Slot Flow Metering: Fundamental Investigations, Pilot-Scale Tests and Industrial Prototype.†

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Abstract

A new technique for measuring the flow of granular materials continuously is described. Slot Flow Metering utilizes the flow from vertical slots to determine flow rate. A Slot Flow Meter (SFM) consists of a hopper with one or more vertical slots in its sides supported by a means for weighing the hopper's contents, eg. a load cell. Solids flow rate can be correlated against the apparent weight of solids in the hopper.

Recent experimental and theoretical work on the flow of granular materials from vertical slots is reviewed and a simple in-situ calibration technique is described. This is tested against direct calibration (bucket and stop-watch) with a pilot-scale unit located in an experimental circulating fluidized bed. The industrial prototype, installed in a Urea plant, is described.

1. Introduction

Flow measurement is routine and commonplace in most chemical processes. There are a wide variety of technologies for measuring gas and liquid flows but very few for measuring solid (granular) flows. Only two techniques have found acceptance in the process industries: impact flow meters (Jimbo and Watanabe (1985)) and Coriolis mass flow meters (Jost (1987)); both methods have disadvantages. Impact flow meters, although suitable for measuring a wide range of materials, require careful empirical calibration which can be difficult (Burkell et al (1988)). Coriolis flow meters are potentially more useful as they are insensitive to the physical properties of the solids and give a true measure of mass flow rate; but the technique suffers from the disadvantage of requiring moving parts in contact with the flowing solids.

Slot Flow Metering is a recently developed method for measuring the dense-phase flow rate of granular materials and is analogous to liquid flow measurement using weirs. In its simplest form, a Slot Flow Meter (SFM) consists of a chamber or hopper with one or more vertical slots in its sides. Solids are fed into the hopper from the top, and flow out through the vertical slots. Out-flow area is proportional to the height of the slots occupied by out-flowing solids: for a given solids flow rate there is an equilibrium height at which the feed rate equals the out-flow. The basis of the technique is to correlate solids flow rate with height of solids in the hopper. This height is termed the active slot height, h, and for a solid of constant bulk density, it is uniquely related to the mass of solids in the meter. This mass can be determined by weighing, provided (i) the slots are sufficiently narrow to give adequate hold up, and (ii) the impact force of the impinging inlet solids stream from above is negligible. Thus the solids flow rate can be correlated with the apparent mass of solids in the hopper. It is necessary that all particles should pass through the meter, leading to two design requirements as follows: (i) the slot width must be sufficiently greater than the maximum particle diameter; (ii) the hopper design must be such that no particle — eg. a large one — becomes permanently lodged in the hopper.

Slot Flow Meters can be of a variety of forms. An example of a prototype unit is illustrated in Fig. 1. This design has been used for small-scale tests and scaled-up to pilot scale for use in an experimental Circulating Fluidized Bed (CFB), see Fig. 6, where the solids circulation rate is measured. The cone located in the
centre of the hopper serves two purposes: to disperse the entering solids and to improve the draining characteristics; without the cone there would be a central stagnant region. Many other variations are possible: the slots need not be rectangular, and different geometries and hopper shapes are possible. Patent applications have been made for the general concept of Slot Flow Metering.

The purpose of this paper is three-fold:
(i) to review recent experimental and theoretical investigations of the nature of flow from vertical slots, beginning with fundamental studies of flow through single slots and moving on to tests on a prototype SFM;

(ii) to report and confirm the validity of a dynamic, in-situ calibration technique using a pilot-scale unit in an experimental Circulating Fluidized Bed; and

(iii) to describe the prototype industrial SFM which has been installed in a Urea plant.

2. Developmental Work

2.1 The relationship between flow rate and SFM geometry

Several practical and theoretical investigations into flow of granular materials through vertical slots have been undertaken. Davies and Foye (1991) investigated flow from both open slots (slots where the solids level is less than the full slot height) and closed slots (whose full height is occupied by the flowing solids). They quantified the effect of slot width (<70mm) and height (<400mm), on the flow of casein and rape seed, using a rectangular vessel 165mm x 155mm with a single slot. Their results were well correlated by:

\[
\dot{m} = K_e (W-w)(L-1) \left[ \frac{2(W-w)(L-1)}{(W-w)+(L-1)} \right]^{1/2} \tag{1}
\]

Here, \( \dot{m} \) is the mass flow rate of solids from a slot of height \( L \) and width \( W \); \( l \) and \( w \) are corrections to \( L \) and \( W \), respectively, and are believed to be related to the average particle size. \( K_e \) is an empirical constant. Davies and Foye (1991) concluded that \( K_e \) is a function of bulk density and other undefined particle properties.

For a long, narrow, open slot (\( L > > 1 \), \( L > > W \), and \( L = h \), where \( h \) is the active slot height ), thus equation (1) reduces to:

\[
\dot{m} = \sqrt{2} K_e (W-w)^{3/2} h \tag{2}
\]

This equation is clearly analogous to the well-known Beverloo equation (Beverloo et al. (1961)) for the vertical flow of granular material, of mean diameter \( d_p \), through a circular orifice of diameter \( D_o \), viz.:

\[
\dot{m} = 0.58 \rho g^{1/2} (D_o - 1.4d_p)^{5/2} \tag{3}
\]

Here, \( g \) is the acceleration of gravity, and \( \rho \) the particle bulk density. If the analogy holds, it is plausible that the slot width reduction, \( w \), is related to average particle diameter: \( w = k d_p \). Davies and Foye (1991), and more recently Davies et al. (1992), investigated this dependence. Experimental values for \( K_e \) and \( k \), denoted \( K_e^* \) and \( k^* \) are reproduced in Table 1, as are the results of Harris et al (1992).

Harris et al. (1992), developed theory from first principles to give the dependence of the flow constant, \( K_e \) of equation (2), on particle properties. They found:

\[
\dot{m} = C g^{1/2} \rho (W - k d_p)^{3/2} h \tag{4}
\]

where

\[
C = \left[ \frac{1}{2a} \frac{K+1}{K-2} \sin \phi \right]^{1/2} \tag{5}
\]

Here, \( K \) is the ratio of major to minor principal
stresses and \( \alpha \) and \( \psi \) are angles defined in Fig. 2.

Harris et al. (1992), used a cylindrical multi-slot flow meter (Fig. 1), 0.1m diameter and 0.1m high, with eight variable width slots (maximum 4mm) to investigate the effect of slot width and particle size (155, 233 and 518 \( \mu \)m mean diameter sand). Their results were regressed against equation (4) and are reproduced in Fig. 3, where \( g^{1/3}d_{50}^{-1}(\bar{m}/\rho)\) is plotted against \( W/d_p \). Here, the slope equals \( C^{2/3} \) and the intercept, \( C^{2/3}K \). The best fit values (solid line), each denoted by an asterisk, are \( C^* = 0.43 \) and \( k^* = 0.12 \). Confidence limits (95%) are also shown (dashed lines). The fit is reasonable although there is some scatter. The value obtained for the slot width reduction constant \( k^* \), is significantly less than those of Davies et al. (1992) and Davies and Foye (1991), see Table 1. This discrepancy may be due to the small scale of the apparatus, and its multi-slot design: also, the catchment areas of adjacent slots are not independent.

The flow constant \( C^* \) measured by Harris et al. (1992) is compared to values obtained by Davies et al. (1992) and Davies and Foye (1991) in Table 1. Note that \( K = \rho g^{1/2}C^*/2^{1/2} \). The validity of equation (5) has not been experimentally verified as systematic measurements of \( \alpha \) and \( \psi \) have not been made, although Harris et al. (1992) estimated \( C \) using values of \( \alpha = 30^\circ \), \( \psi = 30^\circ \) and \( K = 3 \) for sand and casein. Equation (5) was found to over-estimate the flow constant \( C \), and a discharge coefficient, \( C_d \), of order 0.3 was incorporated into equation (4) to account for the discrepancy.

The theoretical developments described above are concerned only with out-flow whose mean velocity shows no variation with height. Davies and Harris (1992) subdivided flow through vertical slots into two regimes: fluid-
ized and unfluidized. In the former, with a controlled flow of fluidizing air, the solids flow like an inviscid liquid and slot out-flow is proportional to $W^{3/2}$. With unfluidized flow, slot out-flow is proportional to $W^{3/2}h$. Davies and Harris (1992) inferred from their observations that some Geldart Group A particles behaved as though they were fluidized or partly fluidized as they flowed through the SFM, even though there was no fluidizing air other than that entrained with the incoming solids. They also found that the flow of 'fluidizable' particles (Geldart Group A or B) through vertical slots could be transformed from unfluidized to fluidized by forced aeration of the particles within the SFM: the maximum flow capacity of an SFM of given volume can be increased by fluidization using forced aeration.

2.2 Dynamic response of a SFM

Davies and Harris (1992) investigated the dynamic response of a single Slot Flow Meter with capacity for internal fluidization (Fig. 4).

They applied step changes to the solids flow to confirm the validity of the above-mentioned relationships for fluidized and unfluidized flow. For unfluidized slot flow they found that for a step change from zero flow to $\dot{m}$, the response of the SFM is given by:

$$t/\tau = \ln \left[ \frac{1}{1-\eta} \right]$$

$$\eta = \frac{M\cdot t}{\dot{m}h}$$

where $\tau = M\cdot t/\dot{m}$ and $\eta = h/h \cdot t$; $\tau$ is the mean residence time; $M \cdot t$ and $h \cdot t$ are respectively the steady state values of the mass of solids in the hopper and the height to which they rise. When the material in the SFM is fluidized, the response is given by:

$$t/\tau = \frac{2}{3} \left( \frac{1}{2} \ln \left[ \frac{1-\eta^{3/2}}{(1-\eta^{3/2})^3} \right] + \sqrt{3} \tan^{-1} \left[ \frac{-\sqrt{3} \eta^{3/2}}{1} \right] \right)$$

Experimental results are compared with predictions for both fluidized and unfluidized flow for sand in Fig. 5, where $t/\tau$ is plotted against $M_{\cdot t}/M_{\cdot t}$. It is assumed that $\eta = M_{\cdot t}/M_{\cdot t} = h/h \cdot t$; this is true when the following conditions are satisfied: (i) the shape of the solids surface is invariant with height, (ii) the container has vertical sides and (iii), the bulk density of the flowing material is constant.

3. Dynamic Calibration

Regular calibration of any flow meter is important. However, where this requires removal of the measuring element, or calibration is difficult or hazardous, it is often neglected. Slot Flow Meters possess a unique characteristic, identified by Davies et al. (1992): online, in-situ calibration is possible. The technique is based on the dynamic response of the SFM to cessation of flow: the inlet flow is stopped at time $t=0$ and the mass, $M$, of solids in the load cell is subsequently measured as a function of time, $M(t)$; $dM/dt$ gives the mass flow rate corresponding to $M(t)$, provided the momentum of the entering particles is negligible.

This technique has been tested on a pilot-scale SFM installed in an experimental Circulating Fluidized Bed (Harris and Davidson)
The experimental rig is shown in Fig. 6. Here, a 0.2m diameter by 0.2m high SFM with eight 10mm x 180mm open slots, of the same geometry illustrated in Fig. 1, is used to measure the external solids circulation rate of Fluid Cracking Catalyst (FCC) \((\rho = 850 \text{ kgm}^{-3}, d_p = 71 \mu\text{m})\). The FCC discharges through a central hole which pierces the distributor plate and plenum chamber of a conventional low-velocity bubbling fluidized bed (the slow bed in Fig. 6), and flows into the SFM. Flow rate is adjusted using a slide valve with variable orifice diameters. The discharge from the SFM flows under gravity, via a double manifold, to the CFB riser.

The dynamic response of the 0.2 m diameter SFM to cessation of flow is shown in Fig. 7. The curve is approximately exponential and has been regressed as such. For short times there is some scatter, but the fit is reasonable \((R^2 = 0.97)\) and adequate for this analysis. The fitted curve \((M = 1.06 e^{-1.45t})\) is differentiated to give \(dM/dt = 1.53 e^{-1.45t}\), the discharge rate from the hopper. \(dM/dt\) is plotted against \(M\) in Fig. 8 as are the data from the direct (bucket and stop-watch) calibration. Agreement between the two calibration methods is excellent. Calibration at higher flows was not possible due to limited bucket volume.

Harris et al. (1992) considered the general case of the dynamic response of an SFM with...
no internal cone and with particles which show linear variation of out-flow with height (un-fluidized). They found that the time variation of solids mass in a hopper of constant cross-sectional area $A$, with $n$ slots, for cessation of flow at $t=0$ is given by:

$$M = \rho Ah_1 \exp\left(-\frac{nCg^{1/2}W^{3/2}}{A}t\right) \quad (8)$$

Here, $h_1$ is the initial active height of solids in the hopper. The mass flow rate from the slots is therefore:

$$\frac{dM}{dt} = -\rho h_1 nCg^{1/2}W^{3/2} \exp\left(-\frac{nCg^{1/2}W^{3/2}}{A}t\right) \quad (9)$$

It follows from equations (8) and (9) that $- (dM/\,dt)/M = nCg^{1/2}W^{3/2}/A$, which is linear with respect to the mass of solids in the hopper and independent of bulk density: an SFM in this situation acts as a mass flow meter, giving the mass flow rate without the need to measure the solids density.

Similar analysis can be performed for slot out-flow which is non-linear with respect to height. Here the out-flow of solids, through $n$ slots, in a vessel of constant cross-section, is $\dot{m} = nC_h h_1^m$, $n_1 \neq 1$. Note for a material which flows as a Newtonian liquid $C_1 = (2/3)C_d \rho (3g)^{1/2}$ $W$ and $n_1 = 3/2$, see Davies and Harris (1992). The mass of solids in the SFM as a function of time is:

$$M = h_1 \rho A \left[1 - \frac{(1-n_1)nC_1}{h_1^{1-n_1} \rho A} t\right]^{1/(1-n_1)} \quad (10)$$

differentiation gives the out-flow:

$$\frac{dM}{dt} = h_1^{n_1} nC_1 \left[1 - \frac{(1-n_1)nC_1}{h_1^{1-n_1} \rho A} t\right]^{n_1/(1-n_1)} \quad (11)$$

The variation of out-flow with mass of solids in the hopper for a fluidized ($n_1 = 3/2$) solid is:

$$\frac{dM}{dt} = \frac{n(2/3)C_d (3g)^{1/2}W}{\rho^{1/2}A^{3/2}} \frac{M^{3/2}}{A^{2/3}} \quad (12)$$

This is clearly a function of bulk density. In general, an SFM of constant cross-section cannot be considered a mass flow meter when the out-flow is non-linear with respect to height.

Non-linear variation of out-flow with height for FCC was observed by Harris et al. (1992). They interpreted the calibration data from the pilot-scale SFM by estimating the active slot height (calculated from the geometry of the SFM and the mass of solids) and found non-linear out-flow behaviour, which at the highest flow rates measured, approached that expected for a fluidized solid. Despite this, the response for this unit was well described by an exponential decay, as expected for an unfluidized solid with no internal cone. From this observation, it appears that the internal cone would be necessary for a SFM to act as a mass flow meter.  

![Fig. 7 Dynamic response of 0.2m diameter 'pilot-scale' SMF to cessation of flow, with FCC, 71 μm mean diameter, Harris et al. (1992).](image)

![Fig. 8 Calibration curve for 0.2m diameter SFM with FCC : comparison of dynamic (solid line, dM/dt against M) and bucket and watch (---) techniques, Harris et al. (1992).](image)
counteracts the non-linear variation of outflow with height. Indeed, it is possible to demonstrate that this is the case by considering the equations which describe (i) the mass of solids in the SFM as a function of height, and (ii) the variation of outflow with height. The mass of solids in the hopper is given by:

$$M = \rho \left( \frac{1}{3} \pi r_h^2 h_0 + \frac{1}{3} (h_0 - h) \frac{1}{2} \pi r_h^2 \tan^2 \theta \right)$$  \hspace{1cm} (13)

Here $r_h$ is the hopper radius, $h_0$ the height of the hopper, and $\theta$ is the half angle of the cone. The mass flow rate of fluidized solids through $n$ slots (Davies and Harris (1992)) is:

$$\dot{m} = n \left( \frac{2}{3} \right) C_{tf} (2g) \frac{1}{2} \rho W H^{3/2}$$  \hspace{1cm} (14)

The discharge coefficient, $C_{tf}$, is assumed equal to 0.3. These two equations, which are parametric in $h$, are plotted in Fig. 9 for a number of different solids densities, as are the 'bucket and stop-watch' calibration data for the 0.2m diameter SFM with FCC. At high flow rates, the calibration curve is approximately linear, which agrees with the observations of Harris et al. (1992). It is also apparent that the SFM is relatively insensitive to the bulk density of the material: the SFM, with a conical insert and fluidized solids flow, has pseudo mass-flow-metering characteristics.

4. Industrial Prototype

A full description of the industrial prototype is given by Davies et al. (1992); only a synopsis is given here. The industrial prototype (Fig. 10), which is installed in a Urea plant, was designed to measure flows of the order of 26 tonnes per hour with peak flows of at least 35 tonnes per hour. It differs significantly from the prototype and the pilot-scale units described in the previous sections. The principal differences are the absence of the internal cone and the different solids dispersal method. The unit is made free-draining using a conical base with a central drain hole; the flow through this drain is only a small proportion of the total flow. Also incorporated into this unit is a device for measuring continuously the bulk density of the flowing solids (readers are referred to the original paper, Davies et al. (1992), for a description): again only a small fraction of the total flow is fed to the density measuring device. The inclusion of the density device within the SFM was necessitated by space constraints.

Solids enter the dispersal chamber via an inclined chute and flow through 'T-shaped' slots to the cylindrical weighing chamber. This

![Fig. 9 Comparison of theoretical calibration for pilot scale SFM with fluidized particles (equations (13) & (14)) against experimental data ( ), with bulk density as parameter. --- 1050kgm\(^{-3}\), --- 850kgm\(^{-3}\), ..... 650kgm\(^{-3}\).]
has three equi-spaced replaceable metering slots in its sides which are offset from the dispersal slots. The entire unit (dispersal and weighing chamber) is supported from above by three rods which are attached to a load cell via a connecting plate. The SFM is kept horizontally stable by three tie wires aligned so that they apply no vertical force. Rectangular surge openings are located above the top of the metering slots.

The response of the unit to cessation of flow is complicated by the internal geometry (density meter and drain hole), and this must be kept in mind when examining the response curve. An example is presented in Fig. 11.

5. Conclusions

1. Slot Flow Metering has been demonstrated from prototype, through pilot scale, to the first industrial instrument, which is installed in a Urea plant.

2. Slot Flow Meters are based on very simple technology: the flow of a granular material from a vertical slot. There are no moving parts:

![Diagram of industrial SFM prototype](image)

**Fig. 10** Industrial SFM prototype: Flow and density measurement of Urea (Davies et al. (1992)).

![Response curve](image)

**Fig. 11** Response of industrial prototype SFM to cessation of flow, Davies et al. (1992).
they are ideally suited to dusty environments.

3. Empirical theory has been developed. The out-flow from a vertical slot for unfluidized flow is given by:

\[ \dot{m} = C g^{1/2} \rho (W - k d_p)^{3/2} h \]

Theory developed from first principles gives the dependence of the dimensionless constant \( C \) on the flow properties of the granular solid.

4. On-line calibration is possible. This is accomplished by observing the dynamic response of the meter to cessation of flow. The resulting response curve is differentiated with respect to time to give the flow rate corresponding to the mass of solids in the hopper.

5. In some cases (unfluidized flow from an SFM of uniform cross-section), an SFM will behave as a mass flow meter, i.e. its characteristics are independent of solids density.

**Nomenclature**

| Symbol | Description                                      | Unit |
|--------|--------------------------------------------------|------|
| \( A \) | cross-sectional area of SFM                      | \( m^2 \) |
| \( C \) | theoretical flow constant                        | [-]  |
| \( C^* \) | experimental flow constant                       | [-]  |
| \( C_d \) | discharge coefficient                            | [-]  |
| \( C_r \) | non-linear flow constant                         | [-]  |
| \( d_p \) | average particle diameter                        | \( m \) |
| \( D_o \) | orifice diameter                                 | \( m \) |
| \( g \) | acceleration of gravity                          | \( \text{ms}^{-2} \) |
| \( h \) | active height of solids                          | \( m \) |
| \( h_s \) | active height of solids at steady state          | \( m \) |
| \( h_i \) | initial height of solids in hopper               | \( m \) |
| \( h_o \) | height of SFM                                    | \( m \) |
| \( k \) | slot width reduction constant                    | [-]  |
| \( k^* \) | experimental slot width reduction constant       | [-]  |
| \( K \) | \((1 + \sin\phi)/(1 - \sin\phi)\)              | [-]  |
| \( K_e \) | empirical flow constant                          | \( \text{kg m}^{-5/2} \text{s}^{-1} \) |
| \( K_{e^*} \) | experimental flow constant                       | \( \text{kg m}^{-5/2} \text{s}^{-1} \) |
| \( L \) | closed slot length                               | \( m \) |
| \( l \) | slot length reduction                            | \( m \) |
| \( M \) | apparent mass of solids in hopper                | \( \text{kg} \) |
| \( M_s \) | apparent mass of solids in hopper at steady state| \( \text{kg} \) |
| \( \dot{m} \) | slot mass flow rate                              | \( \text{kg s}^{-1} \) |
| \( n \) | number of slots                                  | [-]  |
| \( n_r \) | non-linear flow height exponent                  | [-]  |
| \( r_s \) | radius of cylindrical SFM                        | \( m \) |
| \( R^2 \) | coefficient of determination                     | [-]  |
| \( t \) | time                                             | \( \text{s} \) |
| \( W \) | slot width                                       | \( m \) |
| \( w \) | slot width reduction                             | \( m \) |
| \( \alpha \) | flowing wedge half angle                         | [-]  |
| \( \beta \) | half angle of internal cone                      | [-]  |
| \( \eta \) | dimensionless height ratio, \( h/h_o \)          | [-]  |
| \( \rho \) | bulk density                                     | \( \text{kg m}^{-3} \) |
| \( \phi \) | angle of internal friction                        | [-]  |
| \( \psi \) | angle of slip plane to horizontal                | [-]  |
| \( \tau \) | mean residence time                              | \( \text{s} \) |

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