

## **Designing and Operating Reliable Gasifiers**

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### **Abstract**

Handling of bulk solids takes place in gasifiers either at the feed point or at the section of discharging waste and residues of the combustion and gasification. In large gasifiers, significant amounts of waste are expected to be produced, hence a proper gasifier design that allows an effective discharge of the waste from its bottom is essential for a smooth and reliable gasification. Poor gasifier design may result in unwanted flow patterns of the waste and formation of stagnant zones of ash in the discharge section, which may melt and eventually cause slagging and plugging of the gasifier. An experimental investigation was carried out to study the impact of two retrofitting techniques on the flow pattern and rate of discharging solids from a conical bottom discharge section of a cylindrical column simulating a gasifier. The two retrofits were a double pyramid insert and a throttling vertical tube attached to the outlet orifice. Glass beads were used as the bulk solids. The double pyramid insert was able to effectively change the flow pattern in the conical bottom of the surrogate gasifier from the undesired funnel flow to the most desired mass flow. Furthermore, it also promoted a uniform and homogenous flow preventing undesired delays in the discharge of the solid particles. On the other hand, attaching the vertical throttling tube to the outlet orifice developed severe and sudden constriction, causing transition from packed bed to suspension flow regime, hence increasing the discharge rate of the bulk solids by 7 to 8 folds.

### **Keywords**

Gasification, Fuel, Renewable, Coal, Biomass, Design, Hopper, Funnel flow, Mass Flow.

### **1. Introduction**

Handling bulk solids in columns and silos is frequently encountered in many industries and processes such as gasification, paper, cement, mining, and food. There are several problems associated with the flow of bulk solids in gasifiers during discharge of waste, ash, char, and un-reacted coal or biomass from a conical outlet of a gasifier. These problems can be categorized as common flow problems and associated flow problems. These flow problems include no flow, erratic flow, flooding, and flow rate limitation. The Modification of the gasifier outlet would be the most practical mean of correcting these flow problems.

The effectiveness of two retrofitting techniques in enhancing the flow pattern and increasing the discharge rate of solids from a conical hopper of a cylindrical column were examined. A double-pyramid insert was used to alter the flow pattern in a conical hopper from funnel to mass. Experimental results indicate significant changes in the flow pattern when the insert was incorporated in the discharge hopper. The use of the insert not only prevented formations of stagnant zone along the walls of the hopper but also altered the flow from funnel to mass resulting in a complete and homogenous discharge through the hopper outlet. Improper discharge of waste, ash, or char from a gasifier may result in plugging of the gasifier outlet, unwanted combustion of activated char, and ash conversion to slag that may eventually adhere to the gasifier wall.

Flow rate limitation is another problem associated with the flow of bulk solids in hoppers. In the current study, the discharge rate of bulk solids was boosted by suddenly and severely constricting the flow of the solids through a throttling small diameter vertical tube attached to the conical hopper outlet. By using this retrofitting technique, it was possible to cut down the total discharge time by 7 to 8 orders of magnitude. Experimental results are presented and explanations of the observed phenomena are provided.

## **2. Flow Patterns**

All of the problems associated with bulk solids discharge can be attributed to some undesired flow pattern of the solids. Poor choice of flow pattern in a hopper can cause segregation, leading to difficulty in obtaining reliable discharge (Bradley, 1996). The most common and undesired flow pattern is the funnel flow pattern. Funnel flow pattern is one in which some material moves while the rest remains stationary during discharge from the hopper. Funnel flow occurs when the sloping hopper walls of a column, gasifier in our case, are not smooth and steep enough for the particles to flow along them. Particles slide on themselves rather than the hopper walls and an internal channel flow develops. On the other hand, mass flow is the desired flow pattern in solid storage and handling units. Mass flow is defined as the flow pattern, upon withdrawal of any material, where the bulk flow of particles occurs cohesively. Mass flow occurs when sloping hopper walls are smooth enough and steep enough for the particles to slide along them. This type of flow eliminates ratholing and associated problems of flooding and stagnant material as well as maximizes the usable capacity of the gasifier.

The design of the gasifier for mass and funnel flow depends on the slope angle and shape of the hopper, friction between the bulk solids and the wall, and internal friction of the solids (McLean, 1984). The flow pattern can be changed from funnel to mass with the aid of retrofitting techniques such as air permeation systems, inserts, and fluidization.

## **3. Flow Problems**

As bulk solids discharge from conical hoppers several flow scenarios typically arise. The no flow scenario is the most common and serious problem, which occurs either due to arching (bridging) or ratholing (formation of rat hole). Arching occurs when an obstruction in the shape of the arch forms just above the opening of the silo, which prevents further movement of the material. Ratholing is a common problem,

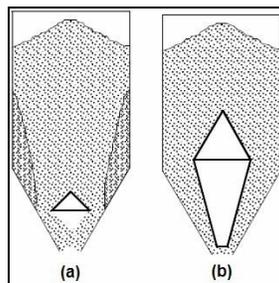
which results in the formation of a channel within the material. This occurs mainly due to the design of the hopper and roughness of the hopper inner surface. Less frequent flow problems include flooding, flow rate limitation and particle segregation.

Flooding or flushing may occur when handling fine powders. When a rat hole collapses, the falling particles entrain fluid and become fluidized. Since most of the solids handling equipment cannot handle fluids, the material floods the discharge hopper and minimizes efficiency by lowering flow rates. Flow rate limitation occurs with fine powders of low permeability that are affected by the movement of interstitial liquid. The pressure gradients developed as a result of this fluid movement can retard the discharge from the hopper. Finally, particle segregation occurs when handling homogenous substances with a wide range of particle size distribution or density, which may result in undesired chemical reaction or out of spec product due to poor mixing and resulting in product waste. Segregation of fines from the coarse during flow may also have similar effects (Carson et al., 1986). Poor flow patterns in hoppers and/or silos cause segregation that can ruin product and plant (Bradley and Peach, 1996).

#### 4. Enhancing Gasifier Performance

The problems that can be solved by hopper modification are flow stoppages or erratic flow due to ratholing and arching, flooding or flushing of the fine solids, certain types of segregation, incomplete or non-uniform processing, column vibrations and structural problems (Marinelli and Carson, 1992). To achieve mass flow two conditions, at minimum, must be met. The sloping walls of the hopper must be steep enough and have sufficiently low friction to allow particles to flow along them, and the hopper opening must be large enough to overcome arching.

Hopper modifications may not be the only solution to funnel flow problems. Hopper modifications necessitate the increase in headroom requirements for a given column capacity. Inserts can be used instead of hopper modifications to ensure mass flow patterns. The insert concept offers a possibility to obtain mass flow in considerably lower and thereby cheaper hoppers. Small-scale tests have indicated that this is possible (Fuerll et al., 1998). Generally, there are three types of inserts: inverted cone insert, bullet insert and Binsert® (Prescott and Hossfeld, 1994). An inverted cone insert is intended to expand flow in a funnel flow bin, thereby increasing its “live” volume. Figure 1(a) shows the schematic of the inverted cone insert. This insert will not convert funnel flow into mass flow, but will cause more material to move during discharge. If the inverted cone is designed and placed correctly, a bin with a tendency to form ratholes will flow reliably. A bullet insert has an inverted cone on the top followed by a conical tail section. Figure 1-b shows the schematic diagram of a bullet insert in a bin. The top section of the bullet is generally placed above the transition point in the hopper. The bullet, if properly designed, can be used to convert funnel flow to mass flow. In addition, the velocity gradients are reduced in comparison to a similar mass flow bin, thereby reducing segregation.



**Figure 1: Schematic of the two basic types of inserts to convert funnel flow to mass. (Prescott and Hossfeld, 1994).**

Inserts also influence the overall pressure distribution in the silo (Kobielak and Zamorski, 2003). The location of installation of these inserts has a considerable effect on their capability to change the flow pattern from funnel flow to mass flow. Ding et al. (2003) used a numerical approach to study the effect of the position of the inserts on flow patterns. They were able to infer that the inserts should be installed at higher levels close to the transition rather than at lower positions close to the outlet, especially with the cone-in-cone insert and the inverted inserts.

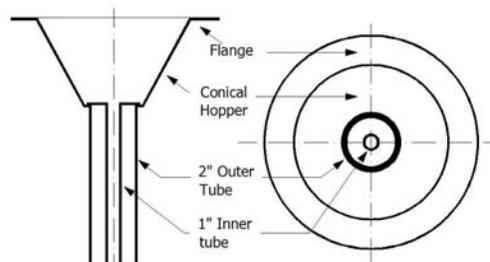
## 5. Experimental Setup

The experimental setup used in the current investigation is shown in Figure 2. The setup consists of a 7-ft column, loading assembly, and instrumentation. The column is made of an acrylic tube measuring 12" OD and 11 1/4" ID. It has various ports for instruments. The hopper, located at the bottom of the column, is made of 316 Stainless Steel screen. The screen wire is defined as #63 VEE wire and is supported by #93 support rods both vertically and circumferentially. The slot size is 0.010 inch axial providing a 0.007 inch passage for fluids. The screen is attached to the column by a 3/8" thick 15" OD flange. The screen slot size restricts the solid particles from passing through but allows fluids to move upward through the solid bed.

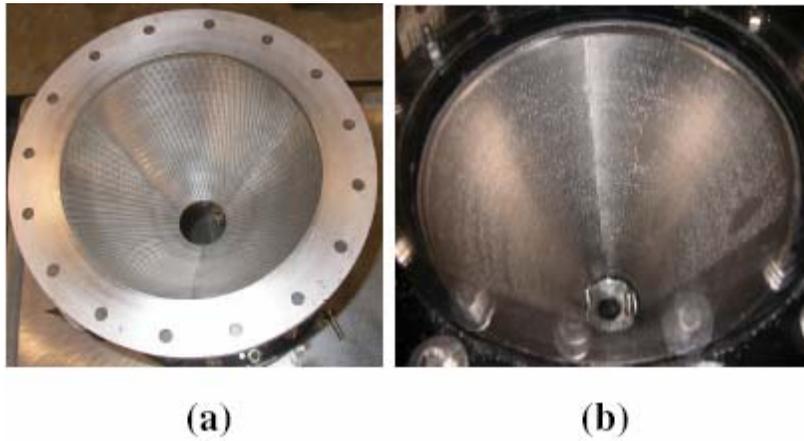


**Figure 2: (a) Experimental setup and (b) Instruments used in the experiments.**

Two retrofitting techniques were tested for their influence on the discharge rate and flow pattern in the column. The first technique involved a sudden reduction in the outlet diameter of the conical hopper at the bottom of the column. This was achieved by attaching a 1" OD, 18" long stainless steel vertical tube (throttling tube) to the 2" standard orifice of the conical screen hopper, effectively halving the venting diameter. Figure 3 illustrates a schematic of the new assembly. The throttling tube was held in position by screwing its flange to the outlet orifice as shown in Figure 4.

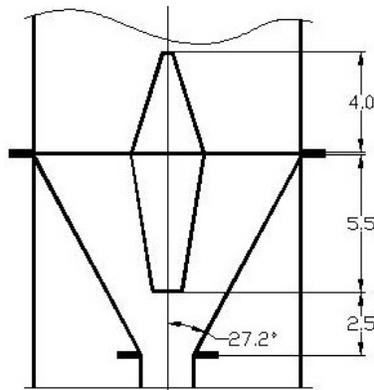


**Figure 3: Schematic of the throttling tube attached to the outlet orifice of the conical screen.**

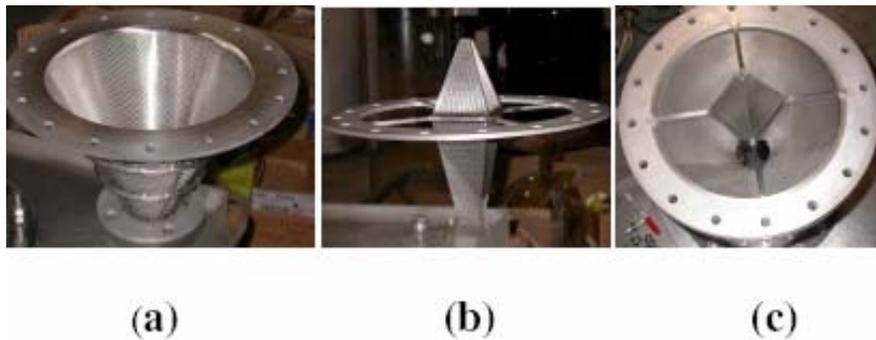


**Figure 4: (a) Conical bottom with a regular 2-inch diameter outlet, and (b) Throttling tube attached to the outlet orifice reducing its diameter from 2" to 1."**

The second approach incorporated a double pyramid insert in the conical bottom of the column. The double pyramid insert was placed just above the conical screen as shown in Figure 5, forming an annular space. Figure 6 shows both parts assembled together.



**Figure 5: Schematic of the double pyramid insert assembled with the conical screen.**



**Figure 6: (a) Conical screen (b) Double pyramid insert, and (c) Double pyramid insert assembled with the conical screen.**

## 6. Methodology

Glass beads with an average particle diameter of 350  $\mu\text{m}$  were used as the bulk solids. The bulk density of the dry glass beads was 1450  $\text{kg}/\text{m}^3$ , whereas the density of glass beads-water mixture was 1825  $\text{kg}/\text{m}^3$ . Experiments were carried out on dry as well as wet basis.

Each discharge test starts by loading the column with glass beads or a mixture of glass beads and water. The glass beads and/or water were transferred to a loading tank manually. The lid of the loading tank was securely closed. A flexible hose connected the bottom of the loading tank to the top of the column through a ball valve. Compressed air was supplied to the loading tank through an air regulator. When the tank pressure reached 20 psi, the glass beads started to flow in the flexible hose and to the column. Once a sufficient amount of glass beads had been discharged to the column to maintain a bed height of 60 inches, the air release valve on the loading tank was opened to vent the compressed air.

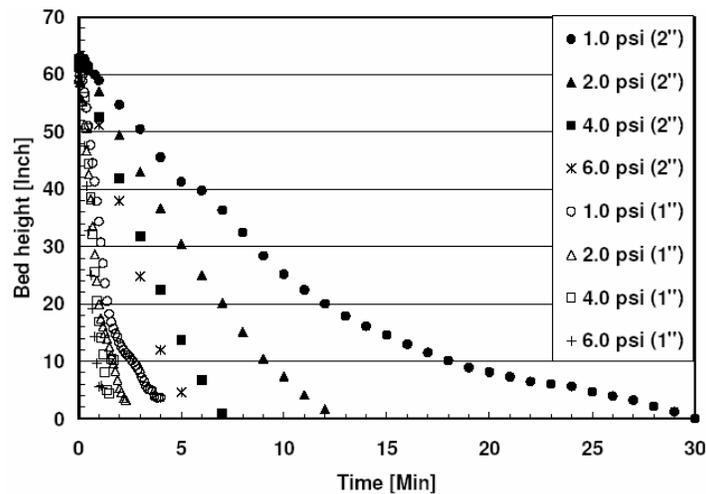
In wet experiments, a drainage valve at the bottom of the column was opened to remove the excess water from the column in order to maintain around 1 inch of water above the bed of wet glass beads. This kept the water content of the solid bed in the column the same for all experiments.

A laser level sensor was used to monitor the height of the solid bed in the column. The laser level sensor was checked for its alignment to assure that the laser beam was vertical. This was done in order to prevent loss of level data as the bed level drops during the discharge experiments. The section of the column above the bed was pressurized with compressed air via a pressure regulator to maintain particular pressure during each discharge experiment (Figure 1). Generally, the pressure fluctuations were slightly high at the beginning and end of each of the discharge experiment. An experiment begins by opening a release valve allowing glass beads/water to discharge from the column to a receiving container. Measurements of bed height and column pressure were monitored and logged. The discharge experiments were carried out at various column pressures ranging from 11  $\text{lb}/\text{in}^2$  to 6  $\text{lb}/\text{in}^2$ .

## 7. Results and Discussion

This article presents sample experimental results and discusses the impact of the double pyramid insert and the throttling vertical tube on both the flow pattern and discharge rate of bulk solids in a conical-bottom cylindrical column. The demonstration of the constricted outlet was carried out, in some cases, in combination with the double pyramid insert in order to evaluate the effectiveness of both retrofitting techniques on the column's performance. Figure 7 shows the influence of constricting the outlet diameter on the discharge rate of the solids with respect to time at different column pressures. It is evident that the discharge rate of the solids from the column increased significantly when the throttling vertical tube was attached to the conical screen orifice. For example, it took around 30 minutes to discharge a bed of 60-inch height from the column at a gauge pressure of 1 psig and when the throttling tube was not utilized. The corresponding time to discharge the same amount of solids was around 4 minutes as a result of forcing the solids through the throttling tube.

In order to explain the significant increase in the solids discharge rate as a result of suddenly and severely constricting the conical bottom orifice, it is important to point out to the variation in the flow characteristics in the vicinity of the transition zone from the cylindrical column to the conical screen hopper and then to the restricted cylindrical tube. The flow characteristics, such as dynamic pressure and solid bed voidage, change as the material approaches the outlet orifice. Flow regime transition often takes place as a result of these variations. In general, the flow of granular materials in proximity of hopper outlet can be divided into two different motion regimes; packed bed and suspension flow (Barletta et al., 2003).



**Figure 7: Influence of constricting the column's outlet on the discharge rate at different column pressures, the double pyramid insert was not installed.**

Faderani et al. (1998) were the first ever to report measurements of dynamic voidage profile of granular solid-liquid mixture discharging from a hopper through a vertical stand pipe. They showed that a marginal density difference between the solid particles and the interstitial liquid will magnify the interstitial drag effects thereby causing transition from packed bed to suspension flow regime, within few orifice diameters below and above the plane of the hopper orifice, as the materials flow from the conical bottom to a vertical stand pipe attached to it. Furthermore, Faderani et al. illustrated that two transitions occur: the first is from packed bed to suspension flow as the mixture flows out of the conical hopper and into the vertical stand pipe. The second is from suspension flow to packed bed state as the settling solid particles pack more closely further down the stand pipe. These transitions are observed to become more abrupt and to be confined to the immediate vicinity of the hopper orifice as the mixture discharge rates are increased.

A possible explanation for the significant increase in the discharge rate may be found in the work of Pennec et al. (1998). As the glass beads move toward the conical-bottom of the column, the pressure imposed on them increases, resulting in packing them closer together, thus elevating the bulk density. As the glass beads continue to move from the conical bottom to the vertical tube, the solids dilate in order to accommodate the shear which is caused by the constriction. This dilation will create more void space between the solid particles, thus leaving more room for the interstitial fluid; water in our case. An interface will exist between the packed bed and dilated solids. The dilation will also create local pressure gradient in the shear zone causing a drag force on the moving solid particles. Pennec et al. (1998) proposed an intermittent flow which consists of repeated cycles. During each cycle the interface between the dilated solids and packed bed region propagates upward in the conical part. After the interface reaches certain critical height it collapses and suddenly falls down resulting in a significant increase in the mass flow rate. This cycle repeats itself constantly. Recall that when the constriction is increased, as in our case, the shear in the constriction zone becomes more intensified, thus the solid dilation and the subsequent collapse of the interface and the discharge rate of the solids.

Moreover, it is believed that the pressure gradient associated with the dilation is responsible for local cavitation. Such cavitation will increase in the voidage and intensify the intermittent cycles described above leading to greater mass flow rates. This assumption is supported by the findings of Yang and Thorpe (1990) which indicate that the inception of cavitation does not necessarily require that the minimum static pressure at the vena contracta downstream of the orifice be equal to the liquid vapor pressure. In fact, it is well above the vapor pressure at the point of inception.

Bertho et al. (2002) investigated the flow of powders down a vertical pipe. They found that when the constriction increases, the flow switches to a regime with density waves of constant velocity. In such a case, a system of high-density plugs of solids and lower density pockets of interstitial fluid move at a constant downward velocity. Current measurements of variation in the solids bed height with respect to time, as shown in Figs. 6 and 8, illustrate constant discharge rate when the conical outlet was constricted by the throttling vertical tube. These observations are in line with the constant velocity density-wave flow described by Bertho et al. (2002). Furthermore, it believed that the permeability of the plugs is sufficiently enough to allow down flow of the water, thus accelerating the motion of the waves and, thus mass flow rate.

The terminal readings of several plots in Figure 7 were greater than zero indicating that a stagnant layer of solids remained in the bottom of the column at the end of the discharge experiment. Figure 8 illustrates an incomplete discharge as a result of funneling and rat hole formation. It is evident that the throttling vertical tube increased the discharge rate significantly, but failed to prevent funnel flow from occurring. Another benefit of this modification is demonstrated by triggering the onset of the flow in a very short time at low pressures of 1 and 2 lbf/in<sup>2</sup>.

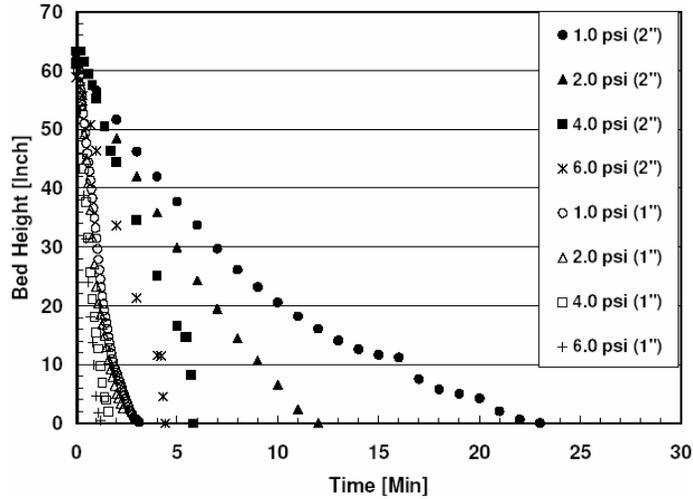


**Figure 8: Throttling vertical tube failed to prevent funnel flow in the absence of double pyramid insert.**

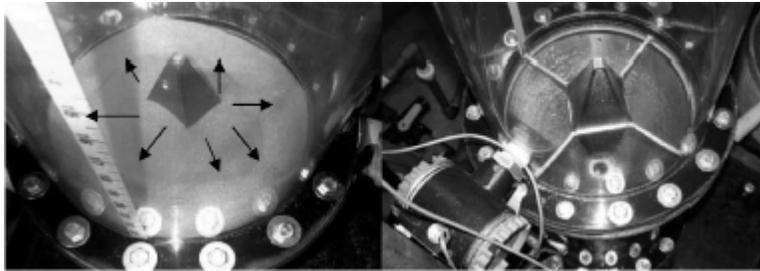
Figure 9 shows the combined enhancement in the column's performance as a result of utilizing both modifications; throttling tube and double pyramid insert. Not only did the discharge rate increased significantly, but also transition in the flow pattern from funnel to mass was possible resulting in a uniform and complete discharge as shown in Figure 10. Figure 11, however, illustrates the insignificant impact of the double pyramid insert on the discharge rate of the column at two different pressures. This figure also shows that terminal readings of the bed height were greater than zero when the insert was not incorporated in the conical hopper, indicating that a stagnant layer of solids remained in the bottom of the column at the end of the discharge experiment.

## 8. Conclusions

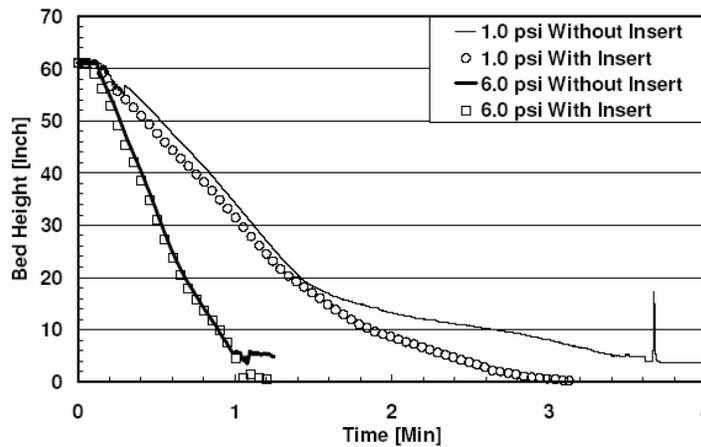
This paper presents an experimental demonstration of the effectiveness of two retrofitting techniques in improving the flow pattern and increasing the discharge rate of bulk solids in a conical hopper at the bottom of a column. The utilization of a double pyramid insert prevented the formation of unwanted flow patterns such as funnel flow, arches, and ratholes and enhanced the flow pattern by converting it from funnel to mass. The double-pyramid insert had little influence on the discharge rate. On the other hand, it was possible to significantly increase the discharge rate through the hopper outlet by attaching a throttling vertical tube to it. Incorporating both examined retrofits in a hopper will promote a mass flow pattern, significantly increased flow rate, and uniform and complete discharge.



**Figure 9: Variations in bed height at various process pressures with and without the reduced outlet. The double pyramid insert was installed.**



**Figure 10: Double insert promoted mass flow, thus uniform and complete discharge.**



**Figure 11: The double pyramid insert improved the flow pattern, but had insignificant effect on the discharge rate. Data are obtained from the setup with constricted outlet.**

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