CHEMICAL ENGINEERING TRANSACTIONS
VOL. 71, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Xiantang Zhang, Songrong Qian, Jianmin Xu

ISBN 978-88-95608-68-6; **ISSN** 2283-9216
DOI: 10.3303/CET1871176

Fluidity Study on Chemical Behavior of Bingham Materials in Pipe Transportation

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Bingham material has commonly been used to control subsidence damage caused by underground coal mining. This paper discusses the Bingham materials fluidity characteristics in the pipe transportation. A general description about the components of the Bingham materials is provided involving the various chemical behavior and rheological performance. The flow characteristics in pipeline has been simulated in the straight pipe and 90° elbow pipe respectively combined with the pressure loss and conveying velocity distribution. With the help of the commercial Computational Fluid Dynamic (CFD) code FLUENT, the modeling is conducted with various materials feeding velocity. These results show the local resistance loss in bending pipe is significantly higher than the resistance in the straight pipe under the same condition associated with Bingham materials transportation. The velocity distribution of the slurry solid particle in the slurry movement forward is more decentralize as the increasing hydraulic inlet velocity. Bingham materials fluidity characteristics based on different chemical behavior was concluded in the paper.

1. Introduction

The cemented gangue-fly ash backfill (CGFB) was utilized in the backfill technology as one type of Bingham materials. The CGFB is mixed on the surface, pumped underground through pipeline to the working face (Yang et.al 2018). The solid content of the fresh CGFB slurry is 78.05% by weight (water accounts for the remaining 21.95%) and is composed of Portland cement (10%), fly ash (20%), coal gangue (49%), and additive (0.05%) (Yang et al., 2014). The chemical element of the components significantly influences the CGFB slurry fluidity. Figure 1 provides coal gangue, fly ash and CGFB chemical components Energy Spectrum Analysis.

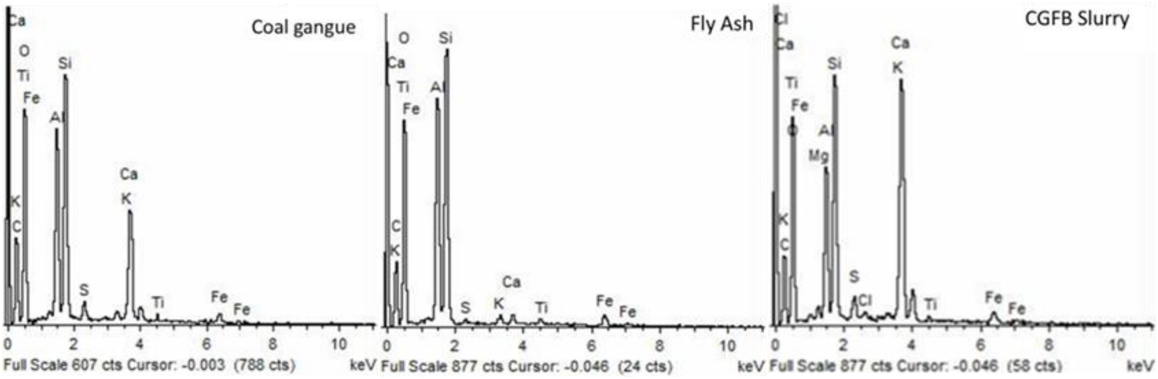
The CGFB slurry was observed to exhibit non-Newtonian behavior (Zhang et al., 2014). The pilot plant loop test with horizontal pipe was conducted during the CGFB pipeline transportation, in which the average loss of frictional resistance in per unit length was observed as 3.80 KPa/m while the average loss of local resistance was 4.11 KPa/m (Latifi et al., 2015). Under this level of transmission resistance, the CGFB slurry can be transported to a longer distance with a larger scale flow that satisfies the coal mine backfilling requirements. The delivery characteristic of CGFB slurry largely depends on the resistance that produced during the process of the pipe transportation. Thus, understanding the slurry flow characteristic, predicting the slurry pressure loss and determining the reasonable transportation parameters is essential to make sure the safety of the CGFB slurry pipe transportation and reducing the risk to block the pipe due to the high solid concentration.

The Bingham materials flow resistance in pipeline is significantly influenced with slurry rheological characteristics and hydraulic conveying velocity (Convery et al., 2010; Sevault et al., 2018). The slurry yield stress and relative viscosity contributes the slurry initial rheology, but the conveying velocity impact on the resistance is not very clear. In the pipeline transportation process, the obvious difference was observed on the velocity distribution of the slurry flow along the slurry movement forward because of the limitation of the pipe wall and the influence of slurry own rheological properties. The offset in the flow conveying velocity can cause the diffusion of the slurry. Thus, the effect of pressure drops and velocity distributions profile needs to be studied thoroughly within the Bingham materials pipe transportation.

The Computational Fluid Dynamics (CFD) was use to predict the flow characteristic has been a long time and the effects show a great agreement with the experiment test. In the present work, an attempt has been made

Please cite this article as: Yang J., Yang B., Li T., Yu M., 2018, Fluidity study on chemical behavior of bingham materials in pipe transportation, Chemical Engineering Transactions, 71, 1051-1056 DOI:10.3303/CET1871176

to reveal the flow movement features in CGFB slurry pipeline using commercial CDF code FLUENT in the aspects of pressure drop and velocity distribution. Simulation study was used to optimize the hydraulic conveying velocity and determine the CGFB slurry transportation crucial parameters in the straight and bending pipe. This paper focus on the CGFB slurry characteristics but intents to revel the Bingham materials characteristics due to the CGFB is one type of the Bingham materials.



(a) *(b)* *(c)*

Figure1: The chemical components of the materials in the Energy Spectrum Analysis test: (a) Coal gangue components; (b) Fly ash components; (c) CGFB slurry components.

2. Materials and methods

The CGFB slurry can be idealized as a homogeneous fluid of the single phase with modified properties because of the Bingham plastic body characteristic. Figure 2 shows the CGFB slurry by SEM.

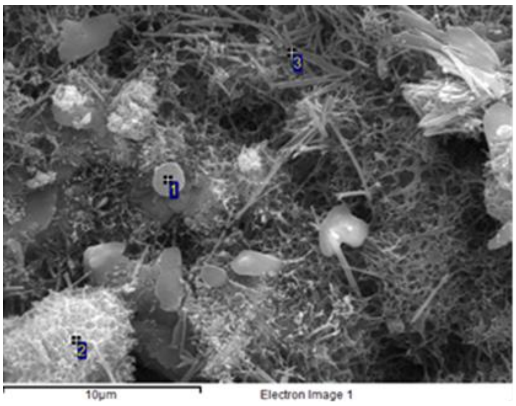


Figure 2: SEM images of interior structure for the CGFB slurry

The Reynolds number was employed to classify the flow layer category to determine the laminar layer and turbulence layer. Typically, the figure of 2100 was used to watershed the laminar or turbulence. Regarding the Bingham flow, the relative viscosity was introduced to calculate the Reynolds number.

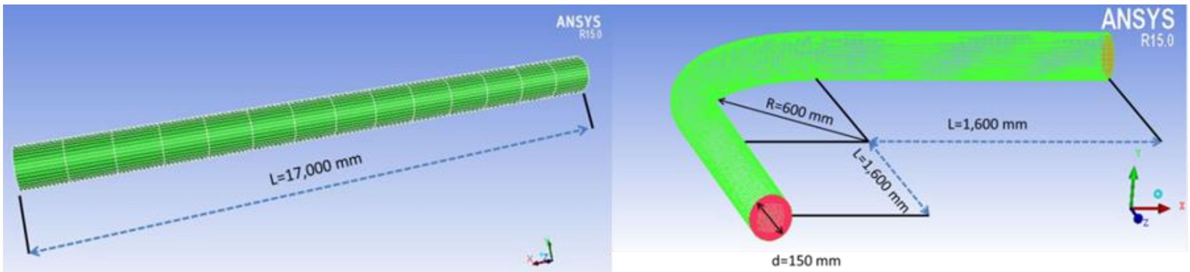
$$Re = \frac{vD\rho}{\mu} \quad (1)$$

Where, Re is Reynolds number, v is conveying velocity, m/s; D is the diameter of the pipeline, m; μ is the slurry relative viscosity, Pa·s, and ρ is the slurry density, kg/m^3.
The CGFB slurry workable test show the density of the CGFB ranges between the 1920 to 2100 kg/m^3, and the relative viscosity is ranging from the 1.64 to 1.78 Pa·s. Thus, the average density of 2000 kg/m^3 and the average relative viscosity of 1.71 pa·s were employed to calculate the Reynolds number.

$$Re = \frac{2000vD}{1.71} < 2100 \quad (2)$$

$$D < \frac{1.8}{v} \tag{3}$$

Refers to the equation (3), assumption the slurry pipeline diameter is 150 mm, under this condition, the CGFB slurry transportation is sustain the laminar flow when the conveying velocity is up to 12 m/s, which means the most case of the CGFB slurry transportation is belonging to the category of laminar layer.
The structuration grid of straight pipe and elbow pipe was established in the ICEM CFD, and then the mesh file was loaded into the ANASYS R15.0 software. The length and diameter of straight pipe were considerate as 17,000 mm and 150 mm respectively. On the 90° elbow pipe construction, the radius was set as 600 mm and an extension for a length of 1,600 mm was develop on the both of inlet and outlet parts. Figure 3 shows the geometry of the constructed straight pipeline and elbow pipeline.



(a) *(b)*

Figure 3: Geometry of the simulated pipe model. (a) Straight pipe; (b) 90° elbow pipe.

3. Computational models

Mathematical model mainly consists of mass, momentum, and energy conservation equation in partial differential form with associated boundary conditions. CFD code FLUENT was used to estimate the pressure drop phenomenon in the slurry pipeline. In FLUENT, the Herschel–Bulkley model (Xu et al., 2016) was modified to represent the Bingham plastic model.
The CGFB slurry is mixed wat a high solid concentration of 76.05% as the single substance. The slurry density is considerate as the constant of 2000 kg/m3. Slurry viscosity was defined under the Herschel-Bulkley model. Type the figure of 1.71 as the Consistency Index and 1 as the Power-Law Index while set the Yield Stress Threshold as 158.91. The Viscous-Laminar model was applied to the high solid consideration of CGFB slurry to determine the flow layer characteristic of the mixture in pipe.
The boundary conditions namely velocity inlet, pressure outflow and no slip conditions were applied to fluid flow domain. The inlet boundary condition was applied to flow the fluid at the velocity of 1.4 m/s, 1.6 m/s, 1.8 m/s, 2.0 m/s and 2.2 m/s respectively and volume fraction which tends to generate a stabilized flow along the length of pipe. The outlet boundary condition was applied at outlet section. On the purpose to simple the analysis, the export pressure was provided with 0 pa at the outlet section. Wall was treated as stationary with no slip. Average roughness height was calculated using water flow data of 0.5 that mentioned in Fluent for uniform pipe surface roughness.

4. Results and discussion

In this present study, the aim is to predict the pressure loss by applying Herschel–Bulkley model in a 17,000 mm long straight pipe and the 600 mm radius of the 90°elbow pipe with the same diameter of 150 mm. The simulations are conducted at velocity 1.4 m/s, 1.6 m/s, 1.8m/s, 2.0 m/s and 2.2m/s, the solid concentration of CGFB slurry sustainment at 76.05%.

4.1 Pressure loss

Figure 4 provides the pressure loss contour of the straight pipe and 90° elbow pipe at various inlet velocities. It was observed that as the feeding velocity increases, the higher pressure loss was founded on the all transportation case. Pressure drop ($\Delta p/l$) is introduced to describe the pressure loss of the CGFB slurry in this paper, which was calculated in terms of press loss over per unit length through the pipeline. For the straight pipe transportation example, the maximum pressure drop of 5,750 Pa/m occurred at the case of the feeding velocity 2.2 m/s. At the same inlet velocity on the bending pipe, the maximum pressure drop is 7,532 Pa/m. This data suggests that the amount of pressure drop is effective increased by a factor of 1.31. These results support the notion that the local resistance is significantly higher than the resistance at the same transportation condition associated with high concentration slurry pipeline transportation.

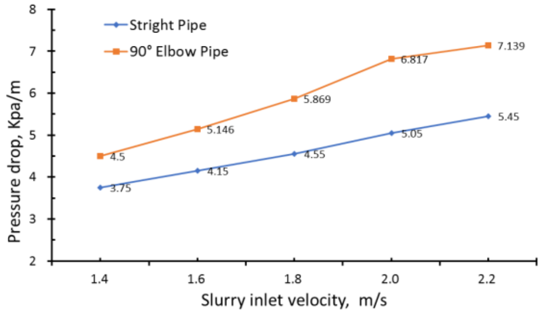


Figure 4: The pressure drop under the different inlet velocity

Figure 5 shows that predicted pressure drop profile on the CGFB slurry suspension flow at straight pipe and 90° elbow pipe at velocity 1.4 m/s, 1.6 m/s, 1.8 m/s, 2.0 m/s and 2.2 m/s respectively.
The profile clearly show as the increasing inlet velocity of the slurry, resistance and local resistance loss both increased but the local resistance incensement is much significant. It was realized on the slurry transportation case with the feeding velocity of 1.4 m/s, the value of pressure drop is notice as 3,650 Pa/m at straight pipe and 4,380 Pa/m on 90° elbow pipe. The factor of the local resistance over resistance is 1.2. Similarly for velocity of 2.2 m/s, the magnitude of pressure drop was notice as 5,450 Pa/m at straight example while 7.412 Pa/m at another. In this situation, the factor extends to 1.36. Under this level of the magnitude of the press drop, the CGFB slurry characters an adequate fluidity on the pipeline transportation. This result is agreement well with the pilot plant test results, and it supports the conclusions that the CGFB slurry can satisfy the coal mine backfilling requirements with the large-scale, large-flow and high-safety.

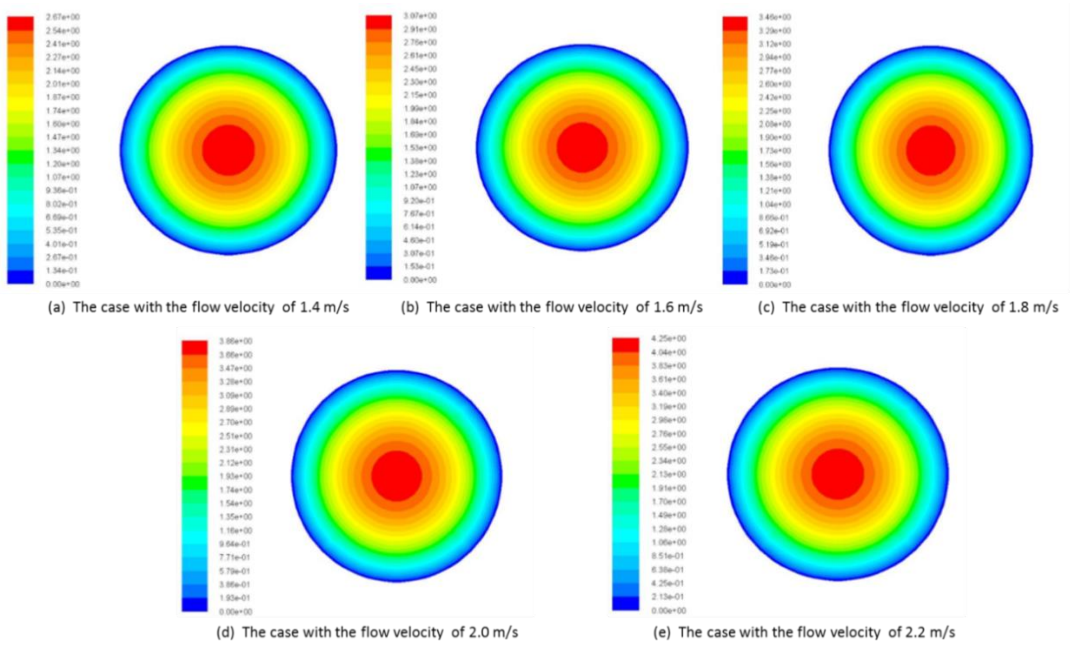


Figure 5: Velocity distribution contours with 76.05% solid concentration of CGFB slurry at different feeding velocity through the straight pipe: a) The case of 1.4 m/s; b) The case of 1.6 m/s; c) The case of 1.8 m/s; d) The case of 2.0 m/s; e) The case of 2.2 m/s.

4.2 Velocity distribution

The velocity distribution of the CGFB slurry flow in the pipe was shown in figure 5 and figure 6 based on the different feeding velocity 1.4m/s, 1.6 m/s, 1.8 m/s, 2.0 m/s, and 2.2 m/s respectively. Figure 8 and figure 9 shows the velocity distributions profiles under the different transportation cases of straight pipe and 90° elbow pipe

The slurry velocity distribution contour on the pipe was conducted to analysis the CGFB slurry flow transportation stability characteristic. The results from the straight pipe show (Figure 5) that the slurry moves forward with the shape of plunger in the pipe due to the different velocity magnitude on the different position of slurry flow. A flow core-zone area and a non-flow core-zone area on the cross-section of the slurry flow were observed and were found to be in good agreement with the conclusions related with flow-core zone distribution. The slurry concentrates on the center region with in certain radius is located at an area with a relative high velocity (show as the red zone in Figure 5). This area was defined as the flow core-zone while the remaining area on the cross-section of pipe was defined as the non-flow core-zone. Beyond the flow core-zone area, within the region of the non-flow core-zone, from the center area to the pipe wall, the slurry conveying velocity presents a constant decreasing trend. At the position near to the pipe wall, the slurry conveying velocity is close to zero, it is considerate as the “wall effects”. With suspension, there is always a slight decrease in particle concentration near the walls of the pipe, due to the steric effects, which resulting in the magnetized of zero in the simulation.

The conveying velocity distribution contour is concentric on the cross-section of the slurry flow. The center is much higher while the side is lower. On the case that feeding velocity is 1.4 m/s, the maximum predicted conveying velocity in the pipeline is 2.67 m/s, which an exceeding increase of 1.27 m/s was found. On the example of 2.0 m/s, the difference is 1.83 m/s and the magnitude rises to 4.25 m/s on the case of 2.2 m/s, which is more than double the feeding velocity. The increasing difference indicts that as the feeding velocity increases, the slurry tends to be more unstable and the slurry plunger shape is more obvious. The difference of the conveying velocity on the slurry flow determines the transportation stable characteristic of the CGFB. The larger difference on the conveying velocity between the jointed points on the slurry, the more significant unstable was occurred on the transportation. Thus, the feeding velocity of CGFB transportation in pipe should be reasonably considerate on the purpose to maintain the stable flow.

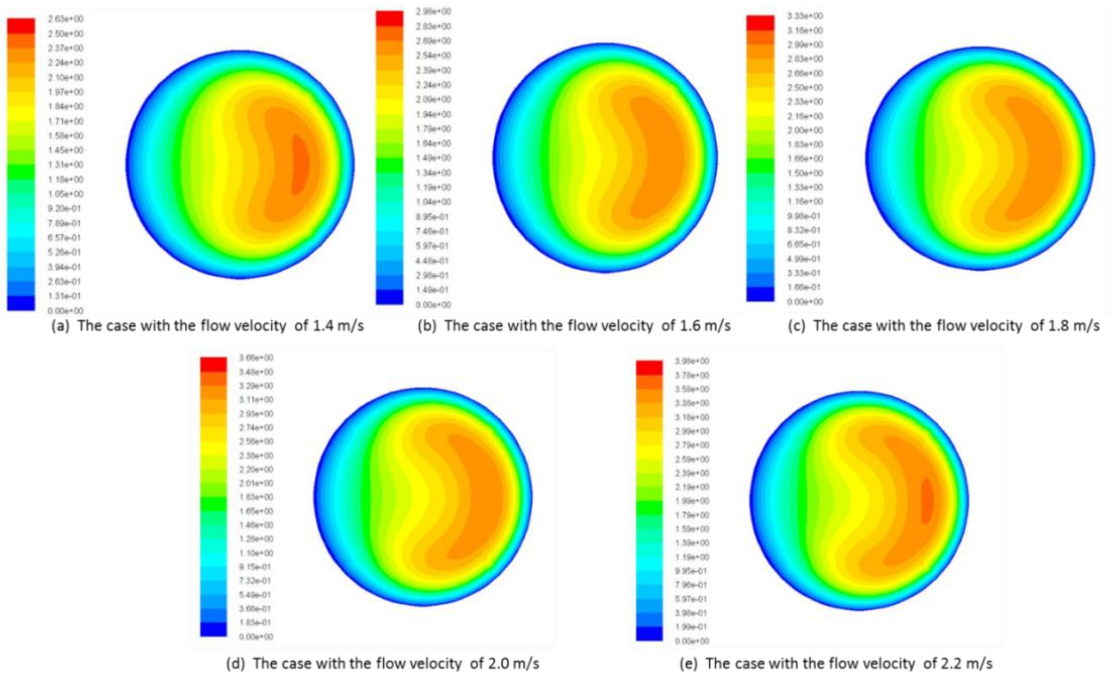


Figure 6: Velocity distribution contours with 76.05% solid concentration of CGFB slurry at different feeding velocity through the elbow pipe: a) The case of 1.4 m/s; b) The case of 1.6 m/s; c) The case of 1.8 m/s; d) The case of 2.0 m/s; e) The case of 2.2 m/s.

When the CGFB slurry pumped into the pipe after configuration on the surface station, under the restriction of the pipe wall and the impacts of slurry rheological characteristic, the slurry flow deforms to the plunger shape to progress along the pipe extension. When the slurry goes through the bending section, a new flow shape was formed to satisfy the pipe deformation. Thus, the core-flow zone (the higher velocity distribution area) moves outside to the pipe latter well while the non-core-flow zone (the lower velocity distribution area)

concentrates to the pipe inner wall (shown as the Figure 6). The conveying velocity distribution of the CGFB slurry in the bending section is diffused without the concentric circles. As the inlet velocity increase, the pressure loss increase but the area of core-flow zone decrease, which indicates a more significant unstable flow characteristic was reached.
The offset on the points of the slurry center and the pipe well in the conveying velocity is gradually decreased compared with the straight pipe. when the conveying velocity is 2.2 m/s, the monitored velocity in the bend is 3.98 m/s, while the responding velocity in the straight pipe is 4.25 m/s. The maximum conveying velocity of straight pipe slurry is higher than the bending pipe conveying velocity, which shows that the restriction impacts of bend pipe is more obvious than that the straight pipe

5. Conclusions

(1) The resistance loss along the length of pipeline gradually increases with the rise of inlet velocity. The local resistance loss in the bend is significantly higher than the resistance in the straight pipe at the same condition associated with Bingham materials transportation because of the pipe deformation impacts.
(2) On the Bingham materials pipe transportation, the higher of the slurry inlet velocity, the more drastic offset on the magnitude regarding the slurry conveying velocity is occurred on the slurry flow cross-section. The velocity difference among the adjacent points on the slurry flow causes the plunge shape of the Bingham materials flow. The higher slurry inlet velocity, the more decentralize conveying velocity distribution occurred on the slurry, which significantly affects the slurry stability in pipe transportation.
(3) The core-flow zone and the non-core flow zone on the slurry flow cross-section were observed at the simulation of the CGFB pipe transportation. When the slurry is transported in straight pipe, the concentric distributes composed of the difference conveying velocity regions was found as the core-flow zone. With the increase of slurry inlet velocity, the conveying velocity of flow core area also increases, but the flow core area decreases. This is occurred on the all Bingham materials

Acknowledge

This study was sponsored by China Scholarship Council of the Ministry of Education, China (File No. 201706430020). Particular thanks are given to China University of Mining and Technology, Beijing for the permission of using the ANASYS software.

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