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Improvements of Ebullated-Bed Technology for Upgrading Heavy Oils

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Résumé — Amélioration de la technologie en lit bouillonnant pour la valorisation des bruts lourds — Les résidus issus des bruts lourds peuvent être valorisés en utilisant différents procédés. Parmi ceux-ci, le procédé d'hydroconversion catalytique en lit bouillonnant *(H-Oil)* présente la particularité d'être capable de convertir sévèrement ces produits lourds contenant de forts taux d'impuretés et pendant une durée de cycle importante. Ceci est accompli par le remplacement journalier d'une petite partie de l'inventaire de catalyseur contenu dans le réacteur. Le réacteur en lit bouillonnant inclut une recirculation interne liquide pour fluidiser le lit catalytique.

Cet article présente des informations de base concernant le procédé *H-Oil* et les récentes innovations développées pour cette technologie. Une étude de la distribution du temps de séjour a été réalisée en utilisant un traçage radioactif sur une nouvelle unité pilote de ce procédé. Cette expérience a permis de caractériser l'hydrodynamique du réacteur et d'estimer le *holdup* de liquide. Ces paramètres sont importants et permettent d'assurer une extrapolation industrielle fiable des résultats pilotes. La technologie de ce procédé a été améliorée pour les bruts lourds. Un nouveau séparateur haute pression a été conçu lors d'une étude R&D dans le but d'améliorer la séparation gaz/liquide en évitant l'entraînement de liquide dans le gaz et de gaz dans le liquide. L'utilisation industrielle de ce nouveau séparateur dans le procédé *H-Oil* avec des débits de charges hors design a permis d'améliorer l'opération de l'unité et de minimiser les coûts opératoires.

Mots-clés : lit bouillonnant, hydrodynamique, DTS (distribution des temps de séjour), séparation, hydroconversion, réacteur multiphasique.

Abstract* — *Improvements of Ebullated-Bed Technology for Upgrading Heavy Oils *— Residue from heavy crude oils can be upgraded through various existing processes. Among these processes, the catalytic hydroconversion ebullated-bed process (H-Oil) has the unique feature of deeply converting heavy feedstocks with high impurity contents while operating with a long cycle time. This is accomplished through daily on-line catalyst replacement of a small portion of the catalyst bed. The ebullated-bed reactor includes an internal recirculation of the reactor liquid to ebullate the catalyst bed.*

The paper will present background information on the H-Oil process and discuss some of the recent improvements that have been developed for this technology. A Residence-Time Distribution (RTD) study was conducted using a radiotracer on a new laboratory bench unit of this process. This experiment quantified the reactor hydrodynamics and the liquid holdup. These parameters are critical to insure a safe extrapolation of the pilot plant results. The technology of H-Oil process was improved for heavy feedstocks. A new hot high-pressure separator design, based on R&D studies, has been developed to improve the separation of gas/liquid avoiding excessive liquid carry-over and gas carry-under. The use of this new separator in a commercial H-Oil plant operation at higher feedstock throughput results in improved operation and minimization of operating costs.

Keywords: ebullated bed, hydrodynamics, hydroconversion, RTD (Residence-Time Distribution), separation, multiphase reactor.

INTRODUCTION

The ebullated-bed technology utilizes a three-phase reactor (liquid, vapor, and catalyst). It is most applicable for exothermic reactions and for feedstocks which are difficult to process in a fixed-bed or plug flow reactor due to high levels of contaminates (Morel *et al*., 1997). The first application of this reactor technology was for vacuum residue hydroprocessing, using the H-Oil process. This process accounts for 50% of this market due to its unique flexibility to handle a wide variety of heavy crude oils while producing clean fuel oil and transportation fuels. The H-Oil process is now licensed by *IFP NA* (Colyar and Wisdom, 1992, 1994, 1997; Kressmann *et al*., 1998). The improvement of this process and the technology are an important challenge for the treatment of heavy crude oils. H-Oil industrial licensees require a quick response to their problems or to require improvements due to new regulations or changes in the selectivity of the process. One of the important technical methods for responding to these demands is the chemical engineering studies and all the procedures of scale up/down associated with the design of facilities such as the cold mockup and bench unit. These tools and methods need to be simple but close to the industrial operating conditions. Due to the complexity of the process and petroleum feeds, the engineers and researchers have to develop new methods to quickly solve these problems. The purpose of this paper is to present two cases which give a special emphasis of those methods and tools applied to multiphase reactors and namely to the ebullated-bed reactor.

The first case is a Residence-Time Distribution (RTD) study that was conducted using a radiotracer in a bench unit representative of the industrial unit. The objective of this experiment is to set a methodology to better understand the hydrodynamics of this process and subsequently develop a reactor model for the bench unit. This can be combined with a kinetic model to aid in process scale-up.

The second case shows how a technology improvement was evaluated for the design of the hot high-pressure separator. The vessel is directly downstream of the H-Oil reactors and operates at essentially reactor conditions with a relatively short residence time to avoid possible coking. The processing of heavy feedstocks outside of the design feed rate range can create problems on the industrial unit due to the high viscosity of the fluid, which induces a poor liquid/gas separation at the outlet of the reactor. A new hot high-pressure separator design, based on R&D studies, has been proposed to improve this separation avoiding excessive liquid carry-over and gas carry-under. The development study was conducted using cold mockup facilities and evaluated at representative operating conditions. Several different separator internals, based on the use of centrifugal force for the separation, were developed and evaluated using a relative efficiency index.

The development of these two methodologies applied to three-phase reactors involving ebullated-bed technology will be described in this paper, but first we shall describe the ebullated reactor system.

1 BACKGROUND ON THE H-OIL PROCESS

Typical operating conditions for the H-Oil process are shown in Table 1. It is a high-pressure, high-temperature process. The operating pressure is relatively high to insure a sufficient reactor outlet hydrogen partial pressure, resulting in good hydrogenation and stable operation.

TABLE 1

H-Oil process operating conditions

Temperature (°C)	410-440
Total pressure (bar)	100-200
Catalyst Space Velocity (h^{-1})	0.25-1.5
Catalyst Replacement Rate (CRR) (kg/ton feed)	0.3-2.5
Single Train Throughput (bpsd, demonstrated)	up to 34 000

The reactor design allows for catalyst replacement and a rate of 1.0 kg of catalyst per ton of feed is typically used. For heavy crude oils, the Catalyst Replacement Rate (CRR) is adjusted to maintain catalytic activity and an acceptable level of impurities (Ni + V) on the catalyst. Commercial H-Oil plants have been designed and operated with a feedstock throughput of up to 34 000 bpsd in a single train. With the use of even larger H-Oil reactors, throughputs of over 40 000 bpsd have been considered. Most commercial H-Oil process applications operate in the 50-70-vol% residue conversion range with a desulfurization level of 70-85 wt%.

1.1 Description of the Ebullated-Bed Reactor

A schematic of the ebullated-bed reactor is shown in Figure 1. It is a fluidized-bed three-phase system with an excellent continuous mixing of liquid and catalyst particles. The inherent advantages of a good back-mixed bed are excellent temperature control and since bed plugging and channeling are eliminated, low and constant pressure drops over several years of continuous operation. Therefore, ebullated-bed reactors have the unique characteristic of stirred reactor type operation with a fluidized catalyst. This results in the ability to handle exothermic reactions, solid-containing feedstock and a flexible operation while changing feedstocks or operating objectives.

The catalyst used for the ebullated bed is typically a 0.8-mm diameter extrudate with nickel-molybdenum active metals. The catalyst used is held in a fluidized state through the upward lift of liquid reactants (feed oil plus recycle) and gas (hydrogen feed and recycle) which enter in the reactor plenum and are distributed across the bed through a

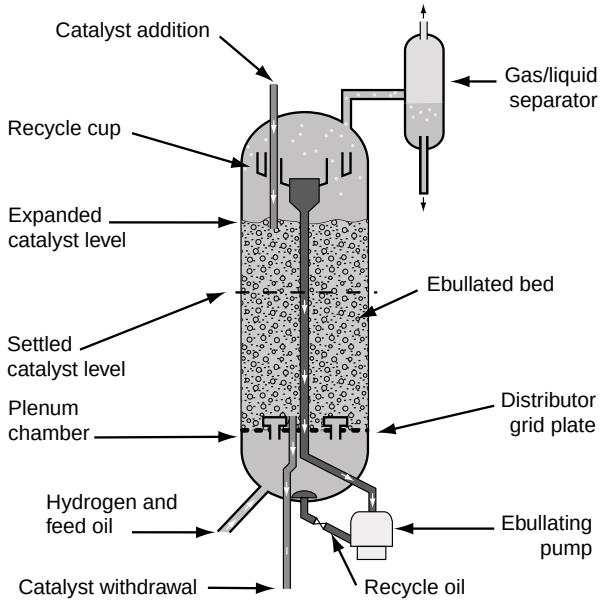


Figure 1

Schematic representation of the H-Oil reactor.

distributor and grid plate. The height of the ebullated catalyst bed is controlled by the rate of liquid recycle flow. This liquid rate is adjusted by varying the speed of the ebullating pump *(i.e.*, a canned centrifugal pump) which controls the flow of ebullating liquid obtained from the internal vapor/liquid separator inside the reactor.

Operation in the ebullated mode results in low reactor pressure drop, and a back-mixed and nearly isothermal bed. Fresh catalyst can be added and spent equilibrium catalyst withdrawn to control the level of catalyst activity in the reactor (*i.e.*, desulfurization). The capability of the daily addition of a small quantity of catalyst is a key feature of the ebullated-bed reactor and results in constant product quality over long time periods. To adjust operation for different feedstocks or levels of desired performance, the type of catalyst used can also be changed without shutting down the reactor.

The run length of an ebullated bed is typically determined by other factors such as the inspection schedule of an entire processing facility. Because of this advantage, ebullated beds are well suited for applications requiring a long, uninterrupted run length such as for pretreatment of FCCU (Fluid Catalytic Cracking Unit) feedstocks (typically 3 years).

1.2 H-Oil Technology

H-Oil reactors have taken advantage of some of the new metallurgy and expanded manufacturing capabilities of reactor fabricators resulting in larger reactors and therefore higher throughputs in a single train plant. Enhancements to the reactor internals have resulted in a more efficient reactor system and the capability to process more feed in a single reactor train. These enhancements include an improved internal vapor-liquid separator that allows operation at higher gas rates while providing a nearly vapor-free suction to the ebullating pump and a reduction in the amount of reactor gas holdup. Since there is excess gas holdup in the H-Oil reactor, a reduction in gas holdup will increase liquid holdup and result in more efficient kinetics. Due to these process improvements and the use of large H-Oil reactors, the investment cost for an H-Oil unit has been minimized.

Consequently, it was important to correctly estimate the liquid gas holdup in the reactor to maximize performance and reduce the investment cost. The Residence Tracer Distribution study is one method that could answer this problem.

The primary operating cost for the H-Oil process results from hydrogen and catalyst consumption. Although the chemical hydrogen consumption is high relative to other less severe processes, the loss of hydrogen through the process must be minimized. Optimization of the process scheme and the design of internals utilized in different vessels are the key parameters. Recent development has been completed for the design of the hot high-pressure separator with the objective to reduce the loss of hydrogen through the low-pressure section. The geometry of the vessel has been investigated and optimized for the treatment of heavy crude oil.

2 RTD STUDY

2.1 Objectives

For the development of ebullated-bed process, a new bench unit has been constructed and commissioned. This unit operates at commercial operating conditions (temperature and pressure) and closely simulates the commercial yields and product qualities. The qualification of the reactor is an essential point of the methodology of scale-up of data obtained on this bench unit to the commercial unit. The RTD tool has been used for the characterization of the reactor model of the H-Oil process on the bench unit with the objective to set correctly the scale-up procedure. The reactor model has a great importance for the calculation of performance and namely the conversion of the residue (*i.e.*, perfect stirred reactor, perfect plug flow or series of continuous tanks). The results of this RTD study can then be compared to a CSTR (Continuous Stirred Tank Reactor). Also, the conversion of heavy product is kinetic-enhanced if the liquid holdup at the operating conditions is maximized in the reactor. Therefore, the objective is to trace the liquid phase and estimate the liquid holdup repartition in the reactor *versus* different operating conditions such as the recycle flow of liquid and the feed hydrogen flow.

2.2 Experimental

Argon 41 was selected using many criteria: interaction with catalyst, detection, solubility in liquid phase, etc. The injection of this radiotracer was performed in the hydrogen make-up line which is mixed with the feed coming from discharge feed pump. Figure 2 shows a schematic representation of the bench unit in the RTD configuration. A first detector was positioned on the line going to the reactor to measure the inlet pulse. Several detectors were located along the length of the reactor for the estimation of liquid holdup in the reactor. The last detectors were intended to evaluate the flow at the reactor outlet and in the recycle (ebullating) line.

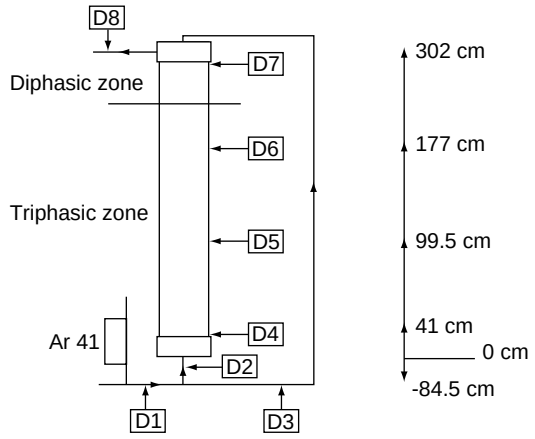


Figure 2

Schematic representation of the bench unit.

The configuration of the bench unit is equivalent to the commercial unit. A recycle cup is installed in the reactor to separate liquid and gas before the suction of the recycle pump. The liquid coming from the discharge pump is re-injected at the reactor bottom for the ebullation of the bed. An expansion of bed of 30-40% over the settled catalyst bed was performed.

A gas-liquid equilibrium calculation shows that argon 41 could be either in the gas or liquid phase depending on the recycle flow in the reactor. Figure 3 shows the relationship of the solubility of argon in liquid (v/v%) *versus* the liquid recycle flow applied on the bench unit. This curve has been established nearly identically using two different thermodynamic laws.

The argon 41 is completely dissolved in liquid phase if the flow rate is above 18 l/h. The range of variation of liquid recycle flow depends on the viscosity of the charge at operating conditions; the flow rate could vary from 10 to 50 l/h to maintain the catalyst expansion.

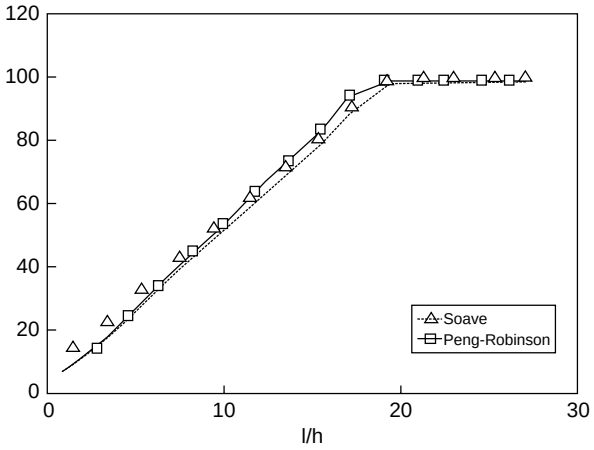


Figure 3

Solubility of argon at operating conditions.

2.3 Methodology of Radiotracer Study of the Ebullated-Bed Reactor

Argon is injected as one-shot tracer input. The detector D1 will measure the form of the tracer peak at the inlet. The linear velocity between two detectors is determined using the ratio of the distance between two detectors and the mean residence time difference between the two detectors.

The knowledge of the mean linear velocity leads to the value of the liquid holdup in this portion of the reactor by dividing this value by the superficial liquid velocity:

$$\varepsilon_l = \frac{v_{sl}}{v_l}$$

with:

ε_l liquid holdup

v_{sl} superficial liquid velocity

v_l linear liquid velocity

2.4 Results on the Liquid Holdup

Figure 4a shows that the liquid holdup increases slightly along the reactor axis for a given set of operating conditions and a fixed recycle flow of liquid. This observation confirms the fact that the solid density is higher at the bottom of the reactor and decreases along the reactor axis. At the top of the reactor there is no catalyst and the reactor hydrodynamics is closer to a bubble column, therefore the liquid holdup is maximum.

Figure 4b shows the evolution of the liquid holdup in the reactor *versus* the hydrogen flow rate. The liquid holdup decreases when the hydrogen flow rate increases. This phenomenon shows the impact of hydrogen flow on the performance of the reactor. This parameter has to be

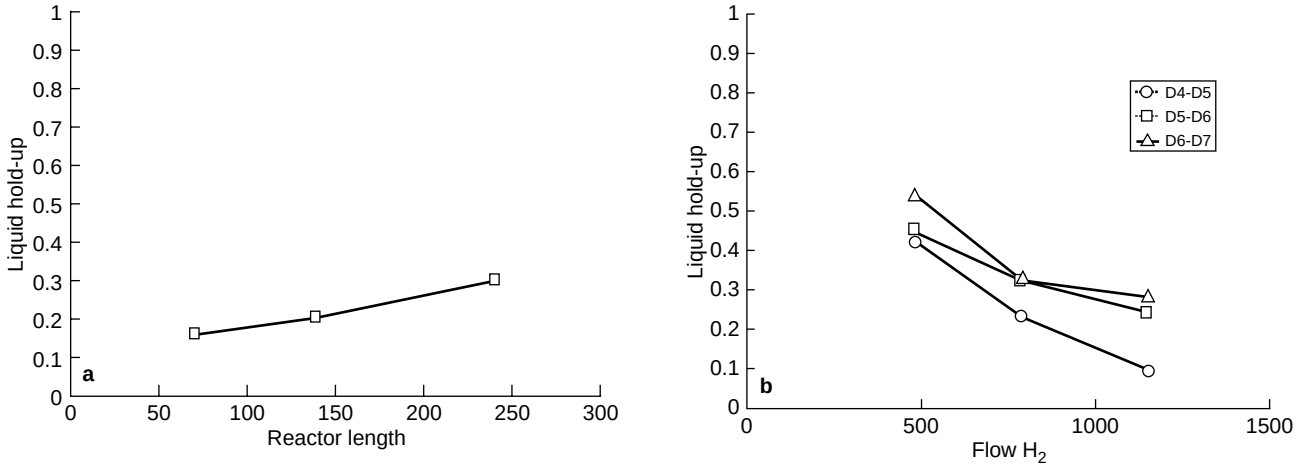


Figure 4

Evolution of liquid holdup *versus* operating conditions.

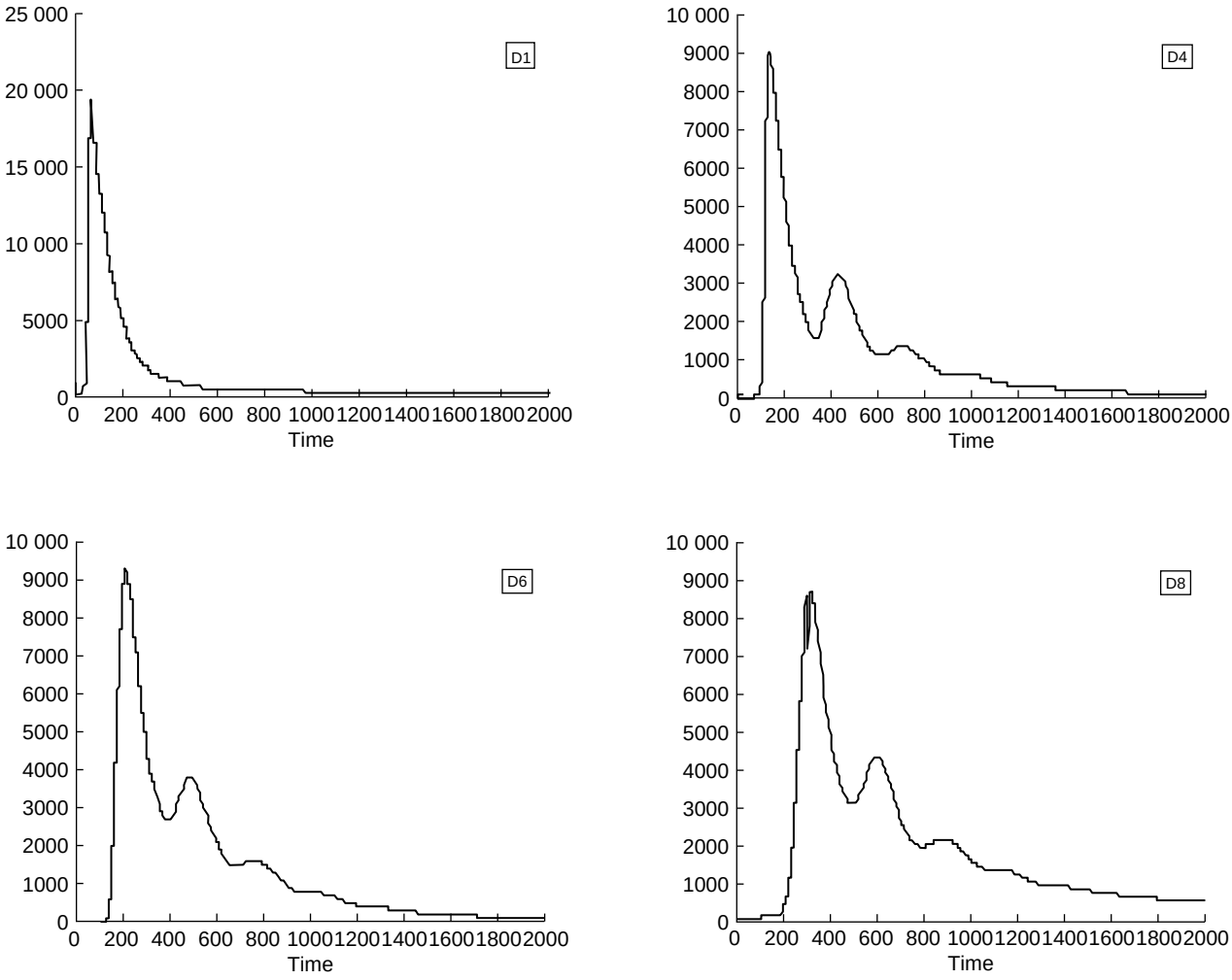


Figure 5

Typical response curves obtained after one-shot tracer.

optimized to minimize excess gas holdup and to maximize the conversion. The lower limit of this hydrogen flow rate is a function of the minimum hydrogen partial pressure required at the reactor outlet.

Figure 5 shows the response of four detectors (D1, D4, D6 and D8) to a pulse of argon 41 for a selected operating condition. The detector D1 shows the inlet pulse, the form here was quite similar to a triangle with a significant tail. The shape of the inlet signal must be taken into account for the outlet signal modeling. The first peak recorded by detector D4 indicates the progression of the pulse along the reactor. The second and third peaks were due to the argon re-injected *via* the recycle line. This point confirms the presence of argon in the liquid phase. These multiple peaks are typical signals coming from a recirculating system (Levenspiel, 1972). The decrease of the intensity of the successive peaks is due to the loss of the tracer at the outlet of the reactor as we are in open system.

Reactor $D_{ax}\cdot\frac{\partial^2 C}{\partial z^2} - u\cdot\frac{\partial C}{\partial z} = \frac{\partial C}{\partial t} \Leftrightarrow \frac{1}{\text{Pe}}\cdot\frac{\partial^2 C}{\partial Z^2} - \frac{\partial C}{\partial Z} = \frac{\partial C}{\partial \theta}$

Recycle line $-u\cdot\frac{\partial C}{\partial z} = \frac{\partial C}{\partial t} \Leftrightarrow -\frac{\partial C}{\partial Z} = \frac{\partial C}{\partial \theta_r}$

$\text{Pe} = \frac{u\cdot L}{D_{ax}} \quad Z = \frac{z}{L} \quad \tau = \frac{L}{u} \quad \theta = \frac{t}{\tau} \quad \tau_r = \frac{L}{u_r} \quad \theta_r = \frac{t}{\tau_r}$

Recycle ratio $r = \frac{Q_2}{Q_1}$

$\text{Ce} = \frac{1}{1+r}\cdot\text{Co} + \frac{r}{1+r}\cdot\text{Cs}$

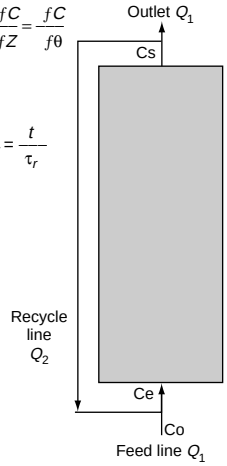


Figure 6

Equations for reactor modeling.

2.5 Modeling of Results

This recirculated system can be represented as an association of a dispersed plug flow model for the reactor itself and a perfect plug flow for the recycle line. We have modeled the bench reactor using these assumptions and the equations used are described in Figure 6. The first equation for the dispersed plug flow model takes an axial dispersion coefficient (D_{ax}) into account in the conventional plug flow equation. After simplification of these equations, the Peclet number, which is the ratio of convective term under dispersion coefficient, is the only unknown parameter which is determined by adjusting the model with our RTD results.

Figure 5 shows the results for the detector D6 at a low recycle flow rate (13 l/h). A Peclet of approximately 8 was estimated *(Fig. 7)* after adjustment of the model to the data. The Peclet number was determined based on the first peak representation. We have also plotted the exponential decay of an ideal stirred tank using the same residence time and made the superposition with our recirculating system. We can conclude that the response of our bench reactor is intermediate between a perfect CSTR and a perfect plug flow reactor.

The second and other peaks are not correctly represented by our model. In order to correct this point, we assume that during the separation of gas/liquid we have lost the argon in gas phase due to low recycle flow rate in the reactor. The calculated quantity of argon in the gas phase to fit correctly the experience *(Fig. 8)* is approximately 60 v/v% (gas phase). This molar fraction is more or less in agreement with the thermodynamic prediction (40 v/v% of argon in gas phase, see Figure 3). Using this molar fraction of 60%, the modified model response is presented in Figure 8 and shows a very good agreement between the experimental results and the

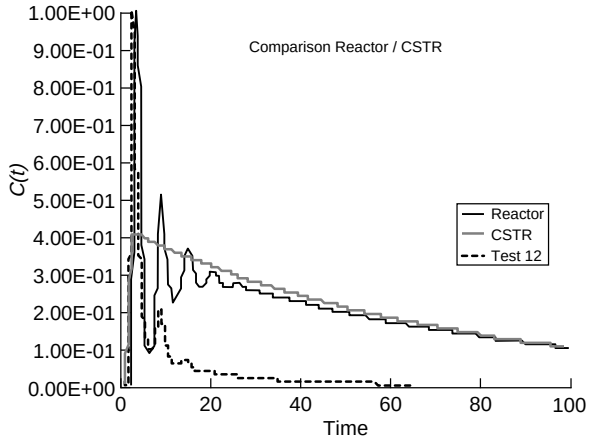


Figure 7

Modeling curve compared to experimental and perfect CSTR reactors.

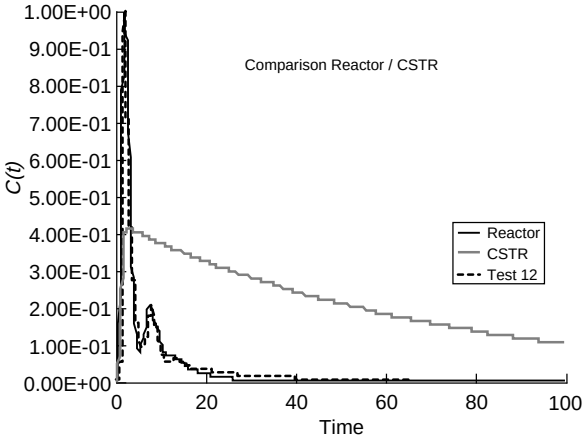


Figure 8

Integration of the vaporization of argon in the model reactor showed in Figure 7.

model. The dispersed plug flow model, which integrates gas/liquid separation for the prediction of argon in the recycle line, gives a perfect representation of the experimental curves (namely the successive multiple peaks of the experimental RTD curve).

2.6 Conclusions of the RTD Study

The radiotracer study is a useful method to determine the liquid holdup inside an ebullated-bed reactor at different operating conditions. This knowledge enables one to characterize the hydrodynamic behavior of the ebullated-bed reactor and to compare the system (reactor and recycle line) with a CSTR. The tests show that the bench unit catalytic zone is equivalent to a dispersed plug flow reactor associated to a Peclet number around 8.

However, a special attention must be paid to the tracer solubility and the recycle flow rate of the reactor. The knowledge of the bench unit hydrodynamics is useful to support the comparison of pilot plant data with industrial data and to scale-up pilot plant results.

3 IMPROVEMENT OF THE HIGH-PRESSURE GAS-LIQUID SEPARATOR TECHNOLOGY

3.1 Description of the Industrial Problem

The separation of liquid and gas at the outlet of the reactor can show liquid carry-over in the outlet gas stream. This problem can occur when the range of operating conditions is significantly outside the design. Consequently, as liquid level has to be decreased, some gas carry-under can occur in the outlet liquid flow inducing pressure variations in the reactor and hydrogen losses. The challenge of this R&D study was to improve the high-pressure separator technology to avoid liquid carry-over and gas carry-under problems. This will minimize operational problems under these specific conditions and therefore minimize the operating costs of the unit.

The existing separator is typically a high-pressure vessel with a gas-liquid flow inlet through a 45°-inclined pipe at the top of the vessel. An impacting plate in front of the two-phase flow ends this pipe. The gas leaves the vessel through a pipe at the top on the opposite side from the gas-liquid flow inlet. The liquid flows out of the vessel through a pipe at the bottom. During the H-Oil operation, the inlet liquid superficial velocity ranges from 0.4 to 0.8 m/s and the inlet gas superficial velocity ranges from 4 to 8 m/s. The inlet volumetric fraction is approximately 10 vol%.

To improve the separation performance it was decided to build a cold mockup in order to test and compare the gas-liquid separating efficiency of different separating systems. The first step was to develop a specific methodology for the scale-down and the design of the cold mockup.

3.2 Scale-Down and Mockup Design

To characterize the two-phase flow configuration at the vessel inlet, the industrial flow conditions were plotted on two classical two-phase flow regime maps. Those of Baker (1954) for horizontal flow and those of Golan and Sterning (1969) for vertical downward flow were used. Figure 9 shows these two flow regime maps.

Industrial operating conditions, defined by the dark squares, correspond to the *dispersed annular flow* in horizontal flow and to the *annular mist* or *annular flow* in vertical downward flow *(Fig. 9)*. It can be concluded that the inlet two-phase flow is a dispersed droplet flow where the gas phase is the continuous phase. Therefore, the liquid flows as dispersed droplets in the pipe core and through a liquid film at the wall. Due to the lower pressure in our test conditions, it is not possible to have the same flow regime in the cold mockup at the same flow velocities. Consequently, to be representative of the flow regime in the test conditions, a spray ejector was built to create an inlet spray flow.

To study equivalent physical separating phenomena on the cold mockup, some design criteria have to be followed. We can mainly consider that the two-phase flow separation occurs at two different levels:

– at the impacting plate outlet, the liquid is separated by centrifugal force;
– inside the vessel, the liquid is separated by gravitational force.

To be representative of the force balance corresponding to the centrifugal separation, the following ratio must be constant between the mockup case and the industrial case:

$$\frac{\text{Centrifugal force}}{\text{Drag force}} = \frac{(\rho_L - \rho_G) d_p^2 V_{in}}{9 \mu_G L_0} = \text{cste} \qquad (1)$$

To be representative of the force balance corresponding to the gravitational separation, the following ratio must be conserved between the test and industrial conditions:

$$\frac{\text{Buoyancy force}}{\text{Drag force}} = \frac{4}{3} \frac{(\rho_L - \rho_G) g d_p}{C_d(\text{Re}_p) \rho_G (V_p - V_G)^2} = \text{cste} \qquad (2)$$

Equations (1) and (2) were therefore used to scale down the separator. One challenge was to create a liquid spray with droplet granulometry representative of industrial conditions. To address this point, the liquid droplet cut diameter (Cooper, 1982) of 150 µm considered in industrial case will be conserved in the mockup case. The gas velocity was chosen to keep the two ratios (1) and (2) constant taking into account the phase densities at atmospheric pressure.

The fluid phases used in the mockup were water and air. The geometry scale of the mockup was that of the industrial separator and the mockup walls were transparent to allow flow visualization. Figure 10 gives a schematic representation of the mockup.

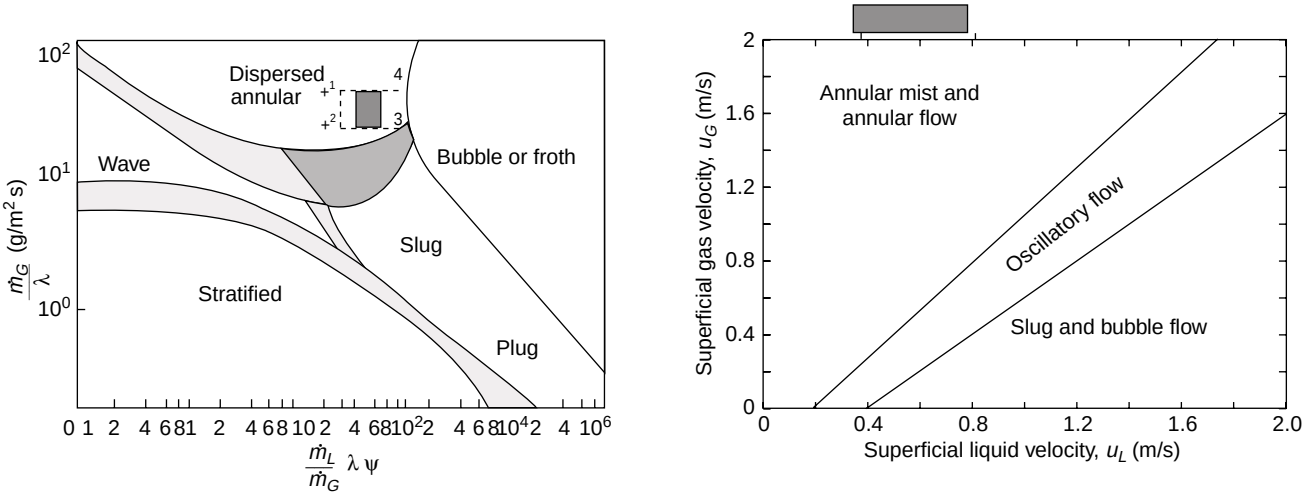


Figure 9

Industrial inlet conditions plotted on two-phase flow regime maps.

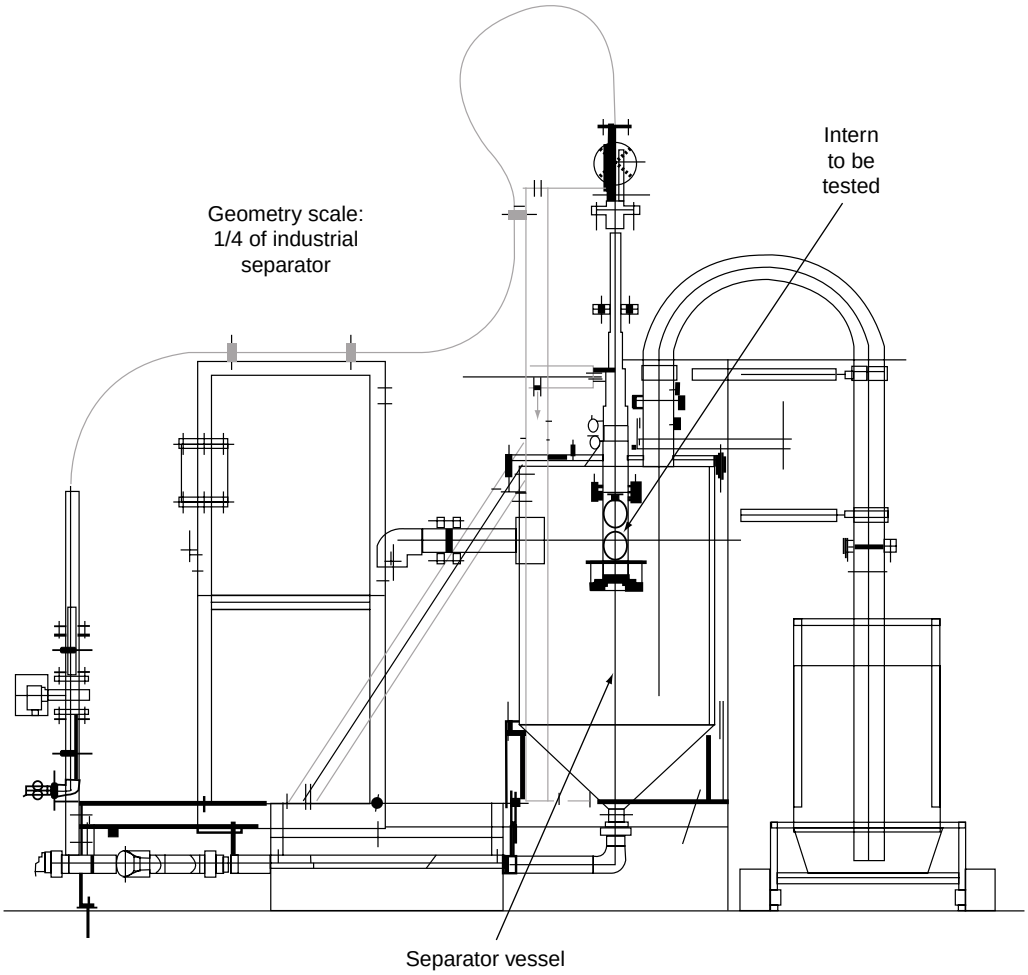


Figure 10

Schematic representation of the cold mockup.

3.3 Test of Different Separating Systems

To improve the existing gas-liquid separator, several separating systems were tested and compared to the existing impacting plate. Mainly, four different designs have been tested:

- an impacting plate (existing gas-liquid separator);
- a pipe ended with two opposite bends that create a tangentially fluid outlet after centrifugal separation (helix type separator No. 1). The objective of this geometry is to induce a swirl flow at the pipe outlet in order to create centrifugal effect on the liquid and gas;
- a same design as the precedent one with a helix inserted in the pipe before the gas-liquid outlet (helix type separator No. 2). The added helix was intended to increase the swirl effect;
- a cyclone. The geometry of this cyclone is quite classical with a tangent inlet pipe for the gas-liquid flow inlet, the gas outlet at the cyclone top following the cyclone axis and the liquid outlet at the cyclone bottom following the cyclone axis.

Table 2 shows the different separation designs tested. The separation efficiency is expressed relatively to the liquid fraction carried out by the gas phase when no separating device is used (liquid fraction corresponding to droplet diameters lower than 150 µm). This liquid fraction, collected at the gas outlet when there is no separating intern at the separator inlet, is called the *reference collected liquid flow rate*. The relative efficiency η is therefore expressed by the following equation:

$$\eta = 1 - \frac{\text{Liquid collected flow rate at gas outlet with a separating system}}{\text{Reference collected liquid flow rate}}$$

Figure 11 presents the results for relative efficiency η obtained with the different separation internals as a function of the G/L ratio (gas flow rate over liquid flow rate).

As shown, the helix type separator No. 1 significantly improves the separation efficiency of the existing system from approximately 40 to 80%. The addition of a helix in the helix type separator No. 2 allows an increase of the gas-liquid separation efficiency from 80 to 90%.

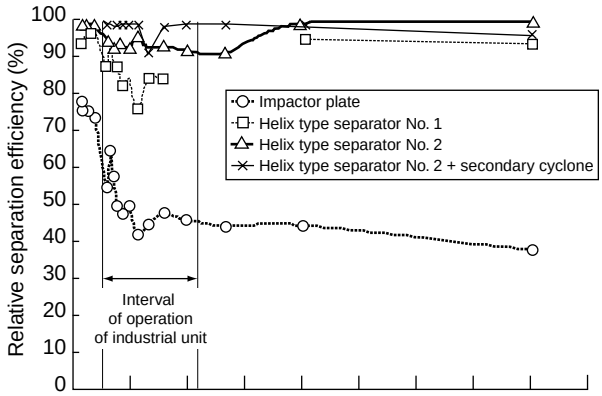
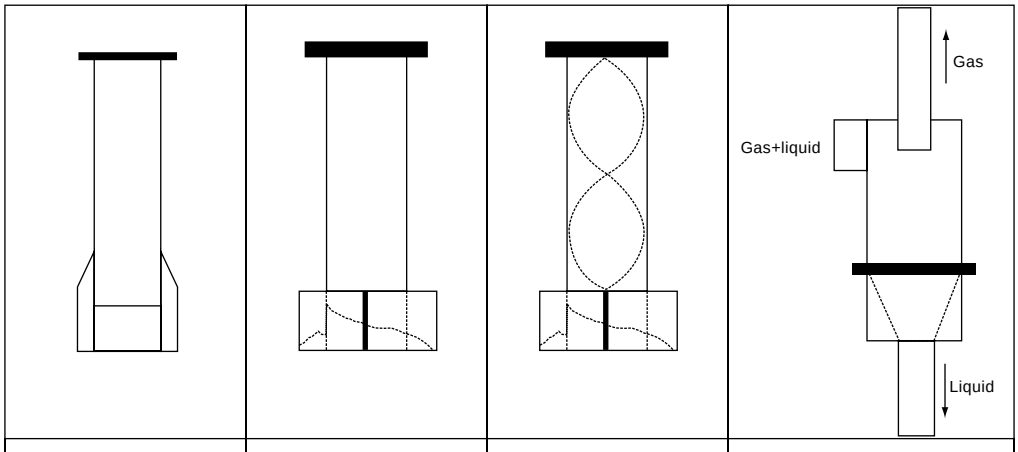


Figure 11

Relative separating efficiency obtained with the different separating designs.

TABLE 2

Geometry of the different separating designs tested



a Impacting plate (existing separator)	**b** Helix type separator No. 1	**c** Helix type separator No. 2	**d** Cyclone

The first results obtained with the cyclone show a very efficient gas-liquid separation (near 100%) but liquid fouling occurs at the liquid outlet when the liquid fraction in the inlet gas-liquid flow is higher than approximately 10%. To avoid liquid fouling, the cyclone geometry was modified with a larger liquid outlet. In this new geometry, the liquid outlet diameter was increased to the cyclone body diameter. Also, four baffles were added to break any vortex formation in the liquid outlet and to force the gas vortex inversion in the upper part. To reduce the liquid fraction at the cyclone inlet and considering the good results obtained with the helix type separators, this cyclone was then used as a secondary separating system at the gas outlet. This cyclone was downstream of the helix type separator, which was used as the primary separation system at the gas-liquid inlet. This combination gave very high separation efficiency, near 100% for a large range of G/L ratios.

3.4 Extrapolation to Industrial Case

The helix type separator allows an increase of the separating efficiency up to 80 and 90% to be compared with the existing impacting plate efficiency of 40%. Those configurations were implemented on existing industrial units and are particularly suitable for revamps with spacing and geometry constraints.

For new design of unit, a two-stage separating system may be proposed and would result in a separation efficiency of 100%. This is comprised of:

– helix type separator at the G/L inlet (first stage);
– cyclone at the gas outlet (second stage).

The separator technology of H-Oil was improved to make easier the transition period as startup and to increase the flexibility of operation on heavy crude oils (feed rate and temperature adjustments, etc.).

CONCLUSION

The ebullated-bed reactor, although invented over 30 years ago, is now a corner-stone reactor technology for the heavy oil upgrading requirements of the new century. The capability of processing heavier feedstocks with the flexibility of adjustment in operating conditions to meet changing market demands are the key features of the ebullated-bed reactor technologies which can be extended to other applications (*i.e.*, T-Star Process, SDA: see Colyar and Wisdom, 1992, 1994, 1997; Kressmann *et al.*, 1998).

The scale-up of the process can be achieved through pilot plant operation and process modeling. It is very important to ensure the scale-up procedure and to characterize the pilot plant operation. The RTD study discussed in this paper was useful to address those points.

In this multiphase flow process characterized by severe operating conditions, reliable and flexible technologies must be provided to control the hydrodynamics of the flow phases. Proper scale-down in test conditions is required to evaluate relevant phenomena and develop appropriate solutions and designs.

The process evolution greatly depends on the reduction of operating cost and investment. Technology and development will be the key of innovation for this process. These improvements need to be responsive to the market and the methodology utilized must be technically sound and readily applicable to the industrial case.

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