

Optimisation of Integrated Gasification Combined Cycles in Refineries

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Abstract

In this paper, a systematic methodology has been presented for the optimal integration of the IGCC systems with the existing refinery infrastructure, the hydrogen network and the utility network. The proposed approach determines the new unit investment scheme for the existing refineries, as well as operational strategies of all the units in order to maximise the annual profit taking into account the annualised capital cost. The proposed methodology follows a two-stage procedure, namely analysis stage and optimisation stage. The analysis stage screens among various integration alternatives and identify the promising options considering the trade-off between the economic and environmental benefits and the capital expenditure. Because only economically viable options are included, the superstructure will be potentially much smaller than a general superstructure which includes all the candidate options. With a reduced superstructure, the mathematical optimisation problem is formulated as an NLP model which can be solved effectively even for large problems.

Keywords: IGCC, refinery, NLP, utility network, hydrogen network

1. Introduction

A common operational feature of the refinery is the production of heavy oil residues. In many refineries these heavy residues are used as fuels which cause severe environmental problems. Gasification has been emerging as a “clean” technology for the treatment of the heavy residues which converts the 'bottom of barrel' into valuable products such as hydrogen, clean fuel, steam and power. The production of hydrogen is important because of increased demands for hydrogen in hydrotreating operations as a result of changing environmental regulations. The growing prevalence of heavy, sour, metal-laden crudes, the highly competitive nature of the refining industry, and environmental regulations, all work together to make gasification an increasingly attractive process option (Heaven, 1996). The reasons for including a gasifier in the refinery often derive from the combination of crude oil quality trends and increasingly

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severe restrictions on levels of sulphur dioxide emissions from combustion of heavy fuels (Heavon, 1996). Forecasts indicate that crudes will be progressively heavier and also higher in sulphur content. Some crude oils, particularly Mexican Maya crude and several Venezuelan crudes, also have much higher metals content than the crudes for which the typical refinery is configured (Smith, 1992). At the same time, environmental restrictions are forcing fuel oil sulphur reductions in many parts of the world. The value of high-sulphur fuel oils is expected to drop significantly, as these legislative restrictions further restrict the market (Simbeck and Dickenson, 1986). Another potential reason for including a gasifier is the desire to use the products to generate electricity, thus reducing costs and emissions (in areas where refinery firing of residual fuels is still allowed), or to produce additional hydrogen.

Thus, oil refineries are increasingly concerned with the use of gasification for the processing of heavy oil residues. Texaco Refining & Marketing started up in 1996 a gasification unit at its El Dorado, Kansas, refinery. The unit currently gasifies delayed petroleum coke and other refinery waste products (Rhodes, 1996 and Swanekamp, 1996). The 100,000 barrels/day complex oil refinery consists of fluid catalytic cracking (FCC) and delayed coking units, hydrotreating units and hydrogen production units. Another successful example is the Pernis refinery that uses the Shell gasification process to produce hydrogen for the hydrocracker and for power generation (Sadhukhan and Zhu, 2002). In this project, gasification technology has been applied as an integrated system to make pure hydrogen for the hydrocracker, while power and steam for refinery usage are generated in an independent island.

It looks sensible to consider the possibility of integrating IGCC (integrated gasification combined cycles) with the refinery in order to satisfy its demand of power, hydrogen and electricity. However, no methodology for gasification integration to an existing refinery infrastructure is available. The objective of this paper is to propose a systematic methodology for the optimal integration of the IGCC systems with the exiting refinery infrastructure, the hydrogen network and the utility network.

2. Problem definition

Given a refinery as shown in Figure 1, which generates a certain amount of heavy residues (some of them in the form of petroleum coke), the objective of this paper is to develop a optimisation model for an IGCC plant which is able to optimise the plant performance in order to maximise the total profit on such a facility.

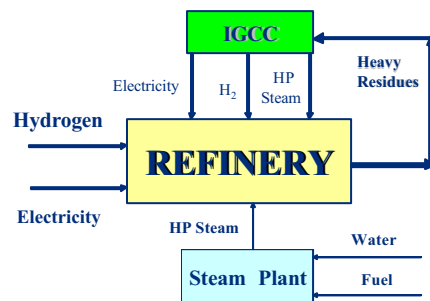


Figure 1. Integration of IGCC with a refinery

Given the feedstock inputs (flowrate and composition), the IGCC plant model is able to predict the IGCC outputs. The outputs are essentially hydrogen, high pressure (HP) steam, and electricity. Once rates for each output are well defined, integration should be carried out, which implicates that both hydrogen and utilities generated are returned to the refinery in order to satisfy its demand under optimal conditions. Criteria for the optimal IGCC system integration with the refinery are dictated by capital investment and products produced of the IGCC system. Hence, as total profit maximisation is to be achieved, refinery's demand of a certain utility may not be completely satisfied. Under such conditions, the required utilities would need to be purchased from an external utility company or to be generated on site.

2.1. Hydrogen network optimisation

First of all, make-up gas rates of hydrogen consumers (e.g. hydrotreater and hydrocrackers) heavily depend on the hydrogen make-up purity. In other words, the purer the hydrogen contained in the make-up gas, the less the gas flowrate and thus the less compression work is required for the same throughput. Secondly, in order to increase the hydrogen purity, low-purity hydrogen needs to be purified, which results in hydrogen loss and extra operating cost. Therefore, there is a trade-off between the hydrogen purity, hydrogen production, gas flowrate and cost penalties. Furthermore, where to locate the hydrogen purification process is a key issue in the hydrogen network optimisation, since the purification process can take purge gases from different processes at different purity and pressures as feed. Proper integration of both purification and production enhancement can contribute to the reduction of overall hydrogen cost. In overall, the objective of optimising the hydrogen network is to minimise the hydrogen operating cost, so that hydrogen generation by IGCC offsets the refinery demand and thus its purchase is avoided.

2.2. Utility system optimisation

For the utility system integration between the refinery and IGCC, power generation and fuel consumption in boilers are the major concerns. Obviously, there is a trade-off between these two aspects. In other words, power is generated by expanding high-pressure steam through steam turbines, which is at the cost of fuel consumption in boilers. In addition, products slates and process operating conditions vary frequently with the type of crude oils used. This results in changes in steam demands and generation from processes, which in turn affects the utility system. Nevertheless, it has to be highlighted that for the scope of this paper both the amount and type of crude oil and, subsequently, its heavy residuum are assumed to be constant. Therefore, the overall objective of the utility system optimisation is to minimise the operating costs including fuel consumption in boilers, power import, cooling duty in the condensing turbine and water make-up. In order to achieve this target, IGCC must provide sufficient amounts of such utilities without affecting negatively hydrogen rates.

3. IGCC System Optimisation

In this section a stepwise description of the procedure followed to model and optimise IGCC plant performance is provided. Figure 2 shows the IGCC system considered in

this study. Heavy residues (petroleum coke) are gasified in the presence of pure oxygen and HP steam. Raw syngas at 1300°C is cooled down to 350°C, using the recovered heat to produce MP steam. Hydrogen sulphide contained in the raw syngas is removed by means of a single train of isothermal absorption columns using Selexol as process solvent. At this point syngas is split up into two streams, one feeds the HRU where CO is steam shifted and hydrogen recovered, and the other is sent to the combined cycle. Next, bypassed syngas and HRU offgas are mixed up and burnt in a gas turbine, generating power from the expansion phenomenon. Exhaust or flue gas is then employed at the HRSG where HP steam is raised at 35 bar and 500°C. A fixed amount of the steam is sent for gasification. The remaining steam goes through a splitting process, where there is a trade-off between its export to refinery or its usage in a steam turbine to enhance power output.

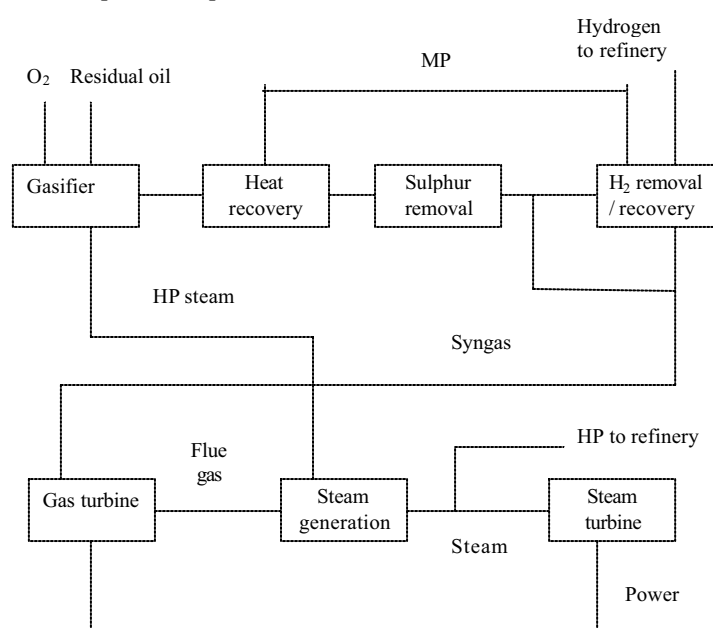


Figure 2. Integration of IGCC with a refinery

In order to model and optimise the IGCC plant performance, the starting point is to define the feedstock which the refinery supplies to the IGCC facility. The most important data for the feedstock are the percentages of each component that constitute the heavy crude oil. Next, all the units that comprise the IGCC plant as shown in Figure 2 will be modelled using either reliable and documented empirical correlations or realistic thermodynamic principles. Finally, once all process units have been modelled, an arrangement of equations that relate power for export, hydrogen production and steam at different levels (LP, MP, HP) to the optimisation variables will be clearly shown. It is worth highlighting that the most important units, on which the whole modelling is based are the gasifier and the gas turbine. Thus, special attention should be paid to how their corresponding equations are selected. The gasifier model was selected

from an arrangement of correlations available in the literature and obtained from simulation using HYSYS. Empirical correlations available in the literature were used in order to calculate shaft work and flue gas temperature at the gas turbine. The only input for this unit was the fuel consumption (kW), which was determined from syngas and refinery offgas heating value.

The objective of the model is to determine the optimal operating conditions and the structure of the IGCC system to maximise total profit given the refinery demands. The objective function of the model is as follows:

$$\text{Maximise Total Profit} = \sum_i (S_i - D_i) \times P_i - U - \text{annulised capital cost}$$

where i refers to the final products from IGCC (Hydrogen, steam and power); S_i the amount of stock i supplied to IGCC; D_i the amount of stock i demanded by refinery; P_i the market price of stock; U the total cost of utilities and other supplies for IGCC performance.

4. Case Study

The way in which this methodology is applied was illustrated using the following case study. Real data from a refinery were utilized. The Refinery processes 92 kBPD blend of ARL/ ARH crude oil and generates 690 tons/day petroleum coke which could be used in a gasifier. Table 1 shows the hydrogen, steam and power demands of the refinery. The objective of this case study is to develop an IGCC plant which is optimally integrated with the refinery with the maximum net profit. It is assumed that the deficit utility demands could be satisfied by importing and the surplus utilities generated could be sold. The utility prices used in the case study are given in Table 2.

Table 1. Refinery demands

Hydrogen	140 tons/day
HP steam	1000 tons/day
Power	65 MW

Table 2. Utility prices

Power	45 \$ / MW.hr
Process water	0.00053 \$/kg
HP steam, 35 bar	0.0085 \$/kg
Oxygen	0.060 \$/kg
Hydrogen	1.28 \$/kg

Optimal results obtained after carrying out the optimisation are shown in Table 3 where figures for power generated by steam and gas turbines, hydrogen production and total HP steam are provided. It can be seen 70 tons/day steam should be imported and 60 tons/day hydrogen could be exported.

Table 3. Optimal results

Gas turbine power, MW	27.86
Steam turbine power, MW	8.003
HP steam, tons/day	930
Hydrogen, tons/day	205
Profit, \$/year	8,462,026

5. Conclusions

A mathematical model has been developed to identify the best integration between the refinery and the IGCC system. It is written using suitable mathematical notation, and subsequently it has been programmed using a highly powerful software (version 2001 *MATHCAD* ® professional). Validation for core units (gasifier, gas turbine etc.) using real industrial data has been undertaken and good comparisons have been achieved. IGCC has been demonstrated to be quite a powerful technology with economically attractive features, which provides the industrialised society of the 21st century with clean and highly efficient electricity and an abundant source of hydrogen to be integrated within refinery systems. Beyond any doubt, future work on the possibility of enhancing hydrogen production and utilities generation may lead to improvements on IGCC integration.

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