

A Rheological Study on the Pumpability of Co-Mingled Biomass and Coal Slurries

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Abstract

There is considerable interest in the gasification and subsequent conversion of coal and biomass mixtures to synthetic liquid fuels as a means of reducing the overall net life cycle CO₂ emissions when compared to petroleum. Our laboratory has developed a steam hydrogasification technology which has been shown to be very efficient for gasification of biomass and coal feedstocks and mixtures. However, the pumpability of coal and biomass slurries in gasification processes is a critical issue that needs to be more fully understood in order to maintain the high efficiencies of the technology. The pumpability is dependent on the slurry's rheological properties (e.g. shear rate, shear stress and viscosity) which in turn are related to the slurry's physical properties.

In this study, wood was initially hydrotreated to make a high solid content biomass paste and then mixed in varying percentages with a coal-water slurry. The effect of solid particle size of the slurry, the initial coal and wood particle size distribution, and the solid/water ratio on shear rate and viscosity were determined using a rotational rheometer. Our experimental results show that larger particle size offers better pumpability. The presence of a high percentage of biomass in solid form significantly decreased slurry pumpability. The optimum solid/water ratio has been determined with various coal/biomass mixtures. The results of these experiments will be presented.

Key words: Slurry Rheology, Co-Mingled coal-biomass slurry, Pumpability

Introduction

Interest in the development of alternative transportation fuels has increased considerably in recent years as the worldwide vehicle population continues to increase and the resources for the production of petroleum-based fuels continue to be depleted. Gasification and subsequent conversion to synthetic liquid fuel from coal and biomass mixtures have been shown to be a promising alternative resource for transportation fuel production. It can provide clean synthetic liquid fuels while potentially reducing the overall net life cycle CO₂ emissions compared to petroleum-based fuels or coal gasification^[1].

Our laboratory has developed a steam hydrogasification technology which has been shown to be very efficient for gasification of both coal and biomass feedstocks; either alone or co-mingled. One unique feature of this technology is that it utilizes water to provide an internal source of

hydrogen and to control the synthesis gas ratio over a wide range ^[2]. This requires the formation of a slurry with a high carbon to water ratio, but with a viscosity to allow ease of handling during preparation, storage and transfer to the reactor. Prior studies have concluded that the rheological properties of coal-water slurries, such as shear stress and viscosity, are dependent on the type of coal, solid loading, coal particle size and size distribution, temperature, and additives ^[3-5]. Other studies have addressed biomass suspension and the effect of particle size on rheological properties of cellulosic biomass slurries ^[6]. However, biomass slurry rheological studies and its potential as a gasification feedstock when co-mingled with coal have not been reported. This paper presents the results of a series of experiments that systematically examine the rheological properties and pumpability of various coal-water, wood-water, and comingled wood-coal-water slurries. The major factors considered are particle size, solid loading, viscosity, and a proprietary wood pretreatment procedure for the wood for the purpose of increasing the solid water ratio. Finally, the maximum solid content of co-mingled coal-wood slurries that are pumpable was evaluated.

Experimental Procedures

A. Preparation of coal and wood particles

Coal and wood particles were prepared from bituminous coal from Utah and poplar sawdust. Each material was initially ground and then pulverized in a pulverizing grinder. The pulverized particles were then sieved into three particle size ranges: 0-150 μ m, 150 μ m -250 μ m and 250 μ m-500 μ m. The particles were then dried in a vacuum oven for vaporization of the moisture content at 70 $^{\circ}$ C. The analysis of the solid content of the coal and wood particles after the vaporization process was determined by Thermometric Gravitation Analysis (TGA). The results of the TGA are presented in Table 1. Finally, particles were mixed with water to form numerous coal and wood slurries. The solid loading for coal-water slurries ranged from 40 wt.% to 65 wt.% by every 5% and 5 wt.% to 12.5 wt.% by every 2.5% for the wood-water slurries. Mixtures were settled overnight for complete mixing of the particles and water and were then gently stirred just before the rheological tests to avoid settlement of particles. Harsh stirring was avoided to prevent small air bubbles which would impact the rheological tests.

Table 1 Solid content of the coal and wood particles by TGA

	Coal particles	Wood particles
Ash content (wt.%)	7.6	0.6
Moisture content (wt.%)	4.0	5.75
Volatile matter (wt.%)	36.2	72.8

B. Pretreatment of Wood slurry

A portion of the prepared wood particles within the particle size of 150 μ m -250 μ m were pretreated using a proprietary method developed by our laboratory. The wood particles were mixed with water at solid weight percentages of 20 wt.%, 30 wt.%, and 40 wt.%. The mixtures were then heated at 230 $^{\circ}$ C at 100psi of hydrogen for 30 min. The process was carried out in a sealed batch reactor; thus the difference in the solid content before and after the pretreatment was assumed to be negligible and was confirmed by thermal analysis of the biomass slurry after

pretreatment. The 20 wt.% pretreated biomass slurry was then mixed with up to 35 wt.% of the 0-150 μ m coal particles to form comingled biomass-coal-water slurries.

C. Determination of the Slurry Rheological Properties

Rheological properties of slurries were determined by using an Anton Paar Reolab QC rotational rheometer with temperature control. The rotational rheometer is a coaxial-cylinder rheometer with the center rotor rotating at a defined speed or torque. A six-blade vane spinner with 1 inch outside diameter was utilized as the rotor. The reason for employing a vane spinner as the rotor is that the vane-cup system causes much less error when testing large particles and has less impact on the slurry structure^[7].

Pump selection for handling slurries for industry applications is based on rheological data that are obtained from slurry rheology tests. The crucial parameters for pump selection are shear stress at certain shear rates, viscosity of the slurry, yield point, and settlement rate of the slurry. Other physical properties such as attrition and the friction of particles inside the slurry may also need to be considered for pump selection. The shear rate and shear stress curve of coal-water and wood-water slurry coordinates can be characterized by the Generalized Bingham Plastic model^[8] as shown in Eq. 1. where τ is shear stress applied to the system when the shear rate of γ is maintained. τ_y is the yield stress of the starting slurry. K and n are empirical parameters determined by fitting the equation with experimental data. The correlation between shear rate and shear stress corresponds to a power law with a constant coefficient of K. Thus, the viscosity of the slurry is defined as the slope of change in shear rate with a change in shear stress as given by Eq. 2. A change in viscosity can be obtained by either shear thinning or shear thickening. In a shear thinning flow, the viscosity decreases with increasing shear rate, while in a shear thickening flow, viscosity increases with increasing shear rate.

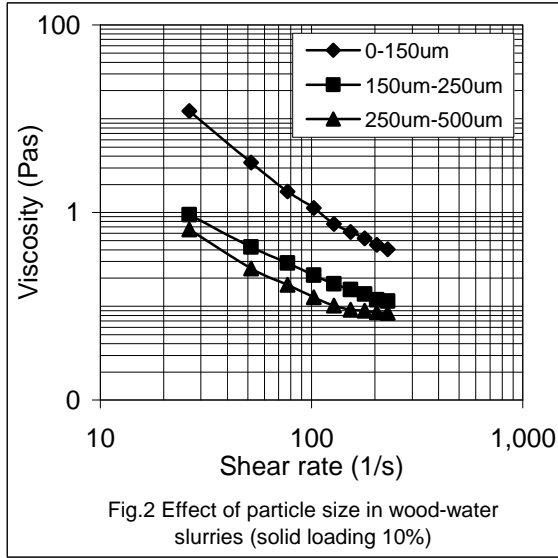
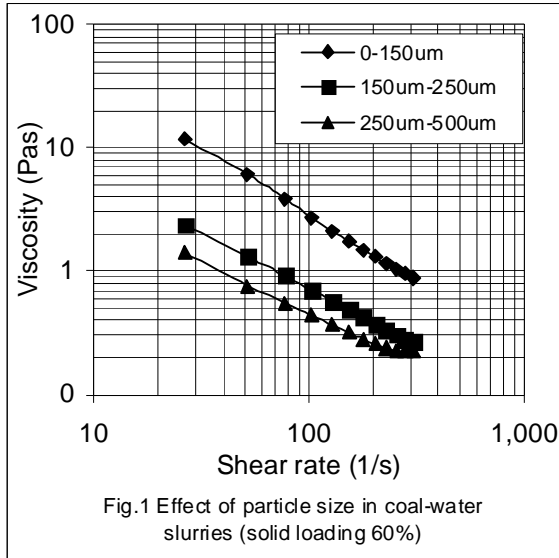
$$\tau = \tau_y + K\gamma^n \quad (\text{Eq. 1})$$

$$\mu = \frac{\Delta\tau}{\Delta\gamma} \quad (\text{Eq. 2})$$

Results and Discussion

A. Effect of shear rate on viscosity

The effect of an increase in shear rate on slurry viscosity was evaluated for different particle sizes and solid loading for both coal-water and wood-water slurries. The relationship between shear rate and viscosity was obtained for different particle sizes for coal-water and wood-water slurries. The results are shown in Fig. 1 and Fig. 2, respectively. The solid loading in the coal-water and wood slurries was fixed at 60 wt.% and 10 wt.%, respectively.



Non-Newtonian shear thinning was observed for both coal-water and wood-water slurries. The viscosity of the coal-water slurries, shown in Fig. 1, decreased rapidly with increased shear rate up to 200s^{-1} but then reduced at a slower rate beyond 200s^{-1} . Also, larger particle sizes had lower slurry viscosity. A similar trend was observed in wood-water slurries tests as seen in Fig.2. The viscosity of wood-water slurries decreased rapidly with increased shear rates of up to 100s^{-1} but decreased at a slower rate beyond 100s^{-1} . Similar to the coal-water slurries, the viscosity decreased with increasing particle size. A comparison of these two figures shows that much higher shear thinning properties were observed for wood-water slurries. A possible reason may be that water is highly hydrogen bonded with wood particles. Therefore, higher shear stress was needed for wood-water slurries to maintain a same shear rate compared to coal-water slurries.

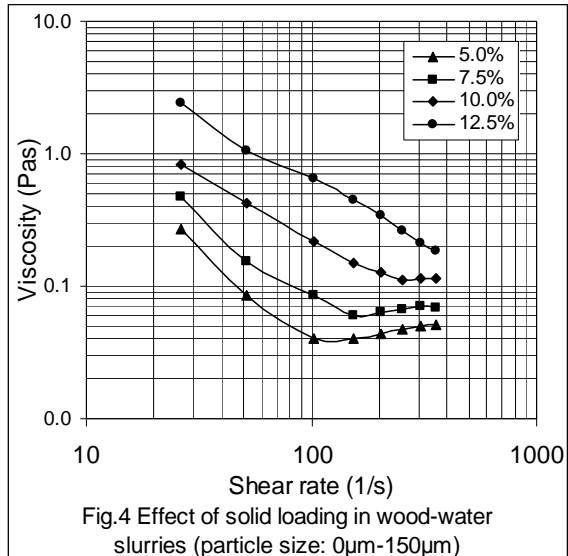
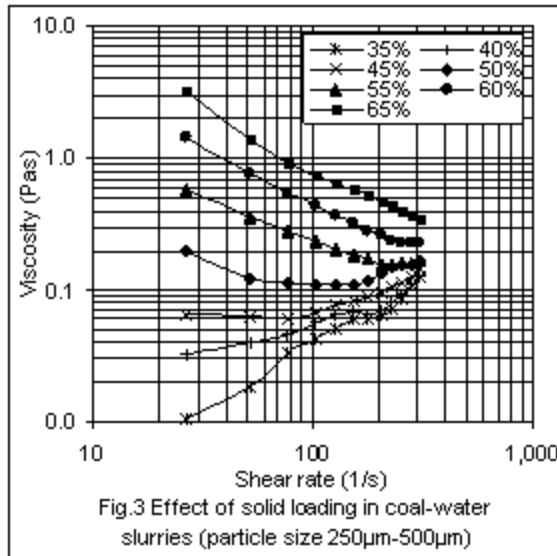
B. Effect of solid content

The maximum solid loading in coal-water and wood-water slurries varied for different particle size. When the maximum solid loading was exceeded, the mixture was not uniform as slurry and particles bound together to form larger particles. Table 2 shows the maximum solid loading for coal-water and wood-water slurries.

Table 2 Maximum solid loading in wood-water and coal-water slurries

	Maximum wood loading in slurry (wt.%)	Maximum coal loading in slurry (wt.%)
0-150 μm	13%	65%
150 μm -250 μm	13.5%	66.5%
250 μm -500 μm	15%	68%

Experimental results for different solid loading on coal-water and wood water slurries are shown in Fig. 3 and Fig. 4, respectively.



It can be seen from Fig. 3 that the coal-water slurries changed from a shear thinning property to a shear thickening property as the coal-loading decreased from 50 wt.% to 45 wt.%. The shear thickening property of coal-water slurry was rarely observed by other studies. S. K. Majumder reported^[9] that the reason for the thickening was due to the emulsion-solids exhibiting dilatant flow behavior with low solid loading range. It is also seen that the viscosity of coal-water slurries increased with increasing solid loading. There was not much difference between slurries with solid loading of less than 55 wt.% for shear rates over 150s⁻¹. Similar to the coal-water slurries, the viscosity of wood-water slurries also increased with increasing solid loading. However, at a shear rate over 100s⁻¹, Newtonian fluid properties were observed at solid loading less than 7.5 wt.% and the viscosity increased slightly with increasing shear rate, as shown in Fig. 4.

C. Properties of pretreated wood-water and comingled wood-coal-water slurries

The effect of shear rate on viscosity in pretreated wood-water slurry was also evaluated. Fig. 5 shows the rheology properties of pretreated biomass slurries with weight percentages of 20%, 30% and 40%. Unlike the wood-water slurry before pretreatment, the viscosity profile of pretreated wood-water slurry dropped rapidly as shear rate increased from 10s⁻¹ to 200s⁻¹, then decreased slightly beyond 200s⁻¹. The viscosity increased with increasing solid loading which is consistent with a wood-water slurry before pretreatment. The important result is that with pretreatment there is an increase in the solid loading of a wood-water slurry to 40% as compared to 12.5% before pretreatment. It is believed that the treatment in the presence of hydrogen under 230°C and 100 Psi help break down the cellulose and semi-cellulose structure of wood which resulted in breaking the hydrogen bond between the wood and water. However, no analytical experiments were performed to confirm this.

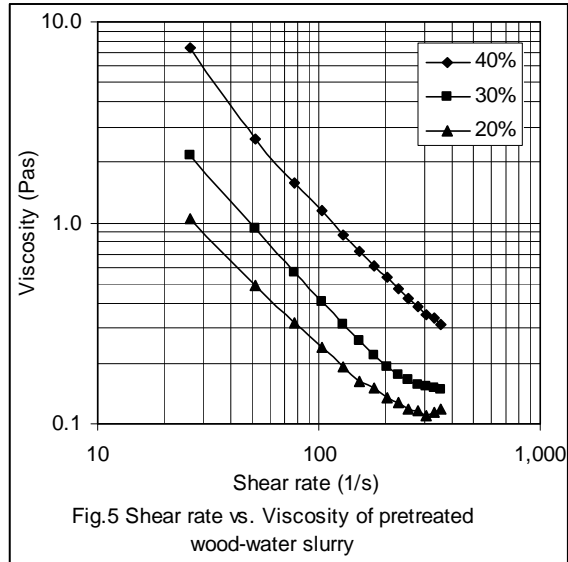
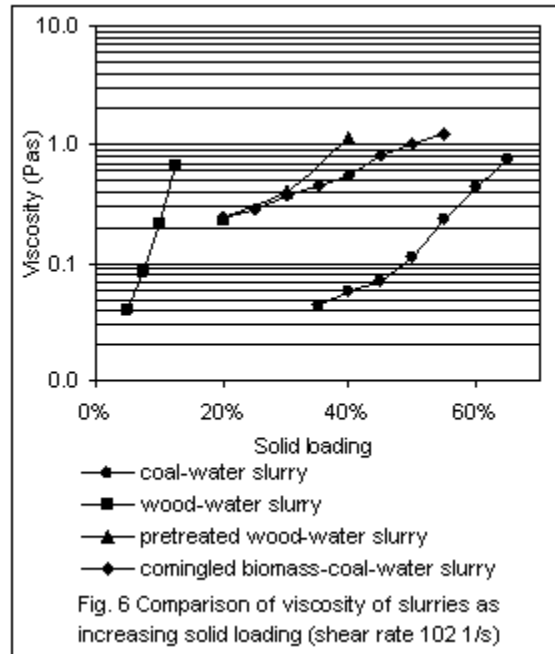


Fig.6 shows the comparison of the viscosity of slurries with increasing solid loading. It is clear that the pretreatment process greatly helped increase the solid content in wood-water slurry at a similar viscosity. At the same viscosity, the coal-water slurry had the highest solid content. The comingled coal in pretreated wood-water slurry had a solid content up to 55 wt.%.



D. Solid loading of pumpable slurries

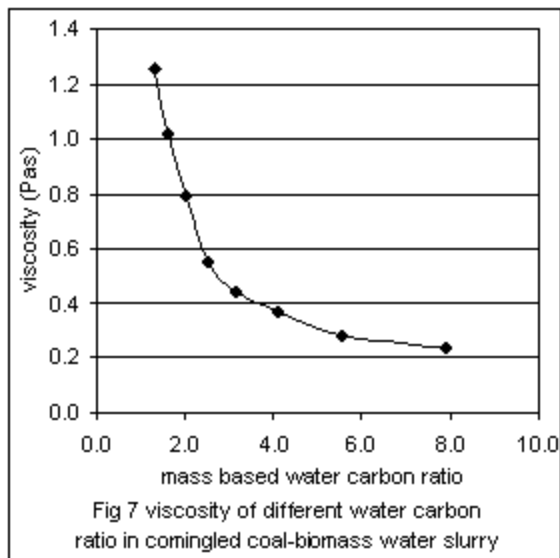
We have found that a viscosity of less than 0.7 Pas is preferred for easy pumping of slurries to our reactor. We successfully increased the solid loading in the wood-water slurry by using our pretreatment method while maintaining the viscosity. The solid loading of pretreated wood-water

slurry under 0.7 Pas was less than 35%. We comingled the pretreated wood-water slurry with coal to increase its solid loading and carbon content. The results of viscosity with increased solid loading of coal-water, wood-water, pretreated wood-water and comingled coal-wood water slurries are shown in Fig. 6. It is shown that at 0.7 Pas viscosity, coal-water slurry had the highest solid loading of up to 65%, and wood-water slurry before pretreatment had the lowest solid loading of less than 12.5%. After pretreatment, the solid loading in wood-water slurry of 0.7 Pas increased to nearly 35% and when comingled with coal, the solid loading increased to nearly 45%. Closer investigation of the water to carbon ratio of these slurries further suggested that the comingled coal-wood water slurry provided a water to carbon ratio of 2:1. The optimized water to carbon ratio is 3:1 when using our gasification process. Thus, with pretreatment, the rheological properties of the comingled coal-wood water slurry are improved for use as a feedstock for gasification. Table 3 shows the results of mass based water to carbon ratio of different slurries at a viscosity of 0.7 Pas.

Table 3 Mass based water to carbon ratio of slurries (0.7 Pas viscosity)

	coal-water slurry	wood-water slurry	pretreated wood-water slurry	comingled biomass-coal-water slurry
Ratio	0.78	13.82	3.67	2.01

The viscosity plot of different water carbon ratio in comingled coal-wood water slurry is shown in Fig. 7. Under an optimized water to carbon feed ratio of 3:1 preferred in our gasification process, slurry viscosity is less than 0.45 Pas and provides good pumpability.



Conclusion

A rheological study of coal-water, wood-water and comingled coal-biomass-water slurries has been performed. Results showed non-Newtonian properties of slurries and shear thinning behavior for most cases except the coal-water slurries with a solid content below 45%.

Comparison of the viscosity of slurries under shear rate of 100 s^{-1} shows that thermal pretreatment increased the solid loading of wood-water and comingled coal-biomass-water slurries for the same viscosity values. The important result is that pretreatment of the co-mingled coal-wood slurries provided a pumpable slurry with a solid carbon content for optimum feed to the steam hydrogasification reactor.

Acknowledgement

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