

DEVELOPMENT OF A THERMALLY-INTENSIVE REACTOR AND PROCESS FOR UPGRADING HEAVY CRUDE OIL

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ABSTRACT

A successful development and pilot test program of a 15 bpd, very high thermal flux, short vapor residence time reactor has been completed. The reactor features: a flowing, free surface channel of molten metal salt; placing small droplets of heavy crude mixed with catalysts on the flowing surface; a free vapor space for removing and condensing clean, particulate-free cracked hydrocarbon vapors; a simple means for removing and separating the coke, catalyst and heavy metals for processing and recovery. Additional steps in the process recover chemicals and energy, while producing useful liquids that add to the overall process economics.

INTRODUCTION

Preliminary development of process technology to upgrade heavy crude in an energy and cost-efficient manner has been completed and demonstrated in a 15 bpd plant. The main features of the process are outlined in Figure 1. Proprietary catalysts are mixed with the heavy crude prior to feeding to the upgrading reactors. The coke, catalyst and heavy metals are then further processed to recover and recycle catalyst, produce high-quality liquids and provide energy for reuse in the process. Development of the reactors is described in the following; a complete review of upgrading process is given in Rana *et al* [1]. A review of short residence thermal cracking (pyrolysis) processes and reactor types is given in Hulet *et al* [2].

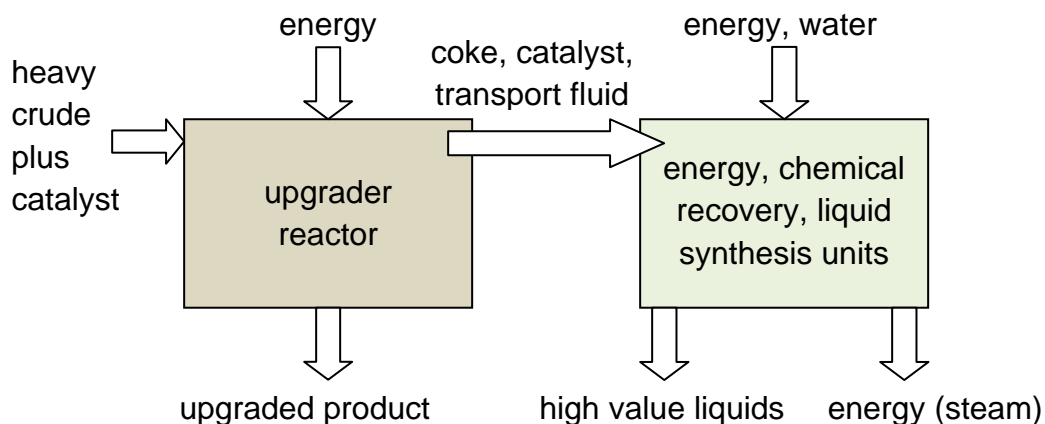


Figure 1. The overall Refinery Science process for upgrading heavy crudes.

Past work by Chianelli *et al* [3, 4] has shown the benefit of extreme thermal cracking; hydrogen is “borrowed” from the coke product and diverted to the product liquids. This operation requires high rates of thermal flux while maintaining very short reactor residence times to avoid overcracking the product, a point amplified by Hulet *et al* [op cit]. These features and requirements are met in the reactor layout shown in Figures 2(a), (b).

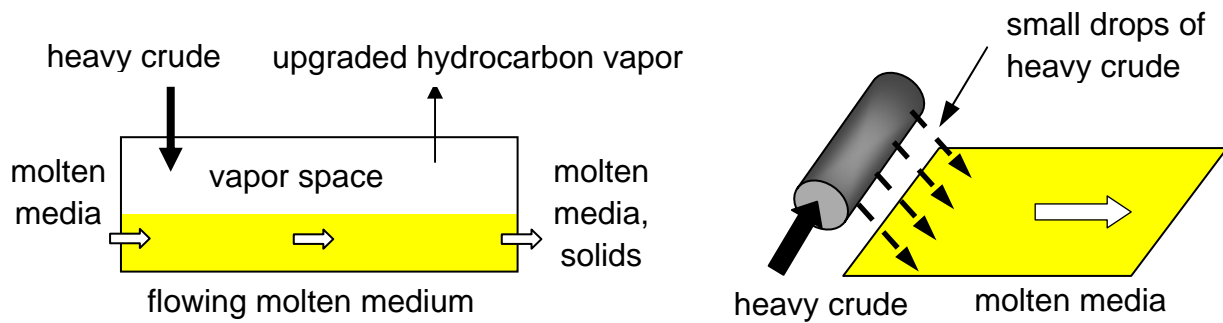


Figure 2. (a) Reactor arrangement for optimum vapor separation. (b) Schematic method for placing heavy crude on the surface of a flowing heat transport medium.

THERMAL PROCESS FEATURES

Placing heavy crude onto a hot surface evokes the familiar “hot skillet” effect (more formally, the “Leidenfrost” effect); small drops are observed to either “float” or “sputter” on the surface before disappearing. Figure 3 shows a schematic representation of this behavior.

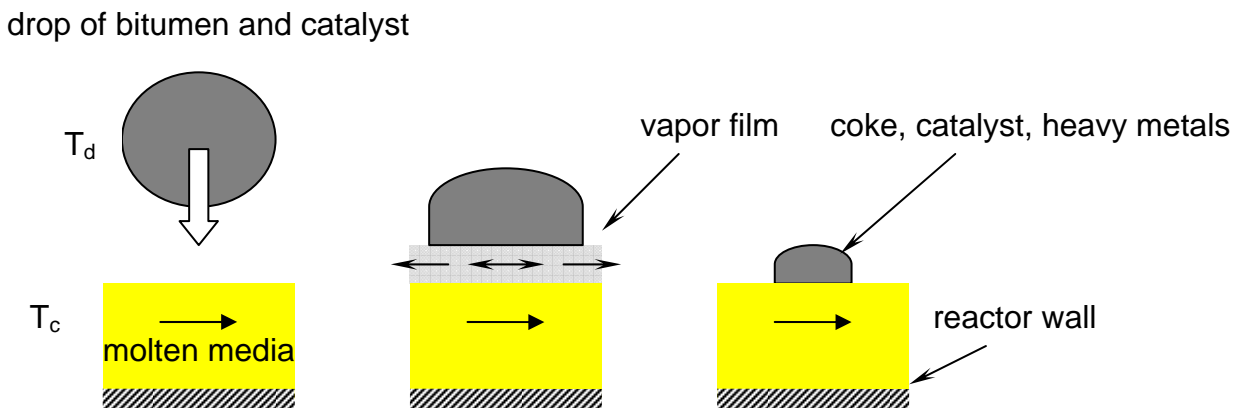


Figure 3. Stages of contacting heavy crude with a hotter flowing medium

Immediately following contact (or near-contact) of the heavy crude drop with the much hotter heat transport fluid, a thin vapor layer of the most volatile crude component is formed between the drop and the hotter medium. As the vapor escapes from underneath, a pressure is generated in the vapor film sufficient to keep the drop levitated. The heat transfer coefficient in this region is generally low, owing to the relatively low thermal conductivity of the vapor.

As the drop temperature rises, the stable vapor film becomes thinner and breaks down at the so-called “Leidenfrost Point”, schematically indicated on Figure 4 by the point marked “L.P.”. As the drop alternately touches the hotter surface and creates a partial film, the heat transfer coefficient rises sharply (following the direction of the red arrow). A peak heat transfer coefficient occurs during intense nucleate boiling at the drop surface, with rapid evolution of the remaining (now cracked) drop volatile components. Eventually the surface of the drop approaches the temperature of the heating medium and the heat transfer coefficient diminishes. The curve shown in Figure 4 is the familiar boiling heat transfer curve, albeit in this case the process transits from right to left, more like that in a quenching operation. Experimental results reported by Ma [5] with a variety of oils indicate peak nucleate heat transfer coefficients as high as 3,500 W/m²C.

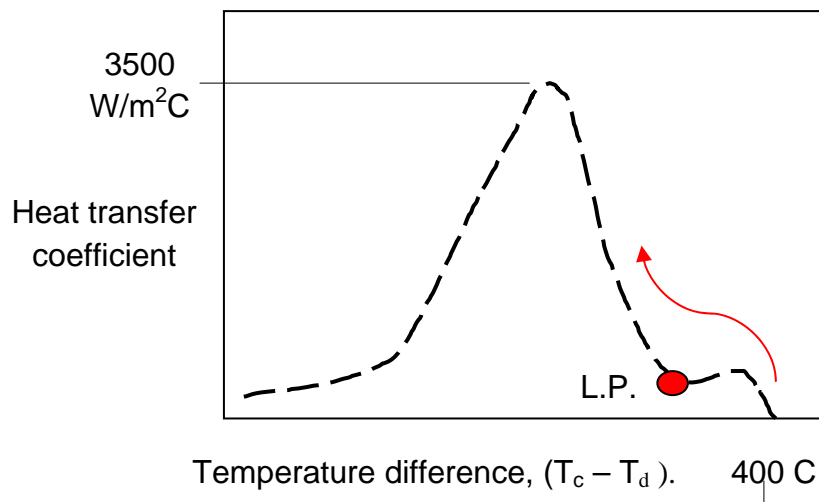


Figure 4. Heat transfer coefficient to a heated heavy crude drop, starting from the right part of the diagram and moving left along the curve. The maximum heat transfer coefficient occurs with peak nucleate boiling of cracked volatiles from the drop surface.

The rate of temperature rise in the heavy crude drop during the region of nucleate to peak nucleate boiling approaches that normally experienced only in the case of fast pyrolysis of very small particles (up to 1000C/s). As the rate of temperature rise is inversely proportional to particle size, Figure 5 shows how intense thermal heating can occur even with much larger particle sizes...in this case larger drops of heavy crude carrying catalyst.

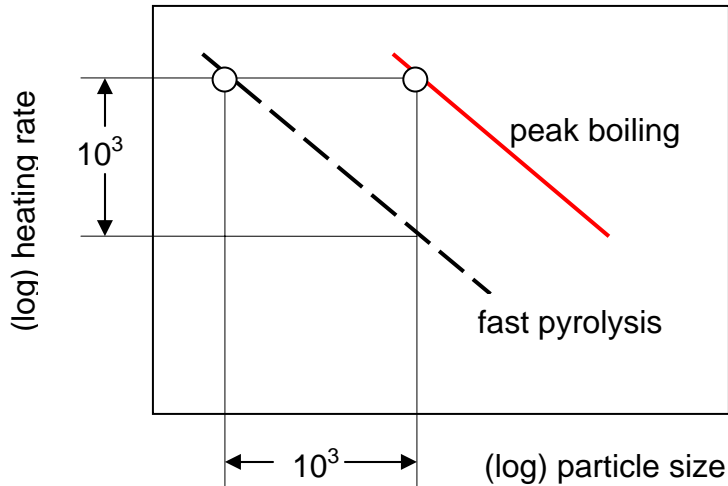


Figure 5. Schematic rate of temperature rise (heating rate) as a function of particle size and external heat transfer coefficient. Much larger particles (drops) can match fast pyrolysis heating rates owing to much higher external heat transfer coefficients.

The heavy crude is cracked through the combined effects of rapid heating and intimate presence of catalyst within. In this way maximum catalyst concentration occurs with maximum temperature for cracking the remaining least volatile components. No particulate matter leaves the drop, which then experiences an intense increase in temperature and catalyst concentration until only coke, heavy metals and catalyst remain. The clean, cracked hydrocarbon vapors are immediately removed from underneath the drops and away from the heating source, thereby minimizing the possibility of further overcracking. The residual coke, catalyst and heavy metals leave the reactor through a simple over-under weir shown schematically in Figure 6.

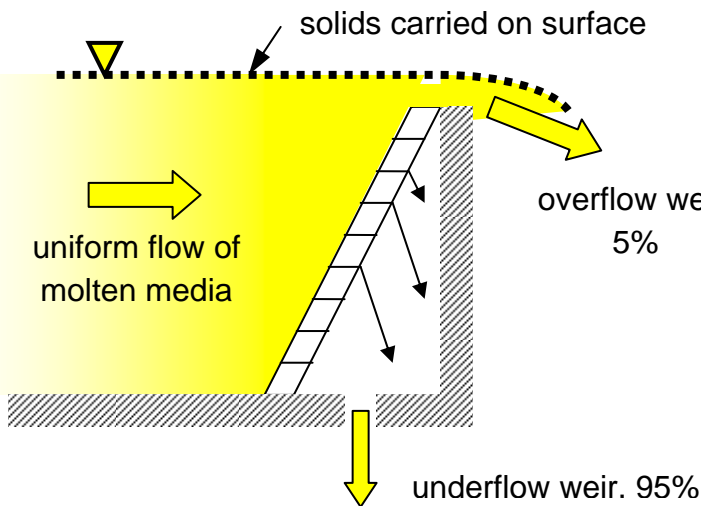


Figure 6. Schematic arrangement for solids removal from the upgrader reactor. Subsequent process steps recover catalyst, heat transport fluid, produce further high-quality liquids, and recovery energy (steam) for process and field use.

15 BPD PILOT PLANT RESULTS

An overall view of the main upgrader reactor during assembly is shown in Figure 7. Several heavy feedstocks have been evaluated; samples of process streams were collected over operating periods typically lasting one hour to get good steady-state behavior. All samples were analyzed by independent third-party labs.



Figure 7. Overall view of the main upgrader reactor during assembly. Heavy crude enters the reactor on the right and proceeds toward the discharge on the left.

Table 1. Summary of third-party analysis of a feedstock and typical upgraded product.

TABLE 1	Hardisty Heavy	1.0% Catalyst
Bromine number	7.1	25.1
n-Pentane Insolubles, %	12.31.	0.04
Sulfur, Wt%	3.87	2.18
Kinematic Viscosity, cSt	590	4.23
Micro Carbon Res., Wt%	11	0.21
API	12.8	26.4
Carbon, Wt%	84.28	85.37
Hydrogen, Wt%	10.80	12.04
Nitrogen, Wt%	<0.75	<0.75
Iron, ppm	3.16	0.33
Nickel, ppm	58.2	<0.5
Vanadium, ppm	108	<0.1
Asphaltene Content, Wt%	8.2	<0.5
UOP K Factor	-	11.2

The results in Table 1 indicate a substantial reduction in liquid product viscosity (suitable for direct pipelining), sulfur and micro carbon residue content, with good API increases using a modest concentration of proprietary catalyst recycled to the reactor inlet. Heavy metals are removed from the liquid product and are discharged from the reactor with the coke and catalyst. Figure 8 shows the fractional analysis of the upgraded product compared with the incoming feedstock.

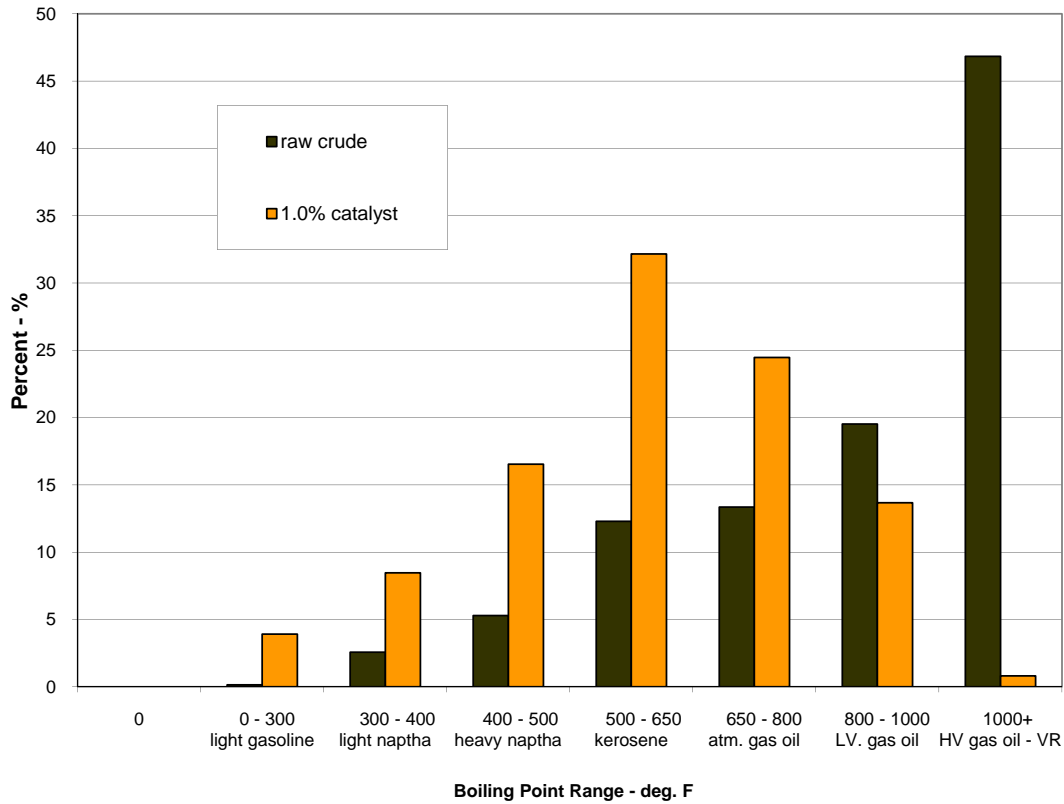


Figure 8. Fractional analysis of the upgraded product compared to the Hardisty heavy (weathered) feedstock. Independent analysis by Intertek Labs, Houston.

	Mass %	Volume %
Liquids out	65.88	72.10
Solids out	21.27	-
Gases out	12.85	-
Total	100	-

Table 2. Mass balance for the test results reported above.

The mass balance results in Table 2 reflect significant coke production (21.27%) owing to the coking catalyst used, and also a considerable amount of non-condensable gas (12.85%), typically light end hydrocarbons which can be used to generate energy for the process. More energy is also released in the subsequent recovery processes, not described here.

The test results given above have been incorporated directly into projections for the performance of a stand-alone 1000 BPD upgrader, placed at a SAGD wellhead or collection battery. Figure 9 is a representation of typical performance factors for a 1000 BPD installation.

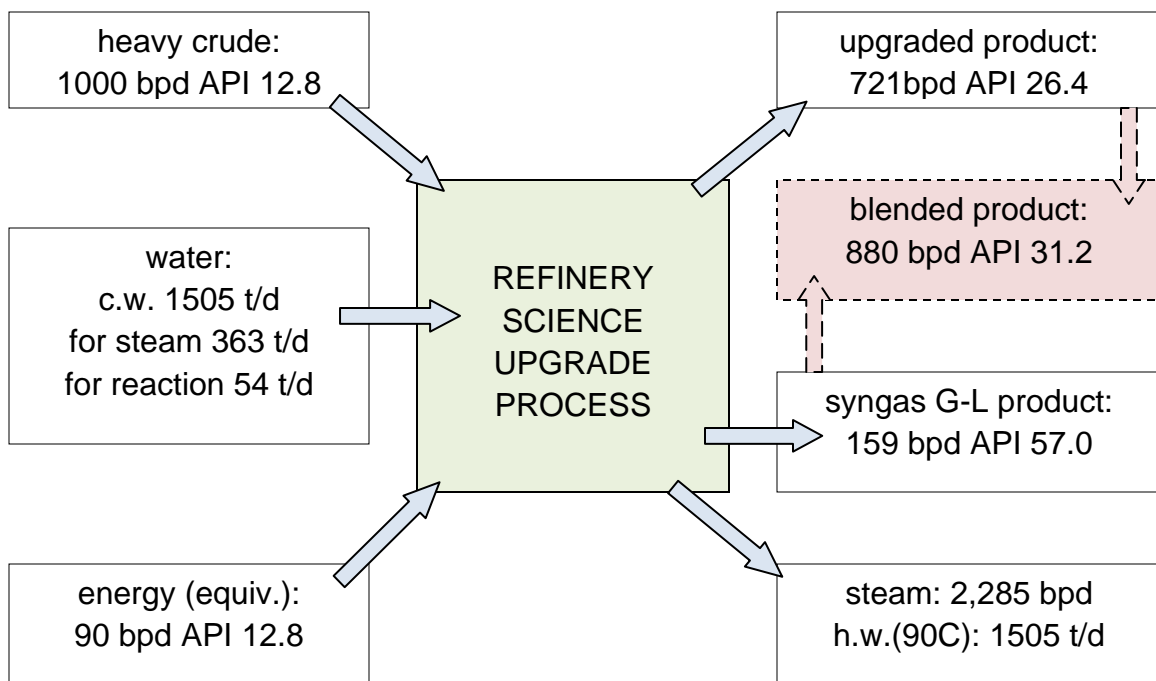


Figure 9. Operation of a 1000 bpd plant based on pilot plant data.

Good process economics are projected owing to the fact that significant surplus energy in the form of steam is available, for example, for SAGD reservoir steam flooding. Water consumption is low (equivalent to 10 USGPM), with all process water being recycled. Additionally, catalyst is recycled and other consumables are minor. No external fuel is required for continuous operation beyond start-up. Detailed engineering of modular, field assembled plant components for a 1000 bpd plant is underway.

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