Fuel Processing Technology 127 (2014) 105–110

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Synthesis and characterization of a thixotropic coal–water slurry for use as a liquid fuel

Tran X. Phuoc *, Ping Wang, Dustin McIntyre, Lawrence Shadle

National Energy Technology Laboratory, Department of Energy, P. O. Box 10940, MS 84-340, Pittsburgh, PA 15236, United States

ARTICLE INFO

Article history:
Received 18 March 2014
Received in revised form 10 June 2014
Accepted 14 June 2014
Available online 1 July 2014

Keywords:
Coal–water slurry
Thixotropy
Co-intercalated laponite

ABSTRACT

We reported here a novel approach to synthesize a low-viscosity and stable coal–water slurry for use in many practical applications. The slurry was prepared by mixing coal particles with a gelling solution containing water and 1 wt.% of cobalt-intercalated laponite. The coal particle sizes were less than 75 μm and the coal loading was 50% by weight. The slurry prepared this way was able to transform to a high-viscous and unflowable gel holding coal particles uniformly throughout its volume when it was stored at rest. When it was sheared, its gelling network structure was immediately broken down becoming a low-viscous flowable liquid. The transport and thixotropic properties of the prepared slurry were measured and they were described very well by the Bingham model and the thixotropic model proposed by Usui, respectively.

Published by Elsevier B.V.

1. Introduction

Coal–water slurry (CWS) is a viscous liquid that contains pulverized coal particles and water. CWS is an attractive alternative fuel to oil due to its lower cost and similarity to oil with respect to transportation and handling. CWS can be used as a reburn fuel or as a main fuel in low NOx burners. It can be directly used in low-speed diesel engines and combined cycle gas turbines for CO_2 recycling and management. It also has potential applications in gasification processes [1–3]. The combustion efficiency of CWS is about 96–99%. It produces lower emissions of harmful pollutants such as particulate matter, soot, carbon monoxide, hydrocarbons, SO_x and NOx. Thus, use of CWS will allow the utilization of coal, which is cheap, abundant, and still remains as a main energy source many for countries, in a cleaner and more efficient way [3].

Conventional CWS is a mixture of micronized-coal particles and water. It generally contains high coal fraction (from about 60 to 70 wt.%) with a coal particle size of about 100 μm. Different CWS preparation techniques can be found in the review reported by Papachristodoulou and Trass [1] and Polyakovs et al. [4]. The preparation of a CWS fuel usually consists of two major stages: the crushing stage and the wet milling and homogenization stage. During the prior crushing, the raw coal is first crushed using a jaw crusher and then dry ground in a ball mill. During the wet milling and homogenization stage, the crushed coal is milled and mixed with water using a mixer. To prepare a homogeneous CWS, depending on the coal type, particle size distribution, special surfactants or mixtures of two or more surfactants, or mixtures of one or more surfactants and an inorganic or organic salt might be needed [5–10], and various mixers or dispersers (propeller mixers, rotary pulsation devices, etc.) are used [4].

Since CWS is a solid–liquid suspension system, it is highly viscous and subjected to thermodynamically unstable. As a result, coal particles quickly settle and form sediment during storage and buildup in equipment even as it is being used. Under long period of storage, coal particle sediment will become more compact and hard to break. It is difficult to transport, atomize, and spay a CWS fuel with high coal content because of its high viscosity and paste-like behavior. Large particle sizes require longer time to burn and a significant amount of coal particles will remain unburned. Thus, commercially available CWS fuels are not practically desirable especially for gas turbine and diesel engine applications because the presence of unburned coal particles can damage the turbine blades, engine cylinders, and cylinder seals, etc.

To avoid these disadvantages, we have conducted a study on the synthesis and characterization of a CWS fuel that contains low coal fraction with small size particles (less than about 75 μm) and behaves as a thixotropic substance. Such innovative slurry has two particular advantages: (i) the first one is due to its thixotropic behavior that is when it is stored at rest, the slurry becomes gelled holding the coal particles uniformly throughout its volume; thus, no particle sediment is formed. When it is sheared, however, it immediately breaks up becoming a low-viscous flowable liquid that can be pumped, transported, atomized, and sprayed. (ii) The second advantage is due to its small particle size. Small particle sizes result in larger reactive surface areas leading to a near one-hundred percent burning efficiency, leaving virtually no coal particles in the ash or in the resulting gases. (iii) Conventional use of CWS in boilers requires the removal of the water content before the coal particles are fired and burn with excess air in a burner producing

* Corresponding author.
E-mail address: tran@netl.doe.gov (T.X. Phuoc).

http://dx.doi.org/10.1016/j.fuproc.2014.06.019
0378-3820/Published by Elsevier B.V.

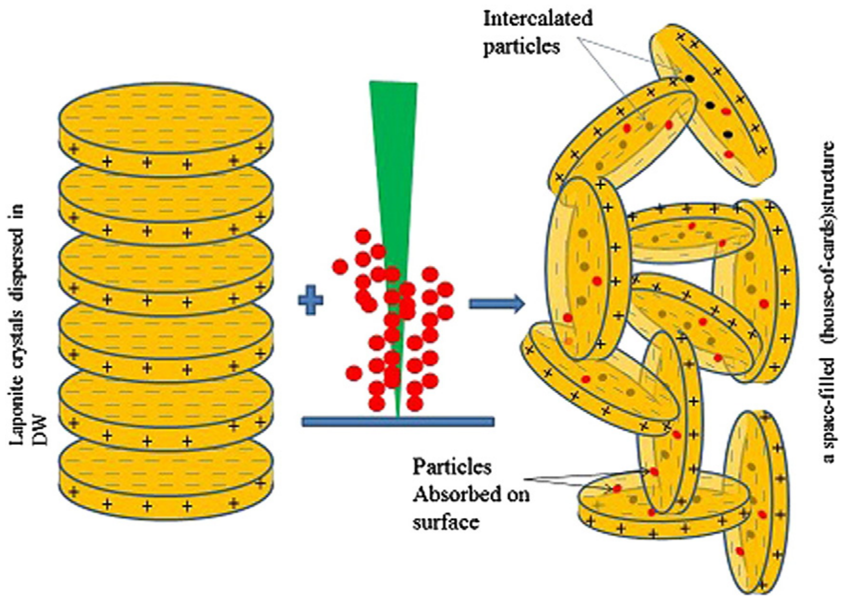

Fig. 1. A conceptual sol–gel transformation of an aqueous solution containing Co-intercalated laponite.

hot gases. Water is either flowing in tubes arranged across the hot gas stream or being injected along the burner wall is heated to generate steam. Although slurries of low coal fraction might not burn in air-fired conditions, they can burn directly in oxygen or oxygen/CO_2 environments [11]. In this case, using low coal content CWS is favorable because the power required for fuel pumping, transporting, and atomizing is reduced and its high water content can be converted directly to steam without the need for water tubing or injection.

To synthesize such a thixotropic CWS we use laponite clay intercalated with metal cation as a gelling agent. Laponite is a synthetic sodium magnesium silicate clay. In dry powder, the edge of a laponite crystal has a small amount of positive charge while the face charge is always balanced by the sodium ions in its interlayer [12]. When laponite crystals are dispersed in water, the sodium ions are released and their faces become negatively charged. Since the amount of the positive charge on the edge is about 10% of the negative charge on the face [12], the electrostatic repulsion between the negatively charged faces is dominant. Thus, if the laponite concentration is low, the dissolved laponite crystals will remain separated [13]. However, when metal ions are used to replace the dissolved sodium ions and intercalate into the interlayer separation of the laponite crystals, the amount of the negative charges on the faces can be significantly reduced. As a result, the electrostatic repulsive forces between the negatively-charged faces become weak compared to both the van der Waals and electrostatic bonds between the positively-charged edges and negatively-charged faces. In this case, the dispersed laponite is able to form a space-filled structure which is essential for gelation transformation [14,15]. Such space-filled structure is conceptually represented in Fig. 1.

In previous experiments, Phuoc and Ruey [16] used the laser ablation in liquid technique to ablate micronized-metal particles dispersed in water diluted with 1 wt.% of laponite. They reported that the water diluted with 1 wt.% laponite crystals remains as a free flowable liquid even after several weeks of aging. When these suspensions were irradiated with a laser beam of 532 nm, a sol–gel transition was induced. The suspension became a strong gel when it was allowed to rest. The gel, however, was easily reverted to a low viscosity liquid with simple shaking. Such fast breakdown and buildup behaviors are critical. One of the most important requirements of any good coal–water slurry fuel is its stability, especially when circulation is stopped. If the slurry does not develop its gel strength quickly to hold the particles during this time, particle sedimentation will occur. In order for the slurry to have an adequate suspending ability it must develop high gel strength quickly when it is not in motion. A slurry with high gel strength usually requires high energy to initiate circulation, generating pressure surges while the flow is being reestablished. Although cation-exchanged laponite suspensions have a great gel strength at rest, the structure can be quickly broken. Therefore, they can be transformed into a low-viscosity fluid that does not induce significant friction losses during circulation and, yet, can quickly develop high gel strength after the pump is turned off, preventing solid coal particles from settling.

In the following sections we will report some preliminary results on the thixotropic properties of a model coal–water slurry that is prepared using cobalt-intercalated laponite crystals as a gelling agent.

2. Experiments

The present experimental slurry was prepared by slowly adding coal powder with a particle size of less than 75 μm into a gelation solution while it is stirred at a high speed. The proximate analysis of the coal used is tabulated in Table 1. The gelation solution, which was made of water and about 1 wt.% of cobalt-intercalated laponite crystals, was prepared following the experimental apparatus and procedures described in details by Phuoc and Chen [15]. In summary, we simply mixed laponite powder
(Laponite RD from Southern Clay Products) and cobalt powder (Alfa-Aesar, 1–1.5 μm) with deionized water (dw) and stirred the solution for 24 h using a magnetic stirrer. We then ablated the cobalt powder with a laser beam until the micron sized-cobalt particles have been ablated and intercalated into the interlamellar separation between the clay layers. Laser fluence was 0.265 J/cm^2 for all tests. For all samples, the weight fraction of laponite was 1%, the weight fraction of the cobalt power was 0.050% and the weight fraction of coal particles was 50%.

Viscosity measurements were carried out using a coaxial cylinder rheometer (RS115LS, Brookfield Engineering). The rheometer consists

Table 1
Proximate analysis of power river basin sub-bituminous coal (% dry basis).

Ash	6.6
Volatile matter	46.2
Fixed carbon	47.2