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Temperature fluctuations in down-fired reformer furnaces

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The reformer furnace is the largest and most expensive equipment item in a conventional syngas plant. Though the overall operation of the reformer is simple in concept, there are several known problems that occur in the operation of some reformers. These problems are not universal with all down-fired reformers with some reformers affected while others of similar design are not affected. For down-fired type of reformers, one of the complications that can result during operation is evidenced by large swings in reformed gas outlet temperatures and tunnel exit flue gas temperatures. These temperature swings are transient in nature and seem to appear randomly with apparently no explanation. Some operators have observed these temperature swings during turndown or startup but they have also been observed during normal operation. Catalyst tube and outlet pigtail failures have occurred as a result of this behaviour causing unsafe operating conditions and costly shutdowns.

A number of studies have been conducted by BD Energy Systems personnel to investigate the cause of these temperature swings and determine the actions required to correct this behaviour. It has been determined that the design of the arch burners plays a critical role in correcting this operational anomaly. This paper addresses the factors involved in these temperature swings and the corrective action that can be taken to rectify this problem.

INTRODUCTION

Down-fired reformers have the same general layout of the radiant section with rows catalyst tubes located between rows of burners. Flue gas tunnels are located at the floor level directly beneath the burners to collect the flue gas and transport it to the convection section for heat recovery.

The design of the radiant section as a whole should result in balanced firing, uniform catalyst tube metal temperatures, uniform coil outlet temperatures, and the straight flow of flue gases down to the collection tunnels. In general, the designs of most reformers result in these goals but it has been observed that some reformers develop a severe problem of temperature fluctuations in the coil outlet temperatures. Even reformers of the same design have been observed with one reformer operating as designed while another experiences the swings in temperature.

This paper addresses the approach taken to identify and correct this problem.

THE PROBLEM OBSERVED

These events are transient with some reformers experiencing swings several times per day while other reformers have had swings occur only once or twice per day. Some reformers have been observed to operate several days without any swings and then swings seem to occur without notice or cause. Though these changes in temperature have been observed to affect the coil outlet temperatures to varying degrees across the entire reformer, the swings usually affect one or two catalyst tube rows to a much higher degree than the other tube rows. CFD analyses have also indicated that only a few catalyst tubes on a single tube row affected by the temperature swing account for the entire temperature swing in the coil outlet temperature.

The following two figures illustrate this problem with plots of the process temperatures exiting the catalyst tubes in the collection headers. It should be noted that the firing conditions of the reformer including fuel flows, fuel pressures, combustion air distribution, and excess air were examined and were found to be normal with no imbalances that would account for the swings in temperature. It should also be noted that the swings do not occur in regularly spaced patterns, but are random in nature.

Figure 1 shows the temperature fluctuations experienced in a large methanol reformer over a period of eight hours. It can be seen that the largest fluctuations occurred in Row A followed by Row B which is located next to Row A. Rows C and D are located three and seven rows, respectively, away from Row A and on the opposite side of Row A than Row B. Row D is relatively constant by comparison to the other three rows but this figure illustrates that several rows of tubes are affected by these temperature swings.

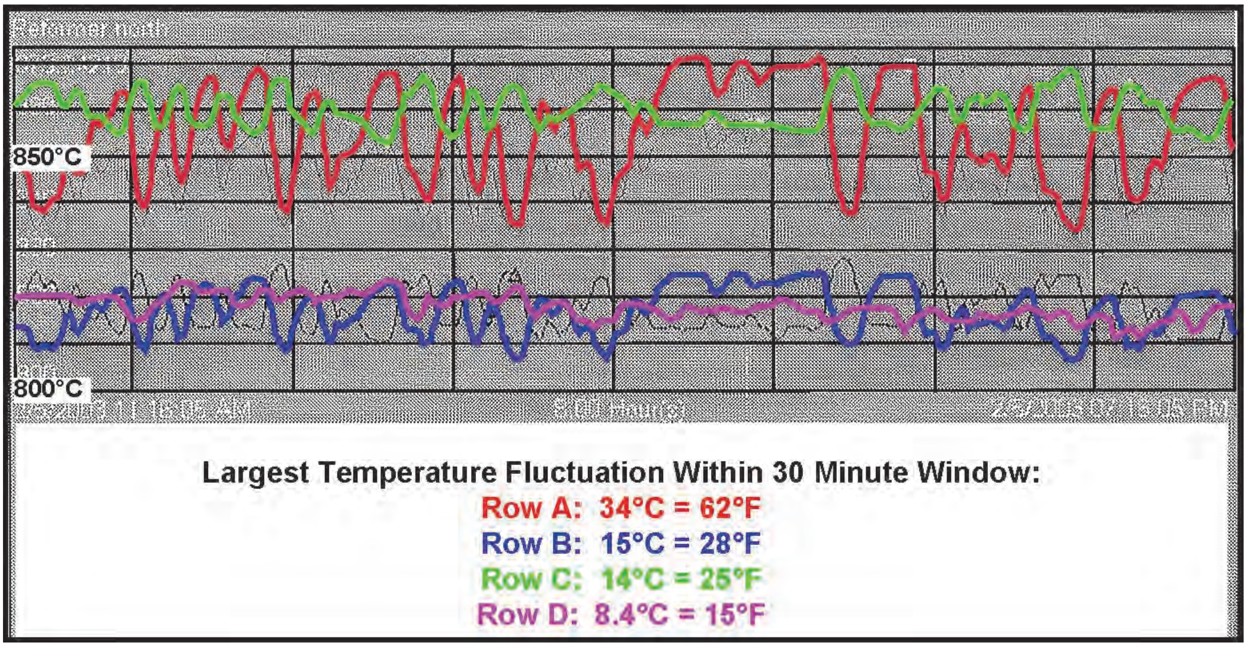

Fig. 1: Process Outlet Temperature Fluctuations in a Methanol Reformer

Figure 2 is another illustration of this behaviour. This figure shows the temperature fluctuations in a moderately sized hydrogen reformer over a period of six hours. The largest temperature swings can be plainly seen in Header A. It is also apparent that when the swings occur, that the entire furnace is affected to varying degrees as evidenced by the corresponding temperature fluctuations in the remaining headers. Header B has the next highest change in temperature and is located four rows from Header A while Headers C and D are located two and three rows, respectively, from Header A.

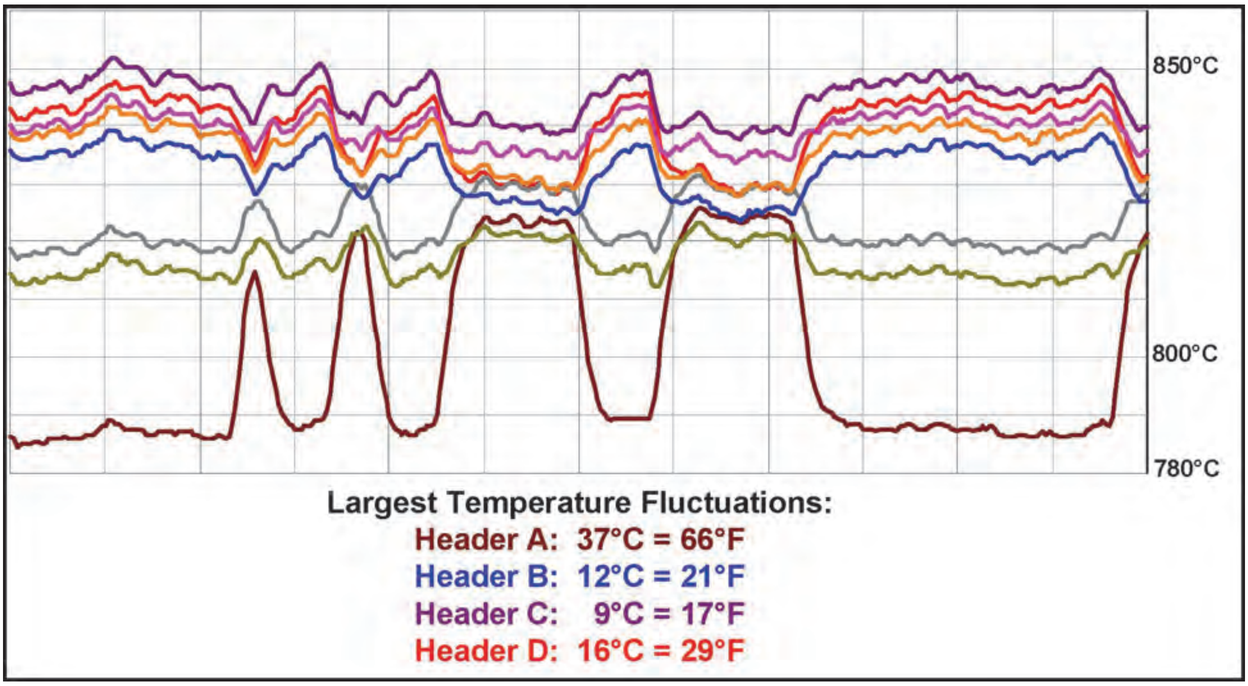

Fig. 2: Process Outlet Temperature Fluctuations in a Hydrogen Reformer

Figure 3 is a plot of the tunnel exit flue gas temperatures that correspond to Figure 2. Though all of the trends do not show correspondingly large swings in flue gas temperature, the temperature of those tunnels that do react generally moves in the opposite direction of the process temperature swing.

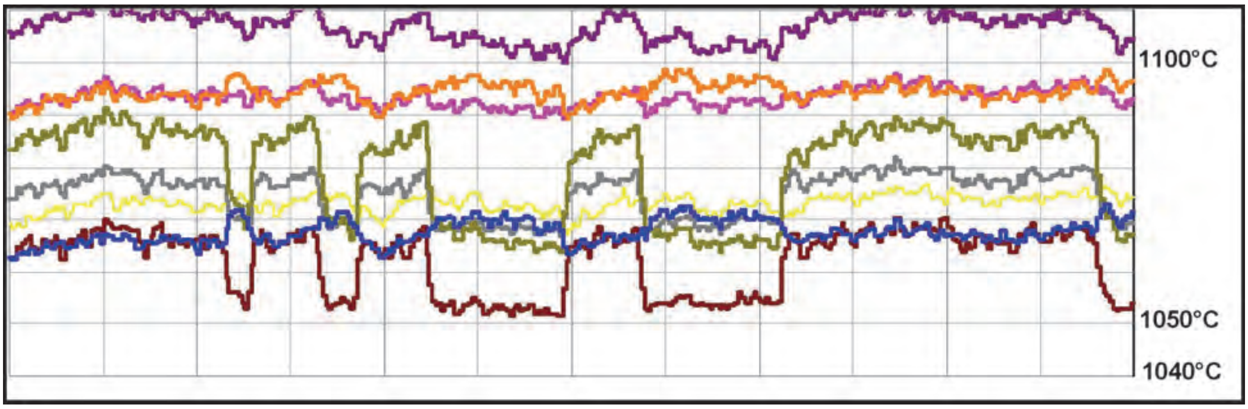

Fig. 3: Tunnel Flue Gas Outlet Temperatures Corresponding to Figure 2

THE EFFECTS

This phenomenon has been observed by BD Energy Systems' personnel in several reformers over a period of over twenty years. At least one other paper by Barnett and Wu has addressed this behaviour in one methanol reformer.[1] It is known that in both of the reformers mentioned above, this phenomenon resulted in catalyst tube failures. These failures were in localized areas of the radiant section as opposed to being wide-spread. When this behaviour was first being analysed several years ago, computational fluid dynamics (CFD) modelling was limited both in its development and in computational power to drive it. Since then CFD has become a much more powerful analytical tool.

In the case of the hydrogen reformer mentioned above, CFD analysis was performed to determine the flow and behaviour of the flue gas flow patterns inside the radiant section. The results of the CFD run confirmed what had been experienced in the field, namely that the catalyst tubes connected to Header A were being affected to a much higher degree than the remaining tubes. A tube rupture had occurred in one of the tubes connected to Header A and several tubes next to the ruptured tube indicated signs of excessive creep damage compared to the remaining tubes.

The CFD analysis indicated that approximately 25% of the catalyst tubes on Header A were being overheated and were the cause for the 37°C increase in the combined process fluid temperature. A weighted average calculation indicates that the process outlet temperature in the 25% tubes would need to increase by 140°C (255°F) to bring about a combined increase of 37°C with a corresponding increase of maximum calculated tube metal temperature (TMT) of 149°C (270°F). This is a large change in temperature and in this specific case, caused the catalyst tubes to exceed their maximum allowable temperature on a recurring basis leading to the tube failures and in some cases outlet pigtail failures.

These swings also have long term negative effects with regards to the constant overheating and cooling of the affected catalyst tubes which creates a crushing effect on the catalyst inside the tube due to the expansion and contraction of the tubes. This can lead to higher pressure drop in these tubes resulting in lower flow and therefore less cooling via reaction, further exacerbating the higher TMTs experienced by these specific tubes.

The Problem Defined

In the past, both CFD modelling and Cold Flow Modelling have been used with similar results defining the cause of these temperature swings. The CFD modelling used in the case of the hydrogen reformer reaffirmed what has been identified in the past as this main cause of the temperature fluctuations.

All down-fired reformers have flue gas recirculation patterns that develop during the normal operation of the reformer. For most reformers, this recirculation of flue gas occurs at a point in the furnace where the impact on the flame shape is minimal. Larger scale reformers tend to develop stronger currents and the burner flames in methanol and hydrogen reformers, which usually have higher concentrations of hydrogen in the fuel, tend to be shorter and more susceptible to this effect.

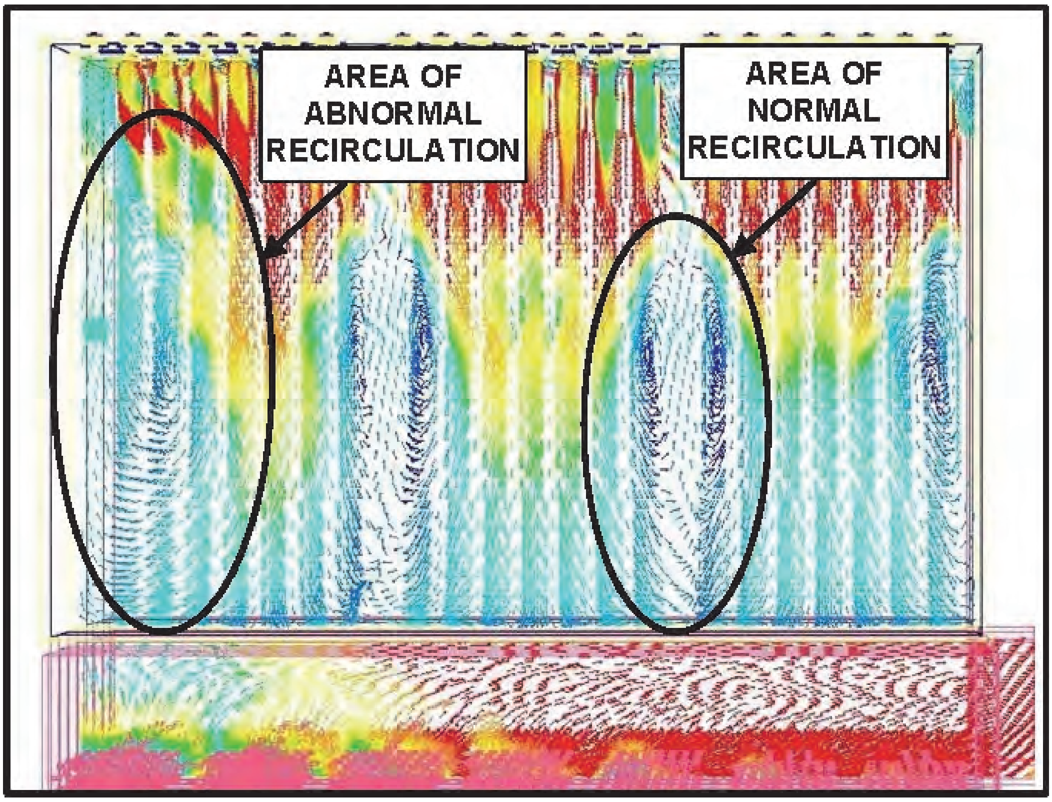

Fig. 4: Flue Gas recirculation Patterns

Figure 4 illustrates two flue gas recirculation regions with one region indicating normal recirculation while the second region shows an abnormal recirculation pattern.

The main causes that have been found for these temperature swings is an insufficient burner flame momentum, an inconsistent burner momentum from row to row, or a combination of the two. Some of the reformers the authors have studied were experiencing problems due to an inconsistent momentum between burner rows. These inconsistent levels in momentum are a key factor in creating areas of abnormal flue gas flow patterns. In the case of the hydrogen reformer the cause for the temperature fluctuations was both an inconsistent momentum between burner rows and an overall low momentum in the design of all the burners. The following is a step by step explanation of the development of the flue gas pattern that led to the high TMTs in the affected catalyst tubes.

First Event: Recirculation of Flue Gas at Burner Row B1

A difference in burner momentum between burner rows can be the result of an imbalance of combustion air but is more often cause by designing the outside row burners to fire at a lower rate, usually 60% to 70% of the inside row burners. While this design practice is highly recommended, there are instances where the downsized burners were not designed to deliver the same momentum as the full size burners. Because of this lower momentum, the burner flame rigidity is low and a recirculation pattern develops early in relation to the downward flow of the flue gas. This can be seen at Point 1 in Figure 5 in burner row B1. This recirculation pattern also causes the flame to lean toward the catalyst tube row T1. Figure 6 reveals that this recirculation also occurs in the plane of the burner row which increase the volume of the recirculation zone.

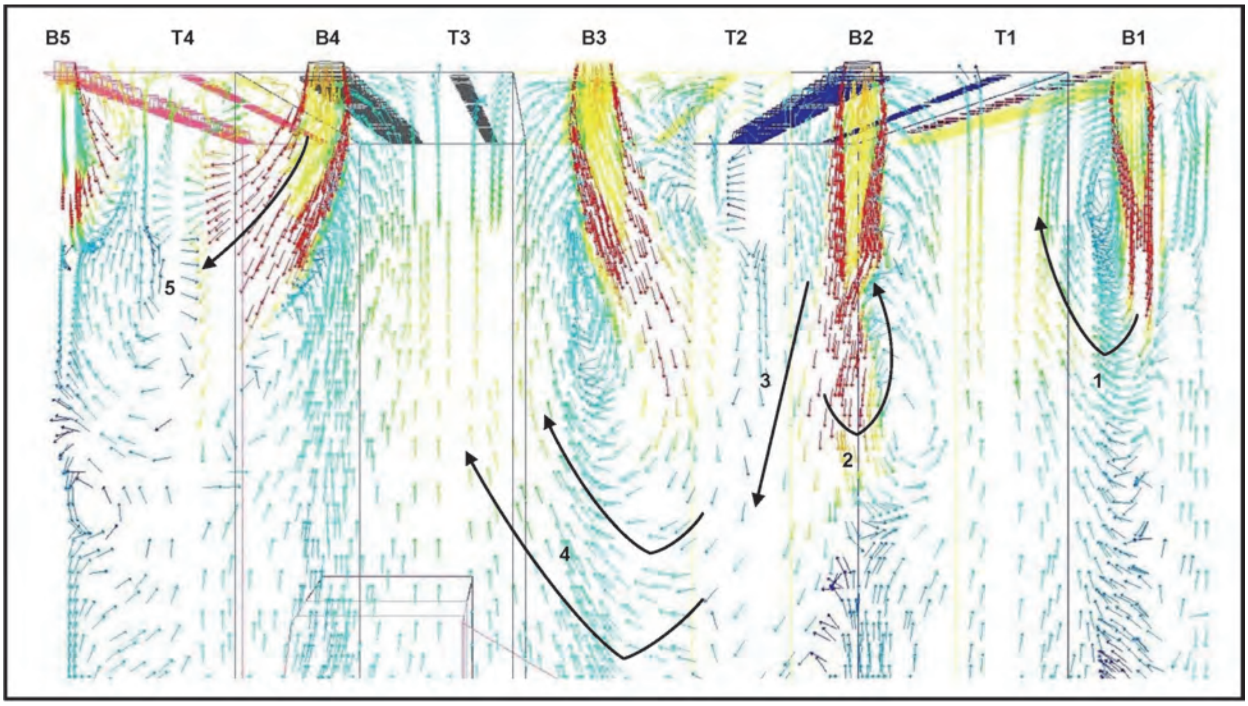

Fig. 5: Development of Abnormally Large Flue Gas Flow Pattern

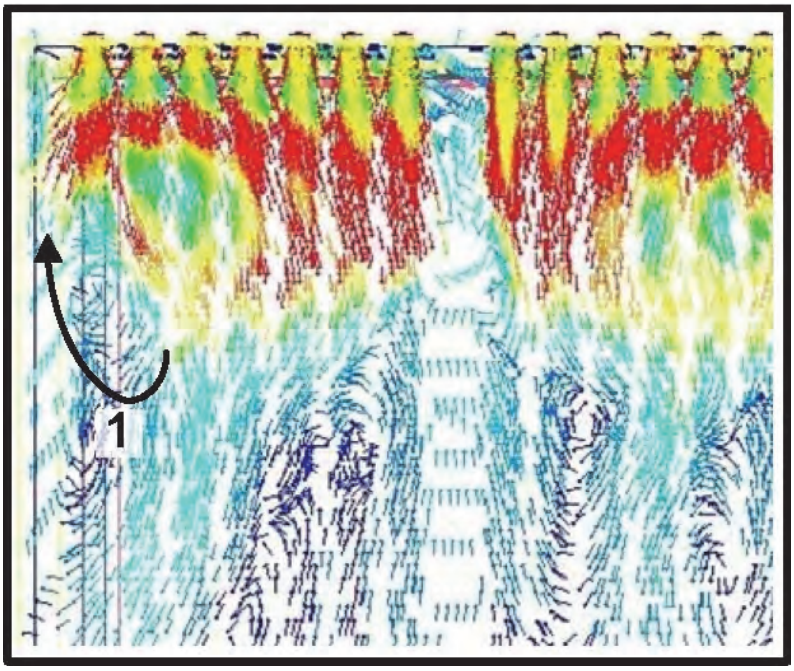

Fig. 6: Recirculation Pattern in Burner Row Plane

Second Event: Pushing of Burner Row B2 Flame Pattern

While past studies have shown that the magnitude and direction of the momentum is an important design aspect of the burner, other studies done by BDES personnel have shown that other reformers with burners designed with consistent but low momentum were susceptible to the same type of recirculation patterns. Calculations have shown that the momentum of the burners in the hydrogen reformer have a similar low magnitude in comparison to other reformers with similar flow instability problems. This suggests that there is a minimum threshold for burner flame momentum, below which the flow direction of the burner flame is at risk of distortion by the flue gas recirculation patterns.

As the recirculation pattern from row B1 develops, it reduces the amount of space between rows B1 and B2 for the row B2 burners to recirculate properly and basically “pushes” the row B2 flame towards catalyst tube row T2.

Third Event: Interference with Burner Row B3

As burner row B2 is pushed toward catalyst tube row T2, it causes a change of direction in the momentum of burner row B2 (point 3) towards burner row B3 which pulls the flame pattern of burner row B3 toward burner row B2. Note that this effect would be minimized or overcome if the burners had a higher magnitude in momentum resulting in a stiffer flame.

Fourth Event: Establishment of Large Recirculation Zone Between Burner Rows B3 and B4

The result of burner row B3 bending toward catalyst tube row T2 is that the momentum effect on burner row B4 is minimized and the flame of burner row B4 is now pulled toward burner row B5 because there is no counter-effect from burner row B3 (Point 5). This creates a very large recirculation zone between burner rows B3 and B4 (Point 4) which exacerbates the bending of burner rows B3 and B4. These effects can be further understood by noting:

- There is virtually no upflow between burner rows B2 and B3. The velocity vectors indicate all downflow at this location
- There is virtually no downflow between burner rows B3 and B4. The velocity vectors in this region indicate all upflow.

This large recirculation zone is the same region where the catalyst tubes experienced the highest temperature fluctuations and where the catalyst tubes experienced noticeably higher creep damage and where the catalyst tube failures occurred.

APPROACH TAKEN TO CORRECT THE PROBLEM

As stated above, CFD analysis was conducted to evaluate the flue gas flow patterns and burner flame shapes in the radiant section. Heat absorption by the catalyst tubes, the combustion envelope, and the flue gas collection tunnels were included in the model in order to perform a more complete analysis. Past studies have been performed which utilized a step-by-step approach to determine the cause of temperature fluctuations by making several adjustments to the radiant section including adjusting flue gas tunnel openings, narrowing the outside burner lanes, adding staged fuel risers, and inserting partitions between burner lanes among others. The conclusions resulting from these studies are summarized in the following paragraphs.

Adjustments to Flue Gas Tunnels

Four different modifications were made to the tunnels. These modifications include:

- The number of openings in the tunnel side wall were adjusted
- The top of the tunnels were removed.
- The overall tunnel pressure drop was increased
- Short partitions were installed on the top centreline of the tunnels.

These modifications were modelled with no visible or measurable effect on the flue gas recirculation flow patterns with the exception of the removal of the tunnel tops. This adjustment slightly lessened the severity of the recirculation patterns but created a secondary problematic flue gas flow pattern with the flue gas flow bending towards the exit end of the tunnels.

Combustion Air Distribution

The flow of combustion air to each burner row and burner was analysed and the overall distribution was determined to be uniform to the degree that it was not a factor. However, in one case the excess combustion air was increased from ~10% to 30% thereby increasing the momentum of the flame and the magnitude of the temperature fluctuations decreased though they were not eliminated.

Burner Modifications

Modifications made to the burners resulted in favourable responses in the flue gas recirculation patterns. Several modifications were analysed with some modifications having a greater and more favourable effect that others. The following is a summary of the more favourable changes made.

- The addition of staged firing tips increased the momentum, length, and stiffness of the flame making it less susceptible to strong flue gas recirculation patterns. The number of staged tips and the size and angles of the firing ports also play an important part in making this modification work.
- Most burner tiles have a burner throat that diverges as the fuel and air leave the burner. Narrowing of the burner throat and reducing the diverging angle also aid in producing a stronger flame pattern and reducing abnormal recirculation patterns.

The addition of staged tips and narrowing of the burner throat, both of which result in a higher velocity and thus a higher momentum, reduced the temperature of the flue gas in direct contact with the catalyst tubes by 320°C (575°F). In one case, the flow to one centre row of burners was reduced by 10% which resulted in a large area of recirculation and when the flow was restored to normal, the normal flue gas pattern was re-established within ten minutes.

CONCLUSIONS AND RECOMMENDATIONS

All of the modifications tested on the burner lead to the conclusion that the momentum of the burner flame is important in establishing normal and stable flue gas recirculation patterns in the radiant section. Studies have shown that both the magnitude and consistency of the momentum between burner rows is also important.

The reformer is the largest and most expensive item of equipment in a conventional syngas plant. The catalyst tubes are also expensive due to the high degree of metallurgy of which they consist and the failure of one tube can lead to very costly downtime in the unit. With the affordable cost of CFD modelling available now, it is reasonable to run CFD analyses on the entire radiant section of a reformer to identify and minimise any potential operational problems. While analysing the radiant section, the following items should be considered:

- The burners should be designed primarily for the normal operating fuel with startup fuel performance as a secondary consideration.
- Shorter, wider flames are more prone to distortion than longer thinner flames. The short wider flames also allow less space for recirculation to occur.
- The outside row burners need to be designed with a higher velocity to match the momentum of the inside row burners.
- Both the uniformity of the momentum between burner rows and the magnitude of the momentum are important.
- The combustion air distribution should also be analysed for uniform delivery of combustion air.

References:

1. Flue-Gas Circulation and Heat Distribution in Reformer Furnaces, Daniel Barnett & Deyuan Wu, Ammonia Technical Manual, 2001.