Utilizing Interactive 3D Visualization for Optimum Emissions Control

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Computational modeling is now an every day tool for engineering. Advances in affordable computing power have enabled the engineers to meet ever growing challenges. Every good designer has a three dimensional model of the product in mind as the engineering details are worked out. This model is laid down into drawings so that the product can be manufactured, shipped, and constructed. The structural and process requirements are developed through powerful simulation software run on computers performing billions of calculations. Even inexpensive desktop computers are used to calculate sophisticated models. It is remarkable that the performance calculations for many of the very large power plants operating in the world today were done with slide rule and hand calculations. However, today's increasing demands for efficiency, reliability, and environmental protection require that designers continually "push the envelope". With high performance visualization the powerful capabilities of design innovation and detailed analysis come together.

The control of pollutants in combustion systems is a particularly challenging engineering problem. Chemical reactions taking place in milliseconds under complex mixing conditions must be controlled to limit harmful species to part per million levels, or less. Computational fluid dynamics (CFD) modeling is a powerful simulation technique to handle the physics of the system. After many years of development CFD is now well accepted as an essential tool for the design of emission control systems. It is a complex, powerful, and evolving technique which must be used carefully. The system, for example a burner, furnace, ESP, bag-filter, or back-end scrubber, is set up as a model comprising millions of mathematical cells. Governing equations of mass, momentum, and energy determine the conditions in each cell after the convergence of iterative calculations leading to a solution for the entire system. Typically, ten to twenty variables are computed for each cell. The result is an enormous quantity of data. There is no practical way to deal with such huge volume of results without visualization.

A synthetic 3D environment facilitates human capacities for evaluation and decision-making by resembling a real world experience. Interpreting a 2D plot of 3D data requires analytical abstraction. Computers are good at transforming data into information when guided by rule-based techniques. However, interactive 3D realization activates powerful skills, allowing the user to experience information and achieve a higher level of interpretation and evaluation. When information is effectively presented, human perception is very efficient at recognizing complex patterns, synthesizing opportunities, and evaluating alternative processes. Software for interactive 3D computing has now achieved the necessary levels of fidelity for effective, interactive evaluation of simulation results. This provides the engineer with the means to find better solutions to problems and opportunities to achieve greater performance in multi-pollutant control systems.

Alstom Power, Inc. (Alstom) and Fuel Tech, Inc. utilize CFD modeling to design their products. Alstom supplies a full range of power products encompassing low-NOx firing systems, combustion turbines and steam generators, and back-end systems for capturing particulate, SOx, and NOx. Fuel Tech supplies urea-based SNCR and SNCR/SCR hybrid systems for NOx control, and slag control systems which help consumers of difficult fuels, such as low emissions fuels like PRB coal, handle ash deposition problems. Fuel Tech developed its ACUITIV™ software to visualize CFD model results in a 3D workspace. Faster computation and better visualization were seen as ways to improve design productivity and decision quality. Alstom was instrumental in the beta development of the code and continues to provide suggestions for improving the commercial code.

THE DECISION WORKSPACE

The objective of such software is to create a meaningful world from complex data. The data may be generated from simulation programs and also from measured data. Visualization objects are generated to explore information details. The observer is then able to use visualization tools to examine behaviors, explore causation, and evaluate opportunities to solve problems and improve the design. High fidelity representation and vivid visualization objects produce an experience similar to a physical inspection of an actual device. In such an environment people from various disciplines with diverse but complementary experience can work together. The process of working together--literally, collaboration-- provides rich opportunities to discover the optimum, explore the unexpected, and best solve problems.

Computational Fluid Dynamics (CFD) data are readily transformable into a 3D workspace. CFD data are typically in terms of m, x, y, z, and t. Derivatives with respect to time yield velocities and acceleration, and thus momentum, pressure, and energy. The results are easily visualized in a 3D world. Visualization objects are generated to trace flows, reveal complex or intricate flow details, and map computed values. Color maps and surfaces keyed to quantitative values present analytical information. It is also possible to bring into the workspace other information. Detailed CAD drawing information for the objects in the system, structural results from a finite element analysis (FEA) model, or data from physical measurements add layers of information.

The goal of the software is to provide a robust, powerful, evolving, and universally applicable visualization code that meets the ease of use expectations of commercial-off-the-shelf (COTS) software. Computing power that was once "supercomputing" is now available at the local consumer electronics store. There is no longer a reason to associate "high performance" with "high cost". The balance of the task is to provide polished software that is easily used by the problem solver. To be truly practical it must promote full attention on the engineering problem and minimize distractions by software operations. The development at Fuel Tech has focused on meeting these goals. Initially, the software was developed for Fuel Tech's internal proprietary technology. In 2002, the software was released as a commercial product. It is now available under the product name ACUITIV.

Seamless integration of a growing suite of analytical tools within the decision workspace is planned as a rich developmental path for the future. Fuel Tech is working with Iowa State University on the development of virtual engineering tools. In the long term, fully interactive visualization-simulation is the goal. Along this path, rapid recalculation and optimization techniques will be incorporated within the visualization environment as they are put into practice. Experience from users such as Alstom is valuable for future improvement of visualization technology.

CODE STRUCTURE FOR POWER AND EASE OF USE

ACUITIV was designed with a modular structure and fully utilizes the programming capabilities of C++ and OpenGL. The structure facilitates efficient communications among the modules and with other programs. The code is object oriented utilizing a design pattern approach. This facilitates easy modification of the code for future adaptation and growth. A very flexible capability is built-in for reading various types of data. It is designed to take full advantage of mature, yet continually improving projection technology. This foundation provides hooks and pathways for the incorporation of virtual engineering and interactive simulation capabilities for future evolution.

The current version is able to read the native case and data files from Fluent® and data outputs in CGNS, Tecplot and Plot3D formats for other CFD codes. The ability to read native files is desired to reduce the loss of fidelity that could result from multiple translations of the data. Also, older results can be read without reprocessing. Fuel Tech has had occasion to re-examine older CFD results from studies conducted before ACUITIV existed. Reading native format avoids the complication possible in attempting to re-run an old model. The three dimensional world can be generated from cell-based models, or "cell-less" models such as particle tracking type programs. The module design allows for two-way communication with the CFD program in the future as fully interactive techniques evolve.

Information for the geometry of the model is used to create the model environment. The world representing the model is stationary with up, down, and around established in a natural (to the extent possible with the model) configuration. The concept is to explore the world of the model as if examining the real structure. This module has the capability for future extension to modify spatial input to the CFD program. Geometry information can be generated from the CFD mesh. Or, CAD data in STL format may be used to generate geometry. This can be useful in revealing discrepancies between the physical design and potential errors made when generating the CFD mesh.

ACUITIV is ported to VrJuggler, which drives the projection system. VrJuggler is an open source library developed and supported by the Virtual Reality Applications Center (VRAC) at Iowa State University. It is continually evolving as an active project to incorporate new ideas and hardware requirements. It handles the projection of visualization objects on systems from as simple as a single monitor or head-mount to as complicated as a multi-projector, multi-surface, flat, or curved theater.

THE INFORMATION VISUALIZATION EXPERIENCE

The user visits the world created from the data. A visit to a computed world is much safer and productive than visiting the reality of, say, the combustion chamber of a gas turbine or furnace of an 800 MW utility electric power boiler. Location within the world is controlled by simulator style navigation inputs. In a multi-wall theater, a wand is used to control movement and activate menus. On the desktop, a 3D input device like the Spaceball® or Spacemouse® (from 3Dconnexion) may be used to control movement. Such devices are commonplace in the CAD industry and allow the user to translate, rotate, and twist within the 3D world. Simple keyboard controls are also available and effective for navigation. Through a second mouse on the desktop, or by using a button on the wand in a 3D theater, menu selections are made through the immersed menus.

Alstom was very helpful in testing the software. Suggestions, such as the Spaceball controller, provided valuable input on making the software easy to use. Experience with models of different scale, such as a full furnace model and a detailed model of circulation within an individual waterwall tube, was beneficial in tuning the code.

The desktop system may be considered as looking through a window into the 3D world. Some would argue that a desktop monitor is not truly immersive. That would be the case if the user was looking through the window and moving the model, as is done with the typical 3D drafting program. However, the experience is different. It is as if looking through the windscreen of a vessel that is immersed within the world. A 360° view is obtained by simply twisting about an axis. Indeed, it is easy to twist simultaneously about three axes while also thrusting linearly along those axes. It is like a tour in a helicopter, or a submarine, or looking through the facemask of diving gear.

The same software will run in what all would consider a fully immersive VR theater (Figure 1). The six-sided C6 VR Theater in the VRAC at ISU is an example of a fully immersive environment. Several observers can visit the world in this 10'x10'x10' room. Rather than navigating the desktop to look in the opposite direction, the user simply looks in that direction. Unlimited peripheral vision enhances the effect. A further advantage of the VR Theater is that each visitor can look in different directions simultaneously and alert others to items of interest. Different viewpoints can combine

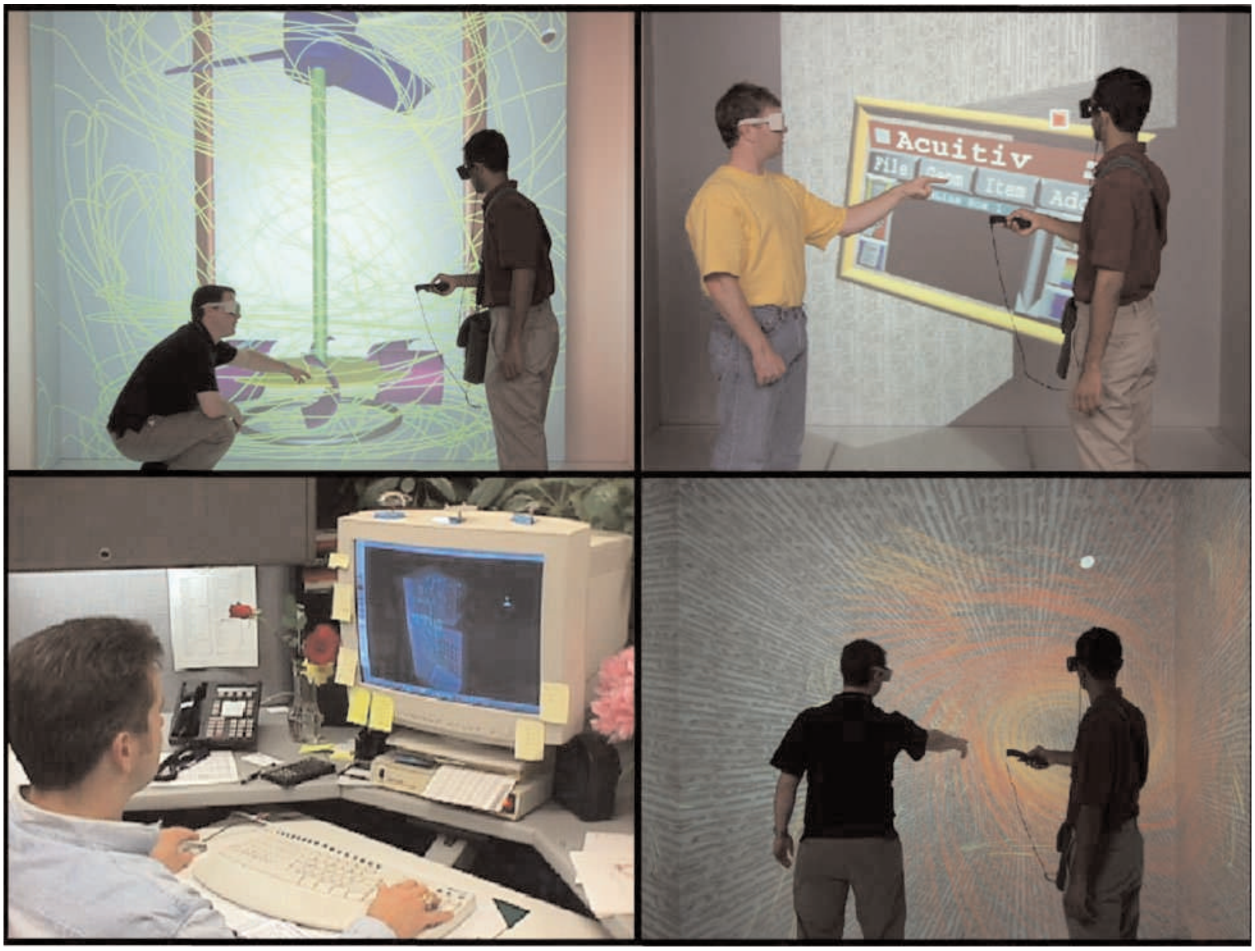

Figure 1 - Immersive Visualization - from Desktop to VR Theater

with different points of view, such as those of the project manager and the engineers responsible for controls, mechanical, chemical, electrical, or styling design. The VR Theater may be considered an immersive conference room in which people can easily work together to arrive at optimal decisions. It is very much as conducting a live inspection of the system-while it's running.

The first and most important decision is to test whether the model world makes sense. The computer model is only as good as the input data and the model processes. Human beings have a very valuable store of experience and a powerful intuitive sense. In an immersed examination it is very often easy to pick up features that are at odds with experience. Just as easily, a good model may reveal something very unexpected, yet obviously understandable when viewed in a natural and realistic setting.

An extensive suite of visualization tools is available to aid exploration of the model. A common starting point is to observe the flow fields using real time streamline animation. The starting points of the streamlines can be selected as individual points, or as a distribution of points in a dynamically selected volume. Objects like boxes or 3D arrows that are sized and oriented to the local velocity magnitude and direction along each streamline are then animated. The color of the 3D arrows or boxes can be mapped to the local value of any variable. For example in combustion applications, it is typically useful to color the streamline animation by temperature or the concentrations of combustion products to get a visual sense of the burning and heat release processes while observing the flows.

Observation of the flow traces while exploring the model domain provides a sense of what is important to examine more closely with other analytical tools in the ACUITIV software suite. Dynamic control of the streamline animations is available with VCR-style buttons and other options on control panels immersed with the engineer in the visualization session. When controls panels aren't needed, they are hidden with a "virtual desktop" technique, minimized, or simply slid out of the way in the 3D environment. The user interface is designed to help but not distract from the design tasks.

Graphs of variables along the streamlines as a function of time or distance are instantly displayed, and histograms of summary streamline data add to understanding the problem. Immersed in the VR environment, the engineer can inspect the flow and auxiliary data and discover recirculation zones, twisting flows, residence time information, and other features.

Once the flow is inspected, contour planes in various orientations may be used to further analyze the data. Multiple planes provide broader spatial sampling of the data. In addition, the planes can incorporate a field of vectors to show local velocities. As with the flying boxes and darts, color is used to represent quantitative data. The user has complete control over color mapping. Various scale types are available. Some are well suited to thermal data, others to species concentration. Non-linear scales help represent widely ranging data. High and low cut-off values facilitate searching for a critical range or threshold target. Contour planes and point queries help scan model data and match measured data when available. The engineer is able to bring up histograms of contour plane data to further quantify and confirm design decisions. Similarly, isosurfaces are very useful for observing a critical value with a complex spatial distribution. A region of specific temperature range, species concentration, vorticity, or other values computed in the model may be of particular interest for the design.

INVESTIGATING BURNER BEHAVIOR IN OIL-FIRED FURNACES

Computational Fluid Dynamics (CFD) is an important design and analysis tool used by Alstom. At their Power Plant Laboratories (PPL) located in Windsor, CT complex Fluent models are generated to solve challenging problems for both internal and external clients. An important aspect of the CFD analysis process is post-processing of the results to optimize designs and to discover the improvements possible. Whether investigating the thermal performance of an ultra low NOx burner replacement in a complex 3.5 million-cell combustion simulation or, optimizing a simple set of turning vanes, CFD has become a mainstream activity for many companies like Alstom. Flow patterns in a detailed model of an oil burner compartment in a 300MW tangentially fired furnace were studied with ACUITIV.

During start-up of the unit, consistant satisfactory low excess air operation was elusive. Different oil gun atomizers were evaluated in the field, and CFD was used to study how the ignition characteristics were altered using different orifice drilling patterns tested in the field. CFD was applied to provide a perspective of the near burner flow patterns for several arrangements. Both full furnace and detailed corner combustion models of the oil burner compartment were generated with Fluent.

In the large-scale model of the furnace, the geometric scale variation between the burner details relative to the size of the full furnace presents a meshing challenge to adequately represent the details and still have manageable mesh size. Computing hardware and parallelization of the software now allow multi-million cell simulations to be generated routinely. However, a combined modeling approach was also found to be useful. The

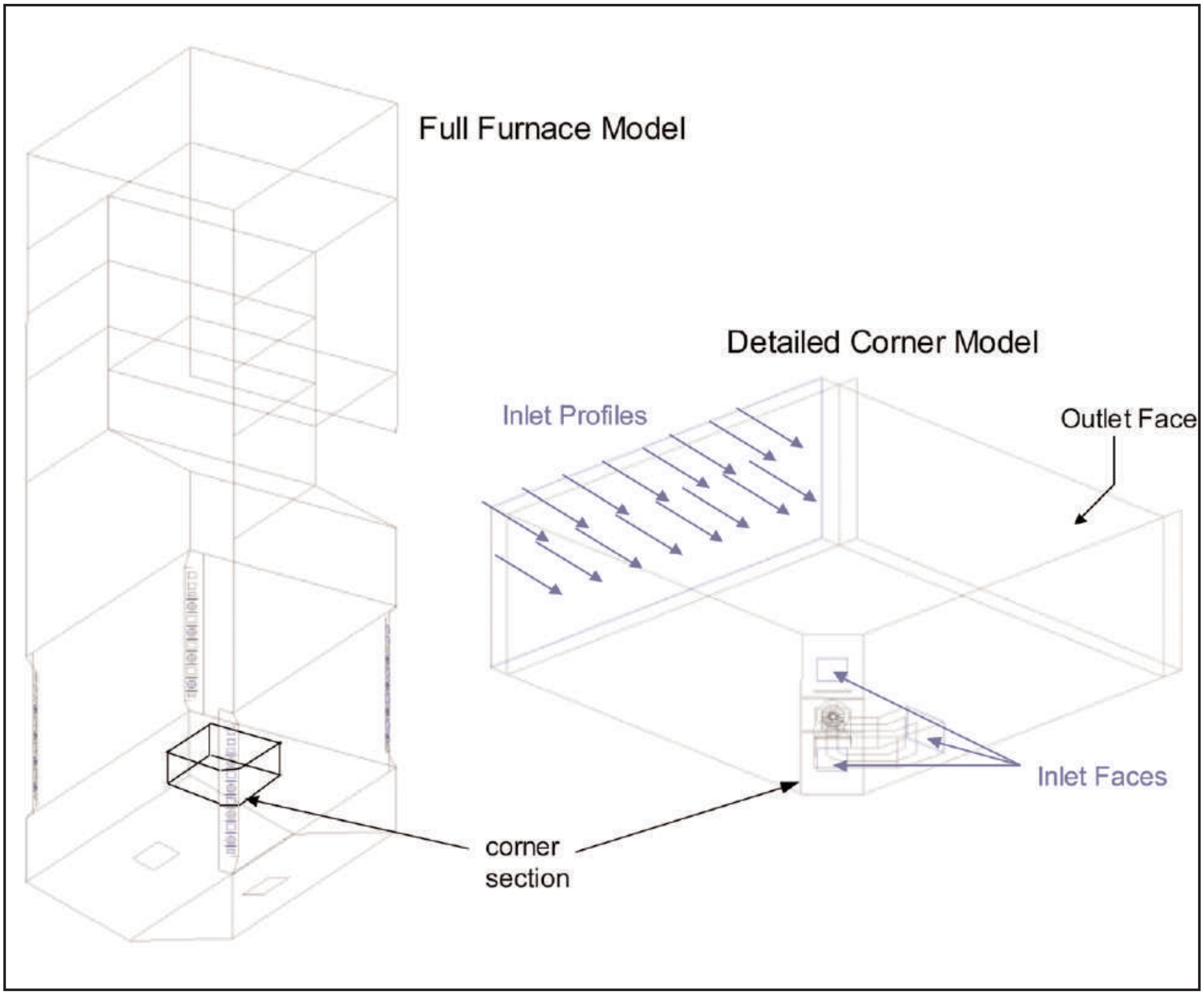

Figure 2 - Geometry of Full and Detailed Models

furnace was modeled from the hopper through the economizer outlet. The furnace model included all four levels of oil gun compartments with the adjacent air compartments. In combination with the furnace model where all the individual compartments were modeled with a relatively coarse mesh, a detailed model of a typical corner was generated. This included a single oil gun and adjacent air compartments along with the upstream air ductwork. In this model, the individual swirler vanes and steam/oil jets were represented for several of the tips tested. The swirler provides a flame stabilization region to keep the flame anchored in the quarl.

The corner model's inlet boundary conditions were prescribed at the upstream windbox plenum, where the total flow rate to the burner compartment could be determined based on the pressure differential between the windbox and the furnace. What was not known was how the air flow distributed itself to the various zones downstream of the common duct. The flow bias and 3D velocities leaving the swirler and adjacent air compartments were predicted by the detailed corner model, and then applied to the respective primary, secondary and adjacent air compartments in the full furnace model.

To provide a basis for the tangential flow field at a typical mid-windbox compartment, data was passed from the furnace model to the corner model upwind inlet face. This swirling flow merged with the corner jets emerging into the surrounding furnace gases and exiting on the downwind face. Figure 2 shows an outlet of full furnace model and

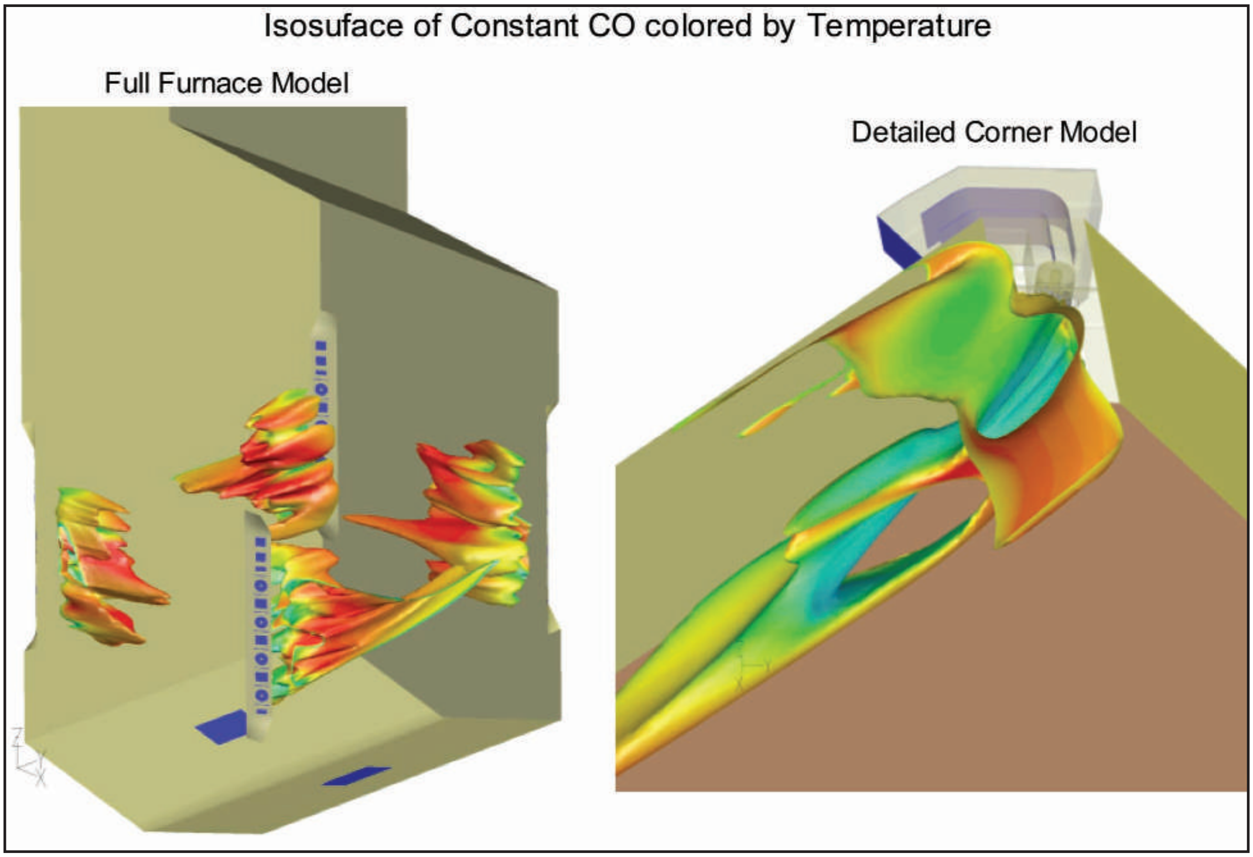

Figure 3 - Comparison of Flame Patterns

the section of the windbox used for the detailed corner model. The location of the profiles used to provide the flow environment for the corner model are also identified.

The profiles passed to the corner model included velocity components, temperatures, and gas species. The top and bottom faces of the corner model were assumed to be symmetry boundaries in the corner model. Because the flow distribution in the center of the windbox near the corners is dominated by the swirl pattern, the impact of the top and bottom faces was tolerated since the area of interest was close to the swirler tips. Figure 3 represents the flame surfaces with an isosurface of CO mole fraction colored with a temperature scale for both the furnace model and the corner model.

The visual analysis of the near corner model swirl patterns was augmented using ACUITIV. It was observed that the swirling burner entrained gas from the upwind flow and adjancent zones in a complex set of pathways. The burner swirl and ignition pattern is represented with traces colored by temperature in Figure 4. Ultimately, the CFD models suggested that the ignition pocket was not significantly altered for the different oil atomizers tested. For the post-processing experience, interactively moving the

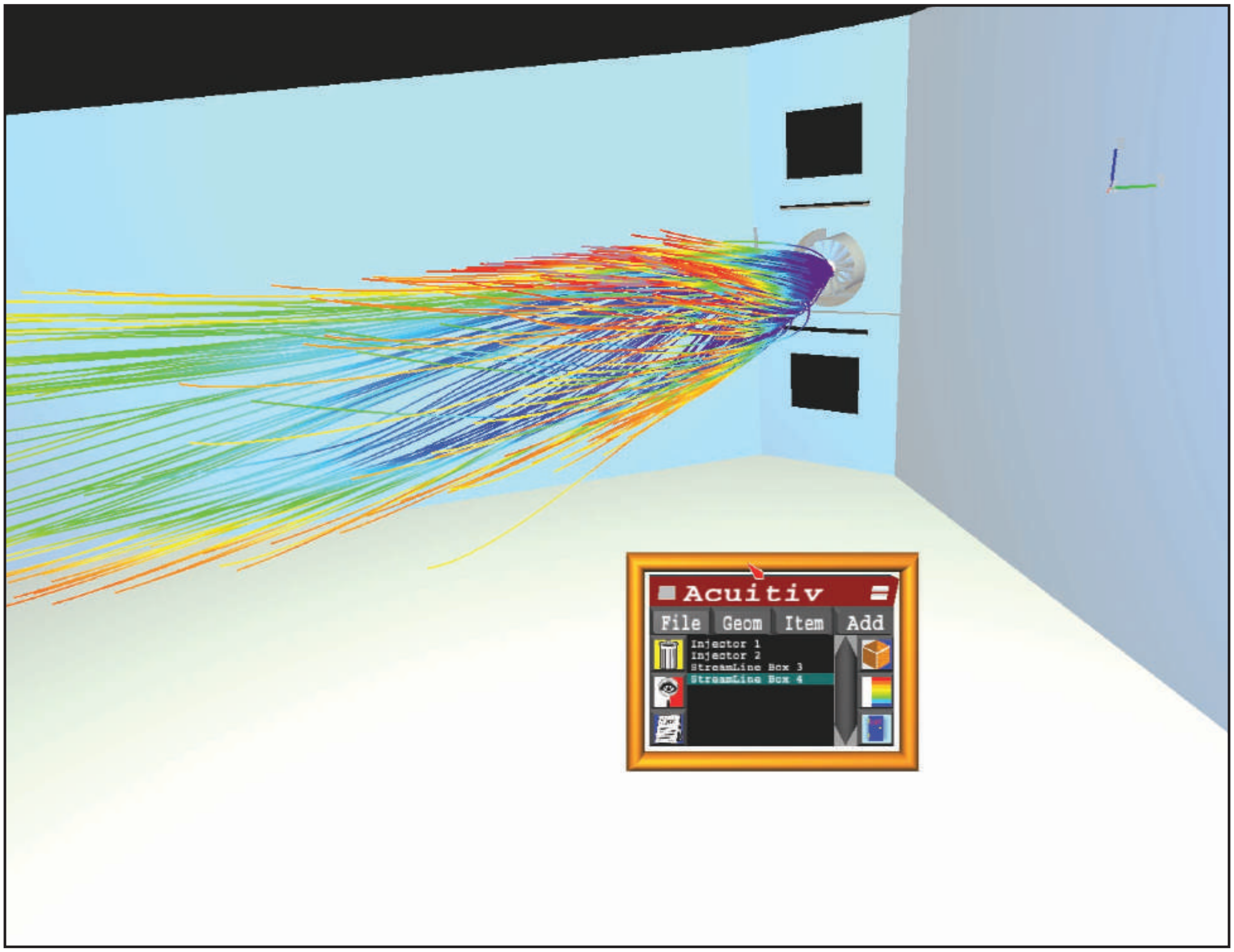

Figure 4 - Swirl Burner Flow - Colored by Temperature

injector location combined with stereo viewing in a fly-through tour was found to be extremely informative to illustrate the burner patterns.

CONTROLLING OPERATIONAL PROBLEMS WITH LOW EMISSIONS FUELS

Very low emissions are possible with sub-bituminous coals from the Powder River Basin in the Western United States. These are low in sulfur, low in fuel nitrogen, and generally low in ash content. However, the ash frequently has constituents which lead to low softening temperatures. Temperatures prone to deposition are often found in convective sections where fouling strongly degrades performance. Even units designed with generous furnace size to keep temperatures in the upper furnace low can encounter problems with slagging as fuel characteristics vary. Many electric power utilities are switching to PRB blends in boilers originally designed for coals with relatively high softening temperatures. An effective slag control program is then an important component in achieving the required control of emissions levels.

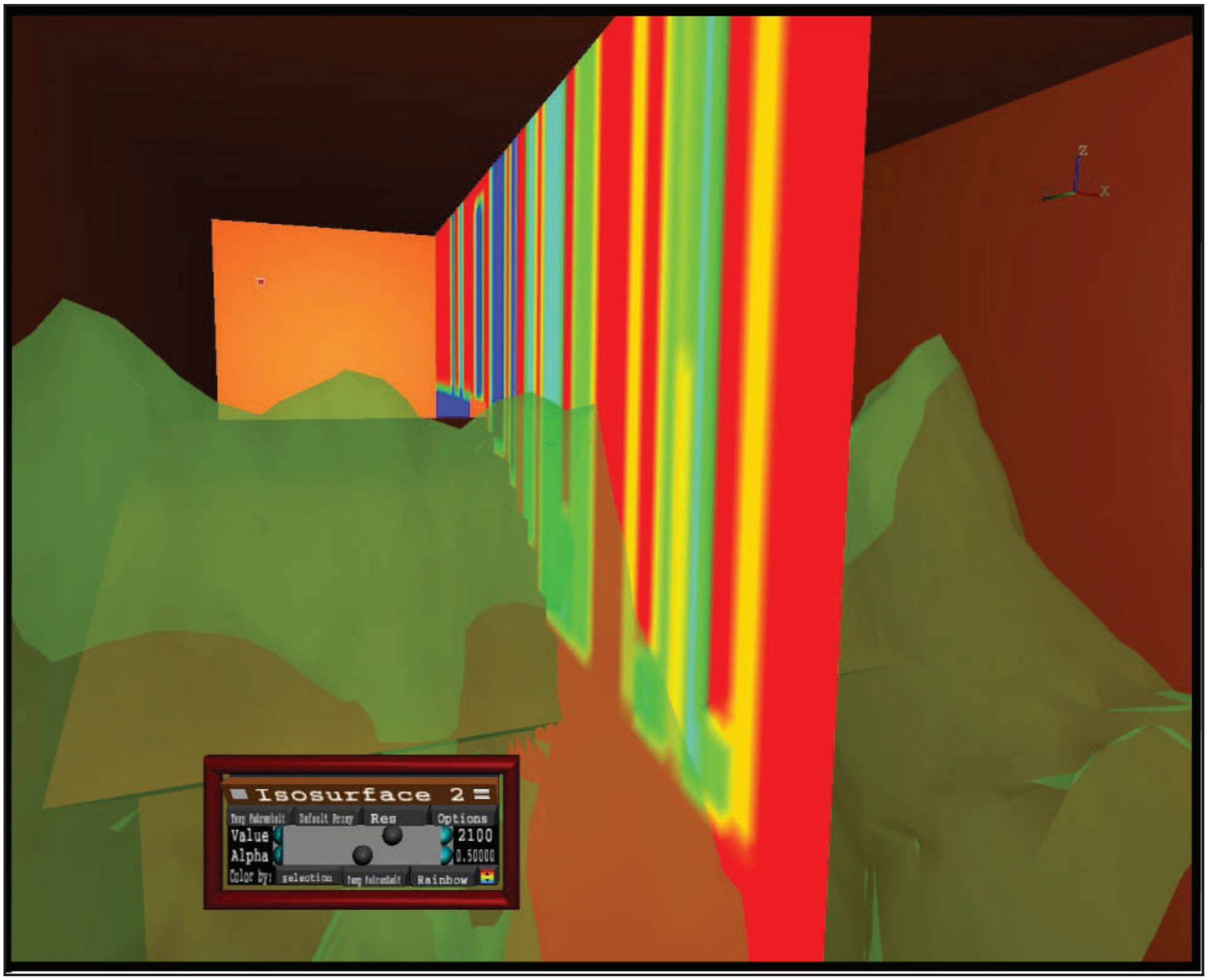

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Figure 5 - Slag Deposition Target Zone

Fuel Tech has developed a chemical injection technology to control fouling. Small quantities of specially formulated magnesium hydroxide are injected. When targeted on problem areas the magnesium prevents the ash deposits from forming a tightly bonded structure. Deposits are friable and easily cleaned. CFD modeling is used to identify regions with temperatures likely to result in slagging conditions and to target chemical injection to treat problem areas (Figure 5). The CFD technology is similarly applied with Fuel Tech's selective non-catalytic reduction (SNCR) products for NOx reduction.

Interactive 3D visualization is a key capability in designing the slag control system. An interactive spray injection model was developed as an example of high performance computing. Initially, it was prototyped on a supercomputer. Today, an inexpensive workstation has sufficient computing power. The spray model is a one-way coupled particle injection simulation. This is sufficiently accurate for predicting spray behavior because the spray mass flow is small compared to the gas mass flow. The design engineer is able to place and move injectors in order to find an optimal injection arrangement. Droplet size and velocity can be adjusted as needed to hit the targeted areas.

Fuel Tech's engineers have found that the interactive spray model reduces the time by approximately 20% to determine an optimal spray arrangement. Moreover, the simulation-visualization system has been an essential part of a very successful track record in hitting predicted performance on the first try.

DESIGN OPTIMIZATION FOR UTILITY SCR SYSTEMS

The design of utility boiler retrofit SCR systems requires integration of large sections of ductwork and reactor cavities within the constraints of structural steel and existing equipment. This often cramps the design space to efficiently layout the ducts, and necessitates many elbows and other non-ideal transitions. The transfer ducts from the boiler's economizer outlet often include economizer gas bypass streams for maintaining gas temperatures to catalyst surfaces at lower operating loads. This minimizes the potential for ammonium bisulfate formation on the catalyst. Additionally, reactor bypass ducts may be installed for use during unit startup, nonozone season operation and maintenance. Ammonia injection ahead of the catalyst section requires a relatively uniform flow field to achieve balanced ammonia/NOx ratios to attain high reduction without slip. While traditional physical flow models were used to optimize flow controls and mixing systems, CFD is now being used extensively for development of flow controls and to simulate the gas concentration ratios entering the catalyst. Measured NOx , gas temperature and velocity profiles leaving the boiler can be used as boundary conditions for CFD simulations that include representation of the ammonia injection grid.

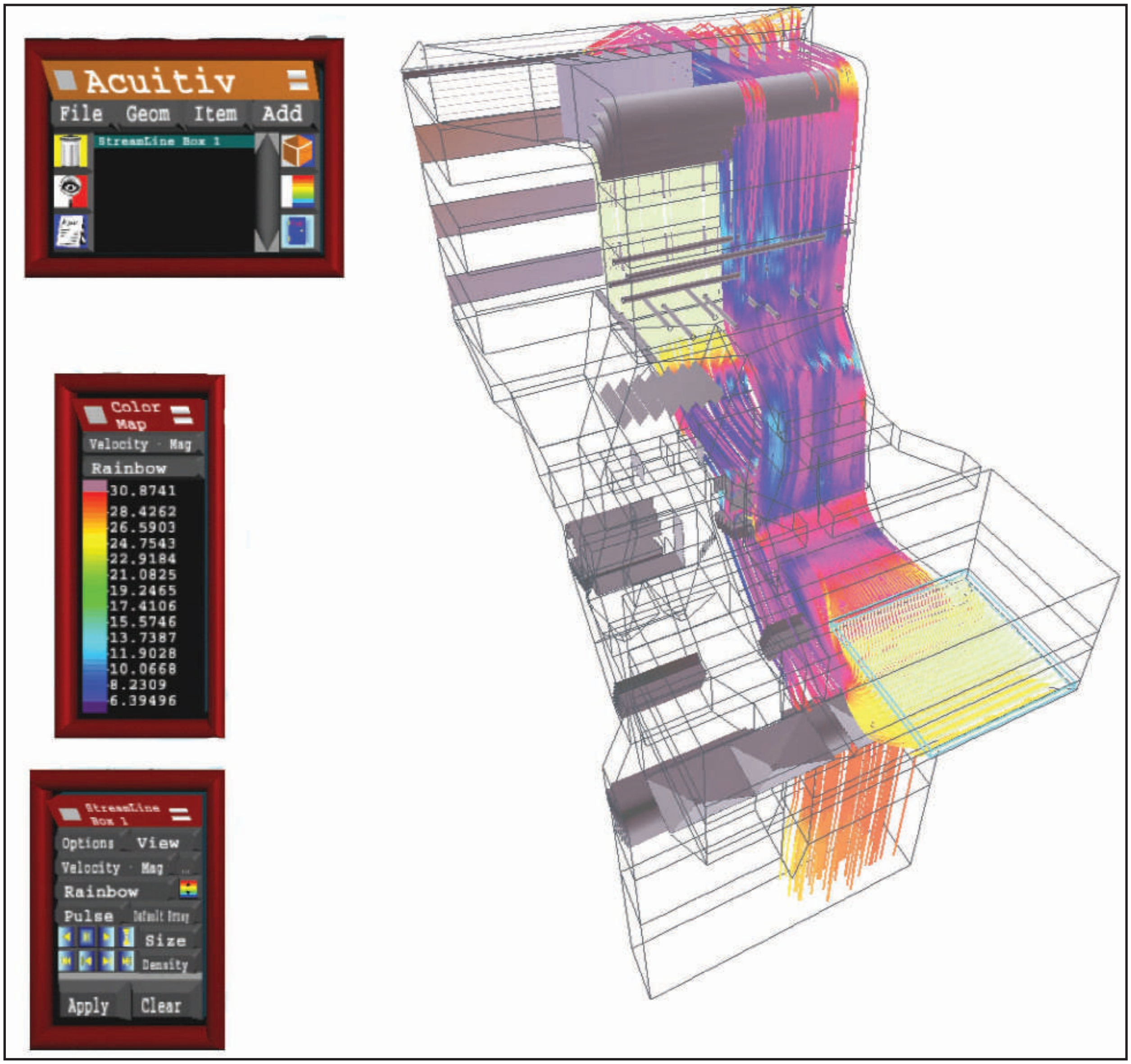

Figure 6 - SCR System Flow Profiles

CFD simulations of the SCR system can represent the envelope of expected operation conditions, and determine whether a given design can achieve the stringent performance targets before fabrication begins. CFD is also a valuable tool when designing large particle capture devices, for minimizing ash carryover to catalyst surfaces. Here again flow visualization and animation tools that can illustrate the flow distribution, migration of particles and temperature distributions throughout the system can be used effectively to optimize the design. An example of an SCR system that includes both SCR and partial economizer gas bypass is shown in Figure 6. Gas tracers released from one side of the economizer are colored by velocity and tracked through the SCR and to the air heater return duct. The mixing of the flow was studied to determine how the ammonia injection flows would be tuned in response to variations in NOx profiles leaving the economizer. A set of guide vanes before the injection pipes was found to improve the gas flow profile uniformity for better performance.

VIDEO CAPTURE

The ability to communicate design opportunities to others is important to achieving optimum results. Video files provide a means of showing results to those unable to directly experience an immersive session. The software generates a naturally smooth stream of images that can be captured as video. With real time rendering of the model and visualization objects it is easy to generate a natural sequence of scenes. The experience is much like guiding a guest through an inspection or tour of the model. With a little practice and planning a "storyboard" guides the tour. If a picture is worth a thousand words, what is the value of a thousand pictures? One answer is "about 33 seconds of video", which can speak volumes when well done.

Fuel Tech uses a high quality video capture and editing system. It was supplied by Avid® and was designed for professional multi-track, non-linear editing. Video reports are very effective and have essentially supplanted the paper report. A significant advantage is that more people at the customer's establishment see the results. A few technical people look at paper reports fairly closely. The video report is easily presented to a wide audience. In our experience, the video reports are of interest to key leaders, such as plant managers.

Excellent video results, suitable for most needs, are also achievable with a very low cost system. A high quality scan-converter is a critical component. These are now available for around $1,500. Video can be fed from the scan converter to a digital MiniDV camcorder as the "tour" is conducted. The cost of high quality digital camcorders has dropped to well under $1,000. Video clips are captured from MiniDV via a firewire or USB2 link into editing software. Very good results have been achieved with Video Factory 2.0 software from Sonic Foundry®. It is available for under $150, including upgrades to the latest MEPG2 codecs. Alstom Power uses Adobe Premier which is very effective. The video editing software makes it easy to create a finished movie with transitions between clips, titles, and an audio track. The finished report can be rendered to a variety of formats including MPEG, AVI, Video for Windows, back to MiniDV tape, or to VHS tape and DVD.

ACUITIV includes a function for outputting a stream of still captures as JPEG files. An MPEG video can then be created from the JPEGs using a separate program for this purpose. High resolution still images can also be produced for papers and presentation.

VISUALIZATION PROVIDES NEW OPPORTUNITIES FOR OPTIMIZATION

Interactive 3D visualization is here now for solving problems. We have passed an important threshold in the steady and relentless growth of affordable computing power. Realistic representation of complex models provides the work environment for high-level decision processes. This offers the potential to revolutionize how engineering is done.

Ease of use is essential to continuing success. Custom, one-of-a-kind viz-sim projects take too much time and effort to be practical for everyday design. Fuel Tech has experienced the benefits of having powerful and easy to use interactive 3D realization. Significant reductions in design time with major increases in quality have been achieved. Most important as a quality improvement is the ability to reveal the unexpected, discover new opportunities for improvement, and readily see beneficial decisions.

Software is now available that meets the goal of commercial-off-the-shelf software for high performance interactive visualization. Virtual engineering will further increase the power of the work environment for decision-making. High performance visualization of CFD data is a natural first step. Combinations of models such as CAD and FEA extend analysis to more complete systems. A toolbox of seamlessly integrated, highly flexible techniques will expand the power of decision-making within the visualization environment. These are steps toward the ultimate goal of fully interactive visualization-simulation.

Environmental protection benefits from advances in design technology. Emissions control is significantly affected by small defects. An imbalance in a burner, the effect of small changes in ash constituents, or a deviation in reagent distribution may substantially change performance. In the push to approach the goal of essentially "zero emissions" interactive visualization is crucial to continual advancement of emissions control technology.