

# The Many Colors of Glass

Numerical simulation helps guide the color change process in the glass industry.

By Mustafa Oran, SISECAM Research Center, Turkey



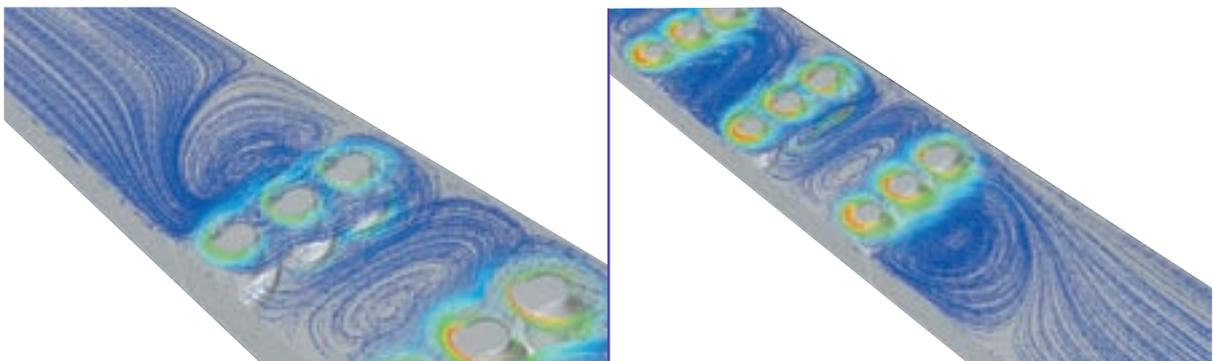
Colored glass products have many commercial applications. One way to change the color of molten glass is to add a colorant material to one particular channel of the glass furnace called the forehearth (F/H). The forehearth is where molten glass is conditioned while being transported to the downstream forming machines. By adding colorant to one of the forehearth channels, the original color of glass can remain unchanged in the melting tank. A CFD project has been under way at the Research Center of SISECAM to develop a numerical model for the coloration of glass melt in an F/H for the production of table-

ware products. The model simulates the coloration phenomenon of the glass melt by calculating the distribution of the colorant agent in the glass melt as it flows through the channel.

Coloration is essentially an unsteady mixing process of two or more fluids resulting from natural (diffusion) and forced (advection) mechanisms. Molecular diffusion can be from a point source in a static field or from a point source in a velocity field in which relative motion exists between the source and the field. Therefore, the spread of a colorant, referred to as "frit," in molten glass can be obtained by solving Fick's second law for

diffusion when the source and other boundary conditions are defined. The advection process is driven by the movement of the fluid, which is molten glass in the case of the forehearth. Because the colorant is carried in all directions by the flow in the F/H, a 3-D time-dependent species transport equation must be solved to track its distribution throughout the glass melt.

In addition to the CFD work, a set of experimental studies also has been performed at SISECAM to obtain the diffusion coefficient of the frit in the molten glass. Measurements made use of a laboratory setup based on image processing of a time-lapsed



Two views showing the pathlines of molten glass flow in the vicinity of the stirrers in the forehearth

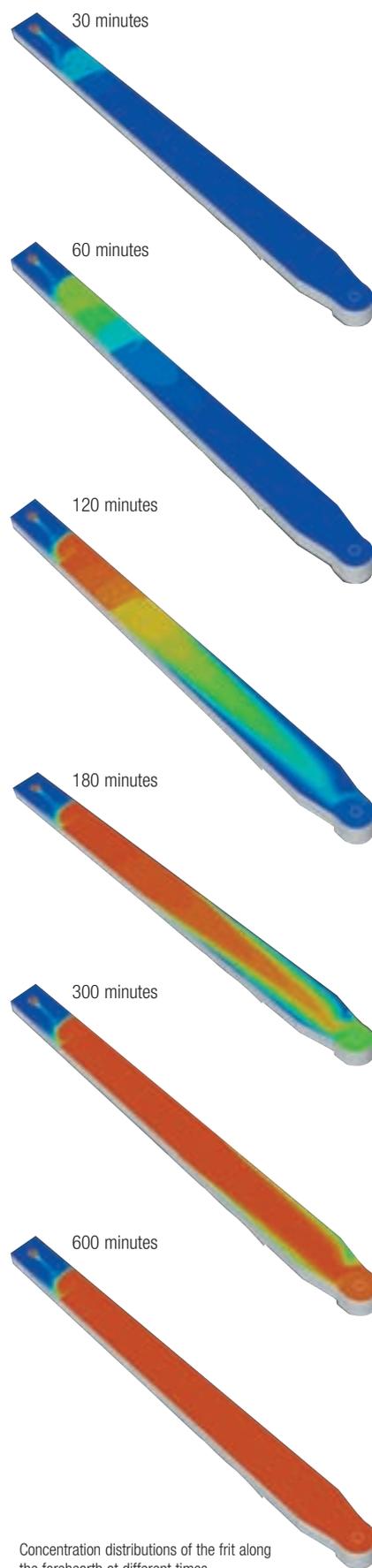
video record. The raw image data representing the rate of change of area occupied by the frit on the molten glass surface for different temperature values are digitized and transformed to a curve representing the diffusion coefficient of the frit as a function of temperature. This value is used in the numerical model in the form of a polynomial function.

The frit is fed to the glass surface from the top of the F/H through a hole. The F/H has a mixing zone, where 12 stirrers are located in four banks. A rotating tube is located in the spout section at the downstream end of the F/H to generate a gob for the production of the glass item at the forming station. One of the main aspects of color control is the requirement of homogeneity of the frit in the glass melt to obtain color uniformity in the end product. Another goal is to achieve on-time delivery of the end product with a target color value. Because the frit is added near the end of the entire glass process, a strong stirring action is required to create uniform mixing in a short time. Two different configurations of screw stirrers that rotate in the clockwise and counter-clockwise directions are used in the numerical model.

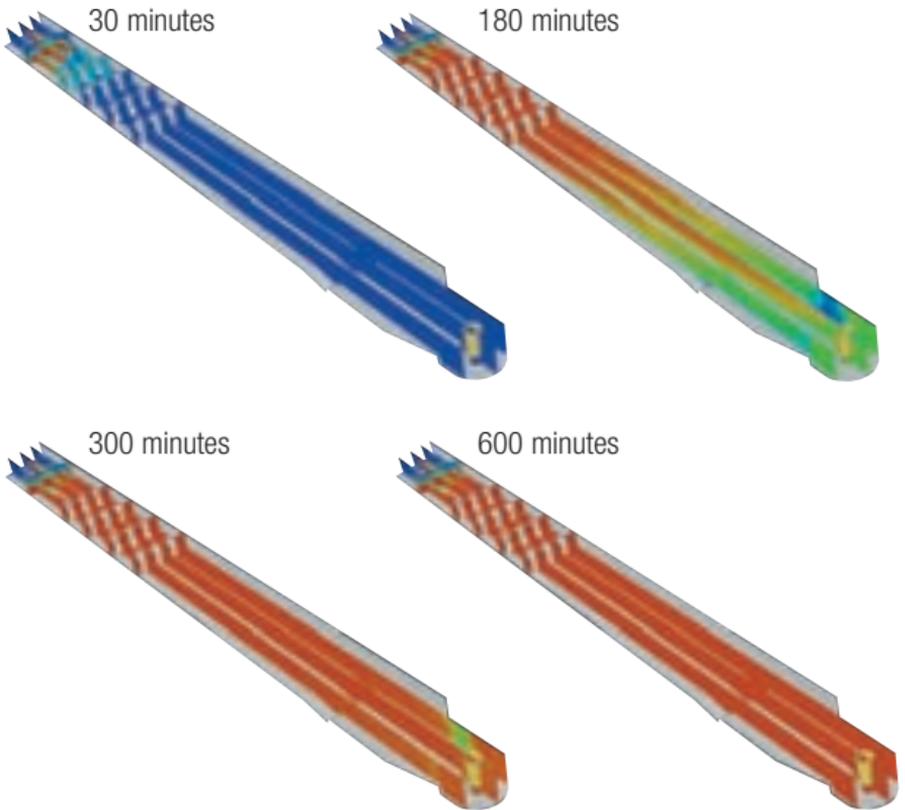
A typical forehearth was chosen for the numerical solution, which was carried out using FLUENT software.

For the first phase of the simulation, the initial velocity distribution of the glass melt was obtained using a steady-state approach. The multiple reference frames (MRF) model was used to simulate the rotational motion of the stirrers, and the rotation of the tube in the spout region also was taken into account. These results show that strong vortices occur between adjacent banks of stirrers. In general, the glass melt is pumped upward along the axis of the stirrers and downward in the mixing vortices between the stirrers. The up-pumping action of the stirrers is necessary because the frit used in the process is denser than the glass melt. The results reveal that the two different configurations of stirrers create the same circulation effect in the glass melt in the vertical direction. This flow pattern enhances the mixing between the molten glass and frit so that a homogenous blend can be generated.

In the second part of the numerical study, the transient tracking of the frit concentration was performed. The sliding mesh model was used to capture the motion of the stirrers. The results show



Concentration distributions of the frit along the forehearth at different times



The vertical spread of the frit below the glass surface at different times

that a considerable amount of frit reaches the stirring zone 30 minutes after feeding, following the flow pattern of the glass melt. Axial slices of frit concentration show that the initial direction of the frit motion is toward the bottom of the channel while only a small amount of frit travels near the glass surface. This result occurs because of the high density of the frit, which tends to sink toward the bottom of glass immediately after feeding. As the time proceeds, most of the frit is pumped upward as it passes through the stirring zone. There, the frit and molten glass are progressively mixed and a uniform distribution is gradually achieved.

Mixing between the glass melt and frit is accelerated in the stirring zone and, after one hour, a cross-sectional view of each stirrer bank shows a more or less homogenous frit distribution. As the coloration process continues, the target concentration of frit is obtained homogeneously in the stirring zone before three hours have passed. The simulation shows that the target value of frit (0.5 percent of the pull rate) is uniformly distributed along the F/H well before 10 hours.

The color of the final glass gob does not change during the first 90 minutes. After that point the glass gradually changes color, but the production glass is not discarded because the early color changes are not visible and the product can still be accepted commercially. The simulations show that the target value of frit concentration at the end of the forehearth is obtained after nine to 10 hours, whereas the real process in the plant starts to accept the new color value after eight to nine hours. Since the variation in frit concentration during the final hour is very small, the numerical simulations can be safely accepted for practical use. ■