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Handling delayed coker disturbances with APC

An advanced process control system provides automatic detection of disturbances during drum switch in a delayed coker to raise performance levels

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A delayed coker unit (DCU) is an established candidate for the application of advanced process control (APC) with an attractive return on investment. The challenge in DCU-APC lies in handling the big disturbances that occur during drum switch-over and vapour heating events when the vapour enthalpy feed to the main fractionator is suddenly reduced. Timely actions need to be taken on several control loops to minimise the effects of sudden cooling of the column, which leads to large variations in coker gas oil quality as well as flow rates. The exact occurrences of these events are unmeasured and a conventional control system is not adequate to handle such big disturbances. The resulting economic losses due to quality give-away and off-spec product generation are substantial, not only in the DCU but also in downstream units where the disturbances are propagated. Hence continuous operator attention is required for managing these events.

Effective disturbance handling with APC requires DCS logic for unambiguous detection of the various events that lead to major disturbances in the downstream fractionation sections. Detected discrete events are then used for generating continuous disturbance functions, which, in turn, are utilised for multi-variable modelling as well as for predictive feed forward control, honouring multiple constraints. Since manual actions in the field are also involved in these events, the extent of disturbances varies in each coking cycle. This article also describes how intermediate variable and state observer (Kalman filter) concepts are utilised for robust control.

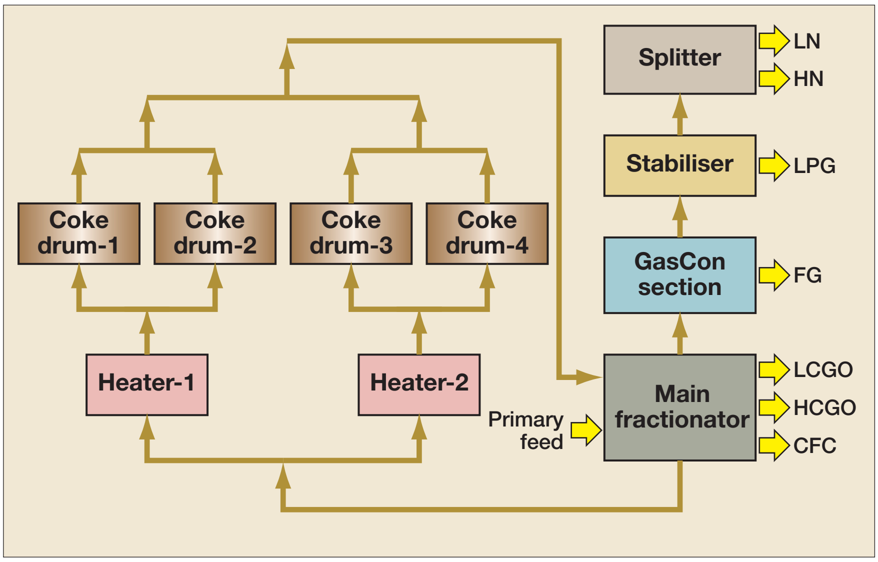

Figure 1 Block diagram of a typical delayed coker unit with two pairs of coke drums

A DCU is one of the most profitable refinery units. The process involves thermal cracking for upgrading (converting) asphalt-like residue, typically from the vacuum distillation unit, into lighter distillates, coker gas oils and solid coke, which are further processed into marketable fuel products such as LPG, gasoline, diesel, fuel oil and petroleum coke.

Delayed coking is a semi-batch process where one or more pairs of coke drums are used for the thermal cracking and coking process. Simultaneously in each pair of coke drums, one drum is online for the coking process while the other drum is offline undergoing decoking. **Figure 1** is a simplified block diagram of a typical delayed coker with two pairs of coke drums. Vacuum residue (fresh feed) after preheating (by exchanging heat with run-down streams), is injected into the main fractionator bottom. The fractionator bottom is heated again in the two coker furnaces to a high cracking temperature (about 500°C), and hot, partially cracked feed flows from the coker furnace into the coke drums, where cracking continues. Cracked distillate vapour ascends in the coke drum and flows into the fractionator where it is separated into wet gas, unstabilised naphtha, light coker gasoil (LCGO), heavy coker gasoil (HCGO), and recycle oil. Coke is deposited in the drum. Two drums (one from each pair) are online at one time, accumulating coke until almost full. About every 24 hours, the filled coke drum is switched off for coke removal and the empty drum is connected. The drum that was just filled goes through a cycle of steaming out, cooling, opening, coke removal, closing, steaming, pressure testing, heating, and

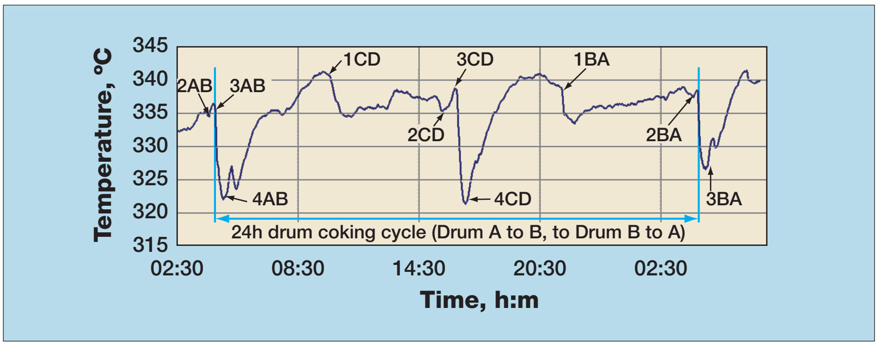

Figure 2 Variation in HCGO draw temperature during drum coking cycles of two drum pairs

finally reconnecting to the furnace and fractionator.

The semi-batch process poses unique challenges for APC in DCUs, and the challenges are discussed in this article.

Disturbances due to drum switch events

The operations of two pairs of coke drums are staggered, and the coking-decoking cycles in each pair are scheduled in such a manner that drum switch-over happens every 12 hours (twice in every day). Vapour from the furnace at about 500°C is passed through a specially designed four-way valve to the bottom of the drum which is in operation. Vapour leaving the top (after cracking and coke deposition) is quenched on temperature control to 425°C, and fed to the main fractionator bottom for separation of the product streams. About six hours before the drum switch-over, a portion of (quenched) hot vapour from the operating (on-line) drum is diverted from flowing to the main fractionator towards the offline empty drum for gradual 'vapour heating'. The hot vapour flows from the top vapour line of the empty drum and the condensate is removed from the bottom. The empty drum is gradually heated from about 150°C to about 300°C for six hours before eventual complete switch-over after every 24 hours. During drum switch-over, the flow of hot vapour to the top of the empty drum is stopped and is instead diverted to the bottom of the empty drum through a four-way valve gradually in three steps. In the first step, one-third of the vapour is diverted to the empty drum and two-thirds to the filled drum. In the second step, two-thirds of the vapour is sent to the empty drum and one-third to the filled drum. Eventually, the empty drum is taken on-line by diverting the entire (100%) vapour flow towards the empty drum and isolating the filled drum, and taking it off-line.

The load on the main fractionator thus varies widely due to drum switch events and feedstock quality fluctuations. The effects of vapour heating and drum switch events on the main fractionator temperature profile are shown in **Figure 2**, where the disturbances in the trend of HCGO draw temperature are shown for one complete coke drum coking cycle (24 hours). Two drum switches between the AB pair, from drums A to B and from B to A, occur at 24-hour intervals. Since the drum switches between two pairs of drums, AB and CD, are staggered (see **Figure 3**), two drum switches occur in a 24-hour period at 12-hour intervals. Each drum switch involves four major disturbance events (see **Figure 2**):

Event 1

The hot vapour is diverted for the purpose of vapour heating (of the empty offline drum) about six hours before the switch-over between the drums of a pair (AB or CD). The sudden and substantial reduction of vapour flow from one of the coke drum pairs disturbs the main fractionator.

Event 2

Once the drum is warmed up with vapour heating for about six hours, the vapour flow to the empty drum is stopped by closing the condensate drain (at bottom). Then, about one-third of the total hot vapour from the on-line drum is diverted to the bottom of the empty drum, by partly opening the four-way valve (at the bottom). As the direction of flow is changed, the lighter, uncondensed vapour hold-up inside the empty drum is flushed out, thereby suddenly increasing the vapour load on the main fractionator and increasing the temperature profile.

Event 3

The drums are completely switched. Vapour from the furnace is completely diverted towards the empty drum and the filled drum is isolated, thereby taking the empty drum on-line. The temperature in the drum is around 400°C, which is much less than that required for cracking. The cracking reaction is abruptly quenched, causing a major disturbance to the main fractionator as both the heat and vapour mass flow are suddenly reduced.

Event 4

As the empty drum heats up, the cracking reaction gradually resumes. The temperature and vapour flow to the main fractionator increase gradually over the next 3-4 hours.

APC design challenges

The main fractionator is the key unit operation in the DCU and determines product yields and quality. The major disturbance to the main fractionator occurs during switch-over (see Event 3 and **Figure 2**) where the vapour flow from one of the drum pairs is almost cut off for a few minutes as the thermal cracking reaction is quenched due to lower temperatures in the empty drum. The heat as well as mass flow to the main fractionator bottom are reduced abruptly, resulting in sudden cooling of the column. The effect of this disturbance can be minimised by pre-emptive and quick manipulation of the circulating refluxes, product flows and other heat duties in order to restore the mass and heat balances. If timely actions are not taken, the column tends to cool down, resulting in quality give-away and off-spec generation due to condensation of the valuable

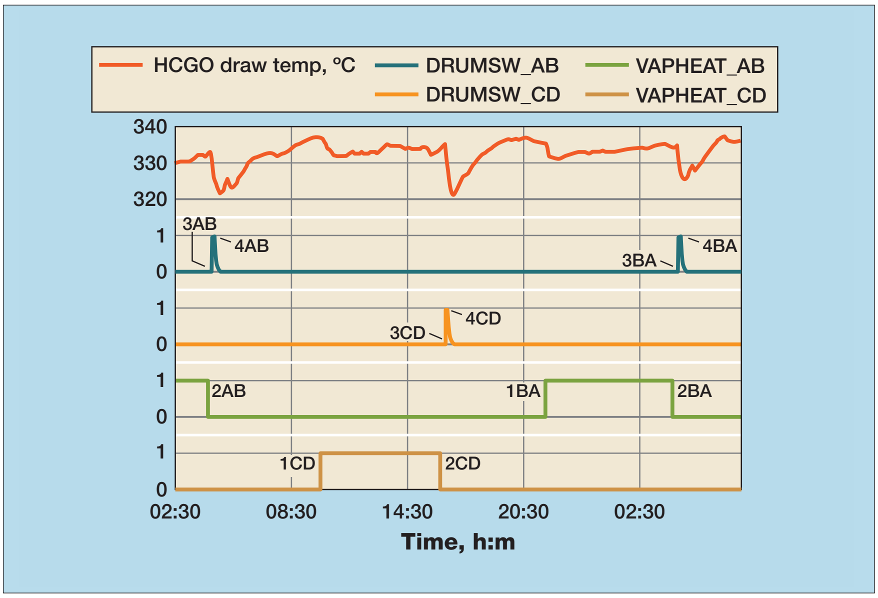

Figure 3 HCGO draw temperature vs (inferred) drum switch disturbances

lighter components into heavier product streams. The sudden changes in product flows can also lead to upsets in tray and side stripper levels. The large variations in product qualities and flows result in economic losses not only in the DCU but also in downstream units where the disturbances propagate.

The conventional (feedback) control system is not adequate for handling these sudden and big disturbances. Hence continuous operator attention is essential. APC comprising multivariable predictive control (MVPC) and inferential quality estimators has long been established as a promising solution for stabilisation of the DCU. However, design and implementation of APC for the DCU involves unique challenges discussed in the following sections.

Automatic detection of drum switch events

The automation of drum switch disturbance rejection is the most important part of DCU APC. However, there are no specific measurements for directly identifying the various drum switch events. These events must be logically inferred from various switch positions and measurements in each pair of coke drums. Furthermore, events detection must be unambiguous as false detection would lead to unnecessary control actions, which may cause upsets during stable operation. The various events described above and shown on the HCGO draw temperature trend in **Figure 2** are detected (using logical conditions) as pulses, and continuous disturbance functions are generated to represent disturbance dynamics. The HCGO draw temperature trend shown in **Figure 2** is reproduced along with drum switch disturbance trends in **Figure 3**.

Step test and model identification

Dynamic models are the backbone of MVPCs. Hence, step test in stable plant conditions is crucial for APC design and performance. However, coker units are rarely at a steady state. Drum switches occur every 12 hours and each switch is associated with two major disturbances: vapour heating and drum switch. As seen in **Figure 2**, the temperature profile in the main fractionator is rarely steady throughout the day due to major mass and enthalpy disturbances. Furthermore, the vapour composition keeps changing with states of coker operations and also due to feedstock changes.

Consequently, the plant is available in a relatively stable condition for just 3-4 hours in a 24-hour period, requiring excessively high step test time. Also, as the operating conditions keep changing during different modes of coker operation, the dynamic models are expected to be different. Hence for robust design, it is essential to account for disturbances as inputs for modelling and obtain the 'average models' that would be valid for all stages of the coking cycle.

Since disturbance events are measured, it is possible to include these events as inputs for multiple input single output (MISO) model identification. **Figure 4** shows a step test on HCGO circulating reflux (HCGO-CR) with the response of HCGO draw temperature. It can be seen that the variation in HCGO draw temperature, which is completely dominated by disturbance variables, could, in fact, be satisfactorily represented by a MISO model.

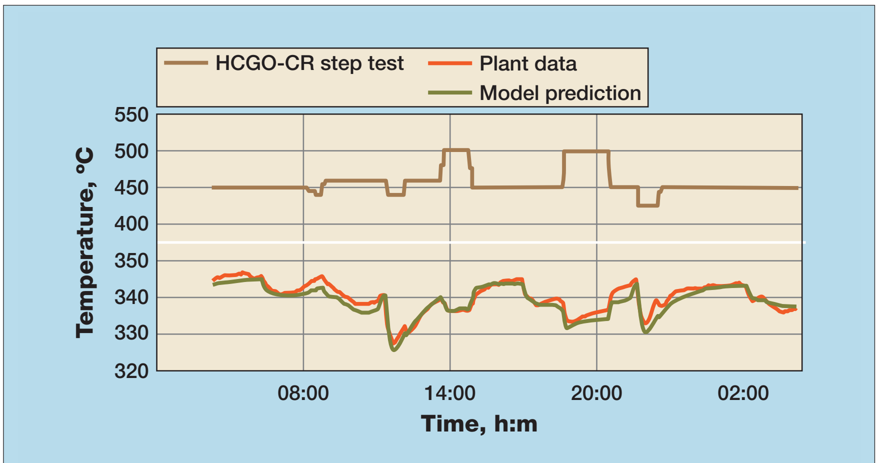

Figure 4 MISO model identification with drum switch events as measured disturbances

Conflicting constraints and change in control priorities during drum switch

In the main fractionator, the HCGO components are partly condensed with a circulating reflux stream, wherein part of the vapour enthalpy is recovered at a higher temperature, mainly by preheating the feed stream and by providing reboiler heat duty for the debutaniser column.

During drum switch-over (see Event 3 and **Figure 2**), the vapour flow and enthalpy of the feed vapour are substantially reduced. In order to maintain heat balance, heat removal from the HCGO circulating reflux needs to be reduced proportionately. However, reduction in HCGO-CR is mostly constrained by the feed preheat requirement. Though the heat input to the column is reduced during the drum switch, the fresh feed to the DCU remains unchanged, which results in cooling of the feed stream. The reduction in feed preheat due to the reduction in HCGO-CR further cools the feed stream, resulting in a higher furnace heat load, which in many cases is limited by skin temperature constraint. The limitation on the reduction in HCGO-CR results in excess heat removal from the HCGO-CR circuit, which in turn leads to cooling of the lower section of the column. The valuable LCGO components are condensed with HCGO, resulting in quality give-away and the loss of internal reflux from the LCGO draw tray.

During stable operation, when the draw temperature is reduced, the product flow is increased to restore the temperature and maintain the quality of the product. The steady state material and heat balances are ensured with inventory and temperature (or quality) control strategies. However, as previously explained, as the column tends to cool down during the drum switch, the control priorities must be changed and, despite the reduction in temperature, the LCGO product flow must be reduced to ensure minimum internal reflux flow from the LCGO product draw tray. The priorities for temperature control should be restored once the vapour flow increases sufficiently after the drum switch-over. These issues must be addressed satisfactorily in APC design to ensure robust automation during drum switch.

Unmeasured disturbances

Process dynamics in the DCU are dominated by unmeasured disturbances, mainly due to drum switch events and feedstock changes. The occurrence of particular types of discrete events can be inferred from various operating conditions. However, as some of the drum switch operations are carried out manually in the field, the extent of disturbance for each event differs in each coking cycle. Hence the models obtained for these disturbances are approximated. A robust control strategy must deal effectively with these modelling errors, process or measurement noise, and unmeasured disturbances. The control algorithm for handling unmeasured disturbances forms one of the important differentiating features of MVPC technologies.

Shell multivariable optimising control (SMOC) is known for its

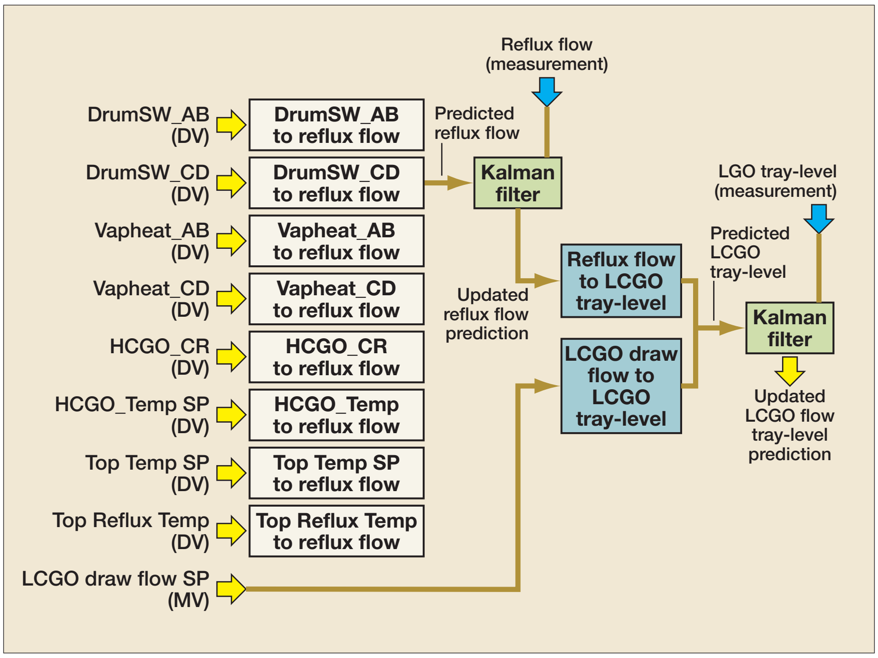

Figure 5 Grey box representation of a LCGO tray level prediction model with reflux flow as an intermediate variable

unique way of handling unmeasured disturbances with grey box model representation, involving feedback from measurements of intermediate process outputs (called 'intermediate variables'), and also for its use of the Kalman filter (state observer) as an output feedback mechanism. There follows an example of an intermediate variable for robust control of the LCGO tray level in the presence of unmeasured disturbances in the main fractionator.

The LCGO tray tends to lose level rapidly during the drum switch event as LCGO components condense in the HCGO section due to over-cooling caused by excess heat removal in the HCGO circulating reflux circuit. The level is controlled by aggressive manipulation of the LCGO draw flow. The level loss implies a loss of internal reflux from the LCGO tray, which affects fractionation between LCGO and HCGO. However, for aggressive manipulation of the LCGO draw flow, it is essential to predict accurately the future behaviour of the LCGO tray level, which is only possible if all the variables affecting the LCGO tray level are measured and their effect on the level is accurately modelled.

The LCGO tray level is affected by several factors. While the most important variables like feedstock composition are unmeasured, the following variables are measured:

1. Drum switch for pair AB
2. Drum switch for pair CD
3. Vapour heating for Pair AB
4. Vapour heating for Pair CD
5. LCGO draw flow
6. HCGO-CR flow
7. HCGO-CR return temperature
8. Total secondary feed flow to furnaces
9. Top temperature set point
10. Top reflux temperature

Among these variables, the most important models involving drum switch related disturbances are only approximated; hence the level control is not expected to be robust. However, with a better process understanding, it is known that all the inputs listed, except for LCGO draw flow, do not directly affect the tray level. These inputs affect the vapour flow to the top section, which in turn, depending on the top temperature set point, determine the reflux flow from the top section of the column. Thus, only reflux flow and LCGO draw flow directly affect the LCGO tray level. This process knowledge can be utilised for grey box representation with measured reflux flow as an intermediate variable, relating several inputs to the level output (see **Figure 5**).

The feedback from reflux flow (intermediate variable) is used for correcting the model prediction using a Kalman filter, which mini-

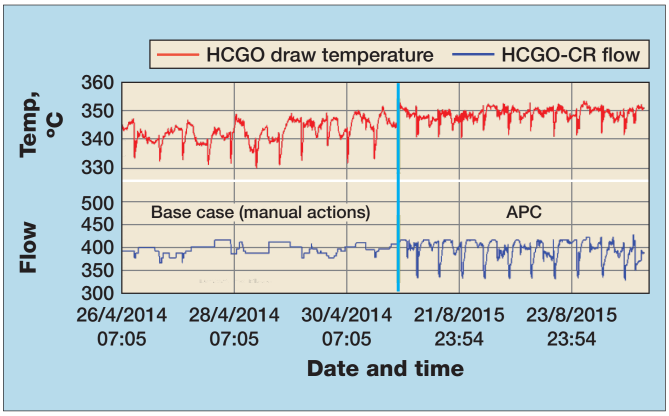

Figure 6 Improved control and maximisation of HCGO draw temperature with aggressive manipulation of HCGO-CR flow with APC

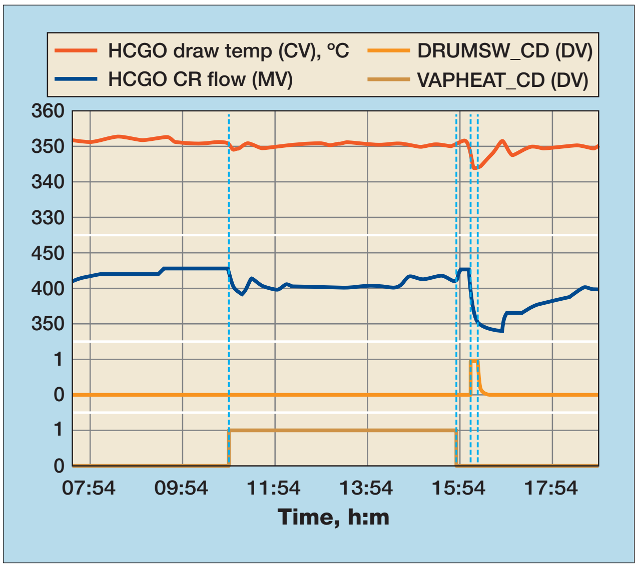

Figure 7 Control of HCGO draw temperature by feed-forward actions on HCGO CR flow for each drum switch related event

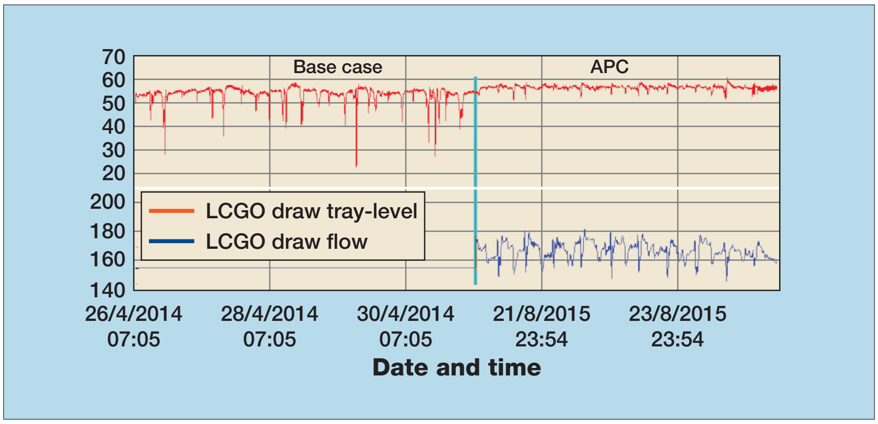

Figure 8 Better control of LCGO tray level with feed-forward actions on HCGO-CR and LCGO draw flows

mises the effect of unmeasured disturbances. Kalman filtering, also known as linear quadratic estimation (LQE), is an algorithm that uses a series of measurements observed over time, containing statistical noise and other inaccuracies, and produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone. Thus the concept of intermediate variable and Kalman filter, along with process knowledge, is used for robust control in the presence of unmeasured disturbances.

Disturbance rejection with APC

The inferred drum switch events are used as disturbance variables for predictive feed-forward control. The onset of these disturbances predicts the wide variation in column temperature profile and product qualities, thereby providing feed-forward compensation by making aggressive moves on circulating refluxes and product draw flows. As **Figure 6** shows, the HCGO draw temperature control significantly improved due to timely and aggressive actions with APC (standard deviation reduced by 45%). The draw temperature is maximised by a reduction in heat removal from the HCGO-CR circuit, thereby increasing LCGO yield (by about 2%).

Figure 7 shows how timely feed-forward actions are taken with APC on HCGO-CR flow for each drum switch related event for effective disturbance rejection.

Figure 8 shows that, before APC, due to excess cooling of the column, LCGO was condensing on the HCGO section, resulting in a loss of LCGO tray level and internal reflux. With APC, pre-emptive actions are taken on HCGO-CR and LCGO draw flows, which ensures that the level is stable with sufficient internal reflux. This ensures better fractionation between LCGO and HCGO products, with a maximum yield of valuable LCGO product.

Conclusion

An APC system has been successfully implemented in a DCU with very high uptime (exceeding 95%). Automatic and unambiguous detection of various types of events involved in the drum switch, and the reliable handling of these disturbances, are the main challenges in APC design and implementation. Process stabilisation with effective disturbance rejection, while honouring conflicting constraints, results in substantial tangible benefits from product upgrading and throughput maximisation.

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