COUNTERFLOW REACTOR (CFR) FOR COPROCESSING OF COAL AND PETROLEUM FEEDSTOCKS

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ABSTRACT

CED/GfK evaluated different processes for the simultaneous upgrading of coal and heavy oil/bitumen during the past five years. The development work on the BSU (I.D. 1.2") and PDU (I.D. 3.5") scale led to a new Counterflow Reactor concept characterized by the counterflow of the liquid or slurry feed and the hydrogen recycle gas stream.

Among others, this counterflow reactor (CFR) has the following advantages over the co-current reactor:

1. Optimum internal recovery of the exothermic heat of reaction and thus less severe feed preheating;
2. No concern of solid settling as liquids and solids are removed from the bottom of the reactor;
3. Lower recycle gas rates determined by reaction kinetics only; and
4. Favorable profile of the hydrogen partial vapor pressure.

During the past years, over 10,000 hours of tests have been performed successfully with different heavy oils and heavy oil/coal slurry feeds with distillable oil yields of up to 85 wt% for heavy oil upgrading and up to 74 wt% for coprocessing. The results have been used as a basis for a technical and economical screening study for a commercial size upgrader in Canada. In the paper, results of the test work and the screening study will be presented.

INTRODUCTION

In 1984, Canadian Energy Developments Inc. (CED) had an extensive feasibility study performed to evaluate upgrading options for the vast energy resource (heavy oil and coal) of Alberta. Upgrading options considered were: heavy oil upgrading, coal liquefaction and coprocessing. At a certain price for heavy oil and at the same production capacity of synthetic crude oil, the feasibility study concluded that 1) coprocessing is economically slightly more attractive than heavy oil upgrading, 2) a heavy oil upgrading facility requires approximately 10% less capital than a coprocessing facility, and 3) coal liquefaction has the lowest return on investment and requires about 75% more capital to be built. Based on these conclusions the feasibility study recommended that for the overall development of the energy resources of Alberta, coprocessing would be the more favored option for a commercial facility.

Up until 1984, process development for coprocessing had not reached a point for commercialization. CED therefore decided to embark on a R & D program to develop its own coprocessing technology. During the past four years, CED performed extensive experimental work on both the Bench Scale Unit (BSU) and the Process Development Unit (PDU) scale and the following coprocessing technologies were evaluated:

1) PYROSOL Technology - i.e. hydrogenation plus coking process,
2) Co-Current Upflow Bubble Reactor Technology - as a one or two stage hydrogenation technology, and
3) Counterflow Reactor (CFR) Technology.

Based on the experimental results and the operation of the PDU for these three technologies, CED has selected the CFR technology for scale up to a commercial coprocessing facility.

COUNTERFLOW REACTOR (CFR) TECHNOLOGY

Process Description and Experimental Results

The CFR technology is a single stage hydrogenation process operating at conditions which promote coal solubilization, solubilized coal and heavy oil hydrogenation and hydrocracking in a single reactor. As the name implies, the CFR features a downward flowing coal/heavy oil slurry in contact with a counter-current make-up plus recycle hydrogen stream. CED's German partner, Gesellschaft für Kohleverflüssigung (GfK) mbH has operated a continuous PDU (8 kg/hr coal/heavy oil feed slurry) using the CFR technology for more than 10,000 hours since the second half of 1987. Individual runs lasted for up to about 700 to 800 hours.

In the CFR technology (Figure 1), the coal and heavy oil are slurried, pumped to reactor pressure and preheated to 150-250°C prior to being charged to the top of the reactor. Recycle and make-up hydrogen is preheated to 400-450°C and injected into the bottom of the reactor. The exothermic heat of reaction is used to raise the incoming feed slurry to reaction temperature. Solubilization of the coal occurs in the top portion of the reactor at a temperature of approximately 400°C, and hydrogenation/hydrocracking takes place in the main reactor zone at temperatures of 445-455°C. Reactor pressure is 18-20 MPa (2,600-2,900 psig).

Hydrogenation products are vaporized as they are formed and are withdrawn from the top of reactor, cooled, condensed and separated in a cold separator. The condensed liquid product, a full range distillate hydrocarbon product is transferred to the secondary upgrading. The hydrogen rich gas stream is scrubbed and recycled.

Unconverted heavy oil/solubilized coal and unreacted coal flow downward in the reactor, counter-current to the upward flowing hydrogen to promote solubilization of the coal and hydrogenation of the coal and heavy oil. The highest hydrogen partial vapor pressure exists at the bottom zone of the reactor where needed to promote conversion of coal and heavy oil fractions that are the most resistant to hydrogenation/hydrocracking. A slurry stream containing unconverted residuum and unreacted coal and ash is withdrawn from the bottom of the reactor, depressurized in the let-down system and charged to a vacuum flash unit.

When processing typical Cold Lake vacuum residue and Alberta subbituminous coal (Table 1) total distillable oil yields of 70-74 wt% are consistently achieved (Table 2) with a hydrogen consumption of 2.9 wt%. The distillate product (Table 3) is a full range product containing, on average, 30% naphtha, 40% middle distillate and about 30% VGO. (Typical operating conditions are shown in Table 4).

Advantages of the CFR

Most reactor technologies produce about the same total distillable oil yield and the same product distribution. The CFR, however, has significant advantages with regard to its operation and reliability which are the direct consequence of the counterflow concept used in the process.

1. No Settling Problem

Since the unconverted feed material, ash and other solid particles are allowed to settle naturally in the reactor, the settling problem associated with co-current reactors does not occur in the CFR. High superficial gas velocities typically in excess of 6 cm/sec. in co-current flow reactors are not required in the CFR as only vaporized and gaseous products leave the reactor overhead and "solids" are withdrawn at the bottom together with the liquid hydrocarbons as a slurry.

2. Low Superficial Gas Velocity

In the CFR technology, superficial gas rates are determined by reaction kinetics only and are not defined by the requirement to keep "solids" in suspension and to carry them overhead in the reactor. All PDU runs with the CFR were performed with superficial gas velocities of 0.5 to 1.9 cm/sec. Maximum duration was about 800 hours of continuous operation.

3. Low Scale-Up Risk

For a commercial size CFR the superficial gas velocities are estimated at around 3cm/sec., i.e. a commercial CFR will operate in the bubble flow regime. Since the PDU also operates in the bubble flow regime the scale up from the PDU to commercial size reactors does not pose a major problem as the reactor scale up parameters are essentially known.

4. Recovery of Exothermic Heat of Reaction

As the vaporized reaction products and hydrogen gas stream rises through the downward flowing feed slurry the exothermic heat of reaction is recovered internally within the CFR. As a result, the preheat duty for the feed slurry is reduced and lower feed slurry preheat temperatures are possible.

5. No External Hot Separator

Because of the counterflow concept, the CFR combines the reactor and the hot separator. An external hot separator is not required to separate the slurry from the distillable oil.

6. Capital and Operating Costs

With the above "technical" advantages, the capital and operating costs for a commercial coprocessing facility will be lower when CFR technology is used as compared to co-current flow reactor technology. For example, as the CFR technology operates at lower superficial gas velocities, recycle gas rates will be reduced significantly which decreases the equipment size for the recycle gas system. Because the slurry preheating requirements are lower, operating costs are decreased as fuel consumption is decreased.

Feasibility Study for Commercial Coprocessing Facility

On behalf of CED, Kilborn Inc. performed a technical and economic feasibility study for a grass-roots commercial coprocessing facility for a suitable location in Alberta. The facility (Figure 2) was designed to process Cold Lake heavy oil and Vesta Mine subbituminous coal and to produce 4,450 cubic metres per day (28,000 BPD) of synthetic crude oil (Table 5).

Capital costs, product revenue and operating cost estimates (Table 6) were prepared and formed the basis for a financial and sensitivity analysis to evaluate the economic potential of a commercial coprocessing facility.

Total Estimated Capital Costs of $671,100K (1989) is composed of:

Direct costs were estimated from actual cost data wherever possible. For licenced processes (secondary upgrading for example) information from potential licensors was used.

Indirect costs (home office engineering construction management, construction indirects, special winterization costs) were estimated as percent of total direct cost. Project contingency was applied at 20% of total direct costs plus home office engineering, construction management and construction indirect costs.

Other costs include allowances for initial catalyst charge, initial chemicals inventory and paid up licence and royalty fees.

Owner's costs include allowances for owner's engineering, project management, environmental application costs, permit costs, spare parts inventory and start-up costs.

Total estimated annual revenue of $206,720K per year (1989) is based on 320 operating days per year. Unit product prices were provided by the Alberta Energy Department, Government of Alberta. It should be pointed out that about $6.8M per year of revenue is created from 22MW excess electricity generated in the commercial facility.

Total estimated operating cost of $129,670K per year (1989) includes the costs of feedstocks, operating and maintenance labor, maintenance parts, utilities, catalysts and chemicals, local taxes and insurance. The unit prices for the feedstocks are based on forecasts from the Alberta Energy Department. The heavy oil price excludes the cost of diluent as the diluent is recovered and returned to the heavy oil production field for use as additional diluent. Plant labor and overhead costs are based on an estimated operating supervision, maintenance and plant overhead staff of 270 personnel. In addition, a contract maintenance labor allowance has been applied for major process unit turn around equivalent to 25 maintenance personnel over the entire year or 150 personnel for two month. A pipeline tariff of $2.00 per cubic metre of heavy oil feedstock, recovered diluent and synthetic crude oil product has been allowed to cover the construction and operating costs of heavy oil diluent and production pipelines amortized over a 20 year period.

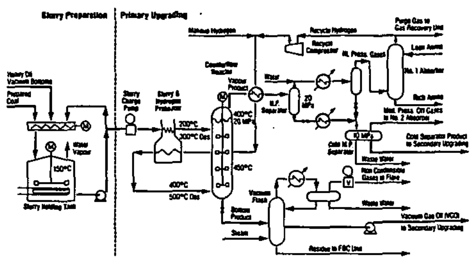
Financial and Sensitivity Analysis

A financial and sensitivity analysis was prepared on the basis of a 32 year project life including a 7 year demonstration, engineering and construction period plus a 25 year operating period. The financial analysis uses a cash flow generator model for before and after tax calculations. Cash flow simulations were used to calculate discounted cash flow return on investment/equity (DCF/ROE) for 100% equity or a given debt/equity ratio. The sensitivity analysis considered variations in the type of financing, in capital cost, in price forecasts, in the oil yield and in interest rates. The result of this sensitivity analysis is shown in Figure 3. For each of the financing options (100% equity or 60/40 debt/equity) the upper line refers to a constant percent price differential and the lower line refers to a constant dollar price differential between heavy oil and synthetic crude oil. In any case, the after tax DCF/ROE indicate that a commercial coprocessing facility is economically attractive with normal debt/equity financing methods at synthetic crude oil and bitumen price differentials that are only marginally above current differentials. Furthermore, rates of return of 20 to 22% are realized at current differentials, with project financing methods based on cost and revenue sharing and fiscal structure similar to those recently applied to major energy projects in Canada.

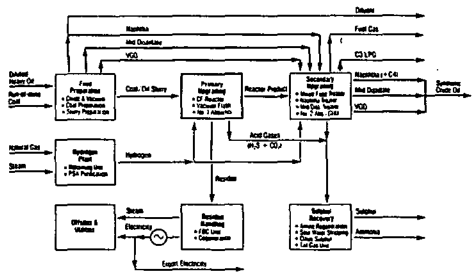
CONCLUSION

The Counterflow Reactor (CFR) technology for the simultaneous upgrading of coal and petroleum feedstocks has been successfully demonstrated at the PDU scale. During 10,000 operating hours, distillable oil yields and product distributions are obtained which are similar to those from a conventional co-current upflow bubble column. The counterflow regime of the CFR, however, brings advantages in operation and reliability which ultimately translates into lower capital and operating costs for a commercial facility. Superficial gas velocities which are only half or possibly one third of those in the co-current mode and the recovery of the exothermic heat of reaction inside the CFR are the main unique features of the CFR technology.

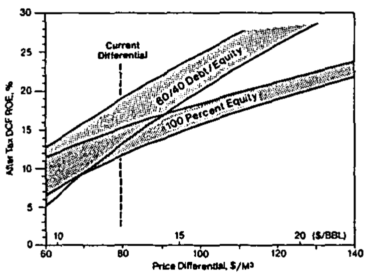
A technical and economic feasibility study suggests that a commercial coprocessing facility with the CFR technology yields attractive return on investments at present price differentials. DCF-ROE of 20-22% can be realized with proper structuring of the financial terms.



Canadian Energy — Simplified Process Flow Diagram - Primary Upgrading Area — Figure 1



Canadian Energy — Simplified Block Flow Diagram — Figure 2



Canadian Energy — Effect of Price Differential on Rate of Return — Figure 3

Heavy Oil - Cold Lake Vacuum Residuum		Elemental Analysis WT% (DAF)	
- Distillation:	IBP 370°C		
	5 WT% 423°C	C	83.57
	10 WT% 443°C		
	20 WT% 471°C	H	10.20
	FBP 480°C		
	(23.6 wt%)	N	0.55
- Density	1.026 G/mL	S	5.30
- Asphaltenes	13.63 wt%	O (By Diff)	0.38
- Viscosity 80°C	80 Poise		
120°C	2.5 Poise		
Coal - Alberta Subbituminous Battle River Coal Field Vesta Coal Mine		C	72.25
- Moisture	4.4 WT%	H	5.00
- Ash	13.8 WT% Dry Basis	N	1.36
- Volatiles	43.9 WT% (DAF)	S	0.62
		O	20.77

Canadian Energy — Feedstock Properties Table 1

	Heavy Oil Hydrogenation	Coal/Heavy Oil Coprocessing
Feeds, WT%		
Vac. Resid.	96.1	67.3
Coal (DAF)	3.9	32.7
H_2 Consumption	1.9	2.9
Products, WT%		
Oil Yield <480°C	83.5	73.7
C_1-C_4 Gas	7.6	10.2
Prod. Water	0.4	4.0
CO, CO_2, H_2S	3.8	4.1
Bitumen >480°C	6.4	9.4
Unconverted Coal	0.2	1.5
WT% Conversion (+480°C)	91.5	87.0

Canadian Energy — Overall Material Balance CFR-PDU Table 2

	Heavy Oil Hydrogenation	Coal/Heavy Oil Coprocessing
Density, KG/Litre	0.898	0.894
Elemental Analysis, WT%		
Carbon	85.81	84.8
Hydrogen	11.64	11.4
Nitrogen	0.40	0.58
Sulphur	1.97	1.47
Oxygen (Diff)	0.18	1.72
C/H	7.37	7.44
Liquid Product Yield (% of oil yield)		
C_5 - 200°C	20.0	30.0
200 - 350°C	50.0	40.0
>350°C	30.0	30.0
C_5 - 480°C	100.0	100.0

Canadian Energy — Hydrogenation Product Quality CFR-PDU Table 3

	Heavy Oil Hydrogenation	Coal/Heavy Oil Coprocessing
Pressure, Bars	200.0	190.0
Temperature, °C		
Top	450.0	451.0
Middle	454.0	457.0
Bottom	446.0	450.0
Hourly Space Velocity KG/HR/LITRE	0.76	0.84
Hydrogen Feed, NM^3/KG	2.9	2.77
Superf. Gas Velocity cm/sec.	1.4	1.7
Throughput, KG/HR	7.2	8.6
Feed - Vac Resid, WT%	96.1	67.3
- Coal (DAF), WT%	3.9	32.7
- Catalyst	None	None

Canadian Energy — Typical Operating Conditions CFR-PDU Table 4

Feedstocks	● Heavy Oil (Diluted)	5000 m^3/d
	● Heavy Oil (Diluent Free)	3500 m^3/d
	● Coal	2200 t/d
	● Natural Gas	972 000 Nm^3/d
Products	● Synthetic Crude Oil	4450 m^3/d
	● Electricity	22 MW
	● Propane	200 m^3/d
	● Sulphur	138 t/d
	● Ammonia	30 t/d
	● Diluent (Recycled)	1500 m^3/d

Canadian Energy — Feedstock and Product Quantities — Table 5

Direct Costs	413,800
Indirect Costs	214,300
Other Costs	14,000
Owner's Costs	29,000
Total Estimated Capital Cost	**671,100**

Canadian Energy — Capital Cost. SK(1989) — Table 6

	Quantity	Price	Operating Cost SK/Yr (1989)
Feedstocks			
● Heavy Oil	3500 m^3/d	S53.90/m^3	60,370
● Coal	2200 t/d	S15.00/t	10,560
● Natural Gas	970 000 Nm^3/d	S 0.05/Nm^3	15,550
Other Operating Costs			36,180
Pipeline Tariffs			7,010
Total Estimated Operating Cost*			129,670

*Based on 320 operating days per year

Canadian Energy — Annual Operating Cost — Table 6 con't

	Quantity	Price	Revenue SK/Yr (1989)
Syncrude	4450 m^3/d	S133.65/m^3	190,320
Electricity	22 MW	S 0.04/KWH	6,760
Propane	200 m^3/d	S 55.00/m^3	3,520
Sulphur	138 t/d	S 95.00/t	4,200
Ammonia	30 t/d	S200.00/t	1,920
Total Estimated Revenue*			206,720

*Based on 320 operating days per year

Canadian Energy — Annual Product Revenue — Table 6 con't