Y., Xie, V., Raghavan, A. S., Rangwala, **“Naturally Entraining Solid Particle Injector,”** *Powder Technology,* 2011 *(accepted for pub).*

Naturally Entraining Solid Particle Injector

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Abstract

The objective of the present work is to develop and calibrate a novel, vertical solid particle injector that uses the pressure drop in the air flow across an orifice plate in a circular pipe, to naturally entrain micron-sized solid particles such as coal dust. The particles continuously drop from a feeder located outside the pipe into the orifice plate through peripheral (side) openings in the pipe, where they are carried upwards by the air flow accelerated near the orifice exit. Three types of designs for the peripheral openings, in terms of the shape, size and number are evaluated by testing which one of them results in maximum particle entrainment. The device is calibrated by recording the mass loss rate of the powder as a function of volumetric flow-rate of air. The results show that there is an optimum area for the side openings, at which the injector performance will be the best for the given pipe and orifice-hole sizes. The entrainment rate is found to be a non-linear function of the flow-rate for low air flow-rates (till around 9.4 grams per minute) and for higher air flow-rates it becomes an almost linear function.

Keywords: Particle or powder injector; Orifice plate; Pressure drop; Natural entrainment; Mass loss rate

Submitted for possible publication as *short communication* to **Powder Technology**

1. Introduction

Injection of solid particles of different sizes into a fluidized flow device or in a pneumatic conveying process has applications in several chemical, food processing and energy related industries. The pulverized coal combustor, coal gasification systems, and dry-forming processes for paper are few examples. In these, there is a need to reliably meter the flow-rate of particle laden fluid mixtures. In pneumatic conveying, the solid particles are mixed with air either under the influence of gravitational force or due to the pressure force resulting from the pressure drop in an accelerating air flow. Typical materials used for conveying are pulverized coal, ash, food grains, sand particles and dry chemicals [1]. Wagenknecht and Bohnet [2] were the first and foremost to study an injector type particle feeder. In their study, a high-velocity air stream exists from a primary nozzle and entrains the particles into a secondary nozzle, where the necessary pressure is built up for conveying the particles. Following them, Chellappan and Ramaiyan [3] and Westaway et al. [4] carried out investigations on the effects of important design parameters of a gas-solid injector feeder, which can be used in pneumatic conveying systems. All these designs utilize a nozzle to create high velocity air flow that carries the solid particles. Apart from the pneumatic conveying application, powder dispensers are designed for particle size measurements [5], including that of aerosols. These devices are usually oriented horizontally. Recently, dry particle dispersion methods, process and the dispersion efficiency have been discussed in a review article by Masuda [6].

The techniques currently available have limited capability for fine control of feeding rate. In certain applications involving fuel characterization and energy studies, the quantity of particle injected has to be precisely known and the particles are to be fed in wide ranges of quantities. In these cases, there is a need to have a particle injecting device, which allows for simple and precise control of both fluid flow and particle feed rates. A typical solid-particle injector is designed, developed and calibrated in this study. This injector, which is oriented upwards, utilizes the venturi effect observed when the flow passes through a reduced area passage such as in orifice plates, converging and diverging passages and nozzles. An orifice plate is used to create the venturi effect in this study because of ease of manufacture and cost effectiveness. The entire setup consists of a pipe having an orifice plate, connected to another pipe having openings of on its periphery from which the powder is easily fed into the orifice plate, and an extension pipe connected to this, to make the particle laden air flow develop further. Furthermore, since the powder does not pass through the orifice hole, erosion of the hole is prevented. The control of the powder feed rate is basically achieved by varying the air flow-rate and/or by changing the area of the side openings in the pipe. Three design configurations are studied and a thorough calibration is done for each case for varying air flow-rates.

2. Solid-Particle Injector

The injector device comprises of three parts:

1. A lower pipe with an orifice plate. A straight hole, sharp edged orifice has been employed.
2. A middle section, which is a pipe with openings in its periphery and with a dust feeder.
3. A pipe on the top of the middle section to further develop the flow.

The assembly is shown in Fig. 1. The upper (124.5 mm long and 3.3 mm thick) and lower (135.5 mm and 3.3 mm thick) pipes can be inserted to the middle section and socket head screws are used to secure these sections intact (Fig. 1). The top end of the lower pipe has an orifice plate of 1 mm thickness with a hole at its center having a diameter of 1 mm. The length of the middle section is 50.8 mm. It has provisions to insert the top and lower pipes at its top and lower ends. The middle section has peripheral openings as shown in Fig. 1. Both the number and size of these openings have been varied in this study.

To study the effects of size and number of openings in the middle section, three different middle sections are used:

1. First middle section (case 1) has six circular openings each with a diameter of 5 mm, amounting to a total particle-feed area of 118 mm^2.
2. The second one (case 2) has three circular openings with 8 mm diameter each and a total opening area of 151 mm^2.
3. The third middle section (case 3) consists of three rectangular openings each with an area of 90 mm^2 and a total opening area of 270 mm^2.

A particle feeder which comprises of an inverted hollow 60º inverted cone made of acrylic is connected around the middle section as shown in Fig. 2. The feeder is open at the top and has a smooth surface to minimize frictional losses. The feeder rests on the outer portion of socket screws.

3. Experimental Setup and Procedure

A schematic of the experimental setup is shown in Fig. 3. Air is supplied with an upstream pressure of 5 psig (34474 Pa) to the lower pipe through a pressure regulator, valve and air flow meter. The air flow meter can supply air at flow-rates ranging from 0 liters per minute (lpm) to 10 lpm in increments of 0.5 lpm. The accuracy of the flow meter at its highest flow-rate is within ±4%. Pittsburgh seam coal dust is used in the present study, and has a particle size in the range of 90 - 106 micro-meters (μm), a reported constant sphericity value of 0.73 [6], and a bulk density of 0.553 g/cm^3. A particle collection pan of 300 mm diameter, as shown in Fig. 3, is used to collect the particles injected out of the top pipe. The injector and the particle feeder are secured in a support frame as shown in Fig. 3 and the entire assembly is weighed using a Cole Palmer load cell (capacity of 4.2 kg with a sensitivity of 0.01 g). The uncertainty in the mass measurement is ±0.03 g. The ring stand is used to support the collection pan so that the particles collected in the pan will not be weighed by the load cell.

The experiments are carried out in atmospheric temperature equal to 300 K. The experimental procedure comprises of fitting the desired middle section, filling the conical feeder with coal dust and then turning the air supply on. The flow meter is set to deliver the desired air flow-rate and the load cell output is recorded as a function of time. The recording of the mass loss rate is continued for 5 minutes and then stopped. Each experiment is repeated at least three times to ensure consistent results within ±2%. An instantaneous photograph showing particle injection and collection in the pan is presented in Fig. 4 (case 2: three circular openings with 8 mm diameter each at an air flow-rate of 5 lpm).

4. Results and Discussions

The particle injection rate is mainly dependent on the flow-rate and the size of the side openings in the three middle sections studied. For each middle section, air flow-rate is varied from 1.57 grams per minute (gpm) to 15.7 gpm (1 lpm to 10 lpm). However, no entrainment is recorded for 1.57 gpm, irrespective of the middle section used. As flow-rate increases, the entrainment of coal dust into the pipe increases due to increased venturi effect. This is shown in Fig. 5, where the mass of dust injected (grams per minute) is plotted as a function of the air-flow rate in gpm. The variation of the coal dust injection rate is non-linear for air flow-rates up to 9.4 gpm. After this, as the air flow-rate increases, the dust injection rate follows an almost linearly increasing trend. For low air flow rates (< 9.4 gpm), the dust injection is found to be the highest for case 3 (three rectangular openings with a total area of 270 mm^2). For instance, at an air flow-rate of around 7.9 gpm, the entrainment for case 3 is around 15%

more than that of case 2 and 50% more than that of case 1 (six circular openings each with a diameter of 5 mm). In fact at an air flow-rate of around 3.15 gpm (2 lpm), maximum deviation is recorded between case 3 and case 2 (35% more for case 3 than case 2) and between case 3 and case 1 (89% more for case 3 than case 1). When the air flow-rate is increased beyond 9.4 gpm (6 lpm), the variation between all the three middle section cases are almost the same with a maximum deviation within ±3%. This shows that when the inertia of air is increased, venturi effect is increased and as a result, the air is capable of carrying the coal dust fed to the orifice plate irrespective of the side opening area. At low flow-rates, the pressure drop created due to venturi effect is partly overcome by the friction, which the inner surfaces of the holes offer to the coal dust flow. Therefore, the injection rate is higher for large openings where the friction effects are minimal. This means that the middle section opening area is critical only for lower air flow-rates and as the air flow-rate increases an optimum opening area can be employed, which in this case can be either case 2 or case 3. The usage of variable opening area, if designed carefully, can be employed to control the particle feeding rate even more precisely.

5. Conclusions

Design, development, and calibration of a novel solid particle injector have been reported. The injector uses the pressure drop in the air flow across an orifice plate fitted in a circular pipe (venturi effect), to naturally entrain micron-sized solid particles such as coal dust. Coal dust is continuously fed from a feeder located outside the pipe into the orifice plate through peripheral openings in the pipe. Three types of designs for the peripheral openings, in terms of the shape, size and number are evaluated by testing which one of them results in maximum particle entrainment, especially at lower air flow-rates. Calibration of the device is carried out by precisely recording the mass loss rate of the coal dust as a function of volumetric flow-rate of air. The results show that there is an optimum area for the side openings, at which the injector performance will be the best for the given pipe and orifice-hole sizes. The entrainment rate is found to be a non-linear function of the flow-rate for low air flow-rates (till around 9 grams per minute) and dependent on the net area of the openings. For higher air flow-rates, the entrainment becomes almost independent of the opening area and also it becomes an almost linear function.

References

1. EEUA, Pneumatic Handling of Powdered Materials, EEUA Handbook No. 15, Constable, London, (1963) p. 1.
2. U. Wagenknecht and M. Bohnet, Ger. Chem. Engg., l (l978) p. 298.
3. S. Chellappan and G. Ramaiyan, Powder Technology, 48 (1986) p. 141.
4. S. F. Westaway, C. R. Woodcock, J. S. Mason and L. S. Fox, Pneumatech 3, Third International Conference on Pneumatic Conveying Technology, Jersey, England, March 1987.
5. P. Tang, D. F. Fletcher, H. K. Chan and J. A. Raper, Powder Technology, 187 (2008) p. 27.
6. J.P. Mathews, S. Eser, P.G. Hatcher, and A.W. Scaroni, KONA Powder and Particles, 25 (2007) p.145.

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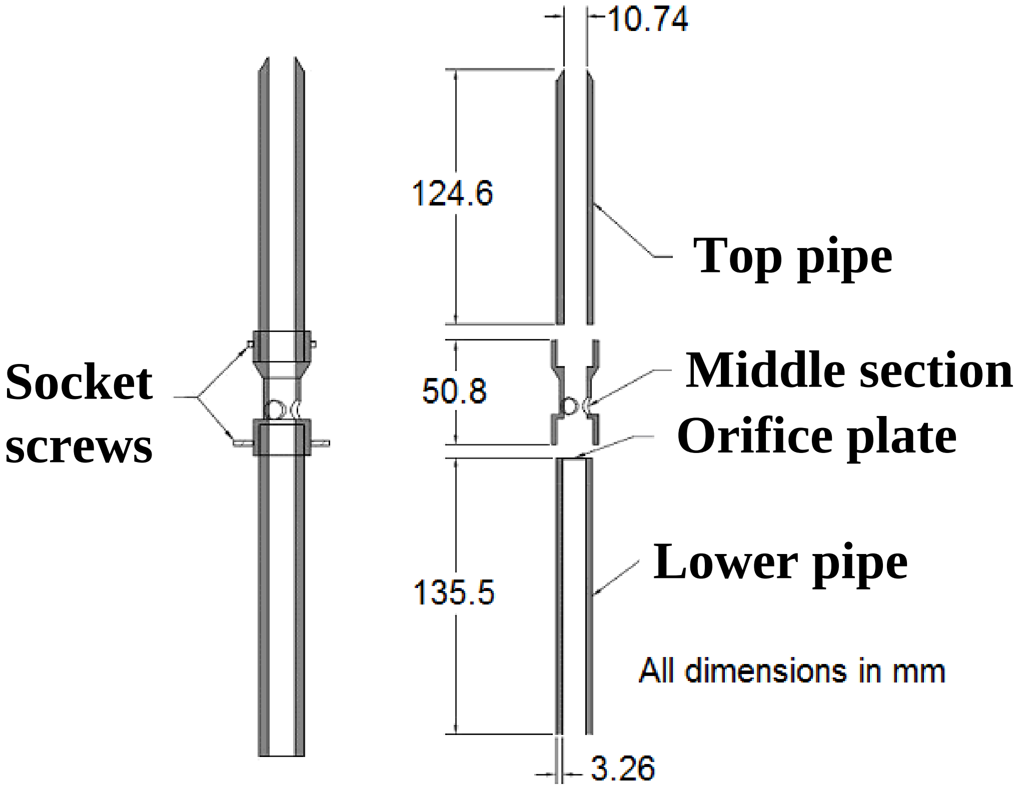


Figure 1: Solid particles injector

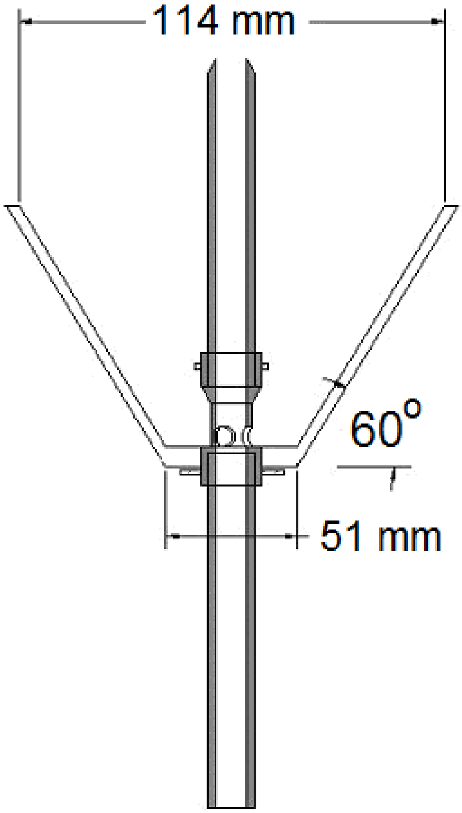
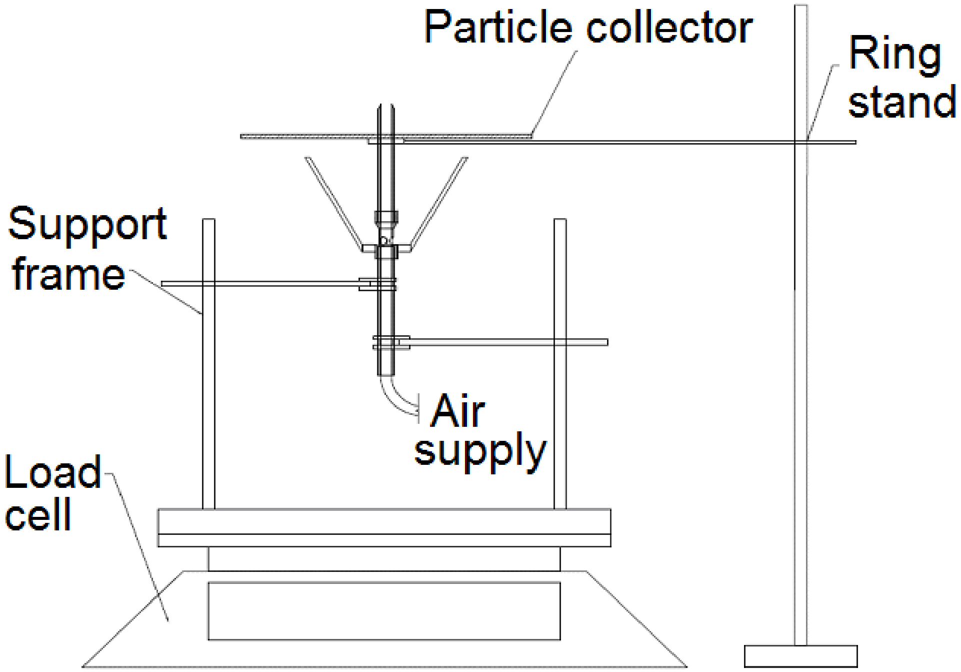


Figure 2: Injector with particle feeder



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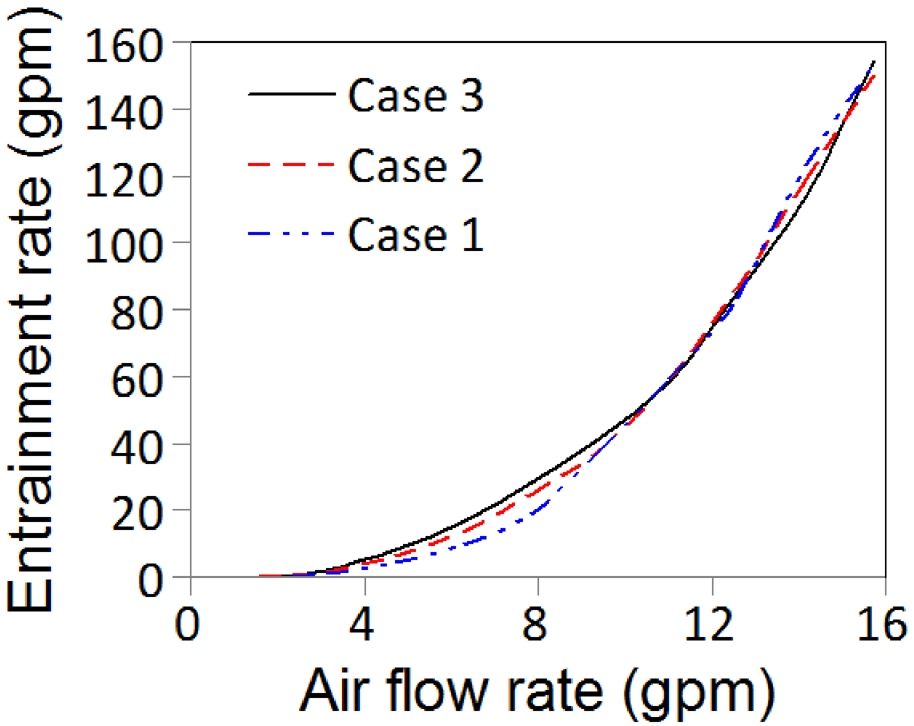

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