Computer Modeling of a Glass Stream Departing from a Pour Spout Knife Edge

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Abstract

Computer modeling of a liquid glass stream departing from a vertical cylindrical pour spout was performed using three different Computational Fluid Dynamics software packages. This flow belongs to a class of free surface flows that start as a film flow on a solid pour spout wall and then turns into a cylindrical jet as it departs from the pour spout knife-edge. Two-dimensional modeling investigated the effects of the liquid Property Parameter number, film Reynolds number, pour spout surface property, and pour spout geometry. Three-dimensional modeling was also performed for low and high flow cases. The analytical results are compared with experiments using glycerin, silicone oil, and molten glass.

Introduction

The subject of this paper is the hydrodynamics of pouring molten glass. This involves a class of free surface flows that changes shape from flat film flow on a wall to a round cylindrical jet in the free fall region, which has not previously received much attention. Certain flow instabilities are encountered during this process as observed during operation of the Defense Waste Processing Facility (DWPF) Melter at the Savannah River Site. Here, highly radioactive sludge is mixed with molten glass and poured into waste canisters. The solidified glass will be stored in a repository.

The DWPF Melter has a riser connected at its bottom at one end and to a vertical pour spout at the other end (Figure 1). Pouring of the liquid glass is accomplished by applying a differential air pressure between the Melter plenum and the pour spout. The glass overflows a weir and flows down a vertical 50.8 mm ID cylindrical pour spout as a lens-shaped film. A sharp knife-edge aids separation of the liquid from the spout wall.

At low flows, the glass stream breaks up into droplets or strings out into thin fibers, which impairs the quality of the solidified glass. At slightly higher flows, the glass stream moves side to side around the cylindrical pour spout knife-edge. Then a region of stable flow is reached. At still higher flows, the departing flow stream bends backwards towards the underside of the spout, similar to the well known “tea pot effect”. If the deflection is large enough, the glass stream contacts internal hardware, leading to flow-blockages that disrupt melter operation. It would be highly useful if the physics of pouring molten glass is well understood. Further, optimum melter operation would be achieved if analytical methods can be developed to be able to predict the flow behavior for varying glass properties, steady and transient flow ranges, changing pour spout geometry due to wear, and alternate pour spout designs.

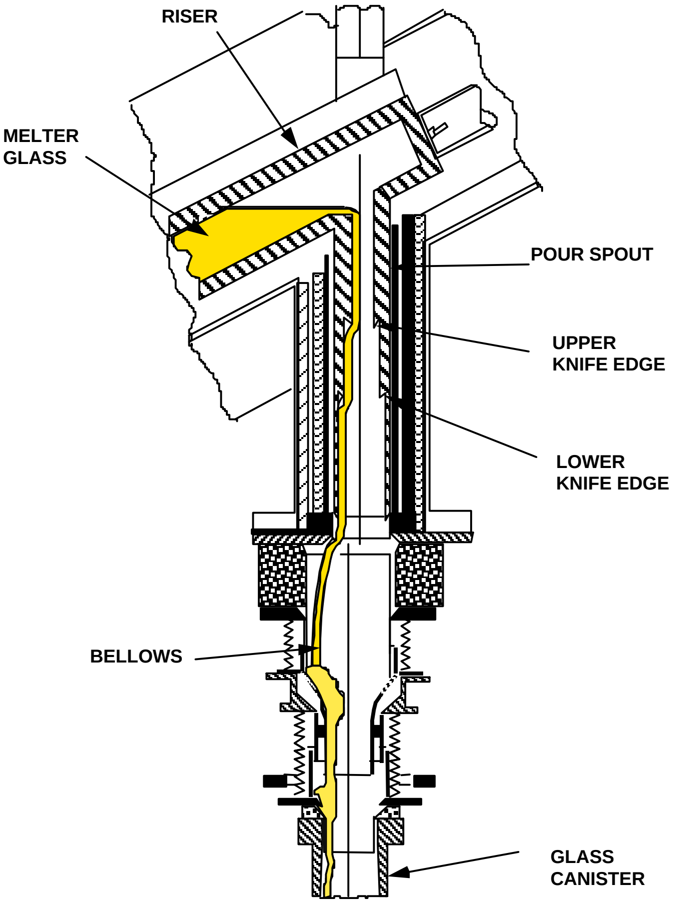


Figure 1 Deflection of Glass Stream During Pouring Process of the DWPF Melter

Previous Studies

Pritchard [1] reported visual observations of liquid being poured over the end of a flat plate inclined at a small angle from the horizontal. He uncovered multiple flow instabilities where a stable flow sheet flowing over the plate turned into several round streams when the flow was slightly reduced. Upon further flow reduction, the streams turned into droplets. Kistler and Scriven [2] performed experiments and two-dimensional finite element modeling of coating flows common in the plastics industry. They investigated the flow of a thin film of liquid over a vertical flat plate which separated from the plate downstream of a sharp knife-edge. They then used the method of spines to predict the configurations of the free surfaces at the wall and in the free fall region. As a result, they were able to predict the deflection profile of the exiting stream as a function of film Reynolds number, liquid Property Parameter value, angle of orientation of the wall, and knife cut-back angle, which was confirmed by test results. The two-dimensional finite element analysis results also provided proof that the mechanism for bending of the exit stream (the "teapot effect") is due to the interplay of viscous, inertial, gravity, and capillary forces. Bending of the stream occurs because the fluid velocity profile changes from parabolic at the wall to plug flow in the freely falling stream. (See Figure 2.) The momentum change results in a torque that bends the flow stream towards the wall direction. Surface tension and gravity act to restore the flow into a vertical stream.

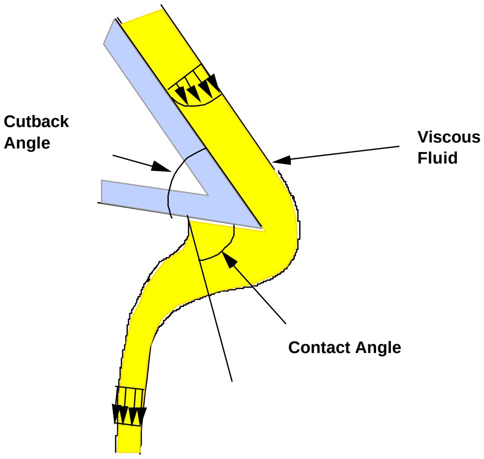


Figure 2 Bending of Exiting Liquid Stream Due to Hydrodynamic Forces

Both the Pritchard and the Kistler and Scriven studies were concerned with basically two-dimensional sheet flows, while the present problem is inherently a three-dimensional one. Here, the nominally flat free surface at the wall region turns into a curved cylindrical surface in the free stream after going through a complicated triangular shaped transition region. The flow also accelerates in going from film flow at the wall to the small round freely falling stream, while in sheet flows the velocities in the two regions do not vary significantly. Further, the surface property of the cylindrical pour spout can be highly influential as it can lead to a wide thin film for a wetting surface or a narrow thick film for a non-wetting surface for the same flow rate.

Theoretical Considerations

Analysis of the glass pouring process, as well as physical modeling efforts with other more convenient liquids, must consider the effects of the following parameters:

- liquid physical properties,
- flow conditions,
- solid wall surface property, and
- pour spout geometry.

First, liquid viscosity affects the parabolic velocity profile at the wall, which is directly related to the momentum change force. Surface tension determines the diameter of the freely falling stream and together with gravity act to restore the bending stream to a vertical path due to curvature of the bending stream. If the inertia force is low enough, surface tension can lead to breakup of the stream into droplets. The effect of liquid properties is represented by the Property Parameter number, $N_s = \sigma / [(4\mu)^4 g / \rho]^{1/3}$, where σ is the surface tension; μ, viscosity; and ρ, density.

Second, flow velocity and film thickness directly affect the momentum change effect. Inertia will also counter capillary effects. The effect of flow conditions is given by the film Reynolds number, $\mathrm{Re} = Vh\rho / \mu$, where V is an average film velocity, and h, an average film height.

Third, pour spout surface property as it relates to wetting of the liquid, together with liquid viscosity and flow velocity, determine the liquid film width and height. Wetting of the knife-edge can also possibly lead to advance of the liquid over the backside of the knife-edge by capillary effect. The effect of pour spout surface conditions is provided by the liquid contact angle. The contact angle is the angle that the liquid free surface makes with the solid wall at the point where the three phases (including air) meet.

Fourth, the orientation of the pour spout surface as it may be affected by design or wear, i. e., whether the film flow is vertical, inclined forward, or inclined backward, must also be considered. Flow orientation affects the flow trajectory in the case of high velocity.

Flow Modeling

Computer Modeling

To understand the physical mechanisms of the pouring of molten glass with entrained solid particles, an analytical study was initiated in conjunction with experiments. This involved the use of three different Computational Fluid Dynamics (CFD) codes to select the most suitable analytic tool. The first was FIDAP's Free Surface Model. This was a two-dimensional finite element model using the method of spines, similar to the work of Scriven and Kistler. Experience with this model entailed extreme difficulty of convergence of the solution for the freely falling stream. This was due to the need for constant re-meshing for large deformations of the front and back free-surfaces, which have the potential for crossing. We have also utilized the two- and three-dimensional capabilities of the Filling Model in FIDAP, which uses the Volume of Fluid (VOF) method, to be described later. Second, we applied NEKTON, a spectral element CFD code, used extensively for laminar flows in the glass industry. The spectral element method is a higher order finite element method, which has the potential for solving three-dimensional problems with fewer elements than traditional finite element methods. Third, we used the VOF model in FLUENT. Selection of a code would depend on its capabilities in solving the large free surface deformations of our present problem and its accuracy considering the effect of surface tension and contact angle.

The VOF method is described briefly, as follows: Within a specified computational grid, two different immiscible fluids A and B exist. Sharp gradients in the characteristic concentration of fluid A represent the free surface of the fluid. The method tracks the motion of the free surface through the elements in time, implying a transient problem. In fact, the VOF method is used extensively in mold filling problems. Its advantages include the possibility of large deformations of the free surface of a liquid not feasible with other approaches. Also, forces such as surface tension are allowed.

Due to computer memory limitations, the 2-dimensional and 3-dimensional models were limited to flow-regions, 70 mm above the knife-edge and 70 mm below the knife-edge as shown in Figures 3-6. The upper spout wall had an incline of 3^o towards the lower wall to represent wear. A uniform flow of liquid was introduced at the top end of the model through a slot. The film thickness adjusted until a stable film velocity profile was established. The vertical film flow distance to the knife-edge was found to be sufficient to establish stable film flow before reaching the knife-edge for initial flow velocities up to 0.3 m/sec. The inlet and outlet were set as constant pressure boundaries. Model cases were solved as transient problems.

The glass contains solid radioactive particles with up to 25% by weight loading. This solid-liquid mixture is considered homogeneous. Together with the chemistry of the glass (oxidizing or reducing), the effect of the solids in the glass is reflected in the mixture viscosity and surface tension. The liquid properties were entered into the codes as primitive variables and were changed to vary the N_σ and Re parameters.

Experimental

Glycerin and silicone oil were used to simulate glass in low temperature tests. At room temperature (21^oC), the liquid properties of glycerin are: viscosity, 2.3 $N\text{-}s/cm^2$; surface tension, 0.06 N/m; and density, 1260 Kg/m^3, resulting in a N_σ value of 0.016. This is equal to the N_σ value for glass with a viscosity of 7 $N\text{-}s/m^2$. The silicone oil had a viscosity of 10 $N\text{-}s/cm^2$, surface tension of 0.021 N/m, and density of 960 Kg/cm^3, resulting in an N_σ value of 0.0008. The test loop included a full scale, clear Plexiglas mockup of the DWPF Melter pour spout, a liquid reservoir and circulating pump. The thickness of the film, and deflection profile of the departing stream, were measured with micrometers.

Limited test results are also available from ongoing model melter tests using a laboratory scale melter and a full-scale pour spout mockup. Glass simulant is used similar to the radioactive glass, but without the radioactive particles. Video cameras provide images of the glass stream from which measurements of the glass film width and falling stream diameter and deflection are obtained.

Results

Two-dimensional Modeling

a. Effect of Reynolds Number

The effect of Reynolds number was investigated by using FLUENT. Figures 3 - 5 shows the flow profiles for Reynolds numbers of 0.0063, 0.211, and 0.63. The N_σ value for these cases is 0.022 representative of glass with surface tension of 0.3 N/m, viscosity of 7 $N\text{-}s/m^2$, and density of 2500 Kg/m^3. At Re=0.0063, the liquid film forms a rounded leading edge at the knife-edge, elongates downstream of the knife-edge, and finally breaks off as a drop.

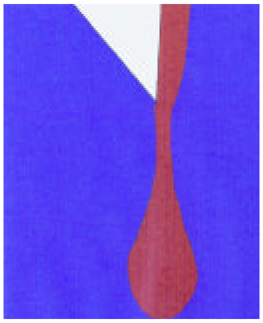


Figure 3 2D Glass Stream Configuration for Re=0.0063 Predicted by FLUENT

At Re=0.211, Figure 4, the profile is quite different. The liquid sheet departing from the wall bends backward towards the downstream wall for a distance of 3.7 mm, before dropping vertically.

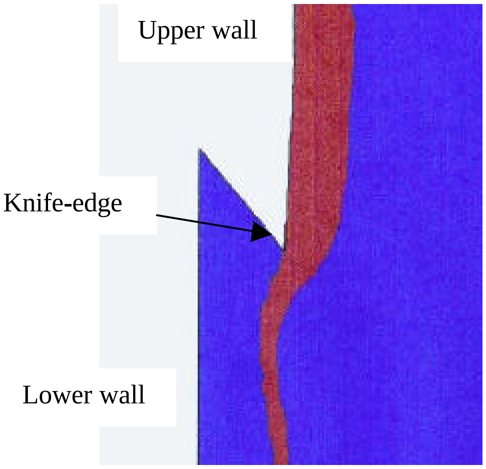


Figure 4 2D Glass Stream Configuration for Re=0.211 Predicted by FLUENT

Figure 5 2-D Glass Stream Configuration for Re=0.63 Predicted by FLUENT

At Re=0.63, Figure 5, the attached film on the pour spout has grown and its backwards deflection is sufficiently large for the sheet to contact the downstream wall, a 10.2 mm horizontal distance from the knife edge.

b. Effect of N_σ Parameter

The effect of the N_σ parameter was also investigated, using FLUENT. The surface tension was changed to a value of 0.06 N/m., the viscosity to 1.57 N/s-m^2 and density to 790 Kg/m^3, which are not too far from the properties of glycerin. The resulting N_σ number is 0.022, close to that of glass. Figure 6 shows the flow profile for Re=0.211. Maintaining the N_σ and Re numbers clearly maintains the geometric shape of the stream. However, the absolute value of the deflections relative to that of glass must be based on the ratio of kinematic viscosities raised to the 2/3 power, as discussed in the Experimental Results section.

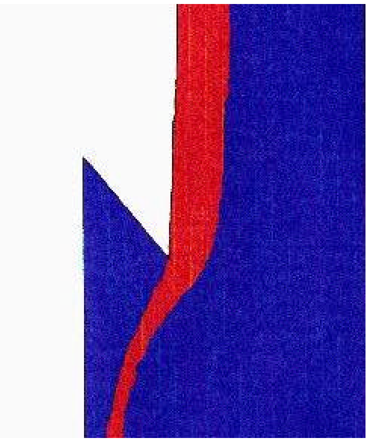
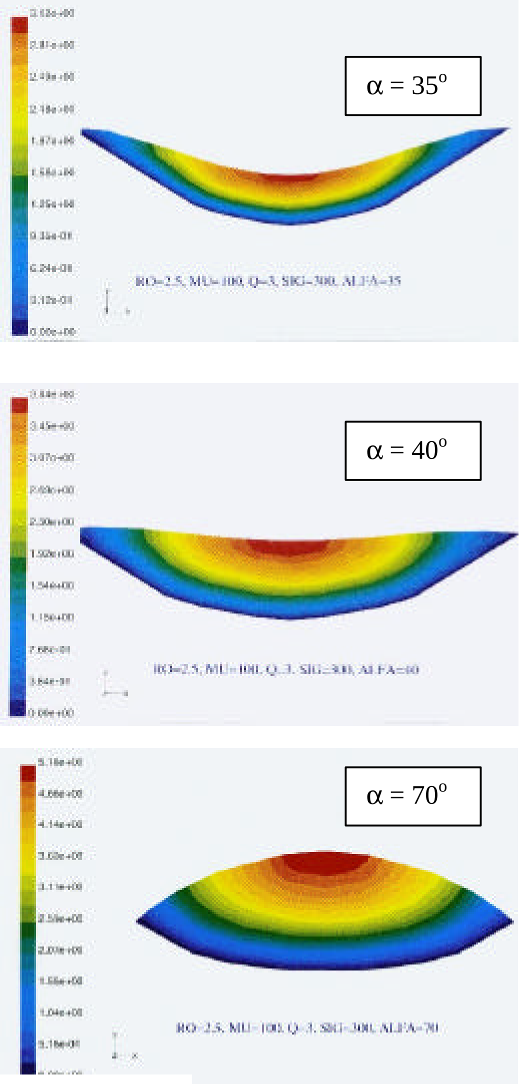


Figure 6 Effect of N_σ Parameter at Re=0.211

c. Effect of Contact Angle

The influence of contact angle that the liquid makes with the solid pour spout surface is manifested in the width and thickness of the film. The thicker the film, the larger is the viscous force term in the torque equation that determines the deflection of the free falling film. NEKTON was used in 3-dimensional models of the liquid on the pour spout. For the same volumetric flow of 3 cm^3/sec, Figure 7 shows the effect of changing the contact angle from 30^o to 60^o. The maximum thickness of the lens-shaped film increases as the contact angle is increased. The peak velocity in the stream also increases since the flow area constricts with contact angle.



Velocities in cm/s

Figure 7 Effect of Contact Angle α on Glass Stream Shape and Velocity, as Predicted by NEKTON

The above results are summarized in Table 1. The table gives the maximum stream width, maximum film height, average velocity for the three contact angles. The maximum film width increases by 92% and the average velocity increases by 60% in decreasing the contact angle from of 35^o to 60^o.

Table 1
Effect of Flow Velocity for a Contact Angle of 40°

Contact Angle, degrees	Max. Width, cm	Max. Height, cm	Ave. Velocity, cm/s
35	4.8	0.56	1.51
40	3.7	0.62	1.87
60	2.5	0.70	2.42

d. Effect of Pour Spout Orientation

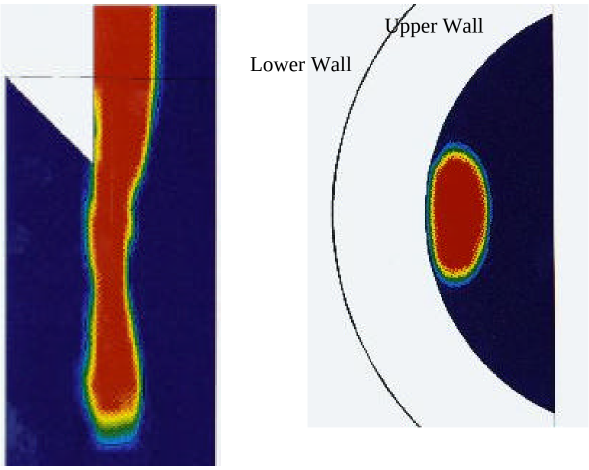
The effect of orienting the pour spout surface along the vertical was investigated at Re=0.63. The resulting deflection profile downstream of the knife-edge was similar to that with a 3° backward slope. A stronger effect may possibly be evident for a larger slope or with the three-dimensional case.

Three-dimensional Modeling

FIDAP was used initially to perform 3-dimensional modeling of the pour spout, utilizing their Filling Model. The flow was set at 8.5 cm^3/sec, density at 2500 Kg/m^3, viscosity at 10 N/m-sec^2, and surface tension at 0.3 N/m. A contact angle of 60 degrees was specified.

Figure 8a shows a cross-section of the flow through the vertical centerline of the spout. A horizontal cross-section just above the knife-edge (Figure 8b) shows the flow to be oval. The contact angle with the curved wall is apparently an obtuse angle and does not agree with the specified value. A horizontal cross-section just below the knife-edge shows the flow to be turning to a round stream.

FLUENT was also used to perform 3-dimensional modeling utilizing their VOF Model. In this case, a low flow was set at 0.1 cm^3/s, the density at 2500 Kg/m^3, viscosity at 7 Kg/m-s, and surface tension at 0.3 N/m and contact angle at 30°. Figure 9 shows an elongated stream with a rounded leading edge that has just passed the knife-edge. Wetting of the knife-edge back surface is apparent, where a contact angle of 30° is maintained. The figure also shows the stream starting to break up where the front and backside free surfaces are pinching together.



(a) (b)

Figure 8 Vertical (a) and Horizontal (b) Cross-sections Predicted by FIDAP for a Glass Flow of 8.5 cm^3/s

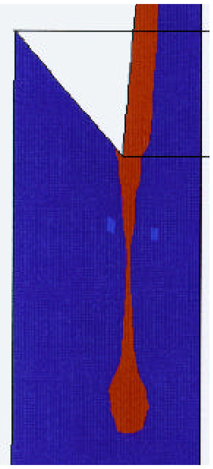
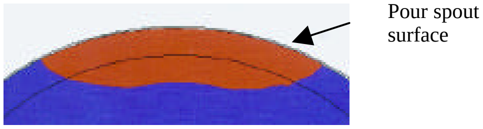
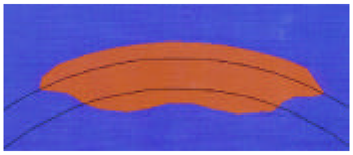


Figure 9 Vertical Cross-section of Glass Stream Predicted by FLUENT for a Flow of 0.1 cm^3/s

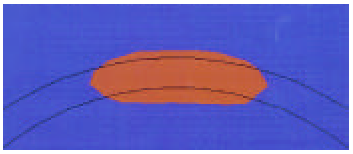
Figure 10a gives a cross-section of the flow just before the knife-edge; Figure 10b is a cross section just at the knife-edge; and Figure 10c shows the stream collecting into an oval shape



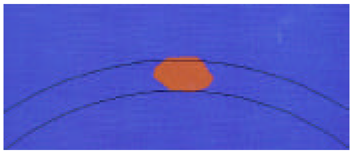
(a) Upstream of knife-edge



(b) At the knife-edge



(c) 4.2 mm downstream of knife-edge

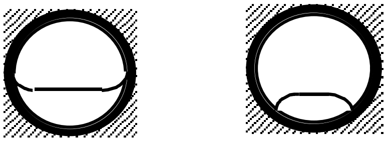


(d) 38 mm downstream of knife-edge

Figure 10 Horizontal Cross-sections Predicted by FLUENT for a Glass Flow of 0.1 cm^3/s downstream of the knife-edge. Finally, Figure 10d shows constriction of the falling stream into a round cross-section.

Experimental Results

The tests with glycerin and silicone oil show some of the distinctly different effects of flow, viscosity, and contact angle. Figure 11 illustrates the shape of the film on the pour spout surface for glycerin and silicone for the same flow rate of 16 cm^3/s. Due to the high viscosity of silicone, the film thickness is about double that for glycerin. This is also shown in the plot of Figure 12, where the film thickness is plotted for a range of flow rates for the two liquids. The film width for glycerin is narrower than for silicone oil, because glycerin has a 60^o contact angle with the Plexiglas spout compared with the highly wetting contact angle of silicone, approximately 30^o.



Silicone Oil
16 cm^3/s, 10 N-s/m^2

Glycerin
16 cm^3/s, 2.3 N-s/m^2

Figure 11 Shapes of Silicone Oil and Glycerin Films on Pour Spout Surface

Stream deflection measurements for glycerin are summarized in the plot of Figure 12. Here, the deflection profiles of the falling glycerin stream (back surface) are plotted for a number of Reynolds numbers. The horizontal and vertical displacements, H* and L*, have been normalized by the factor $Lo = [4(m / r)]^{2/3} g^{-1/3}$ to allow comparison with other fluids. Thus, dimensions in a glass system would be 1.33 times those in a glycerin system. In comparing the 2-D glass results and the glycerin test results at the same Reynolds number and N_σ number, it is observed that the measured glycerin deflections are much higher than expected from the 2D FLUENT results. This is due to the accelerating flow of the 3-dimensional glycerin stream as it narrows into a pencil thin round stream. The higher glycerin velocity increases the momentum change going from the wall to free space; and thus, a larger torque results in a larger deflection than the 2-D sheet flow results. The silicone oil test showed very little horizontal deflection for the same flow range.

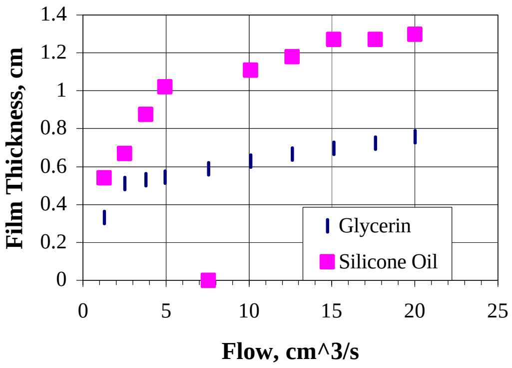


Figure 12 Film Thicknesses for Silicone Oil and Glycerin As a Function of Flow

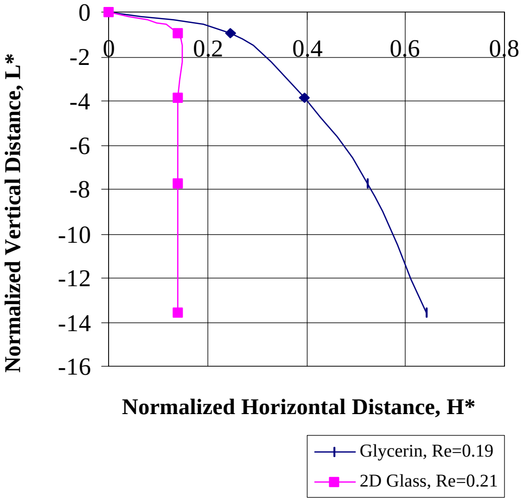


Figure 13 Displacement Profiles for Freely Falling Glycerin Stream as a Function of Reynolds Number

A photograph of a glass film on the pour spout wall and the departing stream during a recent glass-pouring test is shown in Figure 14. The free surface of the glass film is flat due to its high surface tension. The edges of the glass stream turn concavely to meet the pour spout wall at a contact angle of approximately 30^o. This behavior is very similar to that of the silicone oil test.

Discussion

In comparing the three CFD code packages, the observation is that each package works well for a particular area. The NEKTON code does a creditable job for 3-dimensional modeling in the pour spout wall region, but becomes exceedingly unwieldy in the free falling stream region. The FIDAP VOF model works well for 2D problems but suffers inaccuracies for 3D problems because its contact angle option was not working. The FLUENT VOF model provided the most reasonable 3D results, simulating the effect of small contact angle for glass. Thus, it would be our analytical tool of choice for future work.

Two-dimensional modeling is not a good approximation for the actual 3-dimensional flows because of the large change in flow areas and velocity profiles as the flow goes from film

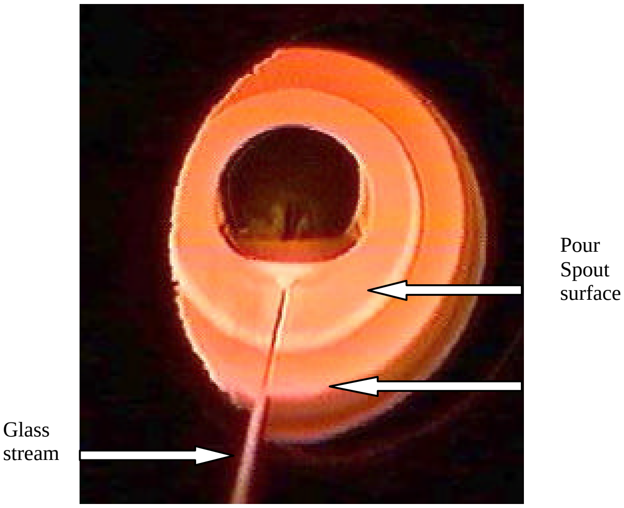


Figure 14 Photograph of Glass Flowing Over an Inconel Pour Spout (Looking Up)

flow to freely falling stream and free surface differences between coating flows and pour spout flows. Two-dimensional modeling would however be useful for determining qualitatively the effects of different parameters.

The results of the experiments with surrogate liquids such as glycerin and silicone oil can not be directly related to expected behavior for glass. This is because, even if the Re and N_σ numbers are matched, contact angle, which has been shown to be important, is difficult to match. However, the glycerin and silicone oil results would provide a good test for benchmarking computer codes.

The cause of the large glass deflections in the DWPF Melter has not been determined with the current experiments and analyses. More extensive three-dimensional modeling needs to be done to investigate effects such as pour spout wear and transient flow conditions.

Conclusions

Two-dimensional and three-dimensional computer modeling of the flow of a liquid down a cylindrical pour spout surface, separating from it, and falling freely in space was performed using three different CFD software packages. The effects of Reynolds number, Property Parameter number, and contact angle were qualitatively similar to those found in experiments with glycerin, silicone oil, and glass. From the current work so far, it appears that CFD software packages such as the FLUENT Volume of Fluid Model with its capability to include surface tension and contact angle has the best potential to provide a realistic simulation for the flow of glass over a pour spout.

References

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2. Kistler, S.F., and L.E. Sriven, “The Teapot Effect: Sheet-forming flows with Deflection, Wetting, and Hysteresis,” J. Fluid Mechanics (1994), Vol. 263, pp. 19-62.