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Characterization of fouling processes in ceramic membranes used for the recovery and recycle of oil sands produced water

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ABSTRACT

In light of the technical challenges associated with performance degradation of ceramic membranes applied to the treatment of produced water, a study aimed at characterizing the nature of fouling was conducted.

Tubular γ-alumina multilayered membranes with titania selective layers used for the treatment of two oil sands impacted water feeds were considered. The first, labelled 'oily water', consisted of physically-separated water and bitumen fractions. The second, representative of steam-assisted gravity drainage (SAGD) process water, was mainly an oil-in-water emulsion.

Saturation of the selective layer through bitumen entrapment had an irreversible impact on the physical integrity of the membrane after treatment of the oily water. Treatment of the SAGD feed produced fouling characteristics typically expected in crossflow membrane filtration, and surface modifications to optimize separation of the oil droplets from the surface and pore percolation of the water phase should be effective to improve performance. Surface foulant accumulation was strongly controlled by linear defects resulting from solvent evaporation during sol-gel fabrication of the selective layer. A better understanding of the impact of such defects on fouling seems necessary. Finally, partial replacement of titania by crystalline $BaSO_4$ suggested that other types of selective layers should be considered for a feed containing Ba.

1. Introduction

As water and energy production in the oil and gas sector are directly linked, development of innovative technologies and processes for managing produced water for treatment and recycling is of significant importance. This is especially relevant with the development of unconventional oil and gas resources (oil sands, shale gas) where extraction by various techniques (e.g. steam assisted gravity drainage, hydraulic fracturing, etc.) has led to the generation of large volumes of produced water (PW). While membrane-based processes are under investigation as a potential treatment approach [1–7], these different PW feeds have a wide range of chemical and physical characteristics that may strongly impact performance. In particular, the nature and concentration of dissolved and suspended solids, as well as the prevalence of organic compounds originating from the oil [3,8,9] can all present distinct challenges during treatment.

Filtration using pressure-driven multilayered ceramic membranes operated in crossflow mode represents an interesting option for PW treatment [10–14]. Although promising, the major technical challenge for the application of ceramic membranes is their susceptibility to fouling, leading to severe loss of flux during operation. Successful and economically viable applications rely on a better understanding of membrane fouling in order to optimize the chemical and physical properties of the selective layer, define efficient regeneration approaches and, consequently, ensure a sustainable economic range of water flux over the life of the membrane.

Characterization of flux and water quality during treatment is commonly used to monitor membrane performance decline related to fouling [10]. Additionally, mathematical models have also been applied (e.g. Hermia's models) to evaluate the mechanism of membrane fouling by oily wastewater [15–17]. Detailed characterization of autopsied membranes can also provide valuable insights on fouling features [18–25], although studies that specifically address the impact of produced water treatment are limited. In this context, the present study aims to document the value of detailed micro-characterization of carefully autopsied γ-alumina-supported titania membranes as a tool to better understand the nature of the main fouling processes leading to the degradation in performance and durability after treatment of two distinct oil sands PW feeds.

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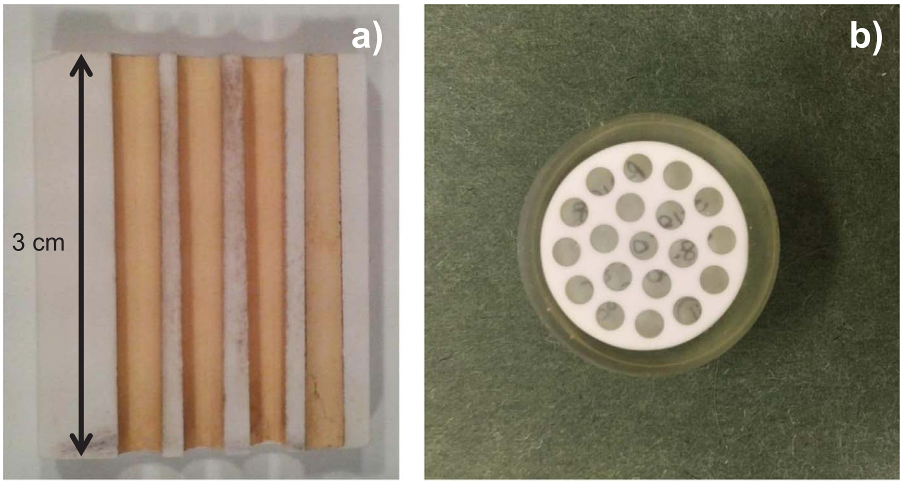

Fig. 1. Sections across a tubular ceramic membrane: (a) longitudinal section giving access to the surface of the channels; b) polished cross-section normal to the long axis of the membrane.

Table 1
List of spent ceramic membranes characterized.

Selective layer composition	Porosity of selective layer (nm)	Feed	Label	Treatment experiment details
TiO_2	5	N/A	5-19-00-Ti	Pristine membrane
		Oily water	5-19-02-Ti	Total of 16 h run time to treat oily PW; P_{feed} = 73–104 psi; T_{avg} = 83 °C
		SAGD	5-19-03-Ti	Total of 16 h run time to treat SAGD PW; P_{feed} = 73–75 psi; T_{avg} = 81 °C
	30	Oily water	30-19-03-Ti	Total of 20 h run time to treat oily PW; P_{feed} = 31–73 psi; T_{avg} = 82 °C

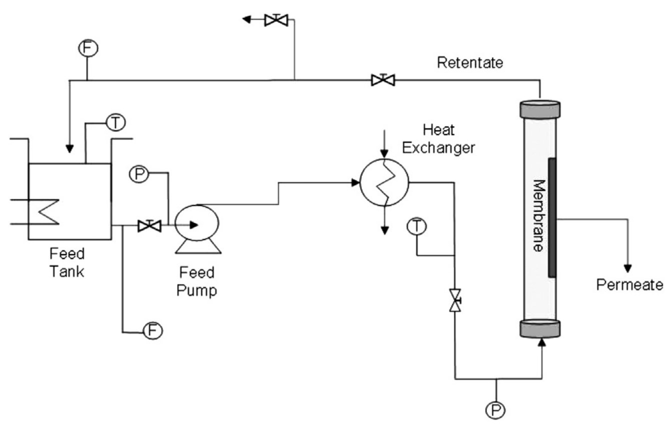

Fig. 2. Schematic of the cross-flow filtration system (P: pressure gauge, T: thermocouple, F: flowmeter).

Fig. 3. < 0.45 µm filtrates for bitumen-impacted feeds studied. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2. Material and methods

2.1. Sample preparation

2.1.1. PW feeds

In order to better describe the factors influencing membrane fouling during the treatment tests, some physical and chemical properties of the feeds were characterized.

The solid portion of each PW feed was isolated through decantation, dried in air and mounted on Al stubs. The phase constituents were identified by micro X-ray diffraction (µ-XRD) analyses, whereas chemical information was obtained by energy-dispersive (EDS) X-ray microanalyses.

The concentration of dissolved ions in the liquid fraction was determined by inductively coupled plasma – atomic emission spectroscopy (ICP-AES) scan of the < 0.45 µm filtrate collected from each feed.

2.1.2. Ceramic membranes

The porous ceramic membranes used in this study consist of 120 cm long extruded tubular γ-alumina (corundum) substrates, 25 mm in diameter, with 19 filtration cylindrical channels of 3.4 mm diameter (Fig. 1). Within each channel, the substrate is lined with two to three γ-alumina transition layers of progressively smaller pore size and a titania surface selective layer with porosity ranging from 3 to 30 nm fabricated through a sol-gel dip coating and sintering process. In order to characterize the impact of the feed treatment experiments on the membranes, longitudinal (Fig. 1a) and normal (Fig. 1b) sections were cut dry using a diamond wafering blade mounted on a Buehler IsoMet low-speed saw and continuously dusted off using compressed air. The longitudinal section allows direct access to the surface of the selective layer within the filtering channels without any potential preparation artefacts. The cut made normal to the long axis of the membrane gives a cross-section view along the filtration path from which valuable information on the integrity of the membrane as well as on the chemical nature and distribution of the contaminants relative to the various porous layers, can be obtained. In order to produce the flat polished surface required for reliable microanalysis, the sections were vacuum-