ISBN : 81-87053-53-4
Processing of Fines (2)
Eds. : P. Bhattacharyya, R. Singh and N. G. Goswami
© NML Jamshedpur-831 007, India, 2000, pp. 345-361

Studies on particle suspension in air-agitated Pachuca tanks

S. P. MEHROTRA and R. SHEKHAR
Indian Institute of Technology, Kanpur 208 016, India

ABSTRACT

The paper presents the findings of an investigation involving extensive experiments on three laboratory scale Pachuca tanks to examine the effect of design and operating parameters, as well as scale up on particle suspension. Some important results, crucial to the design and scale up have emerged. Full center column (FCC) Pachucas with a draft tube to tank diameter ratio (Dd/Dt) on the order of 0.1 are found to be energetically more efficient in suspending particles than Free-Air Lift (FAL) and Stub Column (SC) Pachuca tanks. It has been established that the energy required for generating suspension from settled particles is more than that is required for maintaining the particles already in suspension. The magnitude of hysterisis in FCC Pachuca tanks is of the order of 20%. Effect of novel split air injection technique on critical velocity for particle suspension has been rigorously investigated. Split air injection, with 30% air injected into the annulus from top and 70% air injected from the bottom into the draft tube lowers the critical air velocity for particle suspension by about 37% with respect to bottom blown Pachuca tanks. Mechanisms for particle suspension in bottom blow Pachucas as well as those with split air injection are proposed.

***Key Words:** Pachuca-tank, Air-agitated tanks, Particle-suspension, Optimum-design, Hysterisis*

INTRODUCTION

Pachuca tanks, used in the hydrometallurgy industry for leaching of such non-ferrous metals as gold, uranium, zinc and copper, are air agitated slurry reactors. These are cylindrical vessels with conical bottom, upto 16 m high and 10 m in diameter, and are generally classified as (Fig. 1): (1) free air lift (FAL), where the draft tube is absent; (2) full center column (FCC) which have full length draft tube; and (3) stub-column (SC), which are equipped with a foreshortened draft tube. More details about these reactors are available elsewhere[1-3]. The principal objectives in the operation of Pachuca tanks are suspension of particles, dissolution of solid ore particles (solid-liquid mass transfer), and the mixing. Harriot[4] has shown that beyond the point of complete off-bottom suspension an increase in solid-liquid mass transfer is not as significant as compared to the initial stages of suspension. Since these tanks are operated with slurries containing 50-60 weight percent solid, particle suspension is the most important parameter in the design of energy-efficient Pachucas.

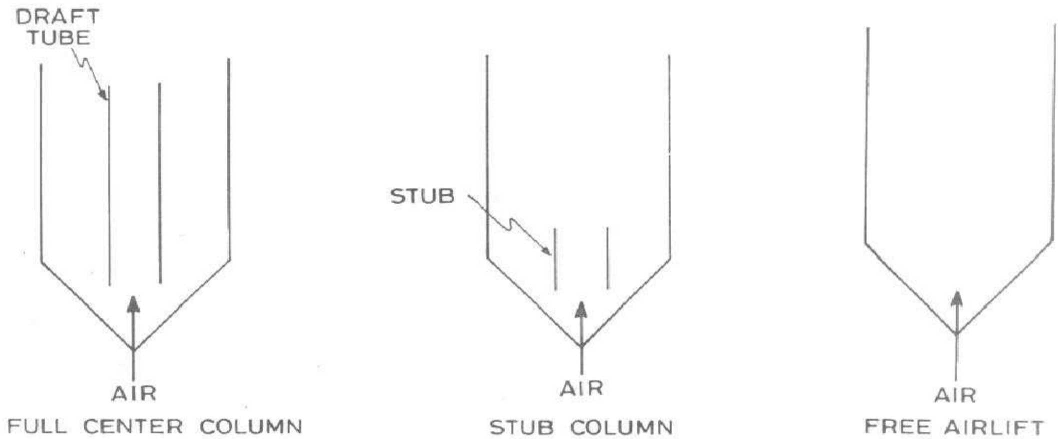


Fig. 1: Classification of Pachuca tanks

This paper presents an overview and summary of the investigations carried out in our laboratory to determine the optimum Pachuca tank configuration by examining the influence of change in the design and operating parameters on the minimum superficial air velocity, referred to as the 'critical air velocity', required to keep the particles in suspension. Experimental data have been used to develop a mathematical model for predicting critical air velocities in industrial Pachucas, based on a mechanism proposed by us. Since it is now well established that the FCC configuration is more efficient in suspending particles than the other two configurations, the major emphasis in this presentation has been given to the former.

Critical air velocity can be defined separately for "maintaining" and "generating" suspensions. For maintaining suspensions, critical air velocity is defined as the superficial air velocity below which particles start settling from a state of complete suspension. On the other hand, critical air velocity for generating suspension is defined as the superficial air velocity above which particles are suspended from a completely settled state. There is a possibility of "hysterisis", for the "two" critical air velocities may be different. Both definitions of critical air velocity have practical relevance. In practice, several Pachucas are operated in series and slurry is continuously fed through each tank. Hence the critical air velocity should be such that solid content of the slurry is "maintained" in suspension. Also, because of power failure or maintenance-related work, air injection into the Pachuca is disrupted leading to a complete settling of particles from the slurry. Under such conditions, the air compressor should have the capability to resuspend the settled solids, and hence its power rating should conform with the critical air velocity required to generate suspension.

Another important aspect is the extent of suspension desirable in Pachuca tanks. While in most investigations particle suspension has been characterized interms of 'complete off-bottom suspension', Roy et al.[5] have used the 'on-set of suspension' to characterize particle suspension. The 'critical velocity' defined with respect to 'on-set of suspension' is the superficial velocity below which all particles settle at the bottom of the tank. A question now arises: should the operating superficial air velocity be in consonance with the critical velocity defined with respect to 'complete off bottom suspension' or the 'on-set of suspension'? The mode of air injection is also an important aspect of Pachuca design. In most conventional Pachucas, air is injected from the bottom only. The effect of split air injection, i.e. addition of air from the bottom as well as top, is also examined, and a comparison of different modes of air injections with respect to the efficacy of particles suspension in Pachucas is made.

EXPERIMENTAL APPARATUS AND MEASUREMENTS

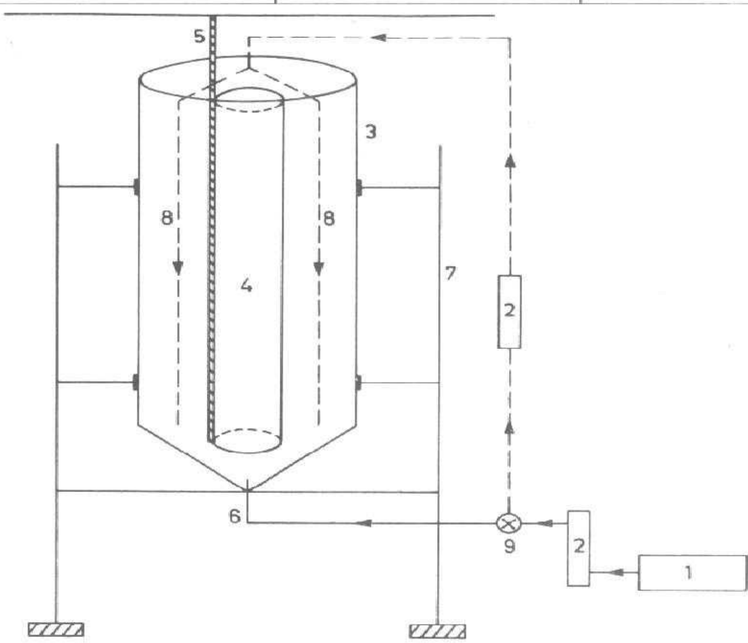
The laboratory scale Pachuca tanks were designed such that important design and operating parameters, namely, H_t/D_t, D_d/D_t, cone angle and superficial air velocity, U_g were in the same range as typically used in industry (see Table 1).

Experimental Set-up

The experimental set-up, schematically shown in Fig. 2, consisted of a laboratory scale Pachuca tank, a rotameter, a manometer and an air compressor. Pachucas were made of Perspex. Initially a cylindrical tank with a flat bottom was constructed. The conical base was then simulated by inserting a cone, with a (half) cone angle of 45°, at the bottom. Three tanks with diameters of 0.15, 0.25 and 0.36 m and heights 0.45, 0.75 and 1.05 m, referred to as tanks 1, 2 and 3 respectively, were used in our experiments. The draft tube was clamped on to a vertical rod that was suspended from the top through a super structure above the tank. The bottom end of the draft tube was always positioned at a fixed distance of 0.1 Hc from the cone wall, while the top end was at a distance of 0.15 Hd below the free surface of water. A single nozzle, with $D_t/D_n = 80$, was placed 0.1 m below the bottom end of the draft tube. To get a clear view of particle motion near the tank bottom, the conical portion of the tank was illuminated.

Table 1 : Different design and operating parameters used in laboratory and industrial tanks

Parameter	Industry	Laboratory
$Ug \times 10^{-2}$ (m/s)	0.1 - 0.75	0.1-1.0
D_d/D_t	0.1	0 - 0.3
D_t/D_n	-	80
H_t/D_t	1.0 to 3.0	3.0
Cone angle	30 to 60 deg	45 deg
Wt pct solids	50 to 60	5 to 25



(1) COMPRESSOR (2) ROTAMETER (3) TANK (4) DRAFT TUBE (5) DRAFT TUBE SUPPORT (6) AIR INLET (7) TANK SUPPORT (8) SIDE AIR TUBES FROM TOP (9) THREE-WAY VALVE

Fig. 2 : Schematic representation of the experimental set up

The structure shown by dashed lines in Fig. 2 was superimposed on the conventional Pachuca with bottom injection only, and this entire assembly was used in the experiments with split air injection, downwards into the annulus and upwards into the draft tube. Air injection into the annulus was made through two 0.003 m diameter tubes, symmetrically placed around the draft tube such that the air injection points were at the same level as the bottom end of the draft tube. The ratio of the horizontal distance between the tubes and the tank diameter was 0.4. A distributor valve was used in the compressor line to split air in a specified ratio[6].

White river sand with a density of 2500 kg/m^3 and particle size ranging between 150-250 (m was used as the solid particulate.

Determination of Critical Gas Velocity

Particle suspension in the present investigation has been characterized by visual observation. The bottom conical section of tank was illuminated to have a clear view of particle motion near the tank bottom. To ensure adequate visibility of solid particulates in slurry, experiments were carried out with slurry densities much lower than those generally employed in industrial Pachucas. At high slurry densities it was not possible to identify various stages of suspension. Each experiment was repeated 2-4 times and the mean values have been reported in this paper. Variation in the critical velocity values in most cases was less than 5%. Critical air velocities could be measured for both "generating" and "maintaining" suspensions. Depending on the criterion used for characterizing particle suspension, four critical air velocities can be defined[6].

U_{c1}: Critical velocity for 'on-set of settling' for a slurry which is initially in full suspension, i.e., the minimum velocity below which particles in a fully suspended slurry just begin to settle down.

U_{c2}: Critical velocity for 'complete settling' for a slurry which is initially in full suspension, i.e., air velocity below which all particles in slurry settle down.

U_{c3}: Critical velocity for 'on-set of suspension', i.e., the air velocity at which initially settled particles just begin to go into suspension.

U_{c4}: Critical velocity for 'complete suspension', i.e., the minimum air velocity at which all particles in the slurry are brought from fully settled state to full suspension state.

For measuring U_{c1} and U_{c2} air was initially injected at a high enough flow rate to ensure complete particle suspension. The air flow rate was then gradually reduced, and the suspension behaviour of particles continuously monitored. The air flow rate at which solid particles just began to settle on the cone wall was recorded as U_{c1}. On further reduction of the air flow rate, a stage came at Uc2, when recirculation of slurry stopped completely and all particles started settling. At this stage air injection was stopped. Once the particles fully settled, air injection was restarted and the air flow rate was slowly increased. The air flow rate at which solid particles just started getting into suspension corresponded to the critical air velocity U_{c3}. A further increase in air velocity above U_{c4} led to complete suspension of all particles, a state characterized by continuous motion of particles, or the absence of a static particle layer on the cone wall.

In the first set of experiments which were carried with bottom air injection to examine the effect of design and operation parameters, the critical air velocity corresponding to U_{c3} only was measured. For experiments carried out to establish the existence of 'hysterisis' and also with split air injection, all four critical air velocities were measured.

RESULTS AND DISCUSSION

Effect of Design and Operating Parameters

For conventional Pachucas with bottom injection only, experimental results describing the effect of particle size, slurry density, draft tube diameter, tank height, tank diameter are presented in this section. The critical superficial air velocity, U_c, wherever not specified, refers to U_{c3}.

Effect of particle size:

Fig. 3 shows the effect of particle size on U_c. It is seen that U_c increases with particle size and that an increase in U_c is more pronounced when particle size is changed from medium to coarse than from fine to medium. The reason for increase in Uc is straight forward. For similar slurry densities, particle settling velocity increases with particle size. Consequently, higher slurry velocities in the cone, and, therefore, higher U_c, are necessary to keep particles in suspension.

Effect of solid concentration:

Fig. 4 shows that U_c increases with solid concentration, the increase being more rapid between 10 to 13 wt pct than between 30 to 50 wt pct solids. The effect of weight percent solid on U_c is influenced by two counter factors. First, with an increase in the weight percent, solid turbulence at tank bottom is damped. Therefore, higher slurry velocities are required to attain the required level of turbulence for suspending particles. Secondly, the settling velocity of particles decreases with an increase in weight percent of solids, thereby requiring lower slurry velocities for suspending particles. At a low weight percent solid, the contribution of the second factor may be negligible leading to a steep increase in U_c with weight percent solid. At a high weight percent, however, the second factor may start to be important and, consequently, be responsible for relatively less rapid increase in U_c.

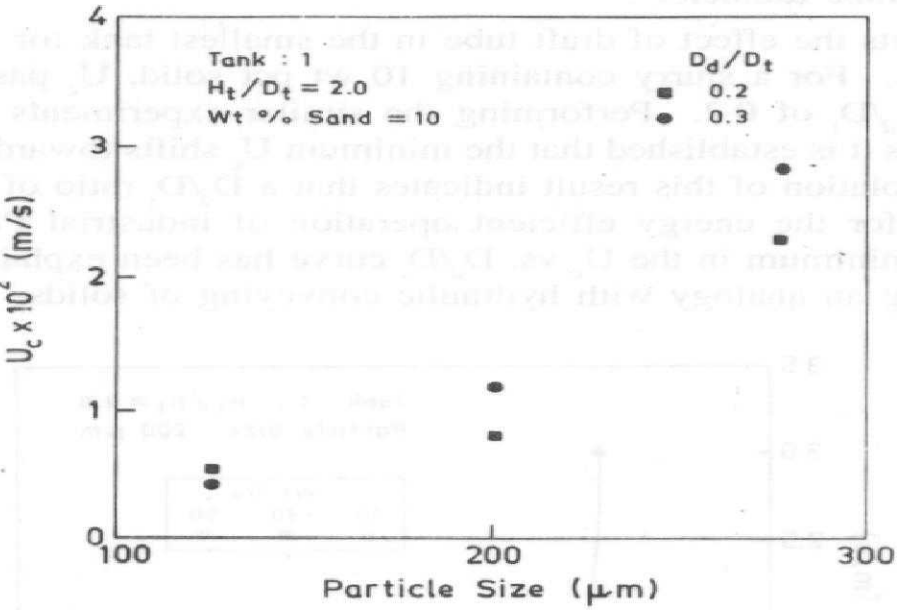


Fig. 3: Effect of particle size on critical air velocity[5]

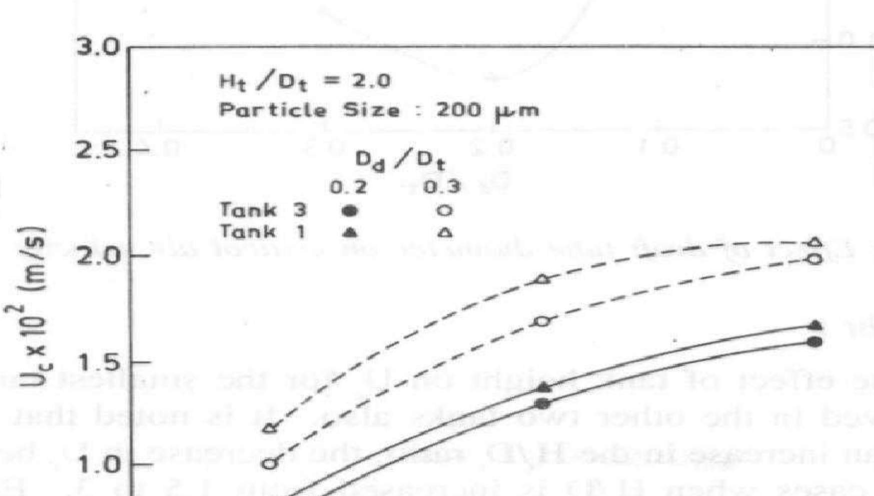


Fig. 4 : Effect of weight percent solid on critical air velocity[5]

Effect of draft tube diameter :

Fig. 5 depicts the effect of draft tube in the smallest tank for three different slurry densities. For a slurry containing 10 wt pct solid, U_c passes through a minimum at D_d/D_t of 0.2. Performing the similar experiments with tanks of larger diameters it is established that the minimum U_c shifts towards a D_d/D_t ratio of 0.1. Extrapolation of this result indicates that a D_d/D_t ratio of 0.1 should be recommended for the energy efficient operation of industrial Pachucas. The presence of a minimum in the U_c vs. D_d/D_t curve has been explained by Roy et al.[5] by drawing an analogy with hydraulic conveying of solids.

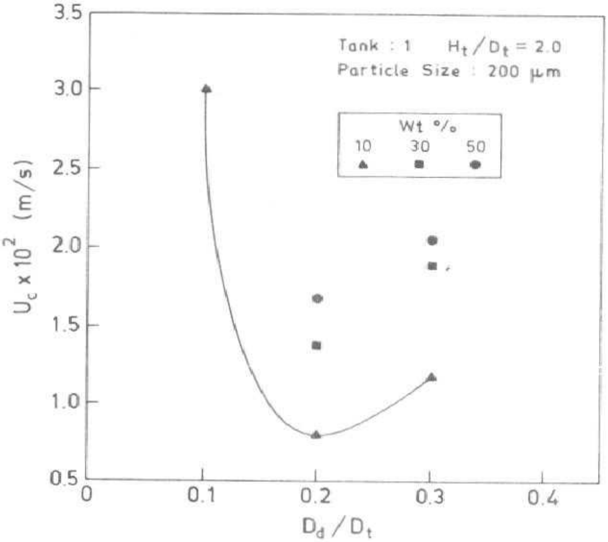


Fig. 5 : Effect of draft tube diameter on critical air velocity

Effect of tank height :

Fig. 6 shows the effect of tank height on U_c for the smallest tank. Similar behaviour is observed in the other two tanks also. It is noted that in all tanks Uc decreases with an increase in the H_t/D_t ratio; the decrease in U_c being as large as 45 pct in some cases when H_t/D_t is increased from 1.5 to 3. Experimental observations, as well as calculations of two-phase gas liquid flow in Pachucas[2,7] show that for a given superficial air velocity, liquid flow rate in the tank increases with tank height, which, in turn, increases U_{ld}. The increase in liquid flow rate is primarily due to the increase in potential energy supplied by air as it expands from a relatively higher pressure in taller tanks. A higher U_{ld} implies lower air velocities for particle suspension.

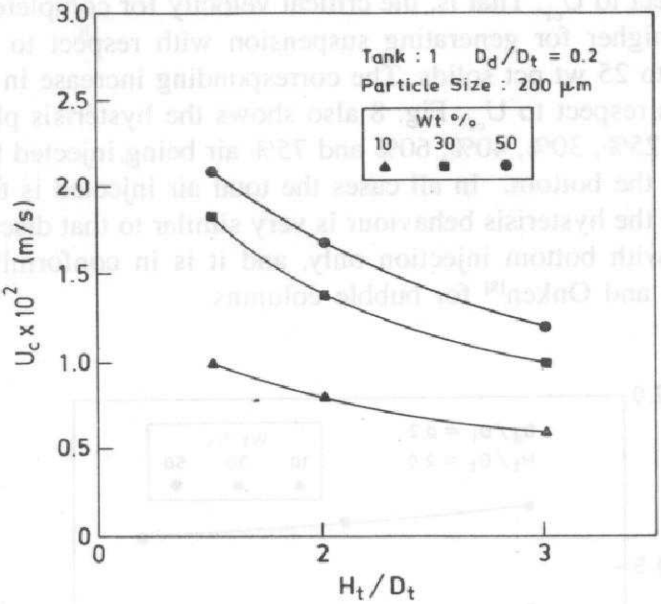


Fig. 6 : Effect of tank height on critical air velocity

Effect of tank diameter :

Fig. 7 shows the effect of tank diameter on U_c in FCC tanks at a $D_d/D_t = 0.2$ and an H_t/D_t ratio = 0.2. It is observed that U_c is not significantly affected by the variation in tank diameter. Similar results are also observed at other D_d/D_t and Ht/Dt ratios.

Hysterisis :

As mentioned above, to establish the existence of hysterisis in critical air velocities for "generating" and "maintaining" suspension, a large number of experiments were performed in which U_{c1}, U_{c2}, U_{c3} and U_{c4} were measured. Figure 8a shows a typical hysterisis plot for a bottom air injection case. It is seen that the critical air velocity for generating suspension is greater than that for maintaining suspension. For both complete suspension and onset of suspension hysterisis is defined as follows:

$$\Delta U_{cs} = U_{c4} - U_{c1}$$

$$\Delta U_{os} = U_{c3} - U_{c2}$$

From Fig. 8a it is apparent that both ΔU_{cs} and ΔU_{os} increase with weight percent solids in the slurry. ΔU_{cs} increases from 0.001 m/s at 5 wt pct solids to 0.004 m/s at 25 wt pct solids, which represents an increase in ΔU_{cs} from 15%

to 29% with respect to U_{c1}. That is, the critical velocity for complete suspension is 15% to 29% higher for generating suspension with respect to maintaining suspension for 5 to 25 wt pct solids. The corresponding increase in (U_{os} is from 25% to 32% with respect to U_{c2}. Fig. 8 also shows the hysterisis plots for split air injection with 25%, 30%, 40%, 60% and 75% air being injected from the top and the rest from the bottom. In all cases the total air injected is the same. It may be noted that the hysterisis behaviour is very similar to that discussed above for the Pachuca with bottom injection only, and it is in conformity with that reported by Heck and Onken[8] for bubble columns.

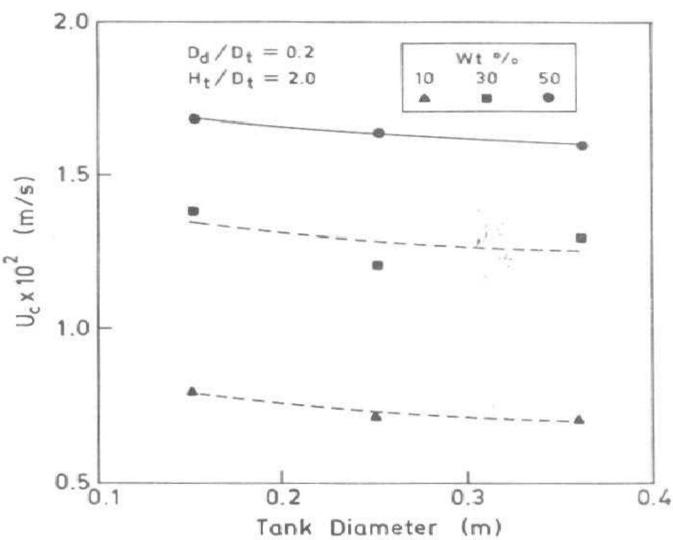


Fig. 7: Effect tank diameter on critical air velocity[5]

Split air injection :

Fig. 9 illustrates the effect of split air injection on U_{c4}. While solid lines are for a tank of 0.15 m diameter, dashed lines are for the 0.36 m diameter tank. The most fascinating aspect of this figure is that in both the tanks minimum U_{c4} occurs when 70% of the air is injected from the bottom and 30% in the annulus. A similar trend is also observed for the other critical velocities, namely Uc1, Uc2, and U_{c3}. These results clearly indicate that split air injection is desirable for operating energy-efficient Pachuca tanks.

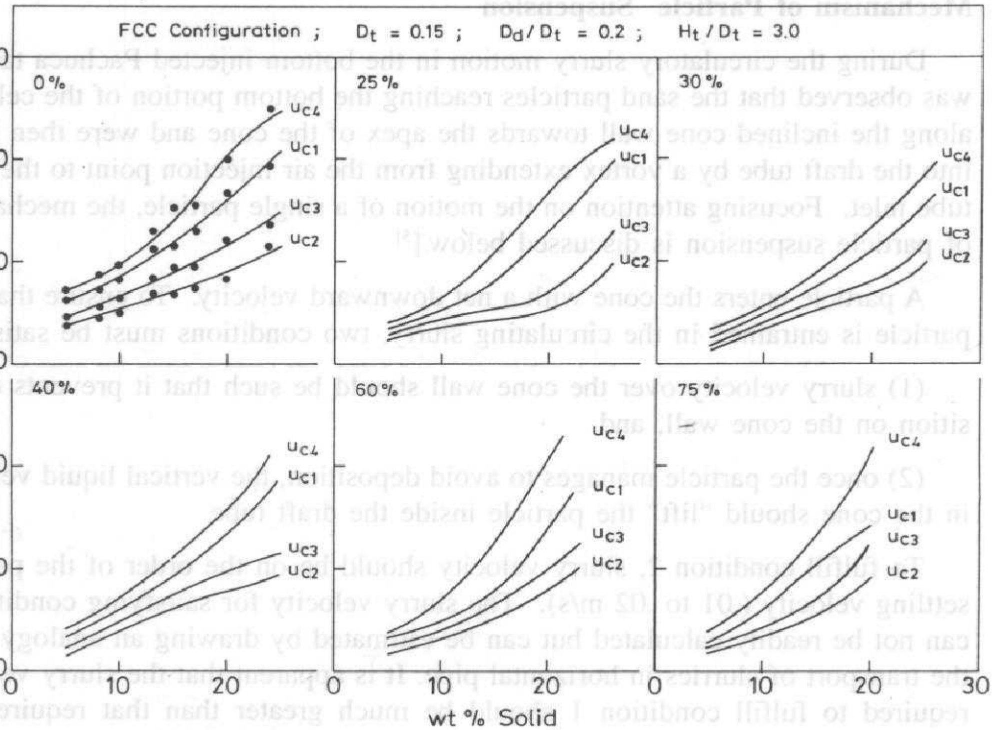


Fig. 8: Typical hysterisis plot showing experimentally measured critical air velocity as a function of wt pct solids for various top to bottom air injection ratios for a Pachuca tank of 0.15 m diameter

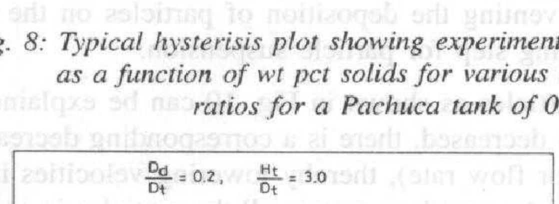


Fig. 9 : Effect of split air injection on the critical air velocity for complete suspension, U_{c4} [6]

Mechanism of Particle Suspension

During the circulatory slurry motion in the bottom injected Pachuca tank, it was observed that the sand particles reaching the bottom portion of the cell slid along the inclined cone wall towards the apex of the cone and were then lifted into the draft tube by a vortex extending from the air injection point to the draft tube inlet. Focusing attention on the motion of a single particle, the mechanism of particle suspension is discussed below.[5]

A particle enters the cone with a net downward velocity. To ensure that this particle is entrained in the circulating slurry, two conditions must be satisfied:

(1) slurry velocity over the cone wall should be such that it prevents deposition on the cone wall, and

(2) once the particle manages to avoid deposition, the vertical liquid velocity in the cone should "lift" the particle inside the draft tube.

To fulfill condition 2, slurry velocity should be on the order of the particle settling velocity (.01 to .02 m/s). The slurry velocity for satisfying condition 1 can not be readily calculated but can be estimated by drawing an analogy from the transport of slurries in horizontal pipe. It is apparent that the slurry velocity required to fulfill condition 1 should be much greater than that required for condition 2. Consequently, preventing the deposition of particles on the cone wall should be the rate controlling step for particle suspension.

The settling behaviour of particles as shown in Fig. 10 can be explained as follows[5]. As the air velocity is decreased, there is a corresponding decrease in the slurry circulation velocity (or flow rate), thereby lowering velocities in the cone. These velocities are not high enough to sustain all the particles in suspension. Consequently, some particles start depositing on the cone wall, thereby reducing the clearance between the draft tube bottom and sand layer. Because of continuity, the reduced clearance leads to higher velocities in the cone. As soon as the liquid velocity in the cone increases to a level such that condition 1 is satisfied, sand buildup on the cone wall stops. This sequence is repeated as the air velocity is further reduced to a lower value. However, below the critical air velocity, the sand layer comes in contact with the draft tube wall, stopping the circulation of slurry in the tank and resulting in the bulk settling of particles.

Air injection in the annulus promotes agitation inside the cone and the cylindrical section just above the cone (Fig. 11)[6]. Increased agitation, in turn, helps in:

(i) overcoming the inter-particle forces, thereby suspending particles, and

(ii) preventing the deposition of particles on the cone wall.

Agitation levels in the conical region are expected to increase with increasing air flow rates from the top. Another possible effect of air injection into the annulus could have been the release of some air bubbles into the annulus leading to a net decrease in the overall recirculation rate which would have the effect of increasing the critical velocities for suspension. However this phenomenon was discounted because experiments with clear water showed that release of free air bubbles into the annulus was negligible.

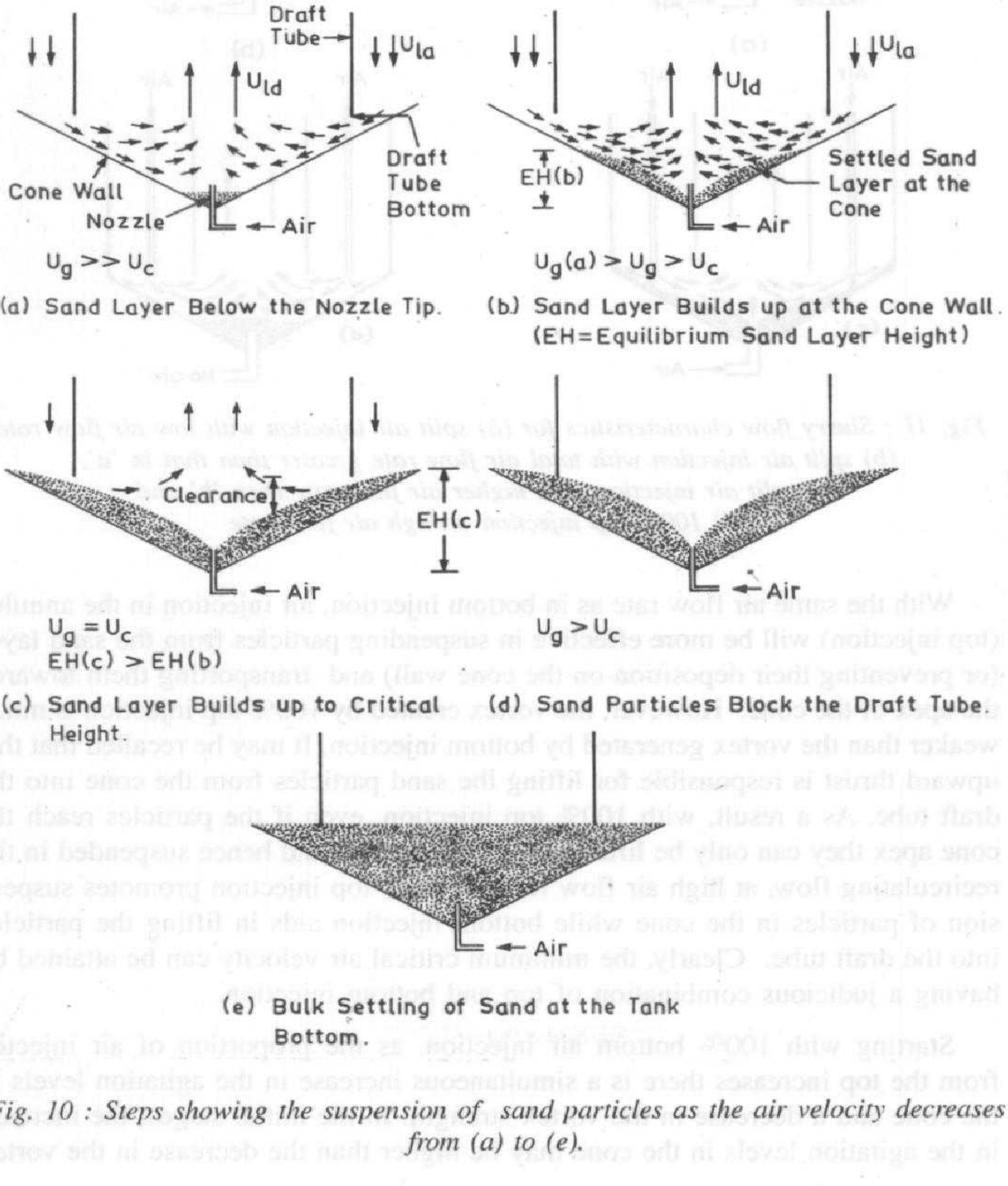


Fig. 10 : Steps showing the suspension of sand particles as the air velocity decreases from (a) to (e).

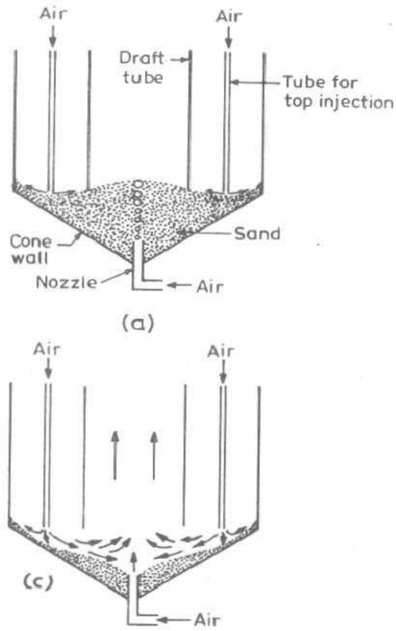


Fig. 11 : Slurry flow characteristics for (a) split air injection with low air flow rate, (b) split air injection with total air flow rate greater than that in 'a', (c) split air injection with higher air flow rate than 'b' and (d) 100% top injection at high air flow rate

With the same air flow rate as in bottom injection, air injection in the annulus (top injection) will be more effective in suspending particles from the sand layer (or preventing their deposition on the cone wall) and transporting them towards the apex of the cone. However, the vortex created by 100% top injection is much weaker than the vortex generated by bottom injection. It may be recalled that this upward thrust is responsible for lifting the sand particles from the cone into the draft tube. As a result, with 100% top injection, even if the particles reach the cone apex they can only be lifted into the draft tube, and hence suspended in the recirculating flow, at high air flow rates. Hence top injection promotes suspension of particles in the cone while bottom injection aids in lifting the particles into the draft tube. Clearly, the minimum critical air velocity can be attained by having a judicious combination of top and bottom injection.

Starting with 100% bottom air injection, as the proportion of air injected from the top increases there is a simultaneous increase in the agitation levels in the cone and a decrease in the vortex strength. In the initial stages, the increase in the agitation levels in the cone may be higher than the decrease in the vortex strength, thereby reducing the critical velocity for particle suspension. At higher air flow rates from the top, effect (ii) may start dominating effect (i). The two effects balance out at 30:70 top-bottom air injection ratio resulting in a critical velocity minimum.

Mathematical Model

Roy et al.[5] have formulated a mathematical model which may be used for optimum design and operation of industrial Pachuca tanks. Criterion for particle suspension is determined drawing an analogy from the horizontal transport of slurries. Combining the Bernoulli's equation and the theory of transport of particles in the horizontal flow the critical air velocity for particle suspension is predicted. The model essentially develops equations/correlations for superficial liquid velocities in the draft tube (U_{ld}) and in the annulus (U_{la}), and critical mean liquid velocity at the cone (U_{lc}). The details of the model are given elsewhere[5]. A comparison of predicted U_c values with those obtained experimentally is given in Fig. 12. Predictions from the mathematical model also confirm the trend obtained in our experiments with respect to D_d/D_t and H_t/D_t.

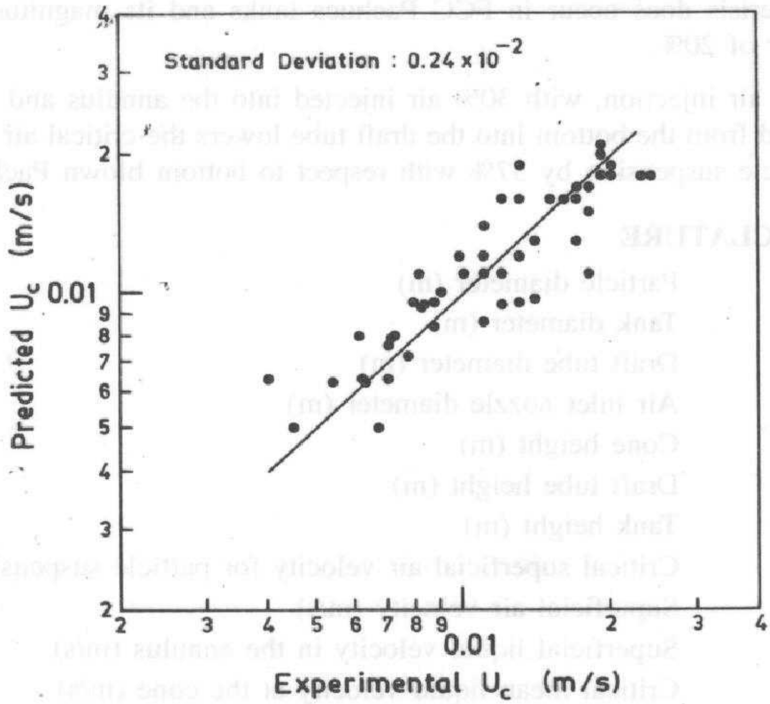


Fig. 12 : Comparison of predicted U_c values with those obtained experimentally[5]

CONCLUSION

Experiments have been carried out in laboratory Pachuca tanks to characterize: (i) effect of design and operating parameters on particle suspension, (ii) phenomenon of hysterisis, and (iii) effect of a new split air injection technique on the critical velocity for particle suspension.

Mechanisms for particle suspension in Pachuca tanks with bottom injection only and also with split air injection have been proposed. A mathematical model based on Bernoulli's equation and the theory of slurry transport, as proposed by Roy et al.[5], has been used to predict the critical air velocities for particle suspension (U_c) for various design and operating conditions. Predicted U_c values match reasonably well with those experimentally measured.

Following important results having bearing on industrial design and operation of Pachuca tanks have emerged:

1. For energy-efficient operation of FCC Pachuca tanks, the optimum D_d/D_t ratio should be on the order of 0.1.
2. Taller tanks should be operated at lower air flow rates than shallower tanks.
3. Hysterisis does occur in FCC Pachuca tanks and its magnitude is of the order of 20%.
4. Split air injection, with 30% air injected into the annulus and 70% air injected from the bottom into the draft tube lowers the critical air velocity for particle suspension by 37% with respect to bottom blown Pachuca tanks.

NOMENCLATURE

d_p	Particle diameter (m)
D_t	Tank diameter (m)
D_d	Draft tube diameter (m)
D_n	Air inlet nozzle diameter (m)
H_c	Cone height (m)
H_d	Draft tube height (m)
H_t	Tank height (m)
U_c	Critical superficial air velocity for particle suspension (m/s)
U_g	Superficial air velocity (m/s)
U_{la}	Superficial liquid velocity in the annulus (m/s)
U_{lc}	Critical mean liquid velocity at the cone (m/s)
U_{ld}	Superficial liquid velocity in the draft tube (m/s)
ΔU_{cs}	Hysterisis for complete suspension (m/s)

ΔU_{os}	Hysterisis for complete on-set of suspension (i.e. complete settling) (m/s)
$U_{c4}(0\%)$	U_{c4} for 100% bottom air injection (m/s)
$U_{c4}(30\%)$	U_{c4} for 30% top - 70% bottom split air injection (m/s)

Subscripts

cs	complete suspension
os	on-set of suspension
1	on-set of settling with respect to maintaining suspension
2	complete settling with respect to maintaining suspension
3	on-set of suspension with respect to generating suspension
4	complete suspension with respect to generating suspension

REFERENCES

1. Lamont A.G.W., (1958), "Air agitation and Pachuca tanks", Can. J. Chem. Engr., Vol. 36, p. 153.
2. Shekhar R. and Evans J.W., (1989), "Fluid flow in Pachuca (air-agitated) tanks" : Part 1. Laboratory scale experimental measurements, Metall. Trans. B, Vol. 20B, p. 789.
3. Hallett C.J., Monheniues A. J. and Robertson D.G.C., (1981), "Oxygen mass transfer in Pachuca tanks", In Extractive Metallurgy '81, Institution of Mining and Metallurgy, London, p. 308.
4. Harriott P., (1962), Mass transfer to particles: Part 1. Suspended in agitated tanks AIChEJ, Vol. 8, p. 93.
5. Roy G.G., Shekhar R. and Mehrotra S.P., (1998), "Particle suspension in (air-agitated) Pachuca tanks", Metall. Trans. B., Vol. 29B, p. 339.
6. Mehrotra S.P. and Shekhar R., "Particle suspension in (air-agitated) Pachuca tanks: Investigation of hysterisis and a novel split air injection technique", Metall. Trans. B (accepted for publ.).
7. Shekhar R. and Evans J.W., (1990), "Fluid flow in pachuca (air-agitated) tanks: Part 2. Mathematical modeling of flow in Pachuca tanks", Metall. Trans. B., Vol. 21B, p/ 191.
8. Heck J. and Onken U., (1987), "Hysterisis effects in suspended solid particles in bubble column with and without draft tube", Chem. Engg. Sci., Vol. 42, p. 1211.