Chapter 2

Literature review

2.1 General

Over a century of pneumatic conveyor application together with more recently spray dryer, dust collector and coal combustion system, numerous studies of gas-solid flow have been performed. Correlation based experimenters are pioneer of this field. Their main purpose is to correlate pressure drop empirical expression with their experimental data. Laterally, two phase turbulence flow mathematical models are continually developed by theoretical based reseacher. Until recent computer era, different groups of researchers involving gas-solid flow are generated . The first group, data based experimenter, measured the primitive variables such as velocity profile, temperature profile and concentration profile with precision measurement devices to collect data bank used for further analysis . The second group is the researchers who create computational algorithm to solve complex-two phase flow mathematical model. These computational techniques enable researcher nowadays to perform computational experiment by the way that mathematical model and its modification is solved by computational method in computer and computational results will be validated against available measurement data from data bank obtained from experimental researchers. If the mathematical model is proven valid, the researcher can perform his computational experiment by changing flow parameter and/or flow geometry in his computer code. This method is proven cost effective especially in fluid dynamics and transport phenomena field. However, its accuracy depends on approximation and interpolation process used in computation and the accuracy of experimental data used for validation.

In this chapter, gas-solid flow experimental work literatures are first discussed. Subsequently, various approach of gas-solid flow mathematical modeling literatures are further discussed. Finally ,computational simulation work literatures are discussed to guide the concept of what will be done in this study.

2.2 Experimental work

Tsuji, Morikawa and Shiomi [1984] measured air and solid velocity in a vertical pipe two-phase flow by use of Laser-Doppler velocimeter (LDV). Five kinds of plastic particles, diameter of which range from about 3mm to 200μm and density of 1020 kg/m^3, were transported in a vertical pipe of 30.5 mm inner diameter. Axial pressure profile was also measured along acceleration zone using pressure transducer. Figure 2.1 show experimental diagram. From the diagram, the distance between the bend outlet and the measurement section was 5110 mm which is long enough to confirm that the particle motion reached a steady state at the measurement section. In this experiment, the mean air velocity ranged from 8 to 20 m/s and solid loading ratio was up to 5.

Compared with experimental work of Lee and Durst [1982] which the gas-solid flow was conducted in a pipe of 42 mm inner diameter with the mean air velocity at 5.7 mm and four kind of glass beads(100, 200, 400 and 800 μm) and solid loading ratios about 1.5 to 3.0, Tsuji et al. [1984]'s work were made at higher velocity using lower density than Lee and Durst [1982]'s work. Another experimental work was performed by Maeda, Hishida and Furutani [1980]. Tsuji et al. [1984]'s experimental results will be discussed in detail in chapter 5 as the experimental data used for mathematical model validation.

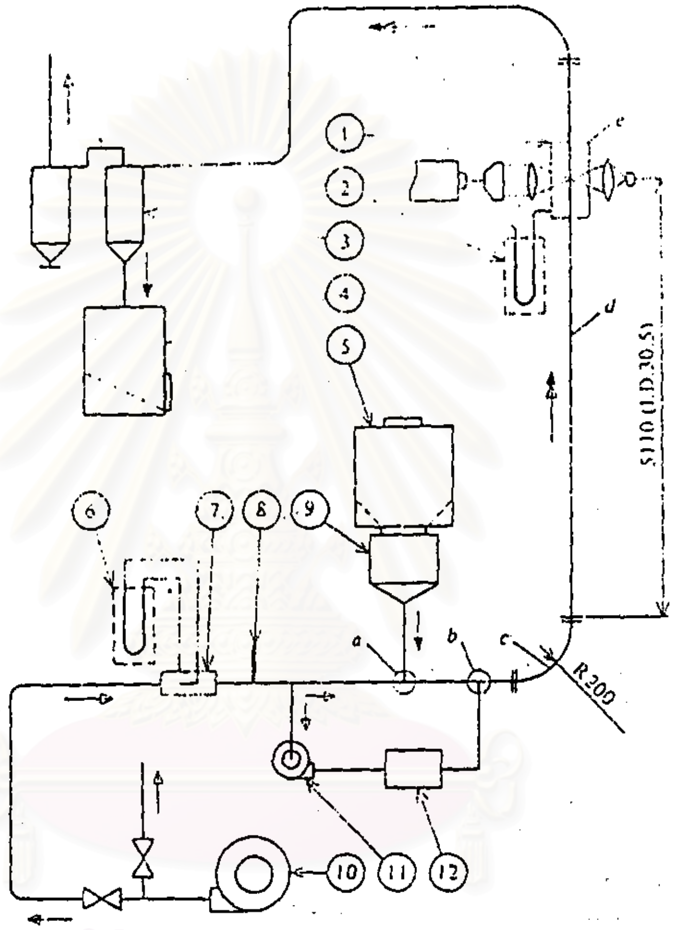

Figure 2.1
Experimental pipeline: 1, LDV test section; 2, manometer; 3, cyclone separator; 4, Solid receiver; 5, solid storage chamber; 6, manometer; 7, measuring section of air flow rate; 8, thermometer; 9, electromagnetic feeder; 10, blower; 11, supercharger; 12, smoke generator

Soo, Trezek, Dimick, and Hohnstreiter [1964] developed an electrostatic mass probe to determine particle velocity distribution and mass flow distribution on vertical, fully developed 5-in diameter pipe flow. Closed loop two phase flow system was run by use of glass and magnesia around 50 to 35 μm, maximum velocity was 130 fps, and hold up mass of air is 1.67 lb. Figure 2.2 show experimental instrument diagram and Figure 2.3 show concentration distribution result. This experiment was also aimed to investigate electrostatic effect so that particles were not coated with anti-electrostatic substance, as a result, high concentration can be found near wall due to electrostatic attractive force between pipe wall and charged particle due to its motion.

Littman, Morgan III, Paccione, Jovanovic, Grbavcic [1993] studied accelerating and non-accelerating turbulent dilute phase flow by transporting 1 mm glass sphere with air in a 28.45 mm electrically grounded stainless steel pipe. Slip Reynolds number for the particles ranged from 5.6 to 17.1 and pipe Reynolds number was the order of 20000. The loading ratio varied from 5.6 to 17.1. The purpose of their work was to measure and correlate the acceleration drag coefficient (or in their literature deceleration, in view of relative velocity).

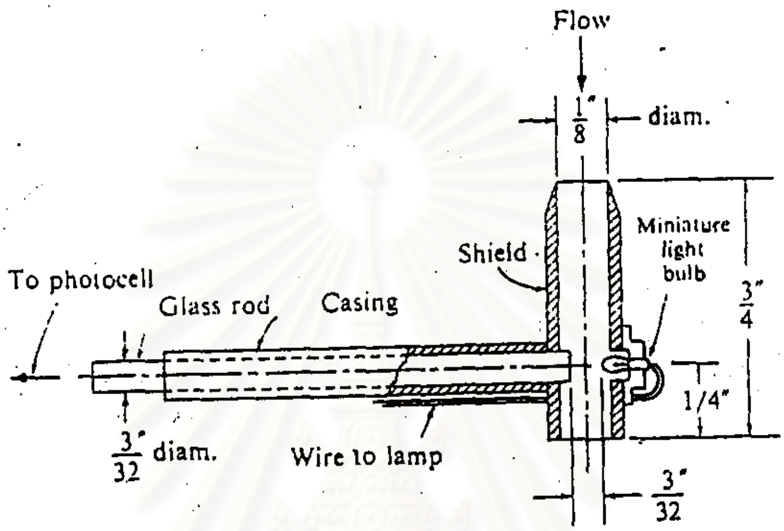

Figure 2.2
Probe with light-in source for pipe flow concentration measurement

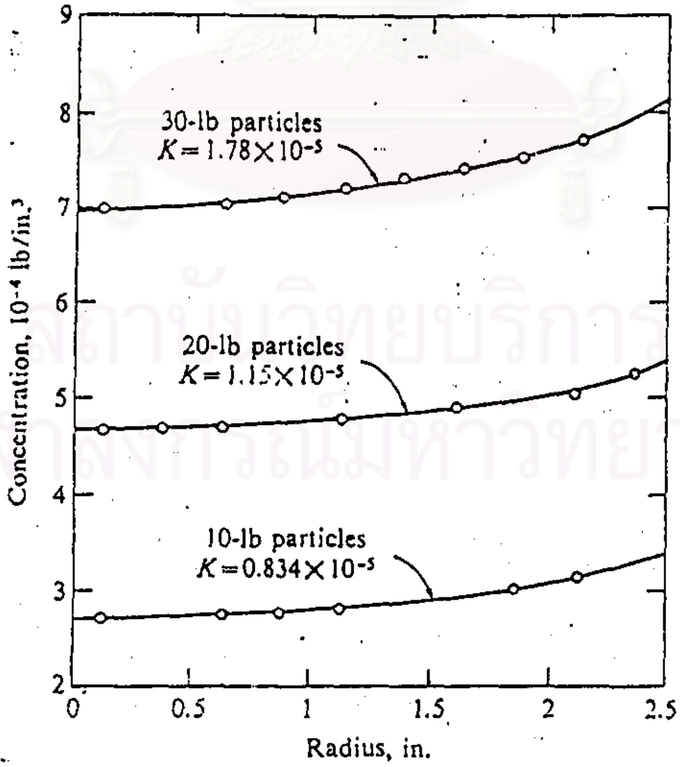

Figure 2.3
Concentration distribution of glass particles 50 μm nominal in air

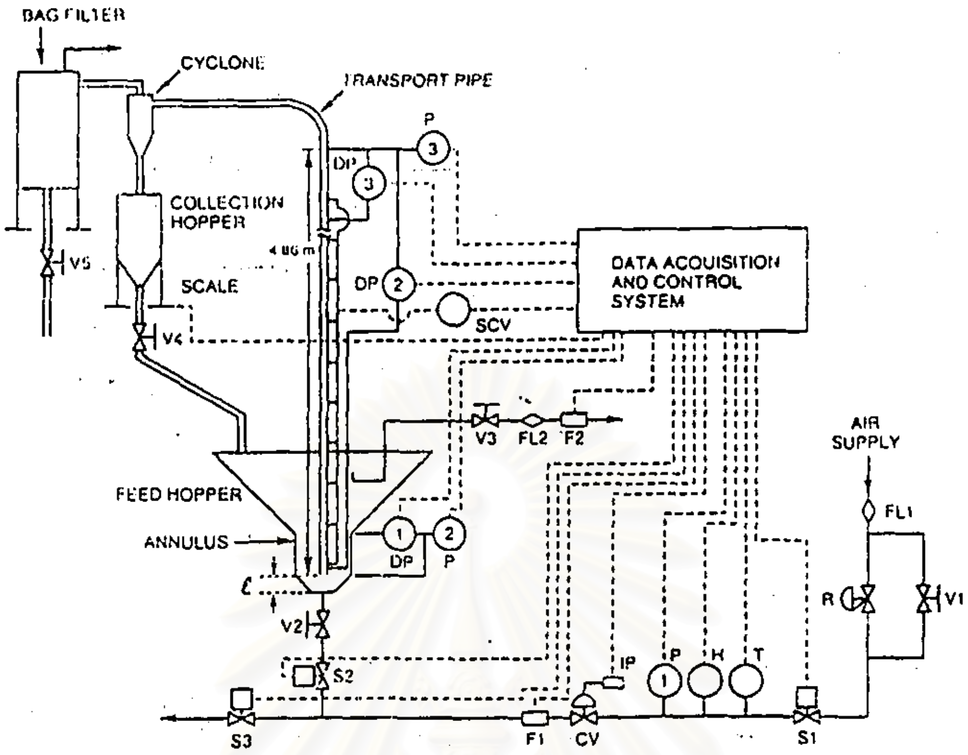

Figure 2.4

Schematic diagram of apparatus; FL, filter; V, valve; R, pressure regulator; S, solenoid valve; CV, control valve; F, flowmeter; T, temperature sensor; H, humidity sensor; DP, differential pressure sensor; SCV, Scannivalve pressure measurement system; IP, current to pressure transducer

Figure 2.4 show schematic diagram of their experimental apparatus. In this experiment, they used 1 mm glass particles to ensure that the experimental data are representative of a choking velocity and that the particle acceleration length is long enough to obtain accurate pressure profiles. The 1 mm particles, density = 2500 kg/m^3 were transported through a 28.45 mm electrically grounded stainless steel pipe 5.49 m in length equipped with grounded stainless steel spouted bed feeder. The particles flow from the annulus into the transport pipe and were collected in closed container. Feeder provided a non-fluctuating controlled flow of particles whose entry conditions to the pipe are essentially those provided by a spouted bed feeding particles from height l above its jet inlet. Figure 2.5 (a), (b), and (c) show axial pressure profile, gas phase volume fraction (voidage), and velocities profile experimental data of the same run. Keep in mind that deceleration region in their work is referred to decrease of relative or slip velocity between two phase which therefore equivalent to acceleration region in this study which is referred to increase of particle velocity.

From figure 2.5(a), (b) and (c), acceleration flow can be characterized. Definition of acceleration length can be investigated from Figure 2.5(a) which H_a represents the length where, start from this length, pressure drop per length will be equal in every section until reaching the pipe exit. Voidage profile can be investigated from Figure 2.5(b) which particle volume fraction axially decrease until it reach steady state at H_a, from this length particle volume fraction remains constant. The same trend can be observed from particle phase and slip velocity profiles in Figure2.5 (c).

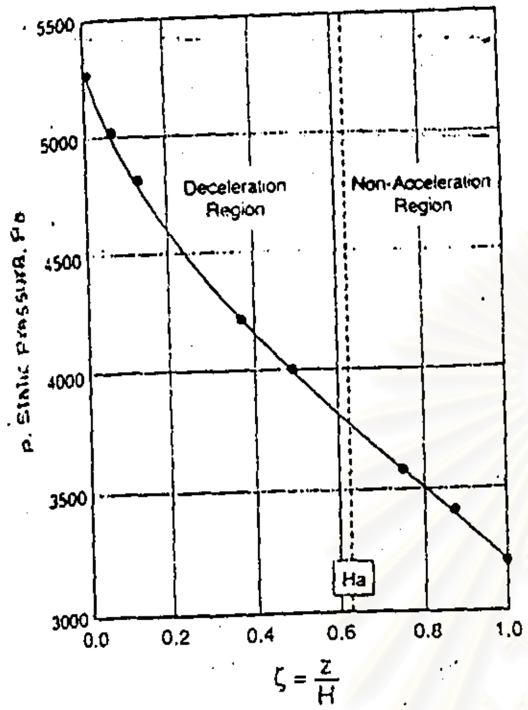

Figure 2.5 (a)
Determination of the length of deceleration region; Run 4, H = 4.86 m.

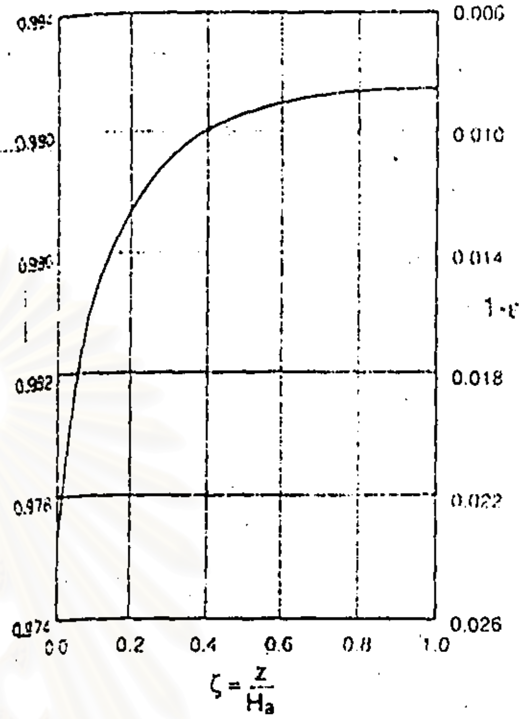

Figure 2.5 (b)
Voidage profile in deceleration region, run4

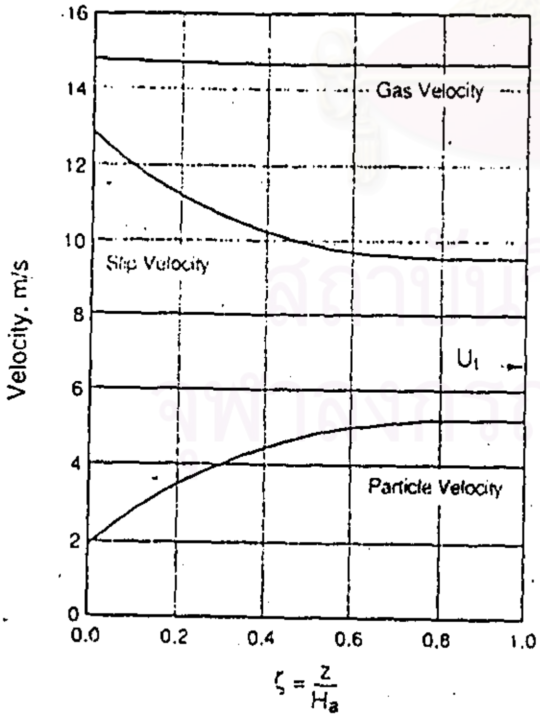

Figure 2.5 (c)
Gas phase, particle phase and slip velocities in deceleration region, run 4

2.3 Gas-solid flow modeling work

2.3.1 Force balance approach

The earliest attempt reported on the study of acceleration length was made by Papai [1955]. This work presented mathematical model for horizontal and vertical pneumatic conveying. The basic force balance presented in their work was treated as follows;

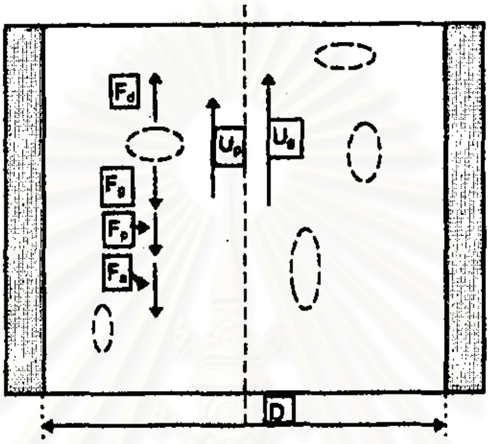

Figure 2.6
Forces and velocities in vertical starting section

From Figure 2.6, F_d is aerodynamic drag, which is proportionate to the square of the relative velocity, F_g is gravity force, F_a is force of inertia due to acceleration which is the difference between F_d and F_p, the force resulting from particle collision. The force inhibiting movement is the sum of force resulting from collision and force of gravity. Thus, in the acceleration section $F_d > F_g + F_p$ must rule and force of inertia must be called into restore the balance.

$$F_d = F_g + F_p + F_a$$

This can be written in the form

$$\frac{\rho_g}{2} f_0 C_e \left(U_g - U_p\right)^2 - Mg - M\xi_{sf}\frac{U_p^{\,2}}{2} = M\frac{dU_p}{dt}$$

C_e the coefficient of aerodynamic drag per f_0 (m^2) particle surface area which can be determined by measuring and ξ_f is the coefficient of collision.

The integration of the above force balance equation yield expression of t in the form of U_p in acceleration section. Taking inverse function yield expression of U_p in form of t . Acceleration length can now be computed.

$$L_a = \int_0^t U_p dt$$

The most quoted expression for the determination of acceleration length was made by Rose and Duckworth [1968]. they analyzed their experimental result for the transport of the various materials indicate that, for pipes of various angles of inclination upward from horizontal to vertical position, the acceleration length L_a is given by

$$L_a = 6\left[\left(\frac{G_p}{\rho_g g^{1/2} D^{5/2}}\right)\left(\frac{D}{d_p}\right)^{1/2}\left(\frac{\rho_p}{\rho_g}\right)^{1/2}\right]^{1/3}$$

Dhodapkar, Zaltash, Myler, Klinzing [1988] derived a force balance model for gas -solid flow in acceleration zone. If a material and force balance is done over the differential element , a general force balance can be written for any inclination as

$$dM_s . \frac{dU_p}{dt} = dF_d - dF_g - dF_f$$

The distance traveled by the particles can be expressed in the form of particle velocity and time elapsed. For the differential element dL, substitution of $dL = U_p.dt$ can be made . The integration, however, is not straightforward because the friction factor and voidage are functions of particle velocity. The integral derived from force balance,

$$L_a = \int_{U_{p1}}^{U_{p2}} \frac{U_p dU_p}{\frac{3}{4} C_{DS} \varepsilon^{-4.7} \rho_g \frac{(U_g - U_p)^2}{D_p(\rho_p - \rho_g)} - g \sin\theta - \frac{2\xi U_p^{\,2}}{D}}$$

In final solution, U_{p1} is set to zero and U_{p2} equal to steady state velocity which is estimated to be 98% of feasible root.

The objective of force balance modeling are mainly for design purpose. Acceleration length, pressure drop correlation, is necessary design parameter for pneumatic conveyor designer. However, understanding gas-solid flow in more detail or in more complex flow geometry require more precise mathematical model as will be discussed in next section.

2.3.2 Particle trajectory model

The most rigorously correct method to model gas-solid flow is to write mass, momentum and energy conservation equation in differential form. But this set of this equation is the rather difficult, and to-date even the simplest cases have not been solved analytically. Numerical mathematical model is therefore called for to make the model possible to be solved numerically. Particle trajectory model is one of this type.

Particle trajectory model is based on Lagrangian mathematical modeling for particulate phase. The particulate phase is treated by solving Lagrangian equation of motion for a group of particles with a prescribes set of initial conditions. The particulate phase is represented by computational particles rather than a continuous distribution function. This amount require a statistical formulation of problem since a finite number of particles is used to represent a very large number of particles presents in the field.

Numerically, the trajectory models which is also called PSI Cell (Particle-source-in-cell) model, is based on treating the particles as sources of mass, momentum and energy to the gaseous phase. The procedure begins by solving the gas flow field using a numerical scheme. The first calculation assumes that no particle is present in the flow field. Particle trajectory and mass, momentum and temperature history on each trajectory are then calculated in the gas flow field. The particle properties on crossing the boundary of computational cells yield the mass, momentum and energy source terms for gas in each cell. The gas flow field is recalculated, incorporating these source terms. New trajectories are calculated and source terms are then evaluated. the process is continued until the flow field failed to change with repeated iteration.

Crowe and Pratt [1972] were pioneer of particle trajectory model and later applied the model to several problems including pneumatic transport problem work of Lee and Crowe [1980].

Mostafa and Mongia [1988] proposed a mathematical model for turbulent gas-particle flows to take into account the effect of both mean and turbulent motion of each phase on the other using trajectory model approach. The equations are solved numerically to predict a turbulent round gaseous jet laden with solid particles. They validated their model with Shuen et al [1983] who measured two-phase turbulent round jet of air laden with sand particles of mean diameter = 119 μm at solid loading ratio = 0.2 and 0.66 using Laser Doppler annemometer (LDA). Results demonstrated that the model is successful in predicting the significant effects of particle on both mean and turbulence quantities of the carrier phase, and the stochastic approach yields reasonably good prediction of the effect of the gas turbulence on particle dispersion.

2.3.3 Two Fluid model

One approach in modeling gas - particle flows is to start with the “Two-fluid” equation. The two-fluid approach (or in some called “Eulerian” approach) is to regard the conveying and particulate phase as interacting and interpenetrating continuum which makes the governing equation of two phase very similar to Navier-Stokes equations, with additional source/sink terms. Detailed mathematical treatment of two-fluid turbulence equations will be discussed in Chapter 3.

Elgobashi and Abou-Arab [1982] developed multi-dimensional, two equation turbulence model for predicting two-phase flow. The equations describe the conservation of turbulence kinetic energy and dissipation rate of that energy for carrier fluid in a two-phase flow. They have been derived rigorously from the momentum equations of the carrier fluid. Closure of the time mean equations is achieved by modeling the correlation up to third order. Preliminary testing indicates that the model is successful in predicting the main features of two-phase round jet with uniform solid particle.

Chen and Wood [1986] developed an two-fluid model for calculating turbulent gas-particle flow. The model was applied to a two-phase round jet in initial region. They validated their model with experimental data of Modarrass et al. [1984] and Girshovich [1982]. Their governing equations of the model are based on the "dusty gas" equation of Marble [1963]. The equation of kinetic energy and kinetic dissipation rate are based on k-ε model of Hanjalic and Launder [1980] but have been modified to account for present of particles. The added terms are added sink term, which are due to the added velocity gradient created by the particles.

Mostafa and Mongia [1987] developed two-fluid (Eulerian) two-phase flow turbulent model with added sink terms in k and ε equation to account for presence of particles. They compared this model with particle trajectory model for evaporating sprays . Result show that both approach are successful in predicting the main feature of this type of flows, however, two-fluid model performs better.

Validation of the above two-fluid models were ranged in quite small (<150 μm) particles and relatively low solid loading ratio (<1) flows in turbulent round jet.

These models are although basic and essential but inadequate in describing relative large particles laden in gas flows in pipe considered in this study. The following section describe "two-fluid" model literatures which massive and large particles laden in dilute phase turbulent pipe flows is taken into account.

2.4 Modeling and numerical simulation of gas-solid particle flow in vertical pipe

Littman, Morgan, Paccione, Jovanovic and Grbavcic [1993] developed one dimensional, two-fluid modeling of accelerating and non-accelerating region turbulent dilute phase flow in vertical pipe based on Nakamura and Cape [1973] 's equations. They correlated their experimental data discussed above with mathematical model to obtain drag coefficient and particle-wall friction factor.

Following their study, evidence is present to support the existence of particle-free region near the wall making it possible to neglect particle-wall effects in the modeling. They finally concluded their decelerating and non-decelerating drag coefficient. The effective non-decelerating drag coefficient at $Re_p = 471$, $C_{dn}=0.44$, equal to standard drag curve but falls with increasing Re_p to 0.13 at Re_p=986. This is a factor of 3.48 below the standard drag curve value. The deviation from the standard drag curve is due to free stream turbulence.

Sinclair and Jackson [1989] presented a theory for fully developed flow of gas and particles in a vertical pipe. The relation between gas pressure gradient and the flow rates of both phase was predicted, over the whole range of cocurrent and countercurrent flows, together with velocity profiles for both phases and radial concentration profile for the particles. They discussed a realistic picture of the mechanical behavior of the motion of a gaseous suspension which both fluid and particles velocities have local average and random components, in view of its various interactions that depends on two velocity field as follows ;

a) Interaction between particles and gas that results from the difference between their mean velocity fields, and give rise to the drag force that propels the nonrandom part of particles motion.

b) Interaction of the particles with the fluctuating component of gas velocity. This may cause the flux of kinetic energy in either direction between the fluctuating components of the velocity of the two phases, either damping the fluctuation of gas velocity and stimulating fluctuations in particle velocity or vice versa.

c) Interactions of the fluctuating part of the particle motion with the mean particle motion through interaction forces between particles. These generates stress in the particle assembly and give rise its apparent viscosity.

d) Interactions between the turbulent fluctuations of gas velocity and the mean motion of gas velocity and the mean motion through of the gas, which generate the well-known Reynolds stresses.

In order to formulate a model which include the above a) and c) effect, it is necessary to treat the mutual interactions of particles. If these are small and light they interact via the motion of the interstitial gas, since this gas acts as a "buffer" which prevents direct contacts between particles surfaces (this is the same case as "dilute and small" particles laden flows in turbulence jet studied in the earlier mentioned literature). For larger and heavier particles, however, the momentum of the moving particles is sufficient to carry them easily through the intervening gas film, and interaction occur by direct collision. For the transport of the typical mineral particles of 150 μm dia. or larger, it is likely that interaction by direct collision dominates.

The treatment in their model was limited to situations in which the particles interact with each other only by brief contact, which can be regarded as collision. At high concentration, on the other hand, they will move as a "granular material", with stress generated by normal reactions and frictional forces at the point of sustained, sliding and rolling contact. The latter situations are excluded in their study.

Louge, Mastorakos and Jenkins [1991] analysed dilute, steady, fully developed flow of relatively massive particles in a turbulence gas in the context of a vertical pipe. Their idea was that the exchange of momentum in collisions between the grains and between the grains and the wall play a significant role in the balance of forces in the particles phase. Consequently, the particle phase is considered to be a dilute system of colliding grains, in which the velocity fluctuations are produced by collisions rather than the gas turbulence. The momentum balance of rapid granular flow given, for example, by Jenkins and Savage [1983] was modified to include a drag term that provides the force necessary to suspend the particles and the corresponding energy balance including rates of production and dissipation associated with interaction between the particles and the gas. Finally, the turbulence of the gas was treated using standard k-ε equations closure. They validated their model with the measurements. Numerical solutions of the resulting governing equations provided velocity and turbulent energy profiles in agreement with the measurement of Tsuji et al. [1984]. They also showed the effect of particle shear stress term (which account for particle-particle interaction) to accuracy of their model.

Pita and Sunderesan [1993] presented a computational study of steady, developing (or accelerating) flow of gas-particles suspensions in a vertical riser using a model based on kinetic theory of granular materials, to understand the role of inlet configuration on the pattern of flow development. Their modeling was intended to account for choking or flooding flow of relatively high solid loading ratio with particles lateral segregation, as a result, gas phase turbulence effect is excluded. Three inlet configurations-uniform inlet, core-annulus flow and circumferential injection of secondary gas, as shown in Figure 2.7, were examined. It is found the inlet configuration can have a profound impact on the rate of segregation of particles to the wall and the internal recirculation.

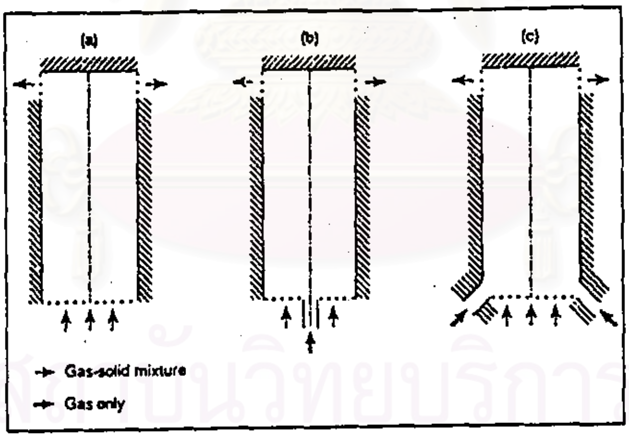

Figure 2.7
Riser inlet configuration according to Pita and Sunderesan [1993]

Bilirgen, Levy and Yilmaz [1998] performed turbulent two phase flow calculation with a CFD code referred to as FLOW3D to determined how well its predictions compare to experimental data of Tsuji et.al [1984]. The mathematical model used in their work employed the particle trajectories computational model. Gas phase turbulence energy was calculated using standard k-ε model and standard wall function boundary conditions. They ignored particle-particle interaction but included particle-wall interaction in their model. They concluded that the computational results are in good qualitative agreement and frequently in quantitative agreement with published data.