ADVANCED PROCESS MODELING SAVES MONEY

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ABSTRACT

Pulp and Paper process equipment is operationally complex, and design performance depends critically on how gases, liquids, and solids interact. Examples of these interactions include air and black liquor for recovery boilers, white liquor and chips for digesters, gas, oil, or coke and air for lime kilns, pulp fibers and water for headboxes, and biomass and air for power boilers. In these devices, various flow streams are introduced at prescribed velocities, resulting in complex interactions where convection and dissipation forces govern the internal process. Thermal gradients and chemical reactions occur that are dependent on the flow convection and dissipation forces. Processes are three-dimensional, turbulent, and can include heat transfer, combustion, species transport, and multiple phases. Many different designs have been promoted that have not met expectations. The motivation for developing and applying advanced process modeling to such equipment is to reduce the emphasis on trial and error by providing a more rigorous method to achieve sound design and optimized performance, with the end goal of reduced capital and operating costs. Process modeling yields flow, chemistry, and combustion details from which the effects of geometry, operating, and other design parameters can be investigated. This knowledge has been successfully applied to many different types of equipment. Examples include improved combustion air systems, significantly reduced pluggage, reduced down time, reduced environmental emissions, and productive investigations into corrosion mechanisms. Process modeling can also be used to increase a return on investment by better training operators, rapidly providing detailed process analyses various conditions, helping to solve or avoid future operational problems, and reducing the variation in operations between operator shifts. The objective of this paper is to describe what advanced process modeling can and cannot do, how it can be applied in pulp and paper mills, and also to highlight the cost-saving advantages and reductions in capital investment risks.

ADVANCED PROCESS MODELING

Modeling provides a wealth of information about a process by segmenting the equipment into hundreds of thousands of ‘cells’. Relevant flow, combustion, reaction, and heat transfer physics equations are solved in each cell using the laws of conservation of mass, momentum, and energy, chemical reactions, and using a database of fluid and fuel properties. Solutions to these equations provide detailed three-dimensional field information about the process. Advanced process modeling requires a blend of:

- Fundamental engineering knowledge in the area of fluid mechanics, heat transfer, mass transfer, and combustion
- A strong modeling team experienced in performing 3-D modeling with the ability to develop sub-models (models which pertain to certain physical aspects of the process, i.e., radiation heat transfer, fuel combustion, calcination reactions, …) and obtain accurate boundary conditions
- The ability to collect and process valuable information from equipment operators who have developed an intuitive understanding of equipment operation

In this paper, the term *advanced process modeling* represents the application of three-dimensional Computational Fluid Dynamics (CFD) coupled with equipment-specific sub-models to predict the behavior of a complex process and where results are rendered online using simulator technology. Figure 1 illustrates the three main components involved in advanced process modeling. At the heart of this tool is CFD, which solves fundamental force, mass, and energy balances for gases, liquids, and solids. CFD is a large set of non-linear equations that are solved using non-trivial iterative methods.

For each equipment type, the modeling team needs to develop various equipment-specific sub-models, and couple these to the CFD core to solve for the required process variables. The sub-models are very important as they make it possible to increase cost savings and reduce capital investment risks for each process. Common process variables are flow velocities, pressure, turbulence quantities, and temperature inside the equipment. Specific equipment variables are shown in Table 1.

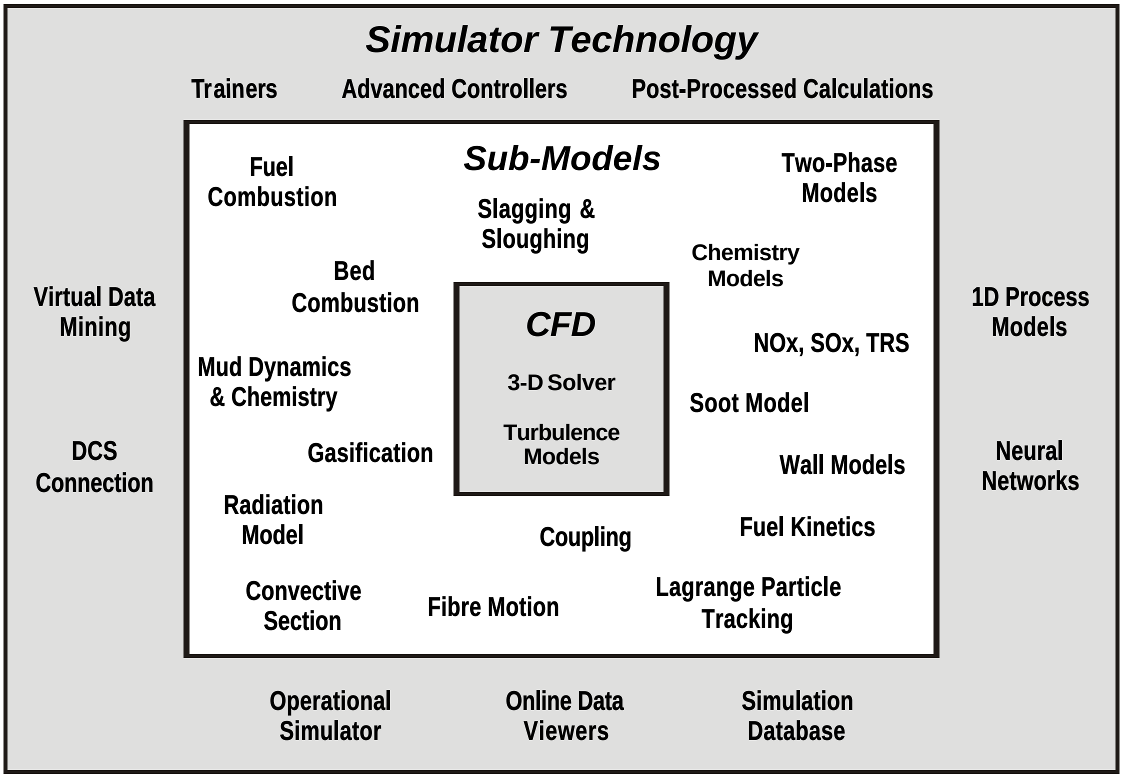


Figure 1: Advanced process modeling: CFD, sub-models, and simulator technology

	EQUIPMENT					
Process Variables	**Recovery Boilers**	**Biomass Boilers**	**Headbox**	**Cyclone Screens**	**Digesters**	**Kilns**
3-D velocity vector	Yes	Yes	Yes	Yes	Yes	Yes
Static and dynamic pressures	Yes	Yes	Yes	Yes	Yes	Yes
Solid pressure					Yes	
Kinetic turbulence energy	Yes	Yes	Yes	Yes		Yes
Dissipation	Yes	Yes	Yes	Yes		Yes
Enthalpy/Temperature	Yes	Yes			Yes	Yes
H_2, O_2, CH_4, H_2O, CO, CO_2, N_2	Yes	Yes				Yes
CmHn	Yes					Yes
NOx (NO, NH_3, HCN)	Yes	Yes				Yes
Sulfur compounds (H_2S, CH_3SH)	Yes	Yes				Yes
Inorganic compounds	Yes					
Fuel trajectories	Yes	Yes				Yes
Fuel state (dry, volatile, char, ash)	Yes	Yes				Yes
Wall heat flux and radiation	Yes	Yes				Yes
Kappa, carbohydrates, AA					Yes	
Two-phase slip velocities					Yes	
Fiber trajectories			Yes	Yes		
Vorticity and fluid stresses			Yes	Yes		
Wall sloughing/slagging	Yes	Yes				
Mud flow						Yes
Wall temperature gradients					Yes	Yes

Table 1: Process variables calculated by advanced process modeling

Owing to the huge volumes of complex data generated by CFD analyses, special technologies are needed to recover the potential benefits. The simulator technology illustrated in Figure 2 maximizes the return on investment when using advanced process modeling. A process is analyzed to map the range of input control parameters of interest. A matrix of input conditions is then developed and the advanced process model is applied to each input condition in the matrix. Input conditions, geometry, and field calculation results are then stored in a database. The results can be fed into a neural network system that learns the relationship between the input data and complex three-dimensional field data that is generated by the process model. The neural network, once trained, can generate new data in real-time for new operating conditions, without the need for time consuming CFD calculations. The simulator technology provides convenient access to modeling results for rapid and easy viewing, training, and for equipment simulators. Process modeling results are made available in real-time, previously the advantage of only simple one-dimensional algebraic models. These results provide engineers and operators with significantly more information for analyzing equipment operations, provide a direct transfer of technology to the mills, and can significantly reduce capital and operating costs when applied in a proper and effective manner.

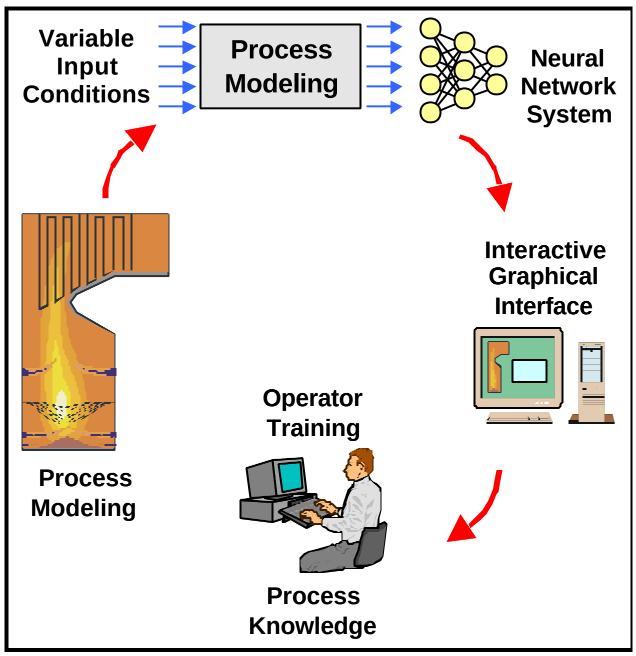


Figure 2: Key components of simulator technology

ADVANTAGES OF ADVANCED PROCESS MODELING

The main reason for using advanced process modeling is to solve equipment design and operational issues thereby improving efficiency and allowing the mill to stay globally competitive. Modeling enables mills that are facing difficult problems operating large capital-intensive equipment to reduce costs and eliminate unscheduled down time. The root cause of complex problems is determined and the success of proposed operational and design changes can be evaluated in advance. "What if" scenarios can be evaluated to improve operation and design, and to evaluate proposed retrofits by different suppliers to determine the most cost-effective upgrade. Return on investment is increased by training operators, providing immediate access to process parameters inside the equipment for various conditions, solving current operational problems, and reducing variations in operation between operator shifts.

Modeling can help evaluate new equipment purchases and base capital expenditures on independent information. It is a powerful tool for improving equipment efficiency by determining inadequate operating procedures and proposing alternatives. Due to more and better sub-models for emission predictions, advanced process modeling is now a tool of choice for evaluating new operating strategies that comply with environmental standards. Modeling can be part of a mill strategy to help secure new environmental permits when deciding to use an alternative fuels. The knowledge provided by modeling has significant impact on decision-making and reduces risk in retrofits and the purchase of new equipment. For combustion equipment (recovery boilers, bark boilers, power boilers, lime kilns), process modeling has been used to increase the load and efficiency, minimize carryover and flue gas emissions, analyze existing air and fuel systems, improve gas mixing and combustion effectiveness, lower excess air necessary for complete combustion, optimize firing strategies for different loads/fuels, and improve stability. In all cases modeling has been able to significantly reduce decision-making risks.

Another advantage of modeling is that results can then be saved as part of a database that contains records of boundary conditions, equipment geometry, field calculations, and fuel combustion and particulate tracking. These can then be made available online to operators, process engineers, and managers. Mill personnel can access the data bank of information to assist in solving problems, optimization, and increase process knowledge. The database containing computed data compliments the information obtained from online measurements and operator knowledge. Measurements are effective in debugging a process, developing ideas as to why a particular unwanted behavior is observed, and to assist in trying to improve the process to maximize production. When looking at a longer time scale to decrease costs, a modeling database has important advantages. Table 2 illustrates the differences between online measurements and a modeling database.

What each tool provides	Tools	
	Measurements	Modeling database
Process variable value at a given location	excellent if environment is not too volatile	excellent
Discrete process data at a cutting plane	difficult and expensive	excellent
Process variable field data (3-D)	impossible	excellent
Data over a large set of normal operating conditions	excellent	now possible
Data outside range of normal operating conditions	often impractical, expensive if production affected	excellent
Transient data	excellent	Excellent, but more time consuming than steady-state
High local resolution	Equipment dependent	Good if emphasis is local
"What if" scenarios for different configuration	too expensive most of the time	excellent
Debugging process problems occurring over short time scales	excellent	requires transient analysis
Debugging process problems occurring over long time scales	possible	excellent
Interpolation between conditions	possible with data interpolators	possible with data interpolators
Picture of what happens inside process	limited to camera output or 2-D scans	excellent
Evaluate retrofits	very limited	excellent

Table 2: Differences between online measurements and modeling database

The alternative to using modeling for retrofits of equipment containing complex flow stream interactions is to base decisions on experience. Experience cannot be used to predict the complex non-linear behavior of the various flow streams and fuel/air interactions in large equipment. This is because both experimental and computational results have shown that small changes can have significant impact on the process and there are often a large number of variables impacting the process. The difficulty stems from trying to account for the complex interactions of solid, liquid, and gas flow streams introduced at many different locations. Assumption on the interaction of these flows and how the process will behave is speculative; in the end Nature follows physical laws, not our speculations. Modeling is currently the best available tool to minimize the uncertainty of how the process will behave for a given set of operating conditions and geometrical configuration of equipment, as experiments are not practical due to high costs.

EXAMPLES OF SAVINGS USING ADVANCED PROCESS MODELING

Three examples of cost savings are detailed below for various levels of advanced process modeling shown in Figure 1. 1.) Application of CFD to a green liquor clarifier, 2.) Application of CFD with sub-models for a recovery boiler, and 3.) Application of simulator technology for a lime kiln.

1. CFD EXAMPLE: GREEN LIQUOR CLARIFIER

At the request of a mill, CFD was used to effect major design changes to a green liquor clarifier. The mill had analyzed several recently retrofitted green liquor tanks from other mills and found that none satisfactorily solved the problem of excessive turbidity. The hydraulic components of a clarifier consist of a feedwell that introduces flow at the center of the tank and a bustle pipe that draws the flow out. The design principle of clarifiers is to facilitate sedimentation and maximize retention time to allow dregs to settle. Application of 3-D modeling to this process revealed that the design of the feedwell used in the last few decades was not appropriate for the desired task. Modeling showed that a typical feedwell creates excessive shear and unacceptable swirl. A new design developed using modeling drastically reduced flow disturbances and removed flow non-uniformity caused by the feedwell, as shown in Figure 3(A). Modeling also showed that a significant amount of liquor was drawn into the feedwell. Modeling of various bustle pipes used in the industry (see example in Figure 1(B)) showed that bustle pipes do not draw flow equally. Only a balanced bustle pipe can ensure maximum settling times for the dregs, utilize the entire tank, and avoid flow short-circuits. Spreadsheet analysis and standard equations used in the industry to evaluate retention times and proposed retrofits are irrelevant when faced with hydraulic components that do not perform. This approach is risky and can be wasteful for mills if turbidity levels less than 100 ppm are sought. Modeling of a few types of feedwell and bustle pipes designs currently offered to mills showed important hydraulic shortcomings. To achieve low turbidity values, an understanding is required of how to (i) diffuse a 0.25 m pipe flow into a 3 to 5 m opening in a distance of typically less than 2.5 m, and (ii) draw flow equally from a bustle pipe where deposit patterns on the inside pipe will tend to accentuate the difference in flow rates from each hole over time. Process modeling provided that understanding in a few weeks. This approach kept costs well below any other alternative, significantly reduced capital investment risks, and provided the mill now with a clarifier that achieves negligible turbidity.

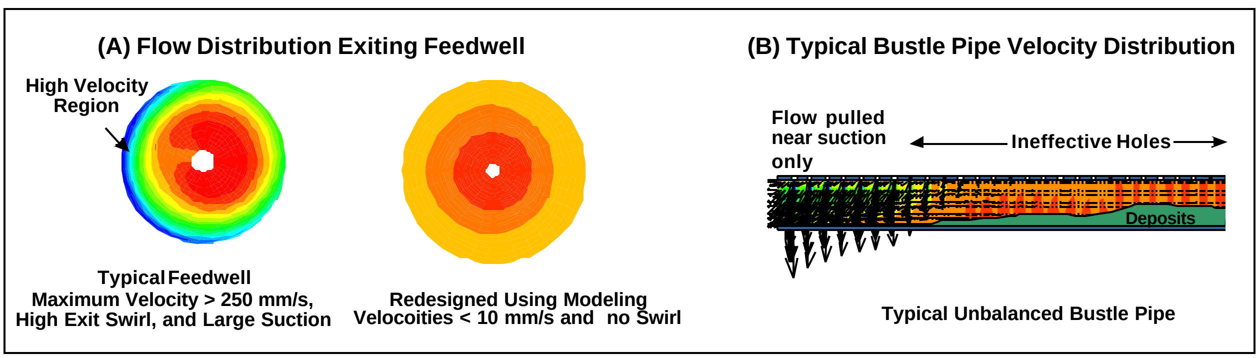
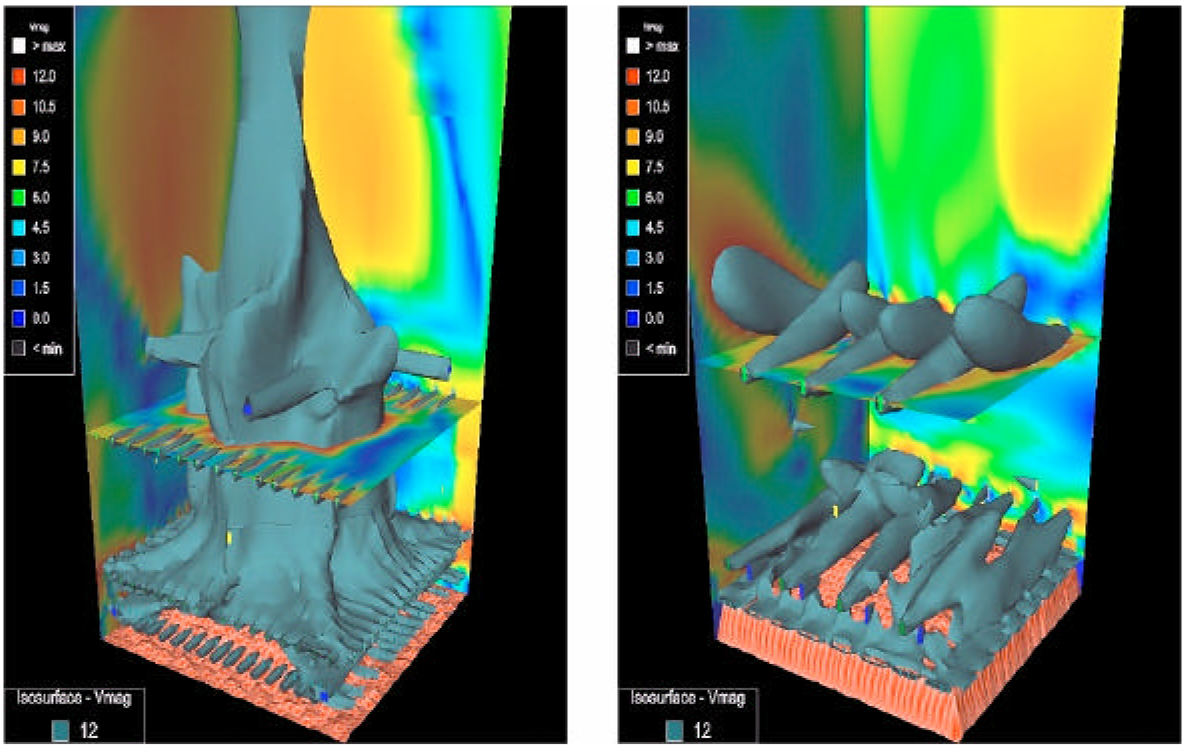


Figure 3: Application of CFD to a green liquor (a) feedwell, and (b) bustle pipe

The simple economics supporting the use of modeling in this example shows that for every green liquor tank with turbidity significantly above the design limit, the following costs are incurred for every unsuccessful retrofit. Hardware costs, fabrication costs, installation costs, ongoing polymer costs, consulting costs, cost associate with dregs recirculating though the mill causing process problems, and the mill's own labor costs for finding ways to fix the problem. In addition, pressure washers installed by mills to overcome excessive turbidity have a high initial capital cost and ongoing maintenance costs. These new costs could be avoided by making installed equipment work. As in most projects where modeling is used *effectively*, the total cost of the retrofit is less than what the mill would have spent without modeling. Modeling was used to find ways to retrofit the feedwell that significantly reduced fabrication and installation costs. The modeling represents a small fraction of the retrofit cost but produced a clarifier that has negligible turbidity.

2. CFD AND SUB-MODELS EXAMPLE: KRAFT RECOVERY BOILER

The real cost benefits of advanced process modeling are obtained when applied to complex processes for large capital intensive equipment like recovery boilers. Recovery boiler performance depends critically on the design of the air and liquor delivery systems. Many different designs are promoted which may not live up to performance specifications. The motivation for developing and applying recovery boiler process modeling is to avoid the trial and error design approach and to provide a more rigorous method to achieve an optimal design. Modeling results help provide a thorough understanding of the combustion air injection, the liquor spray distribution and delivery, and the interaction between the air and the liquor for any boiler configuration. Using this tool, the flow and combustion details are obtained, and the effects of changing boiler geometry, airport design, and operating parameters can be investigated.



(a) (b)

Figure 4: Traditional Versus Advanced Process Modeling Designs of a Recovery Boiler Air and Fuel Delivery System

An example of how process modeling saves costs in the recovery boiler is shown in Figure 4. The air system on the left was developed using experience and arguments based on assumptions of how the liquor and combustion air jets from the primary, secondary, and tertiary air levels interact. The gas flow distribution shown in Figure 4a was obtained by modeling the in place air system. This system has many small secondary and tertiary air ports. Whatever the reasons behind the installation of such an air system, it becomes evident that this boiler operates with a strong fluid core, as shown by the 12 m/s isosurface of gas velocity. It is easy to see that liquor droplets injected in the boiler core will quickly transport to the convection section causing pluggage and operational problems, as were experienced by the mill. To help operate this boiler more effectively, process modeling was used to develop a fuel and air system strategy that would suffice until a better air system can be implemented. The challenge was to find better ways to operate the boiler with such a restricted air system design. Restriction in the control system and the large number of small ports made it impossible to produce the strong penetrating jets so load burners were opened to generate swirl to reduce the amount of carryover. By getting a detailed understanding how the fuel and air system interact using modeling, it is possible to alleviate problems by using physics to improve operations.

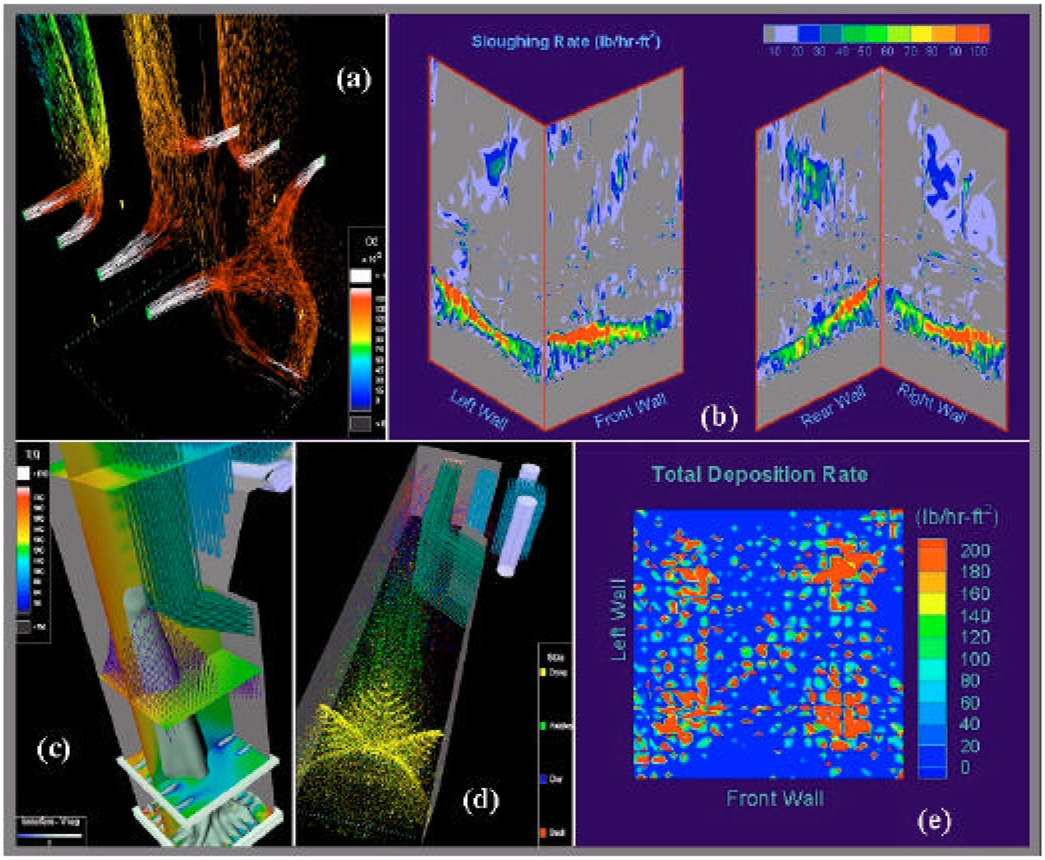


Figure 5: Example of boiler analysis: (a) tertiary air interaction, (b) wall sloughing rates, (c) air split ratios analysis and air core formation, (d) black liquor fuel states, and (e) unburned liquor deposition rate onto bed

By taking the advanced process modeling further, one can develop an air system that is more versatile and will result in a better overall boiler performance, as shown in Figure 4b. In this case, the same velocity isosurface level, 12 m/s, is shown with no air core formed. In designing an air system like the one shown in Figure 4b, it is crucial for the modeling team to be able to properly predict the jet penetration and jet expansion due to density changes as a results of the combustion. A sample of additional analysis performed during recovery boiler modeling is shown in Figure 5. A more complete list of the parameters computed is given in Table 1.

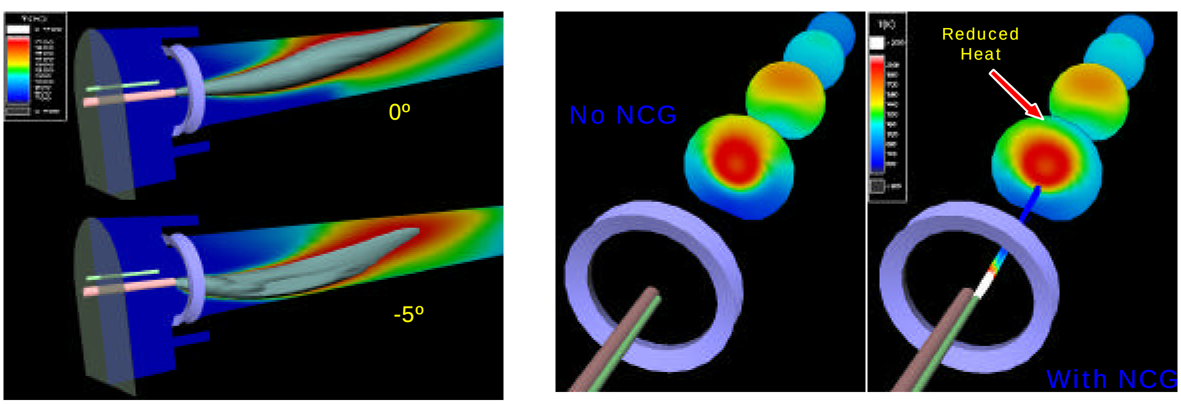
The cost savings associated with process modeling when improving boiler operations are boiler dependent. For the air system in Figure 4a, these include cost reductions associated with reduced pluggage unscheduled waterwashes, the loss of production being an important economic factor driving modeling. Other factors include better environmental compliance through reduction in emissions, better overall stability, reduced excess air, better steam generation, and increased boiler life. When using modeling as the basis to design an air system like the one shown in Figure 4b, the cost savings will be over many years as it will help ensure better boiler performance in addition to reducing capital investment risks. More fuel efficient boilers can be designed that will also handle higher loads, meaning more profits when prices and demand are high.

3. SIMULATOR TECHNOLOGY EXAMPLE

An example of the complete application of advanced process modeling for a lime kiln is shown in Figures 6 and 7. Kilns consume a significant amount of fuel and have common operational problems including poor flame shape, flame impingement, premature brick failure, excessive emissions, low product output, product contamination, poor hood aerodynamics, poor air/fuel mixing for combustion, and low fuel efficiency. These problems are closely related to the gas flow and combustion processes in the kiln and to the heat transfer and interactions with the mud. Advanced process modeling can is used to determine the root cause of problems by performing comprehensive analysis to determine the most cost-effective solution. The economic impact of modeling is seen through reduced fuel consumption, optimizing primary/secondary air and fuel ratios to maximize kiln efficiency, eliminating thermal hot spots that lead to reduced brick liner lifetime, fixing problems with kiln performance due to hood shape, evaluating NCG injection alternatives, comparing alternative fuels, minimizing emissions, and optimizing heat transfer to mud.

Figure 6 shows the discharge part of a lime kiln including the hood and a part of the kiln barrel for different burner angles and NGC injection. The kiln is slightly inclined from the horizontal and rotates in a clockwise direction. The kiln shell is lined and has a dam to control the product discharge. The secondary air enters the hood through an annular gap. The kiln fires natural gas through a multi-annular swirling burner. Figure 6 illustrates how modeling is used to identify at what burner angle the flame causes excessive refractory temperature. To maximize refractory life, it is essential to avoid flame impingement on the refractory lining. The modeling is used to determine the optimal tilt angle which is dependent on the kiln geometry, burner characteristics, and kiln conditions. Figure 6 also shows how modeling is used to determine and optimize NCG injection. Predicted temperature distributions show that the NCG forms a layer between the flame and the refractory and reduces heat flux to the refractory in that area when located above the burner. The gas combustion process and the heat flux to the refractory could be worse if the NCG injection is not appropriate. Process modeling and simulator technology is used to fine-tune the tilt angle and NCG injection location based on current operational conditions.

The simulator technology was developed to package the results of process modeling into an interactive, intuitive, easy to use software. Figure 7 shows an implementation for lime kilns. The system allows users to interactively view process data in a three-dimensional virtual environment. Using proprietary neural network technology, a user can vary input control parameters and instantly view corresponding results. Results can be visualized in terms of flow animations and streamlines, scalar and vector fields, scalar isosurfaces, and particulate animations and distributions. Integrated and summarized process information is shown on organized DCS-like screens. The system has an HTML based module that can be used for classroom and web-based training. The software can be used to rapidly analyze and rectify process problems, or to create virtual equipment for operator training. With this system, the learning curve for new operators is dramatically shortened and their process knowledge is greatly enhanced. If equipment modifications are made, new data from process modeling can easily be added. Common insight into what was previously guesswork means less shift-to-shift operating variation and ultimately more effective operations. Dangerous operating conditions, useful for training, can be safely and easily explored. Engineers can use the software to diagnose equipment problems and managers can evaluate the retrofit before they buy, greatly reducing the risks of wasted capital expenditures and maintenance downtime.



(a) (b)

Figure 6: Optimization of the burner angle and the NGC injection location

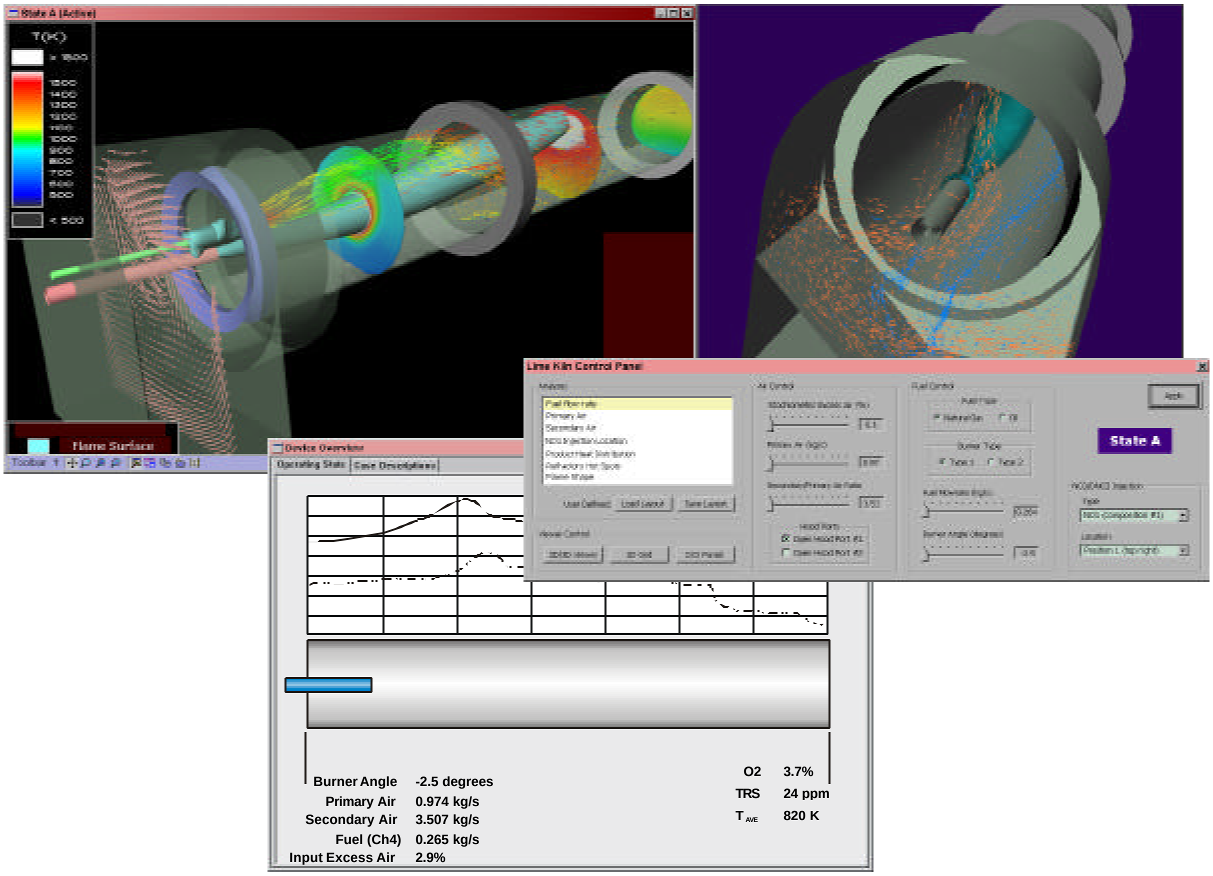


Figure 7: Example of the simulator technology for a lime kiln

WHAT MODELING CAN AND CANNOT DO

The current capabilities of advanced process modeling provide a detailed description of the internal process and thus an enhanced understanding. Models can do an excellent job in predicting trends, in evaluating different designs, and comparing different operating strategies. There are limitations when a rigorous, quantitative evaluation is necessary. Results are generally timed-averaged and do not contain small localized transient effects. Necessary approximations and empiricism often limit the accuracy, but certainly not the usefulness of the tool. It is important to be experienced in using this tool and understand the assumptions and limitations in order to make comparative judgments that can have serious economic impact. For example, small variations in CO production between different designs or operational conditions is not in itself a basis to form a convulsive observation due to the limitation of the prediction of combustion at small scales. Careful consideration between the various levels of errors needs to be understood: errors in the formulation of the equations, model approximations, boundary condition errors, and errors in solving the equations themselves.

SHOULD I DO MY OWN MODELING?

Mills, consultants, or suppliers will sometimes consider licensing and running an advanced process model themselves, thereby being directly engaged in the modeling. Often the licensed models are not used and personnel originally identified to do modeling are occupied elsewhere. Allocating internal resources to cover all aspects of advanced process modeling is expensive. Significant efforts and resources are required to maintain an effective team. In addition, the team has to experience a large array of different problems and work closely with developers to advance this tool and improve in its application. Advanced process modeling as defined in this paper is a difficult task that requires years of experience, dedication, and continual maintenance of skills and expertise. It cannot be done in isolation for complex equipment. It is difficult for a single person attached to this task to succeed in (1) maintaining the development of sub-models that integrates with the main flow solver, (2) performing simulations, and (3) interacting with designers, process engineers, and R&D personnel. To develop and license a model for new type of equipment, a significant amount of time and effort is required. The work involves developing expertise to determine boundary conditions, developing sub-models, verifying results, and putting quality assurance protocols in place to make sure that the tool is used effectively and accurately. An important limiting factor is that advanced process models with the integration of many sub-models are often difficult to converge and obtain a solution. When flow instabilities are encountered, these need to be handled properly. Assumptions need to be continually challenged. Modelers need to have in-depth knowledge of the governing laws and assumptions. Developing a model for new equipment requires that the modeler decide which laws govern the process and what conditions exist at the boundaries of the equipment. The laws that govern the processes, however, are not necessarily fully understood and simplification is often necessary. A true collaborative team spirit is necessary for any successful modeling and implementation.

VARIOUS WAYS TO GET INVOLVED IN THE MODELING MARKETPLACE

For a given capital project, the mill needs to identify the benefits modeling can offer and costs savings for a particular capital project. Depending on the level of involvement the mill is willing to give, several alternatives are possible. If the mill is proactive and knows that modeling will be involved in a given project, then it is best to start looking at process modeling before the selection of hardware vendors that will perform the work. Although it is possible to handle large modeling jobs like recovery boilers in a relatively short time, modeling is best done with longer lead times. This is because advanced process modeling requires a detailed account of the geometry, openings, flow rates, and so is best to have these done beforehand. A better knowledge of what is required and how to approach vendors will be obtained. An alternative method is to ask hardware vendors to supply modeling results as part of their bids. In this situation, modeling is not independent of hardware. An alternative is to contract an independent modeling company that is not tied to any particular vendor and hardware.

MODEL EVALUATION

It is currently common for mill mangers to have to assess modeling performed by manufactures and independent firms who may not possess appropriate background in this area. As modeling can be used as an effective sales tool to obtain more lucrative hardware retrofits, it is important to be able to discern and analyze the modeling results. The ultimate task remains to determine which configuration will provide the best value for the capital funds invested. Various ways to investigate this is to ask a third independent party to evaluate the difference or follow these simplified guidelines:

- Ask if modeling was performed for your particular configuration or for any other equipment configuration that may or may not apply to my configuration. Always request the results on a CDROM to view the details.
- Determine how many different operating conditions were performed using the model and what were the advantages and disadvantages from each configuration. A report should be provided that shows the main results and highlights the important variations.
- Inquire about the modeling software used for the base model, who developed the sub-models for your particular equipment, and ask how these sub-models were validated.
- Ask how many people are actively involved in modeling equipment like yours and how many only do development work.
- Request a copy of the engineering work (usually an excel spreadsheet) that contain a tabulated summary of all the information gathered *before* the data entry into the modeling software began to determine the understanding of the equipment configuration.
- Ask for a list of the parameters calculated (see Table 1) and determined from it the involvement of the modeling team.

CONCLUSIONS

A review of advanced process modeling has been described with special emphasis towards managing capital expenditure risks and reducing retrofit costs and operation costs. Modeling is becoming a very powerful tool for the design and operation of pulp and paper equipment. The use of this tool is still uncommon due to the complexity of the processes and the conservative nature of the industry, but will increase as proven and profitable precedents become better known.

The models are very demanding, as they require very large computations over large domains with very different scales. Continued experiments and validation, and ongoing developments are required. The modeling effort must always occur in cooperation with equipment operators to ensure that the input data is accurate, and that the operator's process knowledge and experience is applied in the modeling. Effective delivery of modeling results and understanding of what lays at the foundation of this tool by the operators, process engineers, and managers will continue to be an important challenge as there lies the most untapped benefits. Currently, the limited number of configurations modeled for each equipment, often because of licensing costs and time, is limiting the use of this tool as it is in visualizing the trends where most of the value is provided. Ways to bring the off-line information obtained through extensive computing for a wide range of parameters are currently being addressed. Advanced process modeling tool will be brought closer to the operators using the simulator core technology. Greater process knowledge in the hands of operators, engineers, and managers will lead toward optimized equipment design and operation, and will have significant impact on mill economics.

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