Effect of Temperature on the Fluidity of
a Coal Water Mixture

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Abstract

The fluidity of Coal Water Mixture (CMW) is significantly lost when CWM is heated over 100°C. This Phenomenon has been analyzed experimentally in this work. Experimental results showed that the degradation of additives at higher temperature range and the extraction of organic substances from coal to solvent were not the reason for viscosity increase of CWM. It was also observed that there existed a little swelling of coal perticles at 150°C~200°C. Semiquantitative discussion about the effect of swelling on the fluidity of CWM has revealed that the swelling of coal is most likely the reason for the anomarous viscosity increase of CWM at higher temperature range.

Introduction

It has been reported[5] that , during the heat transfer experiments of a Coal Water Mixture (CWM), the plugging of pipe line was observed when the bulk temperature of CWM exceeded 150°C. The experimental results of viscosity measurements in the previous work[5] showed that the rapid increase in CWM viscosity was observed at higher temperature range, i. e. $T > 150$°C. It seems to be important to consider the reason of this anomalous behavior of CWM at higher temperature, because it may bring to us a guide for the treatment of CWM heating processes.

If the temperature of a CWM exceed 250~300°C, both the extraction from coal and swelling of coal may easily occur, and these phenomena might cause the tremendous change in viscosity of CWM.[4] However, the anomalous behavior of CWM viscosity has been observed at somewhat lower temperature in the previous work.[5] Thus it was attempted to check the possiblity of next three points as the reason of CWM viscosity increase :
  1. degradation of additives ;
  2. extraction from coal ; and
  3. swelling of coal.

1. Estimation of Near Wall Temperature in the Preheater of CWM Heating Process.

It is necessary to know the maximun temperature near the wall when the plugging of preheater pipe—line has occurred. Precise estimation of temperature distribution in a CWM heating system is very difficult, because the temperature difference in a preheater is large, and physical properties of CWM may change greatly. But, it was found that the heat transfer coefficient of CWM heating system was larger than that of Newtonian fluid at $T > 100$°C.[5] This means that the estimation of wall temperature by a Newtonian fluid gives a safety side result for a CWM preheater. Thus, assuming that the fluid inside the preheater was

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Newtonian, the temperature distribution was estimated by next equation ;[1]

$$\Theta = -4\zeta - \xi^2 + \xi^4/4 + 7/24. \tag{1}$$

The predicted results for the previous experimental conditions[5] are shown in Fig. 1. We can conclude, from this figure, that the near wall temperature is around 200°C when the plugging of CWM occurs at $T_0 = 150°C$.
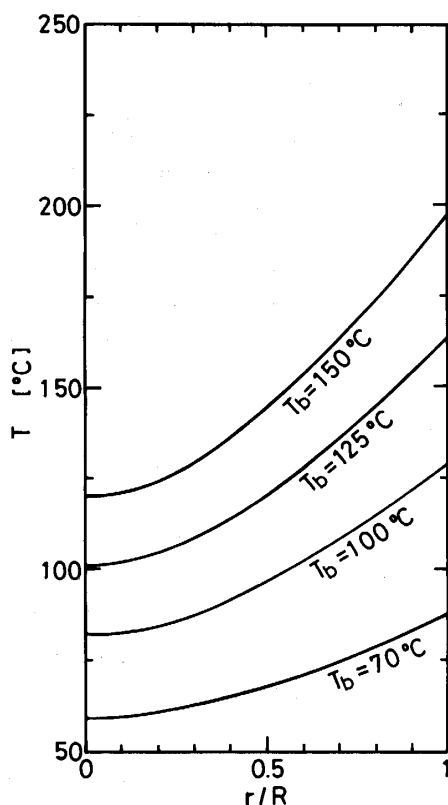

Fig. 1   Temperature distribution at the exit of preheater estimated by Eq. (1) for the case of $\langle V_z \rangle = 0.34$m/s.

2.   Experimental

The CWM used in this study was the same as reported in the previous work.[5] The sample was filled in a high–pressure proof (2MPa) vessel, and this vessel was heated in an oil–bath. Referring to the temperature distribution shown in Fig. 1, the temperature of an oil–bath was controlled within the range of $T = 70 \sim 200°C$. A solution of heat conduction problem for the geometry of sampling vessel gives the time at which the center of vessel become almost the same temperature as that of oil–bath. After this time, more one hour was set as heating time. The heated CWM was cooled to room temperature, and was used as the sample in the following experiments. The flow characteristics of CWM was measured by a rheometer (Iwamoto Seisakusho Co. Ltd. model IR–200).

3.   Degradation of Additives

Fig. 2 shows the comparison of CWM flow curves before and after the heating. Because the heat treated sample was cooled to room temperature, the flow curve indicated by open
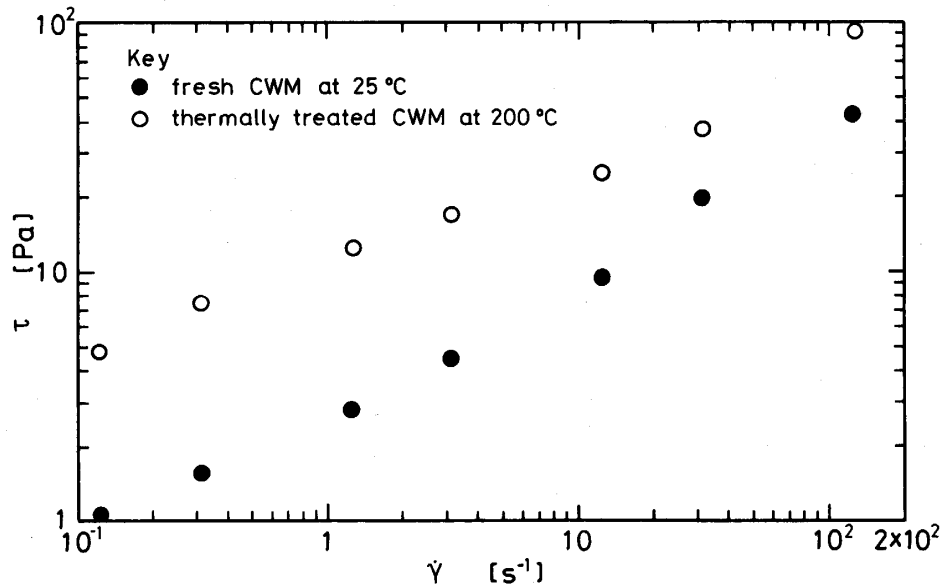
Fig. 2 Comparison of flow curves before and after the thermal treatment for the CWM with additives at C_W=65.0wt%.

circle symbol is not understood as the flow curve of CWM at 200°C. However, it is evident that, once a CWM is heated, the flow curve does not coincide with the former one reversibly. It is observed that the increase in yield stress of heated CWM is more significant than that of Bingham plastic viscosity.

To check the degradation effect of additives, the additives, i.e. a formalin condensation of naphthalene sulfonic acid ammonium salt and xanthan gum, were filled in a vessel, and the thermal treatment described in the previous section was done. Using these additives, a CWM with a fresh coal, i.e. not thermally treated coal, was prepared. The flow curve of this CWM is compared with two kinds of CWM in Fig. 3. One is a CWM with no additive and the other is a CWM with fresh additives. It is observed from this diagram that both fresh and thermally treated additives has the same effectiveness to reduce the CWM viscosity. Thus we can conclude that the additives used in this work do not degrade if the CWM temperature is less than 200°C.

4. Extraction from Coal

The second reason to be checked is the extraction effect. If a large amount of organic compounds is extracted at higher temperature, the viscosity of solvent phase may increase, and this may cause the increase in CWM viscosity. As the separation of solvent phase from a highly loaded CWM was very difficult, a relatively dilute CWM (C_w = 20wt%) without additives was prepared. After heating procedure, the supernatant liquid was analyzed by a TOC meter (Shimazu Co. Ltd. model TOC—500). The results are shown in Table 1. The amount of total organic carbon in the supernatant phase increases when the heating temperature exceeds 150°C. However the amount of TOC even at 200°C is so small that the increase in the solvent viscosity may not be significant. Thus we can conclude that the
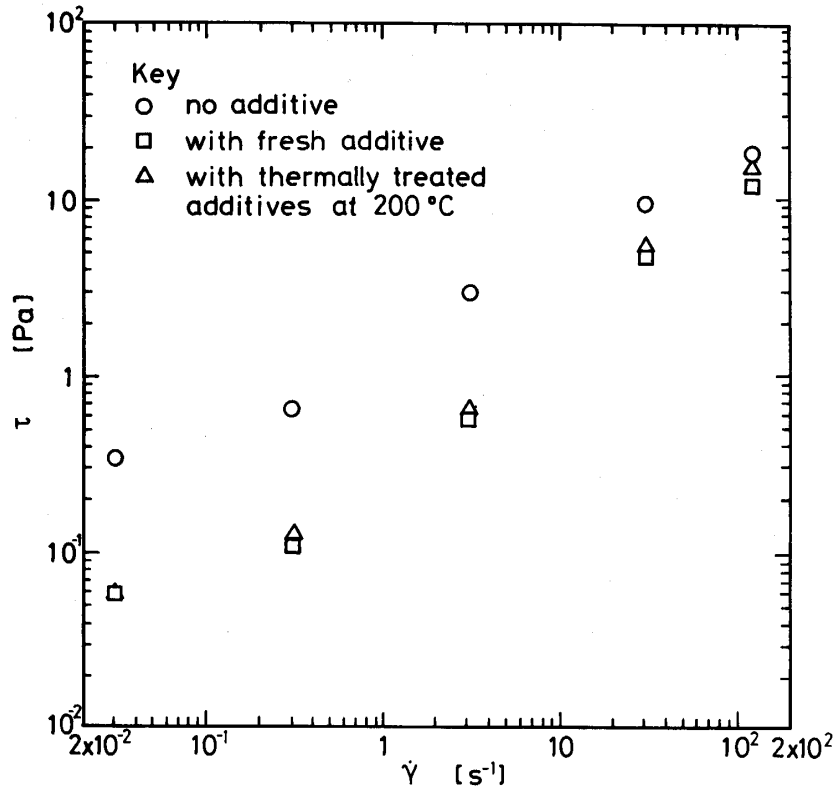
Fig. 3   Effect of additives on the flow curves of CWM at $C_W = 65.0wt\%$.

Table 1 .   The amount of TOC (total organic carbon) contained in the solvent of CWM.

heating temperature [°C]	TOC [ppm]
25	21
70	17
150	24
200	36

extraction from coal is not the main reason for the increase of CWM viscosity, although the extraction of organic compounds may change a little the physical properties of solvent.

5.   Swelling of Coal

It was found in the previous section that the extraction from coal occurred at higher temperature range. Thus it was also anticipated that the swelling of coal might occur. Green et al.[2] have reported a convenient method for measuring the swelling of coal by solvents. Referring Green' method, a little modified technique was employed as follows. A relatively dilute CWM ($C_w = 30wt\%$) was heated to 150°C or 200°C. Both the fresh and heat treated CWM, which contained 5×10^{-3} kg of solid coal, were put in test tubes (inner dia. was 14 mm). These test tubes were set in a centrifugal separator (rotational speed, arm length,

centrifugal time were 1700 rpm, 150 mm and 5 min., respectively). The swelling ratio was defined as the ratio of the sedimentation layer height for a thermally treated CWM to the sedimentation layer height for a fresh CWM. The experimental results shown in Table 2 indicate that a considerable swelling of coal occurs at T = 150~200°C. The swelling ratio defined in this work is not the exact swelling ratio because the measured sedimentation layer contains solvent. On the other hand, the viscosity change of CWM can be used to evaluate the exact swelling ratio as follows. The relative viscosity of highly loaded suspension system is expressed by Mooney[3] as ;

Table 2. The swelling ratio for thermally treated CWM

heating temperature [°C]	swelling ratio [−]
150	1.02
200	1.09

$$\eta_r = \exp(\frac{2.5\,\phi}{1-K\,\phi})$$ (2)

Using the flow curve data, $\tau = 0.5\,\dot{\gamma} + 1.80$, shown in Fig. 2 in the previous paper[5] for the case of $\phi = 0.586$ (i.e. $C_w = 65.0$wt%) at 25°C, the crowding factor was determined as $K = 1.303$. Assuming that the value of K is independent of CWM temperature, the volume fraction of coal, ϕ, at 150°C is calculated as 0.615 from the apparent viscosity data, $\eta_{ap} = 0.4$ Pa·s at 150°C and $\dot{\gamma} = 95.1 s^{-1}$. This means that the volume of solid phase increases by the factor of 1.13 from the volume at 25°C. Taking into account the fact that the CWM at 150°C measured in the pipeline viscometer was the mixture of CWM of which temperature was varied from 120~200°C in the radial direction of preheater, the above mentioned swelling ratio, i.e. 13% increase in the solid volume, may correspond to a certain extent to the experimentally determined swelling ratio shown in Table 2. However, a quantitative explanation for the viscosity increase of CWM is not exactly possible only by the swelling of coal. This may be attributed to the fact that the surface condition at high temperature is different from that of room temperature condition. The assumption that the crowding factor K is constant may not be realistic. More detailed surface analysis of coal is expected for comprehensive understanding of CWM processing at higher temperature range.

Concluding Remarks

   The reason for the viscosity increase of CWM at 100~200°C was analyzed to give the following conclusions.
1. The additives used in this study was not degraded under the temperature of 200°C.
2. Small amount of extraction of organic compounds from coal into solvent was observed. However, the viscosity of solvent was not changed appreciably because the amount of extraction was so small.
3. The coal after heating at 200°C showed considerable swelling. The measured swelling ratio was used to explain semiquantitatively the viscosity increase of CWM. It was

suggested that the combined effect both of the swelling and the change of surface condition of coal would be most responsible for the viscosity increase of CWM.

Nomenclature

C_w = coal concentration   [wt%]

K = crowding factor of Mooney equation   [−]

R = pipe radius   [m]

r = radial distance in cylindrical coordinate   [m]

T = temperature   [K]

T_b = bulk temperature   [K]

$\dot{\gamma}$ = shear rate   [s^{-1}]

ζ = dimensionless distance in the flow direction   [−]

η_r = relative viscosity   [Pa·s]

η_{ap} = apparent viscosity   [Pa·s]

Θ = dimensionless temperature   [−]

ξ = dimensionless distance in r−direction (= r/R)   [−]

τ = shear stress   [Pa]

ϕ = volume fraction of coal   [−]

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