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## EFFECT OF OPERATING PARAMETERS ON THE MINIMUM FLUIDISATION VELOCITY OF AN INCLINED FLUIDISED BED

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**Abstract.** Fluidisation phenomena in an inclined fluidised bed (IFB) systems are poorly understood and receive less attention as compared to that of vertical fluidised bed although in practice there are many fluidised bed systems not vertically oriented. The objective of this work is to investigate the effect of inclination angle, particle size and particle composition to the minimum fluidisation velocity ( $U_{mf}$ ). The experiments were conducted in a rectangular IFB of dimension,  $7 \times 50$  cm fitted with a 2 mm thick metal distributor plate with 1 mm holes diameter (2.98% opening area), water manometer, flow meter and compressor for fluidising air supply. The gradual decreasing velocity method was used to investigate the  $U_{mf}$ . Three operating parameters were observed, namely angle of inclination, particle diameters and the compositions of mixed particles. The experimental results showed that the  $U_{mf}$  of the particles is lower at higher angle of inclinations. The smaller particles have a lower  $U_{mf}$ . The mixed sand with higher smaller particles mass fraction also has a lower  $U_{mf}$ . Therefore, the effects of inclination angle and smaller particles mass fractions in the mixed sand to the  $U_{mf}$  were observed to follow an inverse function, while, the particle size is linearly related to the  $U_{mf}$ .

*Key word:* fluidised bed, inclined, minimum fluidisation velocity.

**Abstrak.** Fenomenon kebandaliran pada lapisan terbandalir satah condong (IFB) masih kurang difahami dan kurang mendapat perhatian jika dibandingkan dengan lapisan terbandalir biasa walaupun terdapat banyak penerapan lapisan terbandalir yang tidak mengikut ciri lapisan terbandalir biasa. Tujuan kajian ini dilakukan adalah untuk menentukan kesan sudut kecondongan, saiz zarah dan komposisi zarah ke atas halaju kebandaliran minimum ( $U_{mf}$ ). Eksperimen ini dijalankan dengan menggunakan IFB segi empat tepat berdimensi  $7 \times 50$  cm dilengkapi dengan pengagih berketebalan 2 mm yang mempunyai lubang berdiameter 1 mm dan peratusan bukaan 2.98%, manometer air dan pemampat udara. Kaedah pengurangan berperingkat halaju udara masukan digunakan untuk menentukan halaju kebandaliran minimum. Tiga parameter yang diselidiki ialah sudut kecondongan, diameter zarah dan komposisi percampuran zarah. Keputusan yang didapati menunjukkan  $U_{mf}$  berkurangan dengan penambahan sudut kecondongan. Pasir bersaiz kecil mempunyai  $U_{mf}$  yang rendah. Percampuran pasiran yang mempunyai nisbah zarah bersaiz kecil yang tinggi menunjukkan  $U_{mf}$  yang rendah. Oleh itu, kesan sudut kecondongan dan nisbah zarah bersaiz kecil dalam satu campuran pasiran terhadap  $U_{mf}$  menunjukkan hubungan berkadar songsang, manakala kesan saiz zarah memberikan hubungan berkadar linear terhadap  $U_{mf}$ .

*Kata kunci:* lapisan terbandalir, condong, halaju kebandaliran minimum.

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## 1.0 INTRODUCTION

Fluidisation phenomenon of an inclined fluidised bed (IFB) systems have not been well understood and receive less research attention as compared with vertical fluidised bed. The vertical system may be considered as a particular case of inclined system in which the drag force and gravitational force are diametrically opposed. The inclined fluidised bed has been applied in the cracking of heavy oils; coal gasification and iron ore reduction in the form of standpipe and reactors [1]. The lack of basic understanding of the effect of the inclination to the fluidisation phenomenon contributes a large number of hindrances in improving the design, trouble shooting of the inclined system, and to optimise the layouts of a solid circulation and mixing system.

O'dea *et al.* [1] proposed that three flow regimes might exist in both particulate and aggregative inclined fluidised beds. Those were the fixed bed, partially fluidised bed and fully developed fluidised bed regimes. The development of a fluidised bed channel along the upper wall of the inclined bed differentiated the first two flow regimes. In other word, O'dea *et al.* [1] stated that fluidisation in an IFB started by packed bed regime, when superficial air velocity was less than channel break through velocity ( $U < U_{cb}$ ) and followed by steady channelled bed regime, when superficial air velocity was similar or higher than the channel break through velocity ( $U \geq U_{cb}$ ). It was also reported by O'dea *et al.* [1] that the channel break through condition was independent of bed dimension and fluidising medium.

### 1.1 Minimum Fluidisation Velocity

Yamazaki *et al.* [2] were possibly the first to propose that the fluid dynamics in an IFB was not closely similar to that of a conventional fluidised bed. They proposed that fluidisation in an inclined fluidised bed started by channel development and followed by steady fluidisation. The aeration corresponding to the initial fluidisation (channel development) was called the initial minimum velocity ( $U_{mfi}$ ) and the aeration corresponding to steady or complete fluidisation was called the steady minimum velocity ( $U_{mfs}$ ). The difference between the two velocities increased with the angle of inclination. Hence, by considering the effect of the bed inclination, angle of repose of particle ( $\phi_r$ ) and internal friction ( $\phi_l$ ) of the particles in the overall force balance of the bed they derived two equations to predict both minimum fluidisation velocities.

$$U_{mfi} = \frac{\rho_p (\phi_p d_p)^2 g (\varepsilon_{mf})^3}{150\mu (1 - \varepsilon_{mf}) (\cos \theta + \phi_l \sin \theta)} \quad (1)$$

$$U_{mfs} = \frac{\rho_p (\phi_p d_p)^2 g (\varepsilon_{mf})^3 (1 - 0.0833 \tan (\theta + \phi_r))}{150\mu (1 - \varepsilon_{mf}) (\cos \theta + \phi_l \sin \theta)} \quad (2)$$

Unfortunately, a large discrepancy between the experimental and calculated result for glass powder occurred although the calculated curves provided a relatively good representation of the experimental data. This probably was caused by their assumption that internal friction of bed materials was more significant than that of interparticle friction.

In the case of inclined fluidised bed with partitions, Baskakov and Skachkova [3] reported that correlation between angle of repose ( $\phi_r$ ) and the ratio of  $U/U_{mf}$  approached parabolic.

$$\tan \phi_r = \left(1 - \frac{U}{U_{mf}}\right)^2 \tan \phi_{ro} \quad (3)$$

The gas velocity through the layer of the bed can be evaluated using simplified Ergun's equation [3]:

$$U = \left[ \frac{\Delta P_b \varepsilon d_p}{1.75 \rho_f H (1 - \varepsilon)} \right]^{0.5} \quad (4)$$

## 1.2 Pressure Drop

Based on theoretical and experimental basis, O'dea *et al.* [1] suggested the simplified Ergun's equation to predict the pressure drop in the packed bed regime for  $Re < 20$  as:

$$\frac{\Delta P_b}{L} = 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \frac{\mu_f U}{(\phi_s d_m)^2} \quad (5)$$

Yamazaki *et al.* [2] estimated the ratio of pressure drops in the initial fluidisation ( $\Delta P_{mfi}$ ) and steady fluidisation ( $\Delta P_{mfs}$ ) to the pressure drop at minimum fluidisation of conventional fluidised bed ( $\Delta P_{mf}$ ) as:

$$\frac{\Delta P_{mfi}}{\Delta P_{mf}} = \frac{1}{\cos \theta + \phi_l \sin \theta} \quad (6)$$

$$\frac{\Delta P_{mfs}}{\Delta P_{mf}} = \frac{(1 - 0.0833 \tan (\theta + \phi_r))}{\cos \theta + \phi_l \sin \theta} \quad (7)$$

The initial fluidisation happened when the horizontal stress on the wall of the bed was zero, and this bed was then supported by the balance between the frictional resistance due to the vertical stress and the shear stress acting on the vertical plane of the bed [2]. At steady fluidisation, the surface of the bed formed a plane of repose. The bed surface was not normal to the wall, but was almost the angle of repose to the

horizontal plane. The gas concentrated next to the upper wall and bubbles were formed. Gas was then drawn from the lower bed regions to the bubbles, and fluidisation extended progressively down through the bed. Therefore,  $\Delta P_{mfs}$  becomes lower than  $\Delta P_{mfi}$  with the difference between the two being independent to the extent to which the gas was concentrated next to the upper wall at the surface of the bed.

The major difference between the model proposed by Yamazaki *et al.* [2] and O'dea *et al.* [1] was that the internal friction and angle of repose were treated as variable. Although this assumption produced better estimation of the overall pressure drop, it still has significant deviation with the experimental data and results in additional time consuming. This discrepancy might happen because the angle of internal friction ( $\phi_l$ ) of a mass of particles in steady shear was greater than the angle of interparticle friction ( $\phi_\mu$ ). The difference between  $\phi_\mu$  and  $\phi_l$  was due to the increased internal friction losses resulting from large number of relative movements and contacts between particles in a particle assembly in steady shearing flow, even though the ratio of tangential to normal force at each particle contact nowhere exceeds  $\tan \phi_\mu$ .

There are several factors that may affect the minimum fluidisation velocity of an IFB. Those are particle size, density, and composition of mixed bed particles [3], angle of inclination [1,2], temperature and pressure [4].

## 2.0 EXPERIMENT

### 2.1 Material

The particle used in this work was sand particle having average diameter 530  $\mu\text{m}$ , true particle density 2400  $\text{kg/m}^3$ , bulk density 1500  $\text{kg/m}^3$ , bed voidage 0.37 and sphericity 0.92.

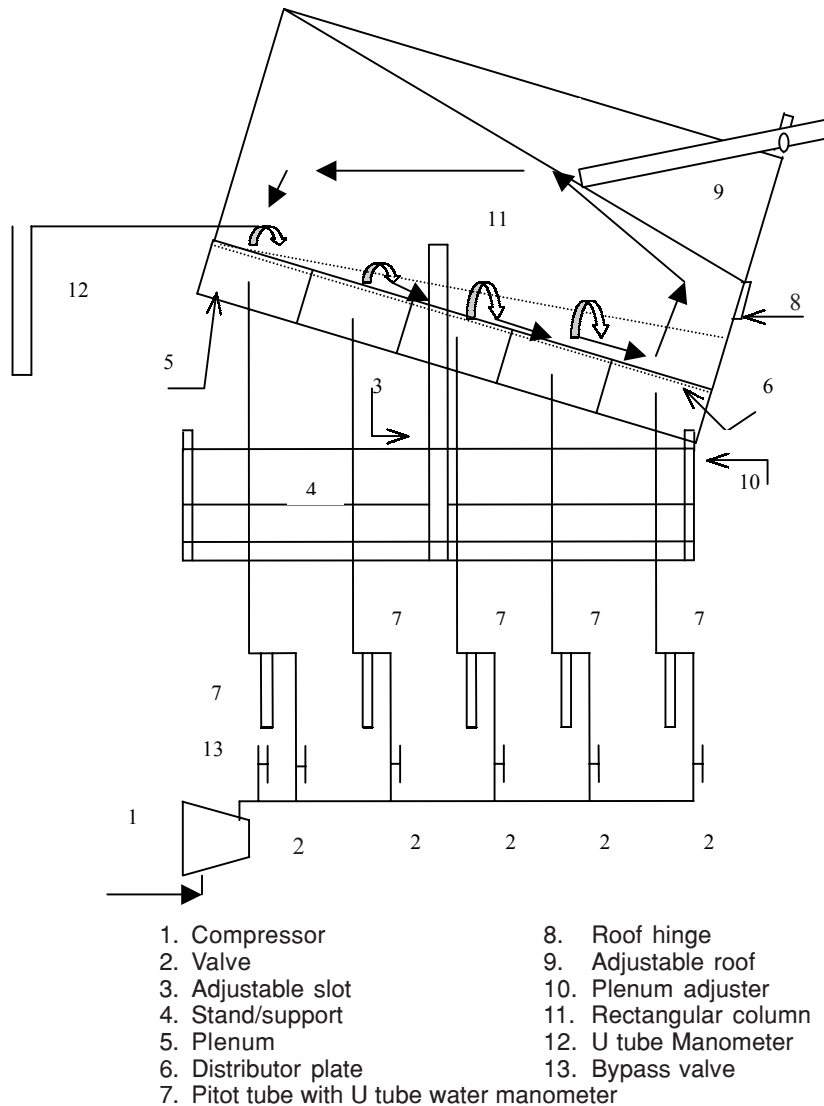
### 2.2 Equipment

The experimental rig used in this research work was a rectangular fluidised bed column of dimension,  $7 \times 50$  cm fitted with a 2 mm thick metal distributor plate with 1 mm diameter holes (2.98 % opening area), water manometer, flow meter and compressor for fluidising air supply. The detail of this apparatus is depicted in Figure 1.

### 2.3 Procedure

Approximately 500 grams of sand was charged into the column, which gave a bed depth of about 8 cm. The bed was initially fluidised in vigorous manner by flowing fluidising air at high velocity in order to breakdown any packing of particles and to assure that this minimum fluidisation velocity measurement is reproducible.

The gas flow rate was then decreased from 500 L/min to zero in a decrement of 10 L/min and corresponding pressure drop was recorded. The volumetric flow rate divided by the cross sectional area gave the required superficial gas velocities. The pressure



**Figure 1** Schematic diagram of the Perspex model inclined fluidised bed.

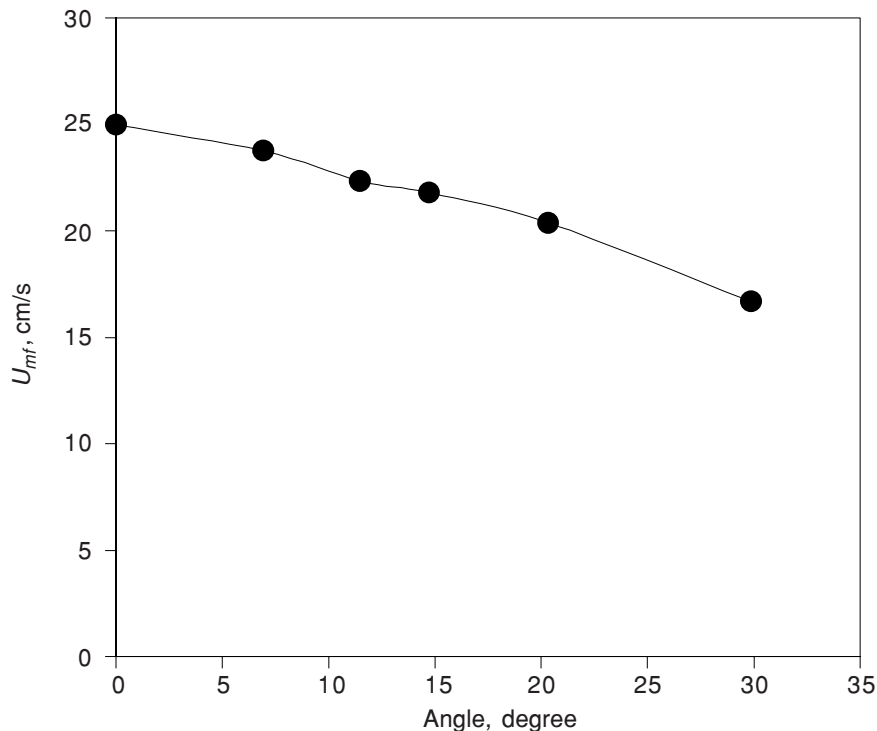
drop of the bed against the gas velocity was plotted to determine the  $U_{mf}$ . The intersection of the sloping line and the horizontal line of the graph is the minimum fluidising velocity. The initial fluidisation was also investigated visually. The fluidising air velocity at which bubbles were first appeared is called minimum bubbling velocity,  $U_{mb}$ . In gas-solid beds of large particles, bubbles were created as soon as the gas velocity exceeded the minimum fluidisation velocity; therefore  $U_{mb}$  equal to  $U_{mf}$  [5]. The minimum fluidisation velocities of particles in the IFB were determined in the range within 0 to 30 degree of inclination.

### 3.0 RESULTS AND DISCUSSION

The results of this experimental work are reported in the following section. Figures 2, 3 and 4 show the effect of inclination angle, particle size and mixed particle composition to the minimum fluidisation velocity, respectively.

#### 3.1 Effect of Angle of Inclination on the Minimum Fluidisation Velocity ( $U_{mf}$ )

From Figure 2, it is clearly shown that the increased of inclination angle decreased the  $U_{mf}$ . This result is in good agreement with the experimental result reported by Yamazaki *et al.* [2] and O'dea *et al.* [1] for inclined standpipes fluidised bed. When the value of the angle is zero, the fluidised bed is considered as vertical fluidised bed. As the inclination increased, the gravity effect on the bed media reduced. The effective gravitational force became the product of cosine ( $\theta$ ) and the normal gravitational force. This inclined orientation lead to lowering of the minimum fluidisation velocity of the particle. When the fluidised bed was inclined, the particle layers tended to experience sliding flow caused by interparticle friction force and shear stress acting to



**Figure 2** Effect of inclination angle on the  $U_{mf}$  (particle size 530  $\mu\text{m}$ , true particle density 2400  $\text{kg/m}^3$ , bulk density 1500  $\text{kg/m}^3$ , bed voidage 0.37 and sphericity 0.92).

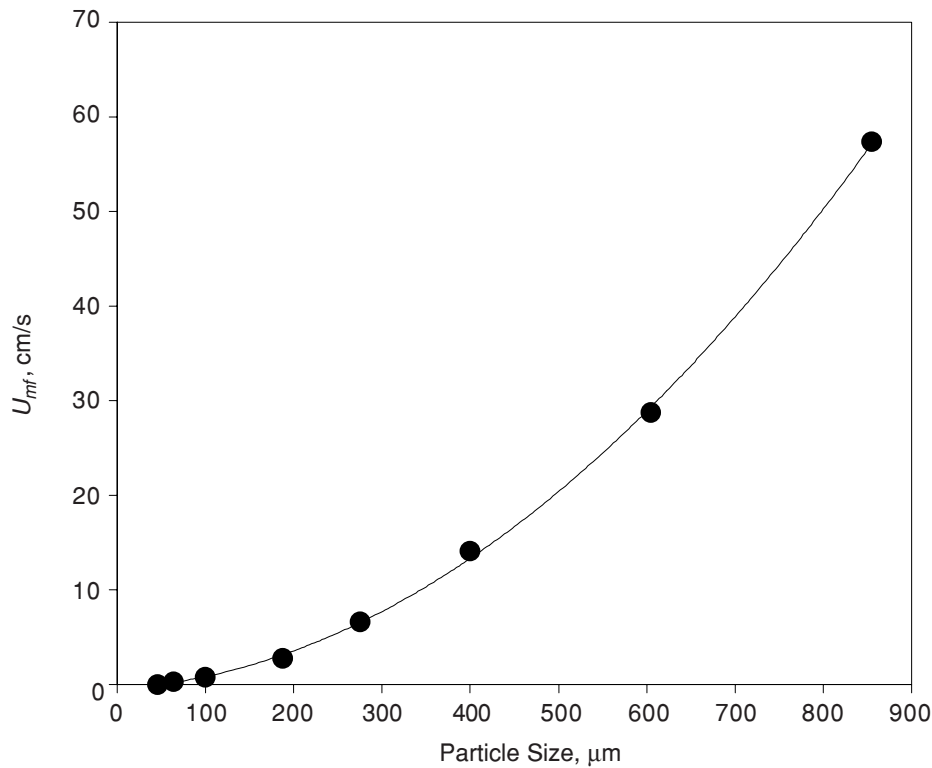
the respective particles besides the normal fluidisation. The visual investigation showed that at a low air velocity, the whole bed of particle in the IFB remained fixed. The fluidising air merely percolated through void spaces among the stationary bed particles. At a higher air velocity, different phenomena were investigated, a condition was reached at which the particles at the intersection between the upper wall and the bed free surface were fluidised. As the air velocity further increased, the channel of fluidised particles and air extended for greater distances down the upper side of the bed, not disturbing the major portion of the bed that was remained in the packed bed state. A transition regime was observed when the channel broke through the distributor plate. At this condition, a fluidised channel of particles and air extended from the distributor through to the free surface created a channelled bed. As the channel had a less resistive path for airflow than the adjoining packed bed section, the entering air excess of that required to create the channelled bed redirected into the fluidised channel and bypassed the major packed bed section. Paterson *et al.* [6] reported that channelling might also occur naturally in moving beds subjected to counter current gas flow, the existence of preferred channels for gas flow would correspond to regions of larger voidage than their surrounding.

### 3.2 Effect of Particle Size to the Minimum Fluidisation Velocity ( $U_{mf}$ )

The size of particle has a significant effect on the minimum fluidisation velocity. The value of minimum fluidisation velocity of particles with equal density for different sizes is shown in Figure 3. The minimum fluidisation velocity, which was required to initiate fluidisation of bed particles, increased as the particle size increased. This finding is in agreement with the investigation of agglomeration in a fluidised bed combustor conducted by Reddy and Mahapatra [7]. They stated that the bigger particles were denser and caused an increase in minimum fluidisation velocity.

Wiman and Almsted [8] reported that gas-particle interaction increased with the decreasing particle size. The smaller particles had bigger individual specific surface area and lead to greater friction from the fluidising media. Minimum fluidisation velocity was defined as a condition where the drag force of the particles especially caused by friction between the particle and fluidising media counterbalanced the net weight of the particle [5]. Therefore, the smaller particle needed lower fluidising gas velocity to fluidise as they got greater effective drag force from the fluidising media at the same weight with the bigger particle.

Reddy and Mahapatra [7] also investigated that the chance of two particles to hit each other and then stuck together depend upon the surface of the particles. Seville *et al.* [9] proposed that intermolecular forces depend more on the particle surface properties rather than on the bulk, so that it might be more plausible to assume a surface roughness and used this to determine the curvature. The Van der Waals force depended upon this local curvature and is independent on particle diameter. Seville *et*



**Figure 3**  $U_{mf}$  of equal density particles with different size at 0 degree of inclination (true particle density  $2400 \text{ kg/m}^3$ , bulk density  $1500 \text{ kg/m}^3$ , bed voidage 0.37 and sphericity 0.92).

*al.* [9] gave an example that spherical particles of diameter  $100 \mu\text{m}$  should exhibit interparticle Van der Waals force that equals to their single particle weight. These  $100 \mu\text{m}$  particles were usually found adhering to surface and resisting the force of gravity, while particles having  $1 \text{ mm}$  diameter were not. Hence, the smaller particles needed less fluidising gas velocity to fluidise as their interparticle forces had counterbalanced their gravitational force. In contrast, the bigger particle needed higher fluidising gas velocity to fluidise, as the fluidising gas had to overcome the gravitational force.

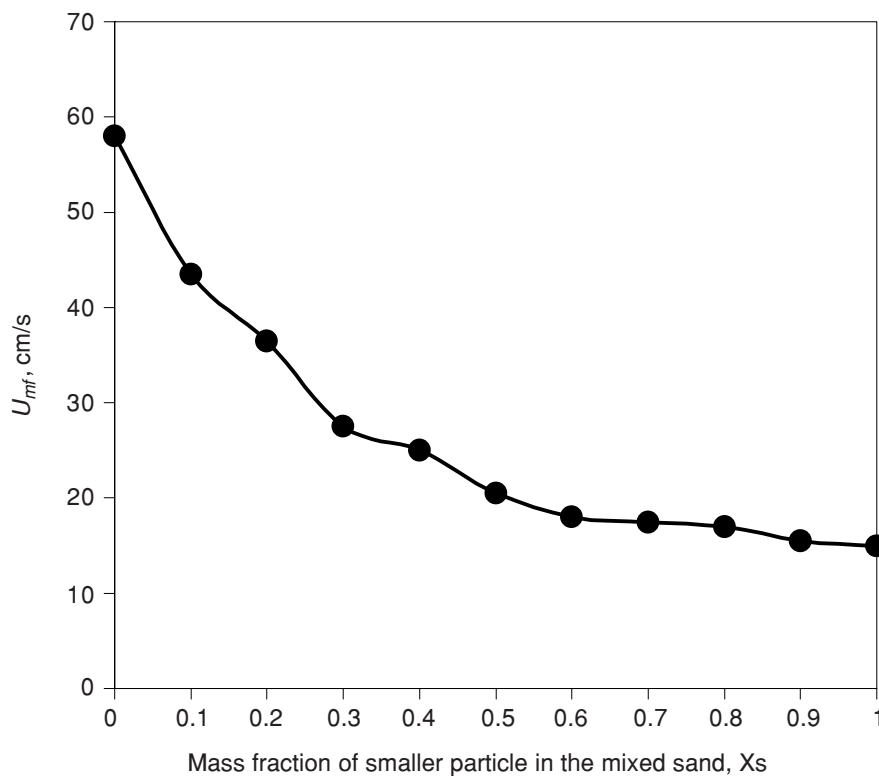
For very fine particles (particles with diameter less than  $20 \mu\text{m}$ ), the gas flow would be consistently within the laminar flow regime [4]. The Reynold's numbers in this work were less than 20, therefore the flow of fluidising gas through the bed of particles might be considered as laminar flow pattern. This opinion was reasonable because the loss of viscous force was more significant than that of the loss of kinetic force.

Therefore, the Ergun's prediction could be simplified into:  $U_{mf} = \frac{(\rho_p - \rho_g) d_p^2 g}{C \mu_g}$  with a high confidence.



### 3.3 Effect of Particle Composition to the Minimum Fluidisation Velocity ( $U_{mf}$ )

The effect of particle composition to the minimum fluidisation of mixed sand is depicted in Figure 4. When a small amount of fine powder ( $30\ \mu\text{m}$ ) is added to a coarser particle, the minimum fluidisation velocity of the mixture is often much less than that of the coarse one. This is because the addition of fines might improve the quality of fluidisation, for a certain gas flow rate, such addition of fines would increase the multiple of  $U_{mf}$  at which the bed is fluidised. Minimum fluidisation velocity reduced with respect to the minimum fluidisation velocity of large particles when the average diameter increased for binary powders. Seville *et al.* [9] reported the improvement of the flowability of fine or sticky powders by the addition of larger particles even though there appeared to be no investigation made of the shear behaviour of particle mixtures.



**Figure 4** Effect of Particle Composition to  $U_{mf}$  at 0 degree of inclination (smaller and bigger particle diameter were  $400\ \mu\text{m}$  and  $855\ \mu\text{m}$ , respectively), true particle density  $2400\ \text{kg/m}^3$ , bulk density  $1500\ \text{kg/m}^3$ , bed voidage 0.37 and sphericity 0.92.

During the flow of a mass of mixed particle sizes, large particles moved bodily while the material sheared across the fines. The coarse particles were a passive agent and like aggregate in concrete, they did not develop yield strength without fines to bind them.

In this experiment, the diameter ratio of smaller particle ( $400\ \mu\text{m}$ ) to bigger particle ( $855\ \mu\text{m}$ ) or ( $d_s/d_b$ ) was 0.4678. As observed by Cheung *et al.* [3] in the vertical fluidised bed, the packing of a mixture of particles with  $d_s/d_b$  more than 0.417 might be in the form of loosest packing. At this condition, the smaller sphere would pass between four equi-sized larger ones. Hence, it was of high probability for both sands to mix well at low fluidisation velocity. While at small values of  $d_s/d_b$  a good mixture was not possible and some segregation was more likely to happen.

#### 4.0 CONCLUSIONS

It can be concluded that the mechanism of fluidisation in an inclined fluidised bed was different with vertical fluidised bed due to the channel development. The effect of inclination angle to the minimum fluidisation velocity was observed to follow an inverse relationship. On the other hand, the particle size and bigger particle mass fractions in the mixed sand gave linear effects to the minimum fluidisation velocity.

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#### LIST OF SYMBOLS

$C$	Constant of simplified Ergun's equation, dimensionless.
$d_m$	Mean particle diameter, $\mu\text{m}$
$d_p$	Particle diameter, $\mu\text{m}$
$g$	Gravitational acceleration, ( $\text{m/s}^2$ )
$H$	Bed height, (m)
$L$	Bed length, (m)
$\Delta P$	Pressure drop, ( $\text{N/m}^2$ )
$\Delta P_{mf}$	Pressure drop at minimum fluidisation of conventional fluidised bed, ( $\text{N/m}^2$ )
$\Delta P_{mfi}$	Pressure drop at minimum initial fluidisation of inclined fluidised bed, ( $\text{N/m}^2$ )
$\Delta P_{mfs}$	Pressure drop at minimum steady fluidisation of inclined fluidised bed, ( $\text{N/m}^2$ )

$U$	Superficial gas velocity, (m/s)
$U_{mf}$	Superficial gas velocity at minimum fluidisation, (m/s)
$X_s$	Weight fraction of smaller particles, dimensionless

### GREEK LETTERS

$\varepsilon$	Bed voidage, dimensionless
$\varepsilon_{mf}$	Bed voidage at minimum fluidisation, dimensionless
$\phi_l$	Angle of internal friction, rad.
$\phi_r$	Angle of repose of the particle, (degree)
$\phi_{ro}$	Angle of repose of the particle without gas filtration, (degree)
$\phi_u$	Angle of particle interparticle friction, (rad)
$\theta$	Angle of inclination of bed to horizontal, (degree)
$\phi_s$	Particle sphericity, ( $m^3/m^3$ )
$\mu_f$	Fluid viscosity, (kg/(m .s))
$\mu_g$	Gas viscosity, (kg/(m .s))
$\rho_b$	Bulk density, ( $kg/m^3$ )
$\rho_g$	Gas density, ( $kg/m^3$ )
$\rho_p$	Particle density, ( $kg/m^3$ )

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