OPTIMIZATION OF THERMAL CRACKING OPERATION USING DIFFERENTIAL EVOLUTION

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Abstract: This paper presents the application of Differential Evolution (DE), an Evolutionary Computation method, for the optimization of Thermal Cracking operation. The objective in this problem is the estimation of optimal flow rates of different feeds to the cracking furnace under the restriction on ethylene and propylene production. Thousands of combinations of feeds are possible. Hence an efficient optimization strategy is essential in searching for the global optimum. In the present study LP Simplex method and DE, an improved version of Genetic Algorithms (GA), have been successfully applied with different strategies to find the optimum flow rates of different feeds. In the application of DE, various combinations of the key parameters are considered. It is found that DE, an exceptionally simple evolution strategy, is significantly faster and yields the global optimum for a wide range of the key parameters. The results obtained from DE are compared with that of LP Simplex method.

Key Words: Optimization, Evolutionary Computation, Thermal Cracker, Differential Evolution, LP Simplex Method.

INTRODUCTION

Cracking refers to breaking of higher boiling petroleum fractions into lower boiling lighter fractions. It is an endothermic reaction. Cracking of heavier fuel oils is done to produce mainly high quality (octane number) petrol. Cracking is also used to produce olefins (feed for petrochemical industry), to produce coke (by coking) and to reduce the viscosity of fuel oil (by visbreaking). There are two types of cracking namely (i) Thermal cracking and (ii) Catalytic cracking.

Thermal cracking

It is defined as the thermal decomposition, under pressure, of large hydrocarbon molecules to form smaller molecules. Lighter, more valuable hydrocarbons may thus be obtained from such relatively low value stocks as heavy fuel/gas oils (boiling up to 540^{0}C) and residues. This is conducted without any catalyst. Thermal cracking is normally carried out at temperatures varying from 450^{0}C to 750^{0}C and pressure ranging from atmospheric to 1000 psig [Hobson, 1975].
The important reactions occurring are:
-Decomposition and destructive condensation.
-Hydrogenation and dehydrogenation.
-Polymerization.
-Cyclization.

The rate at which hydrocarbon crack, is strongly dependent on temperature. Cracking reactions begin about 315-370^{0}C, depending on the type of material being cracked [Hobson, 1975]. Depending upon the pressure and temperature employed for the cracking and the characteristics of feed, there are various thermal cracking processes in which the product yields and characteristics are different [Gupta, 1994]. Mainly there are four commercial processes employed for thermal cracking in oil refineries. They are: (1) Dubbs thermal cracking process (2) Pyrolysis (3) Visbreaking process and (4) Coking.

In the present study, the problem of optimization of thermal cracker (pyrolysis) operation is discussed [Sourander et al, 1984]. The main objective in thermal-cracker optimization is the estimation of the optimal flow rates of different feeds (viz. Gas-oil, Propane, Ethane & Debutanized natural gasoline) to the cracking furnace under the restriction on ethylene and propylene production. Thousands of combinations of feeds are possible. Hence the optimization needs an efficient strategy in searching for the global minimum. There has been a growing interest in algorithms which are based on the principle of evolution (survival of the fittest) since two decades. They are referred as Evolutionary Algorithms (EA) or Evolutionary Computation methods (EC methods) [Dasgupta and Michalewicz, 1997]. The best-known algorithms in this class include genetic algorithms, evolution strategies, evolutionary programming and genetic programming. There are also many hybrid systems which incorporate various features of the above paradigms. Differential Evolution (DE) is

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one such technique which is exceptionally simple, fast and robust. It is basically a computerized search and optimization algorithm and is more likely to find a function's true global optimum.

DIFFERENTIAL EVOLUTION (DE)

DE is an improved version of Genetic Algorithms (GA) [Deb, 1996] for faster optimization. Unlike simple GA that uses binary coding for representing problem parameters, DE uses real coding of floating point numbers. Among the DE's advantages are its simple structure, ease of use, speed and robustness. In 1997, Price & Storn gave the working principle of DE with single strategy. Later on, they suggested ten different strategies of DE [Price and Storn, 2000]. A strategy that works out to be the best for a given problem may not work well when applied for a different problem. Also, the strategy to be adopted for a problem is to be determined by trial & error. The key parameters of control are: NP - the population size, CR - the crossover constant, F - the weight applied to random differential (scaling factor).

The crucial idea behind DE is a scheme for generating trial parameter vectors. Basically, DE adds the weighted difference between two population vectors to a third vector. Price & Storn [2000] have given some simple rules for choosing key parameters of DE for any given application. DE has been successfully applied in various fields. The various applications of DE are: digital filter design [Storn, 1995], fuzzy decision making problems of fuel ethanol production [Wang et al., 1998], Design of fuzzy logic controller [Sastry et al, 1998], batch fermentation process [Chiou and Wang, 1999; Wang and Cheng, 1999], multi sensor fusion [Joshi and Sanderson, 1999], dynamic optimization of continuous polymer reactor [Lee et al, 1999], estimation of heat transfer parameters in trickle bed reactor [Babu and Sastry, 1999], optimal design of heat exchangers [Babu and Munawar, 2000; 2001], synthesis & optimization of heat integrated distillation system [Babu and Rishinder Pal Singh, 2000], optimization of non-linear functions [Babu and Angira, 2001] etc.

DESCRIPTION OF THE PROBLEM

This problem [Edgar and Himmelblau, 1989] deals with maximization of profit while operating within furnace and down stream process equipment constraints. Fig. 1 lists various feeds & corresponding product distribution for a thermal cracker which produces olefins. The variables to be optimized are the amounts of the four feeds (viz. Gas-oil, Propane, Ethane & Debutanized natural gasoline (DNG)). This problem was solved using both the Linear Programming Simplex method and DE. The assumption used in formulating the objective function and constraints are:

1. 20.0×10^6 Btu/hr. fixed fuel requirement (methane) to compensate for the heat-loss.
2. All propane and ethane are recycled with the feed, and all methane and fuel oil will be recycled as fuel.

The fixed heat loss of 20.0×10^6 Btu/hr can be expressed in terms of methane cost (5.38 cents/lb) using a heating value of 21520 Btu/lb for methane. The fixed heat loss represents a constant cost which is independent of the variables x_i, hence we can ignore this factor in optimization, but in evaluating the final costs this term must be taken into account. The fuel added (x_7) will provide for any deficit in products recycled as fuel.

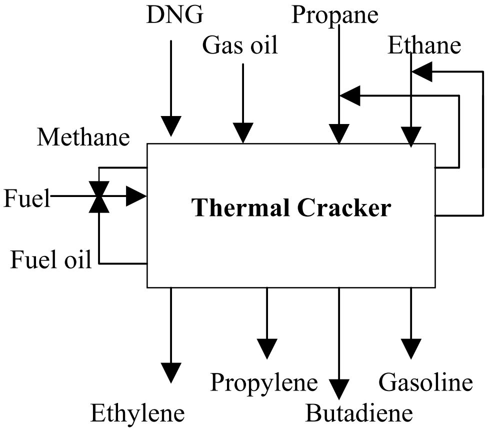

Figure 1. Thermal Cracker.

Objective function for the profit is given by:

$$f = 2.84x_1 - 0.22x_2 - 3.33x_3 + 1.09x_4 + 9.39x_5 + 9.51x_6.$$

Where f = profit function (cents/ hr.)

x_1 = Fresh ethane feed (lb/hr.)

x_2 = Fresh propane feed (lb/hr.)

x_3 = Gas-oil feed (lb/hr.)

x_4 = DNG feed (lb/hr.)

x_5 = Ethane recycle (lb/hr.)

x_6 = Propane recycle (lb/hr.)

x_7 = Fuel added (lb/hr.)

Constraints:

a). Cracker capacity of 200,000 lb/hr,

$$1.1x_1 + 0.9x_2 + 0.9x_3 + 1.0x_4 + 1.1x_5 + 0.9x_6 \le 200{,}000$$

b). Ethylene processing limitation of 50,000lb/hr,

$$0.5x_1 + 0.35x_2 + 0.2x_3 + 0.25x_4 + 0.5x_5 + 0.35x_6 \le 50{,}000$$

c). Propylene processing limitation of 20,000lb/hr,

$0.01x_1 + 0.15x_2 + 0.15x_3 0.18x_4 + 0.01x_5 + 0.15x_6 \leq 20,000$.

d). Ethane recycle

$0.4x_1 + 0.06x_2 + 0.04x_3 + 0.05x_4 - 0.6x_5 + 0.06x_6 = 0$.

e). Propane recycle

$0.1x_2 + 0.01x_3 + 0.01x_4 - 0.9x_6 = 0$.

f). Heat Constraints

$-6857.6x_1 + 364x_2 + 2032x_3 - 1145x_4 - 6857.6x_5 + 364x_6 + 21,520x_7 = 20,000,000$.

PROBLEM REFORMULATION

When DE was applied to the above problem, it was found that the equality constraints were difficult to deal with. Hence, the problem was reformulated by eliminating the equality constraints and incorporating them in inequality constraints thereby reducing the number of constraints and parameters. The reformulated problem is as follows:

Max. $f = 9.1x_1 + 1.88x_2 - 2.5879x_3 + 1.9886x_4$.

Constraints:

a). Cracker capacity of 200,000 lb/hr,

$16.5x_1 + 10.1x_2 + 8.861x_3 + 9.926x_4 \leq 1800000$.

b). Ethylene processing limitation of 50,000lb/hr,

$7.5x_1 + 4.0x_2 + 2.14x_3 + 2.665x_4 \leq 450000$.

c). Propylene processing limitation of 20,000lb/hr,

$0.15x_1 + 1.51x_2 + 1.3711x_3 + 1.6426x_4 \leq 180000$.

RESULTS AND DISCUSSION

The reformulated problem was solved using both the Differential Evolution (DE) & LP Simplex method and the following results were obtained:

Table 1. shows the results obtained by both DE & LP Simplex method. It may be noted that the maximum possible amount of ethylene is produced. As the ethylene production constraint is relaxed, the objective function value increases. Once the constraint is raised above 90,909.0909 lb\hr, the objective function remains constant at 676018.1875 cents/hr. LP simplex solution was crosschecked using a software package named *TORA*, [Taha, 1997], and the same results were obtained as shown in Table 1.

Table 2 presents the comparison, in terms of the number of objective function evaluations, CPU-time and proportion of convergencies to the optimum, between the different DE strategies. In this table, F_A, *NRC* and CPU-time represents, respectively the mean number of objective function evaluations over all the 10 executions, the percentage of convergencies to the global optimum and the average CPU time per execution (key parameters used are NP=40, CR=0.9, F=0.6, accuracy=0.0001%).

Table 1. Results of LP Simplex and DE.

Stream	Flow Rate (lb\hr.) **Using DE**	Flow rate (lb\hr.) using **LP Simplex**
Fresh Ethane feed (x_1)	60,000	60,000
Fresh propane feed (x_2)	0	0
Gas-oil feed (x_3)	0	0
DNG feed (x_4)	0	0
Ethane recycle (x_5)	40,000	40,000
Propane recycle (x_6)	0	0
Fuel added (x_7)	32795.539	32795.539
Ethylene	50,000	50,000
Propylene	1000	1000
Butadiene	1000	1000
Gasoline	1000	1000
Methane	7000	7000
Fuel oil	0	0
Objective function (cents\hr.)	369560.00	369560.00

Table 2. Results of DE with all ten strategies.

S No	Strategy	F_A	CPU-time	NRC
1	DE/rand/1/bin	6268	0.28	100
2	DE/best/1/bin	3168	0.145	100
3	DE/best/2/bin	9076	0.418	100
4	DE/rand/2/bin	11696	0.539	100
5	DE/rand-to-best/1/bin	6052	0.28	100
6	DE/rand/1/exp	5252	0.22	100
7	DE/best/1/exp	2796	0.126	100
8	DE/best/2/exp	10132	0.44	100
9	DE/rand/2/exp	12600	0.55	100
10	DE/rand-to-best/1/exp	6536	0.275	100

From the above table it is evident that the strategy number 7 is the best strategy. It takes least average CPU-time, maximum NRC and minimum F_A. However the best key parameters for strategy no.7 are NP=40, CR=0.8, F=0.5 giving CPU-time of 0.113 s, NRC=95 and F_A=2656.

CONCLUSIONS

In this paper the optimization of thermal cracker operation using Differential evolution (DE) and LP Simplex method has been presented. The best key parameters for the present problem are: NP=40, CR=0.8, F=0.5. The strategy that took minimum CPU-time with highest NRC is strategy no. 7. The results obtained by two methods (viz. DE & LP Simplex) are same and matches with that reported in literature.

Differential Evolution exhibits difficulties in dealing with equality constraint problems but in general, they are the most efficient in terms of function evaluations. Future work will address the comparison of DE with adaptive random search algorithms, as well as the treatment of equality constraints.

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