# Effects of Particle Size Distribution and Packing Characteristics on the Preparation of Highly-Loaded Coal-Water Slurry

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***Abstract*—The effects of particle size distribution and packing characteristics on the rheological behavior and solid loading of Coal-Water Slurry (CWS) have been examined in this study. The coal samples with six particle size ranges; i.e. < 38 µm, 38-63 µm, 63-75 µm, 75-90 µm, 90-180 µm and 180-250 µm, were used and three different packing characteristics were chosen for the experiments, i.e. monomodal, bimodal, and multimodal. The results showed that the coarse to fine ratio had an effect on the rheology of CWS. It is also found that, at the effective apparent viscosity, the bimodal packing characteristic with an optimum coarse to fine ratio can yield the highest in maximum coal loading for the prepared CWS with an accepting rheological behavior.**

***Index Terms*—Coal-water slurry, particle size distributions, packing characteristic, rheology**

## I. Introduction

Coal-Water Slurry (CWS) has been in much of attention due to its various industrial applications ranging from coal combustion to liquefaction or gasification process. About two tons of CWS can replace one ton of fuel oil and the price of CWM is only about 1/3 of heavy oil [1], therefore, expensive fuel oil may be substituted by CWS according to its advantages in technical and economical aspects. The traditional CWS fuel used in boilers and gasifiers has a solid loading of 60-70 %, an apparent viscosity of 800-1200 mPa s [2]. It is suggested that a highly-loaded CWS consists of 60-75 %coal, 25-40 %water, and about 1 %chemical additives [3]. The important factors that affect the CWS preparation are the properties of the coal, the particle sizes and their distributions, solid loading, the type and the amount of chemical additives, the method of preparation, and the rheological behaviors of the slurry [4].

Viscosity is the most important rheological characteristics of CWS. The expected value for the viscosity of CWS used in industry is a Brookfield apparent viscosity of 1000 mPa s at 100 rpm. For the highly-loaded CWS, the apparent viscosity is about 1000-1200 cP at shear rate 100 rpm [4]. The coal particle size less than 250 µm were recommended for CWS [5]. The particle size distribution is found to be closely related to the apparent viscosity of CWS. The selection of optimum particle size distribution is an important characteristic in all CWS technologies since it can reduce the viscosity of CWS to a minimum value. Toda, et.al. [6] studied the packing characteristics of coal powders having bimodal and trimodal distributions of particle sizes and found the influence of particle size distribution on the viscosity and maximum feasible concentration of CWS. However, the rheological properties of CWS also depend on the type of coal and the solid concentration. Each coal type needs the optimization of the particle size distribution or packing characteristics, in order to achieve the highly-loaded CWS.

In this study, the optimum packing characteristics, maximum coal loading, and rheological behaviors of the CWSs prepared from a sub-bituminous coal sample was examined. Three different packing characteristics were chosen for this study; i.e. monomodal, bimodal and multimodal.

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## II. Experimental

### A. Materials

A Sub-bituminous coal originated from Indonesia was used for the CWS preparation. Table 1 shows the results of both the proximate and ultimate analyses for the coal samples.

TABLE I: PROXIMATE & ULTIMATE ANALYSIS OF THIS COAL SAMPLE

| **Proximate analysis (dry basis)** | |
|---|---|
| Moisture (% wt) | 10.50 |
| Ash content (% wt) | 5.59 |
| Volatile Matter (% wt) | 42.31 |
| Fixed carbon (% wt) | 41.60 |
| Gross calorific value (Kcal/kg) | 5,878 |
| **Ultimate analysis (dry basis)** | |
| Oxygen (% wt) | 23.08 |
| Carbon (% wt) | 68.18 |
| Hydrogen (% wt) | 5.24 |
| Sulfur (% wt) | 0.16 |
| Nitrogen (% wt) | 0.71 |

Six different particle size ranges of the coal samples were obtained by using a laboratory-size ball mill for grinding and following with a classification by screening into < 38 µm, 38-63 µm, 63-75 µm, 75-90 µm, 90-180 µm and 180-250 µm. After that the samples were dried at 105 $^{o}$C for 2 hrs before the CWS preparation.

Two additives were used in this experiment; one as a dispersing agent to reduce viscosity and another as a stabilizer to reduce settling. Naphthalene Sulfonate formaldehyde (NSF) and Sodium Carboxy-Methyl Cellulose (Na-CMC) were selected as the dispersing agent and stabilizer, respectively, for the preparation of the CWSs.

### B. *Preparation of CWS*

The highly-loaded CWSs used in this experiment were prepared by mixing the coal samples in desired amounts (60-65 %wt) with the de-ionized water, together with the two additives that fixed the quantities at 0.5 %wt for NSF and 0.05 %wt for Na-CMC. After the mixing, the slurry was continuously stirred for 25-30 min to ensure homogenization.

Three different packing characteristics were chosen for this study; namely i) monomodal distribution – the coal sample used for the CWS preparation contains only one particle size range, ii) bimodal distribution – the coal samples are the mixture of two selected particle size ranges, and iii) multimodal distribution -- the coal sample contains a variety of particle size ranges.

For bimodal distribution, the particle size ranges chosen for the study were the mixture of 75-90 µm and 180-250 µm with a variety in ratios of mixing. Figure 1 presents the particle size distribution of the coal samples employed in the preparation of CWSs through multimodal packing characteristics.

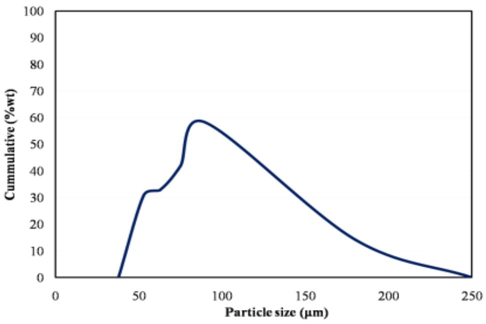



Fig. 1. Particle size distribution of coal samples used for multimodal packing characteristics.

The viscosities of CWSs were measured by MV-2000 series II Cannon® Rotary Viscometer. The shear rates were varied from 10-100 rpm at 25 $^{o}$C. The rheological behaviors of the CWSs were then examined according to the power-law model as follows:

$$\tau = K\gamma^{n} \quad (1)$$

where $\tau$, $\gamma$. K and n referred to the shear stress, shear rate, consistency coefficient and flow index, respectively.

Bed density and void fraction were determined to gain a better understanding on the packing characteristics. The final void fraction of the coal powder beds is the porosity of particle bed when the voids of coal particle bed are filled with water. Void fraction of CWS was calculated by the following equation (Henterson, et.al, 1978).

$$\varepsilon = \frac{V_s - V_c}{V_s} \quad (2)$$

where $\varepsilon$, $V_c$, $V_s$ referred to as void fraction, volume of coal, and volume of slurry, respectively.

## III. Results and Discussion

### A. *Effects of Particle Size*

The CWSs were prepared by mixing coal samples in desired amounts with de-ionized water and chemical additives (Na-CMC 0.05%wt and NSF 0.5%wt). Figure 2 illustrates the variations of the apparent viscosity of CWS with the particle size in a fashion of monomodal size distribution and the shear rate applied. The coal loadings were fixed at 60 %wt for all tests. It is clearly observed that the apparent viscosities of all CWSs prepared with a difference in particle size range decreased when increasing the shear rate applied. This flow behavior characterizes a non-Newtonian fluid-- pseudo-plastics fluid. From the figure, it also shows that the smaller particle size ranges exhibited the higher apparent viscosities of CWSs than those of the larger one. Among these, only the particle size range of 180-250 µm offered the apparent viscosities that are not higher than the effective apparent viscosity, which is 1200 cP with shear rate at 100 rpm. This is due to the fact that the coarse particle size range contains relatively large voids of particle bed, so it allows the water to flow in the voids and enhance the fluidity of the slurry. However, the particle size range of 180-250 µm that giving the minimum apparent viscosity was found to settle rapidly after the mixing was completed.

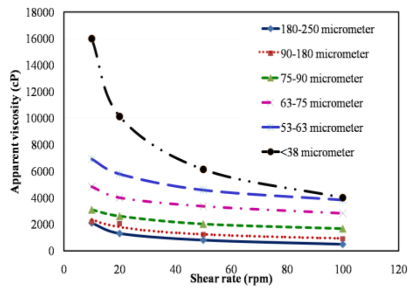



Fig. 2. Effect of particle size on the apparent viscosity of CWS with 60% coal loading, Na-CMC 0.05%wt and NSF 0.5%wt.

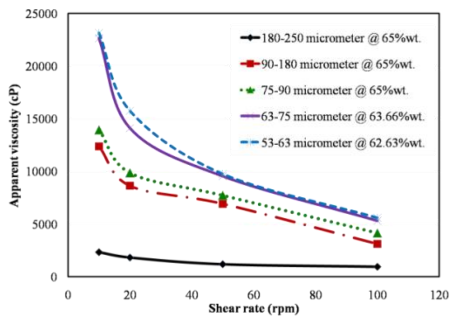



Fig. 3. Effect of particle size on apparent viscosity of CWS at maximum coal loading of each particle size range, Na-CMC 0.05%wt and NSF 0.5%wt.

Fig. 3 depicts the variations of the apparent viscosities of CWSs prepared by the monomodal distribution at the maximum coal loading for each particle size range with the shear rates applied. As expected, the CWSs prepared with the particle size ranges of 180-250 $\mu m$, 90-180 $\mu m$ and 75-90 µm could achieve the maximum coal loadings at 65 %wt, while those that prepared with the particle size ranges of 63-75 $\mu m$ and 38-63 $\mu m$ could reach the maximum coal loadings at 63.66 %wt and 62.63 %$wt$, respectively, and the one that prepared with the particle size range < 38 $\mu m$ could give the maximum coal loading at 60 %*wt*. However, all CWSs prepared at their maximum coal loadings are found to present the higher in their apparent viscosities than the effective apparent viscosity. This suggests that the highly-loaded CWS may not be accomplished by monomodal distribution and further reduction in the viscosity may be made by the use of different packing characteristics and/or chemical additives.

### B. *Effects of Packing Characteristics*

To achieve the highly-loaded CWS, the bimodal and multimodal distributions were used in the preparation. For bimodal packing characteristics, the particle size distributions for the study obtained from the mixture of particle size ranges of 75-90 μm (fine particles) and 180-250 μm (coarse particles) with a variety in ratio of mixing. This is based on an assumption that the selected fine particles can fill the voids between the selected coarse particles and therefore higher coal loading can be obtained, while there are still enough of free spaces available for the free flow of water through the voids. For multimodal distribution, it has also been indicated that in the case of wide range of particle distribution, more fine particles can fill the gaps between relatively coarse particles and thus higher coal loading should also be expected. Figure 1 shows the particle size distribution of the coal samples used for multimodal distribution.

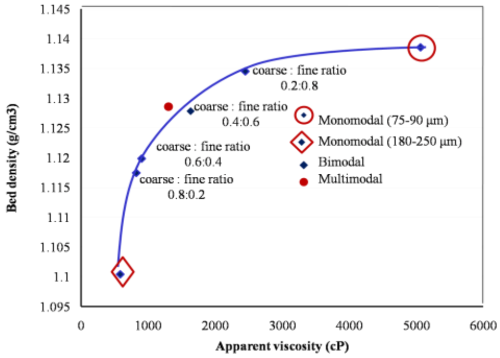
As the results of this study, the maximum coal loadings attained by different packing characteristics with the apparent viscosity of 1200 cP at shear rate 100 rpm are listed in Table 2. It can be seen that the bimodal distribution provided the highest in the maximum coal loading with a good stability, whereas the monomodal presented the lowest. It is noted that the multimodal distribution cannot provide the highest in maximum coal loading as expected. This is due to the fact that the ultra fine and fine particles may form agglomerates or compact structure within the voids between the relatively coarse particles and reduce the free space available for the access and free flow of water, resulting in an increase in viscosity with an increase in coal loading.

TABLE II. MAX. COAL LOADINGS OF DIFFERENT PACKING CHARACTERISTICS

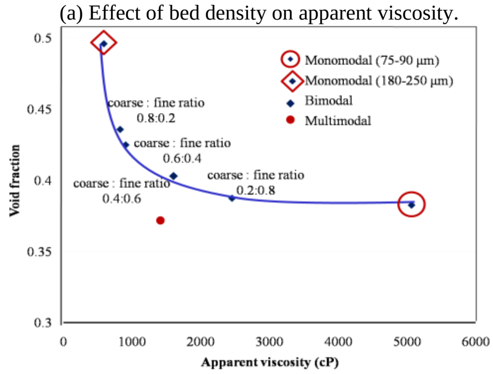
| Packing distributions | Maximum coal loading (%wt) |
|---|---|
| Monomadal | 60 |
| Bimodal | 65 |
| Multimodal | 62 |

The results shown in the table also suggest that the maximum coal loading and apparent viscosity of CWS are influenced by the bed density and void fraction. It is recognized that the void fraction or porosity of the coal particle bed, which is influenced by the particle size distribution and particle shape, prescribes the limiting value of high coal loading for CWS (Toda, et.al, 1988). For this work, the coal samples were assumed to have spherical shape, and the relations between the bed density, void fraction and apparent viscosity of the CWSs prepared with coal loading at 62 %wt by different packing distributions are shown in figure 4a and 4b.

From the figures, it is observed that an increase in bed density, which in turn a decrease in the void fraction, can cause an increase in viscosity. At the effective apparent viscosity (1200 cP at 100 rpm), it can be seen that the bed density of the particle bed having bimodal distribution is lower than that of the bed having multimodal distribution, and therefore higher in void fraction. This implies the possibility of the bimodal distribution, as compared with the others, on having higher in coal loading when considering the effective apparent viscosity.

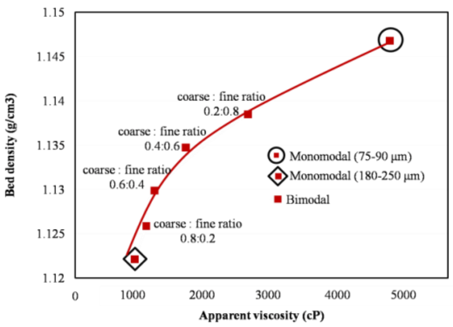



(a) Effect of bed density on apparent viscosity.

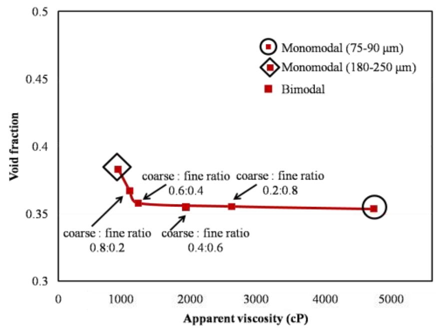



(b) Effect of void fraction on apparent viscosity.

Fig. 4. Effect of packing characteristics on apparent viscosity of CWS prepared with 62 %wt coal loading, Na-CMC 0.05%wt and NSF 0.5%wt. Particle size distribution: monomodal, bimodal and multimodal distributions.




(a) Effect of bed density on apparent viscosity




(b) Effect of void fraction on apparent viscosity.

Fig. 5. Effects of packing characteristics on apparent viscosity of CWS prepared with the maximum coal loading, Na-CMC 0.05%wt and NSF 0.5%wt. Particle size distribution: bimodal and multimodal distributions.

From figure 5a-5b, at the effective apparent viscosity (1200 cP at 100 rpm) of the CWS prepared by the coal samples with bimodal distribution at 65 %wt, the bed density and void fraction were found to be at 1.13 g/cm$^3$ and 0.35, respectively, which is consistent with those obtained for the multimodal at its maximum coal loading of 62 %wt (Fig. 4). This may indicates that, to achieve the maximum coal loading for the studied coal samples, the maximum bed density should be 1.13 g/cm$^3$ or the minimum void fraction should be 0.35. Based on this finding, the optimum particle size distribution for the multimodal and the optimum coarse to fine ratio for the bimodal can be determined. However, additional experiments are still needed for the multimodal distribution to confirm the maximum bed density.

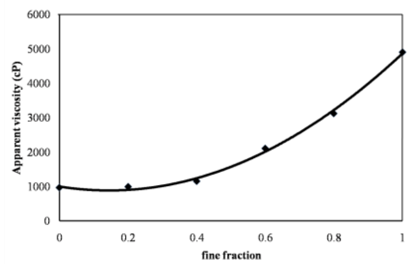
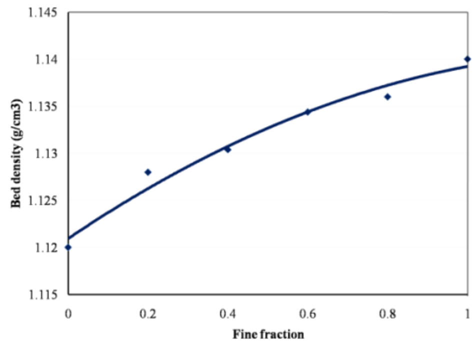
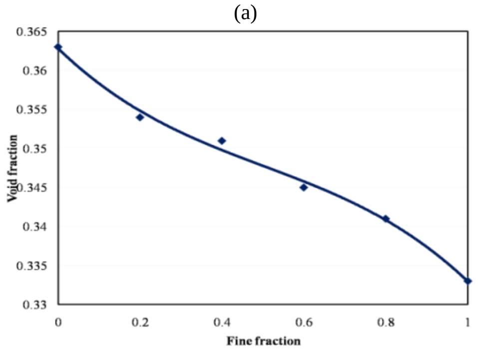



Fig. 6. Dependence of the apparent viscosity on the fine fraction. Shear rate at 100 rpm. CWS prepared by using Na-CMC 0.05%wt, NSF 0.5%wt, 65 %wt solid loading, 180-250 μm:75-90 μm (coarse size range : fine size range).




(a)




(b)

Fig. 7. Relations between fine fraction and packing characteristics of CWS with Na-CMC 0.05 %wt, NSF 0.5 %wt and 65 %wt coal loading, 180-250 μm : 75-90 μm (coarse size range : fine size range). (a) Effect of fine fraction on bed density. (b) Effect of fine fraction on void fraction.

Since one of the factors that affect bed density and void fraction is the fine fraction of coal particle bed, the effect of fine fraction on packing characteristics of CWS was then investigated in this work. The CWSs with coal loading at 65 %wt were prepared by using the particle size range of 180-250 μm for coarse particles and 75-90 μm for fine particles, and varying the fine fraction as follows; 0 (monomodal), 0.2, 0.4, 0.6, 0.8, and 1 (monomodal). The chemical additives were fixed at 0.05%wt of Na-CMC and 0.5%wt of NSF. The dependence of the apparent viscosity on the fine fraction contained in coal loading is illustrated in fig. 6.

It is markedly observed that more of fine fraction can cause an increase in the apparent viscosity of CWS. This can be explained by the fact that more of fine particles tends to form more agglomerates or compact structure within the voids between the relatively coarse particles and reduce the fluidity of CWS. As the result of that, the fine fraction should not be over 0.4 in order to keep the CWS in the apparent viscosity range of use (1000-1200 cP at 100 rpm). As also seen in figure 7a-7b, the fine fraction of the studied coal samples at 0.4 is related to the maximum bed density at 1.13 g/cm$^3$ and the minimum void fraction at 0.35. However, even the fine fractions below 0.4 can hold the apparent viscosity of the prepared CWS at the effective apparent-viscosity range, but the bed density at less than 1.13 g/cm$^3$ or the void fraction at more than 0.35 can cause problems arising in sedimentation. It is therefore suggested that, for bimodal distribution, the optimum coarse to fine ratio for the studied coal samples is 0.6:0.4, where the coarse size range is 180-250 μm and the fine size range is 75-90 μm

### C. Rheological Behavior of CWS

As mentioned earlier, for monomodal distribution, the apparent viscosities of all CWSs prepared with a difference in particle size ranges decreased when increasing the shear rate applied, as shown in figure 2. This flow behavior characterizes a pseudo-plastic fluid. For bimodal distribution, the rheology of CWSs that prepared by using NSF 0.5 %wt and CMC 0.05 %wt with coal loading of 65 %wt and a variety of coarse to fine ratio (180-250 μm: 75-90 μm) are graphically shown in figure 8.

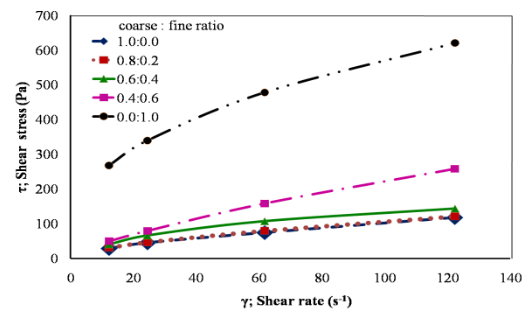



Fig. 8. The flow curves of CWS prepared by using NSF 0.5 %wt, CMC 0.05 %wt, 65 %wt solid loading, 180-250 μm:75-90 μm (coarse size range : fine size range).

It is obviously noticed from the figure that all curves exhibited non-Newtonian behavior, and the flow characteristics can be described by the power law model having the flow index (n) less than 1. As the results, it can be pointed out that all CWSs in the study showed the evidence of non-Newtonian pseudo-plastic fluid. For the ratio of coarse to fine at 0.6:0.4, the rheological model is given by $\tau = 10.696\ \gamma^{0.55}$. These findings on rheology of the CWS prepared from the studied coal samples play crucial information for an analysis on the transport of CWS, the design of CWS pipelines, and the utilization of CWS.

## IV. Conclusions

The experimental studies were performed to examine the effects of particle size and packing characteristics on apparent viscosity and maximum coal loading of the coal-water slurries prepared with the studied coal samples. The results showed that all CWSs prepared with monomodal distribution at their maximum coal loading exhibited their apparent viscosities that higher than the effective apparent viscosity. This concludes that the highly-loaded CWS prepared with the studied coal samples may not be achieved by the monomodal distribution. When compared among the three packing distributions in this study, the results showed that the bimodal distribution provided the highest in the maximum coal loading, whereas the monomodal presented the lowest.

For bimodal distribution, the CWS with the use of coarse to fine ratio at 0.6:0.4 (coarse size range 180-250 µm: fine size range 75-90 µm) can yield the highest in maximum coal loading at 65 %wt with a good stability and accepting rheological behavior. The optimum values for the bed density and void fraction were experimentally found to be 1.130 $g/cm^3$ and 0.35, respectively. The flow behaviors of CWSs prepared with monomodal and bimodal distributions both described non-Newtonian pseudo-plastic fluid.

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