FROM GOB TO BOTTLE: BOTTERO SIMULATES THE COMPLETE GLASS FORMING PROCESS

SIMONE FERRARI
Bottero S.p.A.

INTRODUCTION

Glass container production is generally not an easy process to operate and companies often need to invest a significant amount of time and money to ensure they deliver products with appropriate quality. Glass is indeed a material that exhibits an extremely complex behavior often difficult to predict during manufacturing and, until now, the tuning of the production parameters has been completely bound to the operator's experience.

To overcome this sticky situation, Bottero, a process-oriented company operating worldwide in the glass machinery field, has developed a simulation-based methodology in cooperation with university laboratories and production experts. The aim of this work is to provide the glass plants with the necessary support for manufacturing of tools to ultimately achieve a drastic reduction in time required for starting up a process.

Computer simulations are not only useful to gain a better insight and assist in designing optimal bottle shapes, they also offer a good alternative to time-consuming and expensive trial and error procedures commonly encountered by

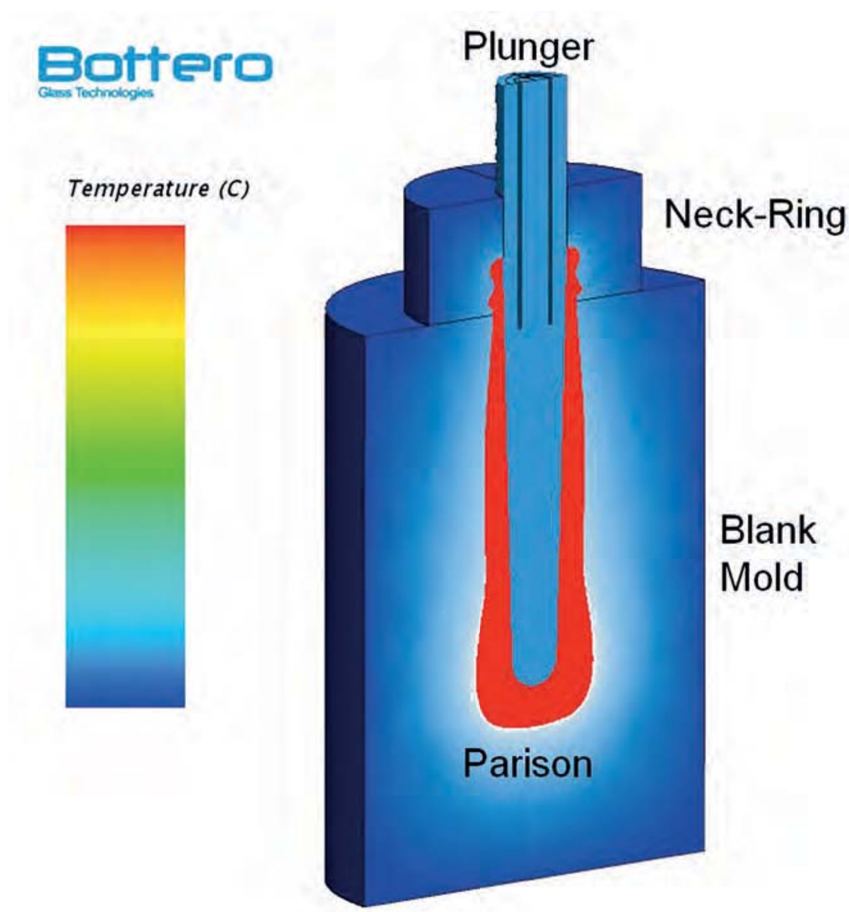

FIGURE 1: Three dimensional temperature distribution of the parison as it is created in the blank mold

factories. Representative numerical simulations can help minimize unwanted variations in wall thickness of containers and reduce their weight while maintaining their strength. Simulations also are extremely valuable in optimizing cooling conditions and increasing the production speed. All this has the potential to significantly decrease the cost of the glass manufacturing process.

THE GLASS CONTAINER FORMING PROCESS

During the process, the container is first formed into an intermediate shape, called the "parison", and then blown into its final shape. Depending on the different ways of forming the parison, two glass processes exist: the "blow & blow", where the parison is formed using compressed air, or the "press & blow", where the parison is mechanically formed with the use of a plunger. Here, the "press & blow" process has been studied and simulated.

When the molten glass leaves the furnace, its temperature is over 1400°C as it goes through the foreheart and then the feeder and is cut into uniform gobs of glass by a shearing and distribution system. After this, each gob is sent to an individual section forming machine where the temperature drops below 1200°C, and the gobs are forced to take the mold shape. The forming machine consists of two sets of molds called the "blank" and "blow" mold.

First, in the blank mold, the gob drops from above and is pressed into the mold shape, forming a thick-walled pre-form or parison. This parison is then removed by a robotic arm from the blank mold, turned upside down and transferred to the second (blow) mold. At this moment, the pre-form starts to stretch towards the bottom of the mold due to gravity. Finally, pressurized air is injected and a vacuum is created to inflate the parison into the final bottle shape. The container is then transferred to an annealing oven where reheating removes the stress produced during forming. After this, the container is cooled under controlled conditions and the process is complete.

THE NEED OF SIMULATIONS FOR GLASS FORMING

The glass forming process involves high temperatures, and it is extremely sensitive to changes in machine timing, glass composition and environmental conditions. As it is nearly impossible to physically visualize what really happens inside the molds during the different phases, numerical simulation is the only tool available to help better understand the details of the physics as they occur during the process.

In this work, the results of the simulation are validated experimentally by comparing infrared surface temperature measurements of both glass and equipment and inspecting the final container, the glass distribution (wall thickness) and the presence of possible defects.

In building the simulation methodology, close attention was paid to ensure that the most realistic model possible was used. This means that approximations in the simulations were limited and that the glass forming process was modeled as a tightly coupled thermo-fluid-dynamic process.

In the process, the hot glass yields heat to the molds through conduction and radiation and the glass is only partially emitting/absorbing the infrared light.

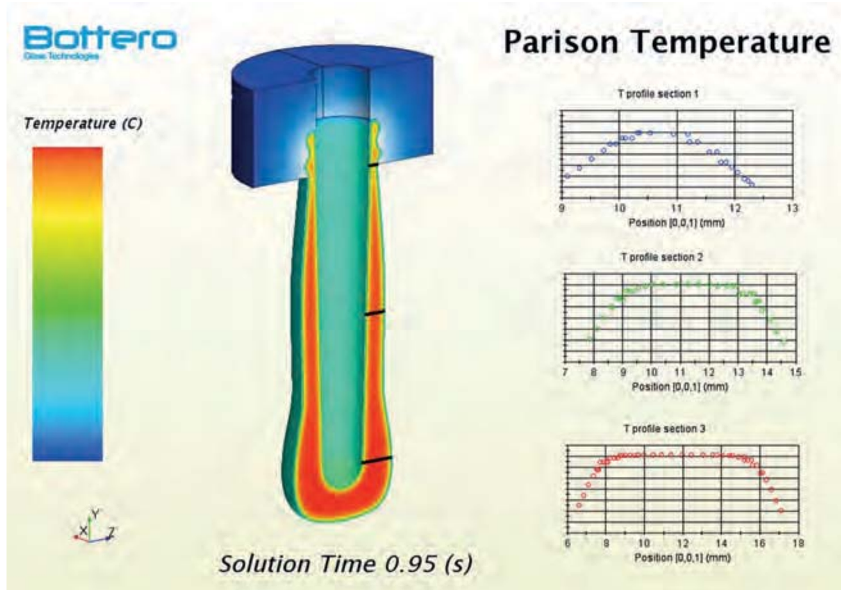

FIGURE 2: Detailed 3D temperature model of the parison, showing realistic vertical temperature trends

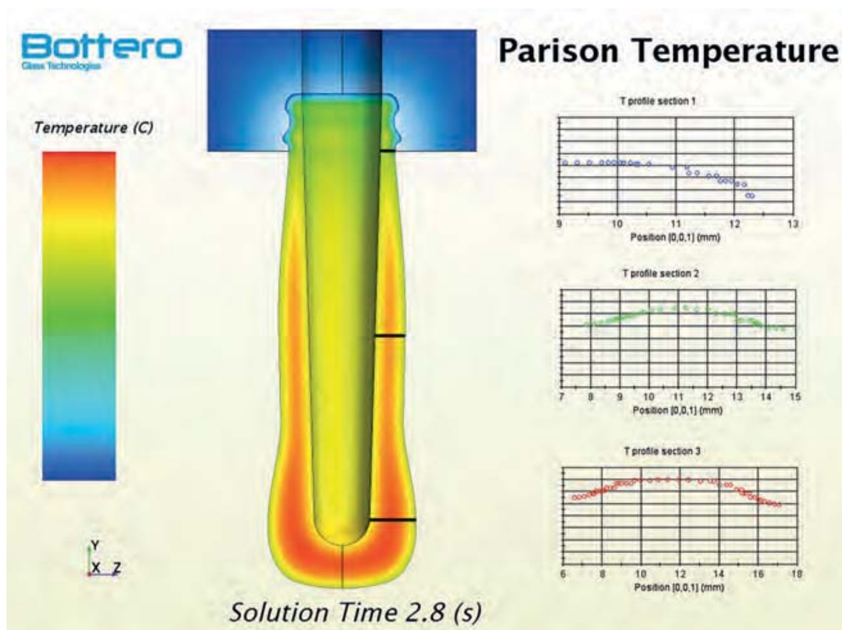

FIGURE 3: Parison temperature during reheating showing temperature redistribution

FIGURE 4: Experimental tests were conducted on the glass and confirmed a good correlation with simulations

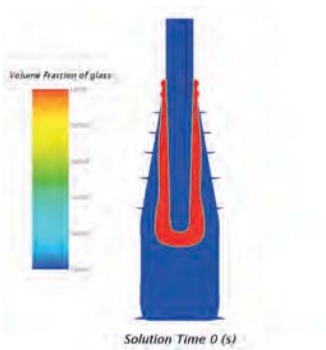

FIGURE 5: Volume fraction of glass in the dynamic model of the parison for simulating shape changes

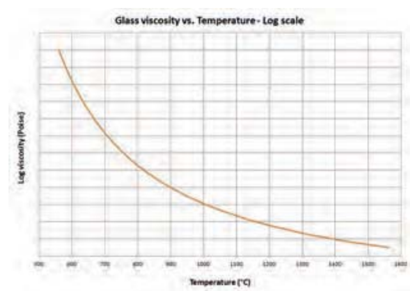

FIGURE 6: Variation of glass viscosity with temperature during the glass forming process

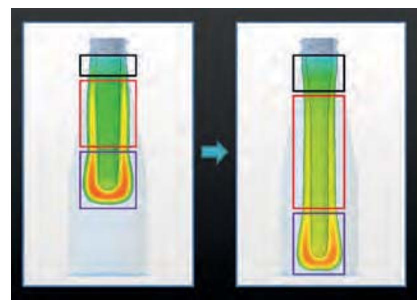

FIGURE 7: Simulation with STAR-CCM+® showing the shape change of the parison in the blow mold

Additionally, a heat exchange also occurs between glass and environment through convection and radiation. These heat exchange interfaces are geometrically complex and drastically change in time during the shaping of the bottle.

THE MODELING METHODOLOGY

STAR-CCM+® has made it possible to simulate the complete physical system of this production cycle, starting from a hot glass gob all the way up to the creation of the finished bottle.

A super-computing facility located in Cuneo, Italy (with 25 servers available that operate concurrently on HPC clusters with over 450 cores) facilitated CFD simulations with a very fine volume mesh, resulting in a large number of elements and ensuring a great space resolution to accurately capture the forming process.

The first step in developing the process was to perform unsteady simulations to obtain the three dimensional temperature distribution of the parison created by pressing the glass gob into the blank mold (figure 1). The numerical model was initialized using the experimental conditions (such as temperature profiles), included all the details of the equipment and solved for both Discrete Ordinate Model (DOM) radiation and conduction.

The contact heat transfer coefficient at the interface between glass and cast iron is not only function of temperature, it also depends on many other parameters (e.g. time, pressure, mold roughness, presence of lubricants, etc.) thus it cannot be considered to be an ideal coefficient. For the simulations, the heat transfer coefficient used was determined by experiment.

The transient simulation led to a detailed 3D temperature model of the parison, and showed realistic temperature trends as expected: the glass was hotter where the parison wall was thicker. This typical vertical temperature trend is required to form a good final product and can be very tricky to control in experiments. As expected, because the glass viscosity highly depends on its temperature, the cold neck zone behaved as solid glass while the hot bottom of the parison was still soft and easy to work with.
A similar approach was used to simulate the reheating of the parison, when the mold opens and the parison temperature redistributes along the thickness for a time period of about two seconds (figure 3).

Simulations with STAR-CCM+® were useful not only for calculating the complete volume temperature (surface and internal) of the parison but also for better understanding of the available thermo-infrared measurements of glass and molds as these give information only on the surface and not on the inner part of the parison. Experimental tests of the glass have been conducted (figure 4) to verify the simulation results, confirming good correlation between simulation and experimental data.

Next, a dynamic model of the parison for predicting the shape changes that occur in the blow mold was built, with the simulations starting from the initial temperature distribution obtained in the previous step. This is one of the most important steps in the glass forming process as it greatly affects the final bottle shape. The Volume of Fluid (VOF) model in STAR-CCM+® was used to model both fluids in the simulation: glass (dense and viscous) and air that surrounds the parison (figure 5).

The VOF method allowed for accurately modeling the details of the glass and air flow, separated by a well-defined interface (free-surface) and solving for its position in a time-accurate manner at every time-step. Mechanical and thermal properties of the materials were taken into account, including viscosity, density, conductivity and specific heat. Additionally, since the viscosity of glass highly depends on temperature, and the temperature changes with time, the heat flux and temperature distribution in the simulation were solved simultaneously with the motion of the interface.

Using the experimental measurements of the specific glass viscosity as a function of temperature (figure 6) and the temperature profile obtained in the previous step, the mechanical behavior (shape change) of the parison was successfully simulated as it developed in the blow mold. The model consisted of the inner surface of the mold that corresponds to the final bottle shape. A pressure inflow where the air is injected was included on the top and several pressure outflows were present on the sides for creating the vacuum in the final step of the process.

For the first 2.2 seconds in the blow mold, the parison stretches down to the bottom solely due to gravity, so no air is injected. This process, also called stretching, is crucially important to get the right thickness of the bottle wall and it is extremely sensitive to the parison temperature, as it affects the viscosity of glass.

Looking at figure 7, simulations showed that starting from the top of the parison, in the neck region, the glass was cold so it resisted stretching even with a high gravity load from below present. Furthermore, it became clear that the central part of the parison was most responsible for stretching while the bottom (with the lowest gravity load) did not stretch even if glass was soft.

This physical process was successfully simulated thanks to the simultaneous prediction of both the dynamic and thermal features in the STAR-CCM+® model. This allowed for taking the temperature redistribution of the glass during reheating into account (and thus the local time-accurate viscosity change) while stretching occurred.

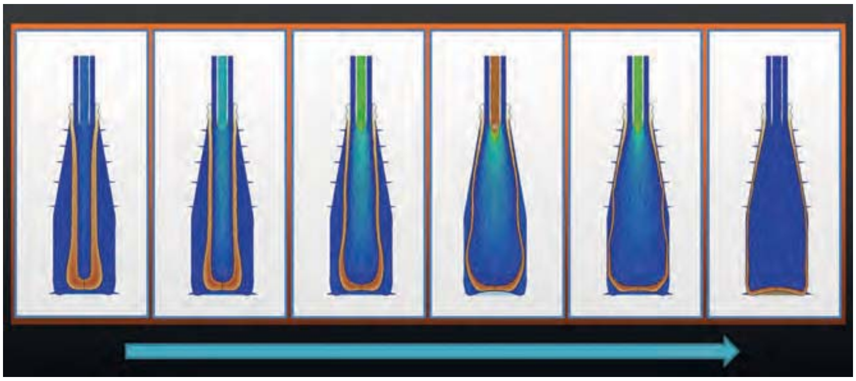

FIGURE 8: Complete simulation with STAR-CCM+® of the glass forming process, starting from the initial glass gob to the final shape

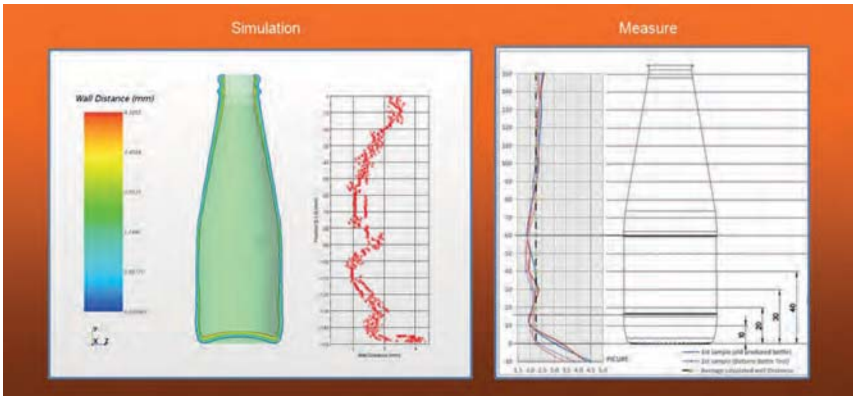

FIGURE 9: Validation of numerical simulations with STAR-CCM+® showing good comparison when comparing wall thickness to real bottles

During the final step in the simulation of the glass forming process, air was injected from the top and a vacuum was created from the side holes to blow the shape into the final bottle, as shown in figure 8. Even though this fast motion is not trivial and presents a challenge, the solver remained stable throughout the simulations.

The simulation results were validated by comparing the wall thickness of real bottles with the values obtained by simulating the process (figure 9). The correlation was very good, confirming that the numerical model is robust, especially considering it is the final result of many consecutive steps. This should come as no surprise since great care was taken to ensure that the numerical model represents a realistic process taking into account the glass (whose properties are strongly influenced by the temperature), the air, the molds and all the production equipment. The glass data has been experimentally measured in a specialized laboratory, and the experimental machine timing was also considered.

CONCLUSIONS

In this study, we presented the numerical implementation of the forming process of glass containers that were previously tested in realistic manufacturing conditions. Both the press and the blow steps of the forming process were modeled using STAR-CCM+®. A realistic non-uniform temperature distribution of the parison was calculated and the final shape of the end product was presented and analyzed.

All calculations were performed in three dimensions, which allows for studying parisons that are not rotationally symmetric, enabling one to assess how a certain imperfection in the initial parison develops over time. The current model is valid for viscous fluids, but it could be modified to, for instance, visco-elastic fluids.

The numerical simulations presented here are extremely valuable to the glass manufacturing industry as they help gain insight into the details of the physics, enable optimization of the production process and will ultimately lead to a significant reduction in manufacturing time and cost.