CFD Modeling of glass melting processes

Presentation strongly reduced, i.e. confidential slides and pictures taken out

TNO | Knowledge for business

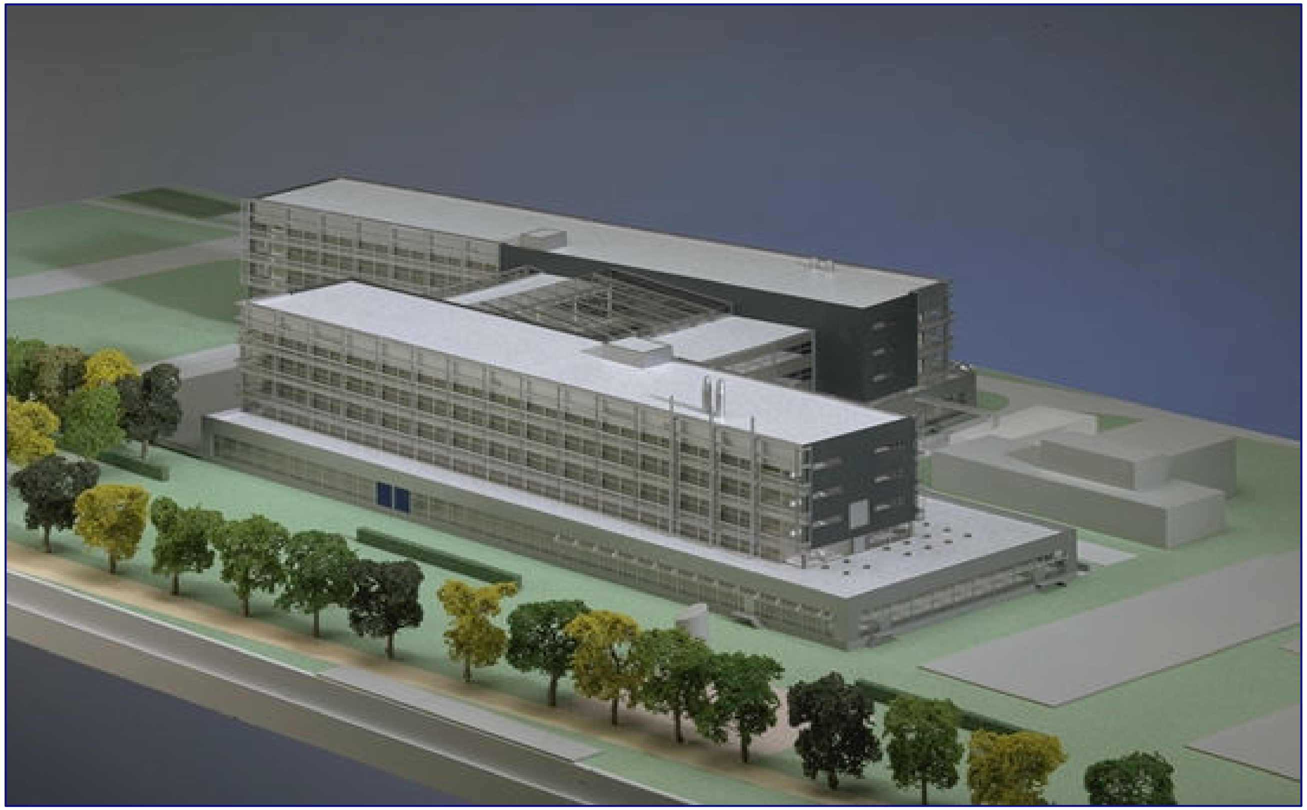
Modeling team

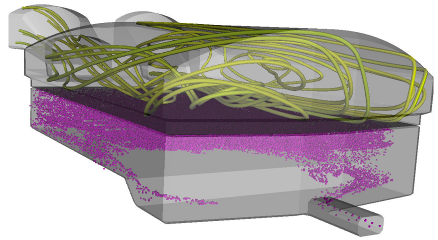
TNO Glass Group, the Netherlands

Glassman Europe

Lyon, France

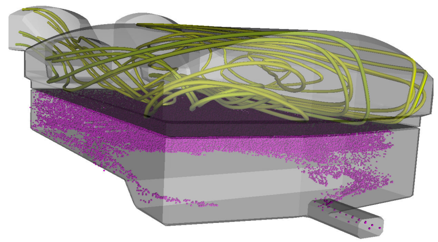
13-14 May 2009





Head Office TNO Glass Group, Eindhoven, The Netherlands

- TNO: Global provider of knowledge and technology
  - around 4,500 professionals
  - 450 patents
- ± 1,000 people serving process industries like oil, gas, chemistry, cement, energy, glass, etc.
- TNO Glass Group: > 30 scientific and industrial experts in glass segment



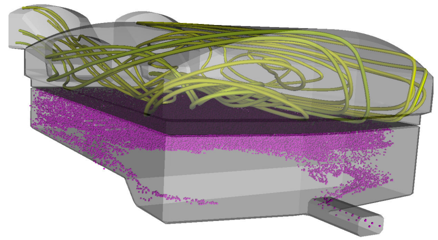
Introduction

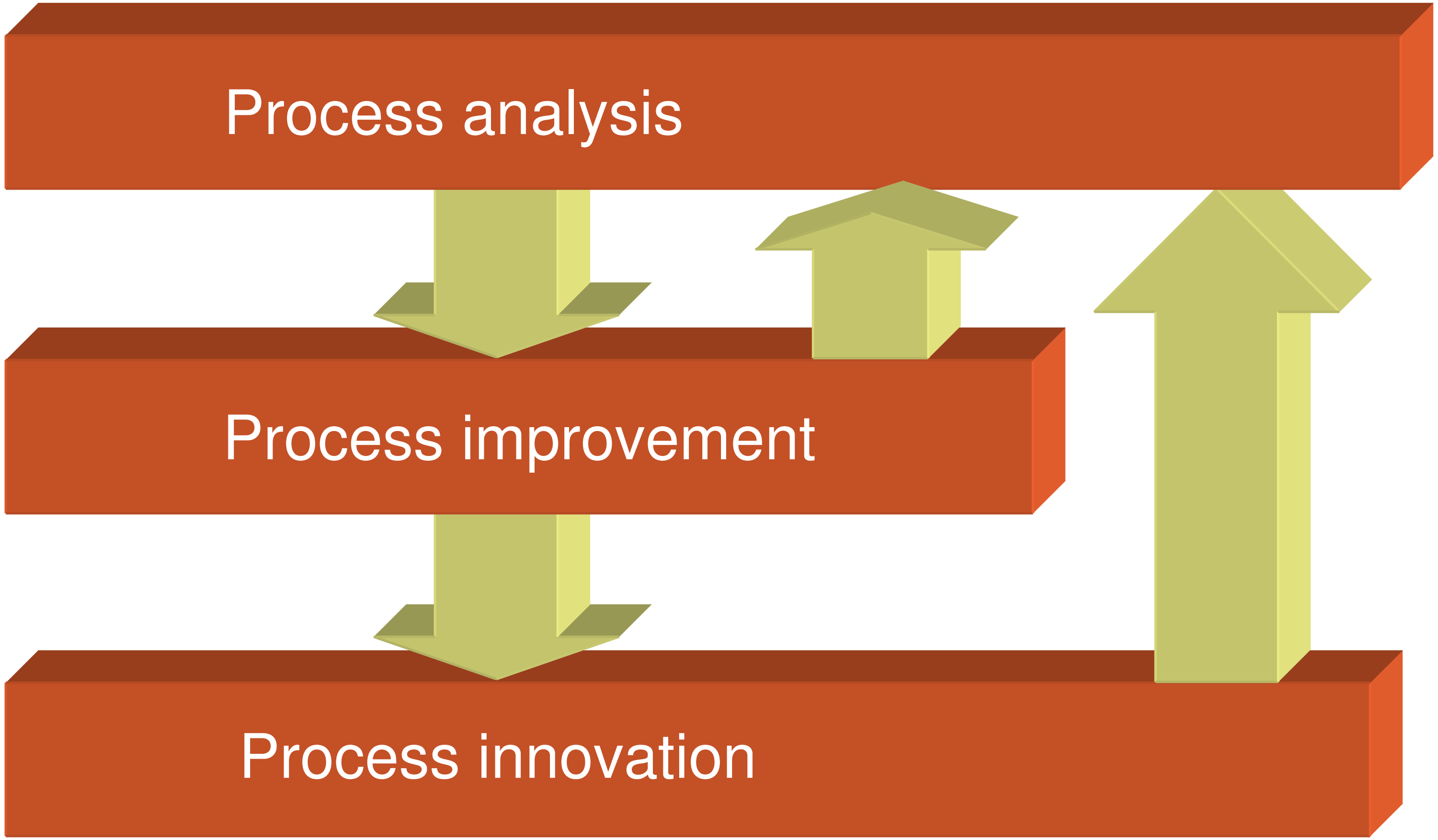
- Critical issues on glass melting for industry:
  - Decrease energy consumption
  - Improve product quality and decrease reject
  - Increase production and reduce production costs
  - Decrease emissions (pollutants, CO_2)
  - Increase furnace life time
  - Stabilize production process

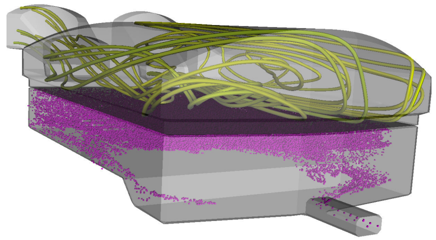
- More often than not:
  - Contradicting requirements
  - Process knowledge difficult to obtain from experiments
  - Trial-and-error methods expensive and time-consuming
  - Contra-intuitive conclusions

- CFD Modeling often a key to make steps forward
  - Mean to analyze, optimize and innovate complex processes involved

TNO CFD Modeling







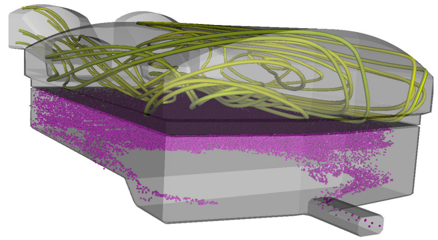
TNO CFD Modeling

What is CFD?

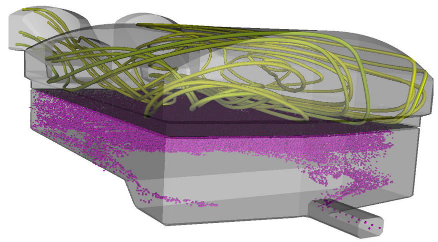
- CFD: Computational Fluid Dynamics
  - And not: Colors For Directors
- Flow, temperatures, etc. governed by:
  - Navier-Stokes equations (mass- and momentum conservation)
  - Energy conservation equation
  - Chemistry (species conservation)
  - ….
- Set of coupled, non-linear partial differential equations:
- Numerical approach as analytical solutions do not exist
- Hence, discretization of geometry in many small volumes
  - typically order of 10^5-10^6
- Iterative procedure to solve for each volume
  - Balances for mass, momentum, energy, chemical species

TNO CFD Modeling

Typical workflow



- Run a simulation and obtain converged result:
  - Typical turn-around time 1 day
    - for a complete glass melting furnace
  - Balances on all volumes for all variables should be “zero”
  - Variables should no longer change
- Inspection of results, e.g by
  - Visualization of variables in post-processor
  - Particle tracing
  - Comparison of monitor and thermocouples values
- Evaluate furnace performance parameters, such as:
  - Product quality
  - Energy efficiency
  - Emission level
- Formulate and implement potential improvements
  - on furnace design and/or process settings
- Run adapted simulation and verify assumptions

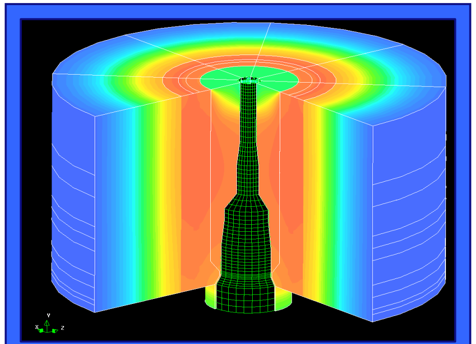


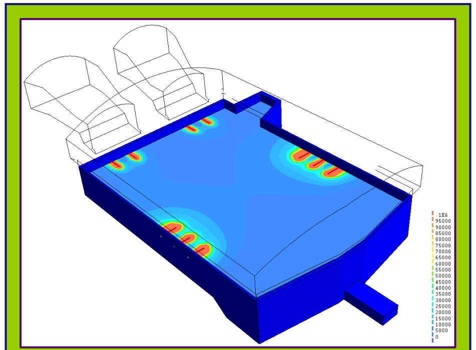
TNO CFD Modeling

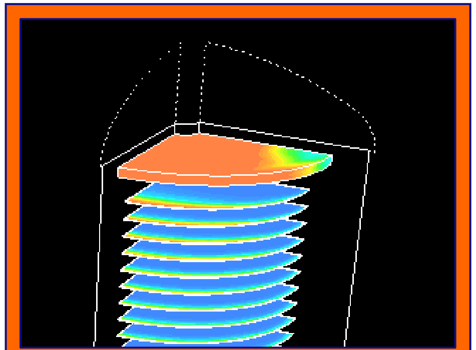
What do you get?

- Quality parameters by particle tracing, such as
  - min. residence time
  - melting and fining index
- Global mass-, species and energy balances
- 1D values on monitoring points of all variables (thermocouple values)
- 2D fields on surfaces / interfaces of:
  - Temperature, heat flux
  - Glass volatilization rate, refractory corrosion rate
  - Fining gas release rate
- 3D fields in melt / combustion space / refractories of:
  - Velocity components, pressure, temperature
  - Species concentrations such as:
    - Primary gas components (CO_2, CO, H_2O, CH_4, N_2, O_2, etc.)
    - Secondary gas components (NaOH, HBO_2, NO_x, soot, etc.)
    - Glass (fining agent, dissolved & released fining gases, coloring components)
  - Boosting potential fields and heat release
  - Properties (viscosity, density, absorption coefficient, etc.)

TNO CFD Modeling



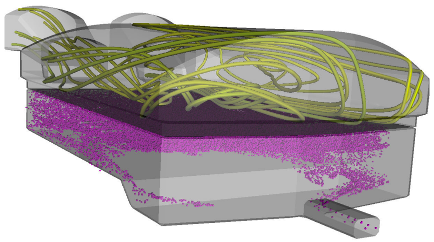




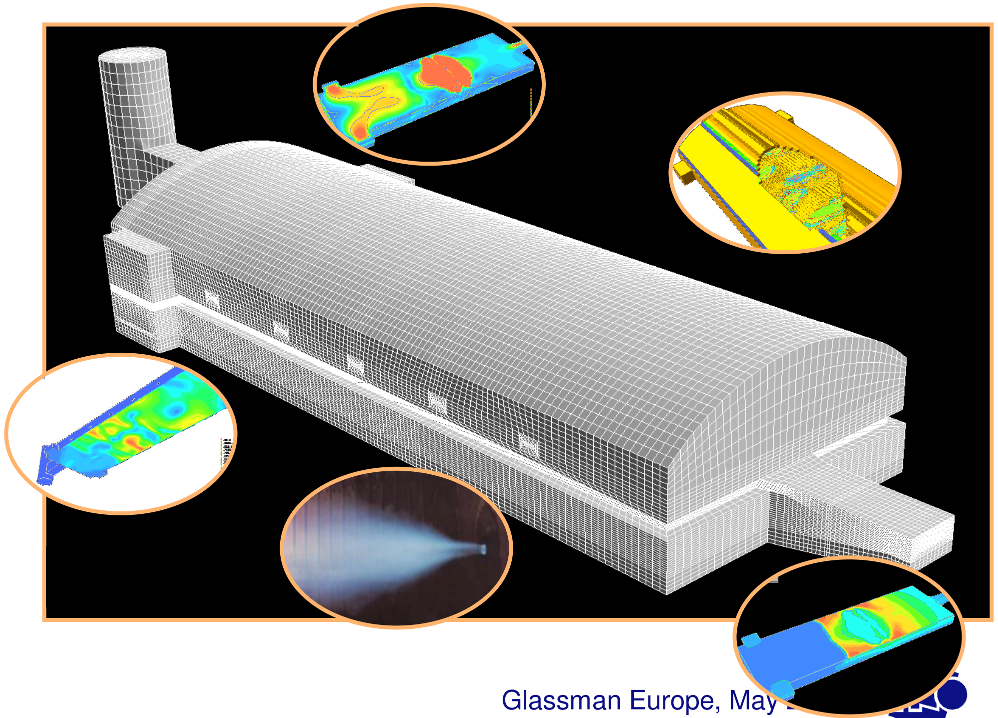
Name	X-Stream	GTM-X	CVD-X
Application	General purpose CFD	Glass-dedicated	CVD-dedicated
Functionality	• Time transient • Steady state • Body-fitted • Multi-domain • Structured/collocated • Parallel • State-of-the-art solvers • Turbulence • Combustion, soot, NO_x • Radiation • 3D & 1D walls • Particle trace • Boundary conditions	• Batch • Boosting • Bubbling • Foam • Redox • Volatilization • Corrosion • Quality indices • Drawdown • Thermal homogeneity • Refractory wear	• Gas phase reactions • Surface reactions • Sticking / ALD sticking • Trench Models • Compressible Flow • Rarefied flow (DSMC) • CHEMKIN interface • Multi-component • Plasma • Stiff systems solvers

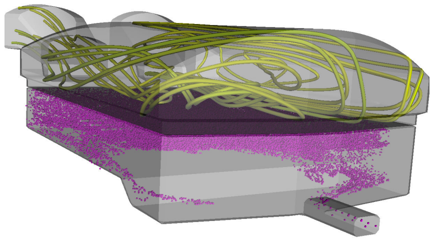
TNO CFD Modeling

GTM-X: Multi-physics / multi-domain



- Refractory:
  - Temperature
- Glass Melting:
  - Laminar buoyancy dominated flow
  - Glass color and properties from redox state
  - Melting and rheology in batch blanket
- Combustion space:
  - Turbulent flow, radiation modeling
  - Combustion
  - NO_x and soot formation/oxidation
  - Transport of pollutants
- Interfaces:
  - Volatilization and depletion
  - Refractory corrosion
  - Foam formation

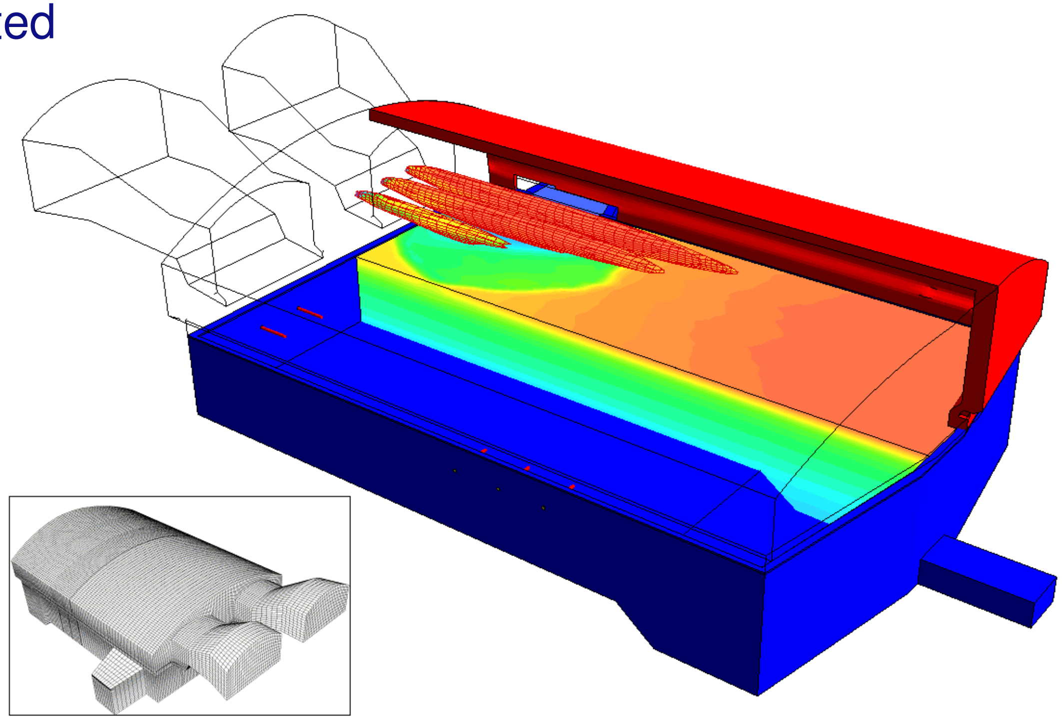


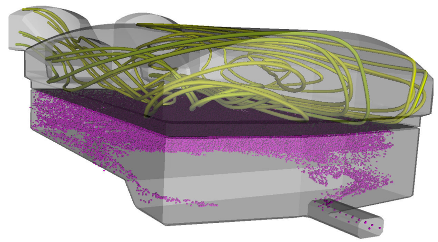


TNO CFD Modeling

GTM-X: Highlights

- Multi-physics modeling
- Non-orthogonal body-fitted grid
- Parallel computing and local grid refinement
- One GUI for pre- and post-processing
- Developed in close collaboration with industry
- Extensively tested and validated
- Equipped for design studies

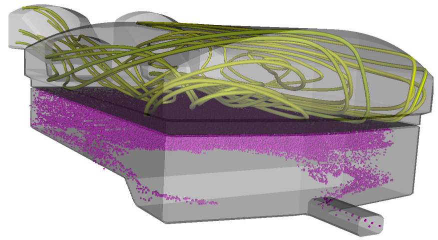




TNO CFD Modeling

GTM-X: Solutions and services for industry

1. Case studies: Base case and parameter variations
   - Stepwise approach in close cooperation with glass manufacturer
   - Main results
     - GTM-X model of furnace
     - Expertise & Consultancy
     - Optimized/enhanced furnace operation/design
2. Furnace support contracts
   - GTM-X model of furnace serves to answer (short-term) questions from production
3. Application support contract
   - Model set-up for furnaces mainly done by TNO
   - Delivery of models with GTM-X license attached
   - Customer able to perform additional modelling activities such as parameter variations



TNO CFD Modeling

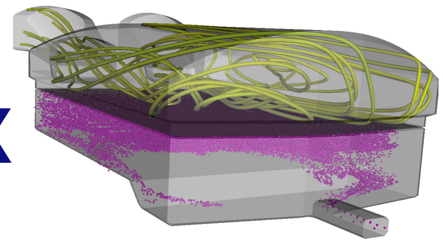
GTM-X: Solutions and services for industry

4. Licenses on GTM-X
   - Covering number of users and specific modules
   - Includes user support

5. Participation in GTM-X consortium
   - Development, testing & validation in close cooperation with group of major glass manufacturers
   - Execution of 3-year programme on further development of GTM-X
   - Running already since last century
   - Includes significant number of licenses with support

Industrial application of GTM-X

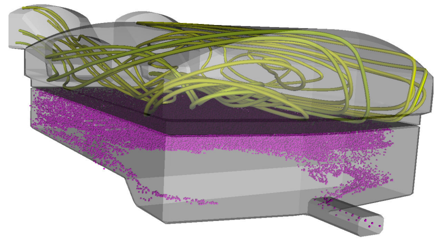
Characteristics



Fiber glass furnace characteristics

- Glass melt
  - Borosilicate fiber glass (E-glass), ± 100 tons/day
  - Two bubbler rows
  - Electrical boosting, ± 500 kW
  - Melting surface area ± 90 m^2
- Combustion space
  - Oxy fuel
  - Staggered positioned burners
  - Heat input ± 7.5 MW

Industrial application of GTM-X



Volatilization

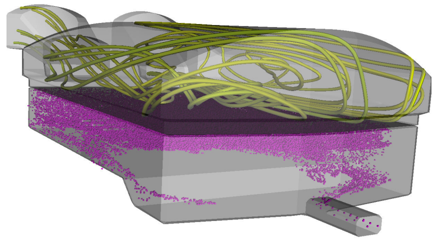
- Major volatile component from boron (B_2O_3)
- Most important reaction mechanism:

$$B_2O_3(m) + H_2O(g) \Leftrightarrow 2HBO_2(g)$$ (meta-boric acid)

- Depletion of boron due to evaporation has to be compensated by expensive overdosing
- Pollutant boric acid must be removed from flue gas by scrubber

Industrial application of GTM-X

GTM-X volatilization model



- Empirical relation obtained from
  - extensive lab experiments
  - measurements in industrial furnaces

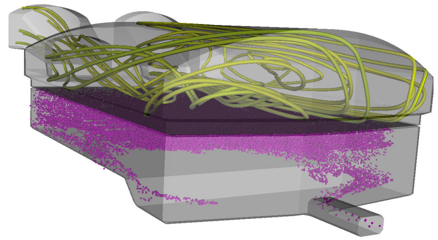
- Volatilization flux depends on <u>local</u> values:

$$\Phi_{HBO2} = f(T_{glass}, p_{H2O}, p_{CO2}, p_{CO}, \underbrace{V_{gas}, I_t}_{\text{Turbulent mass transfer coefficient}}) \quad [kg/s]$$

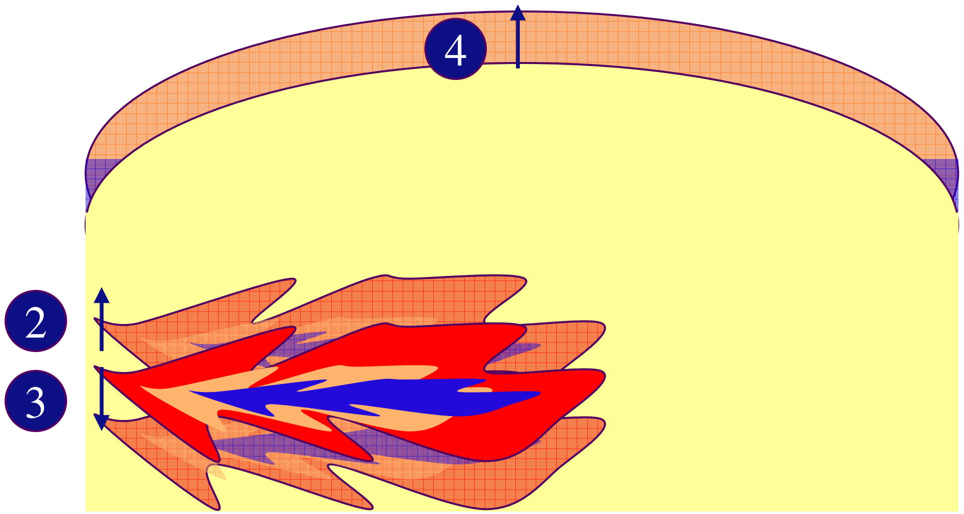
- Relation available in GTM-X:
  - Strong combination of empirical and detailed flow/temperature data
  - Accurate prediction of emission levels of volatile components

Industrial application of GTM-X

Parameter variations

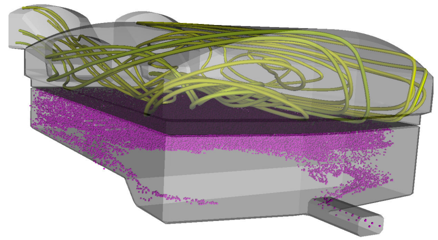


1. Base case
2. Burners lifted 10 cm
3. Burners lowered 10 cm
4. Crown lifted 10 cm with respect to glass surface



Industrial application of GTM-X

Summary of parameter study



	Volatilisation flux HBO_2 kg/s	HBO_2 in exhaust gr/hr	measured similar furn gr/hr	Change in Vola flux %
basecase	3.11E-03	11211	10646	0.0%
burners 10 cm lifted	2.93E-03	10553	10646	-5.9%
burners 10 cm lowered	3.24E-03	11667	10646	4.1%
crown 10 cm lifted	2.39E-03	8612	10646	-23.2%

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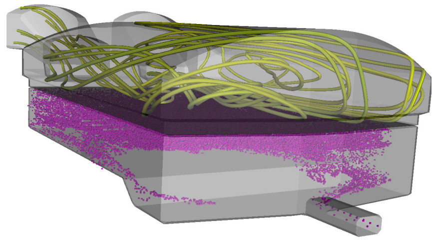
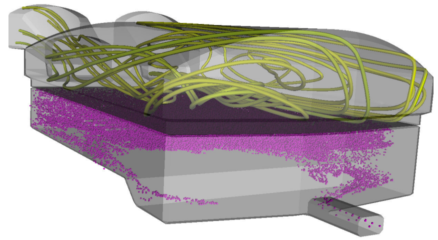
Conclusions on industrial application



- 25% lower evaporation rate of boron can be achieved
  - 100 tons/year of colemanite (boron batch compound) can be saved
- Volatilization rate
  - in agreement with measurements in similar furnace
  - not very sensitive to burner height
  - very sensitive to crown height
- Predicted foam thickness corresponds well with industrial observations

TNO CFD Modeling

Conclusions on general application for glass melting



Validated CFD modeling tools, such as GTM-X, useful for melting process to predict (amongst others):

- Pollutant emission levels
- Evaporation rates of volatile components

TNO's CFD model is offered and applied (in several settings for industry) to optimize melting processes and to accomplish:

- Energy consumption decrease
- Product quality improvement
- Reduction of production costs
- Production increase
- Furnace life time increase
- Production process stabilization