Computational Fluid Dynamic Modelling of Boiler Furnaces for Engineering Analysis

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Introduction

Energy Systems Associates (ESA) is an engineering consulting firm giving special emphasis to helping industry with energy and energy-related problems including combustion engineering, air pollution control technology, and energy conservation and utilization. The company is headquartered in Pittsburgh, Pennsylvania with regional offices in Washington, DC, Minneapolis, MN, and Brooklyn, NY. ESA personnel have conducted a multitude of emissions reduction projects during the past twenty years, which have resulted in resolution of emissions and operating problems for utilities across the United States and abroad.

In response to advances in computer power and sophistication of numerical algorithms, ESA has developed furnace modelling capabilities based on the use of the computational fluid dynamic (CFD) technology. ESA has adapted this technology to develop a useful product which can be applied to evaluate distributions of properties such as temperature, stoichiometry, fluid flow and gaseous species inside the furnace and to gain insights not possible with conventional boiler testing. This technology characterizes the sophisticated tools currently available for resolution of combustion related problems.

NOx and Combustion Problems

Boiler operators at electric utility and industrial sites are faced with resolving an increasingly difficult array of combustion related problems. These include:

- Federally and Locally mandated emission reductions for Nitric Oxides, NOx; Sulfur Dioxide, SO2; Particulates; etc.
- Boiler Availability and Outage requirements
- Boiler Efficiency
- Superheat and Reheat Temperatures
- Coal specification and purchasing

Of current concern to the electric utility community is the NOx and SO2 reductions mandated by the Clean Air Act Amendments of 1990, Titles I and III. These federal mandates place the boiler operator in the difficult position of fundamentally altering the boiler operation to reduce emissions, while simultaneously maintaining the boiler operability.

Nitric Oxide abatement proves to be particularly difficult because the Nitric Oxides forms from the nitrogen present in the fuel and in the combustion air. The level of NOx produced depends on the availability of oxygen and the intensity of the combustion process. Because of this, reduction of NOx emissions generally requires changing the combustion process to limit the NOx formation or altering the flue gas chemistry to promote NOx reduction.

NOx Reduction Techniques

The chemistry of NOx formation and reduction has resulted in a wide variety of NOx reduction technologies. The include:

- **Low Excess Air Operation**: reducing the overall combustion air supplied to produce a reduction of oxygen availability for NOx production
- **Uniform Combustion Air introduction**: adjusting air registers to achieve uniform introduction of air to prevent local regions of air richness from forming NOx
- **Burners out of Service**: Diverting fuel flow from a portion of the burners to produce oxygen lean environment at the remaining burners
- **Overfire Air**: Staging the introduction of combustion air to combust some of the fuel in an oxygen lean, low NOx, environment
- **Low NOx Burners**: Retrofit of burners designed for staged combustion of the air to produce alternating oxygen rich and oxygen lean zones
- **Flue Gas Recirculation**: Dilution of the combustion gases with oxygen depleted combustion products
- **Reburning**: Combustion of additional fuel downstream of the main combustion zone to produce a region of fuel rich stoichiometry to promote a reversal of the NOx formation
- **Selective Non-Catalytic reduction**: Introduction of chemical agents that selectively reduce NOx to N2
- **Selective Catalytic Reduction**: Introduction of chemical agents in a catalyst bed that selectively reduce NOx to N2

All of these techniques produce impacts on the performance of the boiler as well as NOx reductions.

Need for Modelling

Faced with such a wide variety of choices, and given the desire to maintain boiler operability, the need arises for a basis of comparison. ESA has employed computational fluid dynamics techniques to address this need. Computational Fluid Dynamics (CFD) is the solution of mass and energy transport by numerical methods. A CFD simulation of a boiler furnace results in wealth of information including velocity, temperature, and concentration distributions within the furnace and along the walls, calculated based on deterministic science. This information is used to evaluate the combustion and heat transfer characteristics of a given boiler furnace.

However, the computer simulation of the boiler is not the end of the problem in itself, but simply a tool to assist engineers in reaching the end of the problem. Only with the introduction of experience in combustion problems can this sophisticated tool be employed effectively to sort through the various option available and zero in on the most cost effective solution.

Example Problem Faced by PSI Energy Gibson Station

PSI Energy of Indiana requested a modelling tool for the Gibson Generating Station Unit 1 to assist in the selection of a low NOx system. Their intention was for computer modelling to allow for NOx reduction to be weighed against possible performance degradation. Gibson Unit 1 is an opposed fired Foster Wheeler boiler, generating 635 megawatts net at full load. At the time the model was employed, NOx emissions from this unit were on the order of 1.0 lb/MMBtu, well above the legal limit of 0.5 lb/MMBtu.

CFD modelling of the Gibson Station allowed for a variety of low NOx burners and overfire air combinations to be evaluated. An example of the experience encapsulated in the computer model were numerical indices incorporated to allow for comparison of the potential for increased unburned carbon or wall slagging problems. Potential low NOx burner and overfire air combinations were evaluated based on achieving the required NOx reduction while limiting all negative impacts on the boiler operation.

An important insight gained from the computer modelling was the impact of how the overfire air was introduced on the boiler operability. Modelling results indicated that by introduction of the overfire air through multiple small openings, better furnace conditions could be achieved for the same NOx reductions.

The benefits of the computer modelling were realized after the unit was retrofit with the low NOx equipment. Gaseous emissions predicted by the model included a reduction in

NOx emissions of 55%. Emissions measurements at the same conditions verified a NOx reduction of at least this amount. Carbon in ash measurements taken during testing confirmed that the LOI did not increase significantly with the chosen configuration. Utilization of computer modelling enabled successful reduction of NOx with minimal impact on the unit performance.

Current and Future Directions

Application of CFD modelling of boiler furnaces does not need to be limited to resolving technical issues. The distributions of combustion parameters calculated by CFD can be used to effectively communicate an understanding of the complex processes occurring in the furnace. By developing a CFD simulation of a well documented boiler operating condition, considerable weight can be given to the calculated distribution of combustion parameters.

Modern rendering techniques can develop three dimensional isosurfaces from these distributions to represent flame regions, NOx formation regions, or overfire air penetration. These graphics, when viewed side by side, provide dramatic illustration of the effects that changes in furnace parameters can have. This type of documentation effectively communicates technical solutions to non-technical groups such as regulatory agencies.

As with any model, simplifications have been required to represent certain phenomenon and to limit the model to a reasonable scope. The current CFD model employed by ESA is restricted to representing and analyzing a boiler furnace. As modelling gains greater and greater acceptance, there is always a desire for improvement. An important direction for improvement is combination of this type of model with a performance evaluation typified by the PEPSE model. This allows for the scope of the combined models to address the entire boiler system.

For example, ESA's CFD based simulations currently employ assumptions concerning waterwall heat absorption. These assumptions effect the furnace exit temperature prediction and the internal temperatures of the combustion region. By linking together with PEPSE at this junction, an enhanced model can be developed that improves predictions of the boiler thermal performance and combustion emissions.

Conclusion

Computational fluid dynamic modelling has been employed to resolve problems faced by industrial and utility boiler operators. This resolution has required experience in modelling as well as combustion, and has employed the modelling as a sophisticated tool. Extension of the CFD modelling to mesh with performance modelling will provide a new generation of engineering tools to attack a new generation of problems.