Reexamining Conventional Burner Design with Computational Fluid Dynamics Leads to NOx Compliance for Less than $4/Kw

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Welding the flame stabilizer to the coal burner.

Optimizing conventional burner design can lead to NOx compliance for less than $4/kW without external flue-gas recirculation or overfire air. Extensive computational fluid dynamic (CFD) parametric studies of conventional gas, oil and coal burners have resulted in new concepts that use combustion dynamics for radial and circumferential staging (oil and coal) or to induce inert gas NOx control effects (natural gas) within the burner/furnace.

For natural gas burners, simple changes to gas injection characteristics and new flame stabilizers are the only mechanical changes made to the burners. Fuel nozzle changes and staged flame stabilizers are the only modifications required for oil and coal burners. These changes reduce NOx, making it possible to meet the latest federal regulations as well as all state regulations except for California. The key to these improvements was optimizing burner dynamics through the use of FLUENT CFD software from Fluent, Inc., Lebanon, New Hampshire. This software aids in determining NOx production for alternate design concepts and also produces graphical output that provides a clear understanding of how the proposed design will perform.

RJM Corporation is an engineering services company that provides products and services to solve combustion and emissions reliability and performance problems for the utility, industrial and marine industries. The 1990 Clean Air Act says that by May, 1995 targeted utility generating plants are required to meet more stringent NOx requirements. In many cases, utilities are mandated to meet even more stringent state government requirements. Since most utilities would prefer not to change their existing burners, we have worked closely with our clients to develop burner add-on designs to reduce NOx. NOx is generated by three different mechanisms. Thermal NOx is formed by the oxidation of atmospheric nitrogen present in the combustion air. Prompt NOx is produced by high speed reactions at the flame front, and fuel NOx is formed by the oxidation of nitrogen contained in the fuel. In coal and oil burners, the primary thrust for NOx reduction is to reduce combustion temperature. A good rule of thumb is that NOx will be reduced by 50 percent for every190^{o}F that the peak flame temperature is decreased.

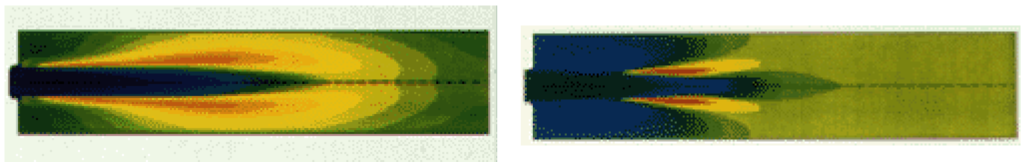
Building from Proven Technology

As part of our NOx reduction project, RJM Corporation first reviewed the operating and performance characteristics of a variety of oil, gas and coal low NOx burners. The conventional approach to NOx reduction involves use of low NOx burners coupled with an overfire air system. Excellent low NOx performance results. These burners operate under fuel rich conditions, which helps to reduce fuel NOx. In addition, the overfire conditions permit lower peak flame temperatures that in turn reduce thermal NOx. Fuel rich/fuel lean techniques via radial staging are also successfully used to meet NOx compliance in oil- and coal-fired units. Low NOx gas burners additionally employ external flue-gas recirculation, which can significantly lower NOx when burning this fuel.

The cost of the new burners typically ranges from $12 to $20 per kilowatt of capacity. Low NOx burners are typically quoted as giving NOx reductions of 20 percent to 40 percent. Adding overfire air will typically reduce NOx by an additional 20 percent to 30 percent while adding about $5 to $15 per kilowatt to the cost. Using these conventional approaches, total NOx reductions of 40 percent to 70 percent are possible at a cost of $11 to $27 per kilowatt. Low NOx gas burners with external flue-gas recirculation can reduce NOx by up to 75 percent at a total cost approaching $24/kW.

Oil and Coal Burners

For the second phase of our investigation, we used the computational fluid dynamics (CFD) software FLUENT to explore applying these basic concepts in new ways to conventional burners. Low NOx oil and coal burners are multizone burners that use radial staging to lower temperature and thus reduce NOx . This effect is easily created in conventional burners by installing carefully designed low NOx flame stabilizers. However, our modeling showed that a circumferential staging approach, which serves to concentrate the fuel into two or three streams, lowers NOx an addition 10 percent to 15 percent. In this design, the flame stabilizer separates the air into six discrete streams of which three sections contain a large volume of air and the alternate three sections contain only a small amount. This patented radial and circumferential flame stabilizer creates an internal recirculating vortex around the fuel source that stabilizes a multizone staging effect in conventional oil and coal burners. The version used in oil-fired plants is a vane cascade stabilizer that maximizes the internal recirculating vortex. This provides a strong stabilizing field that makes it possible to implement further low NOx modifications that otherwise would have a tendency to destabilize the burner combustion zone. For coal burners, a coal flame stabilizer is mounted on the pulverized coal tube to stabilize the flame front over the turndown range of the burner.



Alternate burner designs. FLUENT CFD software helps determine NOx production for alternate burner designs, with a clear understanding of how each proposed design will perform.

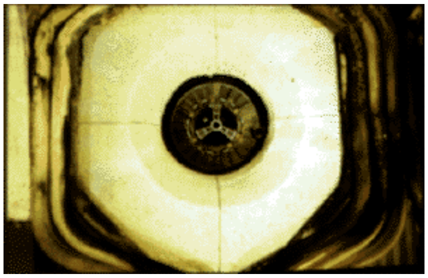
Boundary Layer Staging for Gas Burners

With the knowledge gained from studies of existing low NOx burner designs and the FLUENT simulations, RJM also developed a new gas burner design concept where the fuel is sandwiched between combustion air coming through the burner and combustion products in the furnace. This effect is called boundary layer staging. The effect on NOx is multifold. Shear rate between the gas stream and furnace gases is high, which maximizes mixing. Thus, furnace gases are entrained (internal flue-gas recirculation) in the gas stream, which increases the mass of the stream and helps to reduce peak flame temperature. This layering concept also reduces the surface area of the air/fuel interface thus retarding the reaction rate and further reducing peak flame temperature. Furthermore, the shear rate between the fuel and air streams is reduced, which further retards the combustion rate. Each of these changes have the effect of reducing NOx production. Since this complex combustion process is inherently unstable, another important design consideration in the new burner design was stabilizing the flame. We developed a miniflame stabilizer to anchor the flame front and keep the gas on the perimeter of the burner. This stabilizer involved an original concept whereby a portion of the main gas goes into four small flame stabilizers along with the air to form continuous pilots. The result, in the first application where this was tried, was a 44 percent reduction of NOx with excellent flame stability. NOx reductions approaching 75 percent appear possible. FLUENT is a general purpose CFD code that is ideally suited for modeling combustion systems. A typical FLUENT model of our gas burner includes a multiple set of species and reactions to predict reaction rates and species formation, including NOx. A two-step model is used to simulate the primary reaction of methane in which the fuel burns in air to form carbon monoxide and water vapor, and the carbon monoxide in turn reacts to form carbon dioxide. We used the FLUENT NOx prediction routines that estimate thermal, prompt and fuel NOx formation from the resulting profiles of temperature, species and turbulence. Our models have about 100,000 cells and seven different chemical species.

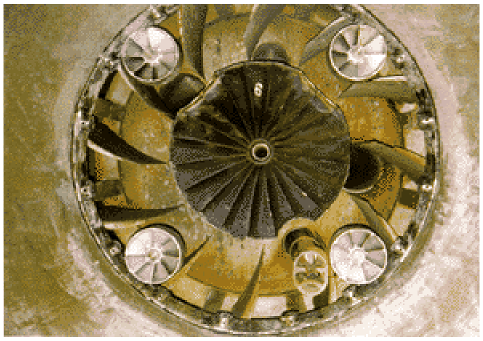
Running on a Sparcstation Model 10, they take about seven days to converge to a solution. Building a complete model takes less than two to three weeks, and major design modifications can be easily made within several days. Investigating design modifications or changes in operating conditions is easy. In one project, for example, we investigated 30 different design conditions by varying the position of the fuel, the injection angles of the fuel in reference to the burner, and the distribution of the fuel through the different staging zones, etc.

Combustion Modeling

Combustion modeling is challenging because of the need to accurately describe a complex flow field subjected to rapid combustion reactions which provide large heat sources. A typical reaction scheme thought to precisely model combustion of a simple gaseous hydrocarbon fuel may consist of several hundred steps. Moreover, the rate at which each of these combustion reactions occurs depends on local instantaneous flow properties that are difficult to model for turbulent flows. Fortunately, several key reactions typically dominate the combustion process and only these were used to simulate the combustion performance with sufficient accuracy for the task at hand. FLUENT allows the key reactions and their governing parameters to be defined. The code will calculate the appropriate reaction rate -- an Arrhenius expression for kinetically-controlled reactions and an "eddy break-up model" for reactions that are limited by turbulent mixing. The effects of turbulence add greatly to the complexity of the problem. One evolving approach to modeling these effects is direct numerical simulation to solve the Navier-Stokes equations. This approach is fundamentally sound but makes it necessary to resolve the model to a very small scale. This means that a huge number of cells are required and the time scale for such a simulation would be extremely small. Both of these requirements contribute to produce extremely long solution times for problems of practical interest. Thus, some type of turbulence model is required to simplify the problem.



Radial and circumferentially staged coal flame stabilizer with RJM coal splitter.



The K-epsilon model uses certain simplifying assumptions that make the model more robust and much easier to solve but also involve some limitations. Here, the most important is that there is a tendency for the flow to act as if it were more viscous than it really is, thus dissipating swirl motion more than is expected. The Reynolds stress model makes fewer simplifying assumptions and is considered to be more accurate, but it requires correspondingly more computing resources. We use the K-epsilon model most of the time because it offers faster solution times but use the more rigorous Reynolds stress model in areas where accuracy is critical such as when dealing with internal recirculation vortices.

Conclusion

We have found CFD to be useful from a problem-solving standpoint as well. Once we had a problem where atomizer tips on several oil burners were experiencing coking buildup. After trying different mechanical adjustments without success, we modeled the burners in FLUENT. The analysis graphically depicted the flow of air in the vicinity of the tip. It was easy to see that an adverse static pressure gradient boundary was attaching to these tips. The boundary was generated when the axial flow coming out of the burner was equal to the flow coming back in. This effect caused particles to attach to the tip. Changing the aerodynamic configuration of the flame stabilizer to move the adverse static pressure gradient boundary away from the tip eliminated the problem.

Each of the burner retrofit systems mentioned above has now been installed and is working successfully in the field. The results have matched the analytical predictions generated with FLUENT. We currently have three coal units running with 42 percent to 50 percent NOx reduction. We also have five oil units working, including three front wall-fired and two tangentially-fired units. The front wall-fired oil units are providing 40 percent to 50 percent NOx reductions while the tangential units are providing 40 percent to 48 percent reductions. Our gas units are showing a 44 percent reduction at the present time. Model results indicate NOx reductions approaching 75 percent for gas-fired units may be possible.

It is important to note that all these concepts can be implemented by adapting existing equipment to these new add-on technologies so the plant can operate using normal procedures. This avoids the need to take burners out of service for NOx control, to use overfire air and to implement staging by burner elevation. It also avoids the need to train staff members in different operating procedures and produce new documentation. All in all, retrofits that were designed and proven using CFD can provide mandated NOx reductions at a cost of only a few dollars per kilowatt.