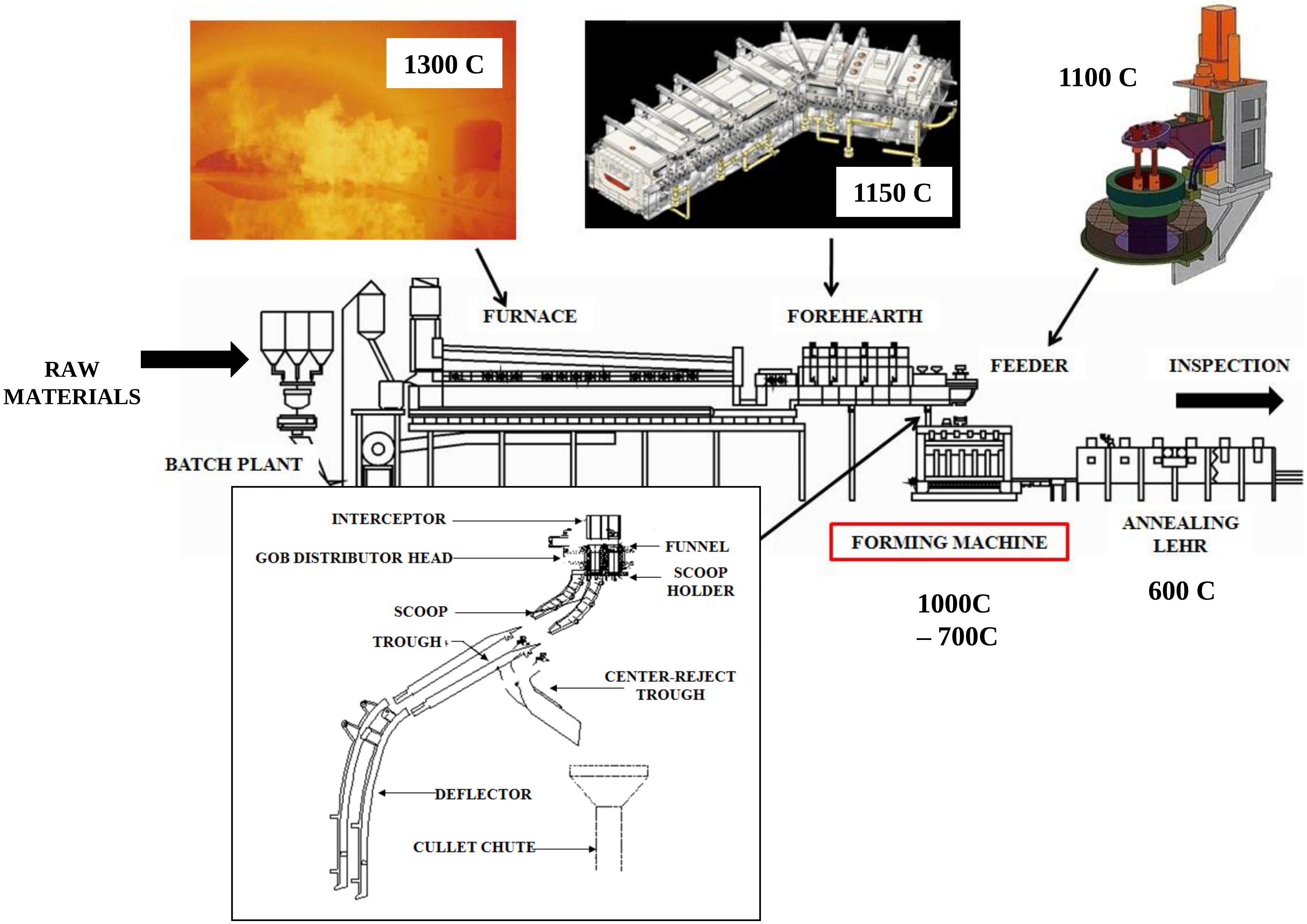
Container forming modeling: Sensitivity to boundary conditions, material properties, and underlying physics modelling

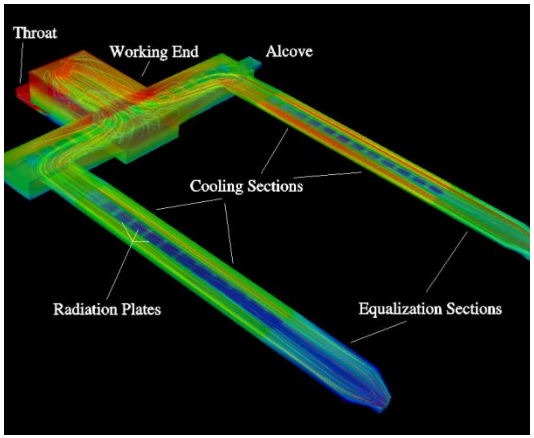
Matthew Hyre, Ph.D.
University of Northwestern, St. Paul

Bottle Making Process

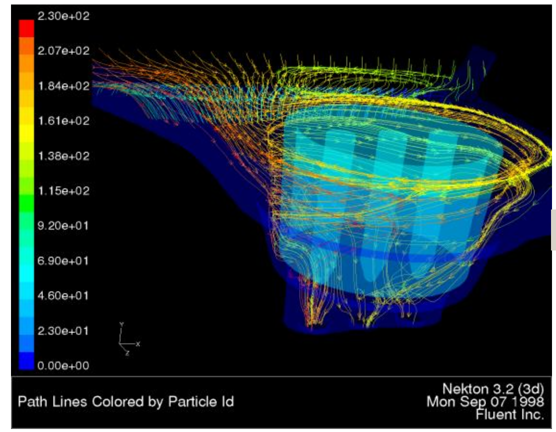


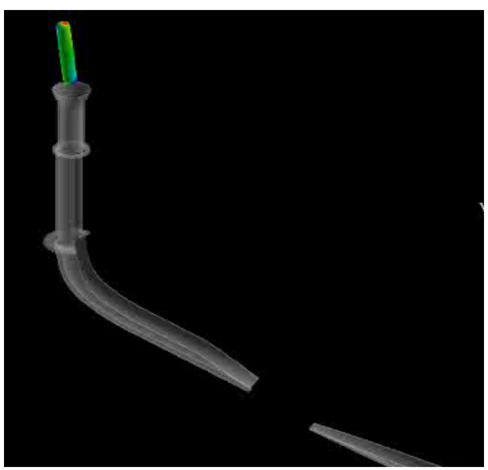
Gob Forming Models

Working End/Forehearth

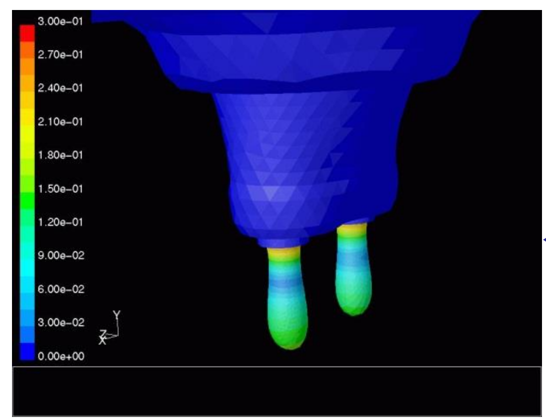


Feeder





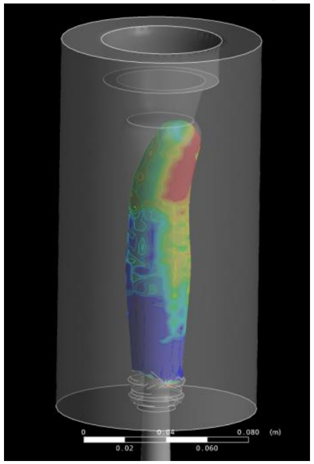
Gob Transfer to Blank Mold



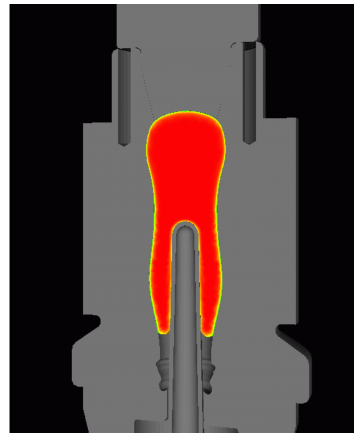
Gob Creation at Feeder

Container Forming Modeling

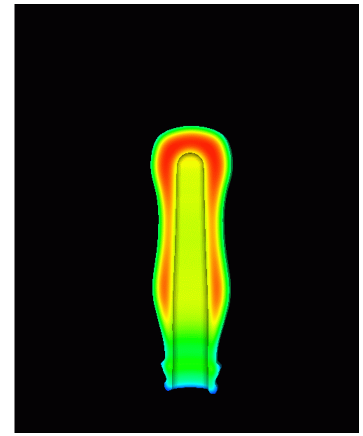
Gob Loading

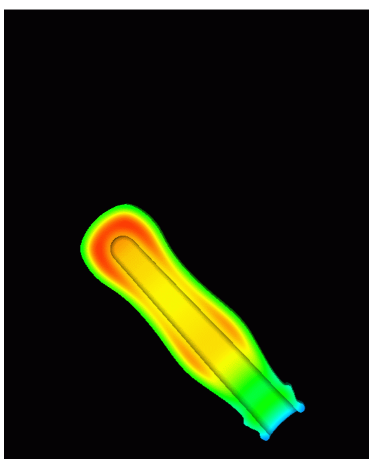


Parison Pressing

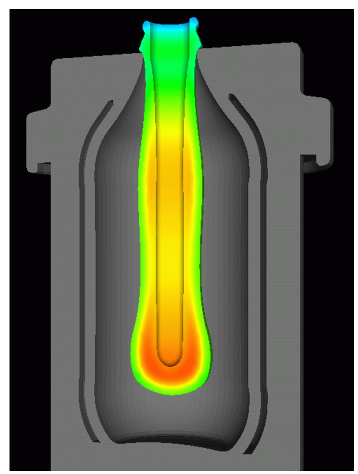


Inverted Reheat

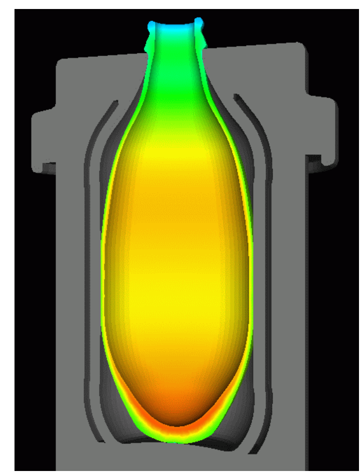




Invert



Reheat/Stretch

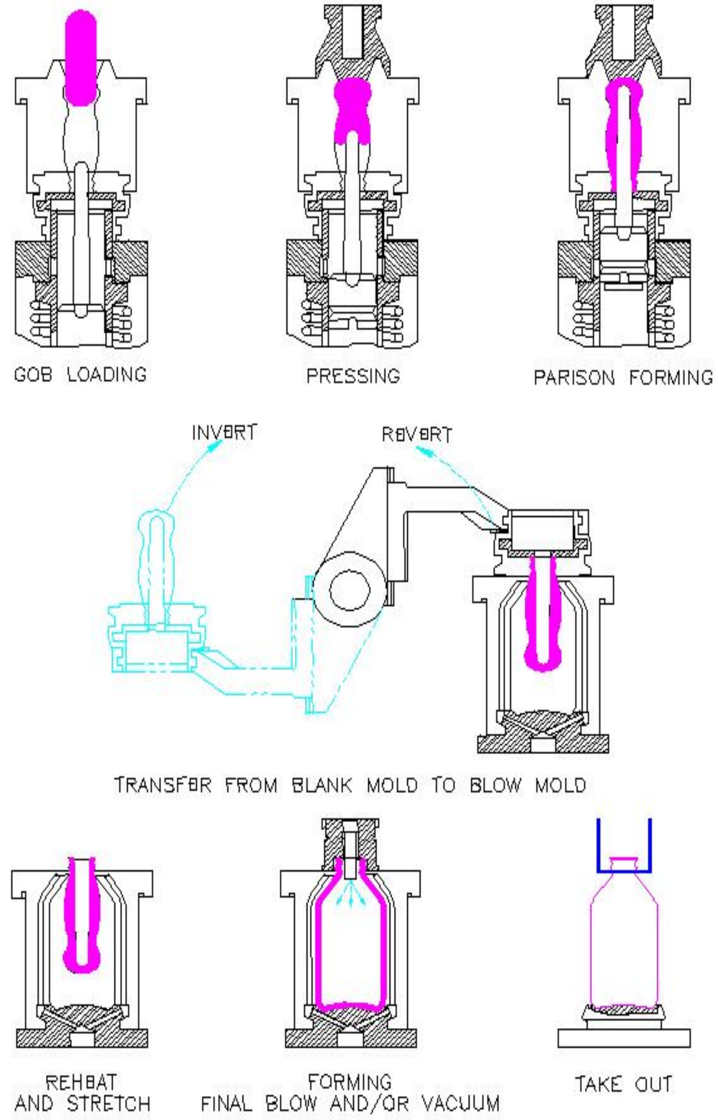


Final Blow

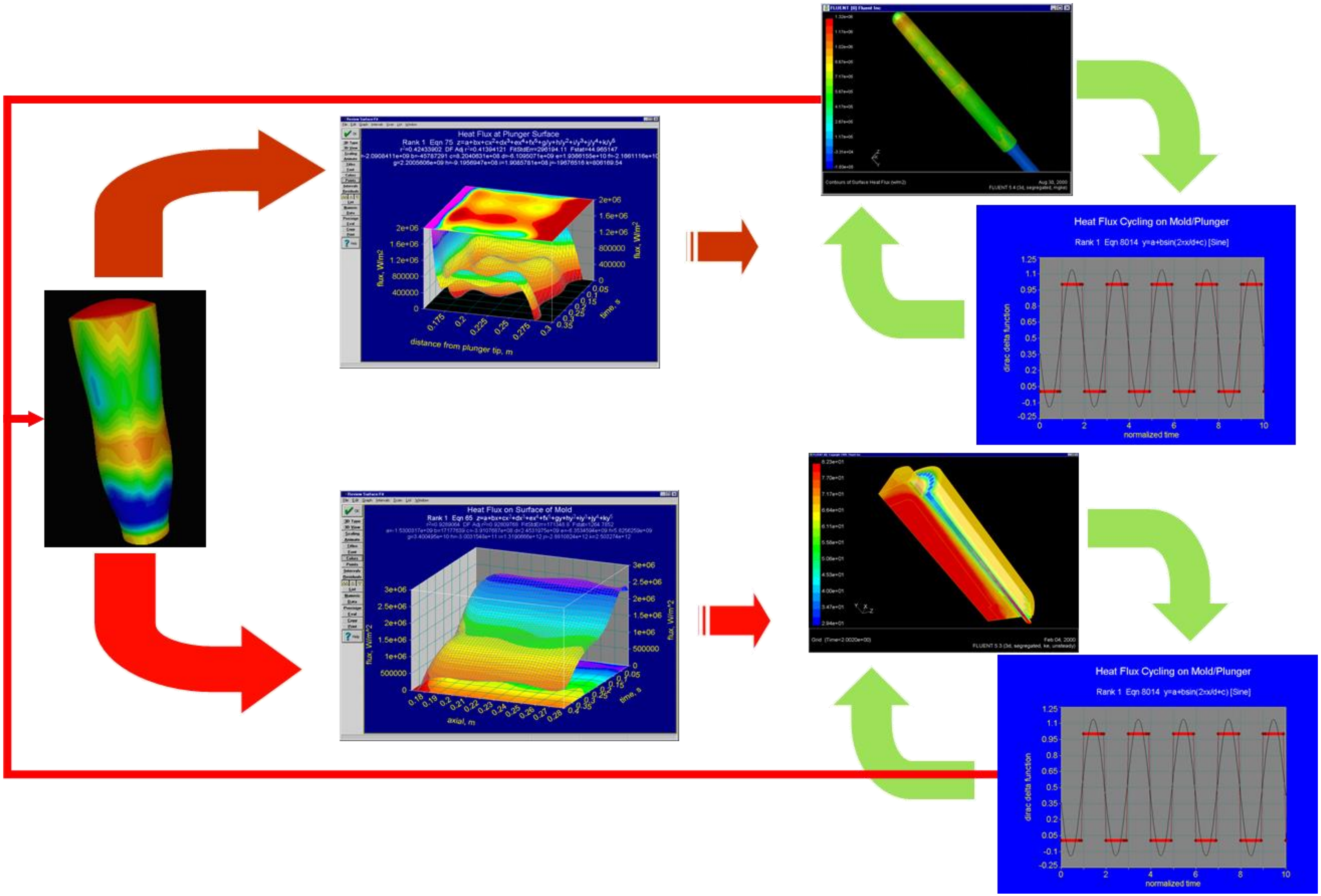
Goals of Container Forming Modeling Effort

- Inverse parison design
- Improved blank mold design and cooling strategies
- Investigation of problem areas during forming process:
  - Large variation in container thickness
  - Non-uniform temperature distribution
  - Poor parison design
- Determine regions of high stress intensity
- Evaluate sources of high stress intensities and develop strategies to eliminate regions of potential check formation

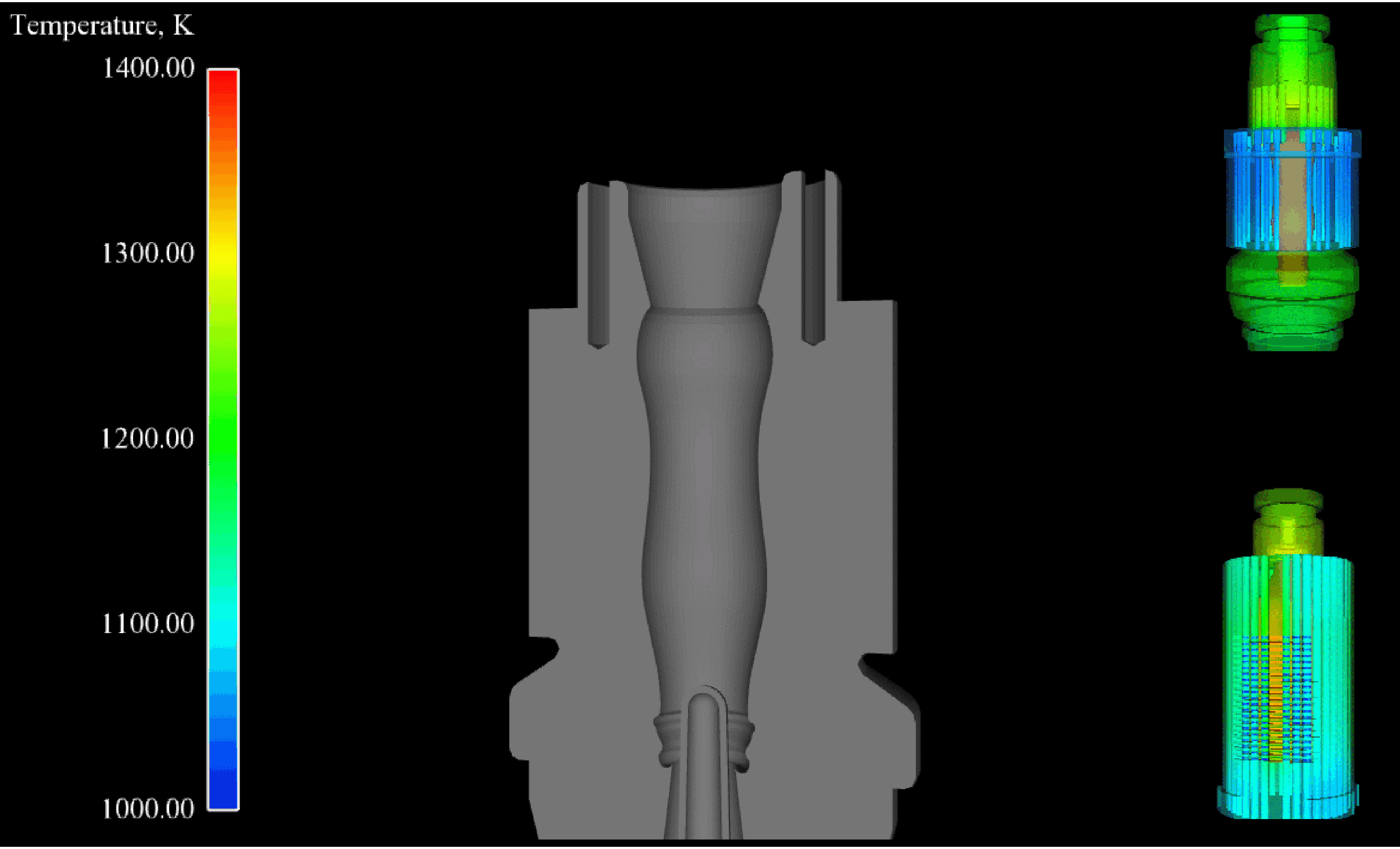
Press & Blow Forming Process



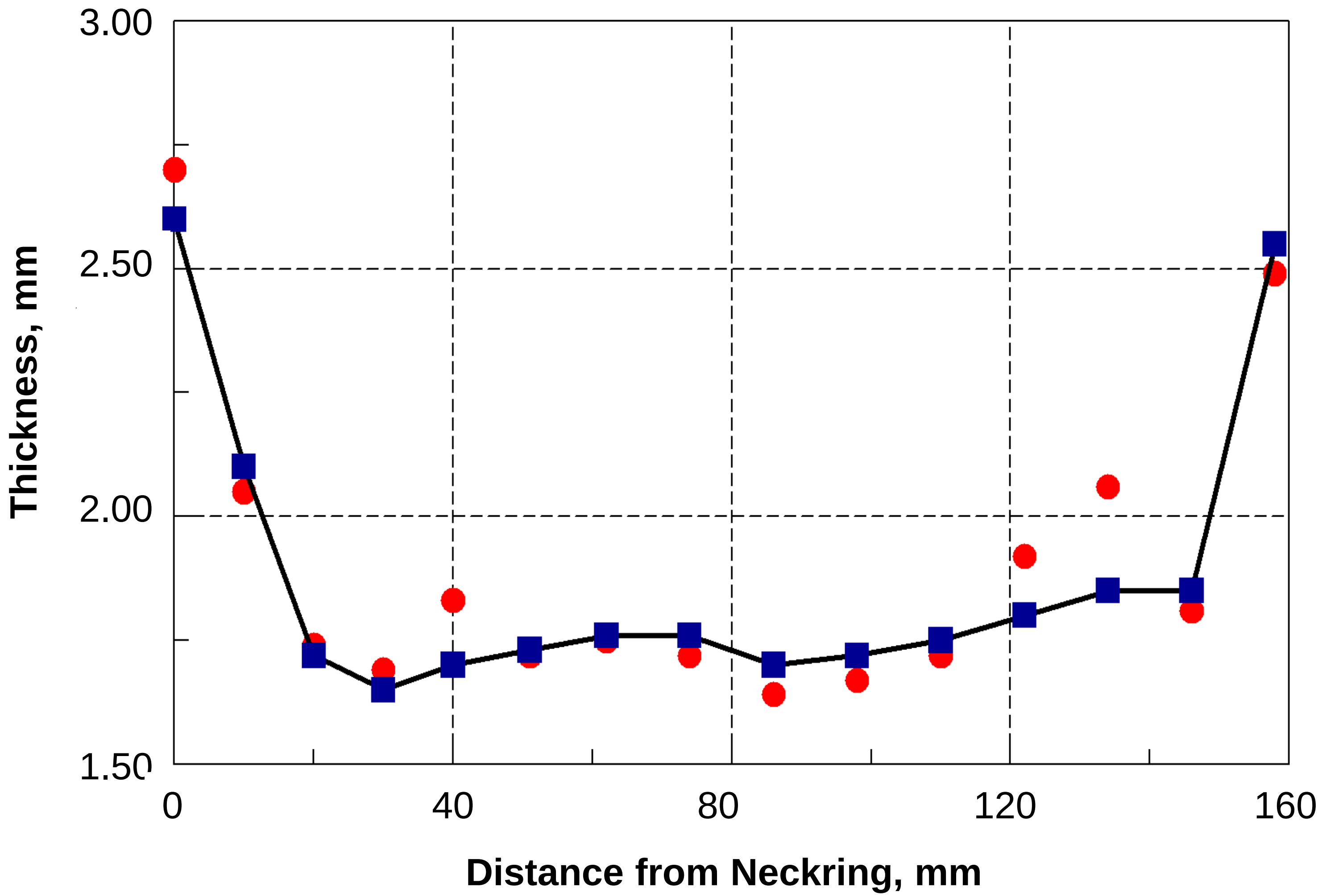
Mold/Plunger Side Heat Transfer



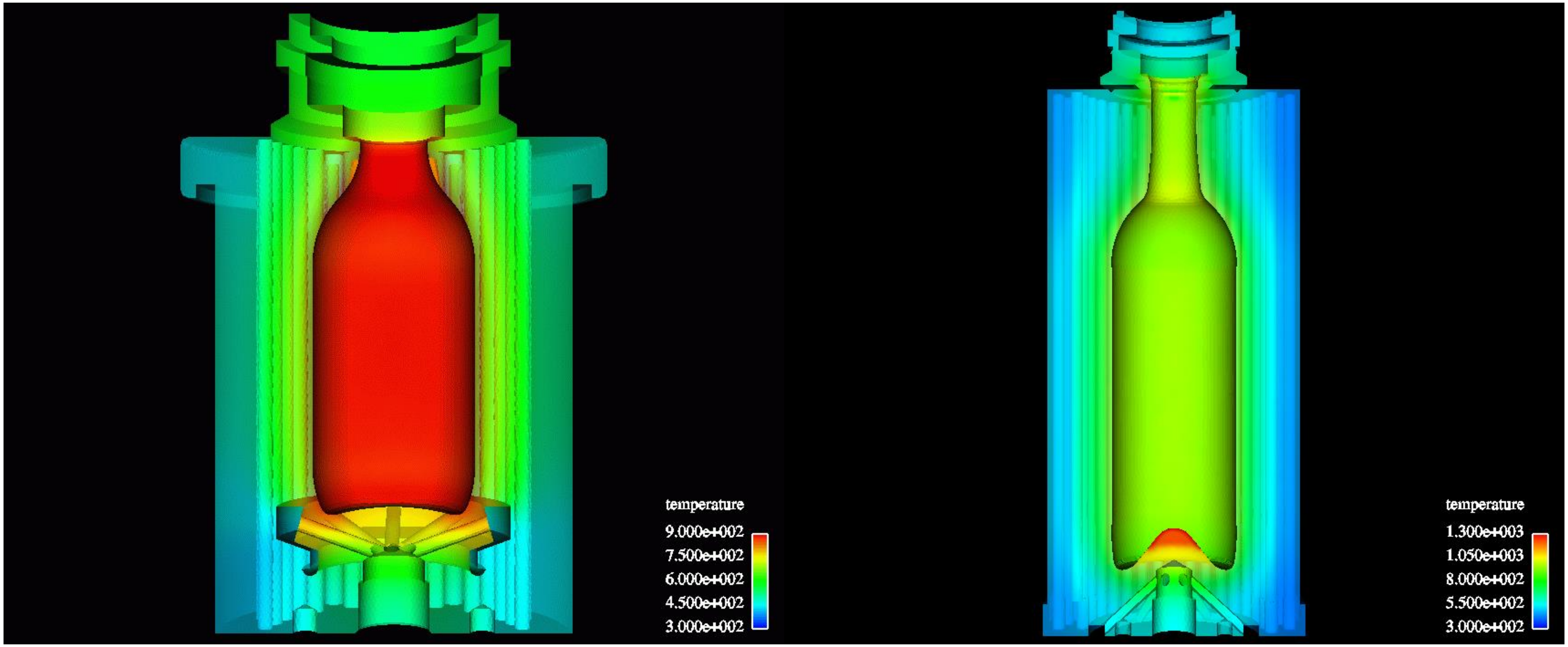
Typical Container Forming Model



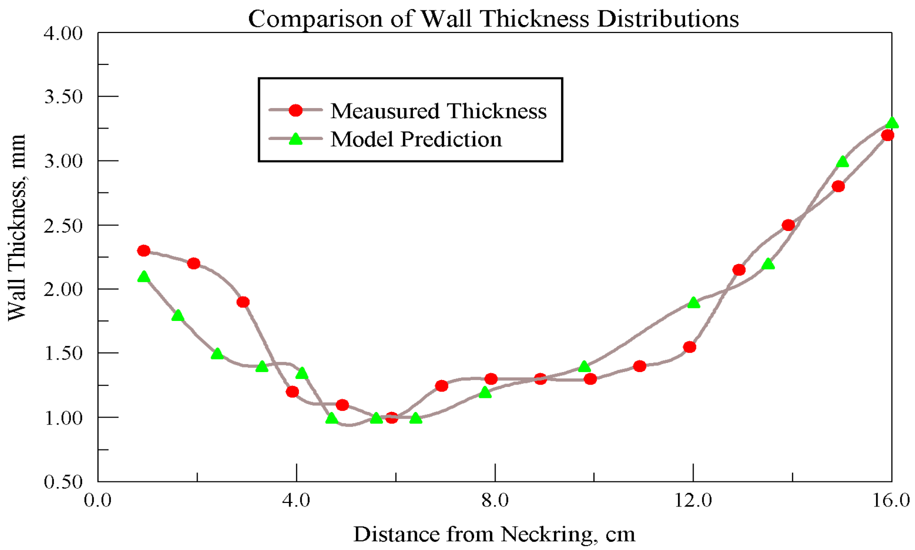
Container Forming Model – Beer

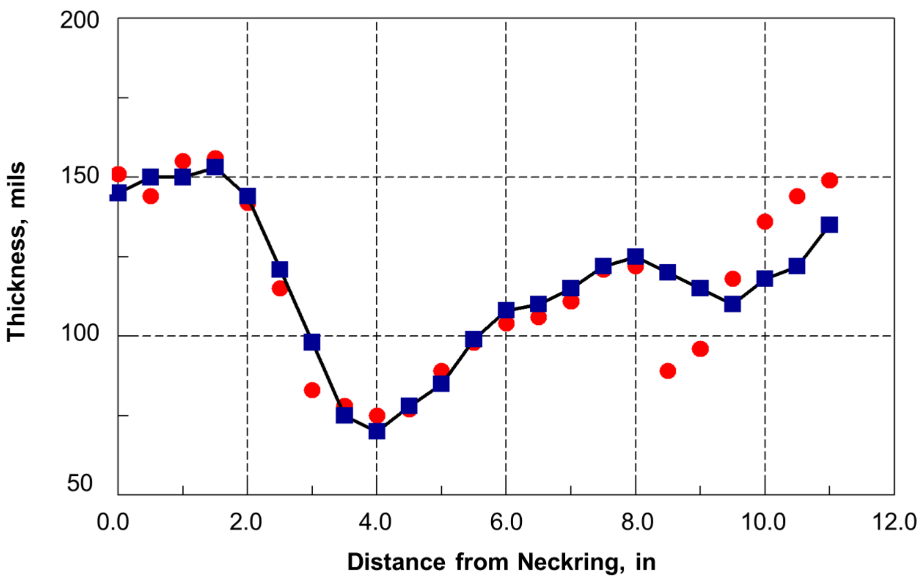


Typical Bottles Previously Simulated



Typical Wall Thickness Distribution Predictions





Why Doesn't it Always Work…?

Outstanding Forming Modeling Issues

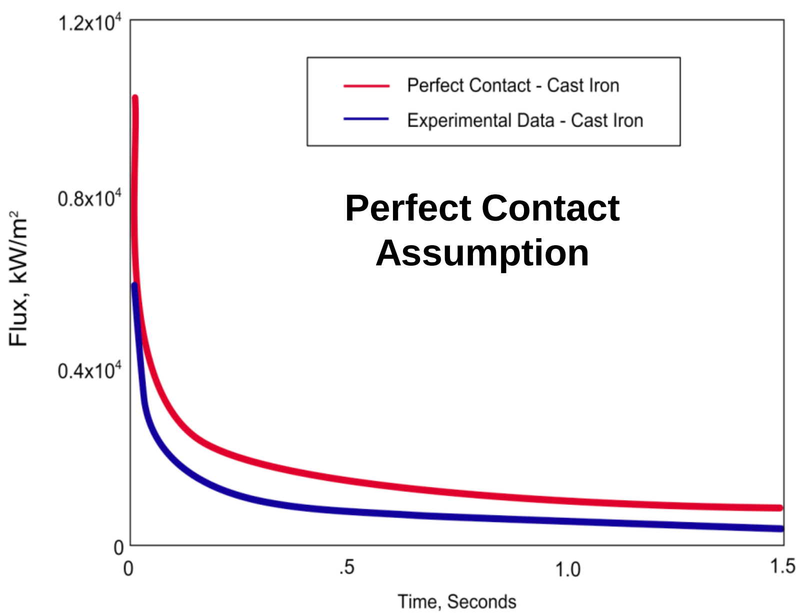
- Fundamental understanding of glass/mold heat transfer and the effects of mold lubricants
- Accurate material properties
- Numerical limits (mesh size/time step)
- Fluid dynamic (“slip”) condition at the glass mold interface
- Radiation modeling during forming
- Viscoelastic stress development and defect formation

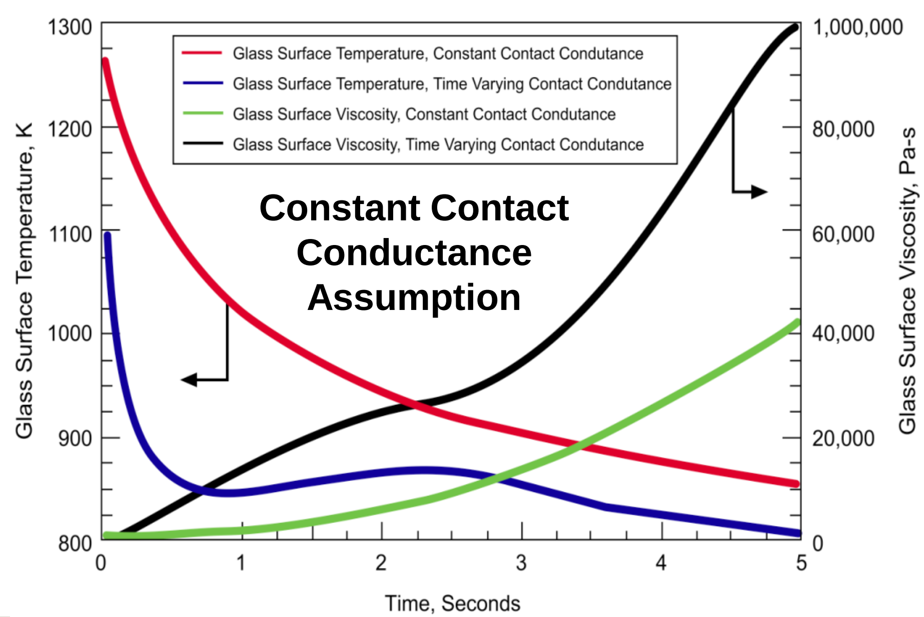
Heat Transfer Boundary Conditions

Most studies assume a combination of the following:

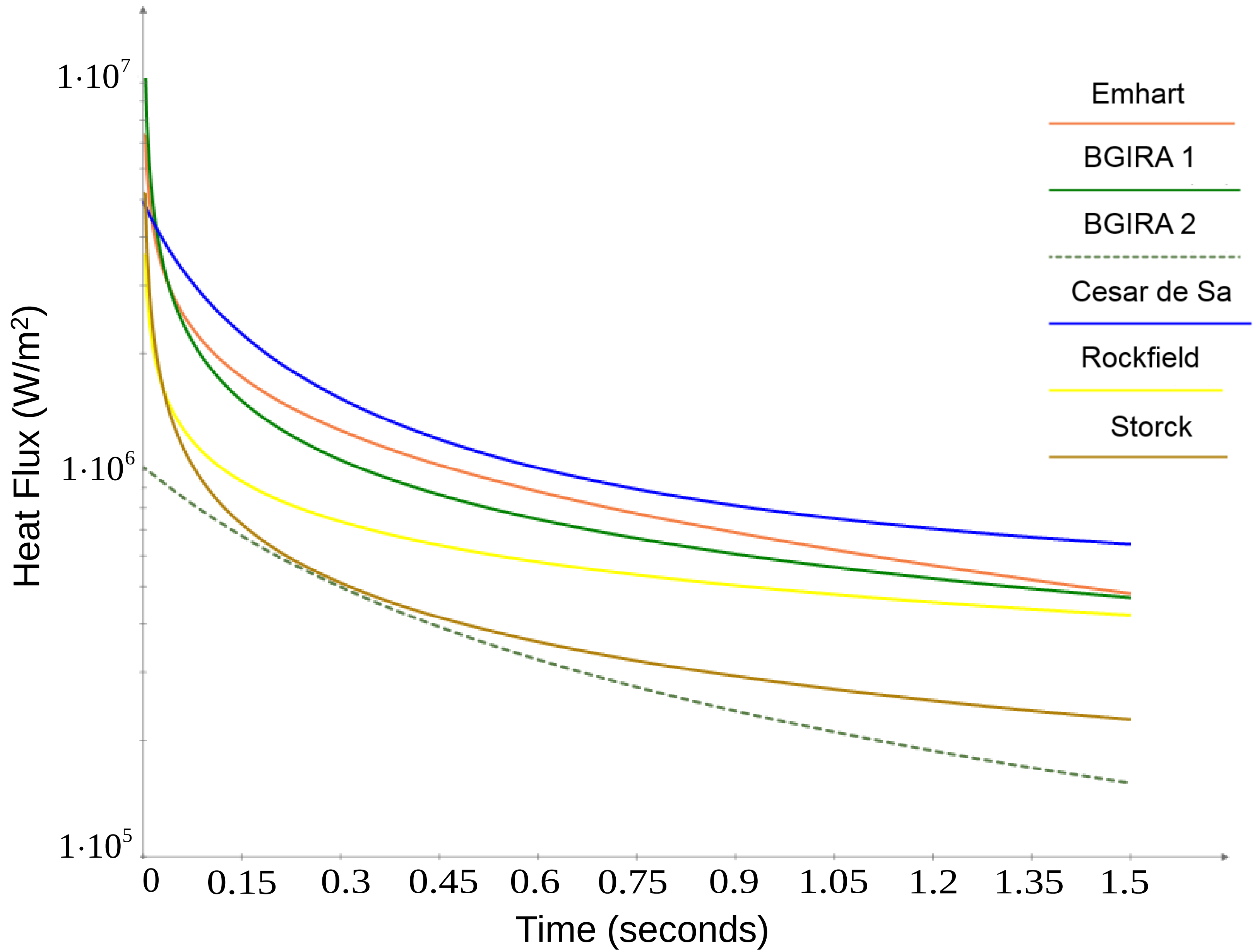
- Perfect contact between mold and glass
- Heat transfer coefficient between glass and mold is constant
- Heat transfer coefficient usually based on overall heat balance rather than local conditions

Glass to Blank Mold Heat Flux Expressions





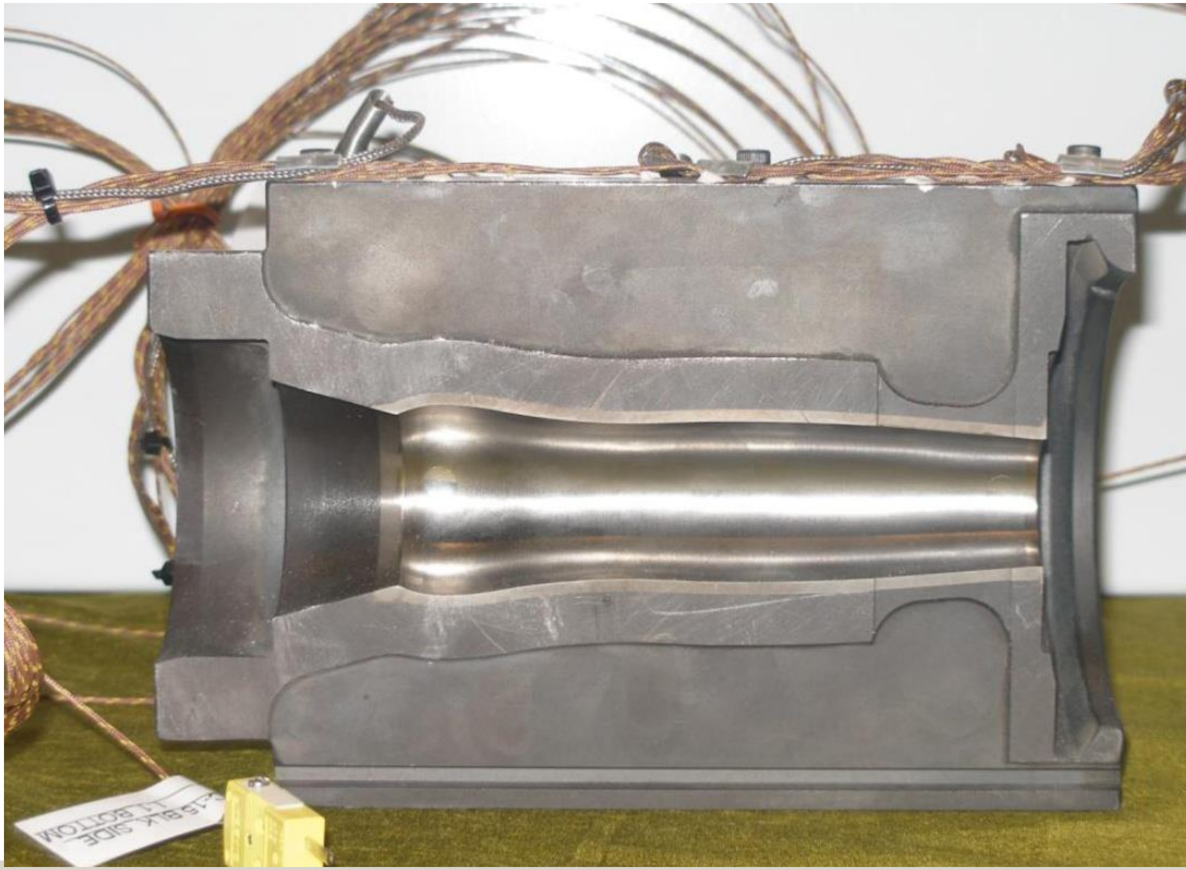
Glass/Mold Heat Transfer: Heat Flux Correlations



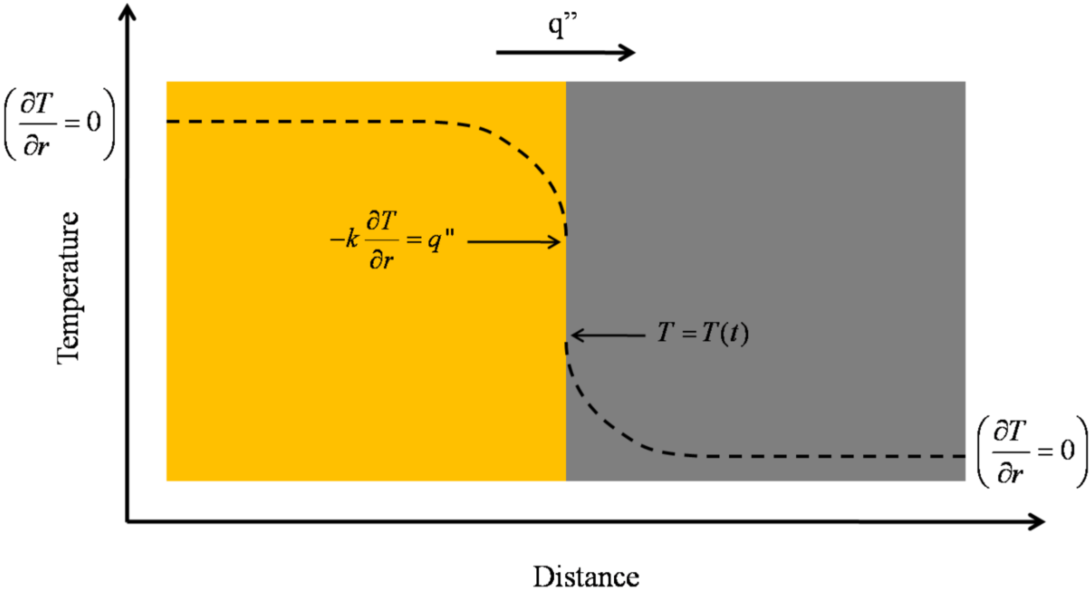
Heat Transfer Measurements

Glass/mold contact conductance experimentally modeled and includes the effects of:

- Glass pressure
- Glass color
- Initial glass temperature
- Initial mold temperature
- Mold type
  - (cast iron vs. Al-Br)



Governing Equation for Data Reduction



$$\rho(T)C_p(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial r}\left(k(T)\frac{\partial T}{\partial r}\right)+k(T)\frac{1}{r}\frac{\partial T}{\partial r}$$

One-dimensional Transient Heat Conduction Equation in Radial Coordinates

Assumptions

- Radial conduction much greater than axial or circumferential conduction
- Radiation is a diffusive process and can be included in an effective conductivity
- Plunger side heat transfer does not affect mold side heat transfer

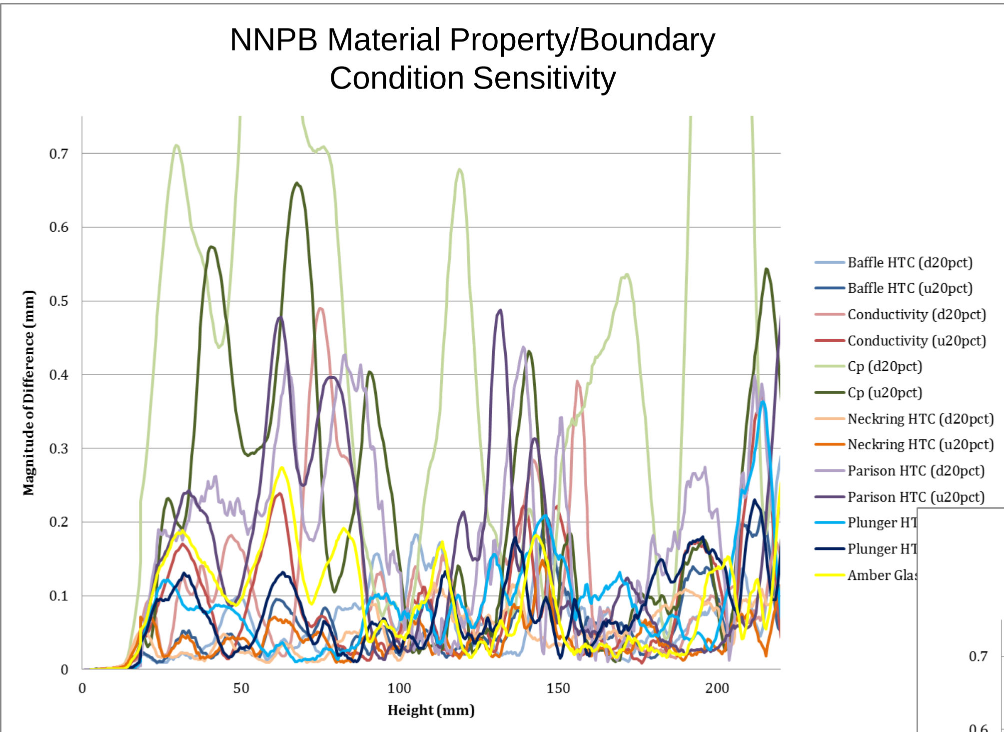
Important Effects to Include in Data Reduction

1	Temperature Dependent Properties
2	Interfacial Heat Transfer Coefficient
3	Time-varying Heat Transfer Coefficient
4	Discrete Ordinates Model for Radiation
5	Plunger/air convective effects
6	Initial Mold Temperature Profile

Measured Material Properties

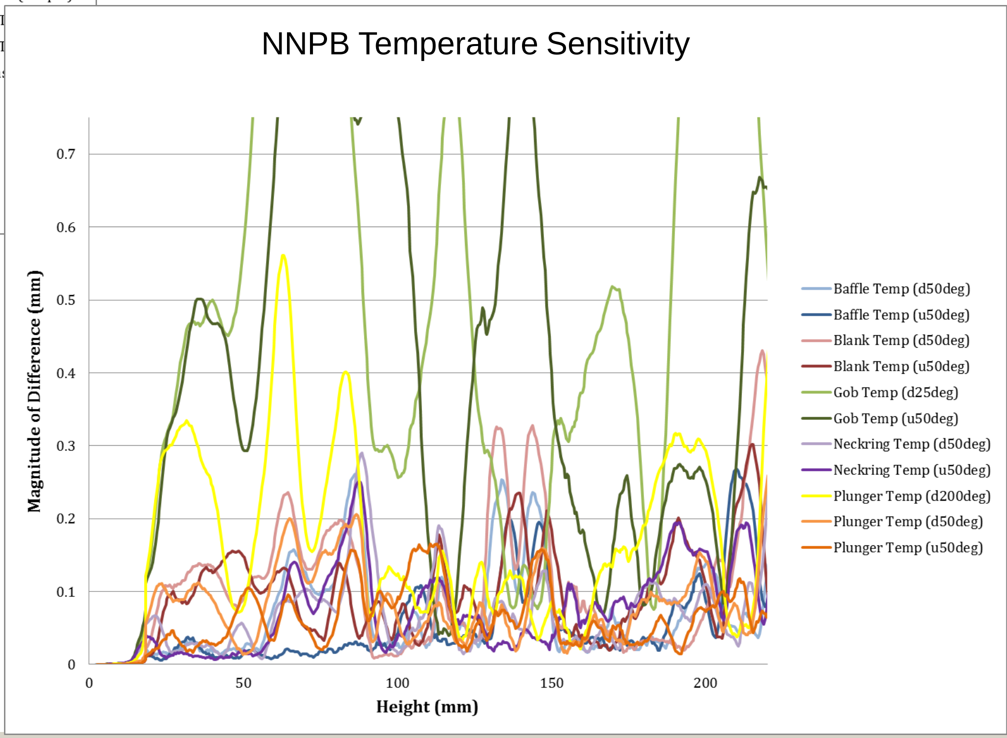
- **Glass Viscosity**
  - Modified WLF equation including Simmon’s correlation for shear thinning and generalized White-Metzner viscoelastic model
- **Specific Heat of Glass**
  - Correlated vs. composition and temperature from 1500 K down to 300 K
- **Glass Thermal Conductivity (Radiative Conductivity)**
  - Surface fit for glass thickness and temperature for various types of glasses (flint, amber, dark green, etc.)
- **Glass Thermal Expansion**
  - Curve fit as a function of temperature
- **Glass Surface Tension**
  - Curve fit as a function of temperature

Glass Thickness Sensitivity to Parameter Input - NNPB



Most Sensitive Parameters:

- Glass specific heat
- Glass/blank heat transfer coefficient
- Glass radiative properties
- Plunger heat transfer coefficient



Most Sensitive Parameters:

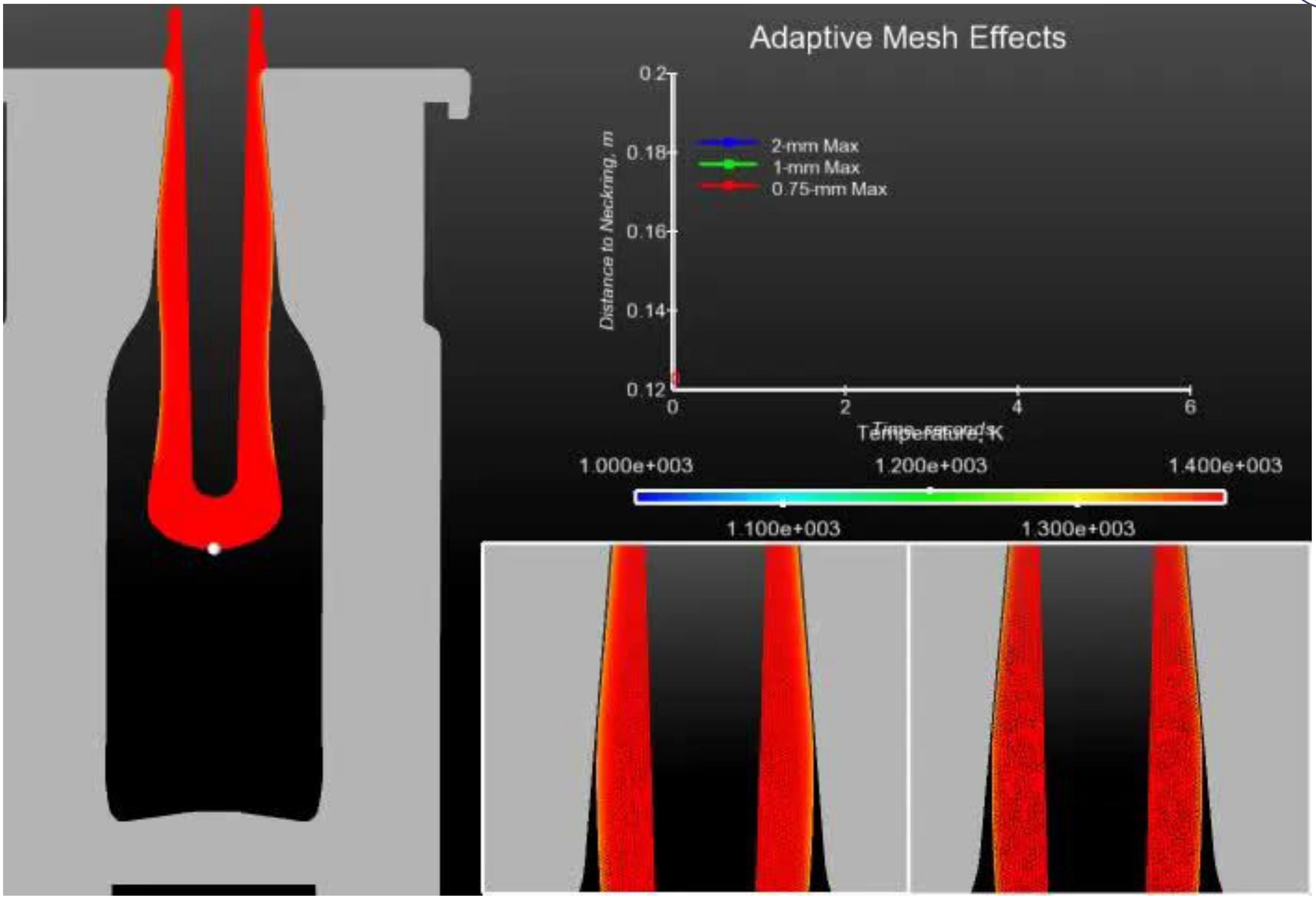
- Gob temperature
- Blank temperature
- Plunger temperature
- Baffle temperature

The material properties were changed by ± 20%, and the temperature parameters were changed by ±50 degrees to test glass thickness sensitivity.

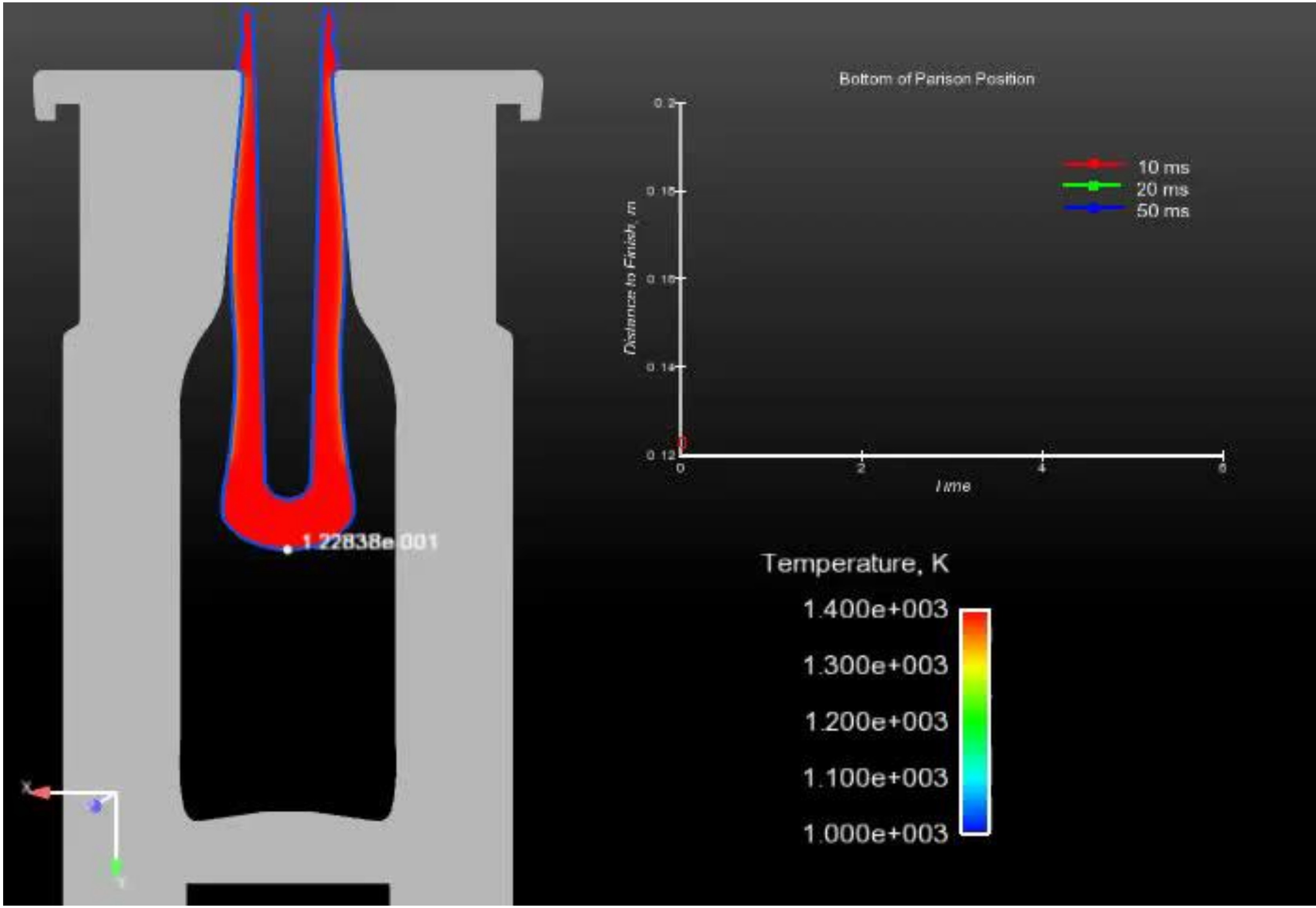
Boundary Condition/Material Property Sensitivity Analysis

1	Glass Specific Heat
2	Gob Temperature
3	Blank Temperature
4	Glass/Blank Heat Transfer
5	Radiation modeling
6	Plunger Temperature
7	Glass/Plunger Heat Transfer

Forming Modeling Sensitivity Studies – Max Mesh Size



Forming Modeling Sensitivity Studies – Time Step

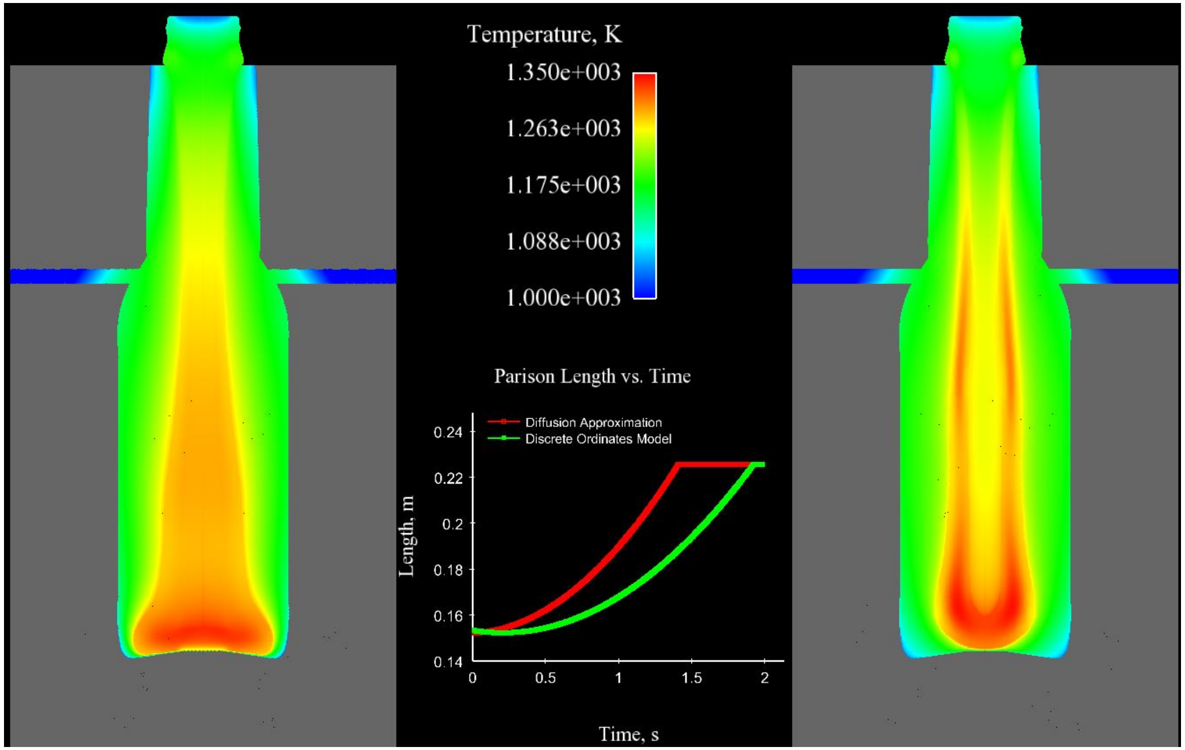


Still Missing

- **<u>Good data and physical model of glass/metal slip</u>**
- Studies on radiation model requirements:
  - Effective conductivity vs. semi-transparent models
  - Single or multi-banded

Initial Radiation Studies – DOM vs. Effective Conductivity

- Using the diffusion approximation resulted in an error in the prediction of reheat stretch time of 41 percent compared to 13 percent using the DOM model.
- There was an increase in heat transfer from the glass to the mold using the DOM model.
- Differences in final container thickness were not large if reheat/stretch times adjusted to account for decreased heat transfer in $k_{eff.}$
- Inclusion of the radiative properties using the DOM/VOF approach is very computationally expensive.

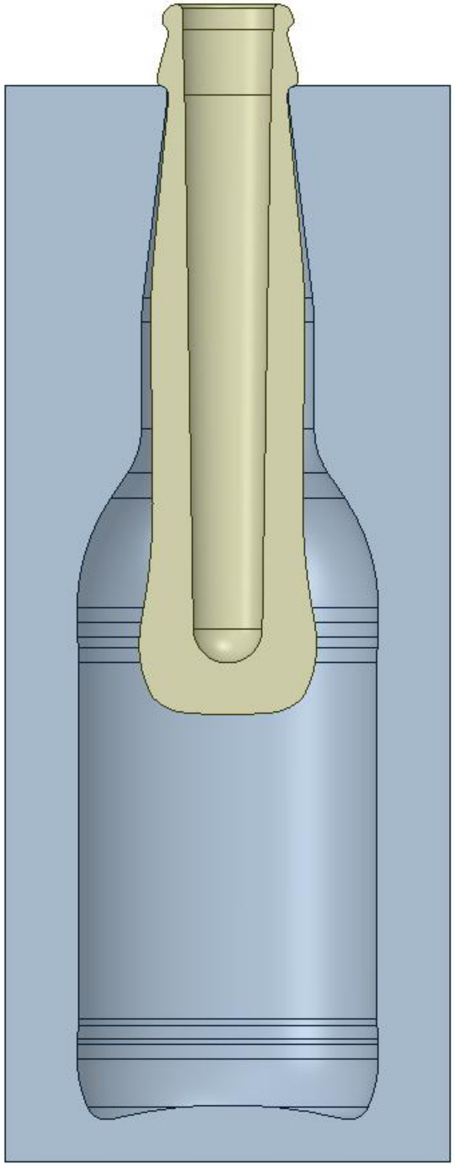


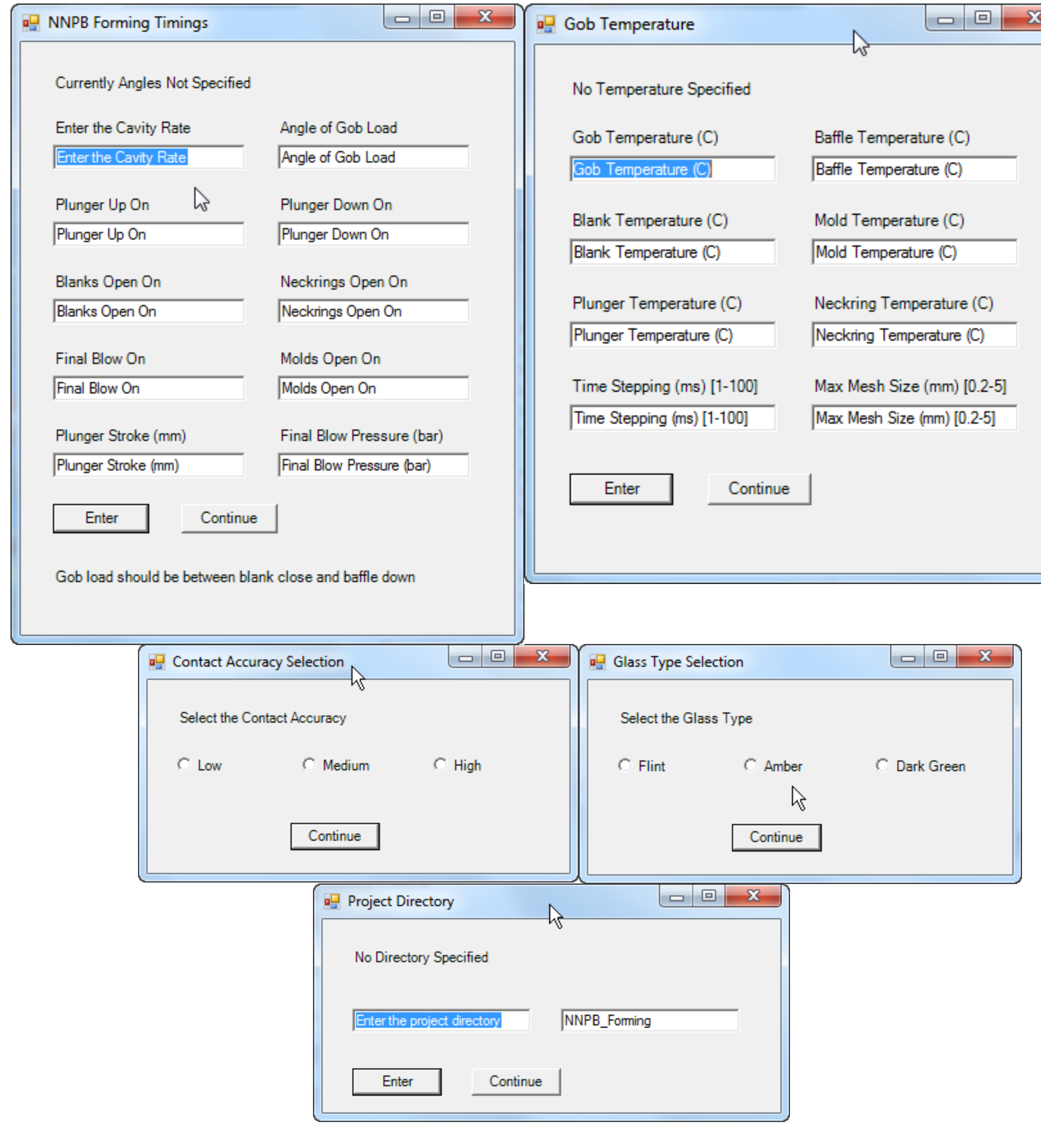
Status of Forming Modeling Outstanding Issues

1	Glass/metal heat transfer
2	Glass Material Properties
3	Numerical Limits
4	Glass/metal slip condition
5	Radiation modeling
6	Glass viscoelastic effects

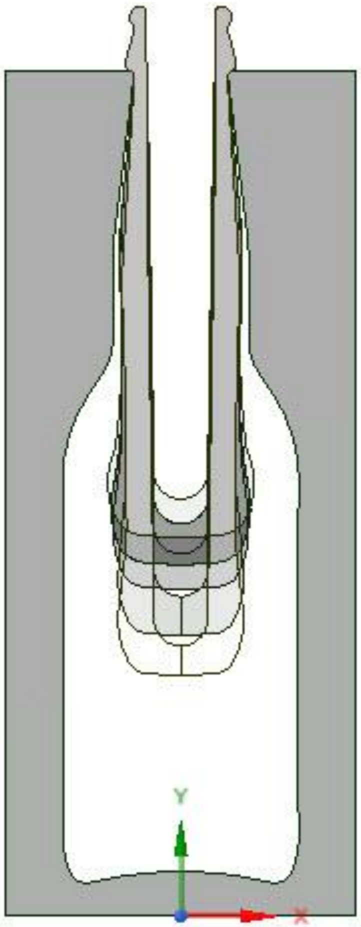
So where is this all going now…?

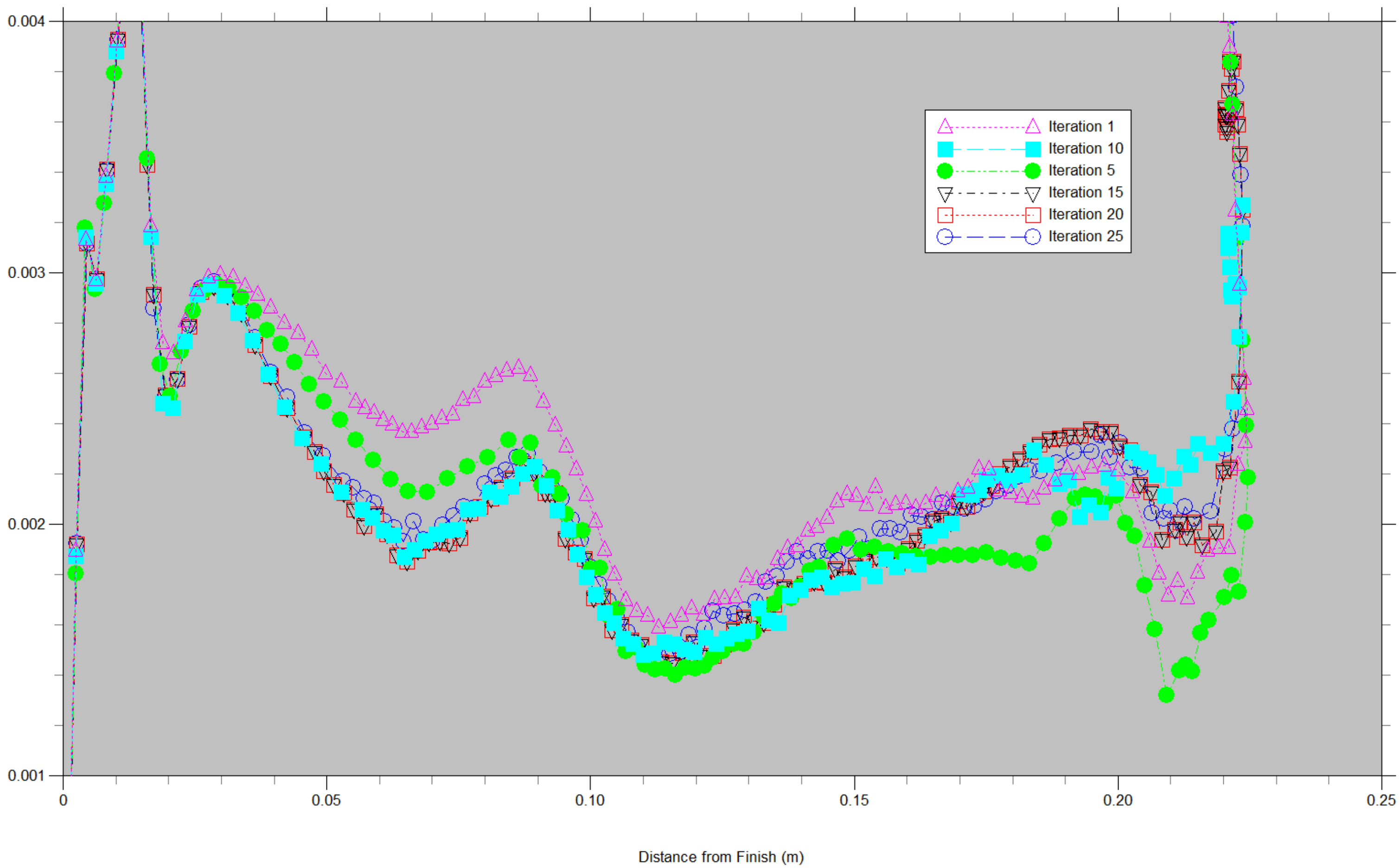
Bottle Analyzed – 300 mL Longneck



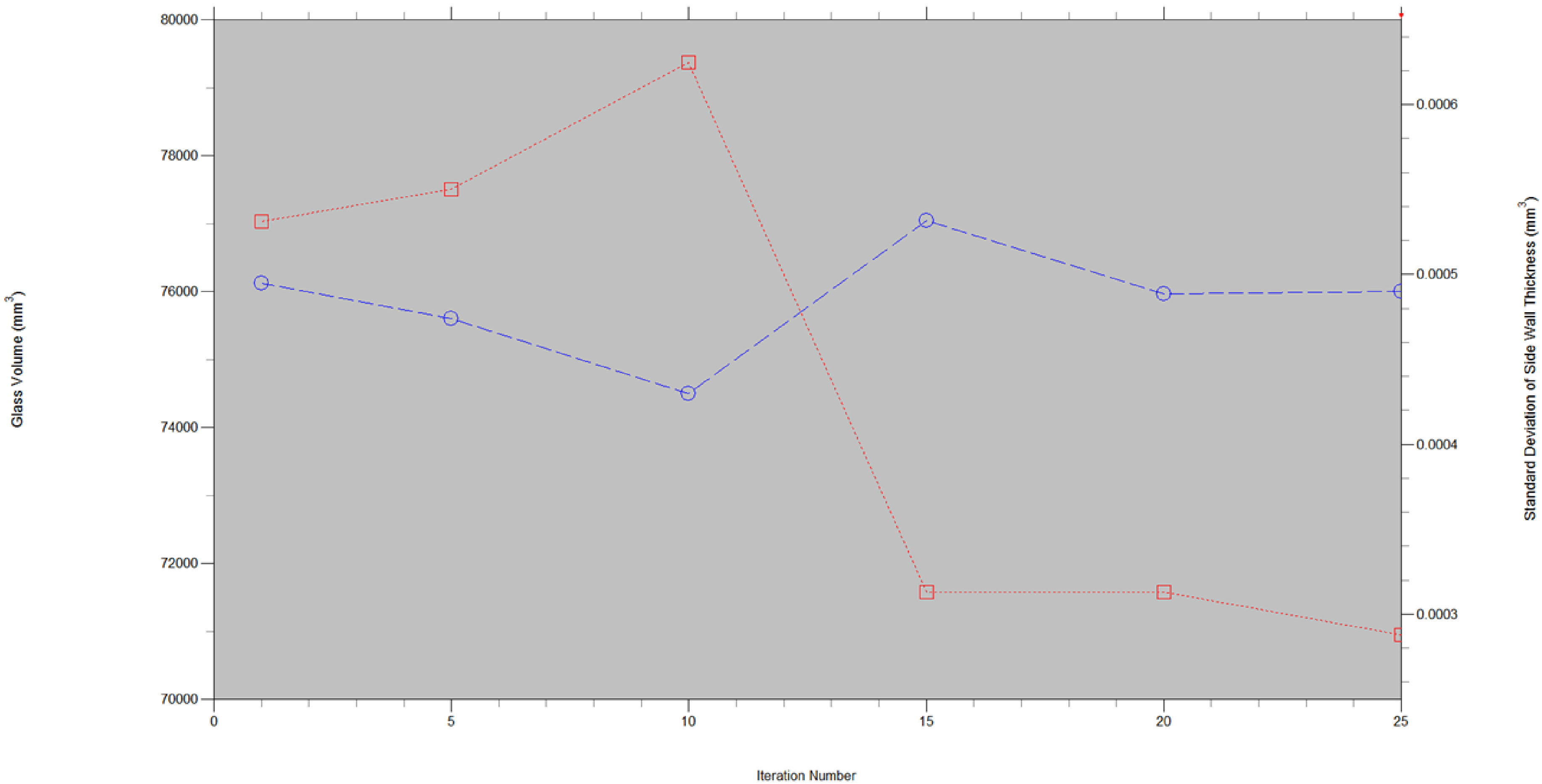


Automated Parameter Changes





Glass Volume and Standard Deviation of Side Wall Thickness Distribution vs. Design Iteration



Conclusions

- There are still no reliable physics based models for glass/mold heat transfer or slip conditions that exist. All forumulations are semi-empirical at best.
- Forming models require intelligent input and evaluation. Too much process variability exists for «canned» solutions.
- Forming models ultimately must be linked with mold and plunger cooling models in order to complete forming process picture.
- Feeder and delivery equipment heat losses continue to be problemmatic in developing accurate forming solutions.
- Even if forming models provide a «solution», it does not mean that they will point to the correct direction in terms of mold cooling or parison design.
- However...we are getting closer.