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SimSci-Esscor™

White Paper

Processing Heavy and Extra Heavy Oils

Problems and Solutions

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What's Inside:

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Problems and Solutions

1. Introduction

The world's energy industry has followed the availability of easily attainable and economically feasible supplies for the oil segment that has moved towards heavier feedstock. The earlier extraction, accessibility, transport and processing centered around lighter crudes with characteristics that could be uniformly and reliably processed in refineries using a stable of proven technologies is no longer possible. As those lighter crude supplies have become exhausted or more difficult to obtain, demand from emerging nations such as India and China has strained the supply chain. Because of their explosive growth, these and other countries experiencing economic growth are usurping an increasing amount of the existing supply of conventional crudes while investing in supplies of heavier sources as well. Heavier crudes have unique physical properties that often present costly refining challenges. Efficient processing solutions require a thorough understanding of the crude's characteristics and operating behavior. Those involved in heavy or extra heavy oil refining must decide what they have and how they should process it.

2. Current Heavy Oil Trends

With increased global demand and elevated prices of crude oil, heavier crudes are still economical to produce using advanced technologies despite the problems associated with their production and processing. Their discounted market prices, relative to West Texas Intermediate (WTI), Brent and other benchmark lighter crudes, can actually provide a financial incentive to the refineries capable of processing the heavier crudes. Conventional heavy oil reserves are plentiful in the Orinoco region of Venezuela, while the largest concentration of extra heavy, unconventional crude oil reserves is found in the rich tar sands of western Canada. Capacity of these heavier oils has been estimated at more than twice those of conventional lighter crudes. The globally estimated six trillion barrels of heavy oil reserves make it an important energy source especially as conventional sources continue to diminish. For United States refineries, the largest supply of heavier oil feedstocks comes from Canada. With increasing global political volatility, this resource provides a most secure supply despite its difficulty in extraction, transporting and refining.

There is a global need for alternatives to lighter, sweeter conventional crudes. The industry has had to adopt methods to recover and manage increasingly heavier oils that require additional processing steps. These heavy and extra heavy oils have characteristics that are complex and need to be identified in order for them to be efficiently processed. The knowledge of how to process these crudes is important in designing and operating the process correctly in order to reduce downtime, increase efficiency, optimize profitability, promote higher environmental standards and effectively eliminate safety concerns.

3. Characteristics of Heavy and Extra Heavy Oil

Heavy oil is generally defined as a viscous crude oil with API gravity between 10° and 22° and a viscosity of less than 10,000 centipoise. Extra heavy crudes are those unconventional oils with API gravity below 10°API, taking the form of bitumen-like substances with extremely low flow rates at the reservoir. In many instances they have been considered as 'bottom of the barrel' when compared to conventional petroleum sources of lower viscosity and higher API gravity. Their 'heaviness' is generally attributed to high molecular weight compounds, including asphaltenes, which contribute greatly to feed viscosity and coking tendency. They contain relatively small amounts of paraffinic components and are more naphthenic and aromatic in nature. While heavy and extra heavy oils are present in many global regions, the predominant supplies are found in the Americas.

In addition to high viscosity, high pour point and low API gravity, heavy and extra heavy oils are characterized by their higher levels of sulfur, nitrogen, and heavy metals, including mercury. They have low hydrogen to carbon ratios and high carbon residue. These feedstocks often contain elevated amounts of particulates and water. They are generally more acidic, with naphthenic acids being among the most problematic.

4. Problems Presented by Heavier Oil

Heavy and extra heavy crudes present numerous problems beginning with their extraction and continuing through transportation to refineries and throughout processing at the refinery itself. As oil sand recovery has progressed, surface extraction of oil sands with strip mining technology has been superseded by several thermal methods, the most predominant being steam-assisted gravity draining (SAGD). This, and other similar technologies, has allowed heavy oil to be exploited at lower depths as surface deposits have been depleted. The newer methodologies have reduced the environmental impact of extraction while accessing a higher percentage of known subsurface reserves. SAGD technologies rely heavily on natural gas as its energy source to raise steam. This extraction process, therefore, generates a higher concentration of CO_2, raising environmental concerns. Low natural gas prices, however, have assisted in making this an attractive extraction process.

Because of its viscosity, transport of heavier oils, especially bitumen-type material from Canada, is not shipped via pipeline unless it is first blended with a diluent. This blend is often referred to as Dil-Bit, a naphtha/bitumen blend, and is needed to facilitate flow. Bitumen properties and ambient temperatures at origin and along the pipeline route determine the percentage of naphtha utilized and can vary widely. Natural gas condensate can also be used as a diluent.

The heavier oil can also be diluted for transport purposes with a synthetic crude oil (SCO) produced by partially upgrading the heavy oil through pre-refining distillation processes to lower its viscosity for transport through a pipeline. This synthetic oil/bitumen blend, known as Syn-Bit, adds to the cost of the heavy crude. As the quality and attributes of SCO and Dil-Bilt diluents can vary considerably from one upgrading facility or supplier to another, their removal and recycle present additional factors that have to be understood in order to effectively deal with the refining process.

5. Refining Challenges

Supply trends impact, and will undoubtedly continue to affect, refining capabilities. Traditionally, refineries were designed to accommodate lighter, sweeter crudes. They were designed and built to handle a specific type of crude or blend which today may no longer be available or is cost prohibitive. The refineries were not initially designed to be flexible with a multitude of feedstocks or used to being dynamic for accommodating newer, heavier feeds. In the United States, there have been no new grassroots refineries constructed for more than 35 years. Refinery closings during that period have reduced the number of refineries by almost three-quarters to approximately 120 and have diminished the production capacity in many instances. With current demand, refinery utilization in the U.S. is greater than 90%, leaving little room for often needed maintenance and revamping. Refiner profitability has also diminished in the past few years, and with regulatory and environmental pressure, closings could continue and profitability margins may increase for remaining refineries.

Heavy oils require additional steps in order to remove impurities and provide the spectrum of products from a variety of feedstocks. The addition of hydrogen through the hydrocracking process is necessary for this purpose. The crude combines with the hydrogen at high temperatures and pressure in the presence of a catalyst to saturate aromatic molecules, separating out lighter streams. Subsequent reactor stages further separate hydrocarbon components, increasing the yield of low boiling, high value fluids and middle distillates while leaving the heavier residue to be converted into coke in a separate operation. The characteristics of heavier oils are not always interdependent, so that refining problems are compounded by having to understand each nuance and address them individually as well as in tandem.

Heavier crudes bring additional levels of heavy metals such as vanadium, magnesium, nickel, and iron, the removal of which has to be considered in the operation of the refining process. It is imperative to assess and remove certain metals, particularly mercury. Even if the levels of mercury are low, their presence in large volumes of liquid hydrocarbons represents significant exposure to processing equipment. Non-removal of mercury can cause metal embrittlement and failure due to corrosion, and may be a dangerous health hazard to refinery workers. Its presence can manifest itself if found in numerous refinery processes. Mercury levels in the C3 through C6 product streams from the crude distillation column and in the water effluent can cause contamination of catalysts, poisoning them and necessitating additional operating expenditures if not removed.

Other materials found in heavier crudes can also cause a host of operational problems if not eliminated. Calcium, present as calcium naphthenate, can cause fouling problems at the desalter, catalyst poisoning, and scaling problems that require increased maintenance for heat exchanger tubes and the internals of other equipment. They often require additional processes for their elimination, such as demulsification.

Many of the new crude sources are heavier with increased content of sulfur and other impurities. Because of the extreme variability of heavier crude from different fields from which it is being supplied, processing technologies cannot be uniform, but need to be structured to accommodate the specific characteristics of the crude.

High density and viscosities require higher temperatures in refining units. Desalters, because of the heavier crude's attributes have to operate at high temperatures which can compromise the heat energy balances that had been designed for lighter weight crudes. Additionally, with the higher levels of solids found in heavier oils, sludge becomes a potential storage problem as does its impact on wastewater treatment and other offsites. The delayed coker residue from the vacuum reduced heavy crude oil, presents another potential bottleneck in the refinery. As a batch process, it accumulates in the coker drums. If it is not removed in a timely manner, the refinery operation could back up and be forced to shut down.

Once refineries have shifted their capabilities to produce high-value products from heavier crudes, it is incumbent on them to continue down that path, as they would have to significantly modify their facility to again focus on processing lighter crudes. U.S. Gulf Coast refineries have that conundrum and rely on the delivery of Canadian crudes. Hence, new, reversed and extended pipelines are a foremost priority in their facilities.

6. Modeling: A Solution for Current and Future Heavy Oil Refining

As the supply of available feedstocks change and their characteristics vary widely, existing refineries are forced to become more flexible in their capabilities and adapt to the diversity of input materials from their supply chain. Operations planning and optimization are critical in an existing facility where constricted margins vary widely depending on processing costs, product yields and adaptability of each processing unit. Fractionation, as one example, requires exact measurements of pressures, temperatures and volumes in order to maximize yields from a variety of feedstock compositions.

All refineries are currently struggling to process heavier crudes economically. Modeling methods that accurately depict the characteristics of heavier feedstocks allow refiners to adapt their processes accordingly, whether by designing new equipment or altering current operating processes.

It is important to be able to predict the performance behavior of heavier crudes at each stage of the refining process. It is difficult to use traditional modeling software as they were developed to predict the behavior of conventional lighter weight, sweeter oils. There is no one solution for heavier oil processing that suits all refineries. Each refinery has its own set of parameters governed by its existing configuration, the composition of the heavy crudes being processed, the conditions within the plant and its desired range of output.

For example, asphaltenes are prevalent in heavy oils. Using processes to precipitate them to lower viscosities can assist in refining. When diluted with solvents including condensates, the Dil-Bits from oil sands are easier to transport via pipeline. To optimize processing, therefore, it is necessary to be able to predict the amount of asphaltene precipitated as a function of the amount and nature of the solvent, temperature and pressure.

7. Addressing Issues Jointly

Utilizing field-proven SimSci-Esscor™ modeling software, Invensys enlisted a consortium of global industry leaders – major oil companies, Canadian heavy oil producers, engineering firms and national oil companies- to provide a forum for defining and solving leading issues on heavier oil processing. Using real operating information, Invensys is using the latest modeling technologies to predict specifically how heavier oils will perform at various process stages during refining. The software has identified several areas needing improvement and has developed new and expanded models to increase the accuracy of prediction and plant optimization through advanced process simulation.

The effort has been directed at multiple issues: crude feed preparation, investigating viscosity and thermal conductivity; hydrogen balance and solubility as part of the upgrading process; mercury and other contaminant removal; and molecular-based characterization.

Viscosity is a critical component of understanding heavy oil properties and potential yield. The newest method of liquid viscosity prediction advances the accepted Twu correlation. It improves the predictive accuracy of viscosities in the 100 cSt – 100,000 cSt range and closely estimates temperature dependence, especially with low temperatures. Utilizing data from more than 125 heavy oil assays from the consortium, proper fitting is possible and the accuracy of prediction of viscosity in simulations is improved.

In addressing liquid phase thermal conductivity in heavy oils, there is limited industry data. However, recognizing the comparable characteristics of Solvent Refined Coal II (SRC-II), for which some data is available, accurate correlations have been established. Recent testing has determined a strong performance using the Sato-Reidel method, requiring only an estimate of critical temperature to produce the best level of accuracy.

Hydroprocessing is required in refining heavier oils in order to remove numerous impurities. Hydrogenation increases the yield and converts low value feedstocks into higher value end products. With the addition of hydrogen in the process, refinery optimization relies on its management and its solubility in hydrocarbons. Laboratory measurements for hydrogen (H_2), hydrogen sulfide (H_2S) and ammonia (NH_3) vapor-liquid equilibrium with defined hydrocarbons have been used to fit equation of state binary interaction parameters to improve the accuracy in predicting their solubility in hydrocarbon mixtures.

Mercury is a contaminant in heavy crudes that creates multiple problems during refining operations. It can poison catalysts, contaminate wastewater, destroy process equipment and impair processes, and is a dangerous health hazard. Accurate understanding of its solubility in hydrocarbons is necessary for its mitigation. Similarly, naphthenic acid is more prevalent and increasingly corrosive in heavier crudes. The ones of concern are those with a molecular weight with a boiling point of 430-750°F. The acid concentration, density and viscosity of the crude need to be assessed in order to predict its corrosion potential.

8. Kinematic Viscosity Predictability

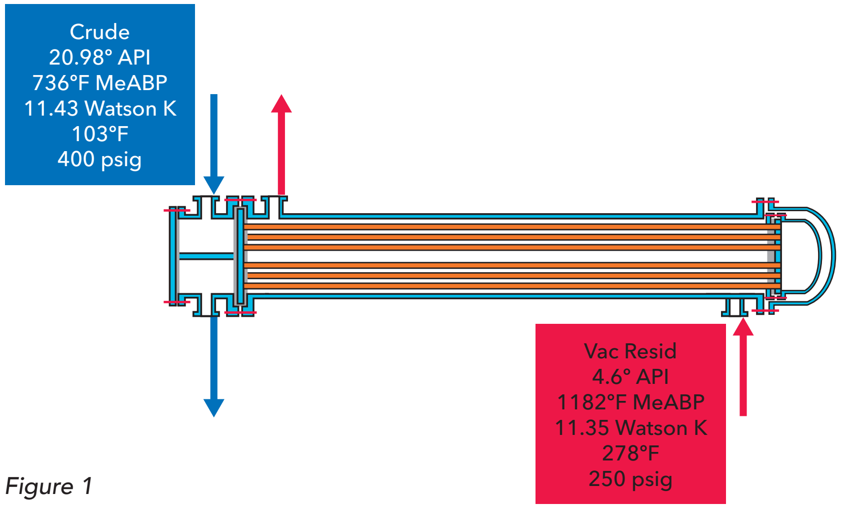

Figure 1

The procedure for characterization developed by Invensys using current data from consortium members focuses on extrapolating molecular weights of critical heavy oil components with normal boiling points exceeding 1,000 degrees Kelvin. Its importance cannot be understated when designing process components, such as the heat exchanger.

Using a newer SimSci-Esscor correlation developed specifically for the attributes of heavy oil and kinematic viscosity, results can be compared to measured data and those derived from the older API Procedure 11A4.2. It points out a significant difference in accuracy in heat exchanger sizing. When compared to measured viscosities, Table 1 below shows the predicted kinematic viscosities in centistokes at various temperatures using the API Procedure 11A4.2 method compared to the heavy oil correlation using the illustrative example of Figure 1 above. Referring to Table 2 below, the comparison shows the duty would be almost 250% oversized. The SimSci-Esscor heavy oil method predicts duty much closer to the measured data especially as temperatures rise.

	Crude Kenematic Viscosity, cSt		
Temperature	Measured	API 11A4.2	Heavy Oil
60°F	49.75	111.6	70.65
80°F	27.95	58.77	39.69
100°F	17.52	34.26	24.38
	Vac Resid Kenimatic Viscosity, cSt		
Temperature	**Measured**	**API 11A4.2**	**Heavy Oil**
210°F	6787	454.0	4784
250°F	1261	147.5	858.5
300°F	274.6	50.83	176.8

Table 1

Viscosity(L) method ➔	Measured Values	API Procedure 11A4.2	Heavy Oil Prediction
Duty (10^6 BTU/hr)	3.654	8.976	5.432
LMTD (°F)	165	150	159
U (BTU/hr/ft^2/°F	4.657	12.62	7.144
Shell Side			
T_{out} (°F)	265	245	258
ΔP (psi)	58	8	27
Tube Side			
T_{out} (°F)	110	119	113
ΔP (psi)	9	13	11

Table 2

The API method overstates the heat transfer values by more than 300% while the newer model is much more accurate. Utilizing inaccurate calculations can result in design flaws that specify oversized equipment escalating both Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Pressure drop undersizing can cause insufficient pump capability which, in turn, could result in poor flow patterns through the exchanger or costly production bottlenecks.

9. Conclusion

The nature of refining is continually changing with increasing global demand and feedstock supplies that are becoming heavier and more difficult to process. In addition to this, increasing governmental regulatory oversight and environmental constraints on emissions heavily impact refining operations. To maximize profitability, refiners are faced with constant decisions to vary their operations to suit the feedstock. Operational challenges are extremely difficult, if not impossible to address, without knowledge of the characteristics of the crude components and nuances.

Heavier crudes are dramatically adding to the global hydrocarbon supplies and have become an economical feedstock. These crudes present numerous operational problems during extraction, transport and refining. They require additional additives to combat high viscosity and high mass density. At the refinery, they necessitate extra treatment phases, adding hydrogen during processing to eliminate or mitigate impurities and alter their molecular structure. Their composition varies, adding complexity to their refinement. While models have been used for years to understand and optimize processing of conventional lighter crudes, the increased demand for heavier oil has led necessary development of models to address the unique attributes of these crudes. To optimize their processing and reduce design and operating costs, accurate simulation models, specifically tailored for heavier crudes, must be used. Without this accuracy, operating and capital costs will escalate and performance will diminish at a time when refiners are seeking any advantage to increase profitability.

10. References

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