Engineering Conferences International
ECI Digital Archives

10th International Conference on Circulating Fluidized Beds and Fluidization Technology - CFB-10

Refereed Proceedings

Spring 5-2-2011

Flow Rate of Solids in L-Valves

Duvvuri Subbarao
Universiti Teknologi Petronas

FLOW RATE OF SOLIDS IN L-VALVES

Duvvuri Subbarao
Department of Chemical Engineering,
Universiti Teknologi PETRONAS, Tronoh 31750, Malaysia

ABSTRACT

Movement of solids in a L-valve by fluid drag due to external aeration is opposed by frictional resistance at the wall/non-moving solids. Model equations developed for the threshold aeration rate and solids flow rate as a function of aeration rate compare well with the literature data.

INTRODUCTION

Transport of solids into and out of process equipment is of critical importance for smooth continuous operation of process units handling particulates such as circulating fluidized beds. Non-mechanical valves such as L-valve (L–shaped pipe) are widely used to control solid flow by fluid drag. Solids discharging from a cyclone at a pressure P_S flow and accumulate as packed bed of height H_U in the vertical standpipe of a L-valve as the drainage at the bottom is arrested by the presence of a horizontal pipe of length H_D. External aeration to the bottom section of the stand pipe at a pressure P_1 control solids flow through the horizontal pipe into the riser at pressure P_R. Pioneering work reported by Knowlton and Hirsan (1) on the characteristics of L-valves has excited further investigations (2 - 8) to explore the effect of particle properties and geometry of the valve on the particle flow rate W as a function of gas flow rate Q. It is to be noted that in industrial units $P_S > P_1 > P_R$ while in laboratory research units $P_S = P_R = P_2$. Some of the empirical correlations proposed to relate solid flux to gas velocity are summarized in Table 1.

Table 1: Correlations reported in the literature for sold flux through L-Valve

Reference	Correlation
Geldart and Jones (2)	$\frac{G_s}{D_t} = 3354\frac{u}{u_{mf}} - 2965$
Smolders and Baeyens (6)	$\frac{G_s}{D_t} = 79600\left(\frac{u}{u_{mf}}\right)^2 D_p^{0.6}$
Daous , Al-Zahrani (10)	$\frac{G_s}{D_t} = 1.08\frac{u}{D_p} - 5450$
Chan et l.(12)	$\frac{G_s}{D_t} = 0.0002\left[ln\left(\frac{u}{D_p}\right)\right]^{8.9}$

Yang and Knowlton (9) presented a model to estimate solid flow rate in a L-valve assuming no slip between flowing gas and particles; the net gas flow was assumed to include external aeration introduced along with the gas flowing through the solids in the standpipe; they adopted the equation of Jones and Davidson (10) (developed for particle discharge through an orifice from fluidized beds) for solids flow rate through an active flow area which increased with L-valve pressure drop; however, the correlation proposed by them reflects the universally observed need of a threshold aeration rate to initiate flow of solids. Daos and Al-Zahrani (11) and Tong and Zheng (12) considered gas-particle slip velocity to be described by Ergun's equation for flow through packed beds. Tong and Zheng (12) considered mechanics of particulate media flow in modeling gas and particle flows in a L-valve; they noted that external aeration rate can split into two streams – one flowing out horizontally through the bend and the other through the vertical stand pipe – depending on the relative resistance in each section for gas flow.

Asymmetry in the introduction of gas flow and two phase flow through a three dimensional 90^{o} bend in a L-valve makes particle flow visualization difficult. In an interesting piece of effort, Chan et al. (13) investigated particle motion by positron emission particle tracking technique to identify particle flow structure and observed solid flow to be stable for u/u_{mf} less than 6. They observed that maximum solid flow rate in a hopper fed laboratory L-valve is limited by the hopper discharge pipe diameter. Agarwal (14) investigated particle flow structure in a 2-dimensional L-valve made of 0.6 cm thick Perspex sheets with a cross sectional size of (13.8 cm x 2 cm). Effect of standpipe height (~150 to 100 cm), length of horizontal section (~30 to 50 cm) and particle size on solid discharge rate as a function of aeration rate were investigated. A typical solid flow trajectories are shown in Fig 1. For gas flow rates below threshold aeration, solids were stagnant; at and around the threshold aeration rate first movement of solids was observed near the 90^{0} bend at the upper edge of the L-valve; coordinates of points farthest from Y-axis upto which solids velocity is zero (y) were noted for each (x) coordinate; these points were plotted as shown in Fig. 1.

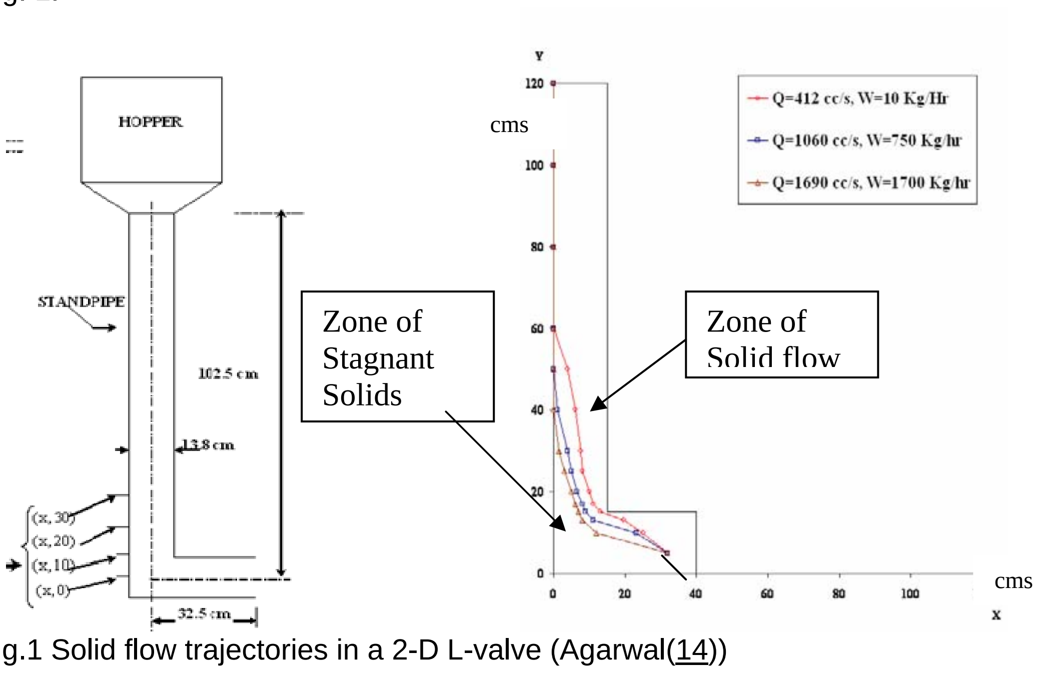

Fig.1 Solid flow trajectories in a 2-D L-valve (Agarwal(14))

At an aeration rate of 422 cc/s with a low solid flow rate of 10 kg/hr, particles movement was restricted to a rather narrow region very near the inside of 90^0 turn and along the top edge of the horizontal section over a stagnant layer; at the exit, particles rolled out over the slope dictated by angle of repose; cross sectional area of particle down flow in the stand pipe increased with distance away from the 90^o bend. At 750 Kg/hr, the stagnant region decreased in size and at 1700 Kg/hr it decreased further but still a substantial portion of the particles in the bend remained stagnant. Similar solid flow profiles were observed at different aeration point locations with the other particles.

A simple equation for solid flow rate as a function of the affecting parameters is needed for rational design of L-valves. In the present work, an attempt is made to develop equations for a L-valve operating with $P_S = P_R = P_2$ considering that a threshold aeration rate is needed to initiate solid flow and solids flow rate increases with fluid drag on particles while their movement is resisted by the drag due to wall / stationary particles on moving solids.

THE MODEL

The aeration rate Q provided to a stand alone L-valve containing particles in the standpipe and horizontal pipe in a packed bed form gets split into an up flow stream Q_U (through the standpipe) and downflow stream Q_D (through the horizontal pipe) depending on their relative packed bed resistance for gas flow. At a threshold aeration rate Q_{Th}, solids flow rate is initiated through a "small throat" at upper wall 90^o bend of the horizontal pipe as the gas drag force overcomes the friction between particles to wall/particles to push the particles to the edge where they roll over by gravity. Particles in the standpipe descend by gravity to the extent of solid flow through the horizontal section. As the particles descend in a section of the standpipe against the up flow aeration rate of Q_U, the gas to particle relative velocity in that section will be at the incipient fluidization condition as the bed voidage is around 0.5. The "small throat" diameter needs to be greater than $5xD_p$ to $10xD_p$ to overcome arching tendency. Further increase in external aeration through the L-valve increases the gas drag force on particles to increase solid flow rate and throat area near 90^o bend near the upper wall. Due to the gas-particle slip velocity and increased sold flow rate, most of the external aeration ends up in the down flow stream assisting solid flow rate. Together, the solid flow rate depends on aeration rate Q above the threshold aeration rate Q_{Th}, standpipe diameter D, height of the standpipe above the aeration point H_U, length of downstream solid flow path H_D through which solids flow out, particle diameter D_p, particle density ρ_p, gas density ρ_g and gas viscosity μ. Based on this hypothesis, equations are developed in the following sections.

Model for Threshold Aeration Rate Q_{Th}:

Threshold aeration rate is the aeration rate at which the drag by gas can just overcome the friction between particles and particles/wall to let the solids flow along with the gas. Aeration flow introduced into the standpipe at a pressure P_1 gets split into upward flow through the standpipe and downward/horizontal flow through the horizontal section depending on the resistance in each section. As both sections are filled with particles in a packed bed form, assuming laminar flow and exit pressure P_2 to be same, from Ergun's equation, the upflow and downflow components can be expressed as

$$Q_U = \frac{\pi D_t^2}{4}\frac{\varepsilon^3}{150\,(1-\varepsilon)^2}\frac{D_p^2(P_1-P_2)}{\mu H_U} \qquad 1$$

$$Q_D = \frac{\pi D_t^2}{4}\frac{\varepsilon^3}{150\,(1-\varepsilon)^2}\frac{D_p^2(P_1-P_2)}{\mu H_D} \qquad 2$$

From ratio of these two flows

$$\frac{Q_U}{Q_D} = \frac{H_D}{H_U} \qquad 3$$

and the two components add upto the aeration rate Q

$$Q_U + Q_D = Q \qquad 4$$

From equations 3 and 4, flow in the horizontal section can be obtained as

$$\mathrm{Q_D}\left(1+\frac{\mathrm{H_D}}{\mathrm{H_U}}\right) = \mathrm{Q} \qquad 5$$

From equations 2 and 5

$$Q = \frac{\pi D_t^2}{4}\frac{\varepsilon^3}{150\,(1-\varepsilon)^2}\frac{D_p^2(P_1-P_2)}{\mu H_D}\left(\frac{H_U+H_D}{H_U}\right) \qquad 6$$

At the point of particle flow initiation, particles flow through a critical throat area (f_U ($\pi D_t^2/4$)). Relative velocity between gas and particles in the moving section of the standpipe will be around u_{mf}. Hence, pressure drop for gas upflow in that section can be expressed as

$$P_1 - P_2 = H_U(\rho_p - \rho_g)(1-\varepsilon)g \qquad 7$$

With this approximation, threshold gas velocity can be obtained as

$$\begin{aligned} Q_{Th} &= f_U \frac{\pi D_t^2}{4}\frac{\varepsilon^3}{150\,(1-\varepsilon)}\frac{D_p^2(\rho_p-\rho_g)g}{\mu}\frac{(H_U+H_D)}{H_D} \\ &= f_U \frac{\pi D_t^2}{4}u_{mf}\frac{(H_U+H_D)}{H_D} = f_U X \end{aligned} \qquad 8$$

with X defined as

$$X = \frac{\pi D_t^2}{4}u_{mf}\frac{H_U+H_D}{H_D} \qquad 9$$

Threshold Aeration Model Validation:

Experimental observations on Q_{Th} reported in the literature are compared with parameter X, defined by equation 9 in Fig. 2. The correlation is reasonably good and an average value for the factor f_U at the initiation of particle flow is estimated to be 0.07.

$$Q_{Th} = 0.07\frac{\pi D_t^2}{4}u_{mf}\frac{H_U+H_D}{H_D} \qquad 10$$

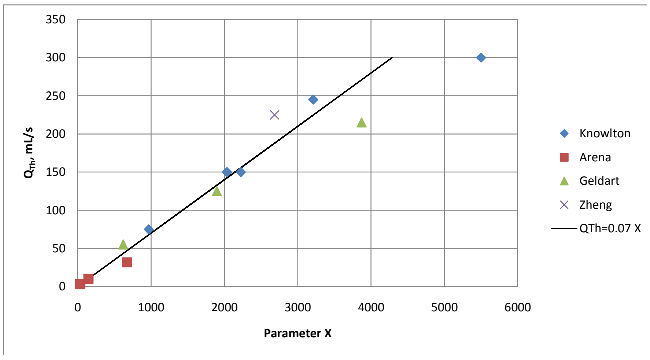

Fig.2 Correlation of data on threshold aeration rate reported in literature with parameter X (Eq.9)

Model for Particle Flow Rate:

Let the interstitial gas velocity be u and solids velocity be v in the horizontal pipe through which solids flow out of L-valve. The flow of solids due to fluid drag is resisted by the friction at the non moving particles/pipe walls.

$$Np\ F_D = \frac{\pi D^2 H_D 6(1-\varepsilon)}{4\quad \pi D_p^3} c_{Dm} \frac{\pi D_p^2}{4} \rho_g (u-v)^2 \quad = \quad f\ \pi D H_D\ \rho_p (1-\varepsilon)\varepsilon \frac{v^2}{2} \qquad 11$$

$$\text{Fluid drag on particles} \qquad = \qquad \text{Friction at the wall}$$

For aeration rates Q greater than the threshold Q_{Th}, area ($\pi D^2/4$) of solid flow increases with gas flow upto ($\pi D_t^2/4$) where the solid flow rate will be W_{max}.

$$\frac{W}{W_{max}} = \frac{D^2 - D_{Th}^2}{D_t^2} \quad \approx \quad \frac{D^2}{D_t^2} \qquad 12$$

Assuming laminar flow conditions, the drag coefficient and friction factor can be taken as

$$c_{Dm} \quad \propto \quad \frac{\mu_g}{D_p \rho_g (u-v)}; \quad f \quad \propto \quad \frac{\mu_b}{D \rho_b v} \qquad 13$$

Rearranging equations 11 with 12 and 13

$$u \quad = \quad \left(1 + \frac{k\ \mu_b}{1-\varepsilon\ \mu_g} \frac{D_p^2}{D^2}\right) v \qquad 14$$

where k is a constant. Combining equation 14 with 12

$$(Q - Q_{Th}) \frac{\rho_p (1-\varepsilon)}{\varepsilon} \quad = \quad \left(1 + k_v \frac{D_p^2}{D_t^2} \frac{W_{max}}{W}\right) W \qquad 15$$

where k_v is a constant incorporating gas viscosity, moving bed viscosity, bed voidage, k and other constants.

Yang and Knowlton (8) suggested that maximum flow rate of solids may be estimated using the equations proposed by Jones and Davidson (10) developed for particle discharge rate from fluidized beds through an orifice

$$W_{max} = 0.56\rho_p(1-\varepsilon)g^{0.5}H_U^{0.5}(D_t - D_p)^2 \qquad 16$$

However, particles move as a packed bed in a section of the horizontal pipe. Hence, maximum flow rate of solids may be dictated by the diameter of the horizontal pipe and may be estimated by the equation of Beverloo et al. (15) given as

$$W_{max} = 0.58\rho_p(1-\varepsilon)g^{0.5}(D_t - 1.5D_p)^{2.5} \qquad 17$$

Validation of the Model for Particle Flow Rate:

Data of Knowlton and coworkers (1), Zeng et al. (4) and Arena et al. (7) on solid flow rate as function of aeration rate are compared with the present model equation 15 in Fig.3 with ε and k_v assigned values of 0.4 and 2640. Table 2 summarizes the details of the properties of the experimental systems. The estimates of maximum solid flow rate by the equation 16 of Jones and Davidson (10) and equation 17 of Beverloo et al.(15) are included in Table 2. Experimentally observed maximum solid flow rates are in the range suggested by the Beverloo equation.

Table 2. Details of the systems used for the evaluation of the equation 15

Reference	D	H_S	H_D	D_p	ρ_p	W_{max}, g/s	
	cm	cm	cm	cm	g/cm^3	Eq.16	Eq.17
Knowlton 1, (1)	7.62	854	45.72	0.02609	2.611	38820	3798
Knowlton 2, (1)	5.08	854	45.72	0.02609	2.611	17253	1378
Knowlton 3, (1)	7.62	854	45.72	0.02609	2.611	38820	3798
Zheng, (4)	4.7	295	32.6	0.0605	1.392	4629	605
Arena 1, (7)	2.7	270	31.7	0.0073	2.55	2678	277
Arena 2, (7)	2.7	270	31.7	0.0156	2.55	2678	277
Arena 3, (7)	2.7	270	31.7	0.0341	2.55	2678	277
Arena 4, (7)	2.7	270	31.7	0.017	4.46	4683	485

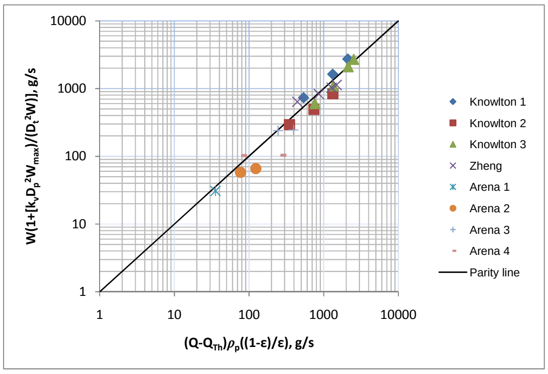

Fig.3. Comparison of equation 15 with the literature data.

Data of Knowlton and coworkers (1) Zeng et al. (4) and Arena et al.(7) are resasonably well represnted by the equation 15 as shown in Fig.3.. Using equations 15 and 17, maximum solid flow rate and corresponding maximum aeration rate Q_{max} upto which the L-valve can be operated can be estimated.

CONCLUSIONS

1). A model for solid flow rate in a stand alone L-valve as a function of external aeration rate is developed considering that a minimum threshold aeration rate Q_{Th} is necessary to initiate solids flow rate in L-valves.

2). Threshold aeration rate increases with increase in L-valve diameter and particle minimum fluidization velocity. The model equation 10 gives a reasonable description to the experimental observations reported in the literature as shown in Fig.2.

3). Equation 15 with k_v assigned a value of 2640 could correlate the data of Knowlton and coworkers (1), Zeng et al. (4) and Arena et al. (7) on solid flow rate as a function of external aeration rate as shown in Fig.3.

$$\left(Q - Q_{Th}\right)\frac{\rho_p\left(1-\varepsilon\right)}{\varepsilon} = \left(1 + 2640\frac{D_p^2}{D_t^2}\frac{W_{max}}{W}\right)W \qquad 18$$

ACKNOWLEDGEMENT

The author is thankful to University Teknologi PETRONAS for the encouragement and support for carrying out this work.

NOTATION

c_{Dm}	Gas-particle drag coefficient
D	Diameter of throat through which solids flow (cm)
D_p	Diameter of particles (cm)
D_t	L-valve diameter (cm)
f	Friction factor for flow of solids
f_U	Fraction of standpipe particles set in motion
g	Acceleration due to gravity (cm/s^2)
G_s	Particle mass flux, (kg/m^2/s)
H_D	Length of down flow section (cm)
H_U	Height of upflow section (cm)
H_s	Standpipe height (cm)
P_1	Aeration point pressure (g/cm/s^2)
P_2	Discharge point pressure (g/cm/s^2)
Q	Aeration flow rate (cm^3/s)
Q_D	Downward aeration flow through Horizontal section (cm^3/s)
Q_{Th}	Threshold Aeration Rate (cm^3/s)
Q_u	Upward aeration flow through standpipe (cm^3/s)

u', v'	Actual gas and particle velocities (cm/s)
u	Superficial gas velocity (cm/s)
u_{mf}	Minimum fluidization air velocity (cm/s)
W	Solids flow rate (gm/s)
W_{max}	Maximum solid flow Rate (gm/s)

Greek Symbols

ε	Bed voidage
$,\rho_g$	Gas density (g/cm^3)
ρ_b ρ_P	Density of moving bed, Particle (g/cm^3)
μ	Gas viscosity (g/cm/sec)
μ_b	Viscosity of moving bed (g/cm/sec)

REFERENCES

1. T. M. Knowlton, I. Hirsan, L-valves characterized for solids flow, Hydrocarbon process, 3(1978) 149-156
2. D. Geldart, P. Jones, The behavior of the L-valves with granular powders, Powder Technol, 67 (1991) 163-174.
3. M.Ozawa, S.Tobita, T Mii, Y.Tomoyasu, T.Takebayashi, K Suziki, Flow pattern and flow behaviour of solid particles in L-valve, CFB Technology III, (Eds) P.Basu, M. Horio and M.Hasatani, Pergamon, Oxford (1991), 615-620.
4. Q.Zheng, Z.Ma, A.B.Wang, Experimental study of the flow pattern and flow behaviour of gas-solid two phase flow in L-valve, in:A.A.Avidan, (ed). CFB Technology IV, Hidden Valley, USA (1993) 246-252
5. M. Rhodes, H. Cheng, Operation of an L-Valve in a circulating bed of fine solids, in:A.A.Avidan, (ed). CFB Technology IV, Hidden Valley, USA (1993) 240-245.
6. K.Smolders and J.Baeyens, “ The operation of L-Valves to control standpipe flow” Advanced Powder Technology, vol. 6 (1995) 163-176
7. U. Arena, A. Cammarota, “L-valve behavior with solids of different size and density”, Powder Technol, 98 (1998) 231-240.
8. W.Yang, T. M. Knowlton, L-valve equations, Powder Technol, 77 (1993) 49-54
9. T. M. Knowlton, “Standpipes and return systems”, in: J.R.Grace, A.A.Avidan and T.M.Knowlton (Eds.), Circulating Fluidized Beds, Chap 7, Blackie Academic & Professional, an imprint of Chapman & Hall, London, 1997, 214-260.
10. D.R.M. Jones, J.F. Davidson, The flow of particles from a fluidized bed through an orifice, Rheologica Acta 4 (1965) 180– 192.
11. M. A. Daous, A. A. Al-Zahrani, “Modeling solids and gas flow through an L-valve”, Powder Technol, 99 (1998) 86-89.
12. H. Tong, Q. Zheng, “Hydrodynamic modeling of the L-valve”, Powder Technol, 129 (2003) 8-14.
13. C.W.Chan, Jonathan Seville, Xianfeng Fan, Jan Baeyens, “Particle motion in L-valve as observed by positron emission particle tracking”, Powder Technology 193 (2009) 137-149.
14. Amit Agarwal, “Solid flow in a 2 D Lvalve”, M.Tech Thesis IIT Delhi (2004).
15. W.A. Beverloo, H.A.Leniger, J, van de Velde, The flow of granular solids through orifices, Chem.Eng.Sci., 15 (1961)260-269.