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Bitumen partial upgrading by mild hydroprocessing in a fixed-bed reactor

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ABSTRACT

Partial upgrading is an approach to processing Canadian oil sands bitumen with the objective to produce a synthetic crude oil that meets specifications for pipeline transportation (API Gravity of 19° and viscosity of 350 cSt at 7 °C). Most partial upgrading technologies under development rely predominantly on thermal conversion processes combined with additional steps such as solvent deasphalting. Owing to the chemistry of thermal conversion, the liquid product resulting from this route tends to be unstable and susceptible to potential operational issues in pipeline transportation and subsequent refining. Hydroprocessing represents another pathway for bitumen partial upgrading, with the advantage of being able to minimize product instability concerns and achieve the target product quality. The objective of this study was to evaluate the feasibility of using mild hydroprocessing in a fixed-bed reactor for the partial upgrading of Canadian bitumen. Experiments were conducted in a pilot plant that underwent various modifications to handle raw bitumen. Systematic tests at different operating conditions were completed in a time period of 1394 catalyst hours without experiencing any plugging issues. It was demonstrated that stable and pipeline-ready product can be produced at residue conversions of 52.4 wt% or above and with a hydrogen consumption level of about 1005 scf/bbl. Future research must be directed at optimizing the process to reduce hydrogen consumption and investigating catalyst deactivation patterns.

1. Introduction

Canadian oil sands bitumen is a type of extra heavy oil containing almost no naphtha and over 50% vacuum bottoms. Because of its high viscosity, bitumen is blended with diluents or upgraded into synthetic crude oil (SCO) before it can be delivered to market by pipeline. Bitumen upgrading is capital-intensive and consumes massive amounts of energy as it involves multiple processing steps that include atmospheric and vacuum distillation, coking and/or ebullated-bed hydrocracking, and hydrotreating [1]. The use of diluent for bitumen transportation is also considered suboptimal because the diluent itself occupies about 30–50% of pipeline capacity [2] and necessitates additional pipeline infrastructure to return the diluent to the production site. The diluted bitumen itself is sold at a much discounted price in the oil market due to its low quality (high aromatics, sulfur, and asphaltene contents). These challenges, along with the current low oil prices, have prompted substantial efforts to develop partial upgrading technologies to process Canadian oil sands bitumen at lower cost per barrel with improved environmental performance [3].

Partial upgrading, also referred to as field upgrading, aims at improving the quality of bitumen by processing it to the point where it can meet the pipeline specifications for API gravity (19°) and viscosity (350 cSt at 7 °C), thereby eliminating the need for diluents for transportation via pipelines. In addition, partially upgraded bitumen also needs to meet the specification for total olefin content, currently set at less than 1 wt%, as measured by the ^{1}H NMR method. The majority of partial upgrading technologies being pursued are based on some form of thermal cracking/conversion [4,5], in some cases combined with solvent deasphalting [6]. Thermal cracking is known to promote the formation of olefins via a free-radical mechanism [7,8]. Moreover, as asphaltenes in bitumen are gradually stripped of their alkyl chains, they become more aromatic and therefore less soluble in oil [9,10]. Under such circumstances, the liquid product becomes unstable and less amenable to blending with other crude oils in a refinery [11,12], thus representing a matter of concern for downstream processing due to potential fouling issues in various refinery units [13]. Consequently, addressing the stability of thermally processed bitumen is still a focal area for partial upgrading development.

A different approach to bitumen partial upgrading involves the use of hydrogen addition technology. Hydroprocessing technologies have proved effective in the upgrading of heavy oils and residues [14,15]. In the context of partial upgrading, hydroprocessing offers the following

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benefits: (1) avoiding the formation of olefins by stabilizing free radicals produced from cracking reactions, (2) suppressing coke formation while maximizing liquid yield selectivity, (3) significantly improving product transport properties, and (4) achieving processing goals in a single conversion step.

Selection of an appropriate hydroprocessing technology is dictated by the objectives of the process together with the feedstock characteristics [16,17]. Ebullated-bed [18] and slurry-phase [19] reactor technologies are suited for achieving high residue (525 °C+) conversions (> 60%) with difficult feedstocks, such as vacuum residues. Fixed-bed hydroprocessing reactors are adequate for pretreating heavy feedstocks with a moderate degree of hydrocracking [20,21], which is more in line with the purposes of bitumen partial upgrading. In this application, however, the difference would be that the degree of conversion would have to be sufficiently high to meet the targets for transport properties while keeping the removal of impurities (e.g., sulfur and nitrogen) at lowest possible levels to reduce hydrogen consumption. These requirements raise the question of whether it is feasible to achieve such targets without falling into a conversion regime in which the process becomes inoperable due to high sediment formation. As is well-documented in the literature [22,23], the formation of fine sediments is the origin of fouling in heavy oil hydrocracking operations, particularly when conversion exceeds 40–50%. A rule of thumb to reduce fouling is that sediment content in the product must be kept below 0.8 wt% [24], meaning that there is an upper conversion limit that can be sustained in commercial practice. Another determining factor to consider in a fixed-bed process is how rapidly the catalyst is deactivated over time, as this consideration ultimately determines whether this reactor type would be chosen over other technologies that are not constrained by catalyst deactivation [25].

In this study we explore the technical feasibility of using mild hydroprocessing in a fixed-bed reactor for partial upgrading of Canadian oil sands bitumen. The specific goal is to identify an operational regime whereby it is possible to produce partially upgraded bitumen that meets current pipeline specifications, while addressing the limiting aspects raised above.

2. Experimental

Bitumen hydroprocessing experiments were conducted in a continuous pilot-scale hydroprocessor. The unit consisted of a fixed-bed tubular reactor (length 100 cm and inner diameter 2.54 cm), a high-pressure phase separator (HPS), and a product stabilizer. The reactor was heated by a four-zone electric furnace and its internal and outer axial temperature profiles were measured by a system of multiple thermocouples installed along its length. This configuration enabled very precise control of reactor temperature. Temperature differences between the inner section and reactor wall of about 5–20 °C were registered. Reactor effluents were sent to a high-pressure phase separator with a de-mister where the hydrogen and light hydrocarbons were separated from the liquid product. An atmospheric product stabilizer was used to separate any remaining gas dissolved in the liquid. The liquid product leaving the stabilizer reported to a product collector, while the gases coming from the HPS and stabilizer column were combined and directed to the vent, with a small slip-stream going to an online gas analyzer (HP5880 GC).

The feedstock used in the experiments was a typical Canadian oil sands bitumen. Feedstock characterization by using standard analytical methods (ASTM D4052, ASTM D5291/D4294, ASTM D2887, and ASTM D2007) is provided in Table 1. Given that the pilot plant unit was originally designed to process lighter feedstocks, such as vacuum gas oil and light gas oil, a number of modifications were necessary in order to process raw bitumen. These included changing the reactor flow direction to upflow mode, applying heat tracing to feed/product lines to ensure bitumen flow throughout the unit without plugging, and installing a feed pump suited for highly viscous fluids. The upflow direction was utilized to provide uniform wetting and reactant distribution across the catalyst bed with the goal of minimizing the presence of stagnant zones that could cause coke deposits and reactor plugging.

Table 1
Physical and chemical properties of the bitumen feedstock.

Property	
Density at 15.6 °C, g/cm^3	1.0146
API gravity	7.96
Viscosity at 80 °C, cSt	591.24
C, wt%	83.38
H, wt%	10.64
S, wt%	4.95
N, wppm	4900
Ash content, wt%	0.03
Toluene insolubles, wppm	100
Solids by shell hot filtration, wppm	1139
SARA analysis	
Saturates, wt%	20.7
Aromatics, wt%	39.0
Polars, wt%	21.0
Pentane insolubles, wt%	19.3
Simulated distillation	
IBP, °C	190.6
5 wt%, °C	273.2
10 wt%, °C	316.2
30 wt%, °C	437.0
50 wt%, °C	540.0
70 wt%, °C	646.8
85 wt%, °C	750.0

A commercial $NiMo/Al_2O_3$ catalyst for residue hydrotreating was selected for the tests. The reactor was packed with 150 mL of commercial size catalyst extrudates. The remaining reactor space above and below the catalyst bed was filled with glass beads of different sizes to ensure proper liquid and gas distribution. Fig. 1 illustrates the reactor packing scheme. These measures were necessary to ensure that the experimental results would be reproducible and scalable. The catalyst was activated *in situ* by liquid-phase sulfiding using light gas oil spiked with 3 wt% dimethyl disulfide (DMDS). Prior to initiating mass balance runs and data collection, the fresh catalyst was stabilized by running with bitumen feed for approximately 140 h at low temperature (330–360 °C). The following operating conditions were evaluated during the experiments: temperature 380–405 °C, liquid hourly space velocity (LHSV) 0.3–1.0 h^{-1}, pressure 4.8–9.0 MPa, and H_2/oil ratio 900 NL/L. Mass balance runs lasted between 18 and 24 h each to ensure high accuracy and collect sufficient product sample for characterization. Periodic check-back tests at base conditions (temperature 380 °C, LHSV 1.0 h^{-1}, 6.9 MPa) were performed to monitor catalyst deactivation. The total liquid products (TLPs) obtained from the experimental runs were characterized using the standard analytical methods mentioned earlier.

3. Results and discussion

The pilot plant unit was operated with bitumen feedstock for a total of 1394 catalyst hours without experiencing any plugging issues. A total of 14 mass balance runs and 3 check-back tests were completed during this period of time. Mass recovery for the entire set of experiments averaged 100.17% with a standard deviation of 1.29%, indicating good unit performance, sampling and analysis.

3.1. Hydroprocessing performance

In this section we analyze observed trends in product quality and other process parameters with respect to the conversion of the vacuum residue fraction (here termed 525 °C+ conversion) in the bitumen feed.