Numerical Study of Fluid Flow Behaviors in an Alkali-Free Glass Melting Furnace

Chien-Chih Yen and Weng-Sing Hwang*

Department of Materials Science and Engineering, National Cheng Kung University, Tainan, Taiwan, R.O. China

In this study, fluid flow behavior of molten glass in a melting furnace, which is characterized by the stirring range of gas bubbles and trajectories of tracer particles, is investigated by a reduced physical model and a mathematical model. The reduced physical model was made of an acrylic tank, which was similar in shape of the actual glass melting furnace but one fifth in size, with heating electrodes and air bubbling devices. The gas flow rates were set at 8.27, 10.42 and 14.75 Ncm³/sec based on similarity conversions. The electrode temperatures were set at 25°C and 150°C. The mathematical model was based on the SOLA-VOF technique, which incorporated a Quasi-single Phase method to accommodate the gas bubbling phenomena. Results from the physical model showed that the trajectories of tracer particles and minimum residence time (MRT) increase with gas flow rates. This is caused by the increase in stirring range of gas bubbles, which was demonstrated by the physical model as well as the mathematical model. The trajectories of tracer particles at the electrode temperature of 150°C were observed to be longer than those for the electrode temperature of 25°C from the physical model. This is due to the free convection induced by the heating electrodes, which is also shown by the mathematical model. [doi:10.2320/matertrans.MRA2007259]

(Received October 30, 2007; Accepted January 28, 2008; Published March 19, 2008)

Keywords: glass melting furnace, physical model, mathematical model, heating electrodes, air bubbling, similarity conversions, SOLA-VOF, minimum residence time

1. Introduction

The melting furnace for alkali-free glass is basically a rectangular vessel with an irregularly shaped bottom. It can be divided into three major parts; the combustion zone, batch zone, and molten glass zone. A schematic illustration of the glass-melting furnace is shown in Fig. 1. Batch materials are fed from the inlet continuously to the batch zone located between the combustion space and molten glass zone. Fuel is burned with air or pure oxygen in the combustion zone to provide heat to the batch blanket for the fusion of the batch materials and to the glass melt surface to obtain a low-viscous melt. Heat from the combustion space can be transferred by radiation, convection of the hot combustion gases and conduction. Another source of energy to melt the glass batch is an electrode array immersed in the molten zone. Electric boosting is an effective method for increasing productivity and enhancing glass-melting efficiency. By arranging the electrodes adequately, glass melt circulation is enhanced as well as lowering the load and temperature on the combustion space to obtain longer superstructure life. Heat flux at the batch-glass melt interface is also increased hence a higher pull rate can be obtained. Higher temperature near the electrodes will cause density gradients, driving free convection flows in the affected zone. The convection of mass in the melt is essential for mixing and heat transfer, in particular for melts with high thermal resistance. The bubbling gases through bubbling tuyeres, mounted on the bottom of the tank enables agitation by bring relatively cold glass melt from the bottom to the surface, and hence the surface temperature of the glass melt is decreased. This increase the temperature gradient between the combustion space and the glass melt surface and consequently increases the net radiation heat flux. Moreover the overall heat transfer from the combustion

Fig. 1 A schematic illustration of a melting furnace for alkali-free glass.

zone into the glass melt will be improved and the circulation enhanced.

The physical modeling method allows for a clear picture of mass exchange in the glass-melting furnace and enables for recommendations to be made on furnace operation. Murnane *et al.*¹⁾ outlined the development of modeling tools used in the analysis of operations and design for electric glass furnaces. The harsh environment of an electric glass furnace makes the observation of glass flow patterns and temperature fields an expensive and risky attempt. Physical models based on the principle of similarity can provide an effective methodology where convective flows and tracer distributions can be easily studied. Murnane *et al.* also commented that although the use of physical model within the glass industry had evolved slowly over several decades, comparatively only few studies had been conducted on physical modeling corresponding to computer modeling. Tolstov *et al.*²⁾ established a physical model based on similarity theory to investigate the glass melt hydrodynamics in a highly efficient melting furnace for container glass. The design has to ensure not only the similarity of the thermal and hydrodynamic processes in the functioning furnace but also convenience in observation and the ability to measure the glass melt routes as well as velocity and temperature fields.

The physical models in previous studies were mostly valid only for traditional glass industries. Currently, the quality

*Corresponding author, E-mail: wshwang@mail.ncku.edu.tw

requirement of glass substrate for liquid crystal display (LCD) is much higher and the design requirements of a glass furnace are of a critical and complex nature. Therefore, this study mainly focuses on the glass furnace that produces glass used in LCD.

In the aspects of numerical modeling, Ungan *et al.*^{3,4)} developed a mathematical model to predict the effects of electric boosting and air bubbling separately on circulation and heat transfer in a glass-melting tank. Schill *et al.*⁵⁾ used two methods, coupled and decoupled, to solve differential equations and discuss important phenomena including heat, mass transfer and melting kinetics for a real glass furnace. However, they did not discuss the fluid flow phenomena. Therefore, in the mathematical model developed in this study, electric boosting and air bubbling effects were coupled together to investigate the fluid flow behavior in the glass furnace.

Due to high temperature operation, it is extremely difficult to visualize inside the glass-melting tank. The number of defects in glasses is considered to directly depend on flow and heat transfer behaviors in the molten glass zone. Consequently, a reduced physical model was constructed for molten-glass zone according to similarity theory. Minimum residence time (MRT), which is the time required for tracer particles to flow from inlet to outlet, four gas flow rates and two electrode heating temperatures were used to investigate the effects of process condition on the fluid flow behaviors in the molten-glass zone. A mathematical model was also established in conjunction with the physical model to explain the flow phenomena in the glass melting furnace.

2. Experimental Method

2.1 Physical model

A one fifth reduced physical model with air bubbling and electric heating system, as illustrated in Fig. 2, was estab-

Fig. 2 Schematic illustrations of the physical model (a) 3-D view (b) Top view (c) Side view.

Table 1 The variables used in this study.

Viscosity of glass melt; μ_g	127 poise
Viscosity of silicon oil; μ_{so}	200 poise
Density of glass melt; ρ_g	2.45 g/cm ³
Density of silicon oil; ρ_{so}	0.965 g/cm ³
Density of tracer particle; ρ_{tracer}	0.9 g/cm ³

lished to study the fluid flow behaviors in the glass furnaces. In order to observe the flow behaviors, the model was made with transparent acryl. A row of six gas blowing tuyeres, 0.8 cm in diameter was installed at the bottom in the center of the acrylic tank. Compressed air at room temperature was used as the bottom blown gas. Four rows of electrodes with three electrodes on the first three rows and four electrodes on the fourth row were installed on the bottom and were connected to the heating control system. Each electrode was attached to a thermocouple and 1.5 cm in diameter and 9 cm in height, which corresponds to the ratio of the actual electrode of 7.5 cm diameter and 45 cm in height. Silicon oil with a viscosity of 200 poise was selected to simulate the molten glass. Acrylic particles with a density similar to silicon oil were used as tracers. Tracers were inserted at the inlet at steady state, and the flow behaviors were recorded by a video camera. The variables used in this study are listed in Table 1.

2.2 Liquid flow rate conversion

Due to high viscosity of glass melt, Reynolds number (Re) was used to converse fluid flow rate between the physical model and glass tank. Applying a Reynolds criterion between the physical model and glass tank, it can be shown that

$$Re_{ac} = Re_{gt}$$

Then

$$\frac{Q_{so} \cdot L_{ac} \cdot \rho_{so}}{\pi \cdot r_{ac}^2 \cdot \mu_{so}} = \frac{Q_g \cdot L_{gt} \cdot \rho_g}{\pi \cdot r_{gt}^2 \cdot \mu_g}$$

Q_{so} can then be calculated in the following equation.

$$Q_{so} = \left(\frac{L_{gt}}{L_{ac}} \right) \left(\frac{r_{ac}^2}{r_{gt}^2} \right) \left(\frac{\rho_g}{\rho_{so}} \right) \left(\frac{\mu_{so}}{\mu_g} \right) \cdot Q_g$$

The results of the liquid flow rate conversion between the physical model and the glass tank are shown in Table 2.

2.3 Mathematical model

A three dimensional numerical model based on the SOLA-VOF⁶⁾ method, which incorporates a Quasi-single Phase method to express the gas bubbling phenomena, was

Table 2 Liquid flow rates in the glass furnace and acrylic model.

	Amount	Glass tank	Acrylic model
Main outlet	1	7400 (Kg/day)	1677.25 (cm ³ /min)
Drain hole	2	600 (Kg/day)	135.99 (cm ³ /min)
Overflow	2	300 (Kg/day)	67.99 (cm ³ /min)
Inlet	2	4600 (Kg/day)	1042.61 (cm ³ /min)

Fig. 3 Flow paths of tracers in the physical model at room temperature without heating and bubbling in the vicinity of (a) Inlet (b) Bubbling zone (c) Outlet. (The inserts show the sketches of the investigated regions in the physical model)

developed to investigate the fluid flow behavior in the glass tank. For solving partial differential equations in the molten glass zone numerous assumptions were made; that molten glass is an incompressible Newtonian fluid, molten glass enters continuously from the inlets and the properties of fluid are constant except for density.

The governing equations are as follows:

(1) Continuity equation

$$\nabla \cdot \bar{V} = 0$$

(2) Momentum equation

$$\rho_l \left[\frac{\partial \bar{V}}{\partial t} + (\bar{V} \cdot \nabla) \bar{V} \right] = -\nabla P + \nu \nabla^2 \bar{V} + \rho \bar{g}$$

(3) Energy equation

$$\rho C_p \left[\frac{\partial T}{\partial t} + \bar{V} \cdot \nabla T \right] = k \nabla^2 T$$

The density variations follow the equation

$$\rho = \rho_l / [1 + \beta_T (T - T_0)]$$

The temperature boundary conditions at the interfaces between the molten glass and atmosphere in the furnace as well as furnace walls and ambient environment are as follows.

$$-\frac{k}{h} \frac{\partial T}{\partial n} = (T - T_\infty)$$

In this study, batch materials were considered as liquid which entered from the inlet continuously. Radiation heat transfer effects were not yet taken into consideration. Subsequently the virtual temperature of mesh, T_ϕ , which is close to the free surface mesh or wall mesh in any direction, can be derived from the equation above and results in the differential equation as follows.

$$T_\phi = \frac{\left(\frac{k}{\delta n} - \frac{h}{2} \right) T_{i,j,k} + h T_\infty}{\left(\frac{k}{\delta n} + \frac{h}{2} \right)}$$

where T_∞ is the temperature of furnace atmosphere or ambient temperature outside the wall.

The Quasi-single Phase method was to address the rising gas-liquid mixture as a homogenous fluid of variational density. A buoyancy force of gas bubbles was introduced by the density differences among gas, glass-liquid mixture, and pure liquid. In this study, a spherical gas bubble was released from each of the six tuyeres once every two seconds for the gas flow rate of 14.75 Ncm³/sec. This releasing frequency was obtained from experimental observations. The radius of the released bubble; R_b , was then calculated by the following equation.

Fig. 4 (a) Sketch of the investigated region in the physical model (b-e) Flow paths of tracer particles at room temperature with bubbling at $8.27 \text{ Ncm}^3/\text{sec}$. (The left hand figures are the sketches of the tracers' positions in the investigated regions of the physical model)

$$R_b = \sqrt[3]{\frac{Q_b \cdot t_b}{4\pi}} = \sqrt[3]{\frac{14.75 \cdot 2}{4\pi}} = 1.916 \text{ cm}$$

As the bubble size is significantly larger than that of the mesh size, the mesh element specified can then be pure liquid, pure gas, or gas-liquid mixture. The density of the element was then determined accordingly. The gas/liquid interface and the motions of gas bubbles were addressed by a marker-and-cell (MAC)⁷⁾ technique.

3. Results and Discussion

3.1 Effects of gas flow rate

In this study, four gas flow rates were used to investigate the fluid flow behavior in the glass melting furnace. Figure 3 shows the flow paths of tracers in the physical model at room temperature without heating and bubbling. It can be found from that the tracer particles move along the free surface from inlet to outlet. Tracer particles did not shift much in the y and z directions. This is believed to be a result from high

viscosity of silicon oil and the absence of stirring mechanism in the physical model.

Figure 4 illustrates the flow paths of tracer particles at room temperature with bubbling at $8.27 \text{ Ncm}^3/\text{sec}$. Initially, the tracers moved along the free surface. Then they begin to aggregate near the third row of electrodes and move towards the bottom. As tracers approach the bubbler, they rise quickly to the surface due to fluid current induced by air bubbling. At the surface some of the tracers moved backward to the third row of electrodes and others moved forward to the forth row of electrodes. There was a flow circulation formed at the bubbling zone. This circulation would cause some tracer particles to residue inside the bubbling zone for many circles. Although the computer simulation developed in this study was a 3-D model, it was difficult to display the simulation results properly in 3-D. Therefore, the results are shown by 2-D cross-sectional views. Figure 5 shows the 2-D section view of velocity field in the cross-section of the bubbler near the bubbling zone. It can be found that there was a downward velocity near the third row of electrodes and upward velocity in the center of bubbling zone. The velocities would cause the particles to move downward near the third electrodes and

Fig. 5 (a) Investigated region in the mathematical model (b) 2-D section view of velocity field in the cross-section of the bubbler near the bubbling zone with gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$.

then rise to the surface near the bubbler.

As the conditions between bubbling at $8.27 \text{ Ncm}^3/\text{sec}$ and without bubbling are compared, the trajectory of tracer particles at $8.27 \text{ Ncm}^3/\text{sec}$ was longer than that of without bubbling. Bubbling caused circulation, which induced the tracers to flow downwards in the vicinity of the third row of electrodes.

The flow patterns for the gas flow rates of 10.42 and $14.75 \text{ Ncm}^3/\text{sec}$ had similar to the pattern at $8.27 \text{ Ncm}^3/\text{sec}$ but with stronger circulations and larger stirring ranges in the

bubbling zone. Fig. 6(a) displays the front view and top view of the bubbles for the gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$. The left hand picture shows the bubbles being injected from the tuyeres and the right side depicts the spread range after bubbles bursting.

Figure 6(b)–(d) are the schematic illustrations of Figure 6(a) at three different gas flow rates. As the gas flow rate increased from $8.27 \text{ Ncm}^3/\text{sec}$ to $14.75 \text{ Ncm}^3/\text{sec}$, the initial diameters of bubbles increased from 1.5 cm to 2.2 cm. The diameters when bubbles reached free surface increased from 2.7 to 3.5 cm. The spread range after bubbles bursting increased from 5.2 to 6.3 cm. These results indicate that bubble stirring range would increase with gas flow rate.

Figure 7 shows the 2-D section view of the velocity contour in the cross-section of the bubbler in the bubbling zone for various gas flow rates with different colors representing different velocity ranges. The red and green sections are the higher velocity regions, which are defined as the gas stirring range in the bubbling zone. From the illustrations, it can be observed that stirring range also increased with gas flow rate. Due to the larger stirring range the trajectory of tracer particles became longer. Therefore, higher gas flow rate would result in longer trajectory. The MRT then increased with gas flow rate because of the longer trajectory as shown in Fig. 8. For the mathematical model, the furnace was first divided into 295,887 elements. As the steady state flow field was obtained for the furnace operation, tracer particles were placed underneath the inlet. The tracers were then allowed to flow with the glass melt. As the first tracer particle was detected at the outlet, the time was

Fig. 6 (a) Front view and top view of the bubbles for the gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$. (b-d) Schematic illustrations of bubbling zone at (b) $8.27 \text{ Ncm}^3/\text{sec}$ (c) $10.42 \text{ Ncm}^3/\text{sec}$ and (d) $14.75 \text{ Ncm}^3/\text{sec}$.

Fig. 7 (a) Investigated region in the mathematical model. (b–d) 2-D section view of velocity contours in the cross-section of the bubbler in the bubbling zone, which depicts the stirring range, from the mathematical model for gas flow rate of (b) 8.27 Ncm³/sec (c) 10.42 Ncm³/sec and (d) 14.75 Ncm³/sec.

Fig. 8 The relationship between gas flow rate and minimum residence time (MRT) from the physical model.

Fig. 9 The relationship between gas flow rate and minimum residence time (MRT) from the mathematical model.

recorded as the minimum residence time (MRT). The MRT results from the mathematical model are shown in Fig. 9. From the figure, it can be observed that the simulated results are all shorter than the observed ones from the physical model. However, the tendency is very similar where the MRT results from the mathematical model and physical model both increase with gas flow rate because of the longer trajectory.

3.2 Effects of electrode temperature

Figure 10 shows the flow route of tracer particles near the inlet of the physical model with the gas flow rate of 8.27 Ncm³/sec and the electrode temperatures at 25°C and 150°C. The differences in the flow patterns between 25°C and 150°C were located in the region between the inlet and the first electrode. In this figure, it can be observed that tracer

Fig. 10 (a) Investigated region in the physical model (b-c) Flow route of tracer particles near the inlet in the physical model with the gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$ and the electrode temperatures at (b) 25°C and (c) 150°C .

Fig. 11 (a) Investigated region in the mathematical model (b) 2-D section view of velocity field in the region between inlet and first electrode with bubbling at $8.27 \text{ Ncm}^3/\text{sec}$ and the electrode temperature of 150°C by mathematical modeling.

particles moved down toward to the first row of electrodes at 150°C . Figure 11 shows the 2-D section view of velocity field in the region between inlet and first electrode at the electrode temperature of 150°C by mathematical modeling. As can be seen from this figure, there was an upward velocity field near the electrode. This velocity field would drive the flow of fluid near the electrode upwards to the surface and hinder the forward velocity from the inlet. Consequently, the fluid in the vicinity of inlet started to flow downward and induced tracer particles to move downwards.

Another difference is the flow trajectory in the vicinity of the second electrode. Figure 12 displays the flow paths of tracer particles in the vicinity of the second electrode for two instants at the electrode temperature of 150°C and gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$ in the physical model. From the figure,

Fig. 12 (a) Investigated region in the physical model. (b-c) Flow paths of tracer particles in the vicinity of the second electrode for the electrode temperature of 150°C and gas flow rate of $8.27 \text{ Ncm}^3/\text{sec}$ (b) Before passing the electrode and (c) After passing the electrode.

it can be observed that some tracer particles close to the electrode would rise to the surface due to free convection induced by the heating electrode. Figure 13 shows the 2-D section view of velocity field in the scope of the electrode by mathematical modeling. An upward velocity could be found in the vicinity of the electrode. When particles were close to the electrode the upward velocity would make particles rise

Fig. 13 (a) Investigated region in the mathematical model (b) 2-D section view of velocity field in the vicinity of the electrode at the electrode temperature of 150°C and gas flow rate of 8.27 Ncm³/sec.

to the surface. Therefore, the trajectories of tracer particles at the electrode temperature of 150°C were observed to be longer than those for the electrode temperature of 25°C.

4. Conclusions

A reduced physical model and a mathematical model were constructed in this study with heating electrodes and air bubbling devices. The effects of operating conditions; mainly gas flow rate and electrode temperature, on the conditions of the flow pattern were investigated. The following conclusions are made.

- (1) The flow patterns for the three gas flow rates at 8.27 Ncm³/sec, 10.42 and 14.75 Ncm³/sec were similar. However, the stirring range, particle trajectory and minimum residence time increased with gas flow rate.
- (2) The differences in flow patterns between the electrode temperature of 25°C and 150°C were mainly located in the vicinity of the inlet and electrodes. The trajectories of tracer particles when the electrode temperature was 150°C were observed to be longer than those for the electrode temperature of 25°C.
- (3) Coupling the effects of air bubbling and electrode heating in the glass-melting furnace would enhance the melt circulation. This promotes the effects of refining and homogenization in the glass melting tank and finally enhances the quality of the glass melt.

Nomenclature

C_p	Heat capacity; J/(g·°C)
$\bar{g}$	Gravitational acceleration; cm/s ²
h	Heat transfer coefficient between fluid and wall or air; W/(cm ² ·°C)
k	Heat conductivity; W/(cm·°C)
L_{ac}	Characteristic length of acrylic model; cm
L_{gt}	Characteristic length of glass tank; cm
n	x, y, or z directions
P	Pressure vector; g/(cm·s ²)
Q_b	Flow rate of gas bubble, Ncm ³ /sec
Q_{so}	Flow rate of silicon oil; Ncm ³ /sec
Q_g	Flow rate of glass melt; Ncm ³ /sec
r_{ac}	Tuyere radius of acrylic model; cm
r_{gt}	Tuyere radius of glass tank; cm
R_b	Radius of bubble, cm
Re_{ac}	Reynolds number of acrylic model
Re_{gt}	Reynolds number of glass tank
t_b	Release time of gas bubble, sec
T	Temperature; °C
T_0	Reference temperature; °C
$T_{i,j,k}$	Temperature of (i,j,k) mesh
T_ϕ	Virtual temperature of mesh, °C
T_∞	Temperature of air or walls; °C
$\vec{V}$	Velocity vector; cm/s
β_T	Thermal expansion coefficient; °C ⁻¹
ρ	Density; g/cm ³
ρ_g	Density of glass melt; g/cm ³
ρ_l	Density of silicon oil at room temperature; g/cm ³
ρ_{so}	Density of silicon oil; g/cm ³
μ_g	Dynamic viscosity glass melt; poise
μ_{so}	Dynamic viscosity of silicon oil; poise
ν	Kinematic viscosity; cm ² /s

REFERENCES

- 1) R. A. Murnane and D. A. Nolet: Conference Record-IAS Annual Meeting (IEEE Industry Applications Society). **2** (1989) 1384–1394.
- 2) V. A. Tolstov, V. N. Kiselev, S. S. Denidova, A. V. Kas'yanova and K. A. Fomin: Glass and Ceramics. **57** (2000) 263–266.
- 3) A. Ungan and R. Viskanta: Journal of the American Ceramic Society. **69** (1986) 382–391.
- 4) A. Ungan and R. Viskanta: IEEE Transactions on Industry Applications. **22** (1986) 922–933.
- 5) P. Schill and J. Chmela: Journal of Non-Crystalline Solids. **345–346** (2004) 771–776.
- 6) C. W. Hirt and B. D. Nichols: J. Comput. Phys. **39** (1981) 201–225.
- 7) S. M. Pan, J. D. Chiang and W. S. Hwang: J. Mater. Eng. Perform. **8** (1999) 236–244.