Integrated monitoring for optimising crude distillation

On-line process analysers in crude distillation units prevent lost throughput caused by non-conforming process conditions and crude oil switching

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Refineries are among the most complex of processing sites. They include many, entirely different, physical and chemical processes. These include atmospheric and vacuum distillation, and chemical reactions such as cracking, isomerisation, hydrogenation, desulphurisation, aromatisation and blending. Many processes are interlinked. The product of one unit serves as the feed for other, consecutive processes. Any failure, shutdown or lack of control of one of these processes will immediately affect another process in the production chain and will have an impact on the entire economy of the refinery, its revenue, profit or loss.

The majority of chemical industries process raw materials with defined specifications. Refineries must cope with a dependency on non-specific, fluctuating crude oil compositions. Trends and differences in crude oil prices, the size of tankers that can make harbour to supply a refinery, political instabilities in oil exporting countries, changing product specifications and the equipment available in the refinery dictate that crude switching and/or crude blending are inevitable. Crude blending is also one of the practices applied by refineries to increase the margin between the cost of the crude feed and the revenue from selling the final products.

Differences in crude oil compositions from various locations impact the production capacity of the refinery to deliver the volume of required distillates that the refinery is committed to bring to market.

The economics of refining are even more complicated because each refinery is unique. Many refineries are designed differently to fulfill their initial target to produce a certain range of petroleum products from a defined quality of crude oil. At present, refineries must be flexible enough to respond immediately to crude oil changes and deviations in product demands as a result of the changing global economy.

The required flexibility in the management of a refinery and the complexity of the different processes, crude oils and distillates can only be achieved by stringent monitoring of the quality of the incoming material and the outgoing product streams in each refinery unit. None of the product streams are standalone. The root of each stream is found in the crude oil that has been delivered to the distillation towers.

Strict and adequate monitoring of all streams is crucial to ensure maximum efficiency of the crude distillation unit

Challenge of crude distillation unit optimisation

The efficiency of a refinery to produce petroleum distillates is directly linked to:

- The crude oil that is delivered to the refinery
- The equipment of the refinery
- The maximum throughput of crude oil and petroleum products
- The ability to produce the distillates with the highest value at maximum yield.

Optimising the process conditions of the crude distillation unit is a main challenge for each refinery. It increases profit by producing the required range of distillates at maximum yield and at minimum cost. To achieve this goal, full and real-time monitoring and control of each incoming stream of crude oil and outgoing distillate stream is an inevitable requirement to ensure:

- Minimum influence on production capacity for each required distillate due to crude oil changes
- Minimum influence on distillate quality upon crude oil switching
- Maximum production of high-value distillates. Overlapping characteristic boiling ranges exist between two neighbouring refinery fractions. Maximum distillation profit is achieved by shifting the cut points towards the highest value products
- Maximum stability of the quality of each distillate throughout the entire distillation process
- Minimised production of off-spec or borderline materials and, as a result, the need for re-reprocessing or blending.

The quality and the cost of crude oil depends on its origin. Blending various types of crude oil is required to reduce the cost of the crude oil feed to be distilled and to adapt the crude oil feed so that it can be processed properly by the equipment available in the refinery.

Crude oil differences result in a

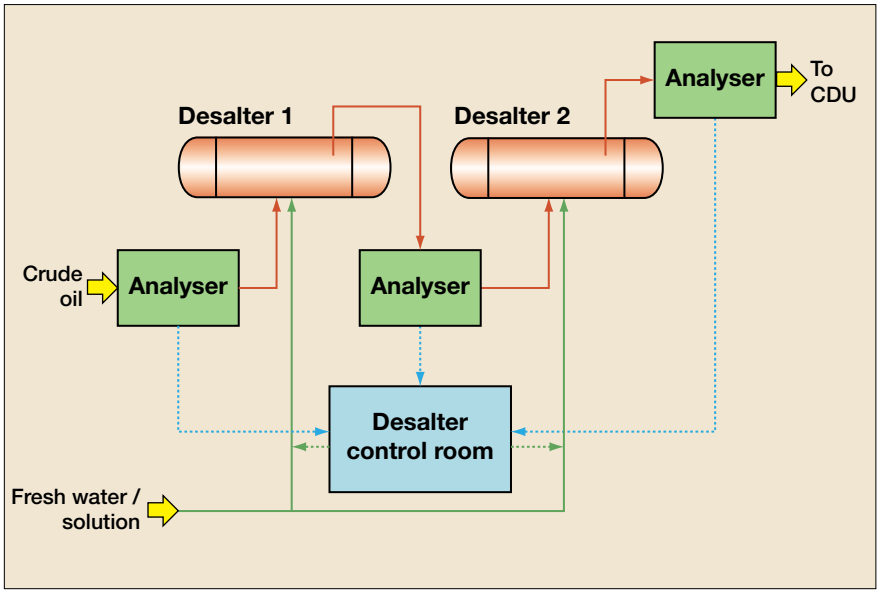

Figure 1 Flow chart of the crude analyser setup in a desalter system

variation in the distillate distribution produced by the crude distillation unit under the same process conditions. To achieve maximum production efficiency and product yield, continuous re-adjustment and fine-tuning of process conditions is inevitable.

Ongoing laboratory analyses are expensive and time consuming. The time lapse from sampling to analytical reporting increases the likelihood of a refinery to produce off-spec or borderline material. Delayed awareness of the deficient qualities of distillates will delay the implementation of process adjustments. The crude distillation unit could operate in an inadequate and non-profitable mode for a long period of time. In addition, any other failure or malfunction of the crude distillation unit could result in reduced production capacity or even a total shutdown of the plant if not handled immediately.

To optimise process parameters to produce the required range of distillates at the highest yields, while taking into account the characteristics of the crude oil to be processed, strict and adequate monitoring of all streams is crucial to ensure maximum efficiency of the crude distillation unit.

Full control of product quality can only be achieved by an integrated system of on-line crude and distillate analysers. The analyser must provide continuous, instantaneous information on the quality and physical properties of the incoming crude oil and the outgoing streams of distillate streams of naphtha, kerosene, LGO and HGO, as well as the vacuum distilled products LVGO and HVGO. Real-time corrective actions need to be taken to guarantee optimised operation of the crude distillation unit.

To achieve this, an integrated system has been developed, to enable full management of the crude distillation unit's performance. It starts with the incoming crude entering the desalter and continues until the final distillates, which are produced by the atmospheric and vacuum towers.

The integrated system is composed of:

- A crude oil analyser (desalter control)
- Near infrared (NIR)-based analysers
- Magnetic resonance spectrometry (MRS)-based analysers
- Analyser management software
- Automatic validation software for on-line process analysers.

Desalter control

The amount of water, salts and sediment in the crude oil received by refineries varies widely according to the source of crude oil, pre-processing at the site of its source and the means of transport of crude from source to refinery.

Crude oil arrives at the refinery contaminated with water, brine, salts that are partially crystallised and dispersed in the oil, sulphides, sediments and traces of heavy metals. Some of the brine is emulsified with the oil fraction, so demulsification and separation of the water fraction from the organic material must be conducted. The crude oil is treated by chemicals and water-washed to remove soluble inorganic salts. Electrostatic separation is applied to break the emulsion, to improve the separation between the water and oil phase. Removal of the salts, halogen ion and sulphides is of high importance to prevent corrosion and excessive fouling of the pipes and other refinery equipment. Installation of a dedicated crude oil analyser enables continuous quantification of critical properties of the crude oil stream. This system of salt measurement is based on the behaviour of saltwater/crude oil emulsions influenced by electromagnetic fields. A main advantage of a crude analyser is that the need for any added solvents is omitted. On-line quantification of any variation of the API number, the salt content, the H_2S content and the water content of the crude oil enables adjustment of the operating conditions of the desalter in real time. Process chemicals and water can be delivered in sufficient — but not excessive — quantities to the desalting process to remove undesired salts and H_2S.

On-line and real-time analysis of crude oil properties processed by the desalter increases its effectiveness to provide crude oil ready for distillation. By continuously monitoring the quality of the crude oil feed to the crude distillation unit, immediate corrections to the desalter's process conditions can be executed, to maintain a constant quality of desalted crude oil and direct adjustments upon crude switching.

The implementation of a crude analyser will have a cost-reducing effect, as it has an impact on the energy consumption of the de-emulsifier, the consumption of wash water, a reduction in the corrosion of the pipelines and equipment, and it predicts the API of the feed

entering the crude distillation unit. Optimal performance of the entire process is achieved by mounting the analysers before, between and after the desalters (see Figure 1).

Crude distillation unit

Crude oil pretreated by the desalter is transferred to the crude distillation unit for fractionation into the different distillates according to their boiling ranges:

- Gases with low boiling points (≤32°C)
- Light straight-run naphtha (32–88°C)
- Heavy straight-run naphtha (88–193°C)
- Kerosene (193–271°C)
- Light gas oil (271–321°C)
- Heavy gas oil (321– 427°C)
- Vacuum gas oil (427–566°C).

Exact cut points between the distillates are determined with respect to the initial and final boiling point, as specified by local and international standards, or by the required physical properties needed for further processing. The boiling ranges of neighbouring distillates partially overlap. It is up to each refinery to shift the exact cut point so that the maximum production capacity for each product towards the most valuable distillates is achieved.

Prediction of the yield of distillation can be made by using algorithmic techniques such as linear programming (LP). However, any unexpected discrepancy between the crude's actual properties and the LP model will directly impact distillation efficiency.

Process control of modern refineries is computerised to a large extent. However, human intervention cannot be eliminated from the oversight and control of the entire process. Both automatic and human control of the refinery units needs to receive a continuous stream of real-time data for the process. Any delay will influence the decision to perform a required action to maintain constant production according to the predetermined programme.

To achieve proper control of process units in refineries, classical analytical methodologies are not adequate. Laboratory analyses are expensive and time consuming and include many steps such as sampling, sample handling, sample preparation, measurements, data handling and reporting. The delay between sampling and production of analytical results prevents process conditions being corrected at the earliest stages in the event of any discrepancy. Efficient processing in the crude distillation unit has the following minimum requirements:

- Actual information about critical properties, which are representative of the crude oil or crude blend to be processed
- Efficient operation of the atmospheric and vacuum towers to provide high-value distillates at the highest feasible yield
- A real-time, accurate and reliable overview of product quality at any stage of the crude distillation process
- The ability to correlate between the quality of incoming crude oil feed and outgoing streams of distillates.

Spectrometric methods are applicable to quantitatively predict physical properties of refinery process streams

On-line spectrometric process analysers

Total analysis of the physical properties of a distillate or final blend is a time-consuming operation. Each analysis is conducted separately according to the appropriate ASTM-defined method.

On-line, dedicated ASTM process analysers are expensive. Each individual physical property to be measured requires a dedicated analyser. Full monitoring requires purchasing a large number of analysers and bearing the cost of maintenance and calibration.

The physical properties of crude oil, distillates or blends are an overall outcome of the influence of the physical properties of each individual substance in the matter. Identification of these compounds enables a quantitative prediction of the physical properties of the entire mixture. As physical properties correlate with their chemical compositions, spectrometric methods are applicable to quantitatively predict physical properties of a composition of chemical substances as in the refinery stream. They make it possible to quickly provide full information about compliance with specified product qualities.

Two spectrometric methods are widely used to control the process conditions of units in the refinery:

- Near Infrared Spectrometry (NIR)
- Magnetic Resonance Spectrometry (MRS).

NIR spectrometry

Near infrared (NIR) technology is

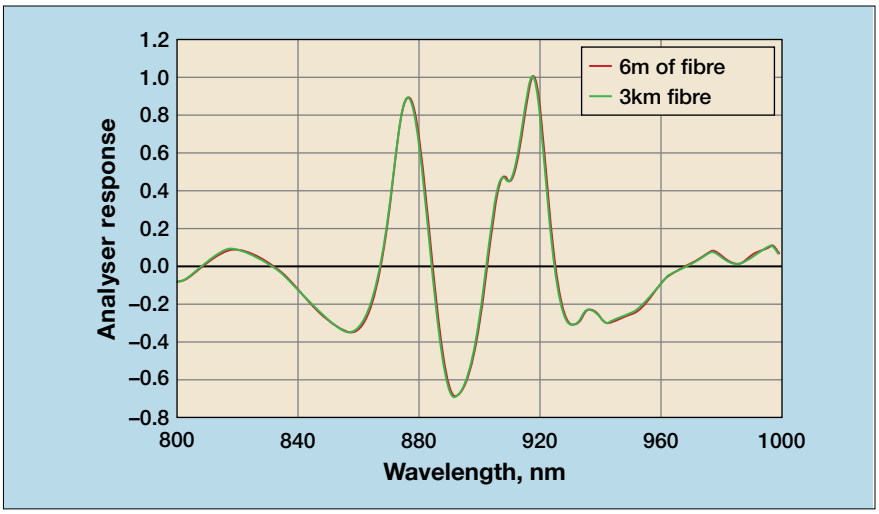

Figure 2 Influence of optical fibre length on the NIR spectrum

based on the absorption spectrum of the near infrared spectrum within the range 750–1050 nm. This covers the spectrum of petroleum products. Each petroleum product has its specific fingerprints in the NIR spectrum, which represent the product's composition. Statistical correlation between NIR data and the results of laboratory analysis enable physical properties to be predicted to a high accuracy.

NIR technology includes a NIR analyser connected to its field units by standard optical fibre cables. The field unit is mounted on a bypass pipe of the stream to be monitored. It can be installed at any location in the refinery, up to 3km from the NIR analyser. The optical signal is not influenced by the length of the optical fibre (see Figure 2).

An advantage of NIR technology is that the distillate to be measured flows continuously through the field probe. This enables measurements to be performed in continuous mode. As an optical method free of mechanical sampling systems, the optical multiplexer enables instantaneous multiple analyses of various streams. Field units are simple and maintenance free. They do not contain any mechanical parts (see Figure 3).

Figure 3 Fixed measuring probes of a NIR on-line process analyser

A light source is transmitted by an optical fibre analyser to the field unit. The beam passes through the distillate that is flowing continuously through the field probe. The transmitted light is returned via the optical fibre back to the detector of the analyser. Spectral data are processed by chemometric models and converted to quantitative values of a predetermined variety of physical properties.

In combination with the proper chemometric, NIR technology quantifies the required physical properties in naphtha, kerosene and gasoil by one single measurement. These properties include density, IBP, FBP, T10%, T90%, freeze point, pour point, flash point, cloud point, cetane number, benzene, naphthenes, paraffins, olefins and the C-number.

Since it is an optical method, the implementation of NIR technology is restricted to transparent solutions only. A second drawback of NIR technology is its lack of linear response. Particularly in certain regions of the infrared, the absorption of light does not correlate linearly with the concentrations of chemical compounds according to the Beer-Lambert law. Moreover, its linear response is also affected by overlapping of spectral peaks and inferior resolution between peaks assigned to various molecular bonds. This is caused predominately by different excitation energies assigned to each chemical bond.

Magnetic resonance spectrometry

Magnetic resonance spectrometry (MRS) is a non-optical method that enables molecules to be distinguished according to their chemical structures. It is based on differences in the alignment of hydrogen atoms under the influence of a magnetic field. When a group of nuclei with spins is placed in a static magnetic field of 60 MHz, each nucleus aligns with the magnetic field. With the formation of small magnetic fields

Comparison between NIR and MRS process analysers

Parameter	NIR analyser	MRS analyser
Method	• Near infrared • Optical method	• Nuclear magnetic resonance • Magnetic method
Analysed species	• O-H, C-H, N-H bond stretch in	• H-Nuclei
Quantitative analyses	• Non-specific towards molecules. Based on fingerprints of the mixture	• Based on exact quantification of hydrogen nuclei assigned to specific molecules
Chemometric models	• No-linear response; linear extrapolations of the model omitted	• Linear response. Enables linear extrapolations of the model
Required sample properties	• Transparent and free of water	• Transparent or opaque or dense, and wet samples
Calibration modelling	• Requires deconvolution of NIR combinations, overtones and chemometrics	• Correlates - distinguishes peaks and linear responses
Sampling system	• Continuous flow through. Fixed probe mounted on pipes (bypass)	• Valve system connected to pipes (stop/flow operation). Fast loop bypass pipes (changes from one stream to another)
Analyser to sampling probe connection	• Optical fibre	• Pipe system
Analyser location from probe	• Remote from probe, up to 3km	• Probe integrated in analyser
Multistream sample switching	• Optical multiplexer	• Mechanical switching between streams. Consecutive measuring mode between streams
Lag time between results and actual sample	• None	• Depends on pipe length
Linear response of measurement	• Low. Deficient linear spectral response in mid and near IR	• High. Linear response of hydrogen content with spectral response
Reliability upon crude change	• Sensitive. Accuracy influenced by compounds, containing elements other than carbon or hydrogen atoms. Non-specific to chemical structures of the molecule	• No sensitivity to crude switching. Accurately quantifies specific hydrogen atoms. Specific to chemical structures of molecules
Stream temperature changes	• Lightly sensitive	• Insensitive

Table 1

that oppose the externally applied field, the effective magnetic field at the nucleus is reduced. Types of nuclei and chemical bonds in the molecule influence this phenomenon in different ways and enable the determination of the chemical structure of different species in molecules.

MRS is an electronic method and has the benefit of being applicable to measuring transparent, opaque and dense solutions alike. It can be used to quantify the physical properties of crude oils, the entire range of distillates, or any other refinery product.

The concept of MRS process analysers is based on the assignment and quantification of the different types of hydrogen atoms of organic molecules or water present in distillates or crude oils. The linear spectral response correlates accurately with the hydrogen atoms assigned to different molecular species of the substances that make up the refinery stream.

The spectrum is influenced by the nature of neighbouring chemical carbon-carbon bonds and neighbouring non-carbons in the molecular structure. Assignments can be made to identify whether these molecules are linear or branched paraffins, olefins, mono-aromatics, polyaromatics, heterocyclic, naphthenic, acids, oxygenates or water (see Figure 4).

In combination with the proper chemometrics, MRS technology is an effective tool to quantify physical properties of the following refinery streams: crude oil, naphtha, kerosene, gasoil, LGO, HGO, bottom residues and vacuum distillates by one single measurements. The physical properties include: density, API, IBP, FBP, T10%, T90%, RVP, flash point, pour point, cloud point, freeze pint, cetane number, PONA, benzene, naphthenes, paraffins, olefines, aromatic content and water.

The majority of currently available on-line process analysers are characterised by their high sensitivity to minor fluctuations in temperature. A newly developed MRS on-line magnetic resonance- based process analyser includes innovative hardware and software to eliminate this temperature sensitivity.

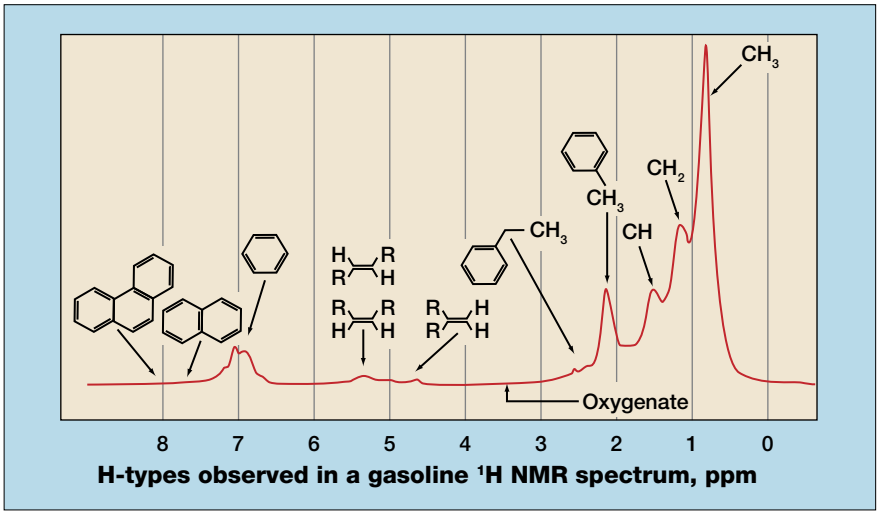

Figure 4 MRS spectrum of gasoline

Comparison of NIR and MRS

The characteristics of NIR and MRS technologies are summarised in Table 1.

Spectrometric methods in crude oil distillation units

Effective operation of crude distillation depends on maintaining the correct temperature profile within the atmospheric and the vacuum towers. It is a direct outcome of the composition of the crude oil and the range and quantity of distillates to be produced.

The composition of each individual distillate and its resulting physical properties is linked to the composition of the crude oil. To achieve maximum distillation yield, on-line monitoring of the crude oil composition is a basic requirement. By on-line monitoring of the physical properties and assay of the incoming crude oil feed, immediate corrections to the temperature profile can be established to maintain a constant stream of distillates. When crude switching occurs, only on-line monitoring of the crude oil assay minimises the impact of the switch on production capacity. Adjustments to process conditions can be implemented without delay and will reduce the impact of

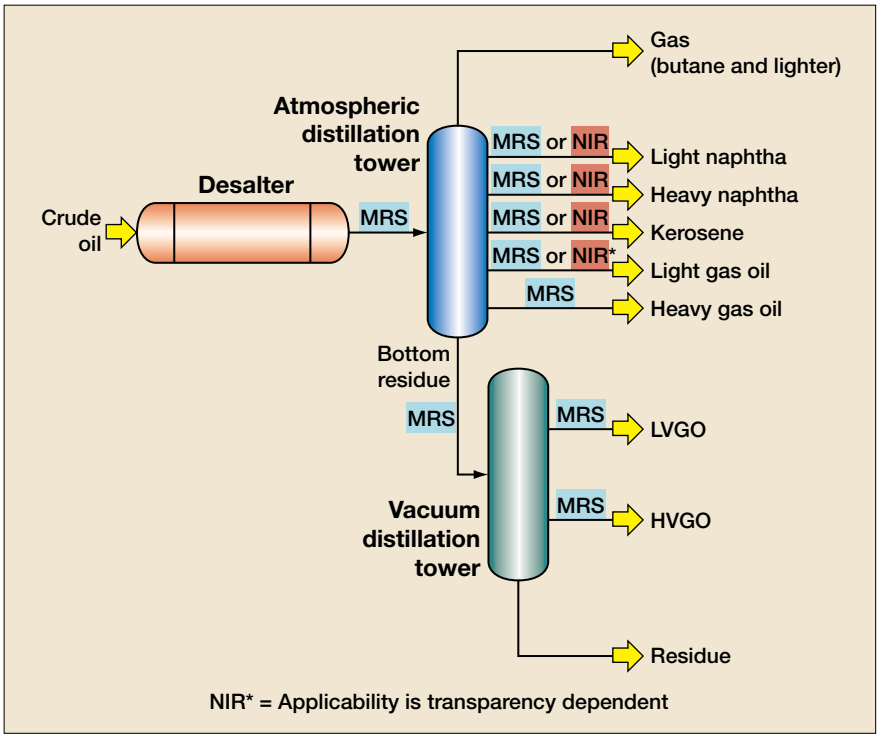

Figure 5 Implementation of NIR and MRS in the crude distillation unit

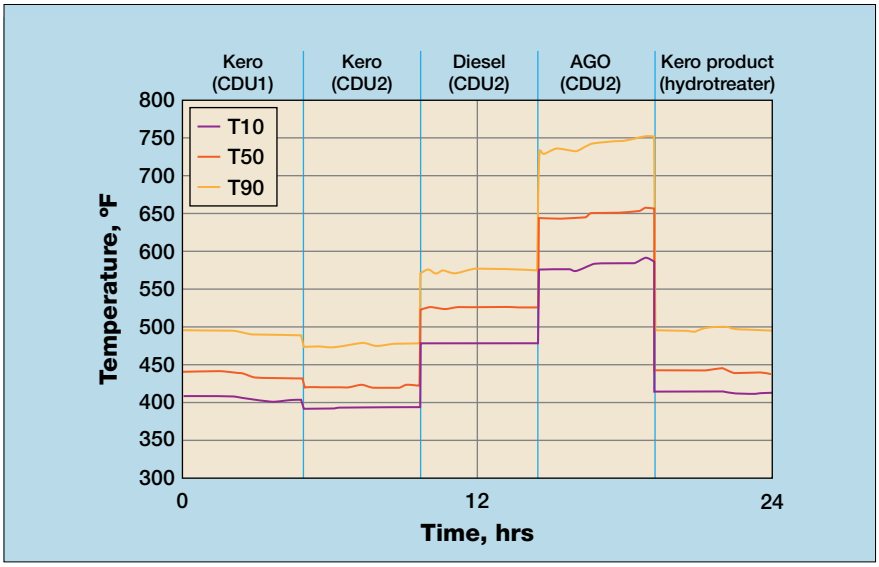

Figure 6 Measurement of crude unit rundown streams

crude switching on product yield and quality.

The limitations of NIR spectrometry as an optical method disqualifies its application to crude oils and heavy distillates. For this reason, only MRS analysers can be applied to crude monitoring.

Combined multiple measurement of the assay and other physical properties of crude oil, such as API number, water content, pour point and flash point, by a single analyser can provide full assessment and control of an incoming crude oil stream.

Monitoring of the distillates from the atmospheric tower can be partially established either by NIR process analysis or by a MRS-based analyser (see Figure 5). The method of choice depends on the transparency of the distillate stream to be measured. In principle, naphtha, kerosene and diesel oil are measurable by NIR and MRS alike. However, traces of heteroatomic molecules, which are present at different levels in crude oils, will distill alongside the required distillates. These molecules absorb light in the NIR region. If they are not included in the chemometric model, interference affects the accuracy of analytical results. This does not apply to MRS spectrometry. Heavier distillates such as heavy gasoil, atmospheric bottoms residue and the vacuum distillation products, LVGO, HVGO and bottoms residue are preferably analysed by MRS only.

A combination of NIR and MRS technology provides an efficient tool to manage all streams of the crude distillation tower for continuous fine-tuning of operating conditions to maximise the yields of distillates.

On-line monitoring of each distillate enables accurate determination of its upper distillation points (T90% - FBP) and its lower distillation points (T10% - IBP). It enables accurate cutting between two neighbouring distillates towards the fraction of higher value (kerosene in diesel, diesel in AGO) from the heavier cut (see Figure 6).

This is achieved by adjusting the distillation tower's temperature profile, while being in control of its response towards the qualities of the distillates. Uncontrolled adjustment of process conditions may lead to the production of off-spec distillates. On-line monitoring of the quality of distilled naphtha, kerosene and diesel is highly important. It indicates the stability of the process and prevents the risk of uncontrolled overshooting when changing the process conditions. Beyond that, any discrepancy in the process or the product quality can immediately be handled. The risk of producing unnecessarily off-spec or borderline materials is drastically reduced, so preventing the need for reblending or reprocessing. Smooth fine-tuning of process conditions can be completed without any risk of overshooting, and any discrepancy or malfunction in the crude distillation unit can be dealt with immediately.

Total on-line analyser management and control

Both MRS and NIR-based analysers are correlative methods. To achieve the highest available accuracy of the analysers, a full-distributed analyser management and control system has been developed. It provides an efficient tool for maintenance calibration and validation of the analyser systems. It is configured to be connected to remote systems. It monitors and records the operating state of the installed equipment and validates a wide variety of analysers and instruments. The software can monitor and control a wide range of analysers. A graphic display of data from multiple analysers provides historical data on analyser performance. Highest accuracy is achieved by two different modes of validation and calibration of the analysers:

- By running samples with the known quantities value of a required physical property
- By a continuous comparison of analyser readouts with laboratory results, referring to the same time of sampling.

The software manages validation procedures according to ASTM D3764. It performs alarm management and controls active streams to be sent to the analyser.

All measurements obtained from on-line analysers of the different streams are localised on one single display. An accurate overview of the quality of all individual process streams is provided to the operator, which enables efficient correction of process conditions to be made, which are based on the response of the operator's actions with respect to the changing physical properties of the streaming distillates. To maintain the highest accuracy, continuous calibration of the analyser is highly recommended.

Conclusion

Strict monitoring of all incoming and outgoing streams in the crude distillation unit is of the highest priority to ensure optimal perform-

ance of the distillation process. Laboratory analyses are time consuming and cause a lag between discovering any discrepancy in product quality and applying a corrective response. Optimal performance of the crude oil distillation unit can only be achieved by a continuous mode of on-line measurement of the physical properties and quality of each stream using accurate, calibrated on-line process analysers. This enables ongoing correlation between the crude oil and the various distillates, as well as between the distillates themselves. Many dedicated ASTM-based analysers are required to achieve this goal. However, their cost of installation and maintenance is high.

Spectrometry-based correlative analysers are able to perform simultaneous multiple measurements of a variety of physical properties. Spectrometry-based correlative on-line analysers provide full coverage of all incoming and outgoing streams, and enable operators to carry out immediate processing adjustments. These tools enable smooth and efficient operation of the crude distillation unit to produce the desired distillates at maximum yield. They also make it possible to minimise the impact of crude switching and maximise the yield and capacity of desired distillates by appropriate shifting of the cut points of the required distillation ranges.

The commitment of each refinery to increase its refinery margin is directly linked to its readiness to install an on-line multiple-stream process analyser. Before a decision is taken on which analyser system is most effective for a refinery, the differences in properties between the NIR and MRS methods should be taken into consideration. However, the best performance can only be achieved by an incorporation of both NIR and MRS technologies.

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