Drag Reducing Effects of Polymer Additives on Coal-Water Mixture in Rotating Disk System

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Using a rotating disk apparatus, the concept of drag reduction produced by polymer additives is applied to Coal-Water Mixture(CWM) transport. Experiments were undertaken for a wide range of polymer concentrations of poly(ethylene oxide : PEO), poly(acrylamide : PAAM), coal concentrations and rotating disk speeds. Drag reduction decreased with higher coal concentrations, and increased with higher polymer concentrations up to 150 wppm for PEO. Further increases in the PEO concentration led to lower drag reduction. Howere, PAAM produced higher drag reduction which remained almost constant over a wide range of concentrations. The effect of polymer degradation was also investigated and it was found that PAAM is a better drag reducer than PEO when applied to long time transportation of CWM.

Key Words: Drag Reduction, Polymer Additives, Coal-Water Mixture, Rotating Disk System

Nomenclature

c_c	: Coal concentration
c	: Polymer concentration (wppm)
$DR(\%)$	: Percent drag reduction
T_p	: Disk torque measured using polymer solution
T_o	: Disk torque measured using water
PAA	: Poly(acrylic acid)
PAAM	: Poly(acrylamide)
PEO	: Poly(ethylene oxide)

1. Introduction

Since Toms reported that very dilute solutions of poly(methyl methacrylate) in monochlolobenzene resulted in large reductions of pressuredrop in turbulent pipe flow relative to that obtained with the pure solvent at the same flow rate in 1949, the phenomenon, which has been observed to occur for a number of different polymers and solvent, is commonly referred to as 'turbulent drag reduction by polymers' or 'Toms phenomenon.'

The pipe flow experiments of Fabula(1965) and Virk et al.(1967) and the rotating coaxial cylinder experiments of Merrill et al.(1966) are some examples of the numerous investigations in this field which have identified major aspects of the phenomena such as the dependence of drag reduction on polymer molecular weight, concentration and solvent wall shear stress. In general, drag reduction with very dilute polymer solutions is observed to increase with all three variables mentioned above and more significantly, does not occur at all for values of the wall shear stress below a certain critical value. The most effective drag-reducing polymers possess a linear flexible structure and a very high molecular weight. From this point of view, the most common water soluble

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drag reducing polymers are known to be poly (ethylene oxide : PEO), poly(acrylamide : PAA M), poly(acrylic acid : PAA) and their derivatives.

Polymers in turbulent flow fields are subject to intense shearing forces, resulting in mechanical degradation and subsequent decrease in drag reducing efficiency. It is not yet clear whether this is solely due to the breaking of molecular bonds which produces smaller molecules, or to the destruction of molecular agglomerations. Kim et al. (1986) showed that decreases in efficiency of drag reduction causesd by PAA with shearing time was not due to polymer bond scission but rather to a drastic coil deformation induced by the shear flow. Although many studies have been on drag reduction and mechanical degradation in flow over the past twenty years, comprehension of this phenomenon is not very clear. Based on computer simulation of polymer conformations and cascade theory of drag reduction, several differnet theories have been offered recently by Brostow et al.(1983, 1990) and de Gennes(1986, 1990).

Many current and potential uses of this phenomenon exist. For example, industrial applications of drag reduction include the transport of crude oil such as in the Alaska pipe line(Sellin and Ollis, 1980). Drag reduction is also applied to sewage system to prevent overflowing after heavy rains, to shipping and to fire-fighting to increase the range of the trubulent water jets. The speed of ship at sea can be extended by injection of polymer solution at the bow and for a given pressure drop, a smaller diameter hose can transmit the same flow of water, enabling firemen to drag less weight per unit length.

Another potential industiral use of the drag reduction effect is in the hydraulic transport of solids in pipes as investigated in this study. We apply this drag reduction phenomena to coal-water mixture(CWM) systems. The fluctuations in fuel supply and oil prices in the last decade has prompted many researchers and private industries to look internally for alternative sources of energy. Recently, tremendous amout or research and development work has been conducted in various sources of alternate energy. One of the major item of these is the CWM. This CWM has the potential to be commercialized and was found to be more economical than any other slurry systems for electric utilities and industrial boilers. Furthermore, concentrated CWMs' have attracted great attention as an economical means of transporting coal through pipelines, and their flow and stability properites are of great concern for the design of industiral flow and process equipment. In light of the objective to reduce the use of oil and to utilize vast coal reserves, some researchers have been investigating the feasivility of converting some of its fired power plants to direct coal firing using CWM. Recently the Belovo -Novosibirsk Coal Slurry system (Ercolani, 1986), which represents the first industrial application of the CWM technology was constructed in USSR. That system consists of a high concentration CWM preparation plant, which was built at Belovo (Siberia) near a coal field, having a capacity of 3MTA of dry coal and a 256 km long, 20in. pipeline to transport the slurry fuel to a power station at Novosibirsk, where it is burned directly without further modification. As shownin the case of the Belovo-Novosibirsk Slurry system, the technical aspect of the transport of CWM by pipeline for such long distances is becoming more important both in the field of application and in the field of basic research. Therefore, it is expected that polymer additives injected into the coal slurry system would be able to reduce the energy required to transport CWM from one place to another.

The maximum percent drag reduction reported is typically much higher than 50%. This means that the energy required to transport the fluid can be reduced by more than 50%. Golda(1986) was the first to perform the experiments on transportation of CWM with the idea of drag reduction by polymer additives. The experiments were undertaken on two diffenent pipe diameters of 40 mm and 250 mm. Through these experiments, he showed that adding small amounts of Separan

(PAAM manufactured by the Dow Chemical Company) to the pipe flow system decreased the pressure drop by as much as 60%.

The aim of this study was to figure out whether the energy required to transport CWM can be reduced by the addition of a drag reducer as with pure water. Therefore, instead of flow through pipes, we adopt the rotating disk apparatus and study the drag reduction produced by two types of polymers in this system. Experiments were conducted to establish the dependence of drag reduction on polymer and coal concentrations, rotational disk speeds, and polymer type. The effcts of polymer degradation in CWM flow system was also investigated.

2. Experimental Methods

2.1 Materials

Polymer additives utilized in this study were PEO and PAAM obtained from Scientific Polymer Products Inc. (Ontario, New York, U.S.A.). The weight-average molecular weights of PEO and PAAM used were 4×10^6 and $5\times10^6-6\times10^6$ g/mole, respectively.

The polymer was initially prepared as a 0.5 wt% solution in distilled water. 1 wt% isopropanol was also added to prevent chemical degradation (Kim et al., 1988). Complete dissolution occurred after the solution was allowed to be homogeneous for five days. Stock solutions were then diluted to the appropriate concentration by injecting carefully measured quantities of the stock solution directly into the turbulent flow field of the rotating disk geometry.

60 wt% of CWM, manufactured by the wet-grinding method with 0.4 wt% of CWM1002 (surfactant) and 0.1 wt% of NaOH, were obtained from the Korea Institute of Energy and Resources. The density and average particle size of the coal were 1.435 g/cm^3 and 40 μm, respectively. Detail analyses of the chinese coal used for the preparation of CWM are reported in Table 1. In addition, the study of rheological properties of CWM are also available in the literature (Kaji et al., 1987). In the production of CWM, it is important to establish criteria for controlling its rheological properties so as to obtain highly loaded mixtures with acceptable fluidity while maintaining sufficient stability against sedimentation of coal particles. It is known that a typical CWM behaves as a non-Newtonian fluid at high solids concentrations.

Table 1 Analyses of coal

Industrial Characteristics (wt%)	
Moisture(air dry)	4.8
Ash	7.5
Volatile Matter	31.6
Fixed Carbon	56.1
Element Characteristics (wt%)	
Carbon	74.66
Hydrogen	4.42
Nitrogen	0.81
Sulfer	0.64
Oxygen	11.58
Ash	7.90

Calorific value : 7060 kcal/kg
True density : 1.435 g/cc
Particle size : 200 mesh pass 82%

The CWM were then diluted to the appropriate concentrations as required by this experiment. In other to compare the drag reduction performance of the polymers used and to obtain the optimum drag reduction conditions for the CWM system, a series of experiments were conducted with coal concentraitions up to 15 wt% and polymer concentrations up to 300 wppm.

2.2 Measurements

The rotating disk apparatus consists of a stainless steel disk whose dimensions are 10.1 cm in diameter × 0.32 cm in thickness, enclosed in a cylindrical thermostatically controlled container, which is made of stainless steel and whose dimensions are 16.3 cm in diameter × 5.5 cm height (Fig. 1). The whole apparatus is surrounded by a water reservior whose temperature is controlled by a constant temperature water circulating system. The volume of polymer solution required to

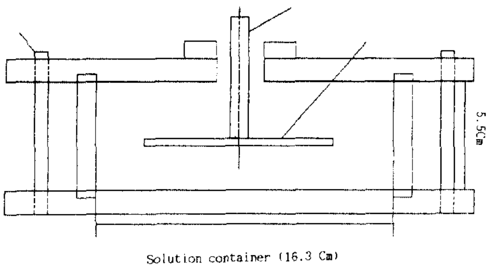

Fig. 1 Side view of the rotating disk device

fill the container was approximately 1100 ml. A DC motor generator, coupled with a controller (Cole Parmer Master Servodyne Unit), was used to maintain a preset rotational speed by delivering a variable torque (T) as required by the load on the disk.

All experiments were performed at 25±0.5℃. The temperature of the fluid and the rotational speed were measured by a K-type thermocouple and a digital tachometer, respectively. Unless otherwise specified, all experiments were performed at a fixed rotational speed of 2800 r.p.m., corresponding to a water-based Reynolds number of 6.3×10^5 for the rotating disk apparatus.

The measurements were undertaken by injecting carefully measured quantities of stock polymer solution directly into the turbulent flow field of the rotating disk apparatus. Drag reduction characteristics were then obtained in all cases by first measuring the torque required to rotate the disk at a given speed in the CWM without polymer. The percent drag reduction is finally determined by measuring the corresponding torque required at the same speed in the CWM with polymer added as follow:

$$DR(\%) = \frac{T_o - T_p}{T_o} \times 100$$

where T_o is the torque measured for the CWM without polymer, and T_p is the torque measured for the CWM with polymer added.

3. Results and Discussion

Figure 2 shows torques obtained for pure water

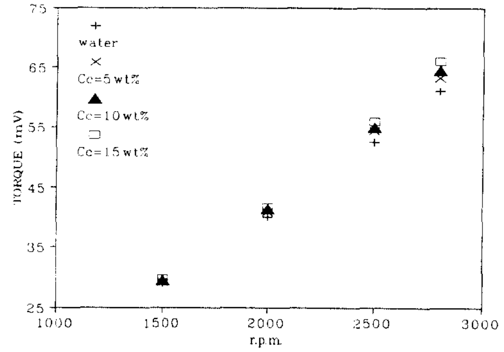

Fig. 2 Torque versus r.p.m. for water and CWM for three differential coal concentration

and for three different concentrations of CWM without polymer additives for different rotation speeds of the disk. The torque increases linearly with increasing content of the CWM.

When small amounts of polymer additives are added to the rotating disk system. drag reduction is obtained as a function of polymer concentration for different concentrations of CWM (Fig. 3). As the coal concentration increases, the effect of drag reduction tends to be attenuated. The optimum polymer concentration which produces the maximum drag reduction was found to be 150 wppm of PEO regardless of the coal concentration. Further increase in the PEO concentration leads to lower drag reduction. On the other hand, for the system with a pipe diameter of 40 mm, a flow veloctiy of 0.9 m/s and PAAM

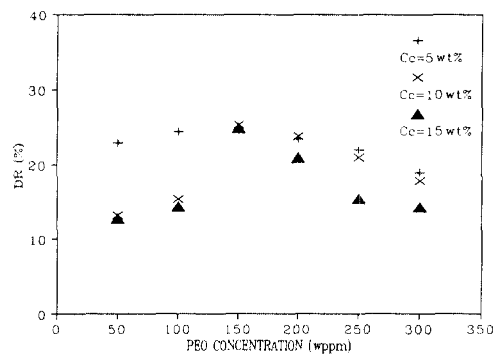

Fig. 3 Influence of PEO and coal concentration on drag reduction.

(Golda, 1986), it was observed that the maximum shifts to higher polymer concentrations with increasing solid concentration. This result can also be compared to the water only system, where 50 wppm of PEO gives the highest initial drag reduction (Yang et al., 1991). In addition, experimental results show that the drag reduction decreases as the coal concentration increases for a given polymer concentration. The decrease in drag reduction produced by increasing the concentration of solids suggests that the coal particles influence the polymer. In fact, since the polymer additives behave as a "pseudo surfactant" or they are themselves flocculants, they can be adsorbed onto the surface of the solids. This adsorption leads to a decrease in the effective concentration of polymer in the system and a subsequent decrease in drag reduction.

Through the experiments described here, the presence of very fine solid particles of CWM was found to give drag reductioin. A number of different additives of solid particles have shown themselves to be successful drag reducers. These consist of different types of sands, rubber granulates, as well as natural and synthetic fibers (Reddy, 1986). Turbulent drag reduction studies were carried out in the same way on both glass and sand in PEO solutions and on asbestos fiber with biopolymers (Malhotra et al., 1987). In addition, Golda(1986) reported that an explanation of the results presented would require a consideration of two types of drag reduction, that due to polymer additives and that due to very fine solid particles, as well as the interactons between them. However, since we observed higher rotational torques for CWM samples than for pure water (Fig. 2), drag reduction due to coal particles can be neglected.

Figure 4 indicates the influence of r.p.m. on drag reduction of PEO (150 wppm) for 5 wt% and 10 wt% CWM. As the rotation speed of the disk increases, the drag reduction linearly increases for both CWM systems.

In polymer degradation experiments using 200 wppm and 300 wppm of PEO and a rotational

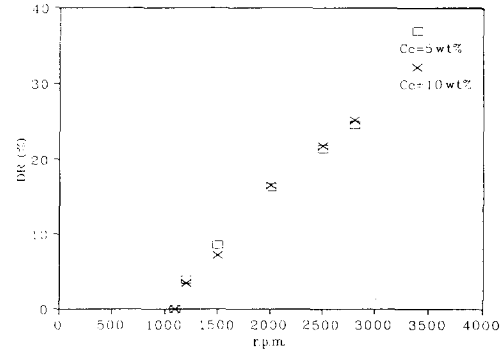

Fig. 4 Influence of r.p.m. on drag reduction of PEO (150 wppm) for CWM (5 wt% and 10 wt%)

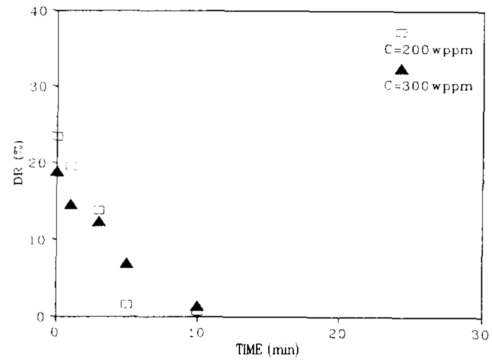

Fig. 5 Drag reduction of PEO versus time for CWM ($Cc=5$ wt%)

speed of 2800 r.p.m., the decreases in drag reduction due to polymer degradation were found to be stronger at lower polymer concentrations (Figs. 5 and 6). The drag reduction effectiveness was rapidly reduced as time increased and almost disappeared after 10 minutes. Therefore, we determined that the mechanical stability of polymer solutions is limited, leading to degradation of the polymer molecules in highly trubulent flows.

Figure 7 shows the dependence of drag reduction of PEO and PAAM on polymer concentrations for 10 wt% CWM and a disk rotational speed of 2800 r.p.m. As shown in Fig. 3, 150 wppm of PEO gives a maximum drag reduction. Drag reduction then decreases with further increment of the polymer concentration. However, compared with PEO, PAAM produces a higher drag reduction which remains virtually constant over a wide range of polymer concentrations. In Polymer degradation experiments for PEO and PAAM, Fig. 8 shows the decrease in drag reduction which occurs as the time increases for 10 wt% of CWM and 300 wppm of polymers. Decreases in drag reduction as a rusult of polymer degradation were found to be strongest during the first 10 minutes of the experiment for both PEO and PAAM. However, for PAAM solution, there was no additional decrease of drag reduction with elapsed time up to 60 minutes.

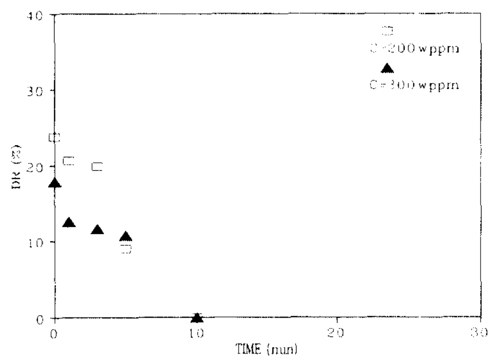

Fig. 6 Drag reduction of PEO versus time for CWM(C_C = 10 wt%)

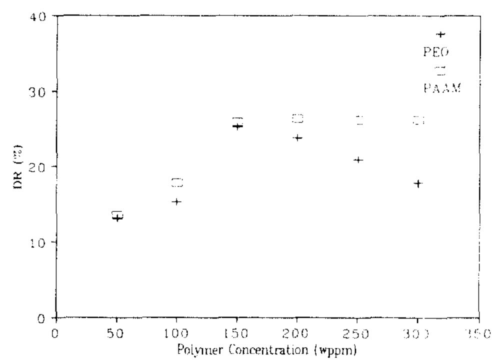

Fig. 7 Influence of PEO and PAAM concentrations on drag reductioin for CWM(C_C = 10 wt%)

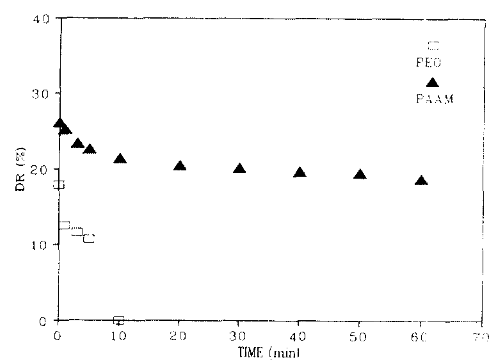

Fig. 8 Drag reduction of PEO and PAAM versus time for CWM(C_C = 10 wt% and c = 300 wppm)

This result clearly shows that PEO solution is more susceptible to mechanical degradation than PAAM solution at the same concentration. Therefore, it can be concluded that PAAM is a better drag reducer than PEO in CWM system.

4. Conclusions

When typical drag-reducing polymers, PEO and PAAM, are applied to the CWM system in the rotating disk apparatus, they produce drag reduction as much as 28% of drag reduction as polymers do in pure water.

Drag reduction decreases with higher coal concentrations and 150 wppm of PEO was found to be the optimum polymer concentration producing the maximum drag reduction. PAAM gives higher drag reduction than PEO which at higher polymer concentrations, and remains virtually constant over a wide range of concentrations.

Decreases in drag reduction as a result of polymer degradation were found to be stronger for lower polymer concentrations and to occur almost entirely within the first 10 minutes of the experiment. However, for PAAM solution, there is no additional decrease of drag reduction with elapsed time up to 60 minutes. This implies that PAAM is a better drag reducer than PEO in the application of CWM system for long time transportation.

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