Performance characteristics of an eccentric venturimeter with elongated throat for flow rate measurement of solid-liquid flows

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The performance characteristics of an eccentric venturimeter with elongated throat for 68 mm NB pipeline having an area ratio of 0.327 for the measurement of flow rates in solid-liquid flow, have been investigated. The modified geometry of the venturimeter is expected to suppress the erosion rate caused by the motion of solid particles. Copper tailings obtained from a processing plant have been used with water to prepare the solid-liquid mixture. Experiments performed over a wide range of flow velocities and solid concentrations show that the value of discharge coefficient of the eccentric venturimeter with elongated throat is slightly higher for slurry flow as compared to the value obtained for clear water flow. It is also seen that the average value of discharge coefficient obtained at different solid concentrations increases marginally with increase in solid concentration. The redistribution of solids at the throat of the venturimeter has also been investigated at different solid concentrations.

Ventrimeter is a simple and reliable obstruction type of flowmeter. The characteristics of this meter, when designed as per the relevant standards are well understood and documented for the single phase flow. Over the years these meters have also been used for metering two-phase flows (gas-solid, solid-liquid). The performance of these meters in terms of value of discharge coefficient and pressure loss have also been investigated by several researchers for two phase flows. Sharma 2 and Lee 3 have investigated the flow of gas-solid mixture using conventional venturimeter, whereas Payne and Crowe 4 have used a non-standard venturimeter for monitoring mass flow rate of similar suspensions. Graf 5 has also proposed a modified venturimeter for measurement of flow rate of two phase flows. Brook 6 and Hasan et al. 7 have investigated the performance of conventional venturimeters for a particular type of slurry. Abbas and Crowe 8 have analytically predicted the characteristics of a conventional venturimeter for two phase flows by solving the fluid flow governing equations. Hirata et al. 9 have also proposed a method for predicting both the discharge and the in-situ concentration for a conventional venturimeter. Although conventional venturimeter can be used for two phase flows, there are a few practical limitations as under.

(i) Horizontal pipelines transporting solid-liquid mixtures are subject to excessive wear specially at the bottom of the pipeline. Conventional venturimeter installed in the horizontal pipeline is also subjected to excessive wear because of increased velocity of solid particles in the converging portion. The nonuniform distribution of solid particles causes coarser particles to travel near the bottom of the pipeline and results in uneven wear of the meter surface. This implies that the discharge coefficient of a conventional venturimeter will keep changing with time due to excessive wear and hence renders the conventional venturimeters unsuitable for long term application.

(ii) It is also known that at low flow velocities, coarser particles do settle down at bottom of pipe thereby resulting in an unpredictable performance of the venturimeter.

In the present study, the cross sectional shape at the throat of a conventional venturimeter has been elongated towards the bottom of the horizontal pipe to overcome the above mentioned practical
difficulties (see Fig. 1). The discharge coefficient of the modified venturimeter has been evaluated as a function of solid concentration. Further, the solid distribution at the throat cross section of the venturimeter as well as in the straight pipeline has also been measured to quantify the effect of the eccentric geometry of the throat on the overall flow field.

**Eccentric Venturimeter**

A conventional venturimeter of 68 mm ND having a diameter ratio ($d/D$) of 0.54 was modified at the throat to get an elongated elliptical shape shown in Fig. 1. The geometric details of this venturimeter are given below:

- $H/D = 40/68$
- angle of convergence $= 7^\circ$ (Half Angle)
- angle of divergence $= 3^\circ$ (Half Angle)
- area of venturimeter throat $= 1188.0 \text{ mm}^2$
- area at the inlet and at the outlet of the venturimeter $= 3631.68 \text{ mm}^2$ (diameter $= 68 \text{ mm}$)

The throat of the conventional venturimeter was machined towards the bottom so that the bottom of the pipe became straight without any constriction (see Fig. 1). The resulting area ratio was 0.327 and equivalent diameter ratio ($d/D$) of the modified venturimeter is $\approx 0.572$. The modified shape is expected to reduce the erosive wear at the throat compared to conventional venturimeter as the constriction at the bottom of the modified venturimeter is negligible where particle concentration remains higher as compared to the top portion. Further, settling tendency of particles is expected to be less at the bottom of this venturimeter design because of minimal obstruction. With the reduction in the obstruction, the pressure loss is also expected to be somewhat lower as compared to a conventional design.

The differential pressure across the venturimeter is measured using pressure taps provided with separation chambers using U-tube mercury manometers (least count of 0.5 mm). The separation chambers filled with water are provided to act as interface between slurry and manometric fluid to prevent solid particles from choking the connecting tubes (see Fig. 1).

**Experimental Set-up**

The pilot plant test loop used for the present study is schematically shown in Fig. 2(a). It consists of a closed circuit pipe test loop of 55 mm diameter having length of 60 m. For the purpose of present experimentation a straight length of 25 m was replaced by pipe of 68 mm diameter (i.d.), as shown in Fig. 2a. The slurry was prepared in a hopper shaped mixing tank provided with a suitable stirring arrangement in order to keep the slurry well mixed. The slurry was pumped from this tank into the pipe loop by means of a slurry pump. The slurry pump employed was of sufficient capacity to cover the entire range of head and discharge needed at all concentrations. The flow rate of the slurry in the pipe loop was varied over a wide range by suitably operating the plug-valve provided in the loop, near

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**Fig. 1**—Schematic diagram of the eccentric venturimeter with elongated throat

**Fig. 2**—(a) Schematic layout of slurry test loop facility, (b) Sampling tube
the delivery end of the pump. Additional auxiliary control over the flow was possible through the operation of a by-pass line provided with the pipe loop. The two corresponding valves were adjusted so as to keep the head developed by the pump at an approximately constant value at all the velocities. After circulation through the pipe loop, the slurry was returned either directly to the mixing tank or diverted by means of a flow diverter to a measuring tank provided adjacent to the mixing tank. The flow rate could be ascertained by measuring the rise in the level of slurry in the measuring tank over a known time. A stirrer provided in the measuring tank kept the slurry in suspension during its use. The modified venturi meter as described earlier was fitted in the pipe loop as shown in the Fig. 2a.

A transparent observation chamber was provided in the pipe loop to facilitate visual observation of the flow. Thus, it was possible to observe the movement of the solid particles near the bottom of the pipe and to visually estimate the deposition velocity without disturbing the flow. The pressure taps with separation chambers were provided to measure the pressure drop in the pipe loop using U-tube mercury manometer.

The specific gravity of the slurry flowing through the pipeline system was monitored by collecting efflux samples through an efflux sampler provided in the vertical section of the pipe loop, near the discharge end. The average solid concentration was then evaluated from the measured specific gravity using a predetermined correlation between the mixture specific gravity and the solid concentration. The measurement of the mixture specific gravity thus provided a rapid procedure for monitoring the solid concentration.

The solid distribution inside the pipe and at the venturi meter throat is measured by traversing a concentration sampler (Fig. 2b). This concentration sampler collects the sample under near isokinetic conditions and has been shown to measure the in-situ local concentration quite accurately. Samples were collected at five different heights from the bottom of pipe at two cross sections: the first one in a straight pipe (Y/D= 0.09, 0.20, 0.45, 0.58 and 0.91) and second one at the venturi meter throat (Y/D= 0.09, 0.20, 0.45, 0.58 and 0.7). The specific gravity of the slurry collected through the sampling tube at any section inside the pipe is measured and from this data variation of solid concentration along the mid vertical plane of the pipe/venturi meter throat is determined.

Properties of Solid Material Used

Solid material obtained from Copper processing plant has been used in the present investigation. The properties of solid material used are given in Table 1. The static settled concentration of the slurry was determined experimentally by allowing the solid liquid suspension to settle in 1000 mL graduated jar. The rheological parameters characterising the

| Table 1—Physical properties of the copper tailings |
|---|---|---|---|---|---|---|---|---|---|
| (a) Overall specific gravity of solids: 2.82 |
| (b) Particle size distribution: |
| Particle size, μm | 850 | 600 | 210 | 150 | 106 |
| % finer | 100 | 99.6 | 97.36 | 80.64 | 71.24 |
| (c) Static settled concentration: 58.67 % by weight |
| (d) Rheological data: |
| Cw, % | Temp., °C | Yield stress, dynes/cm² | Viscosity of slurry, cP | Viscosity of water, cP | Relative viscosity | Remarks |
| 0 | 19 | 0 | 1.03 | 1.141 | 1.03 | 1.108 | Newtonian |
| 10 | 19 | 0 | 1.03 | 1.271 | 1.03 | 1.234 | Newtonian |
| 20 | 19 | 0 | 1.03 | 1.509 | 1.03 | 1.465 | Newtonian |
| 30 | 19 | 0 | 1.03 | 1.982 | 1.03 | 1.924 | Newtonian |
| 40 | 19 | 0 | 1.03 | 1.982 | 1.03 | 1.924 | Newtonian |
behaviour of the solid liquid mixture were measured by using a Weissenberg rheogoniometer at various concentration levels. The specific gravity of the material is 2.82 and the static settled concentration was measured as 58.67% by weight. The particle size distribution of the solid material which shows fairly well graded distribution with approximately 50% particles being finer than 75 microns. The measurement of relative viscosity of slurry at different solid concentrations indicates (Table I) that the slurry exhibits Newtonian character over the solid concentration range used.

Experimental Procedure and Data Analysis
At any given solid concentration, the differential pressure across the venturi meter the corresponding flow rate were measured at different flow velocities. Similar data was obtained at different solid concentrations. The velocities of slurry flow in the pipe loop during the present investigation were varied in the range 0.6 to 2.0 m/s for different solid concentrations in the range 3.4-31% by wt.

From the measured values of differential pressure and the flow rate, the discharge coefficient of the venturi meter has been calculated, using the equation given below:

\[ Q = \frac{C_d}{\sqrt{1 - \beta^4}} \frac{A}{\sqrt{2\Delta p}} \rho_s \]

where, \( A_1 \) is the area of cross-section of venturi meter throat, (m²), \( A \) is the area of cross-section of pipe, (m²), \( C_d \) is the discharge coefficient, \( Q \) is the flow rate of slurry, (kg/s), \( \Delta p \) is the differential pressure, (N/m²), \( \rho_s \) is the density of slurry, (kg/m³) and \( \beta \) is the equivalent diameter ratio \( \left( \frac{A_1}{A} \right)^{1/4} \).

At each flow rate, the Reynolds number is also calculated. The coefficient \( C_d \) has been evaluated from the measured value of flow rate and differential pressure. Dependence of \( C_d \) on flow velocity, solid concentration and solid properties has been established and discussed.

Results and Discussion
Measurements have been made with the modified venturi meter with water and slurry at five different solid concentrations. The results are presented in Figs. 3-6.

Variation of discharge coefficient for water
Fig. 3 shows the variation of discharge coefficient for water with flow velocity. It is seen that venturi meter coefficient remains constant for the range of velocities tested and has an average value of 0.9096. This value is appreciably lower than that for a conventional venturi meter. This can be attributed to the fact that the convergence in the modified venturi meter is not axi-symmetric and hence the losses due to secondary flows are somewhat higher.

Variation of discharge coefficient with solid concentration
Fig. 3 also shows the variation of discharge coefficient at different solid concentrations with flow velocity. It is observed that the maximum deviation of 3.5% in discharge coefficient is at the maximum solid concentration tested. It is also seen that at any given solid concentration, the variation in the measured values of discharge coefficient at different flow

Fig. 3—Coefficient of discharge of the eccentric venturi meter with elongated throat with water at various concentrations and slurry flow velocities.

Fig. 4—Coefficient of discharge of the eccentric venturi meter with elongated throat at different concentrations of slurry.
velocities is within ±0.3%. Similar phenomena was observed by Seshadri and Singh\(^1\) for a conventional venturimeter when used with solid-liquid mixtures.

To bring out the effect of solid concentration on discharge coefficient, the average value of discharge coefficient has been calculated at each solid concentration and its variation has been plotted in Fig. 4. It is seen that average value of discharge coefficient increases marginally with solid concentration till a concentration of 15% by weight and thereafter it remains almost constant. The increase in discharge coefficient is marginal and the increase is found to be only 3.5% even at the highest solid concentration tested. This increase can be attributed to reduction in losses at low solid concentration due to suppression of turbulence\(^10\). At high concentration, reduction in loss is compensated by increased viscosity of the mixture. From the above results, an average value of discharge coefficient can be calculated which could be applicable at all concentrations with an error band of ±1.75%.

Solid distribution pattern
In order to get an insight into the effect of the venturimeter on the overall solid distribution field, the concentration distribution was measured along the vertical plane of the pipe much downstream of the meter and at the throat. The measured values of

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**Fig. 5**—Concentration distribution along vertical plane in straight pipe, at various efflux concentrations and flow velocities
(a) \(C_{wef}=3.4\)%, (b) \(C_{wef}=15.3\)%, (c) \(C_{wef}=31.0\)%

**Fig. 6**—Concentration distribution along vertical plane at venturimeter throat, at various efflux concentrations and flow velocities
(a) \(C_{wet}=3.4\)%, (b) \(C_{wet}=15.3\)%, (c) \(C_{wet}=31.0\)%
concentration in the pipe and the modified venturimeter throat are given in Figs 5 and 6. It is observed that the concentration profiles in the pipe are skewed with maximum solid concentration being close to the bottom (Fig. 5a-c). Further, it is also observed that at a given concentration of solid material, increase in flow rate brings more uniformity in the concentration profile and it is in agreement with the reported trends\(^\text{30}\). This trend is seen at all values of solid concentrations. Fig. 5a-c also show that at any given flow rate increasing solid concentration also increases uniformity in the solid distribution.

Solid distribution at the throat is shown in Fig. 6a-c. The effect of flow velocity and solid concentration on the local concentration distribution is similar to the pipe, i.e., concentration profile becomes flatter with increase in the discharge rate and the efflux concentration.

A comparison of concentration profiles at an efflux concentration of 3.4 % at different discharge rates shows that at any given discharge rate, the concentration profile is flatter at the throat as compared to the pipe. This is expected because of increased velocity at the throat would make the suspension more homogeneous. However, flow still remains in the heterogeneous regime only unlike the conventional venturimeter where strong redistribution of solid particles take place. Thus, the flow disturbances created by modified venturimeter are much less as compared to the conventional venturimeter.

**Conclusions**

Detailed experiments on the modified venturimeter has revealed its suitability for flow metering application in two phase flows. The main conclusions of this study are as follows:

1. The value of discharge coefficient of modified venturimeter is some what lower as compared to conventional venturimeter.

2. The effect of flow velocity on the value of discharge coefficient is marginal over the range of velocities for which experiments have been performed. Hence, we can assume \( C_d \) to be a constant.

3. The discharge coefficient of the modified venturimeter increases marginally with solid concentrations up to 15% concentration by wt. and thereafter remains constant with increase in solid concentration. However, the variation of \( C_d \) over the solid concentration range of 0 to 31% by wt. is only 3.5% and hence we may be able to use an average value based on water data for metering of slurries if high accuracies are not required.

4. The modified shape of the venturimeter throat does not alter the distribution pattern of the solids compared to a conventional venturimeter. The flow pattern in side the modified venturimeter remains heterogeneous at moderate flow velocities and efflux concentrations.

**Nomenclature**

\[
C_{v} = \text{concentration of solids (by wt.)}
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C_{e} = \text{efflux concentration (by wt.)}
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d = \text{diameter of the throat of conventional venturimeter, m}
\]
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D = \text{diameter of pipe, m}
\]
\[
d_e = \text{equivalent diameter of the throat of the modified venturimeter, m}
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H = \text{height of the elongated throat, m}
\]
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Y = \text{distance along the vertical plane from the bottom of pipe/venturimeter, m}
\]

**References**


