Fuel 207 (2017) 262–267

Contents lists available at ScienceDirect

Fuel

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

Three-dimensional optical tomography of bitumen and clay association in oil sands tailings

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ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form 7 June 2017
Accepted 21 June 2017

Keywords:
Oilsands
Bitumen
Mature Fine Tailings (MFT)
Total Internal Reflection Fluorescence (TIRF) microscopy
Clay
Tomography

ABSTRACT

Alberta has one of the largest oil reserves in the world. Large-scale commercial oil production from oil sands in Alberta for the past 40 years has led to accumulation of tailings water in tailings ponds covering areas ranging over 150 km^2. Less than 1% of this area has been certified as reclaimed leading to both economic and environmental consequences. Research is underway to reduce tailings ponds reclamation time from decades to weeks by developing new polymer flocculants, better tailings treatment methods and recovering bitumen from tailings. Information about impact of residual bitumen on the shear strength, trafficability, densification, hydraulic conductivity, consolidation, post-reclamation settlement for oil sands tailings is insufficient. Outstanding challenges exist in understanding bitumen and clay interaction in tailings to help with the development of techniques which accelerate clay sedimentation and enhance bitumen recovery. To shed light on the bitumen-clay interactions, here we develop advanced three-dimensional optical tomography approaches approaching sub-micron resolution. In this paper, we report, the first ever Total Internal Reflection Fluorescence (TIRF) microscope tomography for Mature Fine Tailings (MFT) samples to reveal bitumen distribution on clay in MFT. We employ a unique evanescent wave illumination approach as opposed to conventional fluorescence microscopy with enhanced axial resolution and high signal-to-noise ratio. The resolution of TIRF is further improved by using an Axial Super-Resolution Evanescent-wave Tomography (AxSET) technique. The information obtained from this study not only gives evidence of the presence of hydrophilic and oleophilic clays but with aid of 3D reconstruction using advance image processing also validates that bitumen is partially coating some of clay surfaces, thus verifying the presence of biwettable clays in oil sands MFT. The advances from our imaging work can aid the development of bitumen recovery techniques for environmental and economic impact.

1. Introduction

Oil sands deposits covering over 14000 km^2 and estimated recoverable oil reserves over 300 billion barrels makes this non-conventional oil a major economic driver of Alberta and Canada at large. Oil sands composition can be described as 55–80 wt% sands, 4–18 wt% bitumen, 5–34 wt% fine solids (less than 45 μm), and 2–15 wt% water [1]. Processability of ore can be determined by ease of bitumen detachment from clays and ease of bitumen attachment to the air bubbles [2]. Extraction techniques namely Clark Hot Water Extraction (CHWE) Process and Low Energy Extraction (LEE) Process [3] which are used commercially for oil sands extraction, require hydrophobic nature of the minerals that are separated from the bitumen by an aqueous layer [4]. The presence of biwettable and hydrophobic minerals in oil sands negatively impacts bitumen recovery and froth quality [5].

Efficient recovery of bitumen from oil sands and reduction of its loss to tailings is important economically as well as environmentally. Absence of bitumen in tailings can also reduce the severity of failure of containment events due to relatively reduced toxicity of the tailings. Presence of bitumen in tailings reduces its hydraulic conductivity and consolidation interactions [6]. Bitumen in tailings is suspected to hinder its settling by associating with clays [7]. These bitumen-clay interactions take place at a nanoscale [8].

Methods such as Transmission Electron Microscopy (TEM) [9] and X-ray Diffraction (XRD) [10,11] have been used to characterize various clays in oil sands and oil sands tailings. Researchers have

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http://dx.doi.org/10.1016/j.fuel.2017.06.107
0016-2361/

also used techniques such as Scanning Electron Microscope (SEM) [12] and Atomic Force Microscope (AFM) [13] to study bitumen-clay interactions. But extensive sample preparation and highly altered temperature and pressure conditions are suspected to affect sample chemistry and introduce artifacts in the acquired images [12]. These techniques are also not successful in detecting organic materials. Hence bitumen locations and interaction needs to be inferred in these studies [14]. Techniques such as deak stark [12] and CHNS analysis [15] are used to detect the bitumen content of the oil sands and oil sands tailings but this method does not provide information about free bitumen versus bitumen attached to clay. Studies to detect the exact spacial location of bitumen on clay surface are not yet available. This knowledge will help to obtain clear picture about bitumen-clay interaction and hence help propose solutions to enhance bitumen recovery from oil sands.

Since bitumen has been proved to show natural fluorescence [7] similar to asphaltenes [16] over a relatively broad emission spectrum, therefore successful detection of bitumen in the MFT samples can be achieved with novel techniques involving fluorescence. Techniques such spectrofluorometery have been used in our study in past, to confirm the favorable excitation and emission wavelengths for fluorescence microscopy of bitumen [17]. Confocal fluorescence microscope was also used in this study to ensure that only bitumen will show fluorescence while water and clay will not [17]. These techniques have been mainly utilized in the cell biology field but are recently gaining importance in material sciences as well.

In this paper we present the first direct three dimensional visualization of bitumen covering the clay particles in oil-sands tailings sample. We show the bitumen coverage of clay particles at multiple scales, ranging from 4–5 μm bitumen clay agglomerates to sub-micron single particle coverages. We employ Axial Super-Resolution Evanescent-wave Tomography (AxSET) technique, which was recently developed in our group [18], to get 3D reconstruction of sub-micron scale bitumen clay association with axial super-resolution.These 3D maps of bitumen-clay aggregates have assisted in obtaining first ever images of the non-uniform bitumen coatings in tailings samples. These 3D reconstruction provide valuable insight into bitumen surface associations which will ultimately aid in improving the techniques for tailings treatment. This method can also be successfully employed in oil sands and bitumen froth.

2. Experimental

Mature Fine Tailings (MFT) sample A, B and C were provided by Institute of Oil Sands Innovation (IOSI), University of Alberta. Samples A and B contain approximately 31.4 wt% solids, 3.9 wt% bitumen and 64.7 wt% water. Sample C contained approximately 67.6 wt% water, 28.8 wt% solids, and 3.6 wt% bitumen. The solids, bitumen and water content in these samples was analyzed using dean stark method.

MFT samples were observed without drying to ensure that they are observed in their original state. To enable this, well-type coverslips were made by gluing the coverslip on to a glass slide that has a 10 mm diameter circular aperture drilled in its center. MFT samples were placed in these wells and then sealed on the top with another glass cover to prevent drying or contamination as seen in Fig. 1(b).

2.1. Evanescent wave tomography

Fig. 1(a) depicts the schematic of a Total Internal Reflection Fluorescence (TIRF) microscope used in tomographic imaging of

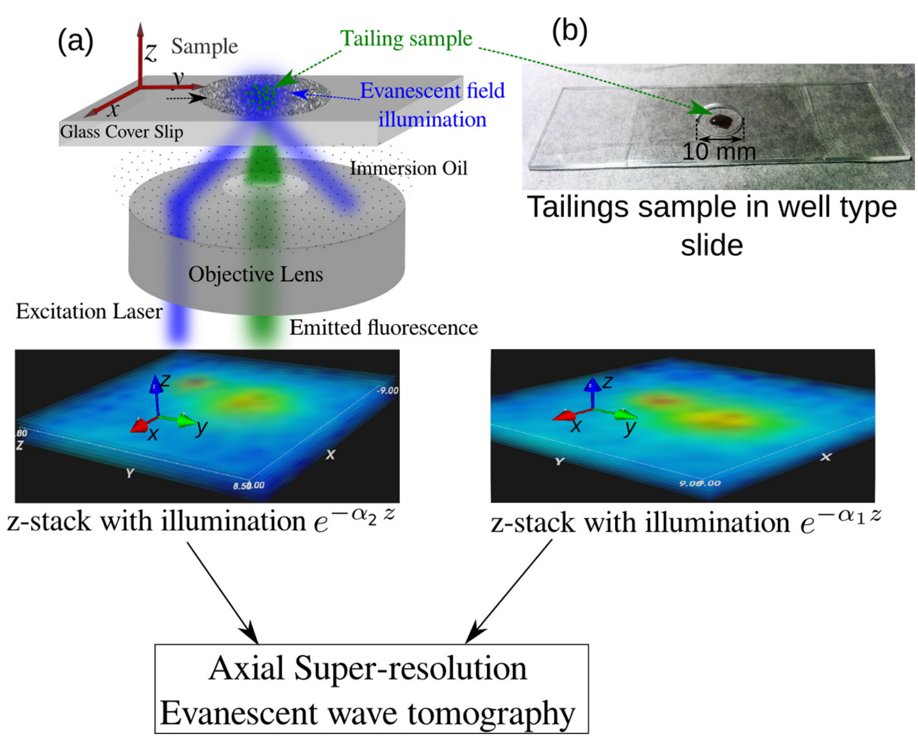

Fig. 1. (a) Schematic of TIRF microscope, in which the incident angle of the excitation laser can be controlled. When the incident angle is greater than the critical angle at the cover-slip/sample interface, the sample is illuminated by an evanescent wave. By controlling the incident angle of the excitation laser (blue) the penetration depth of the evanescent wave can be controlled. (b) shows the tailings sample in a well type cover-slip. Two 3-dimensional images are acquired by optical sectioning of the sample with different penetration depth of the evanescent wave excitation. Axial super-resolution is achieved by extracting the super-resolution features from incremental illumination of the sample from the two 3D images in the Fourier domain [18]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)