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THE CORLISS ENGINE

The first drop cutoff mechanism was patented by Fred E. Sickles in 1841. The Sickles engine was first competing with the older engines, which were then usually arranged to expand steam about one and one-half times by the lap of the single three-ported valve, corresponding in operation to the ordinary double *D* valve of today. A few engines were built of a better design, fitted with an independent cutoff valve on the back of the main valve forming what is known as the riding cutoff. The single *D* valve trolling a throttle valve. This governor was usually a common flyball governor, and its deficiency in power and lack of sensitiveness, and the distance of the regulating apparatus from the engine valves, together with the range of motion required in its operation, made this combination a very ineffective regulating device. The same firm then substituted the Pitcher hydraulic regulator and a register valve

Types of Modern Stationary Engines.

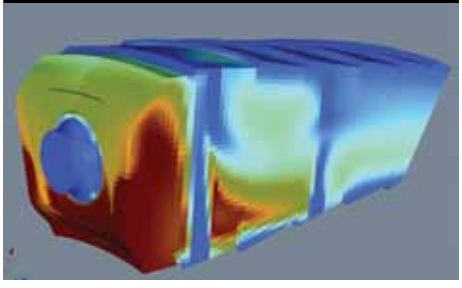
Simulation Tools Deliver Competitive Edge

Representations of fuels can now be used with models constructed from 3-D combustion simulations.

By Scott A. Drennan, P.E., Director of Applications Engineering, Reaction Design

Gas turbine and burner manufacturers are targeting growth opportunities in the power generation markets of developing countries and other regions where the composition of natural gas varies significantly. Other opportunities target the use of alternative fuels that address new environmental regulations. Additional opportunities are inherent in the increased operational flexibility demanded of combined cycle systems as power grids accept more volatile sources of energy such as wind and solar. There is also opportunity due to the recent reinstatement of stricter environmental air quality standards and the specification of CO_2 as a pollutant by the U.S. Environmental Protection Agency. Meeting the challenges these opportunities present with minimal risk requires a change in the traditional product development process to increase its cost effectiveness while fostering design solutions.

FIGURE 1 CFD SOLUTION OF GAS TURBINE COMBUSTOR



Increasingly, engine developers are applying combustion simulation techniques to the design of higher efficiency and lower emissions combustors and burners. Recently, commercialized simulation tools have created higher fidelity combustion predictions which help address new opportunities and lead to a better understanding of how different fuels can affect a product line. High fidelity representations of real fuels can now be used with advanced combustion models constructed from full 3-D combustion simulations. This approach provides combustion models that predict factors such as emissions, ignition and lean blow-out (LBO).

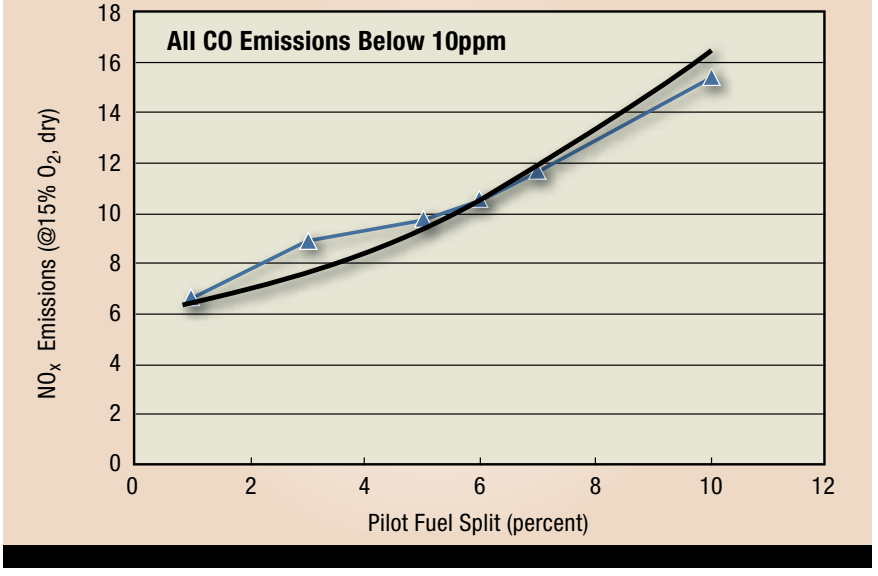
The dominant combustion simulation tool used by gas turbine and burner designers is computational fluid dynamics (CFD, see Figure 1). Modern CFD software is capable of resolving combustor geometries and producing simulations of the flows within the combustor, but with only limited chemistry information. While today's computers are fast enough to handle combustor design models with millions of cells, they still are not fast enough to incorporate all of the detailed combustion chemistry of the fuel.

The process of combustion involves a series of detailed chemical reaction steps that are highly dependent upon the environmental conditions, flow timescales, turbulence levels and chemical concentrations. CFD simulations can only accept greatly simplified representations of the fuel composition. In reality, fuels are a blend of hundreds of chemical compounds. While it is possible to reduce all the detailed chemical steps in the mechanism to a small set of "reduced" reactions, important information about the path of key steps in the reaction is often lost. These "lost" reactions may include steps that control the formation of pollutant species and combustion stability. It is easy to see that the oversimplification required by CFD cripples the combustion designer's ability to reliably explore the impact of real fuel compositions. CFD's inability to simulate key combustion behaviors, such as emissions and stability, prevents it from providing the edge required to dramatically improve design and innovation.

An illustration of the importance of accurate prediction of chemistry is the well-understood result of the newer low-NO_x designs in turbines and burners. These designs are inherently less stable than older technologies and have a much narrower design "envelope." In addition, combustion at lower temperatures makes turbines and burners less amenable to alternative fuels. A typical modern natural-gas-fired turbine, for example, is less tolerant of the variation in composition of LNG or low-carbon fuels from different sources.

Because CFD simulation does an adequate job of predicting temperature globally, it solves the NO_x problem in combustors dominated by thermal NO_x quite well. However, the combustion challenges discussed above are kinetically driven and require detailed chemical simulation. Applying detailed fuel chemistry today in com-

EXAMPLE: PILOT FUEL PARAMETER VARIATION



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bustion simulation requires simplification of the geometry into a series of idealized reactors that enable the detailed chemistry to be simulated in a reasonable amount of computational time.

Simulations that use idealized chemical reactor modeling, like Chemkin, have delivered predictive results for over 30 years. The challenge has always been how to convert the complex 3-D flow field and geometry into a representative network of chemical reactors. Recently, researchers used networks of these idealized reactors that represent a reduced-order model of the flow field and geometry, while including fully detailed chemical kinetics, with excellent combustion results.[1]

FIGURE 3 REACTOR NETWORK REPRESENTATION OF GAS TURBINE COMBUSTOR

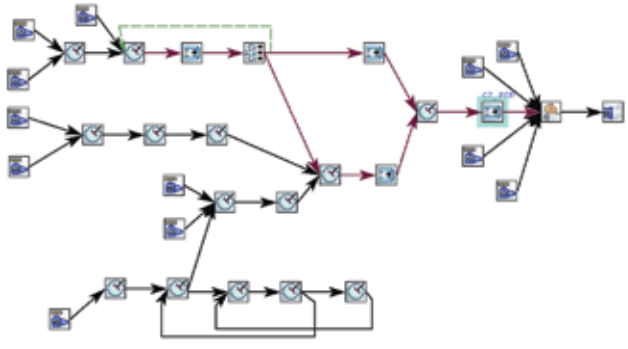


Figure 3 shows an example of how the complex combustor geometry is converted into an equivalent reactor network (ERN). Once the ERN is created through a careful devolution of the combustor flow field, a detailed chemical mechanism can be used to provide an understanding of chemical behavior and performance.

To achieve an accurate simulation result, it is critical that the ERN be a true representation of the actual combustor flow field. Traditionally, expert personnel were needed to create the ERN manually, following a process so time-consuming it was considered impractical for use in a commercial design process. Recent developments in automating ERN generation, such as those found in the Energico software package, have made the ERN creation process fast enough to fit commercial design timelines. This automation has also enabled a repeatable process to create the complex ERNs that do not require manual work by an expert. The resulting ERN analysis with accurate chemistry provides prediction of emissions such as NO_X and CO.

The software package also has the ability to set up and perform parameter studies on the ERN to explore sensitivities of the combustor design to variability in fuel-air ratio, fuel splits and fuel composition. Figure 4 shows the comparison of experimental data to ERN simulations for pilot fuel split in a diffusion pilot stabilized premixed industrial combustor. These types of experimental data are expensive in terms of money and time. Applying ERN analysis reduces test costs and accelerates the design cycle.

Growth markets exist in the use of a variety of non-traditional fuels for power production in gas turbines and boilers. Alternative fuels like bio-fuels that are produced from sustainable plant products are "carbon-neutral" and reduce the global warming impact of CO_2 emissions. On the other hand, liquefied natural gas contains many heavy hydrocarbon gaseous components that affect the ignition, stability and emissions of power equipment. Given the wide palette of alternative fuel options, the traditional approach to design that relies on experimental testing to evaluate combustion performance is simply unrealistic: too long, too costly and too hard to fully analyze.

Using new simulation tools and techniques can extend the ERN approach to the simulation of both fuel flexibility and the use of alternative fuels. For example, ERNs can now be used to answer key real-world fuel flexibility questions:

How do you determine the impact of integrated gasification combined cycle or opportunity fuel composition variations in CO, HC, CH_4, and so on, concentrations?

How do you determine the impact of alternative low-carbon bio-fuels in existing and new combustion system designs?

ERNs provide a platform to simulate combustion performance of a variety of fuels. The ability to use accurate fuel chemistry mechanisms in an efficient model produces greater accuracy in combustion predictions.

The approach to accurate combustion simulation of engines using alternative fuels with detailed chemistry can be summed up as follows. Use the best global or severely reduced mechanism possible in the CFD analysis to get the best starting point for the ERN analysis. Use the appropriate accurate detailed chemical mechanism in the ERN analysis for accurate results. Use the ERN to conduct parameter variations on fuel composition to understand their impact on combustion results.

As combustion temperatures decrease, several undesirable combustion phenomena become more prevalent and must be addressed. In a lean low-NO_X flame, the normally fast chemical reaction time slows to the point that it becomes rate limiting relative to fluid mixing. The result is a flame that is struggling to stay lit and which may extinguish. The primary limiting factor in lean low-NO_X combustion in premixed systems is lean blow-out (LBO). LBO occurs when the heat generated by the burning fuel/air mixture is no longer sufficient to ignite the incoming fuel. Two combustion stability challenges in low NO_X combustion are flashback, where the flame front propagates upstream, and ignition, resulting from

FIGURE 4 INDUSTRIAL GAS TURBINE PILOT FUEL SPLIT ERN PARAMETER STUDY FROM A SINGLE CFD CASE

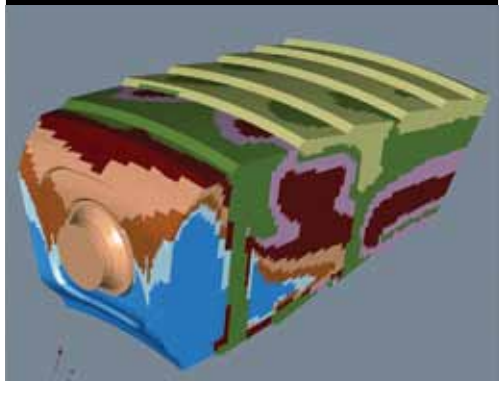
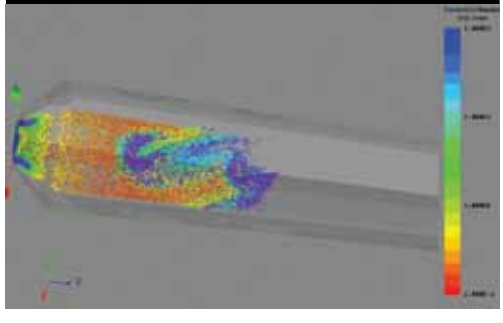


FIGURE 5 LOCAL DAMKÖHLER NUMBER FOR A SIMPLE WALL JET COMBUSTOR



the lower flammability of the fuel mixture. Chemical reaction rates and short-lived chemical species are indicators of LBO and combustion stability.

Detailed chemistry simulations allow designers to better understand how to solve the LBO problem. It is simple to define the local (CFD-cell) flow residence times from the CFD flow solution. The simulation approach then determines local chemical time scale, based on local cell temperature and gas composition, by using a detailed combustion-chemistry calculation for each cell. The resulting LBO analysis verifies the integrity of the flame locally and then provides an indication of the overall soundness of the flame zone visually, as contours of the local Damköhler number. The Damköhler number distribution (Figure 5) exposes location and size of the stable flame core in the combustor.[2] This local Damköhler number data does not immediately indicate whether or not the flame will blow out. It is only by examining the structure and topology of the flame core and the integrity of key regions in the flame that the designer can assess the likeliness of blow-off as well as the adequacy of the CFD mesh for flame predictions in that area.

The industry's ability to take advantage of alternative fuel opportunities will define the markets for gas turbines, boilers and other combustor applications. To that end, combustor designers are seeking to use larger, more refined CFD grid designs to resolve the highly detailed geometry of a modern combustor with its fuel/air injectors, swirler flows and cooling air. Yet the use of reduced-order turbulence models has been identified as a key factor in the inability of today's CFD codes to predict combustion stability. Advanced turbulence models such as large eddy simulation (LES) show promise in predicting the unsteady flow regimes in a gas turbine combustor, but at the cost of 20-times-longer computation times. So even with faster computers, it is likely that combined high-end turbulence and high-end chemistry modeling will not be practical for some time.

Today, new simulation techniques are helping designers employ detailed chemistry with CFD to produce accurate modeling of flows and detailed chemistry for fast, useful simulations of combustion stability. The ongoing study of detailed fuel chemistry mechanisms has shown that various compounds within a fuel can have significant impacts on combustion performance. Designers are adopting new, more effective methods that merge the benefits of CFD modeling and detailed chemistry simulation for complex combustor geometries. Using these methods and new automated software packages they can evaluate key parameters of combustion stability, such as LBO, while reducing the amount of costly and time consuming experimental testing. pe

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