Boosting refinery profitability through hydrogen management technology

Nick Hallale discusses how novel process design technology is helping refiners to use hydrogen to leverage greater profitability

CLEAN fuels regulations are being implemented in many parts of the world including Europe and the USA, and are going to become more and more strict as time progresses. Major oil refinery revamps are necessary in order to meet these specifications, and one of the consequences is that hydrogen demand will increase dramatically.

Hydrogen pinch analysis technology originated from a PhD project at the University of Manchester Institute of Science and Technology (UMIST), and has been refined as a result of feedback and experience gained over many industrial applications. It is a good example of successful collaboration between university and industry.

hydrogen: the issues

Ironically, the lightest element in the universe – hydrogen – is weighing very heavily on the minds of oil refiners at the moment. As people familiar with the refining business know, hydrogen is an important utility and is vital for the operation of many of today's processing units. These include hydrotreating and hydrocracking.

The legislation on low sulphur fuels, particularly in Europe and the USA, has greatly increased the amount and severity of hydrotreating required. Many refineries are revamping their existing hydrotreaters and/or building additional ones. The amount of hydrogen required to operate these hydrotreaters is increased enormously – more than doubling in many cases. In addition, the move to process heavier crude oils and the reduced market for fuel oil is increasing the need for hydrocracking, again leading to a higher hydrogen demand.

Many refineries receive a large amount of hydrogen as a by-product of catalytic reforming on their site. However, current trends to reduce aromatics in gasoline are constraining the use of catalytic reforming and thus removing a source of hydrogen. The combined effect of all these trends is that many refineries are facing a deficit of hydrogen.

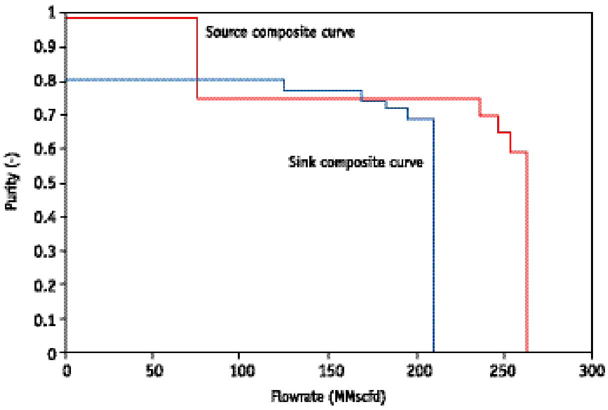

Figure 1: Hydrogen composite curves are a useful way of visualising the flows and purities of sources and sinks in a refinery hydrogen network

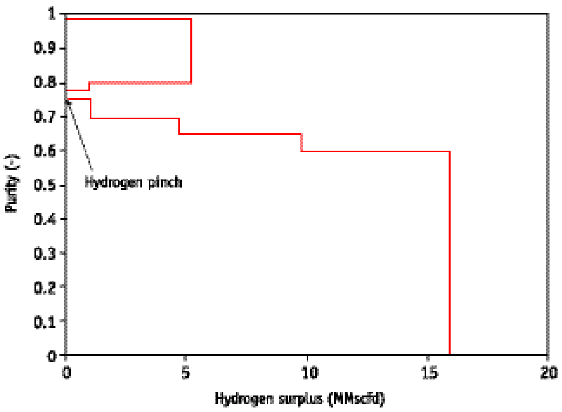

Figure 2: The hydrogen surplus diagram identifies the hydrogen pinch and also sets targets for hydrogen re-use, recycling and utility requirements

hydrogen pinch analysis

In 1996, a research consortium was established at the process integration department at UMIST in order to develop process design methodologies for better hydrogen management. The UMIST department was already well known for its contribution to the development of pinch analysis for heat integration.

The member companies had the foresight to recognise that although hydrogen availability was not then a major issue, it would become so in future years. Member companies included information technology companies, oil companies, consultants and engineering contractors. The companies paid an annual fee to fund the development of the technology at UMIST, but more importantly they contributed engineering knowledge, case study data and industrial feedback. It was this successful collaboration that ensured the technology rapidly became widely used and did not end up on a university library shelf. Four hydrogen-related areas were researched:

- hydrogen pinch analysis;
- refinery modelling;
- refinery optimisation; and
- reactive distillation in hydroprocessing.

Promising results were achieved in all these areas, but hydrogen pinch analysis had by far the greatest industrial impact. The original work is documented in a PhD thesis (Alves, *Design and Analysis of Refinery Hydrogen Distribution Systems*, 1999) and was also coded into a software package by UMIST for the use of the member companies. Hydrogen pinch analysis is a graphical methodology and is based on exploiting an analogy with energy pinch analysis. Energy pinch is used for the design and optimisation of heat exchanger networks and utility systems and has been applied on over a thousand studies worldwide (see ***tce*** September 2001).

Hydrogen pinch analysis identifies sources and sinks of hydrogen in a refinery and then determines the best way to connect them so that hydrogen recovery is maximised. Sources are streams which contain hydrogen while sinks are those processes which consume hydrogen.

Once sources and sinks are identified, the next step is to construct hydrogen composite curves (Figure 1), which are very similar to the energy composite curves of pinch analysis. Instead of plotting temperature vs enthalpy, now we plot hydrogen purity vs flowrate. These composite curves are a powerful way of visualising the hydrogen recovery within the refinery. Another useful tool is the hydrogen surplus diagram (Figure 2) which is used to set targets for the minimum 'on purpose' or utility hydrogen generation that can be achieved. The surplus diagram also locates the hydrogen pinch which is a bottleneck on hydrogen recovery and is analogous to the pinch point in heat exchanger network design.

The pinch point from the surplus diagram defines the purity level where more hydrogen is needed to supply demand. This method also gives insights into the effective use of hydrogen purification units (for example pressure-swing adsorbers or membranes) where direct recovery cannot satisfy the entire demand. In these cases the low purity hydrogen that is in surplus is purified and supplied at higher purity to satisfy the shortage of higher purity hydrogen.

industrial applications, feedback and enhancements

The original technology was applied by UMIST and the member companies on several industrial projects with impressive results. Hydrogen savings worth hundreds of thousands to millions of dollars per year have been achieved for clients in the USA, Europe, South Africa and the Far East. In many cases, significant improvements have been made for zero or low investment cost modifications such as repiping.

After the first few industrial projects, it became clear that there were some issues that the original graphical pinch approach could not handle. These included practical design issues such as pressure constraints, limits on existing compressors, layout constraints, piping costs and safety and operability issues. Once the opportunities for improvement were identified, UMIST developed a mathematical programming methodology to address all of these issues. The enhanced technology is very well suited for retrofitting existing refineries and gives solutions that feature minimal changes to the system. One important constraint on many projects is that solutions should avoid installing new compressors. The enhanced hydrogen pinch technology optimises to solutions where existing compressors are re-used as efficiently as possible (Figure 3). It also allows clients with limited capital budgets to invest the capital in the optimum projects.

One problem that is encountered in hydrogen optimisation projects is that of data reconciliation. It is often the case that there are conflicting data in a refinery hydrogen balance or that certain flowrates and compositions are not measured at all. Also, flowmeter readings are often not corrected for molecular weight and this can give significant errors. In order to model the entire hydrogen network, AspenTech's approach is to develop simplified reactor and separator models to represent the consumers. Data correction and reconciliation software are used to develop a hydrogen balance from the available data. Even the most complex hydrotreater and hydrocracker flowsheets (including reactive distillation) can be simulated by using the appropriate models. Multiple components can be dealt with easily, allowing refiners to track individual contaminants such as H_2S.

To further address the issues of optimisation of hydrogen with limited capital, AspenTech and Air Liquide have formed an alliance, PRO-EN Services (PRO-EN). This partners AspenTech's optimisation software including the enhanced hydrogen pinch, modelling and data reconciliation technology with the world's largest industrial gas company, Air Liquide. With this alliance, not only can an optimum solution be determined with the use of the optimisation software as discussed above, but a vehicle for executing and implementing the optimised projects is delivered using Air Liquide's capabilities to design hydrogen manufacturing and purification units, provide over the fence solutions for hydrogen delivery or purification as well as creative financing options to improve project cash flow.

PRO-EN has found that using hydrogen management techniques such as those discussed above is only part of the picture when it comes to improving refinery profitability. These techniques treat hydrogen as a utility which should be minimised. To maximise profitability, we need to look at optimising its use rather than minimising it. The hydrogen management technology should be used alongside rigorous reactor modelling and refinery linear programming (LP) planning tools in order to best leverage hydrogen for maximum profit. For example, the hydrogen freed up using the hydrogen pinch network design methods can be used to boost partial pressures to enhance reactor conversion, throughputs, yields and catalyst life.

Kinetic modelling can be used to build rigorous simulations of refining units such as hydrocrackers, reformers, FCC pretreaters, and desulphurisers. They rigorously model kinetics for denitrification, desulphurisation, saturation, and cracking, and are capable of accurately predicting the impact of hydrogen purity improvements on yields, hydrogen consumption and product properties for widely different feedstocks and operating conditions. Some models include catalyst deactivation which allow refiners to optimise catalyst life cycle and to forecast conversions, yields, and product properties as the catalyst ages.

It is not necessary to model every reactor and determine the benefits in a trial and error way. PRO-EN uses LP modelling, understanding of current process operations and constraints and enhanced hydrogen pinch analysis to develop a shortlist of key processes and potential changes to the process. For example, the LP model will show the bottlenecks to increasing refinery profit. If increasing hydrogen partial pressure can eliminate one of these bottlenecks, then this unit will be a candidate for applying rigorous reactor modelling and subsequent process analysis.

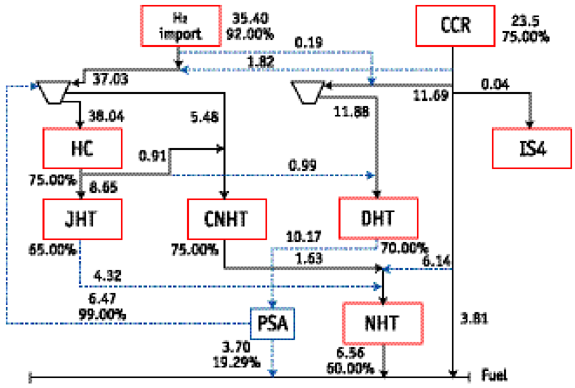

Figure 3: New design technology allows hydrogen network improvements to be compatible with existing systems while making best use of on-site compressors

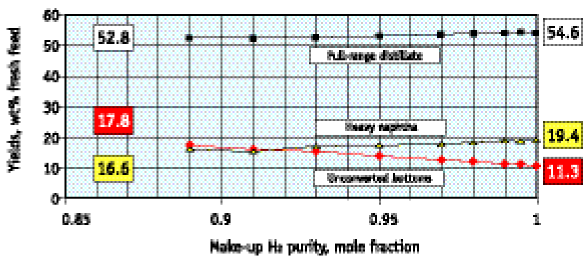

Figure 4: Results of a rigorous hydrocracker model

As an illustration, Figure 4 shows the results of a hydrocracker model. In this model, the hydrogen purity of the make-up gas is varied from (the current) 89% purity to 100% purity, and its effect on product yields calculated. In moving from 89% hydrogen purity to 100% hydrogen purity, the following effects are noted:

- full-range distillate yield is increased from 52.8% to 54.6%;
- heavy naphtha yield is increased from 16.6% to 19.4%;
- unconverted bottoms reduce from 17.8% to 11.3%.

The benefits identified in this case were in the order of $2m per year.

Often, a thorough hydrogen management study will identify a whole range of potential projects, not all of which may be implemented. By carefully considering the refinery's long-term objectives, an optimal road-map of projects can be developed which sets out the strategy for investment over a number of years. This allows projects to take advantage of scheduled revamps and shutdowns so that disruptions are minimised and unnecessary capital investment is avoided. Through creative project financing and implementation arrangements that PRO-EN provides, projects that otherwise would not be implemented due to capital or manpower constraints can be implemented to further enhance refinery profitability. ■

Nick Hallale works for AspenTech