# APPLICATION OF GLASS MELT MODELING FOR EXAMINING FORCED BUBBLING DESIGN

BRYAN C. HOKE, JR.

*Air Products and Chemicals, Inc., Allentown, PA, USA*

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*A glass manufacturer wanted to improve the melting capability of the furnace using bubbling. Computational Fluid Dynamics (CFD) models were applied to examine the effect of bubbling and optimize the number of bubblers to use. Several results were examined and the study revealed that too many bubblers can worsen the melting capability of the furnace. This paper demonstrates how modeling can be used for furnace design.*

## INTRODUCTION

A customer desired to improve profits by adjusting the batch composition. The raw material change requires the melter to be more effective.

Bubbling is commonly used to improve melting in a furnace. Bubbling lifts cold glass from the bottom of the melter to the surface and returns hotter glass from the surface to the bottom. Higher bottom temperatures result which can improve melting, but can also decrease the minimum residence time since the viscosity of the glass is reduced at these higher temperatures. Bubbling significantly changes the flow field in the melt and can have both positive and negative impacts.

The furnace in this study is a cross-fired oxy-fuel TV glass melter. The combustion system uses Cleanfire® HR burners in a staggered arrangement. A throat connects the melter and refiner. The refiner has three forehearths feeding the shops.

The current design of the furnace does not include bubblers. Two proposed bubbler configurations have been suggested: one with six (6) bubblers and the other with sixteen (16) bubblers. For both cases the bubblers are located in a single line at 45% of the length of the tank. The objective of this study is to examine whether it would be better to use a single row of 6 or 16 bubblers to improve the melting effectiveness of this furnace.

## THEORETICAL BACKGROUND

### CFD Model description

The *Glass Model* by Glass Service, Ltd. [1] was used in this study to model the glass melt. The *Glass Model* solves steady-state three-dimensional temperature and flow fields that are governed by laws of conservation, commonly expressed by partial differential equations. The formulation of the model assumes:

a) molten glass is an incompressible Newtonian fluid,
b) variations in density due to temperature is important only in buoyancy forces (Boussinesq approximation),
c) viscous heat dissipation effects are negligible, and
d) molten glass is optically thick (Rosseland approximation).

The resulting partial differential equations are converted into a set of algebraic equations using a differencing technique [2] and solved using the symmetrical coupled Gauss-Seidel iterative procedure [3].

### Boundary conditions

Boundary conditions are required along the edge of the computational domain. They describe the thermal and mass flow conditions at the boundaries.

The mass flow rate for each batch charger was specified based on the batch charger speed. Through the energy balance, the distribution of mass entering the glass melt from the batch region is calculated by the model. Mass flow rates at the forehearths are specified according to shop usage rate.

A zero shear boundary conditions is applied to free surface glass. Since refractory walls are included in the *Glass Model*, zero velocity is applied implicitly on external boundaries.

Cold face refractory temperatures were measured using a Minolta Cyclops 300AF optical pyrometer. These temperatures were used as temperature boundary conditions on the refractory in the model.

Since, in this study, *Glass Model* simulations were calculated without coupling to a combustion model, approximate temperature boundary conditions are used on the glass surface. The temperature is varied along the length of the furnace and held constant over the width of the furnace. This temperature profile is based on optical pyrometer measurements using a Minolta Cyclops 52.

Based on the objectives of this study to determine whether 6 or 16 bubblers would be better to improve

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melting capability, the results generated by this modeling approach without coupling should be sufficient to draw appropriate conclusions. However, if more precise results are required, Hoke and Marchiando [4] showed that coupling to a combustion model can greatly improve the accuracy of the results. Coupled model simulations account for side-to-side variations in the glass surface temperature profile, which influence the glass flow patterns.

### Glass properties

Thermophysical properties of glasses are determined by laboratory measurements and fitting the values to temperature functions suitable for use in the Glass Model. Properties required by the model include density, effective thermal conductivity, specific heat, and viscosity.

### Operating conditions

Three simulations were calculated using the same operating conditions and pull rates. The only differences were with the bubbling parameters. The pull rate was greater than 200 tonnes per day. In both bubbling cases, bubbler flow rates were $4.72 \times 10^{-4}$ N $m^3$ $s^{-1}$ per bubbler. Tube diameters are 0.8 mm and are flush with the bottom.

## RESULTS AND DISCUSSION

### Description of cases

Three *Glass Model* simulations were performed for this study. In case 1, no bubblers were used. In case 2, 6 bubblers were used and in case 3, 16 bubblers were used.

### General temperature and flow patterns

The temperature profile through the depth of the glass is stratified for cases 1-3. If the glass is to encounter higher temperatures, it must flow near the surface. If a ”V” temperature pattern was to exist, the higher temperatures penetrate to the bottom and the glass will always encounter higher temperatures even if it flows along the bottom to the throat. For case 3 with 16 bubblers, there is some local penetration of higher temperature in the region of the bubbler row.

The bulk glass melt temperature is observed to increase for increasing number of bubblers. This temperature increase is a result of the mixing provided by the bubbling action. Cold glass from the bottom is lifted to the surface and hot glass from the surface is sucked down.

Velocity vectors for each case are shown in figures 1-3. The relative vector magnitude is indicated by its length. Batch is charged from the back of the furnace. Recirculating melt flows back on the surface from the

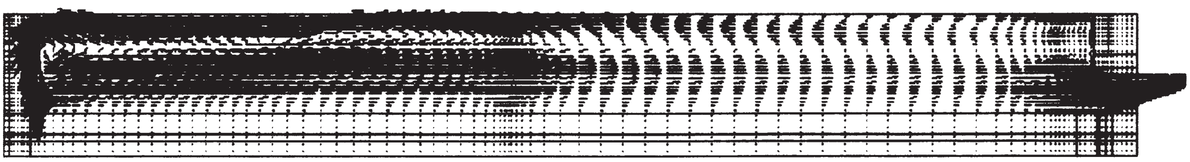

Figure 1. Longitudinal centerline view of velocity vectors for case 1.

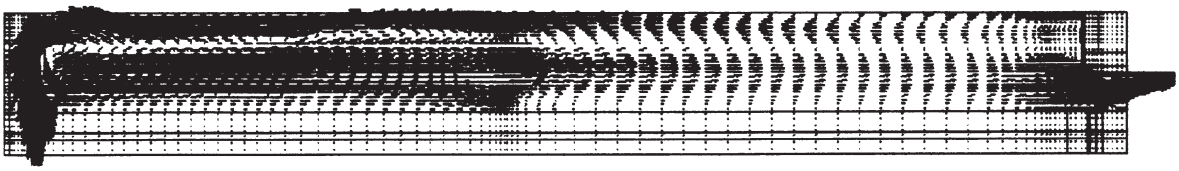

Figure 2. Longitudinal centerline view of velocity vectors for case 2.

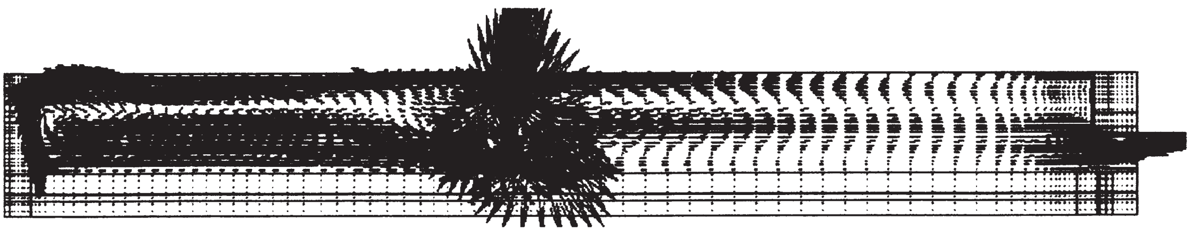

Figure 3. Longitudinal centerline view of velocity vectors for case 3.

spring zone and pushes against the batch blanket. This melt interacts with the melting batch, pushing foam and batch to the charging end. The temperature of the glass melt is reduced underneath the batch due to the shadow effect of the batch, heat transfer from the melt to the batch, colder new glass entering the melt, and heat of chemical reaction.

The newly melted glass which is saturated with bubbles and sand grains during batch melting is colder and heavier than the melt which has returned by recirculation. New glass tends to fall and mixes with the melt. New glass enters the melt over the entire batch area.

As seen in figure 1, there seems to be one main cell and one minor cell for case 1. The main cell moves from the batch, down along the backwall, and forward along the bottom. At this point some glass exits through the throat some moves up to the spring zone and circulates back to the batch. Glass feeding the throat comes from about the middle third of the glass depth. The small minor cell moves forward on the surface from the spring zone, down half of the frontwall, and back to the spring zone.

Bubbling alters the flow pattern for cases 2 and 3. As seen in figures 2 and 3, the two cells existing in case 1 are present with some additional flow features. In the back half of the furnace, some of the forward moving glass on the bottom is moved up at the bubbler row and flows back to the batch. And there is a small cell on the bottom of the melter on the front side of the bubbler row.

This small cell on the bottom provides a flow dam. In addition to the obvious mixing caused by the bubbling action, this dam prevents the newly melted glass from flowing along the bottom (where the temperature is coldest) and directly exiting the throat.
The intensity of flow under the batch for cases 1 and 2 are similar. The flow is much more intense for case 3 where 16 bubblers are modeled. For this case, the velocity under the batch is significantly increased. This may mean that for the case of 16 bubblers, it will be easier for the fast moving glass to erode unmelted batch into the melt and may aggravate stone problems.

### Bottom temperatures

Higher bottom temperatures are often desired to improve glass quality. Comparisons are made between the cases and trends are discussed.

Glass temperatures near the bottom of the melter are compared. Bubbling is shown to raise the overall bottom glass temperatures and the temperatures locally in the region of the bubbler row. The temperature near the bottom for case 1 without bubblers is typically in the range of 1235 to 1250 °C. For case 2, the temperature is generally increased about 5 °C compared to case 1 with a maximum temperature of 1265 °C locally near the bubbler row. A 25 °C general increase in bottom temperature is seen for case 3 with a maximum bottom temperature of about 1300 °C.

### Effect of bubbling

Bubblers are proposed at a position 45% of the length of the melter. For case 2 where six (6) bubblers were modeled, six distinct bubbler zones are observed. For case 3, where sixteen (16) bubblers were modeled, a single wall of upward flow is observed with some down flow near the melter sidewalls.

Bubblers create intensive circulation, mixing cold glass from the bottom with hot glass from the surface which results in higher bulk and bottom temperatures. In addition to the mixing, bubblers can provide a barrier to prevent new glass from short circuiting through the melter on the bottom.

The barrier can be formed in two ways. An obvious way is where the glass on the bottom is forced upward by the bubbles. Another manner is to create backward flow on the bottom down tank of the bubblers. No backward flow is observed for case 1. Backward flow is evident for cases 2 and 3, but is more effective and pronounced for case 3. Backward flow is essentially a dam since the forward moving glass on the bottom must be lifted to a higher elevation and higher temperature above this backward flowing glass. This type of flow behavior is desired especially for cases where there is a stratified temperature profile.

### Backward flow on the bottom between the bubblers and throat

Backward flow on the bottom of the front part of the melter sometimes occurs as a result of downward flow along the front basin wall. Return flow from the refiner will produce backward flow in a melter. As discussed in the previous section, backward flow is enhanced by the bubblers.

For cases 1 and 2, there are very small regions of backward flow immediately adjacent to the front basin wall. The density of the glass close to the walls is increased because of heat losses to the walls. This glass tends to move downwards and in the case of the glass at the frontwall, moves backwards.

In addition to the small region of backward flow near the frontwall, there is also backward flow near the bubblers for case 2. For this case, the amount of bubbling is not sufficient to connect the backward flow at the frontwall with the backward flow generated by the bubblers. For case 3, the backward flow is connected except near the centerline of the melter. Backward flow can penetrate further into the tank because of the coupling with the suction generated by the bubblers.

### Return flow from the refiner

Return flow from the refiner was not observed at this pull rate for any of the cases. Return flow can sometimes occur because of the density difference between the glass in the melter and refiner, depending on the geometry of the throat and the pull rate. The


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refiner glass is colder and therefore has a higher density than the glass in the melter. Return flow sets up backward flow in the melter which may be important for glass melting capability.

This model assumed no throat erosion. Throat geometry has been shown to be an important factor determining return flow [5].

## Locations of spring zone and turning point

The spring zone is defined as the centerline position on the melt surface where surface glass separates and flows toward the batch and throat. The turning point is the place on the bottom centerline position where forward flow is stopped. From the turning point, the flow is either turned back or at least lifted upward.

The spring zone position as a percentage of furnace length is 74.1, 74.7, and 82.9 for cases 1, 2, and 3, respectively. For each case, there is a small circulating cell moving near the surface that moves from the spring zone to the front wall, down half of the front wall, and back to the spring zone. The spring zone location is about the same for cases 1 and 2. The spring zone is moved further down tank for case 3. By moving the spring zone further down tank, the size of this small circulating cell is reduced. It is typically desirable to move the spring zone up tank. Surface scum could more easily enter the throat if the spring zone is moved too far down tank.

No turning point is observed for case 1. For the cases where bubbling is modeled, the turning point is at the bubbler row.

## Residence times and critical trajectories

Massless particle tracing studies were performed to determine residence time parameters. Residence time parameters are given in table 1. The minimum residence time is the time required for the first massless particle which was released from the batch to reach the throat. This minimum residence time particle is called the critical trajectory. The calculated mean residence time is determined by summing residence times of all of the particles and dividing by the total number of particles reaching the throat for a prescribed integration interval. The mean temperature on the critical trajectory is the integrated time averaged temperature of the critical trajectory particle.

Bubbling decreases the minimum residence time. The minimum residence time is shortened 28 % for 6 bubblers and 52 % for 16 bubblers compared to the baseline operations without bubbling. This very short minimum residence time for the case of 16 bubblers may decrease the melting capacity of the furnace. The minimum residence time often increases when bubblers are added since the melt temperature is raised, causing the viscosity to decrease and velocities to increase.

The calculated mean residence time is *increased* 7 % for case of 6 bubblers compared to the base case. This should be better for glass melting. For 16 bubblers the calculated mean residence time is *decreased* 12 % from the base case. For a meaningful comparison of calculated mean residence times, it is recommended to use a prescribed integration interval of at least two times the volumetric mean residence time. The volumetric mean residence time is defined simply as the volume of the melter divided by the volumetric flow rate. Theoretically, the calculated mean residence time equals the volumetric mean residence time if the prescribed integration interval is infinite. For this study, tracing was carried out for a prescribed integration interval of 2 times the volumetric mean residence time.

Both time and temperature are important for glass melting capability. So although the minimum residence time is decreased with the addition of bubblers, better melting could occur since the glass temperature is increased in the melter. The mean temperature on the critical trajectory is increased 10 °C for case 2 and 40 °C for case 3 compared to case 1. Experimental data on melting of the batch could be important to determine what time-temperature relationship is best.

Compared to case 1, the length of the critical trajectory is 10 % greater for case 2 and about the same for case 3.

Table 1. Residence time parameters

| Parameter | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Minimum residence time (% of case 1 min. res. time) | 100 | 72.5 | 47.8 |
| Calculated residence time (% of case 1 calc. mean res. time) | 100 | 107.0 | 88.5 |
| Mean temperature on critical trajectory (°C) | 1263 | 1273 | 1303 |
| Length of critical trajectory (m) | 17.6 | 19.4 | 17.3 |
| Possible dead room (%) | 22.7 | 17.3 | 31.6 |

Dead room or deadwater is defined in Levenspiel [6]. "In a vessel the deadwater regions are the relatively slow moving portions of fluid which we chose to consider to be completely stagnant. Deadwater regions contribute to the vessel volume; however, we ignore these regions in determining the various age distributions." A mathematical definition can also be found in Levenspiel.

$$\text{Deadwater} = 1 - \frac{\text{calculated mean residence time}}{\text{volumetric residence time}}$$

For the same volumetric flow rate in a vessel, the dead room is directly related to the calculated mean residence time. For changing flow rates, it is instructive to compare both calculated mean residence time and dead room.

For a glass tank, we would want to minimize the dead room. We want all of the glass to be about the same age and to see the same conditions in its travel through the melter. Dead room is particularly important if pull rates are changed often. Glass caught up in a deadwater region is likely to have a composition different from the other glass. When the pull rate changes, the dead room size and location changes, allowing the previous deadwater glass to mix with the bulk flow stream. The inhomogeneity of the glass might take the form of cord.

The possible dead room is decreased for case 2 and significantly increased for case 3 compared to case 1. These results suggest that over 31 % of the melter volume is not participating in the glass melting process in case 3.

## Melting index

Since high temperatures, low viscosities, and long residence times improve the melting of the glass raw materials, a melting index has been defined [7]:

$$\text{Melting index of trajectory } i = \int_{t=0}^{t\,=\,\text{particle residence time}} (T / \mu)\, \mathrm{d}t$$

where $T$ is the local temperature of a particle, $\mu$ is the local viscosity, and $t$ is time. The mean melting index for all the massless particles is calculated in the normal way from the distribution of particle traces.

The mean melting indices are 1.82E7, 1.96E7 and 1.80E7 for cases 1, 2, and 3, respectively. Compared to case 1, the melting index is improved for case 2 and decreased for case 3. This suggests that 6 bubblers are better than 16 bubblers for improving the melting capability of the furnace.

## CONCLUSIONS

To improve profits, a customer desired to alter the batch composition. In order to do this without adversely affecting glass quality, the melting capability of the furnace must be improved. This study was initiated to evaluate whether 6 or 16 bubblers would be preferred to improve melting capability.

Since both time and temperature are important for glass melting, no single criterion conclusively determines the number of bubblers to use. Several results were presented to evaluate the effectiveness of adding bubblers.

Key results of this study are summarized in Table 2. Simulation results for cases 2 and 3 are compared with the base case results.

Case 2, with 6 bubblers, shows improvement over the base case for every feature except the minimum residence time. Case 3, with 16 bubblers, shows marked improvement for temperature, but may provide an inadequate amount of time at this temperature. Experiments on the melting the new batch composition to determine the time-temperature relationship may be required to conclusively decide which case is better.

This study suggests that 6 bubblers are better than none. Sixteen bubblers further improve the temperatures in the melt but at the expense of time for melting. Concerns with case 3 are low melting index, short minimum and calculated mean residence times, potential for increased pickup of unmelted batch under the batch piles, and an increased potential for surface scum to move to the throat because the spring zone is moved down tank.

This study illustrates how models can be used for furnace understanding and operating improvements and demonstrates Air Products' capabilities.

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Table 2. Summary of comparisons with base case results.

| Feature | Case 2 (6 bubblers) | Case 3 (16 bubblers) |
|---|---|---|
| Overall bottom temperatures | Improved (increased approximately 5 °C) | Greatly improved (increased approximately 25 °C) |
| Maximum bottom temperature | Improved (increased 15 °C) | Greatly improved (increased 50 °C) |
| Flow under batch | Same | Worsened |
| General flow pattern | Improved (flow dam exists) | Improved (flow dam exists) |
| Return flow from refiner | Same (none exists) | Same (none exists) |
| Spring zone | Same (75 % of furnace length) | Worsened (83 % of furnace length) |
| Turning point | Improved (at bubbler row) | Improved (at bubbler row) |
| Minimum residence time | Worsened (decreased 28 %) | Greatly worsened (decreased 52 %) |
| Calculated mean residence time | Improved (increased 7 %) | Worsened (decreased 12 %) |
| Mean temperature on critical trajectory | Improved (increased 10 °C) | Improved (increased 40 °C) |
| Length of critical trajectory | Improved (increased 10 %) | Same |
| Melting index | Improved (increased 7.7 %) | Worsened (decreased 1.1 %) |

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*Submitted in English by the author.*

## APLIKACE MODELOVÁNÍ TAVENÍ SKLA PŘI OVĚŘOVÁNÍ NÁVRHU BABLINGU

BRYAN C. HOKE, JR.

*Air Products and Chemicals, Inc.,*
*Allentown, PA, USA*

Pro zvýšení tavicí kapacity sklářské pece měl být zaveden babling. K ověření vlivu bablingu a k optimalizaci počtu trysek bylo použito matematické modelování dynamiky tekutin (CFD). Bylo ověřováno několik výsledků a zjistilo se, že nadměrný počet trysek může zhoršit tavicí kapacitu pece. Článek dokládá význam modelování při projektování pece.