Adjusting Surface Heat Flux to Obtain Desired Glass Flow Patterns

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In a glass furnace, the heat flux on the surface of the molten glass drives the motion of the melt. The heat flux is provided by sets of burners in the combustion space above the glass melt surface. Historically, how the burners were fired was determined by experience or by trial and error. However, with the advent of advanced computational fluid dynamics programs, the proper firing pattern can be determined computationally without the costly trial and error period. An operating glass furnace experienced a problem that required a pile of blocks to be put in the molten glass. These blocks radically changed the flow field, thus causing a loss in the quality of the product. This loss of quality forced the plant to reduce the throughput for that furnace. The Glass Furnace Model, developed at Argonne National Laboratory, was initially used to determine the cause of the loss of quality. Then, several computational trials were performed to determine a surface heat flux that would allow an increased throughput while maintaining required quality. This paper will detail the process and some of the computations involved in analyzing the burner firing pattern that would allow improved productivity.

Nomenclature

k	=	particle size group
k_1	=	reaction rate constant for combustion reaction
m_{pk}	=	mass of particle in size group k
n_k	=	particle number density in size group k
S_n	=	source term for nth particle size group
S_ξ	=	source term for ξ transport equation
u_i	=	velocity in direction i
$u_{i,p,k}$	=	particle velocity for the ith particle size group
x_i	=	ith cardinal direction
ξ	=	general subscript for transport equations
Γ_ξ	=	transport equation source term for ξ transport equation
ρ	=	density

I. Introduction

Even though the glass industry is rather conservative, it has recognized that computational fluid dynamics (CFD) simulation is an important tool in analyzing furnaces and in giving suggestions how to help improve the performance of the furnaces. In 1998, the Department of Energy's Office of Industrial Technologies funded a consortium of glass companies (initially, Techneglas, Libbey, Inc., Osram-Sylvania, Pilkington-Libbey-Owens Ford, and Owens-Corning. Pilkington withdrew from the consortia and Visteon later joined the group), two universities (Purdue University and Mississippi State University), and Argonne National Laboratory (ANL) in order to develop a rigorous, coupled glass furnace simulation [1]. Initially, it was decided that the developed simulations would include important coupling issues such as batch melting, foam coverage, and spectral radiation penetration both in the melt and in the combustion space. The goal of this project was to develop a computational tool that could be used by a furnace engineer to investigate and solve operational problems.

It has long been recognized that one needs two separate models in order to build a complete simulation of an industrial glass furnace: one for the combustion space and one for the molten glass. Early on, CFD codes have been used to model the combustion space [2,3] and the glass-melt flow [4,5] of a glass furnace. The early studies found that the flow fields of the combustion space and glass melt region strongly interact with each other. The radiation heat transfer from the combustion space drives the glass melt flow through the melting of the batch and the heating of the liquid glass. Experimentally, it was found that a significant portion of the spectra of the radiation might penetrate into the glass flow [6]. Therefore, a proper spectral coupling of the combustion space and glass melt flows is essential for a realistic modeling of a glass furnace.

Coupled glass furnace simulations are not a new idea [7,8]; in fact, many companies can claim they have coupled models. However, the models developed for the ANL Glass Furnace Model (GFM) have made several significant advances over the last five years. These advances include a new spectral radiation model that conserves energy and is computationally efficient, a true multiphase treatment in the glass melt (explicit transport equations are simultaneously solved for the liquid, solid particles and gas bubbles), three comprehensive validations of the models compared to in-furnace measurements, and, quite recently, a mass coupling to better account for the gas evolution from batch/glass reactions between the glass melt and the combustion space. This paper will present the application of this advanced simulation tool to an industrial problem (blocked flow in the melter).

II. Methodology

Three distinct computational regimes are present in any glass furnace simulation: combustion modeling, molten glass modeling, and radiation heat transport modeling. A communication routine was developed to allow the transfer of pertinent information from each one of these regimes to the other (see Figure 1). When the project began, the communication between the computational regimes was entirely energy transfer. As a result of the measurement campaigns and a computational investigation, it has been determined that mass transfer (gas exchange) between the melt and the combustion space is also essential to proper modeling of a glass furnace.

The combustion space is run first, computing the local temperature, pressure and species concentrations throughout the volume. Then, a spectral radiation model is run to calculate the local radiation heat flux, particularly on the glass surface. With this information, the melt model is executed and the local glass temperature, velocity, and species concentrations are determined. The local glass surface temperature and local gas release rates are then used as inputs into the next combustion calculation.

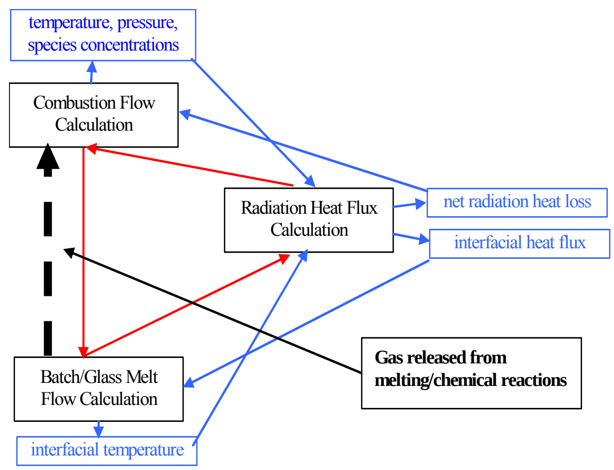

Figure 1: Iteration Routine for Coupling Furnace Computational Spaces

A COMBUSTION SPACE MODELING

The combustion space is modeled in the GFM using an ANL developed CFD code, ICOMFLO, which was created especially to simulate combustion [9] on a structured grid. The code has been modified specifically for glass furnace combustion. Combustion flow simulation is very complicated and often plagued by numerical instability problems. ICOMFLO uses a three step partially, de-coupled computational scheme and divides the combustion species into two groups: major species and subspecies. The three step scheme includes the computations of (1) combustion hydrodynamics (major species calculation), (2) formation and transport of pollutants (subspecies calculation), and (3) radiation heat transfer (absorption).

Initially, the code computes the major flow properties of the combustion flow in the furnace by assuming only radiation emission in the chamber. In this step, pressure, temperature, density, velocity, and species concentrations are locally computed. A combustion model of the major species is needed in this step to establish an initial temperature field. Next, a kinetic model of the subspecies is used to calculate the formation and transport of the subspecies based on the semi-converged major flow properties computed in the first step. Then, a radiation heat transfer model is used to calculate local net radiation heat flux (the balance of emission and absorption) based on the temperature and pressure calculated in the first step and the species concentrations calculated in the second step. The radiation participating media in a glass furnace include carbon dioxide, water vapor, and soot in the combustion space and glass in the glass melt flow. Since radiative emission and absorption of these media depend strongly on wavelength of the radiation, a spectral radiation heat transfer model is used. In the flow field calculations, the emission of radiation is determined each iteration. Absorption is only calculated infrequently since this computational process is very time consuming and the computational results do not change very much once the flow field settles down.

1. Formulation of Hydrodynamic Flow

In the first step of the calculation, major flow properties are computed with a highly reduced combustion model. The primary information required from the combustion model for the flow computation is the heat of combustion and mixture molecular weight change due to combustion, which affects mixture density through the equation of state. The species selected for the first-step calculation include nitrogen, fuel, oxygen, and two lumped products (carbon dioxide and water

a. Conservation Equations: In this step, pressure, temperature, velocity, density, and species concentrations are calculated from the conservation equations of mass, momentum, and enthalpy, the transport equation of species, and the equations of state. The equations of mass, momentum, enthalpy, and species are all elliptic-type partial differential equations. For convenience in numerical formulation, these equations are arranged in a common form, Eq.(1).

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\rho u_i \xi - \Gamma_\xi \frac{\partial \xi}{\partial x_i}) = S_\xi \tag{1}$$

in which ξ is a general flow property, x_i, i=1,3 are coordinates, u_i, i=1,3 are velocity components, Γ is effective diffusivity (calculated from both laminar and turbulent viscosities), and S_ξ is the sum of source terms. The general flow property is a scalar, a velocity component, an enthalpy, or a species concentration for the equations of mass, momentum, enthalpy, and species, respectively. Turbulent diffusivity and the source terms are derived from separate phenomenological models.

b. Lumped, Integral Combustion Model: The computation uses a combustion model based on the integral reacting-flow time-scale-conversion method [10]. The model assumes a simple one-step combustion reaction of the four major species.

$$\boldsymbol{FUEL + OXIDIZER \xrightarrow{k_1} PRODUCT_1 + PRODUCT_2} \tag{2}$$

Based on the time-integral approach, a separate kinetic calculation was performed to determine the time evolution of the extent of reaction for the flow calculation.

c. Turbulence Model: The turbulence model is a modified k-ε turbulence model. The model introduces two additional turbulent parameters to determine turbulent viscosity. Turbulent diffusivities for the enthalpy and species equations are calculated from the turbulent viscosity with an appropriate scaling factor.

d. Formulation of Transport of Subspecies: The combustion in a glass furnace produces many combustion products including CO_2, H_2O, CO, NO, and soot. These products or subspecies are transported by the combustion flow whose major properties have been computed in the previous step. Thus, the transport of these combustion products can be formulated and calculated based on the computed flow properties. The formation of these subspecies can be determined from a set of detailed or reduced kinetics. A soot and a gas subspecies models were developed to provide the source or sink terms for the equations.

e. Soot Model: In the most flames, soot is formed in the flame area where fuel is rich. Since soot is the dominant contributor to radiation heat transfer, a soot model was developed to calculate soot concentration in preparation for the following radiation heat transfer calculation. This soot model was based on kinetic models found in the literature [11,12]. The model developed does not explicitly take into account the agglomeration of soot particles but it does account for local soot formation and oxidization based on the local temperature and species concentrations.

f. Gas Subspecies Model: The reactions of natural gas combustion can be many. For those who are interested in some of the species involved in the combustion processes, a reduced mechanism is enough for computation. In this study of glass furnace, only seven gaseous species, CH_4, O_2, N_2, CO_2, H_2O, CO, and NO, are considered. A five step kinetic mechanism for methane burning and NO formation [13] is used for the subspecies calculation. The source terms of the subspecies transport equation can be obtained from the reaction rates found in the literature. Once the solution of the transport equations is converged, the species concentrations are the used in the computation of radiation heat transfer.

2. Formulation of Spectral Radiation Heat Transfer

The radiation calculation will provide the local net radiation heat flux for the enthalpy conservation equation of the flow calculation and the radiation heat flux to the boundaries (glass melt flow and the furnace walls). The radiation heat flux can be calculated by solving radiative transport equation based on local gas pressure, temperature, and concentrations of CO_2, H_2O, and soot calculated from the previous steps.

By assuming the scattering effect in the combustion flow is negligible, the radiative transport equation is basically the balance of emissive and absorption powers. Local net radiation heat power can be obtained by adding the energy absorbed in a cell from all incoming radiation from all other locations and then subtracting the energy emitted in that cell for every wavelength [14]. In the radiative transport equation, the temperature is known from the flow calculation but the spectral volumetric absorptivity, κ_λ, is yet to be determined. The spectral volumetric absorptivity of the radiatively participating media will be determined from a gas and a soot radiation models.

B GLASS MELT MODELING

1. Solid Batch Flow

In an Eulerian approach, batch (the raw, solid constituents that are melted to created the molten glass) particles are divided into a number of size groups and particles of a size group are treated as a continuum. Conservation equations of solid mass, momentum, and energy are formulated for each size group. The mass, momentum, and energy conservation equations of the batch flow are used to solve for local batch particle number density (throughout the melt, not just on the surface), velocity, and temperature. The conservation equation of solid mass (or number density) for a size group k is derived as,

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i}(m_{pk} n_k u_{i,p,k}) = S_n \tag{3}$$

in which, m_{pk} is the mass of a size-k particle, n_k is particle number density, x_i, i=1,3 are coordinates, $u_{i,p,k}$ is particle velocity, S_n is the source term. Particles start to melt when their temperature reach the melting point. The melting process shifts particles to a smaller size group. The shifting produces a sink term for the size group, a source term for the smaller size group, and a source term for the liquid glass.

The solid momentum and energy equations of a particle size group k can be derived as,

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i}(m_{pk} n_k u_{i,p,k} \xi - \Gamma_\xi \frac{\partial m_{pk} n_k \xi}{\partial x}) = S_\xi \tag{4}$$

in which, ξ is particle general property, representing a particle velocity component, or particle temperature, Γ is diffusivity, and S is the source term. Interfacial drag and heat transfer models are needed to generate source terms for the momentum and energy equations.

2. Liquid Glass-Melt Flow:

It is assumed that the glass-melt is a Newtonian fluid and the flow is laminar and steady state. For the liquid glass-melt flow, the flow properties needed to determine the state of the flow system and to evaluate its performance are pressure, density, temperature, and velocity components. The properties can be solved from the conservation equations of mass, momentum, and energy, and equations of state. The conservation equations of the liquid flow can be arranged in a common form, Eq. (6).

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\rho u_i \xi - \Gamma_\xi \frac{\partial \xi}{\partial x_i}) = S_\xi \tag{5}$$

in which ξ is a general liquid glass flow property, u_i, i=1,3 are velocity components, Γ_ξ is diffusivity, and S_ξ is the sum of source terms. The general flow property represents a scalar, a velocity component, or an enthalpy for the mass, momentum, and energy equations, respectively. Density, viscosity, and thermal conductivity are functions of temperature [15].

3. Phenomenological Models:

The forces on solid batch include buoyancy force, solid pressure, and interfacial drag. The buoyancy force is due to density difference between solid batch and liquid glass. Batch particles are packed together on the top of the liquid glass. When batch moves, particles exert force to the neighboring particles by contact. The force is called solid pressure. The drag force is the shear stress on the interface surface between the batch and the liquid. The buoyancy force, solid pressure, and drag force are the source terms of the solid momentum equation. The drag force is also a sink term of the liquid momentum equation.

The heat fluxes on the batch flow include radiation heat flux from the combustion space, conduction heat flux from the neighboring batch particles, and interfacial heat flux from the liquid flow. The radiation heat flux is calculated from linked combustion and radiation computer codes. The conduction heat flux is accounted for as the diffusive (second) term in the energy equation. The radiation heat flux is a source term in the solid energy equation in the batch coverage area and is a source term in the liquid energy equation outside the batch coverage area. The film conduction heat flux is a sink term of the liquid energy equation. A melting rate can be derived from the film conduction heat flux and becomes a source term of the liquid mass equation.

The batch-melting model operates on the assumption that when the batch temperature reaches the melting temperature, the temperature remains at the melting temperature and radiation heat flux is used to melt batch particles. Note that the radiation melting occurs on the topside of the batch and the film conduction melting occurs on the bottom side of the batch. The batch-melting rate is equal to the ratio of the sum of radiation and film conduction heat fluxes to the heat of melting. The melting rate becomes a source term of the liquid mass equation and a sink term of the solid mass equation. The melting also shifts the batch particles from a larger size group to a smaller size group. The shift rate is calculated based on local particle number density. Batch coverage is determined from local particle number density and velocity.

C. Numerical Scheme

The CFD code uses a control volume approach to convert the governing equations to algebraic equations on a discretized grid system. The grid system is staggered and consists of four grids: one for each of the three momentum component directions for the dominant phase momentum equations, and a scalar grid for all the other equations. The algebraic equations are solved iteratively with the boundary conditions. This methodology is applied both to the combustion space and to the melter regions. For all equations, Patankar's SIMPLER computational scheme [17] is used to solve the pressure linked momentum and continuity equations.

III. The Problem

An industrial glass melting furnace had developed an operational problem that resulted in the short-term solution of dropping refractory material (bricks) into the melter. This partial flow blockage temporarily solved the problem but created a new difficulty. The presence of this blockage caused a degradation of the quality of glass leaving the melter. Engineers at the company, in collaboration with Argonne National Laboratory, applied the GFM to the conditions present in the melter to determine the causes in the reduction in quality but also to investigate firing patterns that would increase glass quality. For this investigation, there were three main objectives: (1) determine the original flow pattern with the original heat flux, (2) calculate the flow pattern with the blockage and the original heat flux to determine the cause of lower glass quality , and (3) run the melt with alternate heat fluxes to see if glass quality could be improved.

A. Furnace Geometry

The furnace in question produces nearly 300 tons per day of glass products. Since the problem being analyzed is in the melter region, this paper will focus on that portion of the work. The melter is approximately 25 meters long by 8 meters wide and a little over 1 meter in depth. Exact furnace dimensions and operating conditions cannot be provided for proprietary reasons. The furnace can be divided into two regions: the melter and the refiner. These two regions are connected by a small channel (at the bottom of the melter) called a throat. Raw materials such as sand and recycled glass are dropped onto the surface of the molten glass in the melter region. The upper surface of the melter receives heat flux from the combustion space and this heat flux melts the raw materials and heats up the glass. In addition, this furnace has two rows of electric heaters on the bottom of the tank to assist in the melting and conditioning of the glass. Once the raw materials have been melted and the molten glass heated up, it must travel to the bottom of the melter to pass through the throat in order to enter the refiner. After the molten glass enters the refiner, it rises up and exits through a number of openings (forehearths) where it is later manufactured into the desired product.

B. The Base Case

The first simulation created was the base case; the conditions present in the furnace before the problem occurred. A combustion space calculation was performed with the prescribed operating conditions to obtain the surface heat flux. This heat flux was then transmitted to the melt calculation and the ensuing temperature and velocity distributions are shown in Figure 2. There are three images in Figure 2. The largest image is the computational results in the plane seen as one looks down on the furnace. The image to the right of the largest on is the computational results that would be seen if one were standing to the left of the largest image and looking down the length of the furnace while the image at the top is the computational results seen if one were standing at the bottom of the largest image and looking across the width of the furnace. The cooler regions where solid batch is melting can be seen clearly on the rightmost image in Figure 2. Of key importance to the analysis of this problem is the flow field in the connecting region (the throat). The velocity vectors indicate that all of the flow is not in one direction from the melter to the refiner. Instead, there is clear evidence of a backflow of cooler molten glass from the refiner back into the melter. When there is some backflow, there is decent homogenization of the molten glass so that the glass leaving the refiner has a relatively uniform temperature.

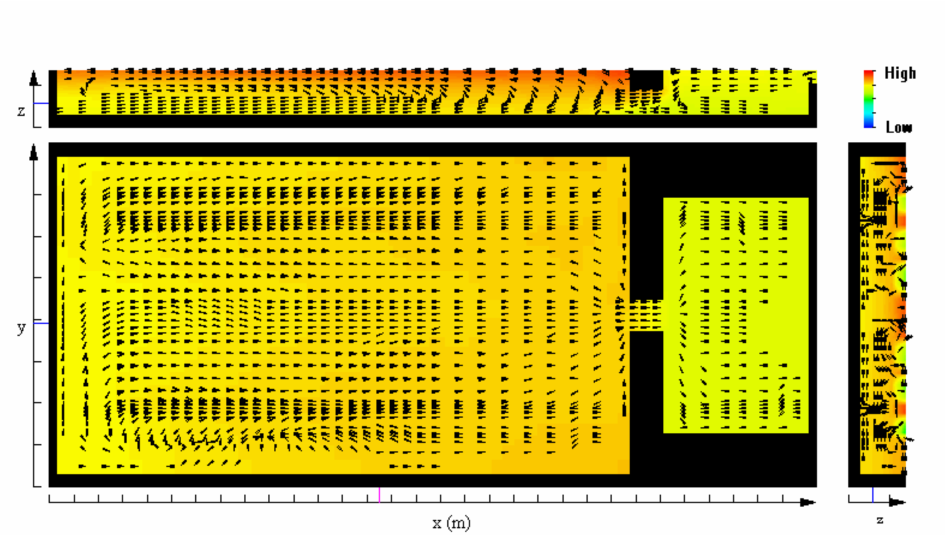

Figure 2: Base Case Temperature and Velocity Distribution without Blockage

B. Case with Blockage

The second case run kept the original heat flux but included the blockage in the melter. This case was run in order to determine the reason for the reduction of glass quality. As it turns out, the design of this melter is not optimal. Since there is a forehearth entrance directly in line with the throat, any shortcutting (hot glass quickly leaving the melter) will allow lower quality glass to enter that forehearth and thus be processed into defective product. Figure 3 represents the temperature and velocity patterns for this case. After the bricks have been dropped in, there is a dramatic difference in the flow field. The bricks are evident by the rectangular blocked region. The case with the blockage and with the original heat flux has significant backflow through the throat while the original case does not show signs of backflow.

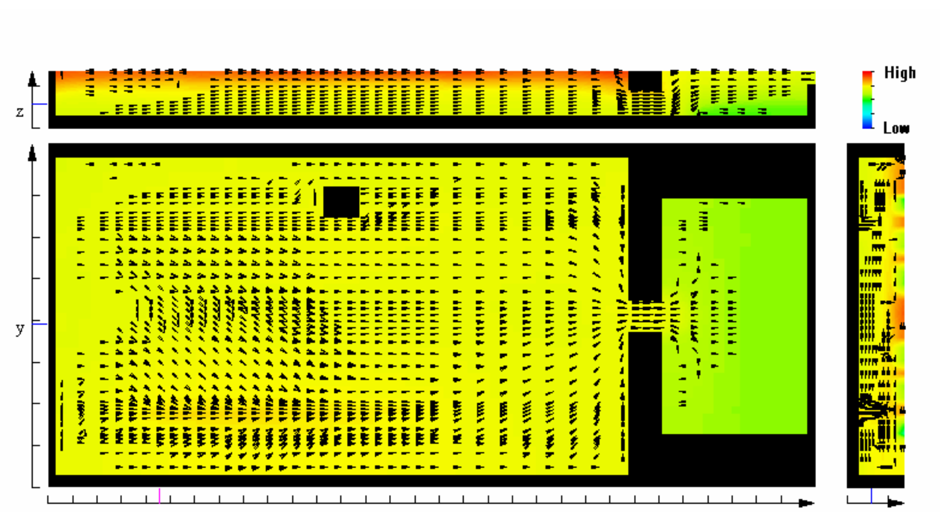

Figure 3: Glass Temperature and Velocity Distribution with Blockage Present and the Original Heat Flux

What can be concluded from this information? In the non-blocked case, there was heat being carried into the refiner through almost the entire width of the throat. This prevented much backflow since the refiner was being heated relatively 'uniformly' and thus created relatively uniform temperatures entering the forehearths. Incidentally, it is the density difference between the glass in the melter and the glass in the refiner that causes backflow. Density is related to glass temperature so if portions of the refiner are cold, the density goes down and the possibility for backflow increases. In the case with the blockage, there is backflow so that means that there are portions of the refiner that are colder than the melter. From the flow field, this leads one to believe that the hotter glass from the melter goes through the top of the throat and exits directly (or near directly) through the forehearth entrance that is in line with the throat.

This takes heat out of the refiner that would normally be used to promote mixing and thermal homogeneity in the refiner. If one looks at the flow field for the case without the blockage, there are arrows pointing in a number of directions (up, down, and back). The flow field in the case with the blockage does not show this mixing.

The short circuiting (lowering of glass quality) was caused by the bricks being located under the region of very high heat flux. The bricks reduced the depth of the glass, thus making the glass in that region get hot. This hotter glass flows easier and part of it may directly flow towards the front wall. Once it hits the front wall, some of it goes down and then exits through the throat without having enough time for proper fining in the melter region.

C. Improved Glass Quality with Alternative Surface Heat Flux

Since the reduction in glass quality was caused by too high a heat flux over the bricking region, the plant reducing the thermal load in that region and applied the combustion heat more over the batch area. Computational simulation of the effect of this new firing pattern on the temperature and velocity distributions are shown in Figure 4. Here, one can see that the backflow in the throat has been re-established and it should be expected that higher quality glass should be produced. This was indeed seen in the plant operations.

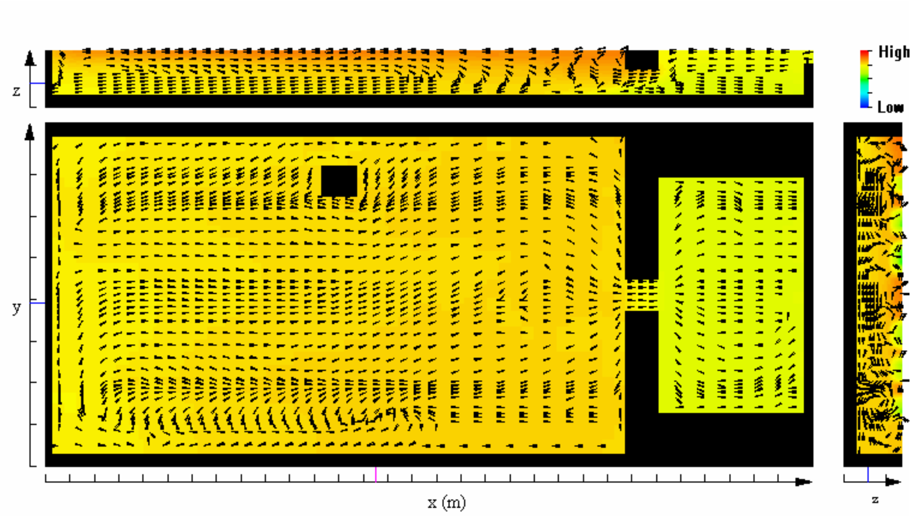

Figure 4: Glass Temperature and Velocity Distribution with New Firing Pattern and Blockage Still Present

IV. Conclusion

The purpose of this work was to investigate the causes of reduced glass quality by applying the Glass Furnace Model to operating conditions before the problem, during the problem and after the problem. The analysis shows that the cause of the reduced glass quality is the presence of too high a heat flux over the blockage. This causes too much hot glass to leave the melter too quickly thus reducing the glass quality. Once the problem has been diagnosed, a simple operational solution presented itself.

Acknowledgments

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