Burner-to-burner interaction is a phenomenon that is characterised by the creation of a dense fire cloud, an increase in NOx emissions and an altered heat flux distribution in the furnace. It occurs frequently in multiple-burner heaters, where vertical cylinder heaters have been observed to have the severest interactions. Although this problem has been around for a while, it has not been well understood. Only ad-hoc solutions have been introduced to mitigate it. However, a comprehensive study has now been completed, which reveals a dimensionless interaction parameter that could identify conditions that are likely to produce burner-to-burner interaction. Observations of interactions were made on lab-scale, small-scale and full-scale burners to validate the parameter.

Two case studies are presented using CFD modelling. The first study shows that interaction was unlikely in a vertical cylindrical furnace where the spacing between burners was decreased. The other study confirms interaction observed in the field and suggests modifications that were successfully implemented and led to the elimination of burner-to-burner interaction. Specific rules of thumb, which are based on experience, are given to predict the likelihood of interactions in ethylene-cracking furnaces.

The problem
In response to the increased demand to reduce NOx emissions from industrial heaters, new burner technologies have been developed to meet the more stringent emissions regulations. Most of these technologies use some type of furnace gas recirculation (Figure 1) to reduce the flame temperature, so that thermal NOx emissions can be reduced substantially. However, diluting the fuel-air mixture with furnace gases results in lower burning rates, which often makes the flames significantly longer. Both longer flames and increased volumetric heat release density (Btu/hr/ft$^3$ or MW/m$^3$) in the newer multi-burner industrial furnaces have led to frequent occurrences of a phenomenon often referred to as burner-to-burner (BtoB) interaction.

The occurrence of this phenomenon is indicated by the formation of a large, bright yellow fire cloud and by an increase in NOx emissions compared to single-burner performance. Although this problem has been observed in all types of multi-burner heaters, it is much more severe in vertical cylindrical heaters compared to other types such as cabin heaters.

It would be desirable to obtain a simple rule of thumb to characterise and predict the onset of BtoB interaction. However, the complexity of the problem limits the application of each rule to the specific case from which it was deduced. Some of the BtoB interaction rules that have been proposed for vertical cylindrical heaters are based on the heat-release rate and the geometrical dimensions of the furnace. The rule usually takes the form of a criterion value that demarcates the absence of interaction from the onset of interaction. Figure 2 shows the dimensions discussed in the following rules. One such rule uses the heat release of a single burner per unit distance between two adjacent burners (Btu/hr/ft or MW/m). A second rule uses the total heat release of the heater per unit area (Btu/hr/ft$^2$ or MW/m$^2$) of the outermost
burner circle, which is the circle that passes through the centres of the outermost burners. A third rule uses the total heat release of the heater per unit area (Btu/hr/ft² or MW/m²) of the tube circle, which is the circle that passes through the centres of the heater process tubes. A fourth rule uses the total heat release per unit volume of the heater (Btu/hr/ft³ or MW/m³).

In extreme cases, when the criterion value is close to zero for no interaction and relatively large for full interaction, these rules can correctly predict the performance of a multi-burner heater. However, predicting the accurate conditions for the onset of interaction is a challenge for any of these rules. In other words, it is easy to predict the sufficient conditions (extreme cases) for interaction, but it is difficult to predict the necessary conditions (onset conditions) for the interaction. These rules fail for two reasons: oversimplification of the problem and failure to account for all significant parameters. For instance, during a research study of this phenomenon, it was observed that BtoB interaction depends on both fuel pressure and fuel composition, while none of the above rules account for such a dependence.

BtoB interaction, sometimes referred to as flame-to-flame interaction (FtOF), is a complex phenomenon that makes the behaviour of the multiple-flame configuration very different from that of an individual flame. Increased flame length, increased NOx emissions, poor mixing, modified heat flux distribution and decreased surrounding gas entrainment are some of the results of FtOF interaction. While aerodynamic interaction of the jets in a multiple-jet system is considered to be the most important factor that governs FtOF interaction, the presence of combustion is also a major factor. In other words, the shape of the flame not only responds to the turbulence in the surrounding medium, but also to the combustion itself, which creates eddies that can affect neighbouring flames.

In vertical cylindrical heaters, the BtoB spacing is more critical than in box-type heaters, because the burner spacing has an impact on the flue gas flow into the centre of the furnace. If the spacing between burners is too small, the interaction of the flames can actually block the flow of flue gases from the circumference of the furnace into the centre. This generates a low-pressure zone in the centre of the furnace that can effectively pull the flames toward the centre of the furnace. This increases the tendency for the flames to merge together and create a large fire cloud that can impinge on process tubes. Another effect is the creation of a reducing (oxygen-deficient) atmosphere in the centre of the furnace. Since the flue gases are blocked, the O₂ concentration decreases at the centre, leading to increased CO formation on that side of the flame and creating the potential for increased flame lengths. Longer flames can also alter the design heat flux distribution, as more heat is transferred higher in the furnace. NOx emissions may also increase because there are insufficient flue gases on the inside of the burner circle that can be pulled into the flames. Many low-NOx burners use furnace gas entrainment to reduce the flame temperature, which reduces NOx emissions.

An extensive theoretical and experimental investigation was completed to develop a suitable criterion for identifying interaction in vertical cylindrical heaters. Details of that investigation are given elsewhere. The developed criterion depends on both physical and chemical parameters; namely, the geometry of the burners and the fuel composition. Interaction is defined here as the influence of flames on each other that leads to the creation of a yellow flame cloud (due to the formation of soot particles) between burners. A dimensionless number was developed that can be used as a measure for the interaction strength. Both lab-scale and small-scale burners were used in the experimental investigation.

Consider two diffusion flames, as shown in Figure 3, that are adjacent to each other. There is a critical height at which jets interact (Zc). The flame height is designated here as Lf. If the flame height is less than the critical height (Lf < Zc), no FtOF interaction will occur. If the flame height is greater than the critical height (Lf > Zc), the flames will interact. FtOF interaction of a group of diffusion flames arranged in a circle, as in a vertical cylindrical furnace, can be characterised in a similar manner.

**Experimental study**

Twelve lab-scale burners were built. Each was a single-jet burner with its diffusion flame stabilised on a conical bluff body downstream of the fuel jet. The objective of testing with a simple lab-scale burner was to study the FtOF interaction on a fundamental basis and to verify the interaction criterion for configurations with a large number of burners. These burners were tested in a small lab furnace equipped with sensors for measuring fuel pressure, temperature, flow rate, flue gas temperature, furnace draft, wet and dry gas analysis of excess oxygen, carbon monoxide and nitrogen oxides.

The parameters were varied to study their effects on FtOF interaction independently. Interaction among the

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**Figure 3** Condition of interaction between two adjacent diffusion flames. Lf < Zc (no flame interaction); Lf > Zc (flame interaction)

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"Computational fluid dynamics (CFD) is a powerful tool for analysing complicated fluid flow problems in combustion"
flames was characterised by the existence of a yellow fire cloud between adjacent flames. The strength of interaction was evaluated by direct visual observation of the yellow cloud. A somewhat subjective interaction index was used to scale the strength of the interaction. FtoF interaction was observed to increase as the fuel pressure decreased, for the same heat release rate. FtoF interaction increased as the burner circle diameter decreased. The dependence of the dimensionless interaction parameter on the number of burners was governed by a spacing ratio, defined as the dimensionless ratio of the burner diameter to the distance between two adjacent burners. Two configurations were tested to investigate the impact of the number of burners on FtoF interaction. Four and six burners were used where the distance between adjacent burners was kept equal in both configurations. The interaction in the case of six burners was weaker than that with four burners. Excess air had an insignificant effect on the strength of the FtoF interaction.

Small-scale burners

The objective of testing with small-scale diffusion burners was to study the FtoF interaction on a true process burner design and to verify the interaction criterion for all the relevant parameters. The following control parameters were varied: heat release, fuel pressure, fuel composition, excess air, burner circle diameter and number of burners. Six fuel compositions of various combinations of natural gas (>90% CH₄), hydrogen and propane were tested.

In these experiments, FtoF interaction was evaluated by direct visual observation of the yellow fire cloud between the flames. Changing both the heat-release rate and fuel pressure, with a fixed fuel nozzle diameter, did not affect FtoF interaction significantly. Keeping the heat-release rate per burner constant, a parametric study was then carried out in which only one control parameter was varied at a time. Interaction increased when: fuel pressure decreased, burner circle diameter decreased, the number of burners increased and the excess O₂ increased. Fuels with more propane tended to have higher interaction than fuels with more hydrogen, which tended to have lower interaction. Fuels with more natural gas had interactions in-between. This corresponds with flame length, as propane tends to make flames longer, while hydrogen tends to make flames shorter, for a given burner configuration.

Full-scale field burners

Data were collected from 12 field installations, which had full-sized process burners of the same design as the small-scale burners. There were both interacting and non-interacting cases. Using the field data, the dimensionless interaction parameter was computed for each case. The three interaction regimes were evident, although the transition regime was narrower. The narrow transition regime was due to the subjectivity involved in visually indexing the fire cloud as well as the small number of cases that fell into this transition regime.

Numerical studies

Computational fluid dynamics (CFD) is a powerful tool for analysing complicated fluid flow problems in combustion. CFD has been used extensively to study burners and heaters in the process industries. One particular topic of interest has been FtoF interaction. The following two examples illustrate some of the issues and results. The first example shows a case where reducing the spacing between burners did not cause FtoF interaction. The second example shows how CFD was used to simulate an existing FtoF interaction problem in an operating heater and the solution to that problem by modification of the burners. CFD was used to study the effects of reducing the burner circle diameter in a vertical cylindrical furnace from 8.66–7.43ft (2.64–2.26m) to determine if FtoF interaction would be a problem. The burner circle is centred at the middle of the furnace and goes through the centre of each burner. The furnace had six burners mounted in the floor in a circular pattern, surrounded by tubes next to the wall (Figure 4). The yellow ring between the burners and the tubes is known as a Reed wall. Its purpose is to control the gas flow in the furnace and minimise the chance for flame impingement on the tubes.

Each burner was fired at 9.3MMBtu/hr (2.7MW). Two different fuel compositions were fired simultaneously through each burner. One fuel had approximately 40% hydrogen and 44% methane, with some other minor components. The other fuel was about 23% methane and 61% nitrogen, with other minor constituents. Each burner was operated with 15% excess air. The exhaust gas temperature was about 1600°F (870°C).

Turbulence, equilibrium combustion chemistry and thermal radiation were included in the CFD model. The flame boundary for the calculated flame pattern (not shown here) is defined in this case as the location where the computed carbon monoxide concentration is 1500ppm by volume on a wet basis, indicating that no FtoF interaction was predicted after reducing the burner circle diameter. Other results also predicted no flame impingement on the process tubes.

The second study involved an operating furnace in a refinery. The problem observed in a xylene reboiler
was that the flames from the ultra-low NOx burners were very long and had the potential to damage the process tubes in the convection section at the top of the furnace. This phenomenon had previously been observed in vertical/cylindrical furnaces with ultra-low NOx burners. The problem was related to the flow pattern within the furnace, as it did not allow complete mixing of the combustion air with the fuel, but rather distorted the flame prior to burnout.

The geometry of the vertical cylindrical furnace is shown in Figure 5. The small wall around the burners is a Reed wall and is used to heat the cold flue gases coming from the tubes. This helps enhance flame stability. Equilibrium combustion chemistry, turbulence and thermal radiation were used in these computations.

Figure 6a shows a CFD simulation of the burners as they were originally installed. The figure shows an iso-surface of OH, which is a good indicator of flame shape. The results reveal that the flames from adjacent burners merged together to produce a single long flame, which was confirmed by observations of the operating furnace.

This burner had two primary fuel tips that fired fuel inside the burner tile, and four secondary fuel tips firing outside the tile. The solution to this flame interaction problem was to change the burner so that only three of the secondary tips actually fired. The CFD results for that configuration are shown in Figure 6b. This solution was implemented and tested in the operating furnace and found to yield qualitatively the same result — the flames became distinct and burned out at the appropriate height. FtoF interaction was negated, which reduced the flame length and eliminated flame impingement on the process tubes.

**Ethylene furnaces**

One example of an application where FtoF interaction is an issue is in ethylene-cracking furnaces. One common type of low-NOx burner used in the floor of these furnaces incorporates fuel staging and furnace gas recirculation (Figure 7a). While this combination of techniques reduces NOx, it also tends to increase flame length. Longer flames move the location of the peak heat flux higher in the furnace and decrease the heat flux at the floor of the furnace. These burners are so effective at pulling in surrounding furnace gases that, if spaced too closely together, they can compete for the same gases. This can cause NOx emissions to increase and flame quality to decrease. On extremely tight spacing, the burners can negatively impact the natural furnace fluid flow currents, leading to FtoF interaction and flame impingement on process tubes. Another burner was developed to
help control the interaction of low-NOx burners that incorporate furnace gas recirculation, where the spacing between burners is tight. These burners control the recirculation of furnace gases by using a venturi and internal ducting, and introduce the fuel and furnace gas mixture vertically (Figure 7b). These burners have low NOx emissions, with better radiant heat flux profiles and flame quality than the previous design. They also allow closer burner-to-burner spacing.

Burner technologies must be correctly applied to get predictable and reliable performance from the furnace. This includes low NOx, no flame impingement and the desired heat flux distribution in the furnace. There are two parameters that can be used to predict burner performance in this application: heat release per burner as a function of burner spacing and total heat release for the furnace geometry.

The first of the two parameters is called linear heat intensity (LHI). It quantifies flame intensity along a furnace wall or along the length of the furnace. LHI is calculated by taking the heat release of all the floor burners in a row and dividing by the length of the furnace. Typical units for this would be MM/MW. For example, if there are ten burners in a row, each firing 10MM/ft (2.91MW), and the total length of the row is 30ft (9.1m), the LHI would be (10 burners) x (10MM/ft/burner)/30ft = 3.33MM/Btu/ft (3.2MW/m). The LHI can be used to determine the extent of possible burner-to-burner interactions and how much NOx emissions may increase compared to NOx measurements from a single-burner test where there is no FtoF interaction.

Different burner designs are more or less sensitive to LHI. Generally speaking, all burner technologies will work predictably when the LHI values are less than 2.0MM/Btu/ft (1.9MW/m). Between 2 and 3.5MM/Btu/ft (1.9 and 3.4MW/m), the burner technology plays an important role and the burner vendor should be consulted and previous experience of the type of burner at similar LHI levels considered. The previous example suggests that BtoB interaction would be a concern for the conditions specified. Above 4.0MM/Btu/ft (3.8MW/m), BtoB interaction is likely and makes it difficult to predict burner and heater performance.

The second parameter, called hearth heat intensity (HHI), is a measure of flame intensity for a given floor area. HHI is calculated by taking the heat release of all floor burners in a furnace and dividing by the floor area inside the box. Typical units for HHI would be MM/Btu/hr/ft² or MW/m². For example, if there are ten burners firing 10MM/Btu/hr (2.9MW), each in a total floor area of 400ft² (37m²), the HHI would be (10 burners) x (10MM/Btu/hr/burner)/400ft² = 0.25MM/Btu/hr/ft² (0.79MW/m²). The HHI measures the flame-to-burner coupling effect. If the HHI is too high, the potential for flame rollover increases. If the intensity of the heat on the floor of the furnace is higher than the burner can sustain, a short circuit in the naturally occurring furnace currents can occur, creating the potential for flame rollover. This rollover will reduce efficiencies and run lengths, and in severe cases reduce tube life.

Generally speaking, there will be minimal burner-to-furnace interaction when the HHI values are less than 0.3MM/Btu/hr/ft² (0.95MW/m²). Between 0.3 and 0.45MM/Btu/hr/ft² (0.95 and 1.4MW/m²), the possibility for negative interaction exists and each burner technology should be compared to existing furnaces to determine the possibility and extent of the interaction. Above 0.5MM/Btu/hr/ft² (1.6MW/m²), burner-to-furnace interaction is likely and heat release parameters such as efficiency and run length will be difficult to predict reliably. For the previous example with HHI = 0.25MM/Btu/hr/ft², the rule of thumb suggests minimal interaction for those conditions.

Conclusions

Burner-to-burner interaction can increase NOx emissions, cause flame impingement on process tubes and alter the heat flux distribution in the furnace. This problem has become more prevalent as low-NOx burner designs use more fuel staging and furnace gas recirculation and firing rate densities increase. Empirical rules of thumb have been developed, but are often limited to fairly specific geometric configurations and operating conditions. As the result of an extensive experimental investigation, a general interaction parameter has been developed to help predict when there may be an interaction problem for a wide range of operating conditions. CFD modelling can be used to both predict potential problems and to recommend solutions. Rules of thumb have been developed for ethylene-cracking furnaces to predict when there is an increased risk of interaction problems.

References


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