GLASS INDUSTRY
GLASS FURNACES
AND
MODELLING OF GLASS FURNACES

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CONTENT

INTRODUCTION

GLASS INDUSTRY

GLASS FURNACES

MODELS RELATED TO GLASS FURNACES

RECENT FEATURES IN GLASS FURNACES
Four Fields of Activity
- Flat glass
- Glassware
- Glass Packaging
- Chemicals

Şişecam Furnaces and Companies
Glass production: 4.2 mtons/year
Soda ash production: 2.1 mtons/year
Industrial raw materials 4.0 mtons/year (2014)
Glass industry is one of the most challenging industries with high operation temperatures, high initial investment and operation costs, long campaign lives and high production capacities involved.

Main inputs of glass furnaces, raw materials and energy, became more critical issues as concern for limited resources and environmental standing of the world have made a peak.

Due to increasing glass quality requirements and limitations to energy consumption, every step in glass production needs reconsideration. The narrowing margins of potential developments require specific investigations.

Besides, as new capabilities arise in consequence of fast scientific and technological developments, concepts are always re-examined and research for new concepts in glass melting are continuing.
Glass is an amorphous solid produced by melting at high temperatures and then cooling without crystallization.

Main raw materials of glass:
- Sand - SiO₂
- Soda ash - Na₂CO₃
- Limestone - CaCO₃
- Dolomite - CaMg(CO₃)₂
- Cullet - Recycled glass

Sand dissolution
Glass plant; view from the melting end of glass furnaces
A view from inside the furnace
A view from inside the furnace

- **Inlet Port**
  - Combustion air inlet at ~1200 °C

- **Exit Port**
  - Combustion gases exit at ~1500 °C

- **Burners**

- **Flame**

- **Crown**

- **Batch** (mixture of raw materials) piles floating on glass surface

- **Glass surface**
Investigations at the end of furnace life;
View from inside the glass melting furnace after glass is removed

Corrosion patterns of refractory material reveal information about glass currents.
Glass investigations at the end of furnace life
Glass Production

Raw Materials

Glass Furnace

Forming

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Glass Industry, Glass Furnaces and Modelling

December 25th, 2015
Glass is **melted** at very high temperatures, **1500-1550 °C**, and it is **formed** into many products at **1000-1100 °C**.

Main type of products;
- Containers (water, wine, beer bottles, jars)
- Glassware (glasses, plates)
- Flat glass (window panes, automotive glasses, solar glasses)
- E-glass (fiber glasses)
There are different types of glass furnaces; main classification can be made as

i) Regenerative furnaces
   - End fired regenerative furnaces
   - Side fired regenerative furnaces

ii) Recuperative furnaces

iii) Electric melting furnaces

In this lecture we will concentrate on regenerative furnaces which are the most efficient type of glass furnaces.
End-fired regenerative furnaces

Energy balance around the furnace

Top view of combustion space showing the flame and combustion gases

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Glass Melting Process

1. Step
   - Batch loading

2. Step
   - Melting

3. Step
   - Refining

4. Step
   - Conditioning

Doghouse (Batch feeding point)
Main processes in glass production;

- Raw material preparation: Particle size adjustments and mixing of raw materials.
- Melting: Melting of glass raw materials at high temperatures (1500-1550°C).
- Refining: Removal of gas bubbles from the glass melt.
- Homogenization: Chemical composition and thermal homogenization.
- Conditioning: Controlled cooling of glass from furnace temperatures to 1000-1100°C.
- Forming: Shaping the melt glass into the products (bottle, glass, window pane..)
- Annealing: Controlled cooling of the formed product to room temperatures.
Heat transfer in glass furnaces

Radiation

Convection

Conduction
Heat transfer in the side-fired regenerative furnaces

Heat transfer from flame to the crown

Heat transfer from flame into the batch and glass melt

Heat transfer from crown into the glass bath

Heat transfer from crown into the glass bath

Combustion space

Flame

Burner

Glass Melt

Batch

Furnace crown

Combustion gases

Heat transfer from flame into the batch and glass melt

Heat transfer from flame to the crown
Glass currents in a longitudinal cross section of glass furnace

- **MELTING END**
  - 1500-1600°C

- **THROAT**
  - 1450°C

- **Working End**
  - 1250-1300°C
  - 1100°C

- **Temperature profile**
- **Hot spot**

- **Glass Currents**

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Convection currents in glass bath

Longitudinal glass currents due only to convection

Glass currents due to amount of glass produced (pull rate)

Combination of glass currents formed by convection and glass produced (pull rate)
Glass currents in a lateral cross section in the glass bath

Glass melt

Convection currents
Physical modelling studies began in 1982 in Şişecam.
Mathematical modelling studies began in 1990 and physical and mathematical modelling were used together until 1996.
Since then mathematical modelling is used for design and operation of glass furnaces.

Mathematical modelling studies were validated
- with physical modelling results and
- with glass furnaces in operation.
Mathematical Modelling

In glass industry, mathematical modelling has been accepted as a powerful tool
• in application of developments in glass melting processes to furnace design,
• in improvement of operating conditions in a furnace,
• in bringing up the criteria for new techniques in glass melting,
• for product quality evaluations related to glass production,
• for environmental considerations,
• in control of the processes,
• for optimization of production and
• as an on-line tool for managing the process.
Modelling of Glass Furnaces involves many topics

**Hardware**
- Fast servers
- Quickly Evolving
- Operating systems
- Versions
- Compatibility with the original code
- Clusters
- Domain decomposition
- // processing

**Types of furnaces**
- Container
- Float
- Tableware
- Fiber

**Types of glasses**
- Soda lime, borosilicate, e-fiber, crystalline,
- Low iron to privacy
- Different colors

**Modelling a furnace**
- Properties
- Assumptions
- Alternative designs
- Availability of additional systems

**Development**
- In glass
- In combustion

**Development of a furnace**
- Dimensions
- Energy
- Emissions
- Furnace life

**Evaluation of Results**
- Critical criteria
- Quality indicators

**Software**
- Needs
- Validation
- Test
- Less assumptions
- Fh
- NOx
- Quality
- Radiation in glass
- Radiation in combustion

**New concepts**
- Melting
- Refining
- Homogenizing
- Combustion
- Fuel
- Exhausts
- Waste heat
- Materials
- Insulation
- Life
Glass Industry, Glass Furnaces and Modelling

Şişecam Furnace Model

- Glass Bath Model
- Combustion Space Model
- Combined Model
  - Results from Glass bath
  - Results from Combustion space
    - Diffusion Model
      - Bubble Model
        - Particle Model
          - Residence Time and Tracer Analyses
    - NOx emissions Model
      - Thermal Performance Analyses
        - Melting and Refining Efficiency Analyses
          - Combustion space
            - Glass Bath model
Equations solved in the mathematical model

<table>
<thead>
<tr>
<th>Equation</th>
<th>( \phi )</th>
<th>( \rho )</th>
<th>( \Gamma_\phi )</th>
<th>( S_\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>1</td>
<td>( \rho )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>x-momentum</td>
<td>( u )</td>
<td>( \rho )</td>
<td>( \mu )</td>
<td>(- \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \eta \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) )</td>
</tr>
<tr>
<td>y-momentum</td>
<td>( v )</td>
<td>( \rho )</td>
<td>( \mu )</td>
<td>(- \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \eta \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) )</td>
</tr>
<tr>
<td>z-momentum</td>
<td>( w )</td>
<td>( \rho )</td>
<td>( \mu )</td>
<td>(- \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left( \eta \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) )</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>( k )</td>
<td>( \rho )</td>
<td>( \frac{\mu u^k}{\sigma_{k,eff}} )</td>
<td>( Gk - \rho \varepsilon )</td>
</tr>
<tr>
<td>Turbulent dissipation</td>
<td>( \varepsilon )</td>
<td>( \rho )</td>
<td>( \frac{\mu u^k}{\sigma_{\varepsilon,eff}} )</td>
<td>( (C_1 G_k - C_2 \rho \varepsilon) \varepsilon / k )</td>
</tr>
<tr>
<td>Mixture fraction</td>
<td>( f )</td>
<td>( \rho )</td>
<td>( \frac{\mu}{\sigma_f} )</td>
<td>0</td>
</tr>
<tr>
<td>Species fluctuation</td>
<td>( g )</td>
<td>( \rho )</td>
<td>( \frac{\mu}{\sigma_g} )</td>
<td>( C_{g1} \mu t \left[ \left( \frac{\partial f}{\partial x} \right)^2 + \left( \frac{\partial f}{\partial y} \right)^2 + \left( \frac{\partial f}{\partial z} \right)^2 \right] - C_{g2} \rho \frac{\varepsilon}{k} g )</td>
</tr>
<tr>
<td>Soot mass fraction</td>
<td>( m_s )</td>
<td>( \rho )</td>
<td>( \frac{\mu}{\sigma_{m_s}} )</td>
<td>( S_{s,f} - S_{s,0} )</td>
</tr>
<tr>
<td>Stagnation enthalpy</td>
<td>( h_0 )</td>
<td>( \rho )</td>
<td>( \frac{\eta}{\sigma_h} )</td>
<td>( 0, \text{ (if no radiation)} )</td>
</tr>
</tbody>
</table>

\( K_\phi \left[ G - 4E_b \right] \)

\( \frac{\partial (\rho u \phi)}{\partial x} + \frac{\partial (\rho v \phi)}{\partial y} + \frac{\partial (\rho w \phi)}{\partial z} = \frac{\partial}{\partial x} \left( \Gamma_\phi \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_\phi \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_\phi \frac{\partial \phi}{\partial z} \right) + S_\phi \)

\( \phi \), dependent variable; \( \rho \), mixture density; \( \Gamma_\phi \), appropriate exchange coefficient and \( S_\phi \) stands for source term.
The conservation equations can be expressed in a general vector form as follows:

\[
\frac{\partial}{\partial x} (u\phi) + \frac{\partial}{\partial y} (v\phi) + \frac{\partial}{\partial z} (w\phi) = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial \phi}{\partial z} \right) + S
\]

where \( \phi \), \( \Gamma \) and \( S \) stand for any of the dependent variables, diffusion coefficients and source terms, respectively.

\( S \) includes

\( S_{e} \) (electrical source term) & \( S_{rad} \) (radiative energy source term)

Equations are linearised with the finite volume method for defined volumes and then solved by Simpler algorithm.
Temperature and velocity distributions in combustion space of an end-fired regenerative furnace.

Particles showing temperature and velocity of inlet air and combustion gases in combustion space.

A view from inside the furnace.
Temperature and velocity distributions in 
**combustion space**
of an end-fired regenerative furnace

A view from inside the furnace
Temperature and velocity distributions in 
glass bath
of an end-fired regenerative furnace

Particles showing temperature and velocity of melted glass in glass bath
GRID DISTRIBUTION

Grid distribution in different sections of a glass furnace combustion space model
Viscosity is a very important glass property

(An example for glass viscosity-temperature curve)
Heat flux and temperature exchange at glass bath – combustion space interface

Outputs from modelling: Pressure, U-, V-, W-velocities, temperature, heat flux, gas concentrations, soot, bubble size and distributions, particle size and distributions, ...
Temperature and velocity distribution in combustion space and glass bath
Convection currents from a transient model for a color change in a float furnace

Distribution and progress of a different input can be followed with time dependent modelling.
At each stage of development in mathematical modelling, modeling results have been validated with results from furnace measurements and actual furnace operation performance.

The high rate of accuracy in predicting the performance of glass furnaces enabled the extensive use of the model in developing new furnace design and operation conditions.

Comparison of throat glass temperature increase with pull rate in the furnace and in the model for a tableware furnace.

Comparison of temperature measurements through the glass depth at the exit of riser for a tableware furnace with modelling results.
New furnace designs developed by mathematical modelling are applied during cold repairs or new investments of furnaces.
Design and operation parameters for end-fired and side-fired furnaces, unit melters and oxy-fuel melters can be determined with modeling.

Besides, production of different glass types and colors from low iron to privacy can be investigated. Each design study requires specific modifications of modelling programs, new glass properties and new criteria for interpretation of results.

<table>
<thead>
<tr>
<th>In combustion space</th>
<th>In glass bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation parameters</td>
<td>Operation parameters</td>
</tr>
<tr>
<td>-Burner type</td>
<td>-Pull rate</td>
</tr>
<tr>
<td>-Excess air</td>
<td>-Cullet ratio</td>
</tr>
<tr>
<td>-Combustion air velocity</td>
<td>-Bubblers</td>
</tr>
<tr>
<td>-Gas velocity</td>
<td>-Electric boosting</td>
</tr>
<tr>
<td>-Fuel distribution within pipe in pipe burners</td>
<td>-Waist coolers</td>
</tr>
<tr>
<td>-Burner angle</td>
<td>-Stirrers</td>
</tr>
<tr>
<td>-Fuel distribution among burners</td>
<td></td>
</tr>
<tr>
<td>-Fuel consumption</td>
<td></td>
</tr>
<tr>
<td>-Preheat temperature</td>
<td></td>
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</tbody>
</table>

Design and operation parameters which are investigated and improved in glass furnaces
In the last glass furnaces installed, an additional 7 % of energy reduction is obtained by furnace design improvements.
Results from investigation on furnace performance and NOx emissions

Many design parameters have been optimized with mathematical modelling studies to achieve energy efficient furnaces with low NOx emissions.

![Graph showing energy transferred to glass bath vs. NOx emissions for different furnace cases]

- **Base case**
- **Improved furnace**
- **Improved furnace with fuel reduction**
An international benchmark for 150 container furnaces
From 1985 to 2015, 25-35 % of reduction in total energy input has been achieved in Şişecam.
Design and operation parameters determine the performance of a glass furnace. The thorough design of interacting variables enable higher efficiencies.

With extensive modeling investigations and feedback from operation, new designs are developed to produce glass
• at higher capacities and
• better quality
• with lower energy input and
• with less emissions.