An Analysis of Plunger Temperature during Glass Parison Pressing

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Abstract: The press and blow (P&B) process is widely used to produce glass containers. The process consists of first driving a metallic plunger upward into the molten glass gob, squeezing the glass into the gap between the plunger and the mold (the bore) to form the parison (pressing-Figure 1). This is then followed by plunger removal, parison inversion and the blowing of air into the parison cavity (blowing). While the P&B process has demonstrated to be capable of reducing container weight by as much as 33% [1], it can also induce the formation of micro-checks that weaken container strength. It is now generally acknowledged that plunger temperature is critical for proper operation of the process. Therefore, in current operation, plungers are subjected to internal air cooling. As the glass industry moves towards fully automated forming machines, it is necessary to understand what happens to a plunger during many press cycles. This paper presents a model of the heat transfer due to the intermittent contact of glass with the plunger during several pressing cycles using COMSOL Multiphysics. The model produces the full thermal history of the plunger and shows how different plunger cooling schemes and other operating variables may affect the plunger temperature over time.

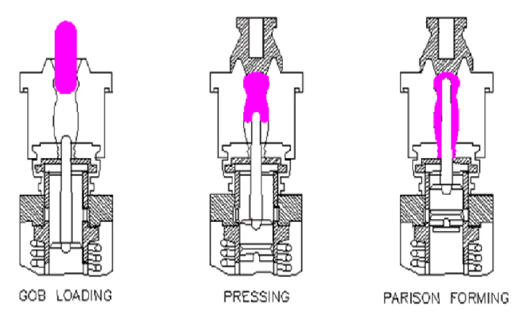

Figure 1. Sketch of the glass pressing process

Keywords: container forming, heat transfer, press and blow, glass, plunger cooling

1. Introduction

As shown in Figure 1, the plunger is in intimate contact with the glass from the moment the gob is loaded to the instant the mold opens for parison invert and subsequent blowing. During the glass contact time, the glass covers the plunger only up to the neck ring line. Plungers (Figure 2) are made out of alloy steel and usually coated with tungsten carbide [1]. Every precaution is taken to prevent the glass from sticking to the plunger to avoid creating defects. Therefore, internal plunger cooling using air is critical for process control. In this study, we look at a narrow neck press and blow (NNPB) plunger currently used at the Emhart Glass Research Center (EGRC) in Windsor, CT. In our analysis we will not solve for the flow of glass into the plunger-mold gap but examine instead the thermal interaction between the inside cooling and the outside heating of the plunger by the hot gob. Results for both 2D axisymmetric and full 3D plunger models will be presented.

Figure 2. EGRC Plunger

Nomenclature

x	x-coordinate
y	y-coordinate
z	z-coordinate
r	radial coordinate (2D)
h	film coefficient
$h_{plunger}$	film coefficient on plunger bore
T	temperature variable
T_∞	ambient temperature
t	time variable
T_{glass}	initial glass temperature
$T_{plunger}$	temperature at plunger bore
k	thermal conductivity
Cp	Specific heat
$zs(t)$	glass front position function
α	thermal diffusivity
ε	emissivity of glass = 0.7
σ	Stefan-Boltzmann's constant 5.6696E-08 $W/m^2 \cdot K^4$ [5]
ρ	density

2. System Description

2.1 Model Geometry

As shown in Figure 2, the plunger has the shape of a hollow tapered pipe closed at one end with a hemispherical cap and with a length of approximately 180mm, an inner radius of 10mm with 2mm thick walls on average. The 2D axisymmetric and full 3D model geometries of the plunger were imported as IGES files from an existing ProE model. The resulting 3D and 2D axisymmetric model geometries are shown in Figures 3 and 4 respectively. The z-axis is the vertical direction in the 2D axisymmetric model while the vertical direction coincides with the y-axis in the 3D model. The surfaces inside and outside the plunger constitute the main model boundaries from the heat transfer point of view. All other boundaries are regarded as insulated

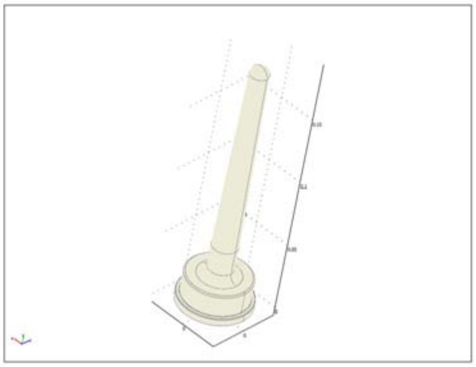

Figure 3. 3D EGRC Plunger Geometry

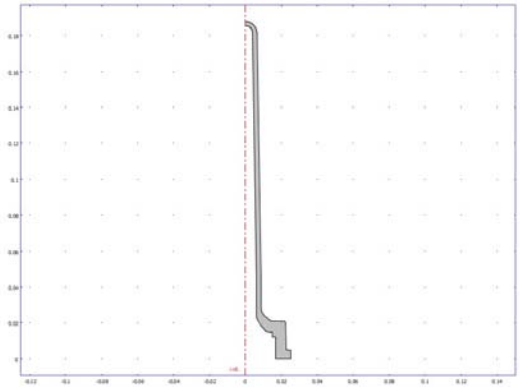

Figure 4. 2D Axisymmetric Plunger

2.2 Governing Equations

The calculation of the time-dependent temperature field inside the plunger wall requires solving the heat equation.. For constant values of the thermo-physical properties this is given by [2] :

$$\alpha \cdot \nabla^2 T = \frac{\partial T}{\partial t}$$

Where $T = T(t, x, y, z)$ is the temperature as a function of time and space, and

$$\alpha = \frac{k}{\rho \cdot Cp}$$

The physical property values used in our calculations correspond to AISI 4340 steel and are

$$k = 44.5 \frac{W}{m \cdot K};\ \rho = 7850 \frac{kg}{m^3};$$

$$Cp = 475 \frac{J}{kg \cdot K}$$

For the 2D axisymmetric plunger the heat equation becomes

$$\alpha \cdot \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t}$$

and for the 3D plunger it is

$$\alpha \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t}.$$

2.3 Global Assumptions

In order to simulate the heat flow due to contact with the deforming glass gob down the plunger length, we define functions that shift the heat flow down the vertical axis simulating the relative motion of the glass and the plunger. In accordance with practical experience, we will assume that it takes one second for the glass to cover the plunger up to the neck ring line, and one second is also the time between presses when the plunger is not in direct contact with the glass. Hence, we are defining a two second cycle where the plunger is subjected to conductive and radiative heat transfer from the glass while being cooled from the inside. Then, it is subjected to inside cooling, thermal radiation and some natural convection. We assume the initial glass temperature to be uniform T_{glass} = 1273K [3]. To simulate the ongoing contact between the glass and the plunger, we introduce the function $zs(t)$; the function becoming zero for the part of the cycle when the plunger is no longer in contact with the glass

$$zs(t) = 0.181367 \cdot \left| \left(\sin\left(\frac{\pi}{2} t \right) \right) \right|$$

This function is shown in Figure 5

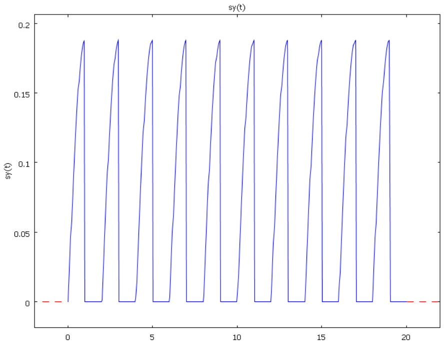

Figure 5. Function zs(t)

3. Boundary Conditions

The boundary condition along the inner wall of the plunger is determined by the forced convective cooling used to control the plunger temperature. Along the body, the assumed boundary condition was

$$\vec{n} \bullet \left(k \cdot \vec{\nabla} T \right) = h \left(T_\infty - T \right)$$

where $h = 250 \frac{W}{m^2 \cdot K}$, $T_\infty = 350K$

On the tip, the same boundary condition is used but with $h = 500 \frac{W}{m^2 \cdot K}$ because of the direct impingement of the cooling air on the tip.

Along the outer plunger wall (bore side) the boundary condition requires accounting for convective as well as radiative heat transfer, i.e.

$$\vec{n} \bullet \left(k \cdot \vec{\nabla} T \right) = h \left(T_\infty - T \right) + \varepsilon \sigma \left(T_{glass}{}^4 - T^4 \right)$$

where

$$h = h_{plunger}(z - 0.05 + zs(t)) \quad \text{(Figure 6)}$$

and

$$T_\infty = T_{plunger}(z - 0.05 + zs(t)) \quad \text{(Figure 7)}$$

These two functions are used to simulate the intermittent contact of glass with the plunger. Recall also that the argument in the functions above in the 3D case is not z but the y-coordinate direction.

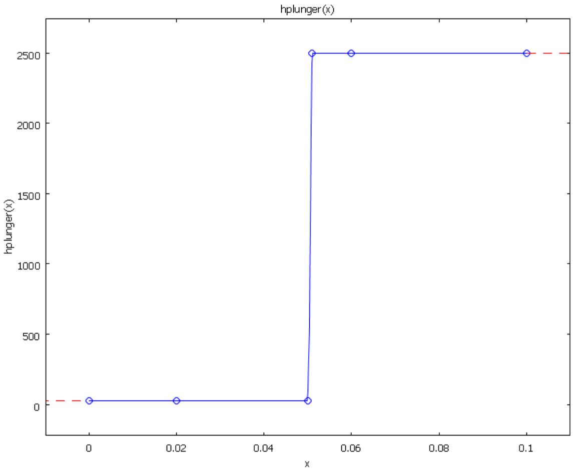

Figure6 . $h_{plunger}(z)$

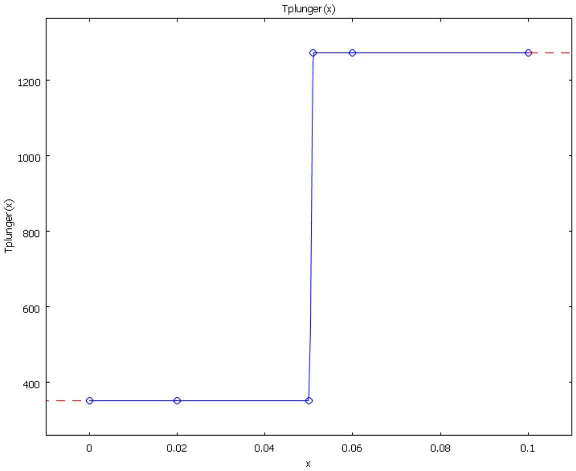

Figure 7. $T_{plunger}(z)$

4. Mesh and Solution

Both models were meshed using free mesh parameters in COMSOL Multiphysics followed by selective refinement (Figures 8 and 9). A plunger initial temperature of 773K was assumed (typical for standard beer bottles). The 2D axisymmetric model involved 392 elements while the 3D model consisted of 23705 elements. Both models were run for ten pressing cycles. Care is needed in selecting the time step in the solver in order to insure accurate capture of temperature variation within each cycle. Although the results for both models were fairly similar, execution time for the 3D model was two orders of magnitude longer than for the 2D model. The computed temperatures at the tip of the plunger for both 2D and 3D models are shown as functions of time in Figures 10 and 11 respectively. After a rapid initial transient, the plunger tip temperature appears to level off although the fluctuations associated with the intermittent contact with the hot glass remain. Figure 12 shows the computed temperature field in the plunger after 10 pressing cycles. From the computed results we have established that our models were at least qualitatively in good agreement with experience.

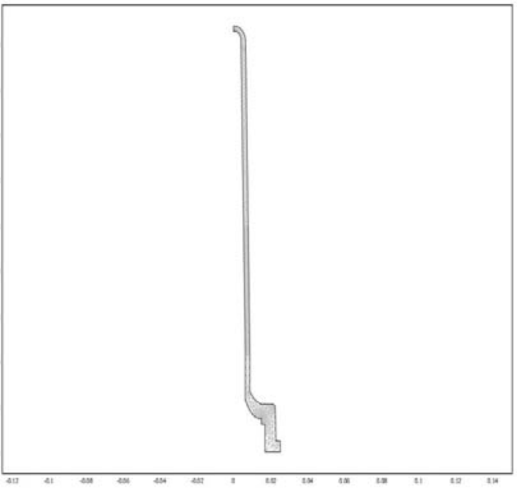

Figure 8. 2D axisymmetric plunger mesh

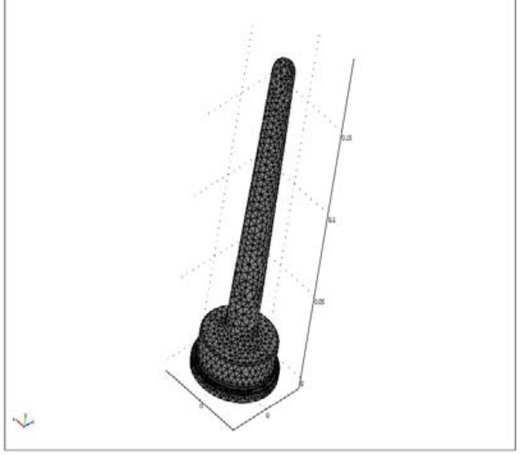

Figure 9. 3D plunger mesh

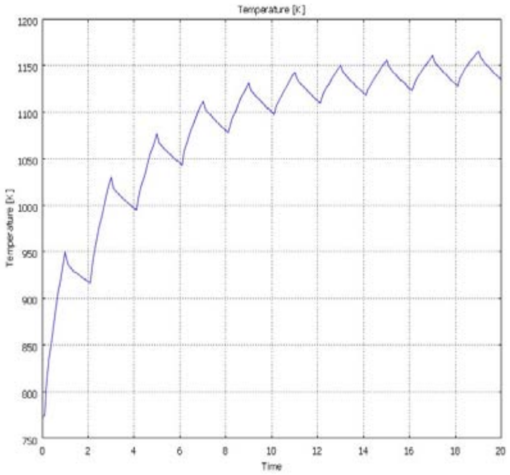

Figure 10. Computed plunger tip temperature (2D model)

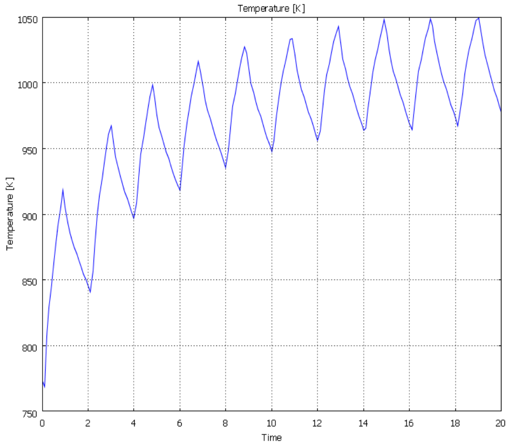

Figure 11. Computed plunger tip temperature (3D model)

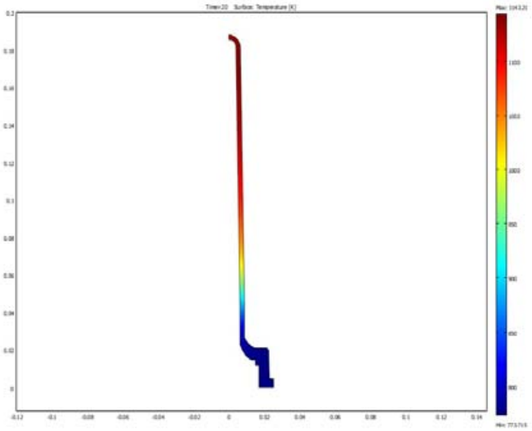

Figure 12. Computed Temperature Field

5. Discussion of Results

The results show that the plunger heats up from cycle to cycle but at decreasing rate, especially in the region near the tip, which is usually the hottest part of the plunger since it is in contact with the gob for the longest amount of time. Because of the large temperature gradients involved there this region also often becomes the site where fracture occurs. After numerous cycles the plunger may heat up to the point where the gob begins to stick; this is an undesirable process condition that must be carefully controlled to ensure longer plunger life. Although many assumptions are made in our model (such as constant heat transfer coefficients and thermal properties) which may be only approximately valid in the glass plant, the results obtained seem rather reasonable and in good agreement with practical experience. A sufficiently fine mesh is required to properly resolve the temperature gradient inside the plunger thickness. The results obtained are also dependent on the cycle time, and type of container. A standard light beer bottle usually has lower heat content and faster cycle time than would a typical wine bottle. Glass type can be a factor since green and amber glasses do not radiate heat as well as flint glass [3], these and several other important issues will be subject of future study.

6. Conclusion

The COMSOL model has provided useful insight into the glass pressing process examined here, but it is only the starting point for our analysis. We could tailor the model to include different types of inside cooling, more realistic process timing and more accurate heat flux data from the field. It would also be interesting to see how a larger container production would be affected in comparison to light weight container. Last but not least, we would want to evaluate the thermal effects on all mold equipment, to acquire more control over the process. This could help increase production speed by eliminating the reliance on adjustments based on observation of defects in the containers.

7. References

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