS Incoherent spouting flow

JF Jet-in-fluidized-bed flow

PC-SIMPLE Phase-Coupled Semi Implicit Method for Pressure Linked Equations

S Spouting flow

SL Slugging flow

T Transitional flow
CHAPTER 1 : INTRODUCTION

This chapter presents a brief introduction to spouted beds and computational fluid dynamics (CFD) as a numerical tool for simulating the hydrodynamic behavior of spouted beds.

1.1. The Spouted Bed

If we consider a column with an open top outlet and filled with coarse granular solid particles, the fluid is injected through an orifice located at the center of the bottom of the column. If the fluid injection velocity is large enough, a high-velocity jet forms and causes a particle stream rising quickly in a central core within the solid bed. These solid particles move downward into the region between the wall and the hollowed core, where the particles move slowly downward and somewhat inward. When the fluid goes upward, it spreads out into the annular field. In that condition, the bed is composed of a dilute phase core at the center with solid particles moving upward entrained by a co-current fluid flow and a counter-current percolation of dense phase fluid at annular region.

This system is called a spouted bed. A conventional spouted bed consists of a cylindrical column and a conical base (in order to remove dead spaces at the bottom of the column) with a circular orifice at the center of the conical base (Figure 1.1-a). A completely conical vessel is also widely used, as is shown in Figure 1.1-b. The bed of solid particles is spouted by the injection of a high velocity fluid through the orifice.

A spouted bed is typically formed of three distinct regions as shown in Figure 1.2: (1) a central spout with upward gas-solid flow, (2) an annulus region of downward granular flow, and (3) a fountain above the bed surface [1]. The volume fraction of solid particles varies from low values in the spout region to large values in the annulus, where the particles fall vertically downward and radially inward, leading to a complex recirculation pattern.
Figure 1.1 (a) A conical-cylindrical spouted bed; (b) Spouting in a conical vessel [2]

Figure 1.2 Schematic of a spouted bed operating in stable condition
Conventional cylindrical-conical spouted beds suffer from difficulties with scale-up [3]. A rectangular cross-sectional spouted bed was suggested to overcome these limitations [4,5,6]; however, significant three-dimensional effects were then found as the column thickness increased [7,8]. The idea of a “slot-rectangular” spouted bed was conceived, focusing on the use of a rectangular cross-sectional column with a large column width to thickness ratio and featuring two vertical parallel plates. Therefore, the term “slot-rectangular” is preferred for these types of spouted beds. It has been suggested that scale-up of such columns can be easily achieved by increasing the thickness [5]. However, three-dimensional instabilities have been shown as an issue for scale-up [9,10].

The fluids in spouting applications are more likely to be gases than liquids. In spite of the fact that the spouted bed was first developed as a replacement for a fluidized bed for coarse solid particles with uniform size to overcome the problem of poor quality of gas fluidization acquired with such type of particles, some of its special characteristics, such as the periodic recirculation of the particles, have proven to be of great worth, making the spouted beds competent of executing particular practical operations more efficiently than fluidized beds (resulting in more random particle motions).

1.2. Brief History

The spouted bed was originally developed in 1954 as an alternative to an extremely slugging fluidized bed for the drying of moist wheat particles [11]. Due to strong particle circulations, much hotter gas could thus be employed without harming the grain in comparison with conventional wheat driers [12].

The first spouted beds with commercial purposes for drying of peas, flax, and lentils were installed in 1962. From that day forward, many spouted bed units have been constructed for different sort of drying duties, such as cooling, coating, granulation, solids blending, evaporative drying of suspensions, solutions and pastes.

1.3. Flow Regime Maps for Spouted Beds

Spouting can be visually observable in a column with transparent walls. This phenomenon occurs over a specific range of inlet gas velocity for various combinations of
gas, solid particles, bed geometry, and configuration. The regime transitions from a stationary bed to spouting, and then often to bubbling and slugging, as the gas velocity is increased, as demonstrated schematically in Figure 1.3.

![Figure 1.3 Regime transitions in the conventional spouted bed; a) static bed (fixed/packed bed), b) spouting, c) bubbling, d) slugging](image)

Based on the entering air flow rate, different flow regimes can be distinguished in a slot-rectangular spouted bed as shown schematically in Figure 1.4. For very low air flow rates, the flow stays at a fixed bed regime. In the internal jet regime, a submerged cavity or jet is formed at the air inlet. The jet-in-fluidized-bed regime is occurred when bubbles separate from the internal jet and there was a fluidization in the upper part of the bed. With the increase in the air flow rate, the internal jet is grown and the solid would spout. This spout is stable and non-pulsating, while the fountain above the bed surface in the incoherent spouting regime has a pulsating variable height.

The transition regime has mixed characteristics of the jet-in-fluidized-bed and incoherent spouting flow regimes. In the slugging regime, slugs originate at the top of the submerged jets, causing the top surface to rise and fall. The detailed descriptions of these flow regimes are presented elsewhere by Dogan et al. [7] and Freitas et al. [8].
Figure 1.4 Schematic representations of different flow regimes for a slot-rectangular spouted bed: a) fixed bed, b) internal jet, c) jet-in-fluidized-bed, d) spouting, e) Dilute-Phase Spouting, f) slugging, g) incoherent spouting [7]

Figures 1.5 and 1.6 show quantitative representations of transitions or regime maps for a conventional cylindrical spouted bed and a slot-rectangular spouted bed, respectively, as plots of static bed height against superficial air velocity. The reported regime maps for conventional cylindrical spouted beds in the literature display significant differences, partly because of differences in terminology [13] and partly because there is no possibility of viewing the spout in full columns. For slot-rectangular spouted beds with small width to thickness ratios, the flow regimes are easily observable through the plane transparent walls.

Figure 1.5 Flow regime map for a conventional cylindrical spouted bed for air entry slot width of $\lambda=12.5$ mm and wheat particles (prolate spheroids: $3.2$ mm $\times$ $6.4$ mm) [14]
Figure 1.6 The regime maps for a slot-rectangular spouted bed obtained by experimentation reported by Dogan et al. [7] for air entry slot width of $\lambda=6$ mm and solid particle size of $d_s=1.44$ mm. FB is fixed bed flow, IJ is internal jet flow, JF is jet-in-fluidized-bed flow, SL is slugging flow, IS is incoherent spouting flow, and T is transitional flow.

1.4. Advantages and Disadvantages of Spouting for Industrial Operations

Some of advantages and disadvantages of spouted beds are summarized as follows:

**Advantages:**
1. The fluid-like and smooth flow of solid particles enables continuous control of operations in an automatic manner.
2. The quick mixing of particles leads to almost isothermal conditions throughout the bed; therefore, the control of operation can be simple and reliable.
3. The circulation of particles makes it possible to transport the large quantities of heat produced or needed in large beds.
4. It is suited for large-scale operations.
5. The rates of heat and mass transfers between the gas and solids are high in comparison with other methods of contact.
6. The heat transfer coefficient between a spouted bed and an immersed object is large; therefore, heat exchangers within spouted beds require comparatively small heat transfer areas.

Disadvantages
1. The hard-to-describe gas flows represent an inefficient contacting method.
2. The quick mixing of particles in the spouted bed leads to varying residence times of particles. For continuous applications, this problem leads to a non-uniform product. On the other hand, this method of mixing is useful for the batch treatment of particles, because it yields to a uniform product.
3. Erosion of pipelines from the abrasion by solid particles can be critical and requires much consideration.

1.5. Industrial Application of Spouted Beds

Spouted beds are used as gas-solid contactors to provide efficient mixing and large gas-solid contact areas for coarse granular materials. A simple example of the application of spouted beds is the popcorn popper. The amount of burnt popcorn will be minimized throughout the chamber due to the uniform temperature distribution of popcorn kernels. Spouted beds have been commonly employed in different industrial applications. They have been successfully applied to various physical and chemical processes in drying [15,16,17,18], granulation [19,20,21], coating [22,23,24], gasification [25,26], combustion [27,28], chemical vapor deposition [29,30], pyrolysis of different wastes such as tires [31], biomass [32] and plastics [33,34], etc.

Slot-rectangular spouted beds can be utilized in similar applications as those proposed for conventional spouted beds. However, investigations on the application of slot-rectangular spouted beds have been mainly limited to the coating of particles [35,36].

1.6. Computational Fluid Dynamics Technique

The detailed information of hydrodynamic behavior of the spouted bed is essential in commercial-scale design. Considering the advances in computer simulations, numerical simulation techniques have become a powerful and popular tool for acquiring detailed...
information about the gas-solid two-phase flow without influencing it [37]. Computational fluid dynamics (CFD) is the most common numerical technique to simulate multiphase flows. The use of CFD simulations for spouted beds significantly reduces the need for experimentation by providing information on the flow pattern, scale-up and optimization for process design.

Two approaches are commonly used for CFD simulation of gas–solid flows in spouted beds. The first approach is Lagrangian-Eulerian modeling, which solves individual equations of motion for each solid particle and employs a continuous interpenetrating model in an Eulerian framework for modeling the gas phase. In huge systems of solid particles, the Lagrangian-Eulerian approach needs powerful computers due to the large numbers of equations to be solved. The second modeling method is the Eulerian-Eulerian approach, which supposes that both phases as fluid and takes the fully interpenetrating effect of the phases into consideration by using interfacial drag forces.
CHAPTER 2: LITERATURE REVIEW

In this chapter, a review on the literature about the experimental and numerical works on spouted beds has been done. Then, the main objectives of this thesis have been summarized.

2.1. Literature Review

One of the advantages of slot-rectangular spouted beds is the capability of achieving different flow regimes with small variations in the air velocity or the orifice width of the air inlet. Some experimental studies on the hydrodynamics, stability, scale-up, and flow regimes of slot-rectangular spouted beds have been reported [5,7,9,38,39,40,41,42].

Chen et al. [10] investigated on the local flow structure in a slot-rectangular spouted bed with slots of equal area but different length-to-width ratios. Dead-zones, spout shapes, and distributions of pressure, particle velocity, and voidage were explored. For a slot entrance, the spout shape evolved to approach circular with increasing height, with local flow properties seeming to “forget” the shape of the slot towards the bed surface. As a result, the local flow structure of slot-rectangular spouted beds showed considerable similarity to the flow pattern of conventional axisymmetric spouted beds. Another consequence was that the effect of slot geometry was small in the upper part of the bed. Spouts from slots of equal area, but different length-to-width ratios approached similarity in spout shape, local pressure, and local particle velocities with increasing height. Local flow properties showed little dependence on the static bed height. For different static bed heights, the flow properties, including the spout size and particle velocity, were nearly the same at a specified level.

Freitas et al. [40] determined detailed local bed voidage profiles using optical fibre probes in a slot-rectangular spouted bed. The spout width was determined from the standard deviations of the voidage fluctuations. Voidage profiles in the spout and annulus were similar to those for conventional and conical spouted beds. Both spout and annulus voidages increased with increasing air flow rate. Annulus voidages decreased with
increasing height, approaching the loose-packed value at the top of the bed. The annulus and spout voidages were sensitive to geometric and operating conditions, such as the air entry slot width and particle diameter. The average voidages in the spout remained nearly constant along the bed height. They reported that significant three-dimensional effects in bed structure developed with increasing height, even for a thin column. Increasing the column thickness made the three-dimensional effects more pronounced, indicating that scaling up this geometry by enlarging the distance between the parallel walls leads to complex hydrodynamics and changes in flow behaviour.

Chen et al. [41] carried out some experiments to determine the flow stability of slot-rectangular spouted beds with slots of different widths, lengths, and depths. The effects of slot expansion angle and diverging base were also investigated. Dependent variables included the minimum spouting velocity, bed pressure drop and standard deviation of pressure fluctuations. Based on the flow regimes and spout termination mechanisms, instability was found to be mainly due to the interaction of multiple spouts. Criteria were identified relating stable spouting to slot dimensions and particle size. They concluded that slots of limited cross-sectional area could provide sustainable and symmetric spouting with little fluctuation, as long as the slot length-to-width ratio and depth are within certain limits, related to those for conventional spouted beds.

Luo et al. [42] conducted an experimental investigation of slot-rectangular spouted beds with air entry slots spanning the full thickness of the column and vertical draft plates intended to help control the solids circulation rate. They showed that with increasing superficial gas velocity, the flow between the draft plates changed from bubbling to slugging and then to spouting with dilute pneumatic between the plates and moving-bed downward motion on both sides. However, there was difficulty maintaining stability and symmetrical flow on the two sides. Once spouting was established, pressure drops and local voidages varied with gas velocity, particle size and gas entry size in broadly similar manners as for conventional spouted beds.

The regimes and stability of flow for a slot-rectangular spouted bed have been obtained experimentally for different slot widths and width-to-thickness ratios (Dogan et al. [7], Freitas et al. [8]). Dogan et al. [7] carried out their experiments with three sizes of
glass beads and with 3.77mm polyethylene particles in a slot-rectangular column of width 150 mm and thickness 29 mm. Changing from a cylindrical geometry to a rectangular geometry with a small thickness-to-width ratio caused significant changes in the quantitative behavior of spouted beds, while most phenomena were qualitatively similar. Their reported detailed regime maps have contained eight identified flow regimes, including two types of spouting regimes. Incoherent spouting tended to occur at high gas velocities and intermediate bed depths due to the growth of instabilities. Maximum bed depths were consistently higher than predicted based on previous work of Passos et al. [6]. Minimum spouting velocities tended to follow expected trends, but values corresponding to the maximum spoutable bed depth were higher than expected when data were included for the incoherent spouting flow regime. Trends for the maximum pressure drop and fountain height tended to be similar to those for cylindrical columns.

Freitas et al. [8] reported that as the thickness of slot-rectangular spouted beds is increased, significant changes occurred in the hydrodynamics. In particular, rather than forming a two-dimensional spout with no variations normal to the front face, it is possible for separate spouts to form, one behind the other, and these may or may not merge within the bed. This leads to more complex flow regimes as the column thickness increases. In addition, varying the column thickness influenced other key hydrodynamic properties of slot-rectangular spouted beds. In particular, an increase in column width to thickness ratio caused an increase in the maximum spoutable bed height, and an increase in the minimum spouting velocity. Also an increase in column width to thickness ratio caused a strong increase in the ratio of maximum value of minimum spouting velocity to minimum fluidization velocity. This observation is of major importance, since it showed that spouting of solids in columns of large column width to thickness ratio ratios requires higher air flow rates than conventional cylindrical beds. This means that slot-rectangular spouted beds with large column width to thickness ratios are unlikely to be suitable as an alternative to conventional cylindrical spouted beds.

Flow regime maps for half slot-rectangular spouted beds with different widths of air entrance and basal angles for 4 mm polyethylene particles were reported by Dogan et al. [9]. The effects of slot width and basal angle of the column were investigated. Flow
regime maps were drawn based on visual observation. The authors reported five different flow regimes consisting of fixed bed, internal jet, jet-in-fluidized-bed, spouting, and slugging. Passage from fixed to spouted bed conditions occurred via two stages, identified as an internal jet regime and jet-in-fluidized-bed regime. Also, correlations for maximum spoutable bed height, minimum spouting velocity, and pressure drop were provided. When a slot entrance was used, it is possible to achieve higher bed heights and to reach spouting at lower gas flow rates than in conventional cylindrical spouted beds with circular entrance nozzles. Maximum pressure drops were found experimentally to be one-third higher than required to support the bed weight.

Practically, the visual observation on the flow behavior inside the bed is not possible in industrial equipment. Hence, Freitas et al. [39] analyzed absolute pressure fluctuations in a slot-rectangular spouted bed to investigate their applicability for flow regime identification without visual observation. Their results suggested that measured pressure fluctuations can be applied to recognize flow regime transitions in spouted beds.

Different flow regimes identified visually in a spouted bed rectangular column of varying thickness and slot width correspond to distinctive pressure fluctuation signals. These signals had been characterized either in terms of statistical measures, such as probability density functions, skewness, cycle frequency, or power spectral density, or in terms of chaotic measures, such as the correlation dimension or Hurst coefficient. The distinctive features could, in most cases, be ascribed to such physical features as jet pulsation and periodic stripping of particles from the spout-annulus interface. While the precise boundaries of the flow regimes would no doubt vary with dimensions and geometry of the systems and the properties of the particles and gas, these statistical and chaos techniques appeared to provide a means of characterizing flow regimes and changes in hydrodynamics in spouted bed systems in cases where opaque walls make it impossible to visualize the flow.

The aforementioned identifications of flow regimes reported in the literature were based on experimental observations. No previous work has been reported in which the preparation of flow regime maps of slot-rectangular spouted beds have been performed using computational fluid dynamics (CFD) simulations.
The use of CFD simulations for spouted beds significantly reduces the need for experimentation by providing information on the flow pattern, scale-up and optimization for process design. Hosseini et al. [43] applied an Eulerian-Eulerian two-fluid model for the study of the hydrodynamics of a two-dimensional conical spouted bed. They studied the sensitivity of the solution to the variation of physical and modeling parameters, including the restitution coefficient, drag function, and frictional stress models. They proved that a careful selection of the drag function and restitution coefficient is a requirement for the optimization of the model predictions.

Duarte et al. [44,45] numerically simulated the pattern of solid and gas flows in spouted beds using an Eulerian multiphase model. They also compared the results with experimental data. Szafran and Kmiec [46] applied the Eulerian-Eulerian multi-fluid modeling approach to predict gas-solid flow behavior during the drying of grain in a spouted bed dryer with a draft tube. They also studied the periodic fluctuations of bed flow in draft-tube spouted beds for two different column geometries [47]. Their simulation results explained that the fluctuations of the bed flow in draft-tube spouted beds were a result of particle cluster formation in the loading region at the bottom of the column.

Zhonghua and Mujumdar [48] developed a heat and mass transfer CFD model to study the drying characteristics of particulate solids in axisymmetric spouted beds. Their calculated particle velocities and concentrations were in agreement with previous experimentations reported by He et al. [2]. They also studied the gas-particle flow behavior in a cylindrical spouted bed and a three-dimensional spout-fluid bed using the Eulerian-Eulerian two-fluid modeling approach [49].

Du et al. [50] assessed the influences of incorporating several drag models into the two-fluid model on the CFD simulation of spouted beds. Their results of hydrodynamic properties were compared with the experimental results reported by He et al. [2]. Their investigation showed that drag models have critical effects on the CFD predictions in spouted beds.

Scientific literature related to numerical simulations of slot-rectangular spouted beds is scarce. Zhao et al. [51] investigated the dynamics of granular particles in a two-dimensional spouted bed with draft plates by employing both particle image velocimetry
(PIV) measurement and discrete element method (DEM) simulation. Their PIV results indicate that, in the spout, the entrainment height had little effect on the particle vertical velocity, although it did exert a great effect on the solid circulation rate of the particles. In the annulus, the flow streamlines of the particles in a common two-dimensional spouted bed were nearly parallel to the conical wall. The addition of draft plates changed the streamlines steeper, especially for those adjacent to the draft plate. Also, the velocity magnitude along the particle streamline in a two-dimensional spouted bed with draft plates became flatter than that in a two-dimensional spouted bed without draft plates.

The effect of draft plates on the solid residence time in the annulus was also evaluated. Their DEM simulation showed that, within a two-dimensional spouted bed with draft plates, the particles flow upwardly individually, not as the particle clusters that are found in a common two-dimensional spouted bed. Their simulations provided a good prediction of the longitudinal profile of the particle vertical velocity along the bed centerline, especially during the rapid acceleration stage at the lower part of the spout. Also, the distributions of the drag forces and net forces were discussed to further explain the mechanism relating to the experimental profiles of particle velocities.

Zhao et al. [52] performed DEM simulation together with a low Reynolds number k-ε turbulence model for the fluid phase, in order to study the periodic spouting of granular solids in a two-dimensional spouted bed. The simulation results corresponded precisely with the data of PIV experiments, including fluid flow fields, time-averaged particle velocity distributions, and spout shape. The simulations yielded the predictions of an unstable spout regime, characterized as a periodic upward-moving particle jet. The imaging experiments indicated that two-dimensional spouted bed has an incoherent spout characterized as a periodic upward moving neck, within which particles move upward as a group. The comparison of whole particle flow fields between the experiments and simulations revealed that the fluid turbulence plays an important role in the DEM simulation.

The low Reynolds number k–ε turbulence model can correct the description of core jet in the spout, yielding an improved prediction of spout shape and particle flow patterns. The simulated particle velocity profiles by DEM were further validated by the PIV
experiments. The particles exhibited greatest drag and acceleration magnitudes near the spout entrance, and the drag forces continuously decreased as particles progress upward in the spout. The simulation indicated that about 80% of the gas flow traveled through the spout, and the rest flowed through the annulus. The peak of the turbulence was in the interface between the spout and the annulus due to the high velocity gradient within this region.

2.2. Objectives

A better understanding of the complex flow field of granular solids in spouted beds is required to obtain optimal mixing for their design improvement. In the present research, a two-dimensional CFD modeling has been performed to investigate the hydrodynamic behavior of gas-solid two-phase flows in a slot-rectangular spouted bed. The main objectives of this research can be digested in the followings:

1. At first, sensitivity analyses were performed on the grid and time interval sizes to obtain optimum mesh and time step sizes with the objective of time efficiency and accuracy.

2. Then, validation of the model was accomplished by comparing the numerical results on the fountain height with experimental data from Dogan et al. [7] for solid particles with a diameter of 1.44 mm for various superficial gas velocities.

3. The effects of operating conditions of the system (i.e. different superficial gas velocities, air entry slot width, static bed heights, and size of solid particles) on the hydrodynamic behavior of the slot-rectangular spouted beds were studied. The results are presented in terms of contours of the solid volume fraction, solid stream function, pressure drop fluctuations, and fountain heights for various superficial gas velocities, bed heights, and solid particle sizes.

4. The prognosis of spout quality, variation in spout stability and possibility of spout termination is essential in the performance of spouted beds. Thus, it is important to be able to predict the spout changes during operations. No previous work has been reported in which the preparation of flow regime maps of slot-rectangular spouted beds have been performed using computational fluid dynamics (CFD) simulations. Here,
CFD simulation was applied to provide diagnostics of flow regime transitions in a slot rectangular spouted bed when viewing is not possible. The flow regimes and hydrodynamic behavior of the slot-rectangular spouted bed were studied for different superficial gas velocities and bed heights. Visual observation of the contours of the solid volume fraction was used to identify the different flow regimes. The regime maps were prepared based on various superficial gas velocities and bed heights for two different solid particle sizes.
CHAPTER 3: HYDRODYNAMIC MODEL AND GOVERNING EQUATIONS

In this study, the Eulerian-Eulerian two-fluid model, which treats the gas and solid phases as fully interpenetrating continua, was used to simulate the hydrodynamics of a 2D spouted bed. The Eulerian-Eulerian model solves the momentum and continuity equations for each phase and also the granular temperature equation for the solid phase. These equations are linked through the pressure and drag forces.

The sum of the volume fractions of all contributing phases is equal to one. The balance in the volume fraction is:

\[ \sum_{q=s,g} \varepsilon_q = 1, \]  

where \( s \) and \( g \) denote the solid and gas phases, respectively.

The continuity equation for phase \( q \) is as follows:

\[ \frac{\partial}{\partial t} (\varepsilon_q \rho_q) + \nabla \cdot (\varepsilon_q \rho_q \vec{V}_q) = 0, \]  

in which \( q \) uses both \( s \) and \( g \) indices to conserve the mass in the solid and gas phases. In Eq. (2), \( \varepsilon_q, \rho_q, \) and \( \vec{V}_q \) are the volume fraction, the density and the velocity vector, respectively for phase \( q \).

The conservation of momentum in the solid and gas phases are given in Eqs. (3a) and (3b), respectively:

\[ \frac{\partial}{\partial t} (\varepsilon_g \rho_g \vec{V}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{V}_g \vec{V}_g) = \nabla \cdot \vec{P}_g - \varepsilon_g \nabla P + \varepsilon_g \rho_g \vec{g} + K_{sg} (\vec{V}_s - \vec{V}_g), \]  

\[ \frac{\partial}{\partial t} (\varepsilon_s \rho_s \vec{V}_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{V}_s \vec{V}_s) = \nabla \cdot \vec{P}_s - \varepsilon_s \nabla P + \varepsilon_s \rho_s \vec{g} + K_{sg} (\vec{V}_s - \vec{V}_g). \]

where \( \nabla P \) is the pressure gradient, \( g \) is the gravitational acceleration and \( K_{sg} \) is the gas-solid momentum exchange coefficient. The solid pressure \( (P_s) \) is comprised of a term due to collisions between particles and a kinetic term. The solid pressure will be computed separately in regions where the solid volume fraction \( (\varepsilon_s) \) is lower than the maximum allowed solid volume fraction \( (\varepsilon_{s,max}) \).

The equations for the stress tensor are governed by Eqs. (4)-(9):

\[ \bar{\tau}_{geff} = \varepsilon_g (\bar{\tau}_g + \bar{\tau}_t), \]  

(4)
The granular viscosity is described by Eq. (8),

\[ \tau_g = \mu_g \left( \nabla \vec{V}_g + (\nabla \vec{V}_g)^T \right) - \frac{2}{3} \mu_g \vec{I} \cdot \nabla \vec{V}_g, \]  

(5)

\[ \tau_t = \mu_t \left( \nabla \vec{V}_g + (\nabla \vec{V}_g)^T \right) - \frac{2}{3} \mu_t \vec{I} \cdot \nabla \vec{V}_g - \frac{2}{3} \varepsilon \rho_g k \vec{I}, \]  

(6)

\[ \tau_s = \varepsilon_s \mu_s \left( \nabla \vec{V}_s + (\nabla \vec{V}_s)^T \right) + \varepsilon_s \left( \eta_s + \frac{2}{3} \mu_s \right) \nabla \vec{V}_s \cdot \vec{I}, \]  

(7)

The granular viscosity is described by Eq. (8),

\[ \mu_s = \frac{4}{5} \varepsilon_s^2 \rho_s d_s g_0 (1 + e) \sqrt{\frac{\theta}{\pi}} + \frac{5\sqrt{\pi}}{48} \rho_s d_s \sqrt{\theta} \left[ 1 + \frac{4}{5} g_0 \varepsilon_s (1 + e) \right]^2. \]  

(8)

The granular viscosity is a summation of three contributions, the collisional viscosity, kinetic viscosity and frictional viscosity. The collisional viscosity is due to collisions between particles. The effect of the friction between particles to the total shear viscosity is described by the frictional viscosity. The dominant part of the granular viscosity changes in different flow regimes.

The resistance of the granular particles to compression/expansion is described by the granular bulk viscosity. The model developed from the kinetic theory of granular flow is expressed as

\[ \eta_s = \frac{4}{3} \varepsilon_s^2 \rho_s d_s g_0 (1 + e) \sqrt{\frac{\theta}{\pi}}. \]  

(9)

The granular temperature describes the increase in the internal energy due to the collisions and random motion in the solid phase. The granular temperature is described by Eqs. (10)-(14).

\[ \frac{3}{2} \left[ \frac{\partial}{\partial t} (\varepsilon_s \rho_s \Theta_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{V}_s \Theta_s) \right] = \vec{\tau}_s \cdot \nabla \vec{V}_s - \nabla \cdot q_s - \gamma_{\theta_s} - 3K_{\theta_s} \Theta_s, \]  

(10)

The four terms in the right hand side of Eq. (10) are as solid phase stress, flux of fluctuating energy, collisional energy dissipation, and exchange term with phase g, respectively.

\[ q_s = k_{\theta_s} \nabla \Theta_s, \]  

(11)

where \( k_{\theta_s} \) is the granular conductivity of granular temperature. It describes the diffusive flux of granular temperature/energy. The Gidaspow model which is based on the kinetic gas theory has been used for the granular conductivity, as specified by Eq. (12),
where \( \gamma_{\theta_s} \) is the collisional energy dissipation.

\[
\gamma_{\theta_s} = \frac{12(1-e^2)g_0}{d_s \sqrt{\pi}} \rho_s \varepsilon_s^2 \sqrt{\theta_s^2}.
\]  

(13)

In Eq. (13), it can be checked that when the restitution coefficient \( e \) is equal to 1, the dissipation of the granular temperature vanishes (perfectly elastic particles). The probability of particles collisions is modified by the radial distribution function, \( g_0 \), as specified by Eq. (14),

\[
g_0 = \frac{3}{5} \left[ 1 - \left( \frac{\varepsilon_s}{\varepsilon_{s,\text{max}}} \right)^{1/3} \right]^{-1}.
\]  

(14)

The drag force acting on a particle can be expressed as \( F_{\text{drag}} = K_{sg} (\bar{V}_s - \bar{V}_g) \). The interphase momentum exchange is computed using Eqs. (15)-(20). The Di Felice drag model is expressed as

\[
K_{sg} = \frac{3}{4} C_D \frac{\varepsilon_s \rho_g}{d_s} |\bar{V}_s - \bar{V}_g| f(\varepsilon_s),
\]  

(15)

where the function \( f(\varepsilon_s) \) is defined as

\[
f(\varepsilon_s) = (1 - \varepsilon_s)^{-x},
\]  

(16)

and the empirical parameter \( x \) as a function of \( Re_s \) is defined as

\[
x = P - Q \exp[-(1.5 - \beta)^2/2],
\]  

(17)

\[
\beta = \log(Re_s).
\]  

(18)

The drag force depends on the local relative velocity between solid and gas phases and the void fraction. However, in deriving general empirical drag correlations, some other parameters such as particle shape and particle size distribution have not been taken into account. In this thesis, the adjusted Di Felice drag model proposed by Esmaili et al. [53] has been employed to modify the interfacial drag force. Using this method, the parameters \( P \) and \( Q \) in Eq. (17) are adjusted to satisfy the following relations:

\[
\varepsilon_s (\rho_s - \rho_g) g = \frac{K_{sg}}{\varepsilon_g} |\bar{V}_s - \bar{V}_g|,
\]  

(19)
\varepsilon_{s,ms}(\rho_s - \rho_g)g = \frac{K_{sg}}{\varepsilon_{g,ms}} u_{ms}^{\text{experiment}}. \quad (20)
4.1. Description of the Model

The structure of the bed used in the current study is shown in Figure 1. The model had a 2D rectangular configuration that attempted to replicate that of the experimental work of Dogan et al. [7]. The height of the column (δ) was 70 cm; and, the widths of the column at the upper (α) and lower (γ) sections were 15 and 4 cm, respectively. The internal angle of the lower section (θ) was 30°. An air entry slot width (λ) of 6 mm and various static bed heights (H_b) up to 30 cm were considered in the simulations.

Figure 4.1 Schematic of the slot-rectangular spouted bed configuration
The particles used in the simulation had a sphericity of 1 and density ($\rho_s$) of 2,520 kg/m$^3$. The regime maps were prepared for particle diameters ($d_p$) of 1.44 and 3.77 mm. For the simulations, the maximum packing limit of solid particles was chosen the value of 0.63 with the assumption of mono-dispersed spheres. The solid in the bed was assumed to be at its maximum packing limit at the beginning of the simulations. The density and viscosity of the inlet air were 1.225 kg/m$^3$ and 1.7894 $\times$ 10$^{-5}$ kg/m.s, respectively, at a bed temperature of 20°C. A restitution coefficient of 0.95 between the particles was assumed for the simulation.

4.2. Numerical Simulation Approach

FLUENT, a commercial CFD software package, was used to run the numerical simulations. The finite volume method was utilized to discretize the set of governing equations. Phase-Coupled Semi-Implicit Method for Pressure-Linked Equations (PC-SIMPLE) provided the pressure-velocity coupling. The quadratic upstream interpolation for convective kinematics (QUICK) and second-order upwind discretization schemes were used to discretize the partial differential equations of volume fraction and momentum, respectively.

The two-fluid Eulerian-Eulerian approach was applied. This technique considers separate sets of the conservation of mass and momentum for each continuous and incompressible phase. For more information about the multiphase models, one can be referred to chapter 4 of the reference [54]. In order to include the momentum transfer between the phases, the interfacial drag force was implemented using the adjusted Di Felice model (Esmaili et al. [53]).

The 2D computational meshed domain was composed of unstructured triangular cells in the cone base and structured square cells in the rest of the domain. Gambit meshing software was utilized to generate the computational grids. The grid used in the domain discretization is shown in Figure 2. The generated grids had node spacing larger than the particle diameter, i.e., 0.0025 m. The mesh independency of the results was checked with variation of the number of mesh elements.
A fixed time step size of $1 \times 10^{-3}$ s was applied. A maximum of 50 iterations were used for each time step, and the convergence criteria of the solutions were assumed to be at scaled residuals of smaller than $10^{-3}$. A value of 0.2 for all under-relaxation factors was chosen. Two seconds of flow time simulation were necessary to ensure a statistically steady-state condition. For large values of the bed height, up to four seconds of flow time were considered.

In order to reduce computational times, the symmetry boundary condition was assumed along the axis of symmetry; therefore, the required simulations were carried out in half of the 2D domain. The boundary condition at the entrance was considered as a velocity inlet with a uniform velocity profile. A pressure outlet boundary condition was applied at the outlet of the system. On the walls of the spouted bed, a no-slip boundary condition was assumed.
CHAPTER 5 : RESULTS AND DISCUSSIONS

The current CFD simulation has been conducted using FLUENT 6.3 software package. The transient Simulations have been performed on a 2D model using a Eulerian-Eulerian approach. The simulations of the gas-solid flows in the bed were conducted for various values of the effective parameters. The effects of different operating conditions of the system (i.e. different superficial gas velocities, air entry slot width, static bed heights, and size of solid particles) on the hydrodynamic behavior of the slot-rectangular spouted beds were studied. The results are presented in terms of contours of the solid volume fraction, solid stream function, pressure drop fluctuations, and fountain heights for various superficial gas velocities, bed heights, and solid particle sizes.

The flow regimes and hydrodynamic behavior of the slot-rectangular spouted bed were studied for different superficial gas velocities and bed heights. Mainly, the visual observation of the contours of the solid volume fraction was used to identify the different flow regimes. The regime maps were prepared based on various superficial gas velocities and bed heights for two different solid particle sizes.

5.1. Model Verification

The verification of the current model was checked through the comparison of the results of the fountain height in a slot-rectangular spouted bed with the experimental data reported by Dogan et al. [7]. The results of the fountain height are presented in Figure 5.1 for the case of $H_b=11$ cm, $d_s=0.86$ mm and $\lambda=6$ mm for different superficial air velocities. This figure shows that the results of the 2D model did agree with the previously reported experimental results.

5.2. Grid and Time Step Dependency Analyses

The mesh size and time step size sensitivity analysis have been performed to examine the effects of time step size and grid size resolution on the numerical results. Thus, some simulations have been executed using different grid interval sizes and different time interval sizes. All the simulations have been carried out at superficial air velocity
\( u = 2.0 \, m/s \), air entry slot width \( \lambda = 6 \, mm \), static bed height \( H_b = 11 \, cm \), and solid particle size of \( d_s = 1.44 \, mm \). The pressure drops were calculated with time averaging on the flow time interval of 1–2 seconds to make certain that statistically steady behaviour was achieved.

It was observed that the simulated result with grid interval size of 2.5 \( mm \) and time interval size of \( 1 \times 10^{-3} \, s \) did not show any remarkable difference in comparison with the result obtained by some smaller grid interval sizes (i.e., 1.25 mm, 0.6 mm, 0.3 mm and 0.15 mm) and time interval sizes (i.e., \( 5 \times 10^{-4} \, s \), \( 1 \times 10^{-4} \, s \), \( 5 \times 10^{-5} \, s \) and \( 1 \times 10^{-5} \, s \)). Therefore, the mesh interval size of 2.5 mm and time interval size of \( 1 \times 10^{-3} \, s \) have been picked out for conducting all the simulations.

![Figure 5.1](image)

**Figure 5.1** A comparison between this study’s numerical results and the experimental data of Dogan et al. [7] on the fountain height for different values of superficial air velocity.
5.3. Sensitivity Analysis of Restitution Coefficient

The restitution coefficient, $e$, clearly describes the proportion of restitution for collisions between particles. In completely elastic collisions, this coefficient has the value of one. A restitution coefficient sensitivity analysis has been performed to examine the effect of various values of this parameter on the numerical results. Thus, some simulations have been performed using different values of restitution coefficient to test the simulated system. All the simulations have been carried out at air entry slot width $\lambda = 6 \, mm$, static bed height $H_b = 11 \, cm$, and solid particle size $d_p = 0.86 \, mm$ (same as the configuration used in section 5.1 for verification of the model). Different superficial air velocities were considered.

The numerical results of fountain height for different values of restitution coefficients were compared with the experimentally reported values by Dogan et al. [7] for different values of air velocities. It was observed that the simulated results with a restitution coefficient of $e = 0.95$ had the best agreement with the experiments and the summation of error magnitudes for different air velocities was minimum for $e = 0.95$. Therefore, the restitution coefficient of $e = 0.95$ has been selected for conducting all the simulations.

5.4. Fountain Height

Figures 5.2, 5.3 and 5.4 present the values of the fountain height versus the superficial air velocity for different values of slot width, static bed height and particle diameter, respectively. In addition to the variable parameter in each one of these figures, the fixed values of the system parameters for these figures were: $H_b = 11 \, cm$ and $d_p = 1.44 \, mm$ for Figure 5.2, $\lambda = 6 \, mm$ and $d_p = 0.86 \, mm$ for Figure 5.3, and $\lambda = 6 \, mm$ and $H_b = 16 \, cm$ for Figure 5.4. These figures show that the fountain height increases with increasing in superficial air velocity.

Figure 5.2 shows that fountain height increased with increases in slot width at constant values of superficial air velocity (increasing the air volumetric flow rate). As a result, with a smaller slot width, a higher superficial gas velocity is required to reach the
same height of fountain. Figure 5.2 also reveals that the rate of increase in the fountain height as a function of superficial air velocity increased with increases in slot width.

![Figure 5.2 Fountain height versus superficial air velocity for different slot widths (H₀ = 11 cm and d_s = 1.44 mm)](image)

In Figure 5.3, two distinct regions can be distinguished for the variations in fountain height with respect to the static bed height at constant values of superficial air velocity. As a matter of fact, when the superficial air velocity was sufficiently low, the air-induced force vanished for high values of static bed height. This finding suggests that the fountain height had a decreasing trend with increases in the static bed height for low values of superficial air velocity, and vice versa. Figure 5.3 also reveals that the rate of increase in the fountain height as a function of the superficial air velocity at a constant static bed height decreased with increases in the superficial air velocity.

Figure 5.4 shows that the fountain height decreased with increases in the particle diameter at constant values of superficial air velocity. This implies that, with a larger particle diameter, a higher superficial gas velocity is required to obtain the same fountain height. Figure 5.4 also suggests that the rate of increase in the fountain height as a function of the superficial air velocity at a constant size of particle diameter decreased with
increases in the superficial air velocity. Although the fountain height decreased with increases in the particle diameter for the condition cited in Figure 5.4, it may increase with particle diameter at different conditions of $\lambda$ and $H_b$ [7].

Figure 5.3 Fountain height versus superficial air velocity for different static bed heights ($\lambda = 6 \text{ mm}$ and $d_p = 0.86 \text{ mm}$)

Figure 5.4 Fountain height versus superficial air velocity for different particle diameters ($\lambda = 6 \text{ mm}$ and $H_b = 16 \text{ cm}$)
5.5. Pressure Drop

In order to estimate the pressure drop, the average pressure difference between the air inlet slot and the upper exit port of the bed is calculated based on both time averaging and spatial averaging. As said earlier, the pressure value at the exit was considered as the ambient pressure. At each time, the spatial averaged pressure at the air entry (the average value for all nodes in the air inlet slot plane) has been recorded. Subsequently, the time averaging of spatial-averaged pressure values after at least one second of real time simulation has been computed.

Figures 5.5, 5.6, and 5.7 present the plots of the pressure drop versus the superficial air velocity for different values of slot width, static bed height and particle diameter, respectively. In addition to the variable parameter in each one of these figures, the fixed values of the system parameters were $H_b = 11$ cm and $d_p = 1.44$ mm for Figure 5.5, $\lambda = 6$ mm and $d_p = 0.86$ mm for Figure 5.6, and $\lambda = 6$ mm and $H_b = 16$ cm for Figure 5.7. These figures do not show a distinct trend for the variations of pressure drop with superficial air velocity.

In Figure 5.5, the pressure drop increased with increase in slot width at constant high values of superficial air velocity. It is obvious that the rate of change in the pressure drop as a function of superficial air velocity increased with increases in slot width (increasing volume flow rate).

In Figure 5.6, two distinct regions can be distinguished for the variations in pressure drop with superficial air velocity at constant values of static bed height. This figure suggests that, for low values of the superficial air velocity, the pressure drop had a decreasing trend with increases in superficial air velocity. However, for higher values of the superficial air velocity, the pressure drop had an increasing trend with increases in the superficial air velocity at a constant static bed height. In Figure 5.6, it can be observed that, for the same value of superficial air velocity, the pressure drop increased when the height of static bed increased.
In Figure 5.7, different trends can be observed for the variations in the pressure drop with respect to the superficial air velocity at constant values of static bed height. The
pressure drop had a decreasing trend with increases in the superficial air velocity for large sizes of particle diameter. The pressure drop decreased with increases in the particle diameter at a constant value of superficial air velocity. This implies that, with a smaller particle diameter, a lower superficial gas velocity should be applied for similar pressure drops. The rate of increase in the pressure drop as a function of the particle diameter at a constant superficial air velocity increased with increases in the superficial air velocity.

![Figure 5.7 Pressure drop against superficial air velocity for different particle diameters](image)

Figure 5.7 Pressure drop against superficial air velocity for different particle diameters  
$(\lambda = 6 \text{ mm} \text{ and } H_b = 16 \text{ cm})$

### 5.6. Solid Volume Fraction and Solid Velocity Stream

The solid volume fraction contours after 2 seconds of real-time simulation at different superficial air velocities are presented in Figures 5.8 and 5.9 for static bed heights of 11 and 21 cm, respectively. In these figures, the three different parts of the spout bed – the annulus, spout and fountain – can be distinguished. The highest concentration of solid particles were seen in the annulus, which is practically constant. Lower values of solid volume fractions could be found in the fountain and the spout regions. The formation of the fountain only occurred after exceeding a certain value of gas velocity for the spouted beds in a specific working condition.
Figure 5.8 Contours of the solid volume fraction for different superficial gas velocities ($\lambda = 6 \text{ mm}, \ H_b = 11 \text{ cm} \text{ and } d_p = 2.28 \text{ mm}$)

Figure 5.9 Contours of the solid volume fraction for different superficial gas velocities ($\lambda = 6 \text{ mm}, \ H_b = 21 \text{ cm} \text{ and } d_p = 2.28 \text{ mm}$)

Figures 5.10 and 5.11 show contours of the solid velocity stream function at operating conditions corresponding to the cases of Figures 5.8 and 5.9, respectively. It can be noticed that the particles had a high upward velocity in the spout region until reaching
the top of the fountain. In the annulus region, the particles formed a fixed bed through which the gas penetrated.

Figure 5.10 Contours of the solid stream function for different superficial gas velocities $(\lambda = 6 \text{ mm}, H_b = 11 \text{ cm} \text{ and } d_p = 2.28 \text{ mm})$

Figure 5.11 Contours of solid stream function for different superficial gas velocity $(\lambda = 6 \text{ mm}, H_b = 21 \text{ cm} \text{ and } d_p = 2.28 \text{ mm})$
The flow regimes in Figure 5.8 were identified as an internal jet for the case of \( u = 1 \) and as spouting for \( u = 2, 3 \) and 4. The flow regimes in Figure 5.9 were identified as an internal jet for the case of \( u = 1 \) and as incoherent spouting for \( u = 3 \) and 4, and as a transition between a jet-in-fluidized-bed and incoherent spouting for \( u = 2 \).

In the case of an internal jet, a submerged cavity or jet was formed at the air inlet orifice, while the rest of the bed remained as a fixed bed. In the spouting flow regime, the bed had the appearance of a conventional spouted bed. Particles were transported individually by the gas flowing upward in the center of the column and moving downward in the outer regions of the bed. In the incoherent spouting regime, the solids in the spout seemed to be entrained in a periodic manner, with a higher frequency in the upper part of the spout. Particles were more likely to be transported in the spout as small aggregates than individually.

The solids in the upper part of the annulus moved downward intermittently. The fountain above the bed surface showed a pulsating variable height. The jet-in-fluidized-bed regime occurred after the formation of the internal jet, during which an increase in the air flow rate led to fluidization of the upper part of the bed. The transition regime had mixed characteristics of the jet-in-fluidized-bed and incoherent spouting flow regimes [7].

5.7. Flow Regimes

In order to observe all the conceivable flow regimes, the simulations of the gas-solid flows in the bed were conducted for various values of the effective parameters. The numerical results were analyzed, and the numerical observation was verified by comparing the regimes predicted by the current model with the regimes that were observed experimentally by Dogan et al. [7] and Freitas et al. [8]. The flow regimes were distinguished mainly by visual observations of the contours of the solid volume fraction.

Various flow patterns were identified at different operating conditions, as shown in Figure 5.12 for the case of \( \lambda = 6 \) mm and \( d_s = 1.44 \) mm. The flow regimes in Figure 5.12 for cases a-g are identified as fixed bed, internal jet, jet-in-fluidized-bed, spouting, transition, incoherent spouting and slugging flow, respectively. For very low air flow rates, the flow is stayed at a fixed bed regime. In the internal jet regime, a submerged cavity or jet is
formed at the air inlet. The jet-in-fluidized-bed regime is occurred when bubbles separate from the internal jet and there was a fluidization in the upper part of the bed. With the increase in the air flow rate, the internal jet is grown and the solid would spout. This spout was stable and non-pulsating, while the fountain above the bed surface in the incoherent spouting regime had a pulsating variable height.

The transition regime had mixed characteristics of the jet-in-fluidized-bed and incoherent spouting flow regimes. In the slugging regime, slugs originated at the top of the submerged jets, causing the top surface to rise and fall. The detailed descriptions of these flow regimes are presented elsewhere by Dogan et al. [7] and Freitas et al. [8]. In all cases of the different flow characteristics, good agreement with the previously reported experimental data was found, revealing the capability of the proposed 2D model.

Figure 5.12 Contours of the solid volume fraction for different flow regimes for $\lambda$=6 mm and $d_0$=1.44 mm: a) fixed bed, b) internal jet, c) jet-in-fluidized-bed, d) spouting, e) transition, f) incoherent spouting, g) slugging ($H_b$=11 cm and $u$=0.5, 0.8, 1.05 and 2 for a, b, c and d, respectively; $H_b$=21 cm and $u$=2 and 4 for e and f, respectively; $H_b$=30 cm and $u$= 3 for g)

The normalized fluctuations of bed pressure drop (the bed pressure drop divided by the mean value of the bed pressure drop) corresponding to the case presented in Figure
5.12 are plotted against time in Figure 5.13. The presented pressure fluctuations are in agreement with the experimental data from Freitas et al. [39], qualitatively.

Figure 5.13 Normalized fluctuations of bed pressure drop versus flow time for different flow regimes for $\lambda=6$ mm and $d_s=1.44$ mm: a) fixed bed, b) internal jet, c) jet-in-fluidized-bed, d) spouting, e) transition, f) incoherent spouting, g) slugging ($H_b=11$ cm and $u=0.5, 0.8, 1.05$ and 2 for a, b, c and d, respectively; $H_b=21$ cm and $u=2$ and 4 for e and f, respectively; $H_b=30$ cm and $u=3$ for g)
The differences between the flow regimes can be seen by comparing the normalized bed pressure drop fluctuations. For example, the particles have a relatively stable configuration in the spouting regime shown in Figure 5.12-d. Therefore, based on Figure 5.13-d, the bed pressure drop fluctuations are small with no periodicity. In the slugging flow regime (Figure 5.12-g), the particle configuration dramatically changes due to the slugs. In Figure 5.13-g, the large bed pressure drop fluctuations are evident.

As can be seen from Figure 5.13, the pressure drop signals at different flow regimes have showed clear differences. Thus, the absolute pressure fluctuations have been analyzed to provide diagnostics of flow regime transitions. The statistical characteristics of the pressure signals are important tools in characterizing the gas-solid system. Here, a useful data analyzing method have been used to find the differences between the regimes' characteristics. The correlation analysis have been performed to examine various data with different flow regimes and to diagnose the flow regime transitions. The correlation coefficients were determined from the pressure signals obtained for different operating conditions of the bed. Hopefully, this method disclosed the significant differences among the regimes transitions, quantitatively.

The correlation coefficient is a measure of the extent to which two measurement signals "vary together". The correlation analysis is used to examine each pair of recorded simulation results of pressure fluctuations to determine whether the two recorded signals tend to move together- that is, whether large values of one signal tend to be associated with large values of the other (positive correlation), whether small values of one signal tend to be associated with large values of the other (negative correlation), or whether values of both signals tend to be unrelated (correlation near zero). The correlation coefficient is scaled so that its value is independent of the units in which the two measurement signals are expressed. The correlation coefficients for static bed height of 11 cm are listed in Table 5.1.

The comparisons between the coefficients show that numbers marked by boxes (near zero values of coefficient, namely the local minimums of correlation coefficient magnitude) reveal occurrence of flow transitions. It has been diagnosed that there were transitions between air velocities of 0.6 and 0.7 m/s, 0.9 and 1.0 m/s, or 1.0 and 1.1 m/s.
Then, another set of data was attempted by bisection method. The second results of correlation coefficients are shown in Table 5.2. Again, more precisely, it has been diagnosed that there were transitions between air velocities of 0.6 and 0.65 m/s, 0.9 and 0.95 m/s, or 1.0 and 1.05 m/s. Therefore the transition points are chosen as 0.625, 0.925, and 1.025 m/s for FB to IJ, IJ to JF, and JF to S, respectively with a precision of ±0.025 m/s.

The presented procedure can be continued till the desired precision is achieved. In comparison with the experimental results of Dogan et. al [22], this numerically obtained transition points have errors of less than 7, 1, and 3 percent for diagnosing transitions between FB to IJ, IJ to JF, and JF to S, respectively.

Table 5.1 Correlation coefficients of pressure drop signals for $\lambda=6$ mm, $d_z=1.44$ mm, and $H_b=11$ cm

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<th>0.9</th>
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<td>0.019237</td>
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Table 5.2 Correlation coefficients of pressure drop signals for $\lambda=6$ mm, $d_z=1.44$ mm, and $H_b=11$ cm; finding transition points, more accurately

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<td>0.088224</td>
<td>0.03193</td>
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</tr>
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5.8. Regime Transition Map

In order to diagnose the regime transitions, the simulations of the gas-solid flows in the bed were conducted for various values of the effective parameters. Based on the aforementioned validations, a full flow regime map for the case of $\lambda=6$ mm and $d_s=1.44$ mm was constructed and is shown in Figure 5.14. The static bed height was varied from 4 to 30 cm. The various superficial air velocities were examined to obtain the transitions in the map. The transitions were distinguished by analyzing the distributions of the solid volume fraction. In Figure 5.14, the new numerical map is plotted beside the experimental map reported by Dogan et al. [17].

![Regime Transition Map](image)

Figure 5.14 The regime maps obtained by current numerical simulations and experimentation reported by Dogan et al. [17] for $\lambda=6$ mm and $d_s=1.44$ mm. FB is fixed bed flow, IJ is internal jet flow, JF is jet-in-fluidized-bed flow, SL is slugging flow, IS is incoherent spouting flow, and T is transitional flow.
Although the analysis partly failed to distinguish the regimes for the lowest static bed height examined (i.e., \(H_b=4\) cm), the numerical simulation was successfully applied in the determination of the mapping boundaries. It can be seen that the presented model gave close results to experimental data for transition lines around jet-in-fluidized-bed (JF) regime. However, deviation between the predicted and experimental transitions from fixed bed (FB) to internal jet (IJ) is evident in Fig 5.14. The reason could be the uncertainty of the experimental measurements due to the low velocities as well as the difficulties in observing the exact transition point.

Examples of the detection of the map boundaries are presented in Figures 5.15-5.22. Although the examples are shown with an accuracy of ±0.025 m/s for more resolution in displaying the transitions, the mapping was constructed with an accuracy of ±0.0125 m/s, except for the transitions between internal jet and jet-in-fluidized-bed flows, which were detected with an accuracy of ±0.025 m/s.

A transition between fixed bed and internal jet regimes is shown in Figure 5.15 for \(H_b=7\) cm, when smooth contour lines for the solid volume fraction can be seen in the case of fixed bed flow. This transition can also be detected from Figure 5.16, in which contours of the solid velocity magnitude are presented. A comparison of the contours presented in Figures 5.16-a and 5.16-b reveals that a transition occurred by increasing the air velocity from 0.55 m/s to 0.6 m/s: at 0.55 m/s, the particles around the air entrance were relatively stagnant.

![Figure 5.15](image)

Figure 5.15 Contours of solid volume fraction in the transition from fixed bed to internal jet for \(H_b=7\) cm: (a) a fixed bed at \(u=0.55\) m/s, (b) an internal jet at \(u=0.60\) m/s
Figure 5.16 Contours of solid velocity magnitude in the transition from fixed bed to internal jet for $H_b=7$ cm: (a) a fixed bed at $u=0.55$ m/s, (b) an internal jet at $u=0.60$ m/s

A transition from internal jet into jet-in-fluidized-bed flows is shown in Figure 5.17, which presents the contours of the solid volume fraction for $H_b=25$ cm. This transition can be detected from Figure 5.18, in which the distributions of the solid volume fraction on the symmetry line are presented. In this figure, it can be seen that increasing the gas velocity above the value of 1.30 m/s resulted in fluctuations on the gas-solid surface, which led to a decrease of more than 1 cm in the area without solids.

Figure 5.17 Contours of solid volume fraction in the transition from internal jet into jet-in-fluidized-bed for $H_b=25$ cm: (a) an internal jet at $u=1.30$ m/s, (b) a jet-in-fluidized-bed at $u=1.35$ m/s
A transition from jet-in-fluidized-bed to spouting flows is shown in Figure 5.19 for $H_b=7$ cm, which presents the contours of the solid volume fraction for the air velocities of 0.80 m/s and 0.85 m/s. Transitions from jet-in-fluidized-bed regime into spouting, transition (have mixed characteristics of the jet-in-fluidized-bed and incoherent spouting flow regimes, as shown in Figure 5.20) or slugging regime (as shown in Figure 5.21) are detected in a similar way when transitions were occurred after reaching the central jet into the gas-solid surface.

Figure 5.18 Variations of solid volume fractions on the symmetry line of a bed with $H_b=25$ cm for different superficial air velocity
Figure 5.19 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting for \( H_b=7 \) cm: (a) jet-in-fluidized-bed at \( u=0.80 \) m/s, (b) spouting at \( u=0.85 \) m/s

Figure 5.20 Contours of solid volume fraction; Transition from "jet-in-fluidized-bed" to "transition" for \( H_b=21 \) cm: (a) a jet-in-fluidized-bed at \( u=1.55 \) m/s, (b) transition regime at \( u=1.60 \) m/s
Figure 5.21 Contours of solid volume fraction; Transition from jet-in-fluidized-bed to slugging for $H_b=25$ cm: (a) jet-in-fluidized-bed at $u=1.60$ m/s, (b) slugging at $u=1.65$ m/s

Figure 5.22 presents an example of the formation of incoherent spouting, in which the contours of the solid volume fraction for $H_b=21$ cm at air velocities of 2.3 and 2.35 m/s are presented. The incoherent spouting occurred just after the slug vanished above the fountain.
Figure 5.22 Contours of solid volume fraction for the change of flow patterns from transition to incoherent spouting for \(H_b=21\) cm: (a) transition regime at \(u=2.30\) m/s, (b) incoherent spouting at \(u=2.35\) m/s

The difference between the spouting, incoherent spouting and slugging regimes could be detected if the larger air velocities were maintained. Different spout types for cases of \(H_b = 7\) and \(21\) cm can be observed in Figures 5.23-a and 5.23-b, in which the contours of the solid volume fraction are shown at an air velocity of \(3\) m/s. If the slug above the central jet did not vanish and instabilities were seen, the slugging flow regime appeared. This case is presented in Figure 5.23-c for the case of \(H_b = 25\) cm at a superficial air velocity of \(3\) m/s. The normalized bed pressure drop fluctuations corresponding to these cases are plotted against time in Figure 5.24. As discussed by Freitas et al. [39], different behaviours can be distinguished in bed pressure drop fluctuations for these different flow regimes.
Figure 5.23 Contours of solid volume fraction of the different flow patterns for the superficial air velocity of 3 m/s: (a) spouting for $H_b=7$ cm, (b) incoherent spouting for $H_b=21$ cm, (c) slugging for $H_b=25$ cm.

Figure 5.24 Normalized fluctuations of bed pressure drop versus flow time for different static bed heights at a large superficial air velocity of $u=3$ m/s for $\lambda=6$ mm and $d_s=1.44$ mm. The flow regimes are (a) spouting at $H_b=7$ cm, (b) incoherent spouting at $H_b=21$ cm, and (c) slugging at $H_b=25$ cm.
The boundary between the spouting and incoherent spouting regimes could be detected if the larger air velocities were maintained. Different spout types for cases of \( H_b = 16 \text{ and } 18 \text{ cm} \) can be observed in Figure 5.25, in which the contours of the solid volume fraction are shown at an air velocity of 3 m/s. The boundary line between spouting and incoherent spouting is taken as \( H_b = 17 \text{ cm} \) with an accuracy of \( \pm 1 \text{ cm} \).

![Figure 5.25 Contours of solid volume fraction of the different flow patterns for the superficial air velocity of 3 m/s: (a) spouting for \( H_b = 16 \text{ cm} \), (b) incoherent spouting for \( H_b = 18 \text{ cm} \)](image)

The boundary between the incoherent spouting and slugging regimes could be detected if the larger air velocities were maintained. Different spout types for cases of \( H_b = 23 \text{ and } 25 \text{ cm} \) can be observed in Figure 5.26, in which the contours of the solid volume fraction are shown at an air velocity of 3 m/s. If the slug above the central jet did not vanish and instabilities were seen, the slugging flow regime appeared. The boundary line between spouting and incoherent spouting is taken as \( H_b = 24 \text{ cm} \) with an accuracy of \( \pm 1 \text{ cm} \).
Figure 5.26 Contours of solid volume fraction of the different flow patterns for the superficial air velocity of 3 m/s: (a) incoherent spouting for $H_b=23$ cm, (b) slugging for $H_b=25$ cm

The successful numerical predictions for the solid particles with a diameter of 1.44 mm allowed for the extension of the analysis to other configurations. A similar procedure was applied to construct a regime map for solid particles with a diameter of 3.77 mm. The transition line between internal jet and jet-in-fluidized-bed regimes was drawn with an accuracy of ±0.025 m/s. For other boundaries, the mappings were prepared with an accuracy of ±0.0125 m/s. The constructed regime map for the case of $\lambda=6$ mm and $d_s=3.77$ mm is presented in Figure 5.27. There are six different flow patterns in this case, i.e., fixed bed, internal jet, jet-in-fluidized-bed, spouting, incoherent spouting and slugging flows. In this flow regime map, the flow pattern of transition was not detectable.
Figure 5.27 The regime map for $\lambda=6$ mm and $d_s=3.77$ mm. IJ is internal jet flow; JF is jet-in-fluidized-bed flow; SL is slugging flow; and, IS is incoherent spouting flow.

Examples of transition points of the transition lines in Figure 5.27 are presented as follows. A transition between fixed bed and internal jet regimes corresponding to the map of $\lambda=6$ mm and $d_s=3.77$ mm is shown in Figure 5.28 for $H_b=11$ cm, when smooth contour lines for the solid volume fraction can be seen in the case of fixed bed flow.
Figure 5.28 Contours of solid volume fraction in the transition from fixed bed to internal jet for $H_b=11$ cm: (a) a fixed bed at $u=0.725$ m/s, (b) an internal jet at $u=0.750$ m/s

A transition from internal jet into jet-in-fluidized-bed flows is shown in Figure 5.29, which presents the contours of the solid volume fraction for $H_b=30$ cm.

Figure 5.29 Contours of solid volume fraction in the transition from internal jet into jet-in-fluidized-bed for $H_b=30$ cm: (a) an internal jet at $u=1.30$ m/s, (b) a jet-in-fluidized-bed at $u=1.35$ m/s
Transitions from jet-in-fluidized-bed to spouting / incoherent spouting / slugging flows are shown in Figure 5.30-5.41 for $H_b=4, 7, 9, 11, 13, 16, 18, 21, 23, 25, 27, 30$ cm, respectively, which presents the contours of the solid volume fractions. Transitions from jet-in-fluidized-bed regime into spouting, incoherent spouting, or slugging regime are detected in a similar way when transitions were occurred after reaching the central jet into the gas-solid surface.

Figure 5.30 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=4$ cm: (a) jet-in-fluidized-bed at $u=0.50$ m/s, (b) spouting or incoherent spouting or slugging at $u=0.55$ m/s

Figure 5.31 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=7$ cm: (a) jet-in-fluidized-bed at $u=0.80$ m/s, (b) spouting or incoherent spouting or slugging at $u=0.85$ m/s
Figure 5.32 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=9$ cm: (a) jet-in-fluidized-bed at $u=1.00$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.05$ m/s

Figure 5.33 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=11$ cm: (a) jet-in-fluidized-bed at $u=1.15$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.20$ m/s
Figure 5.34 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting/incoherent spouting/slugging for $H_b=13$ cm: (a) jet-in-fluidized-bed at $u=1.25$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.30$ m/s

Figure 5.35 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting/incoherent spouting/slugging for $H_b=16$ cm: (a) jet-in-fluidized-bed at $u=1.35$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.40$ m/s
Figure 5.36 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_p=18$ cm: (a) jet-in-fluidized-bed at $u=1.40$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.45$ m/s

Figure 5.37 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_p=21$ cm: (a) jet-in-fluidized-bed at $u=1.55$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.60$ m/s
Figure 5.38 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=23$ cm: (a) jet-in-fluidized-bed at $u=1.65$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.70$ m/s

Figure 5.39 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=25$ cm: (a) jet-in-fluidized-bed at $u=1.75$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.80$ m/s
Figure 5.40 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=27$ cm: (a) jet-in-fluidized-bed at $u=1.75$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.80$ m/s

Figure 5.41 Contours of solid volume fraction in the transition from jet-in-fluidized-bed to spouting / incoherent spouting / slugging for $H_b=30$ cm: (a) jet-in-fluidized-bed at $u=1.75$ m/s, (b) spouting or incoherent spouting or slugging at $u=1.80$ m/s
The difference between the spouting and incoherent spouting regimes could be detected if the larger air velocities were maintained. Different spout types for cases of $H_b = 11, 13, \text{ and } 16 \text{ cm}$ can be observed in Figure 5.42, in which the contours of the solid volume fraction are shown at an air velocity of $3 \text{ m/s}$. The boundary line between spouting and incoherent spouting is taken as $H_b = 14.5 \text{ cm}$ with an accuracy of $\pm 1.5 \text{ cm}$.

![Figure 5.42 Contours of solid volume fraction of the different flow patterns for the superficial air velocity of 3 m/s: (a) spouting for $H_b=11 \text{ cm}$, (b) spouting for $H_b=13 \text{ cm}$, (c) incoherent spouting for $H_b=16 \text{ cm}$](image)

The difference between the incoherent spouting and slugging regimes could be detected if the larger air velocities were maintained. Different spout types for cases of $H_b = 16, 18, \text{ and } 21 \text{ cm}$ can be observed in Figure 5.43, in which the contours of the solid volume fraction are shown at an air velocity of $4 \text{ m/s}$. If the slug above the central jet did not vanish and instabilities were seen, the slugging flow regime appeared. The boundary line between spouting and incoherent spouting is taken as $H_b = 19.5 \text{ cm}$ with an accuracy of $\pm 1.5 \text{ cm}$. 
Figure 5.43 Contours of solid volume fraction of the different flow patterns for the superficial air velocity of 4 m/s: (a) incoherent spouting for $H_b=16$ cm, (b) incoherent spouting for $H_b=18$ cm, (c) slugging for $H_b=21$ cm
CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

The gas-solid flows in a slot-rectangular spouted bed were simulated using 2D computer simulations. The CFD technique with the two-phase Eulerian-Eulerian approach was applied using FLUENT software. The effects of variations in the physical parameters of the system on the flow regimes and hydrodynamic behavior of the bed were investigated. The model verification was accomplished by comparing the predicted numerical results of the fountain height with earlier experimental data. Good agreement was achieved.

Sensitivity analyses were performed to examine the effects of using various values of restitution coefficients in addition to the effects of grid spacing and time interval on the results. The effects of the bed height, slot width, solid particle size and superficial gas velocity on the fountain height and pressure drop were studied thoroughly. The fountain height and pressure drop had increasing trends with increases in slot width at constant values of superficial air velocity. The fountain height had a decreasing trend with increases in static bed height for low values of a constant superficial air velocity, and vice versa. At a fixed superficial air velocity, the pressure drop increased when the height of static bed increased. The fountain height and pressure drop decreased with increasing particle diameter at constant values of superficial air velocity.

The 2D model was applied to assess its capability in predicting flow regimes, which had been experimentally observed elsewhere, for a slot-rectangular spouted bed. The constructed regime map for a bed of solid particles with a diameter of 1.44 mm was verified by a map reported in the literature. In most operating conditions, the model was able to predict the appropriate regime. After the successful predictions of the flow regimes by the numerical model, a regime map was introduced for a bed of solid particles with a diameter of 3.77 mm. The new numerically obtained map was composed of six different flow regimes.

Although the results of 3D simulations will take more time and computation than 2D simulations, they will give more realistic results. Therefore, as future work, 3D simulations can be performed giving more accurate answers, by taking into account the
effects of the walls perpendicular to the third direction. The effect of using three-dimensional analysis versus two-dimensional simulation of spouted beds can also be investigated in the future.

The statistical characteristics of the pressure signals are important tools in characterizing the gas-solid system. The absolute pressure fluctuations provided by conducted numerical simulations can be analyzed to provide diagnostics of flow regime transitions for different superficial gas velocities and bed heights.
REFERENCES


APPENDIX

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