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A Consortium Approach to Glass Furnace Modeling*

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Abstract

Using computational fluid dynamics to model a glass furnace is a difficult task for any one glass company, laboratory, or university to accomplish. The task of building a computational model of the furnace requires knowledge and experience in modeling two dissimilar regimes (the combustion space and the liquid glass bath), along with the skill necessary to couple these two regimes. Also, a detailed set of experimental data is needed in order to evaluate the output of the code to ensure that the code is providing proper results. Since all these diverse skills are not present in any one research institution, a consortium was formed between Argonne National Laboratory, Purdue University, Mississippi State University, and five glass companies in order to marshal these skills into one three-year program. The objective of this program is to develop a fully coupled, validated simulation of a glass melting furnace that may be used by industry to optimize the performance of existing furnaces.

1. Introduction

Competitive and regulatory pressures are motivating glass manufacturers to seek ways to improve productivity and reduce furnace energy utilization and emissions. The pursuit of these goals leads to conflicting requirements in regard to design and operating parameters of the glass melting furnaces. Therefore, it is imperative to develop an accurate, validated methodology for predicting the effects of any specific design or process parameters on the fuel efficiency, melting efficiency, and glass properties. The industry traditionally has used three basic predictive methodologies. The first methodology is empirical models based on measurements and experience in operating glass melters. The limitation of this methodology is that it cannot be used as a predictive tool when introducing design or material changes. The second methodology is physical or experimental models that use small-scale, cold laboratory models where the geometry of the prototype melter is preserved and laboratory experiments are performed on a scaled-down system using liquids other than glass. This methodology is often expensive, and it is not always known if the laboratory results will scale properly to the industrial scale melter.

The final methodology is computational models based on mathematical descriptions of the relevant physico-chemical processes that occur in the glass melter.

There is increasing emphasis on the development of a robust, validated computational model of glass melting furnaces because such codes may be used in a cost-efficient manner to quickly and accurately evaluate new furnace design concepts, to interpret operating furnace performance, to develop an optimal fuel-firing strategy, and to devise strategies which improve cost and environmental performance. While substantial progress has been made during the past decade in the development of models for simulating glass melting furnaces [1], several major shortcomings exist. In spite of the fact that three-dimensional computer models of the different components of the glass melting system (i.e., combustion chamber, glass bath, batch) exist, to date they have not been coupled into an overall furnace model nor been carefully validated against operating glass melting furnace data. This program, sponsored by the Department of Energy, Office of Industrial Technologies, seeks to address this deficiency by establishing a consortium of researchers and industrial representatives to develop such a model.

The program is being undertaken by a consortium of five leading companies from the glass industry representing the plate (Pilkington-Libbey-Owens-Ford), TV tube (Techneglas), container glass (Libbey-Owens-Ford), lighting (Osram-Sylvania) and fiberglass (Owens-Corning) sectors, along with Purdue University (PU), Mississippi State University (MSU), and Argonne National Laboratory (ANL). The industrial representatives produce different types of glass being produced, thus preventing any one branch of the industry from being given an unfair advantage. The universities and the national laboratory have the necessary modeling and measurements skills to complete the project. The program has been structured to facilitate integration and coordination of the unique, but complementary, inputs of the participants to achieve the objectives in a timely manner.

This program is structured into three focus areas: combustion space modeling, glass bath modeling, and experimental measurements. ANL has begun modeling the combustion space on a furnace specified by the industrial participants. Purdue University is currently using its experience and in-house code to model the glass bath of this same selected furnace. This model will then be coupled to the ANL combustion space model to create a total furnace simulation. Concurrent with this computer modeling work, Mississippi State University is undertaking a program to obtain a detailed set of experimental data on the specified glass furnace. This data will be used on the final, coupled simulation to validate the models. In all three focus areas, the industrial participants will be providing technical knowledge of the furnace and furnace operations to assist the modelers in developing a state-of-the-art simulation.

The results from this program will be made available to the entire industry through the presentation of an industry-wide workshop and the establishment of a "user center" at Argonne National Laboratory. This "user center" will help industry staff evaluate their particular problems.

2: Objective

This program has as its objective the development of a complete, validated glass melting furnace simulation model that will have several major innovative features. The two main components of the overall furnace model, the combustion chamber and glass bath models, will be coupled at their interface through the use of appropriate heat flux and temperature continuity conditions. The combustion chamber model will incorporate a rigorous treatment of the radiative heat transfer to the glass bath, since the heat flow from the combustion chamber to the glass surface "drives" heat transfer and glass circulation in the tank. Also, a detailed treatment of the batch melt and foam zones will be incorporated to achieve a more accurate description of the effectiveness of the heat transfer. Finally, a detailed model for NOx kinetics will be incorporated into the combustion zone model to provide a capability to investigate NOx formation under various firing modes. All these innovations will dramatically advance the "state of the art" in glass furnace simulation and provide the industry with a validated, enhanced analytical tool. Once validated with the data collected in the measurement portion of this program, this tool may be used to optimize the performance of existing glass furnaces and to evaluate opportunities which optimize energy use, improve productivity, and minimize emissions from glass furnaces.

3: Program Description

This program has recently commenced. As was mentioned earlier, the program is broken down into three main focus areas with continual oversight from the industrial participants. Each of these focus areas, along with the industrial oversight, is detailed in the following sections.

3.1: Combustion Space Modeling

Fuel (usually natural gas) is burned with air or pure oxygen in the combustion space to provide the heat that melts the glass batch. Any simulation that describes the combustion space should include the three major physical processes that are present: combustion reaction and fluid dynamics, radiation heat transfer, and NO_x formation/transport. State-of-the-art computer codes are being used at ANL for the simulation of each of these three processes. ANL has a long history of computational fluid dynamics (CFD) analysis in a variety of combustion applications. Currently, ANL is working with industrial partners and the Department of Energy's Office of Industrial Technology on the modeling of multiphase, multispecies, turbulent reacting flow systems.

The ANL code, ICOMFLO, will be modified to model the combustion reaction and fluid dynamics in the combustion space. The ICOMFLO computer code is written in FORTRAN language and can be operated on a CRAY supercomputer, a VAX minicomputer, or a personal computer. This computer code and its variations have been used in simulation of many engineering systems such as coal-fired combustors [2], fluid catalytic cracking reactors [3], and internal combustion engines [4]. It is readily adaptable to the combustion environment of a glass furnace. ICOMFLO has been validated by favorable comparisons of calculated results with several sets of available experimental data. ICOMFLO is a multiphase combustion flow computer code that solves conservation equations for gaseous species, droplets, and solid particles of various sizes. General conservation laws, expressed by elliptic-type partial differential equations, are used in conjunction with rate equations governing the mass, momentum, enthalpy, species, turbulent kinetic energy, and turbulent dissipation for a three-phase reacting flow. Associated phenomenological models used in this code include integral combustion, two-parameter turbulence, particle melting, and interfacial models. A two-parameter turbulence model accounts for gas phase turbulence. Interfacial models correlate momentum and energy transfer between phases.

An integral reaction model and a soot formation model will be incorporated into ICOMFLO for a few selected fuel and oxidizer types, including oxy-fuel. The reaction model assumes that fuel and oxidizer react to form the products H_2O and CO_2. Intermediate products will be handled in the detailed kinetics task of this project. A soot model correlates soot volume fraction with the stoichiometric ratio and temperature. Soot needs to be included in the modeling since it is an important component for radiation heat transfer. The two models will be implemented into the ICOMFLO code to calculate local velocity, temperature, gaseous species concentrations, and soot volume fraction in the combustion space. As these models are incorporated, a grid sensitivity study will be conducted to determine a proper grid system for the gas flow simulation. A parameter sensitivity study will be performed to evaluate the effects of operating conditions on the flame structure and on the distribution of temperature and gaseous species.

The efficiency of a glass furnace depends on the amount of heat transferred from the combustion space and super structure to the glass. In a glass furnace, the heat transfer is primarily radiative. The gaseous species (H_2O and CO_2) and soot are mainly responsible for the radiation heat transfer from the combustion space. RAD, a spectral thermal radiation computer code that was developed for calculating gas and soot radiation heat fluxes in a sooty flame structure [5], will be modified to compute radiation heat fluxes from the combustion space of the furnace. The code solves the radiant heat flux equation, including emission and absorption by gaseous species and soot. Gas emissivity is calculated by using a semi-empirical wide band model which correlates the gas emissivity to the integrated band intensity, the band width parameters, the line width parameter, and the effective pressure. Soot emissivity is calculated based on the classical electromagnetic theory that correlates emissivity with soot volume fraction and temperature. The spectral radiation heat flux is obtained by integrating the total band absorptance with the black body radiation function over a computational cell volume.

An iteration routine between the ICOMFLO and RAD codes will be developed to determine a true flame temperature that includes the radiation heat loss. Source terms accounting for the local radiative heat flux will be added to the energy balance equation of the ICOMFLO code. The radiation heat source, or sink, terms will be calculated from the RAD code. The iteration routine starts by assuming zero radiation source terms in ICOMFLO. ICOMFLO calculates local flow properties including temperature, density, concentrations of H_2O and CO_2, and soot volume fraction. Then, RAD will calculate the local net radiation heat flux based on these pre-calculated flow properties. The local net radiation heat flux calculated from RAD will become the new radiation source terms for the next ICOMFLO calculation. The iteration of ICOMFLO and RAD calculations will continue until proper convergence criteria are met. The converged solution will yield the spatial interfacial heat flux distribution, which will then be used as the boundary condition for the glass melt model (calculations) in the coupled overall furnace simulation. This task of developing the radiation model and implementing the model into the combustion space is a critical step in the final development of the furnace simulator because radiation is the primary heat source that drives the glass melt flow.

Before coupling this combustion model to the glass melt model, it is necessary to verify the accuracy of the combustion model. A parametric study will be performed to evaluate the effect of operating conditions on the distribution of temperature and radiation heat fluxes on the walls of the combustion space. The operating conditions include stoichiometric ratio and flow rates. Computed temperatures, species concentrations, and radiation heat fluxes will be compared to a set of measured values (provided by the industrial partners) in order to determine the accuracy of the code. This parametric study will verify that the code properly represents the physics present inside the combustion space.

The flow field of the combustion space, as calculated by ICOMFLO, can be used to determine NO_x. A chemical kinetics code that been used for detailed kinetics calculations in various applications is available at ANL to calculate gas compositions, including NO_x, in high-temperature combustion zones [6]. A simplified flow field and thirty NO-related kinetics equations are used in these calculations. Predictions made with these calculations have shown good agreement with experimental data. Recently, a hybrid technique to couple CFD and chemical kinetics calculations in a multiphase, multispecies, turbulent reacting flow simulation has been developed [7]. This technique will be modified and incorporated into the ICOMFLO code, with the kinetics model being used to compute NO_x concentrations in the combustion flow. These NOx reactions include those contributions from thermal, prompt, and fuel NO_x.

3.2: Glass Bath Modeling

Purdue University, through Professor Viskanta and others, has pioneered and continually led the development of physical/mathematical models and numerical computer programs for simulating glass melters. The three-dimensional glass bath models developed by Purdue during the last decade under the sponsorship of U.S. glass companies (PPG Industries Fiber Glass Research Center, Ford Motor Company Technical Glass Center, and Ball Glass Packaging Corp.) are being enhanced to represent the glass melt. The complete geometry of the tank including the doghouse, waist, stepped bottom, and the lip will be simulated. Heat transfer through walls, from outside surfaces (by convection to the ambient plant atmosphere), and by radiation (to the surroundings) will be taken into account. This code has been setup to calculate local glass velocities and temperatures for the selected furnace.

Once furnace geometry and material properties have been input, the differential equations for the transport processes in the glass bath will be solved using the control volume based methods described by Patankar [8]. One basic grid will be used for computing and storing the temperature, pressure, and various thermophysical properties, while staggered grids will be used for each of the three velocity components. Since the original differential equations are strongly non-linear, it is necessary to solve the resulting equations iteratively until a sufficiently converged solution is obtained for the entire grid.

Currently, the glass bath model needs to utilize a very large number of grid points to accurately model the system. The large grid size slows down the speed of code execution. A grid sensitivity study will be undertaken to selectively refine the grid and thus reduce the number of nodes. The reduced grid size is expected to reduce the computational time.

In addition to reducing the number of grid points, various numerical methods, such as multigrid and block correction techniques, may be employed to help speed up the calculation of the glass melt. A detailed analysis of the numerics present in the glass bath model will be undertaken to identify methodologies that can be adopted to decrease computational times. Additionally, the structure of the code will be altered to accept the input from the combustion space model as boundary conditions. This will facilitate the later coupling of the combustion space and the glass melt zone models.

Batch glass between glass melt and combustion gas flows is heated by the radiative heat transfer from the combustion gas flow and by convection from the bath below. As the batch melts, the molten glass joins the glass melt flow either by directly flowing over the surface or by trickling through the unmelted batch. The presence of unmelted batch in the furnace impedes heat transfer to the glass melt. A more rigorous model of this process will be developed to account for the effect on heat transfer to the batch glass both by radiation from above and by convection from below and to account for the flow of the melting glass from the glass batch zone into the glass melt.

An additional modification will be made to the glass bath model to reflect the well known fact that the glass melt is non-homogeneous (particularly under the batch) and contains undissolved solid particles and gas bubbles. The presence of inhomogeneities influences the thermophysical properties of the glass melt. The fact that a large number of the small gas bubbles in the melt affects the glass circulation and heat transfer has been recognized for some time [9]. Additionally, bubbles in the glass melt rise to the surface of the glass melt and become foam. This foam scatters incident radiation and reduces the effectiveness of heat transfer from combustion gas to glass melt. A model that accounts for the foam absorptivity will be formulated and implemented into the code. The inclusion of foam and batch models will help ensure that the code provides a more accurate representation of the physics of the interface between the combustion space and the glass melt.

Since certain furnaces use electric boosting to increase the heat transfer to the glass bath, the effect to these electrodes will be modeled and incorporated into the glass melt simulation. The inclusion of these three submodels in the glass bath model will provide a more rigorous physical representation of the system.

3.3: Coupled Simulation

The combustion space and glass melt flow computer codes will be integrated to simulate the selected glass furnace. New and innovative techniques developed in previous programs will be implemented to overcome expected numerical difficulties. Coupled furnace simulation allows the industry to evaluate many of the operating parameters of a glass furnace, such as fuel efficiency and pollutant formation.

A critical aspect of the coupling of the combustion and the glass melt zones is the proper representation of the heat transfer between the zones. The glass bath model developed at Purdue will be modified to accept the heat generated in the combustion zone and transferred at the interface. A model that transfers both the diffusive and radiative heat at the combustion/glass melt interface will be developed.

In addition to modifying the glass bath code to accept the combustion side heat transfer, the glass melt code will be altered to incorporate the drag force at the glass melt interface. Because this drag force can have a strong impact on the combustion space flow patterns and the glass melt flow field, it must be included to properly model the physics.

To couple the combustion space and glass melt simulations, the heat generated in the combustion space must be transferred to the glass melt. Although the selected grids for each computational space need to be compatible, the glass melt grid is not required to match the combustion space grid at each point. Instead, an interpolating function will be needed to transform the boundary conditions generated in the combustion space (e.g. heat flux, radiation flux) to those of the glass melt space. This function will ensure that there will be energy and mass balance at the glass melt interface. Once this function is determined, the two codes may be coupled into one simulation.

An iteration routine will be developed between the ICOMFLO/RAD and the glass bath code. Techniques developed in previous programs by ANL to circumvent the numerical problems such as stagnation, singularity, and multiple time scale instability will be implemented. In the iterative approach that will be pursued, ICOMFLO/RAD will first calculate gas velocity, temperature, and radiation heat flux at the interface between the combustion gas and glass melt flows. Next, these properties will be used as boundary conditions for the glass melt flow calculation. The output from the glass melt simulation will then be fed back into the ICOMFLO/RAD code, and the iteration will continue until a suitable convergence criteria is met.

Once this solution methodology has been established and the interface coupling problems are resolved, the two models may be integrated together into one overall simulation, thus achieving a primary objective of the program.

To use the overall simulation effectively, the execution time for the code needs to be reasonable. A variety of existing numerical methods can be implemented to reduce computational time. Once the code has been coupled, these improved numerical methods will be evaluated to establish their potential for improving computational efficiency and then implemented when justified. Examples of the approaches that will be investigated include improved algorithms, novel gridding methods, and implementation of sophisticated singularity analysis.

After the numerics have been optimized, the available data from the reference furnace will be used to conduct preliminary validation studies on the code. The first step in the validation process will be a study of the combustion zone gas and NO_x kinetics calculations. These computed NO_x concentrations will be compared to measured exit values of NO_x concentrations. A parametric study will then be conducted to evaluate the effect of furnace operating conditions and firing modes on the NO_x emissions. Key operating parameters that will be studied include stoichiometric ratio and flow rates. This study will identify those parameters that most strongly influence the emission of greenhouse gases, and thus can be expected to indicate which parameters can be adjusted to reduce the emissions.

Combustion gas/glass melt calculations will then be performed and compared to existing sets of measured values. The comparisons of flow field properties in the glass melt and in the combustion space will be done in areas of interest. These comparative evaluations will provide an early indication of the validity of the coupled furnace model and establish whether the coupled models are performing properly. Analyses of these comparisons will dictate whether enhanced phenomenological models need to be incorporated into the simulation or if the models require adjustments.

Following this preliminary validation, one set of furnace conditions will be designated as the baseline case. The coupled code will be executed, and the calculated results will be compared to the detailed set of diagnostic measurements associated with this baseline case. The comparative evaluation will focus on evaluating the accuracy of the critical submodels developed and integrated into the code. The studies will indicate any areas of the model that need to be adjusted. Adjustments will be made until good agreement is achieved between the coupled code and the baseline data set.

The tentatively validated code will then be used to predict detailed performance parameters for the remaining tests to be conducted on the furnace(s) with widely varying furnace conditions. Detailed comparisons will be made between measured and calculated spatial temperature flow velocities and heat fluxes. The detailed comparisons will be used to judge the accuracy/validity of the furnace simulator.

One of the key objectives of this project is to use the validated code to perform parametric, sensitivity, and optimization studies to evaluate the impact of furnace operating and design parameters on the glass melting and combustion efficiency. These studies will provide insight into steps that can be taken to reduce energy consumption and to minimize greenhouse gas and other regulated emissions. The coupled code will be used to evaluate the furnace performance for various fuel types and furnace burner configurations; in particular, natural gas-air and oxy-fuel systems will be studied. Comparisons of computed combustion efficiencies, glass melt rates, and NO_x emissions for various fuel types will provide an indication of the most cost effective strategies that can be pursued to improve energy utilization efficiency and reduce emissions.

Finally, a preprocessor will be developed for the coupled code. One major difficulty with CFD codes is creating a proper grid for the simulation. Defining a grid system can often be a time consuming and difficult procedure for a novice user. The development of a preprocessor to assist in the input of the grid and other initial data (e.g., material properties, initial flow rates) will greatly assist in the operation of the simulation. The development of a pre-processor to handle the input data will go a long way toward achieving the goal of establishing a convenient code for industrial users.

Another major difficulty is analyzing the data created by a simulation. CFD codes generate large amounts of data. Visualizing and understanding the information contained in this data is an extraordinarily difficult job. The creation of a post-processing program that plots the output data in a meaningful and easily understood manner will allow the user to better interpret the results from the code. This plotting feature will not only increase understanding of what occurs inside a glass furnace, but it will also allow people unfamiliar with CFD codes to interact with this sophisticated design tool. Ideally, the inclusion of the pre- and post-processors will allow the total simulation to be used by industrial personnel who have had adequate training.

3.4: Furnace Measurements

A critical element of the proposed program is the acquisition of the data needed to validate the computer models. The desired measurements will be made by the Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University (MSU) in the combustion space and in the glass melt of the furnace provided by the industrial participants. DIAL personnel at MSU are experienced in using diagnostic instruments in the field to perform measurements at government-sponsored development facilities and industrial facilities.

Various factors will be considered before selecting the diagnostic options best suited for obtaining the necessary data. In addition to the classical methods such as thermocouples, iso-kinetic probes, and sampling, more sophisticated techniques (e.g., optical techniques) will likely be required to gather the desired data.

For the combustion space, flow field studies can be pursued by using either the classic pitot probe or a laser Doppler velocimetry (LDV) system. Measurements of average gas stream temperatures, temperature profiles, and combustion product concentrations may be obtained by using a non-intrusive technique (i.e., Fourier transform infrared [FTIR] emission spectroscopy). The spectrometer quantifies the radiation emitted from the elevated temperature gas stream. Furnace wall temperatures can be obtained by using various two-color pyrometers and a multiwavelength pyrometer (wavelength resolved over the range 0.6 to 1.1 μm).

Glass melt temperature will be measured by inserting thermocouples at various depths from the bottom of the glass bath. By viewing the surface of the glass with an FTIR spectrometer, the relative radiation intensity versus wavelength (2 - 15 μm) can be determined.

A large-scale, high-temperature glass furnace with limited access complicates the collection of experimental data and in most cases necessitates the use of probe-based measurement systems. The standard and specialized probes that will be used must be designed and fabricated to minimize flow disturbance, as well as the chemical and thermal perturbations of the flow. The staff at MSU, in conjunction with the industrial participants, will evaluate all pertinent measurement options. Factoring in their experience, they will select the diagnostic system that is compatible with the access limitations of the selected furnace and will have the capability to acquire the data needed for code validation.

To assure the reliability of the data, the repeatability of the data will be carefully checked and, where possible, comparisons will be made between different measurement methods. Moreover, the performance of these measurement systems will be evaluated and calibrated on DIAL's Combustion Test Stand, where conditions inside the glass furnace will be simulated prior to deployment in an actual melter. The measurement systems will be transported to the furnace site by means of DIAL's 18-wheel mobile instrument laboratory. This mobile laboratory also provides an operating platform for the instrumentation.

After the selected furnace has been modified, preliminary data sets will be collected with the selected and verified diagnostic system. This first set of data will be analyzed to determine the consistency and validity of the data. Also, the data set will be evaluated to determine if additional modifications of the diagnostics are necessary and to confirm that the data needed to validate the computer models can be acquired.

The initial set of additional data needed to perform a critical validation of the codes will be obtained from tests on the specified commercial furnace. The test program will focus on obtaining detailed, accurate measurements of glass flow field properties and combustion space flow properties. These measurements will include entrance, exit, spatial wall temperature, and glass melt combustion interfacial values at various locations (where possible). This data will be used as benchmark data for validation of the coupled combustion space/glass melt code.

The data acquired from the measurement program will be evaluated to determine if the data set satisfies the requirements for code validation. Also, insufficient and/or inconsistent data will be identified in order to determine if additional data needs to be collected. If warranted, additional data will be collected to ensure that the desired complete data set exists for code validation.

3.5: Industrial Participation

In addition to overviewing the project and providing evaluations of the work, the industrial partners will be actively participating in this program. Initially, the industrial participants will identify candidate fiberglass, plate glass, and TV tube glass furnaces within their organizations that could be considered candidates to be modeled. Among the determining factors are design/operating parameters, availability of furnace operating data, access for installation of diagnostics for measurement of combustion/glass melt parameters, and availability of the furnace for testing. The industrial participants will specify a furnace to be modeled and subsequently used for acquiring the data needed for code validation.

After the furnace selection has been made, existing operating and performance data will be collected and evaluated to define the database that would be available for preliminary code validation. Typical data that will be needed include spatial glass temperature measurements, surface glass flow measurements, batch temperature, depth, shape, electrode power measurements, bubbling rates, combustion zone temperature and species profiles, fuel flows, exhaust temperatures, and boundary temperature measurements.

The furnace selected by the industrial partners for this study will be modified to accommodate diagnostic instrumentation. First, measurement locations will be determined jointly by the industrial partners and MSU. Then, whenever possible, the furnace will be modified to accommodate the selected diagnostic equipment. Also, access devices and structures will be built as required to accommodate diagnostic equipment that must move in and out of the furnace.

After the capabilities of the diagnostics have been confirmed from the preliminary tests on the furnace, a test matrix will be designed for the acquisition of the data. This test matrix will establish those sets of operating conditions that will benchmark and validate the coupled computer model. The industrial partners, in conjunction with the modeling groups, will select a series of operating conditions (i.e., gas flow rates, fuel composition, batch feed rates) that will define the test matrix.

The validation results will be independently assessed by the industrial partners to provide an industry perspective relative to the usefulness and the validity of the simulation. The industrial partners will also review the recommendations for follow-up work, and then develop a position as to whether additional modifications to the code are necessary. This assessment will provide a definitive judgment on the simulator's validity and robustness.

4: Dissemination of Information

To ensure that the development of the validated overall furnace simulation will benefit the glass industry in general, a workshop will be held to showcase the capabilities of the coupled furnace model. All interested glass companies will be invited to this workshop. This workshop will allow industry to interact with the code developers and allow the attendees to learn how to use the code to investigate problems of their choosing. The attendees will gain experience in how to utilize the preprocessor to generate a simulation and will learn to interpret the calculated results with the help of the postprocessor. A second objective of the workshop will be to share and discuss the results derived from the parametric, sensitivity, and optimization studies. This objective will serve to stimulate ideas about approaches that can be taken by each company to improve energy use, to reduce emissions, and to improve product quality for their furnaces.

After the workshop, it is anticipated that a number of companies will be interested in further technical support to help them learn how to use the coupled furnace model more efficiently. ANL will establish a software technical support center to assist staff from companies in the use of the code. The type of assistance can vary to include company staff spending time at ANL to become thoroughly proficient in the details of the code or ANL providing electronic support services via the Internet. The support provided would be tailored to meet the specific needs of the requester.

5: Industrial Commercialization

Commercialization and market success for a process model is both relatively assured and somewhat difficult to assess. Computer modeling of processes is undertaken to improve those processes. Models can help assure optimization, which results in improved quality, less scrap and, in some instances (such as the present), improved energy efficiency. In addition, models can facilitate innovation because proposed process changes or enhancements can be tried on a computer rather than online, which holds the risk of failure that often prohibits innovation.

In this proposed consortium, a variety of lead companies have been assembled to insure that a comprehensive coupled model will be written and validated on different glass melting furnaces fired by both oxy-fuel and air-fuel. It is important to note that the validated coupled model will instantly be used in the overall design, operation, and diagnostics of existing furnaces and in the design of new (rebuilt) furnaces, particularly those fired with oxy-fuel.

By using a consortium approach to this work program, validation and acceptance is assured at the lead companies. Since the industrial partners employ modeling in their current operations, the development and validation of this coupled model will result in its immediate application. The technical personnel that assist in this program's activities are often the same people expected to deploy this model, so the learning curve associated with adoption of this modeling capability will be short.

The existence of a validated, coupled model will result in improved glass quality in existing glass furnaces when it is used to develop the optimum process conditions. Additionally, thermal efficiency can be improved and, in some cases, throughput may be increased. Finally, an optimization of the combustion parameters may result in a reduction of pollutants. In all, the deployment of a coupled glass flow/combustion model will result in an improved process for general glass melting. Modeling is currently used to assist in the operation and design of glass melters, which has led to improvements in quality, efficiency, and consistency. With the increased usage of oxy-fuel, modeling has accelerated the normal learning curve of this new technology and has resulted in a smoother transition for this new melting technology than might have been expected with no modeling effort. The use of a coupled combustion/glass flow model will enhance this capability at a time when new oxy-fuel facilities are in the planning stage.

Outside the consortium companies, deployment of the new model will be accelerated by the "user center" at ANL. Here, representatives from any glass company can bring their problems and situations to be modeled. Since this effort is based on existing codes at Purdue and ANL, there are no commercial or intellectual property barriers, license royalties, or other restrictions to the use of this software. This consortium supports the "user center" concept for early use on glass projects once the validation has been completed.

6: Benefits for the Glass Industry and Public

The development and validation of a coupled glass flow/combustion model will benefit the glass industry by providing an important new tool to aid in the design, operation, and diagnostics of glass melting furnaces. This new coupled model will benefit all four segments of the glass industry, as it will be validated on both air and oxygen fired melters within the fiber, flat, and specialty segments. By making the model available to industry through the facilities at ANL, any glass company can derive the benefits of this model without the expense of maintaining the modeling expertise in-house.

The glass industry will benefit from the existence of this new model by using it to optimize the operation of existing melters, thereby improving quality and economics. This model can also aid in diagnostics and problem solving. The use of this model will facilitate more rapid introduction of new glass compositions, particularly in flat glass, where the introduction of new solar glasses benefits the automotive and architectural industries. In some instances, this model can lengthen the campaign of a furnace by minimizing refractory corrosion and optimizing the placement and operation of burners to assure the most efficient transfer of energy into the melt.

The public will benefit from the use of this model in several ways. The consumer will benefit from higher quality products, possible price reductions (particularly in automotive glass and TV glass) due to increased efficiencies, and less energy consumption and pollution. In addition, commercialization of new products, particularly solar glasses, will enhance the quality of the built environment and reduce energy usage for lighting and air conditioning. In automotive glass, new solar compositions reduce A/C loads, enhance the lifetime of interior fabrics, and increase fuel efficiency. All these product enhancements are enabled by the development and usage of advanced computer models to better understand the capabilities and limitations of the glass making processes.

The academic community will benefit from increased employment opportunities and advancement of the state-of-the-art. The Labs will benefit from an increased awareness of the advantages of modeling, and advancements in the capabilities of models which can be applied to other industries that use combustion reactions and high temperature processes.

7: Conclusion

This paper has detailed the consortium approach used to create a simulation of an industrial glass furnace. The strengths of each member of the consortium have been and will be used to the maximum in order to produce the state-of-the-art glass furnace simulation.

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