Mathematical Modeling Of Industrial Glass Furnaces

3rd Summer School On Nuclear And Industrial Glasses For Energy Transition
Nîmes, France

Jiří Brada, Glass Service, a.s.   Vsetín, Czech Republic   September 2023

Glass Service Group – Overview

GLASS SERVICE, a.s.

GS Departments

- R&D Melting
- Expert System
- Simulation Software
- Engineering
- Raw Materials
- Lab Services
- Audits & Data Analysis

A.SENS d.o.o.

Advanced Sensors
AI NIR Camera

F.I.C. (UK), Ltd.

Electric melting

F.I.C. Germany GmbH

Electric melting

FlammaTec, spol. s r.o.

Combustion equipment & accessories

FlammaTec Germany GmbH

Combustion equipment & accessories

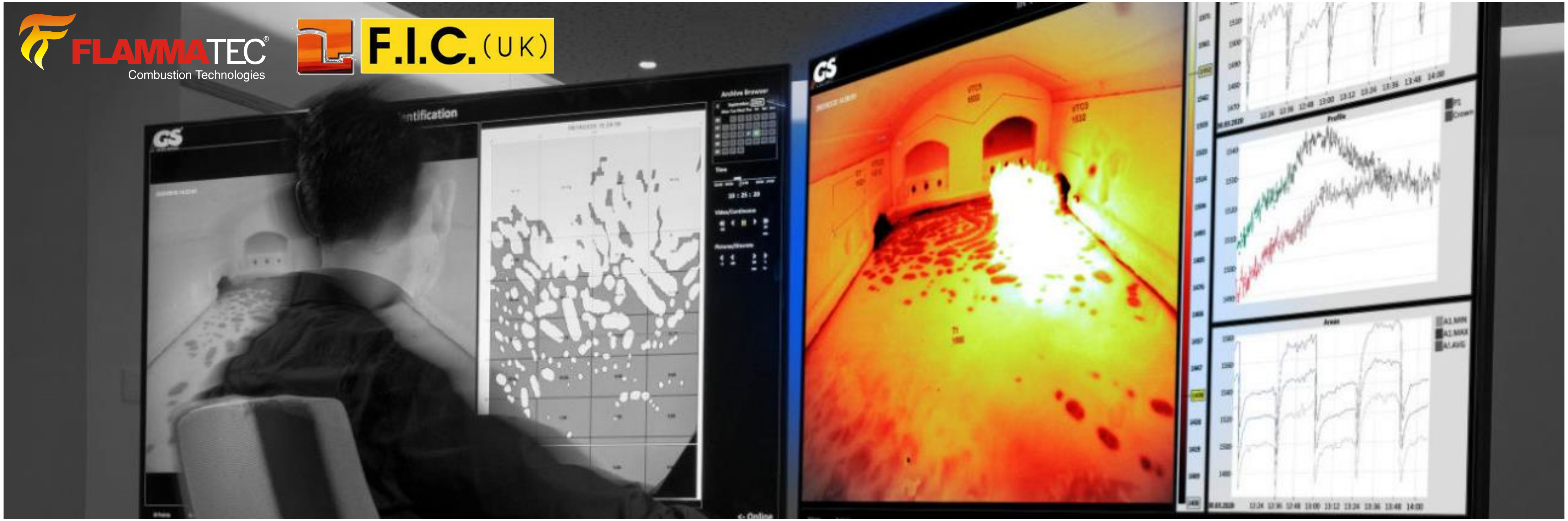
GS Offices

Czechia (headquarters), USA, China, Japan, Germany, Netherlands

GS Agencies

Brazil, Egypt, France, India, Indonesia, Malaysia, South Korea, Taiwan, Thailand, Turkey

Glass Service Group – Products & Services



ASSESSMENT

SIMULATIONS

3D advanced CFD simulation of the complete high temp. glass melting process for regenerator, melter, forehearth and forming.

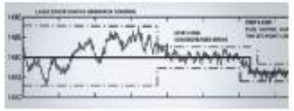
LAB SERVICES

Quick identification of glass defects and their origin to support quality improvements and operating parameter optimization.

AUDITS & DATA ANALYSES

Analyzing production, observing critical conditions and identifying optimization potential.

SMART PROCESS CONTROL



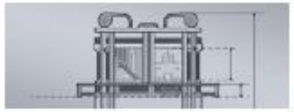
EXPERT SYSTEM *ES III*™

Full automatic process control resulting in stable operations, improved yield, reduced production costs and emissions.

CAMERAS & SENSORS

Smart AR sensors such as Camera systems in the Visible and NIR spectrum, simultaneously and on one chipset, compatible with Expert System.

PRODUCTS



ENGINEERING

Turn-key design and supply of specialized furnaces with high quality demands (for lenses, LCD or crystal).

RAW MATERIALS

Provide glass producers with Commodities, Specialties, Rare Earth Oxides and Polishing Compounds.

Glass Service Group In Numbers

32 years ago was the first seminar on furnace design

33 years ago GS started its journey

35 GFM Licensed companies using approximately 1000 Solvers

36 Million € annual revenue

110 Employees

140 Furnace NIR Cameras with AI BMS Segmentation software

400 *Expert System III* Furnace installations

800 Customers

1.000 Furnace design studies executed with GFM (by GS)

1.600 Furnaces data in our energy benchmarking database

5.000 FlammaTec burners installed

11.500 F.I.C. Electrode Holders installed

30.000 Glass defects analyzed

70.000 Tons of raw materials shipped each year

GLASS SERVICE — FLAMMATEC Combustion Technologies — F.I.C. ELECTRIC MELTING

GS GROUP OF COMPANIES

Glass Production Challenges - Overview

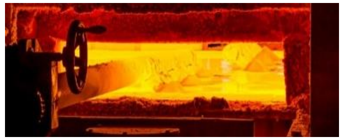
Glass Products



- Float glass: architecture, automotive
- Container glass: bottles, jars, drinkware
- Fiber glass: insulation, reinforcement
- Borosilicate glass: cookware, labware
- Lead glass / crystal: decorative holloware
- Chemically strengthened: Gorilla
- Etc.

Glass Production





- Very high energy consumption
- High pollutant production
  - CO_2 – combustion + batch melting
  - NO_x – high temperature flames
- High temperature process
  - Limited maintenance during lifetime
  - Difficult measurements
  - Limited inspection inside furnaces

Demands

- High quality for low price
  (optical clarity, durability, strength, safety, chemical resistance, etc.)

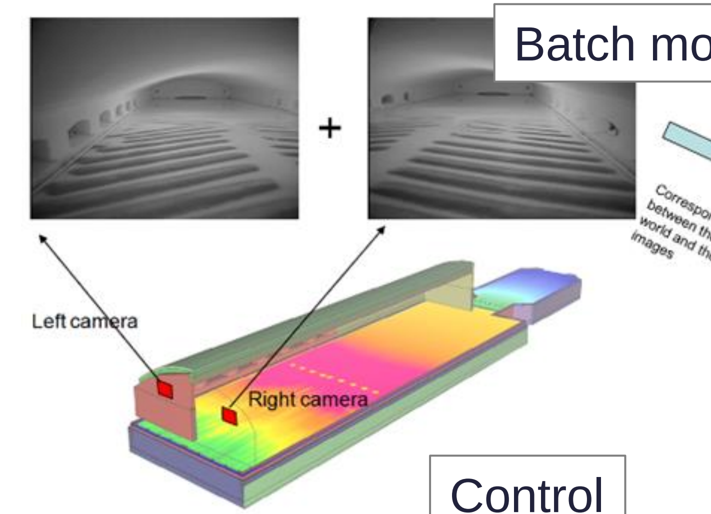
Demands

- **Decarbonization**
- High energy efficiency
- Low energy consumption

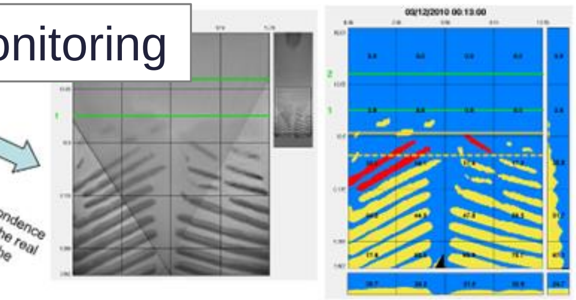
Furnace design optimization, alternative fuels, energy sources and materials, recycling, process innovation, advanced manufacturing technologies, emission control technologies, automation and digitalization

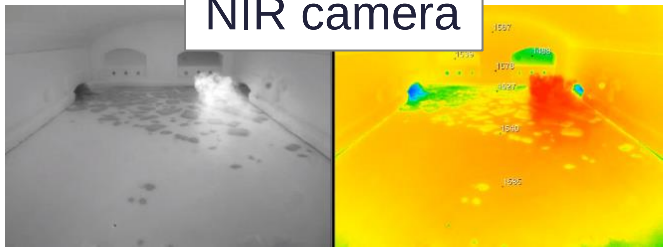
Glass Production Challenges – How Can GS Help ?

- **Analysis, Control, Improvements** using
  - Control system (ES III) + NIR camera + batch monitoring system
  - Laboratory measurements (defect analysis, melting tests, corrosion tests, glass properties, etc.)
  - High temperature observation (HTO) of processes in molten glass
  - **Mathematical modeling (CFD) – GS GFM**
  - Physical modeling (rarely used nowadays)

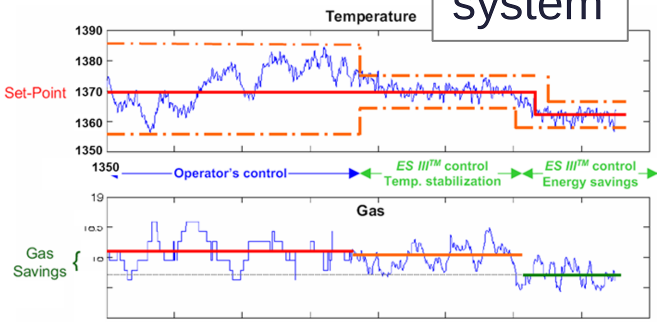


Batch monitoring

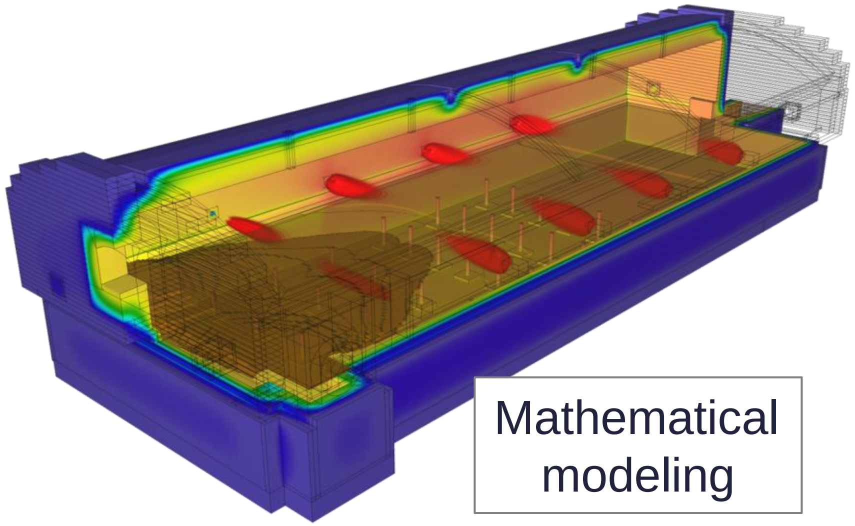




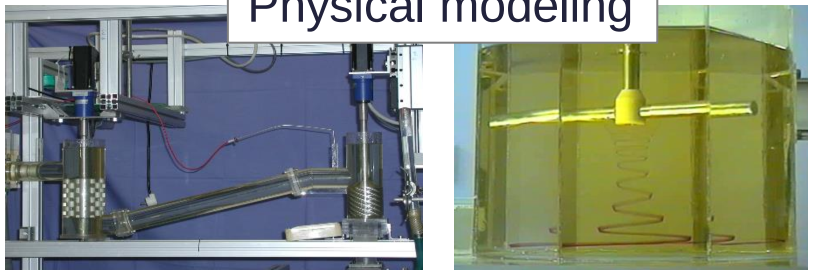
NIR camera



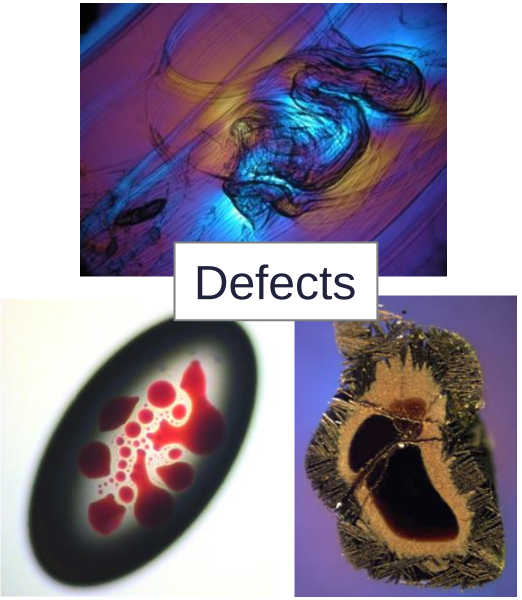
Control system



Mathematical modeling



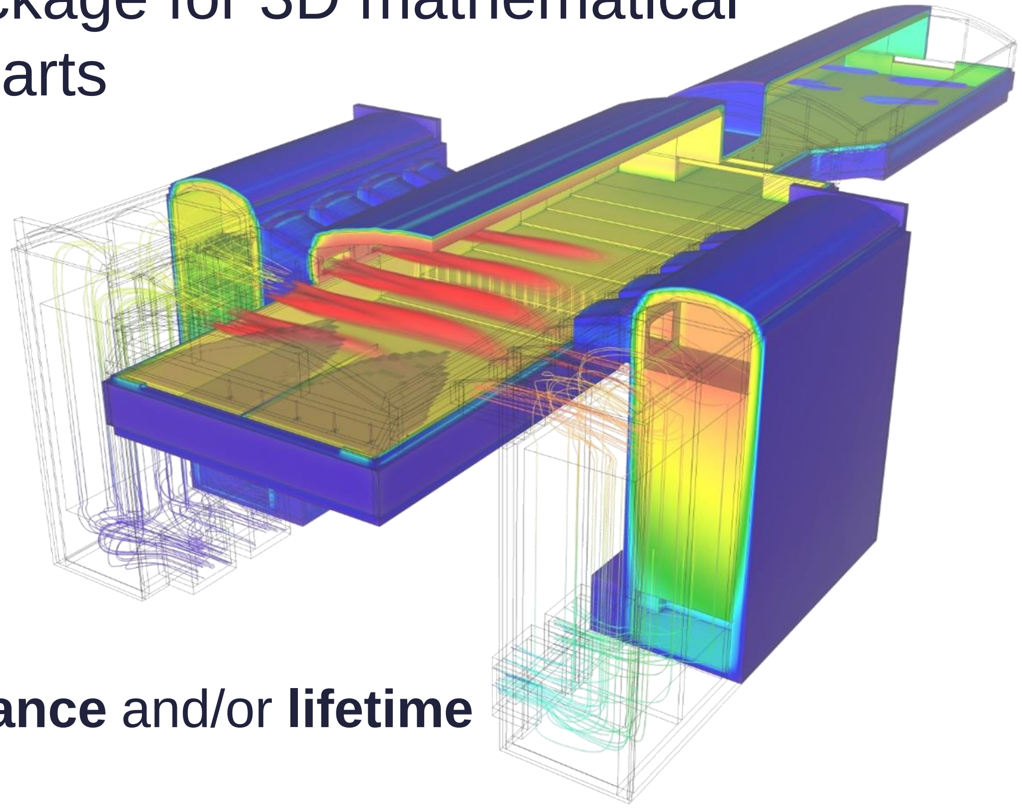
Physical modeling



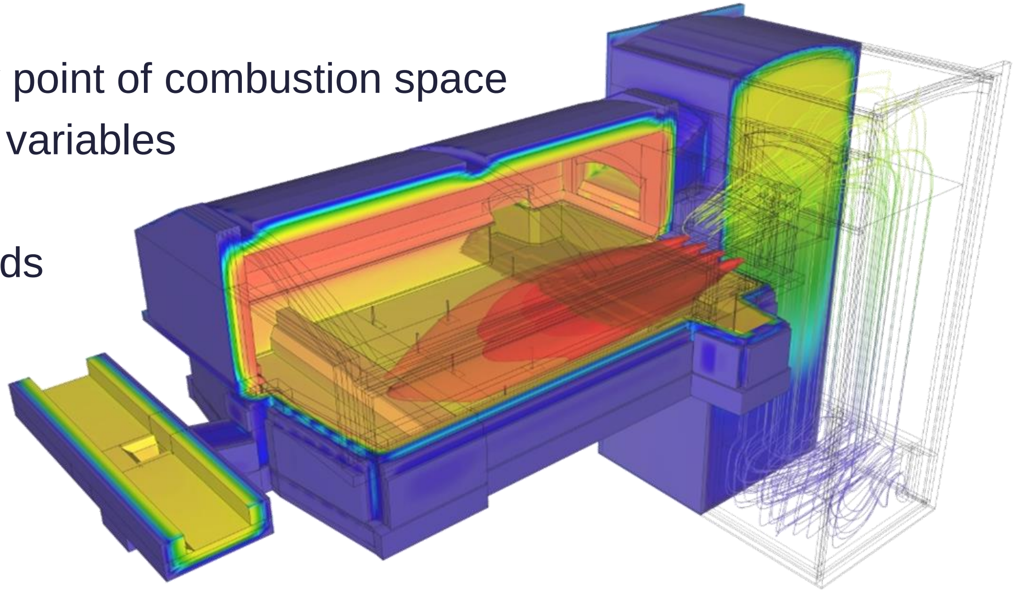
Defects

Glass Furnace Model (GFM) – Introduction

- **Glass Furnace Model (GFM)** is a software package for 3D mathematical simulation of glass melting furnaces and their parts
  - Melters, refiners
  - Working ends, distributors
  - Forehearths
  - Regenerators
  - Tin baths (**Tin Bath Module (TBM)** extension**)**
- What is furnace modeling good for:
  - Get **insight into processes** in glass furnace
  - Test ideas to **optimize furnace efficiency**, **performance** and/or **lifetime**
  - Test furnace **operating strategies**
  - Find good **tradeoff between glass quality and energy consumption**
  - Help **operators understand their furnaces**
- No need to interfere with production, no risk of furnace damage



GFM – Features And Capabilities

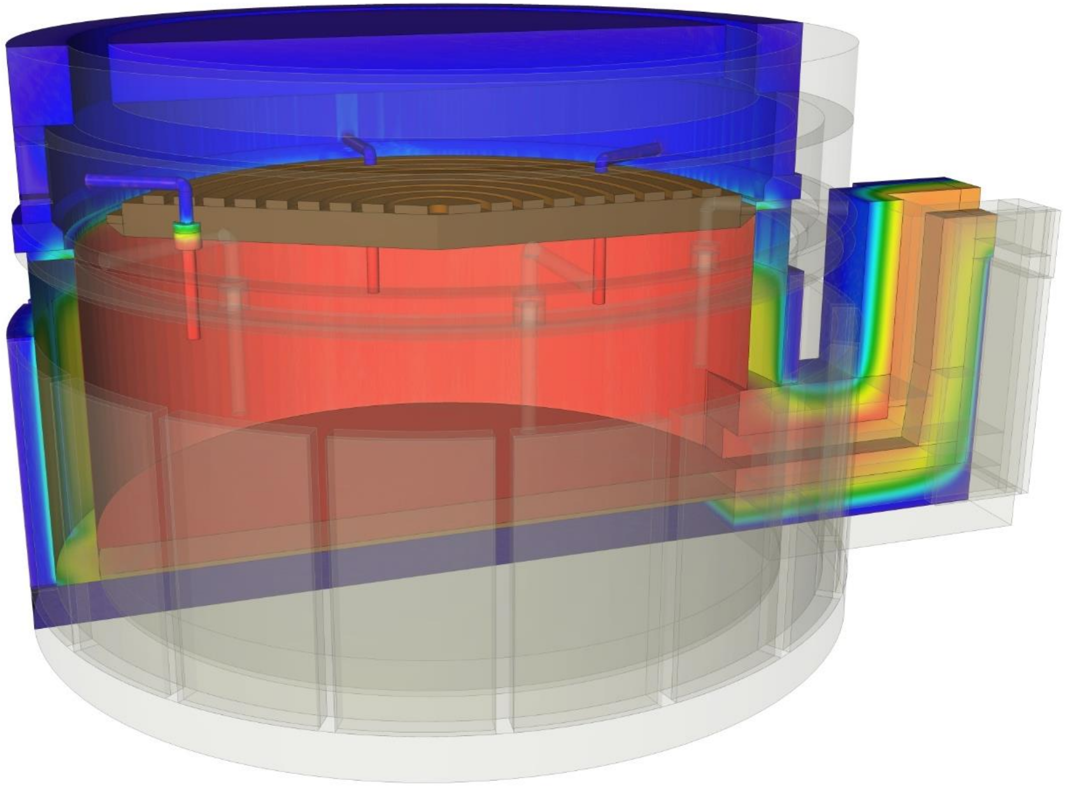


- Simulate what happens in a glass furnace:
  - Temperature, velocity, gas composition and other variables at any point of combustion space
  - Temperature, velocity, electric potential, current density and other variables at any point in glass and batch
  - Temperature at any point of refractories, insulations and other solids
- Simulate all common **features** of glass furnaces:
  - Batch melting, electric boosting, stirring, bubbling, cooling
  - Firing (gaseous and liquid fuels), oxy boosting, staging, air cooling
  - Regenerators / recuperators
  - Common control strategies (PID)
- Predict **steady state** (at constant operating parameters) or how the state develops in time (**transient**, time-dependent models)
- Provide **insight** in distribution of temperatures and other scalars and in glass and gas flow (visualization, particle tracing, statistics)
- Predict **glass quality** – how good is the furnace in removing bubbles, solid particles and inhomogeneities
- Provide information on **energy** consumption, **heat** fluxes and losses
- Predict formation of **pollutants**, calculate **evaporation** of volatile species

GFM – Limitations

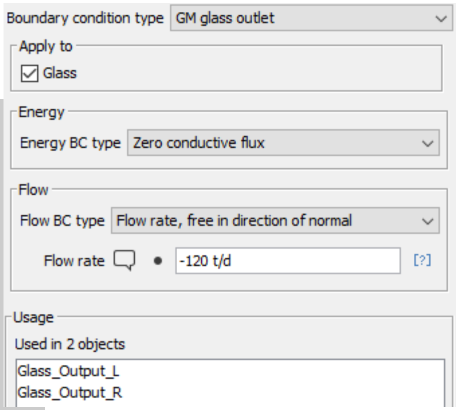
- Multiphase flows
  - There is no gaseous phase (bubbles) in glass melt which is considered a pure liquid
  - Needed in models with high volume fraction of bubbles
- Radiation in glass
  - Heat transfer calculation in glass melt uses effective thermal conductivity approximating radiation (Rosseland approximation)
  - Needed in models with ultra clear glasses
- Low-Re and laminar flow in combustion models
  - Very fine grid is required
  - Needed in detailed simulations of regenerators
- Batch melting
  - Batch chemistry is simplified
- GS long-term experience with
  - Modeling studies (total number 1000 !)
  - Running and tuning simulations
  - Interpreting their results

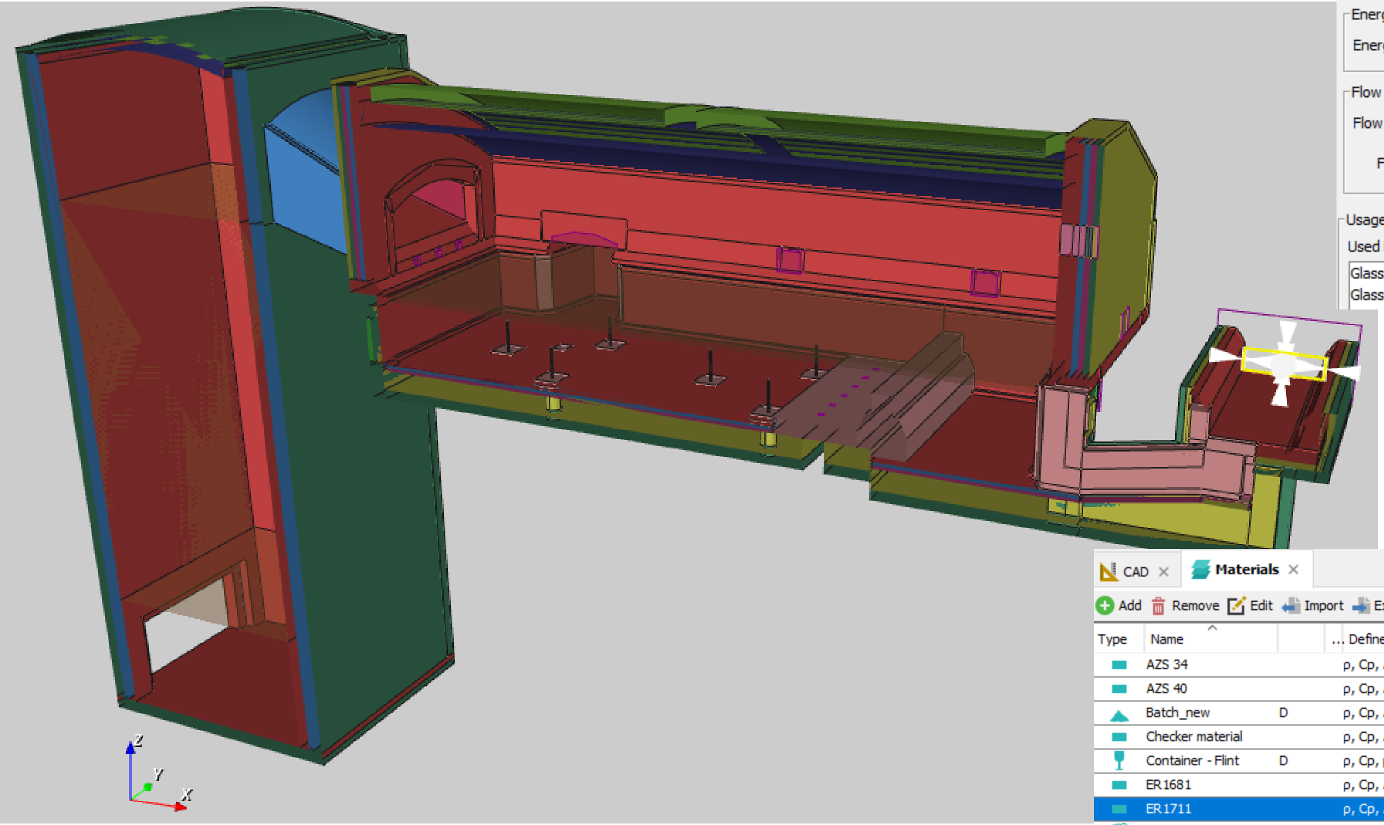
is used to minimize the influence of limitations

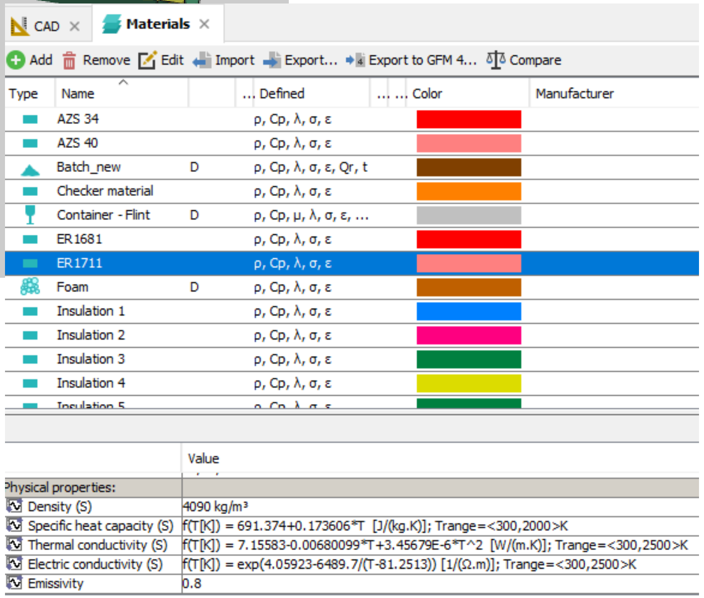


GFM – Modeling Workflow – Preprocessing

- Features integrated in Preprocessor
  - Geometry / design
  - Material properties
  - Glass properties
    - GS measurements
    - Composition based calculator
  - Boundary conditions
    - Burners and ports
    - Batch charging
    - Bubbling
    - Glass exit (pull)
    - Ambient space
  - Physical properties
    - Coolers (heat source)
    - Electrodes' connection
    - Stirrers' parameters
    - Porous wall parameters
  - Grid / mesh
    - Unstructured / structured
    - Controlled by few parameters, Automatic

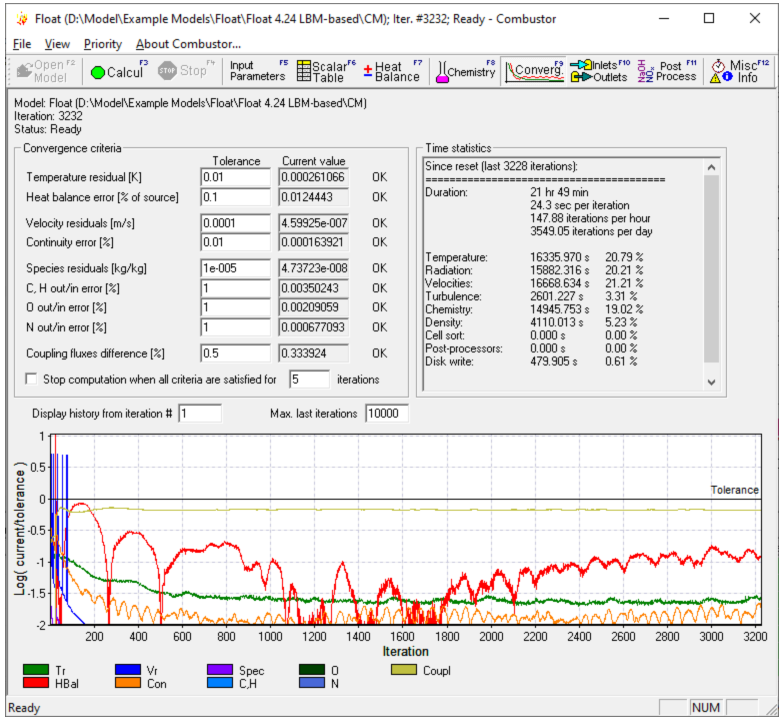


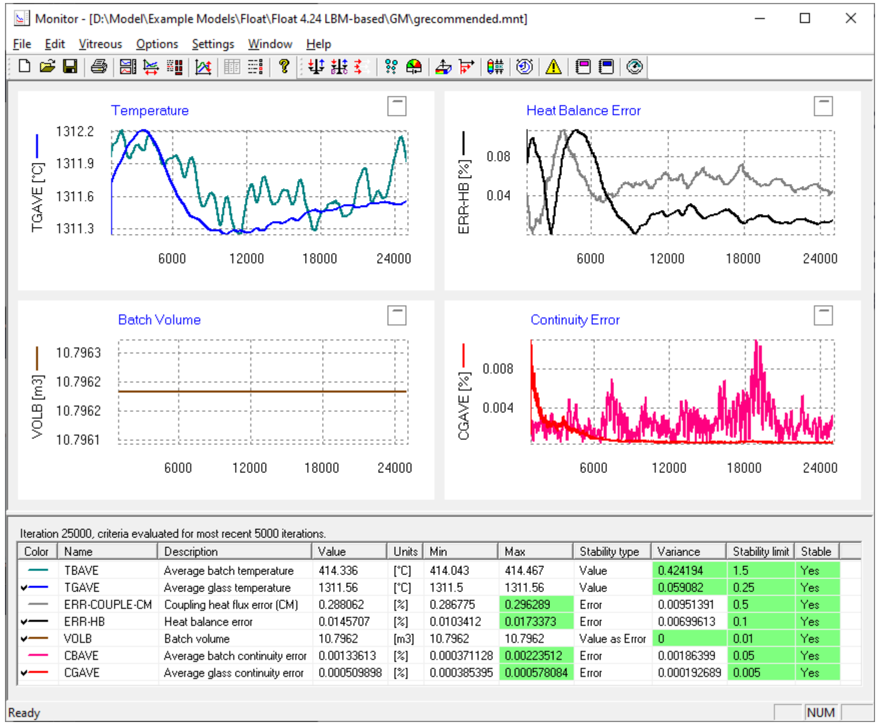




GFM – Modeling Workflow – Calculation

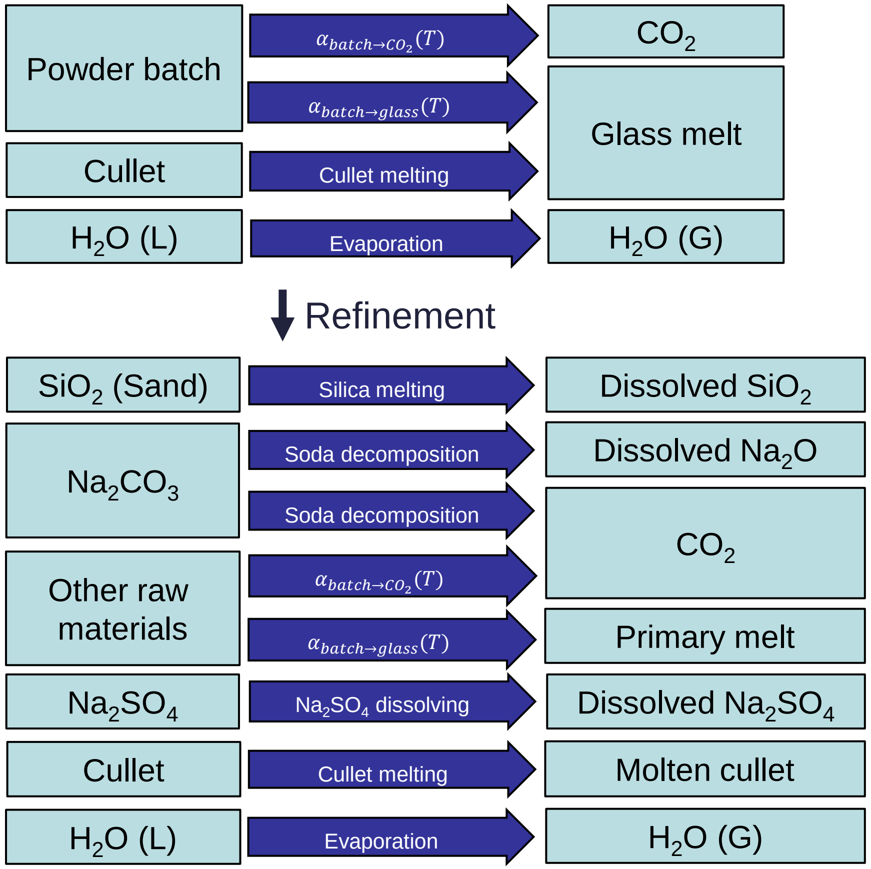
- Different phenomena and regimes are simulated using 3 solvers
  - Combustion model solver: chemistry (combustion), heat transfer (radiation, convection, conduction), gas flow (turbulence), porous walls (regenerators), pollutants (NO_x, NaOH)
  - Batch model solver: motion, chemistry, heat transfer
  - Glass model solver: glass flow (bubbling, stirring), heat transfer, electric boosting, foam
- Coupled calculation: simultaneously running solvers exchange data on their mutual interfaces
- Parallelization: OpenMP shared memory multiprocessing is used

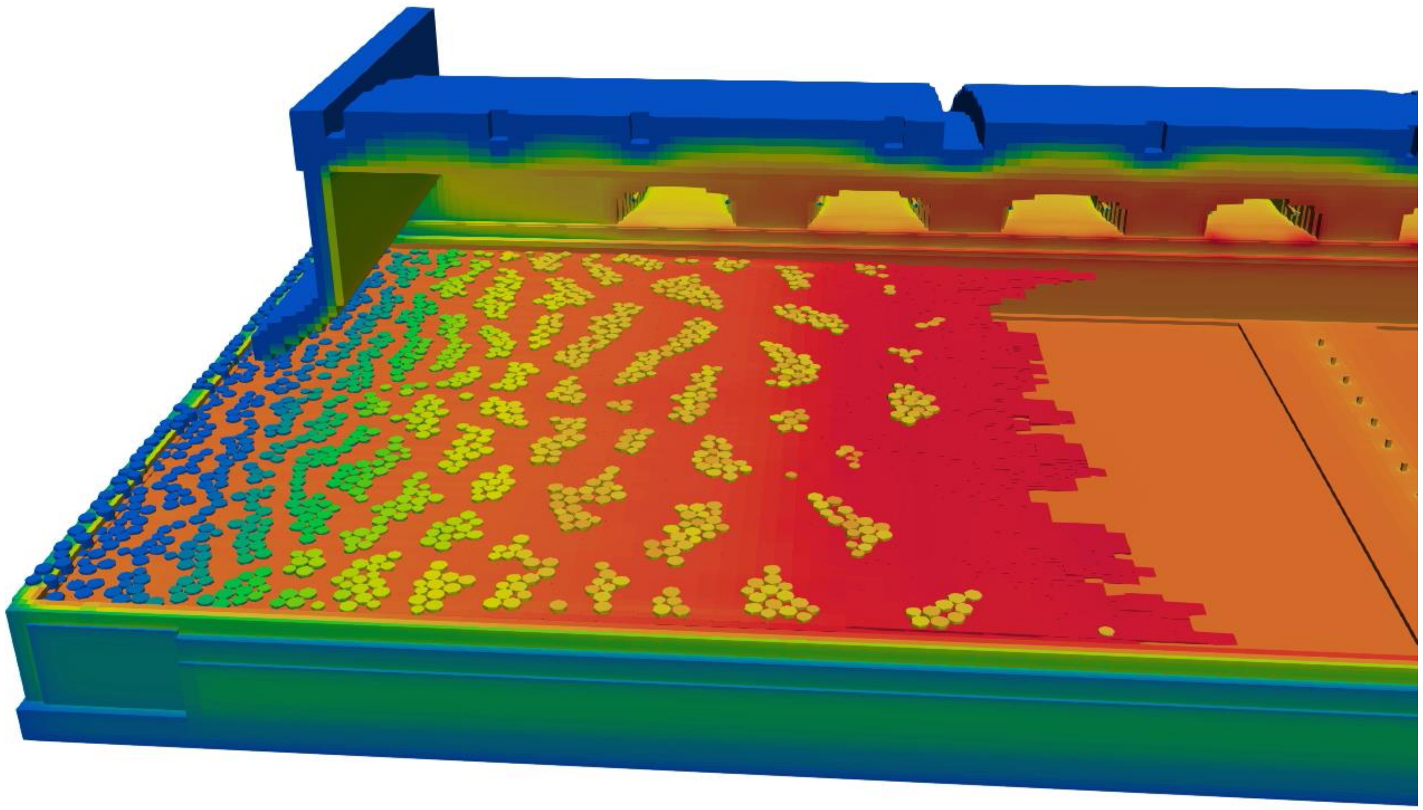




GFM Development – Recent New Features – DEB

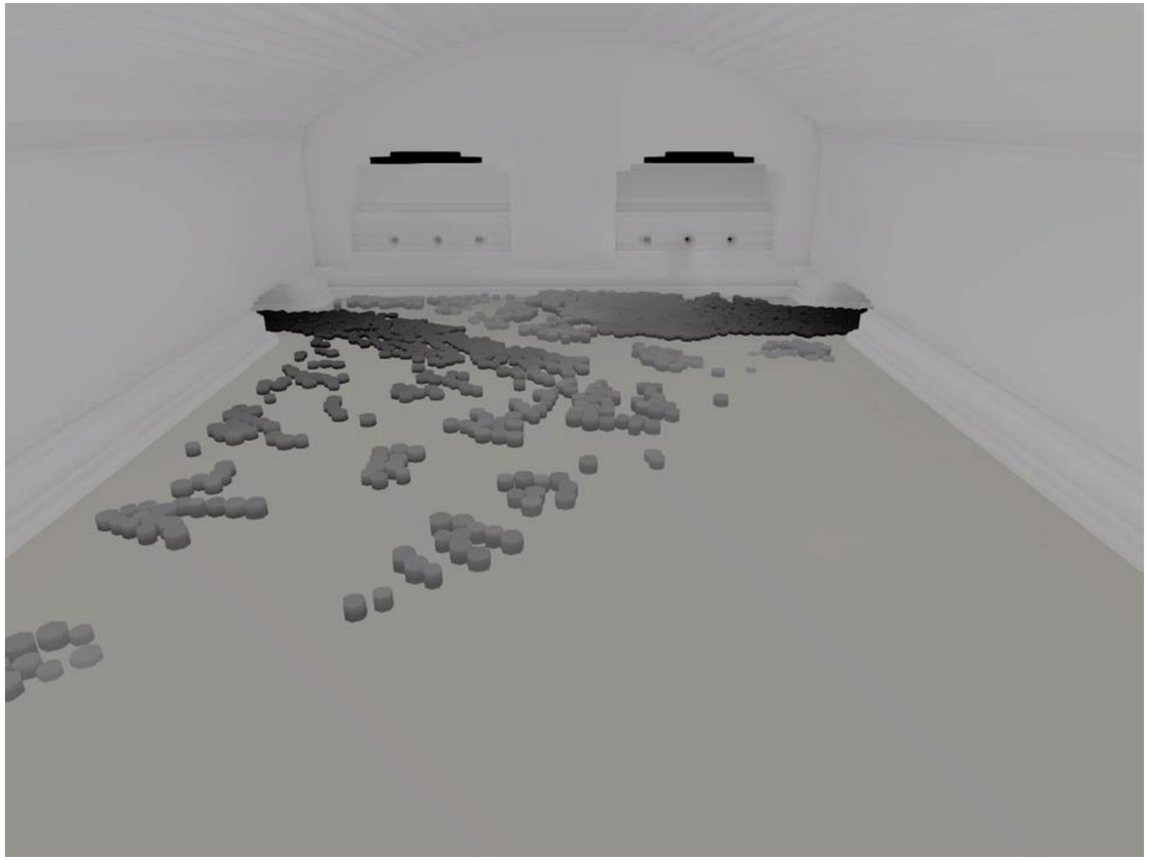
- DEB – Discrete Element Batch, particle-based model of batch motion
- Each input component transforms to one or multiple product components (open, refinable system)
- Heat transfer (conduction, radiation) is calculated in each 1D element
- “Product outflow model” determines production of batch gases and liquid glass melt





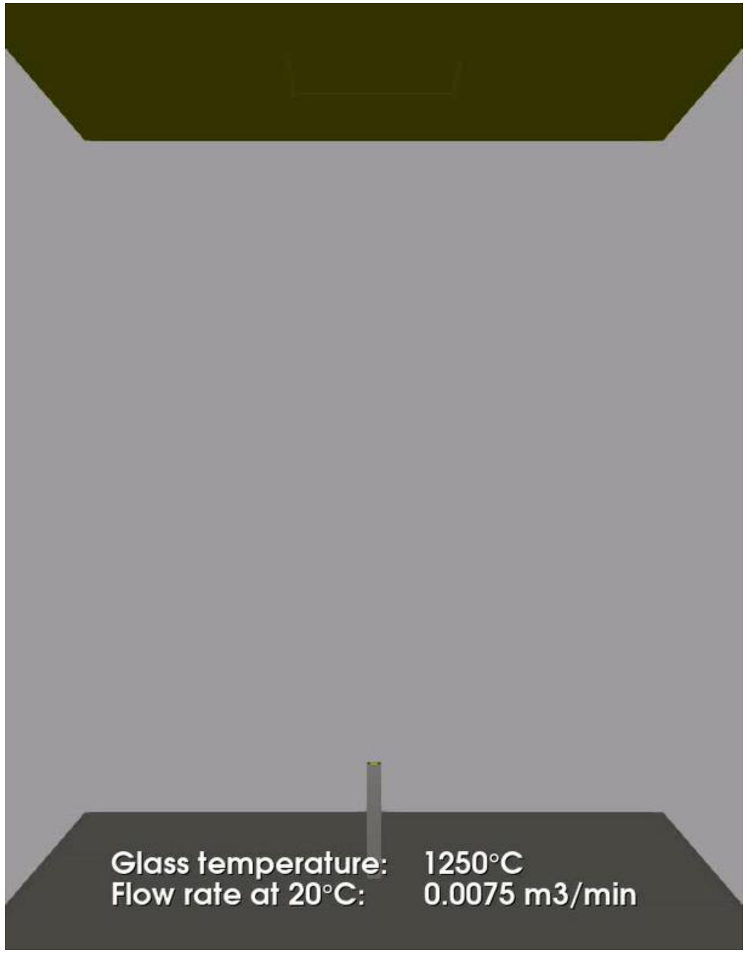
GFM Development – Recent New Features – DEB

- Time-averaged data are provided to combustion model and glass model
- Interaction between batch elements and flow of combustion gases and glass melt is considered
- Calibration is required to for parameters having the strongest influence on batch coverage, motion and heat transfer

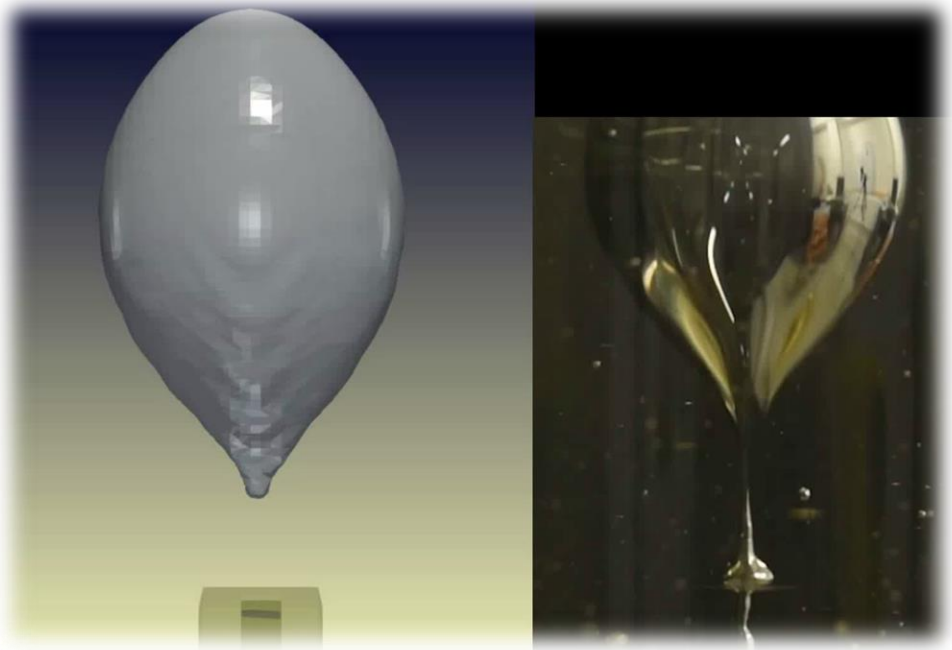


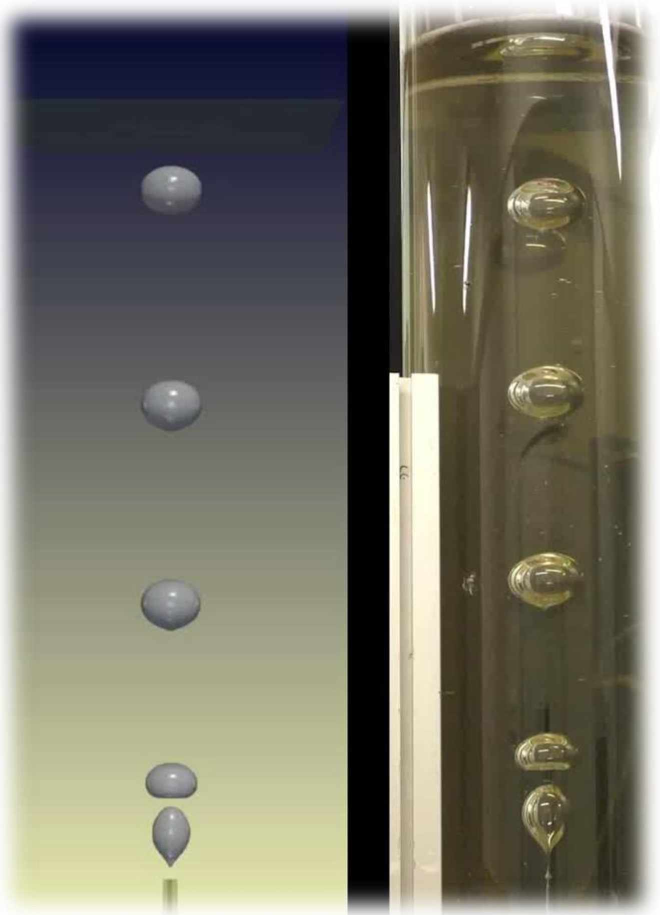
GFM Development – Recent New Features – Bubbling

- LBM (Lattice Boltzmann Method) based solver was used for detailed simulation of bubbling
- Comparison with physical model for validation
- Glass viscosity, glass depth and bubbling gas flow rate were varied to cover production ranges



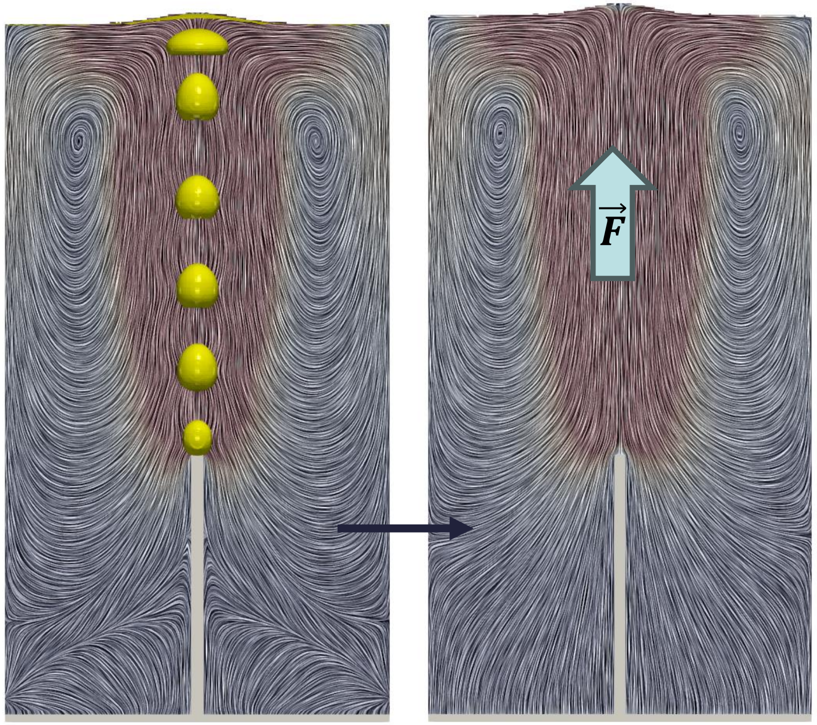
Comparison with physical model



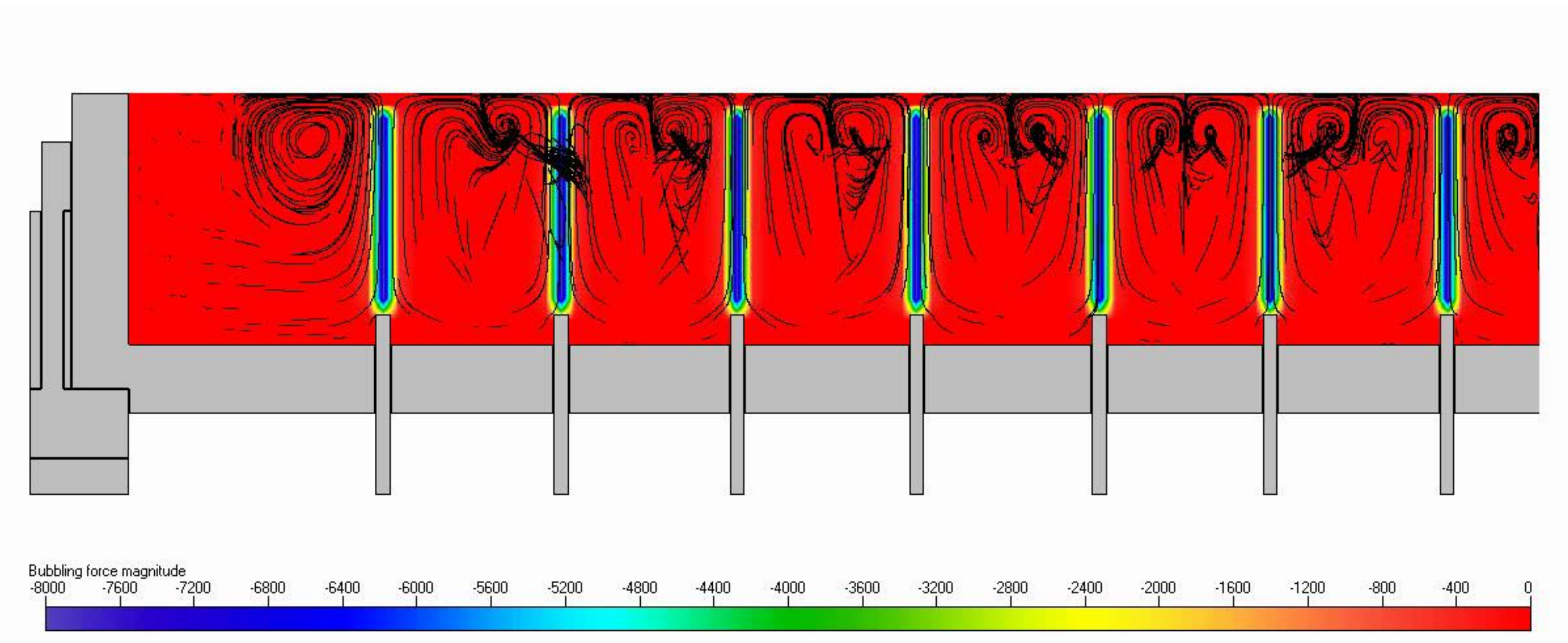


GFM Development – Recent New Features – Bubbling

- Time-averaged force evaluated in detailed models is used in calculations of full models ⇒ computational cost reduced



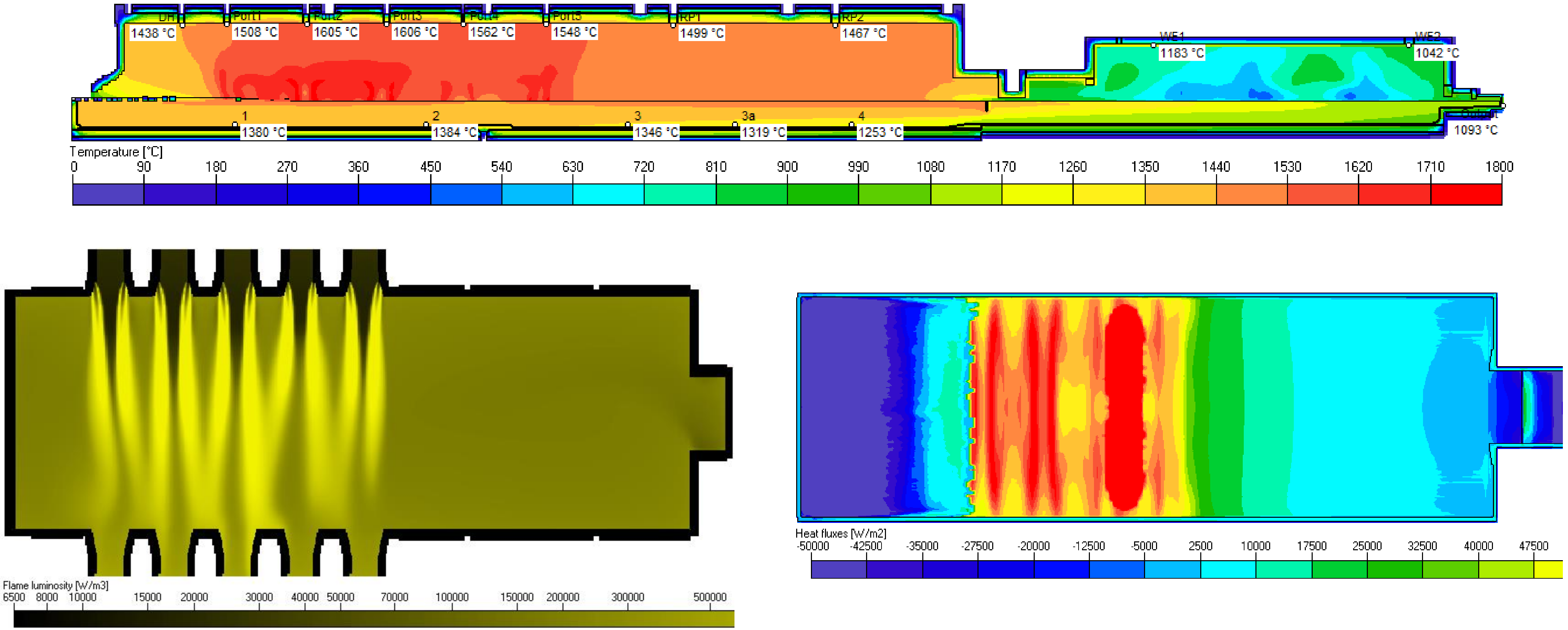
Detailed Simulation Approximation Model



Glass flow around bubblers in a float glass furnace (color shows bubbling force magnitude)

GFM – Modeling Workflow – Postprocessing – Visualization

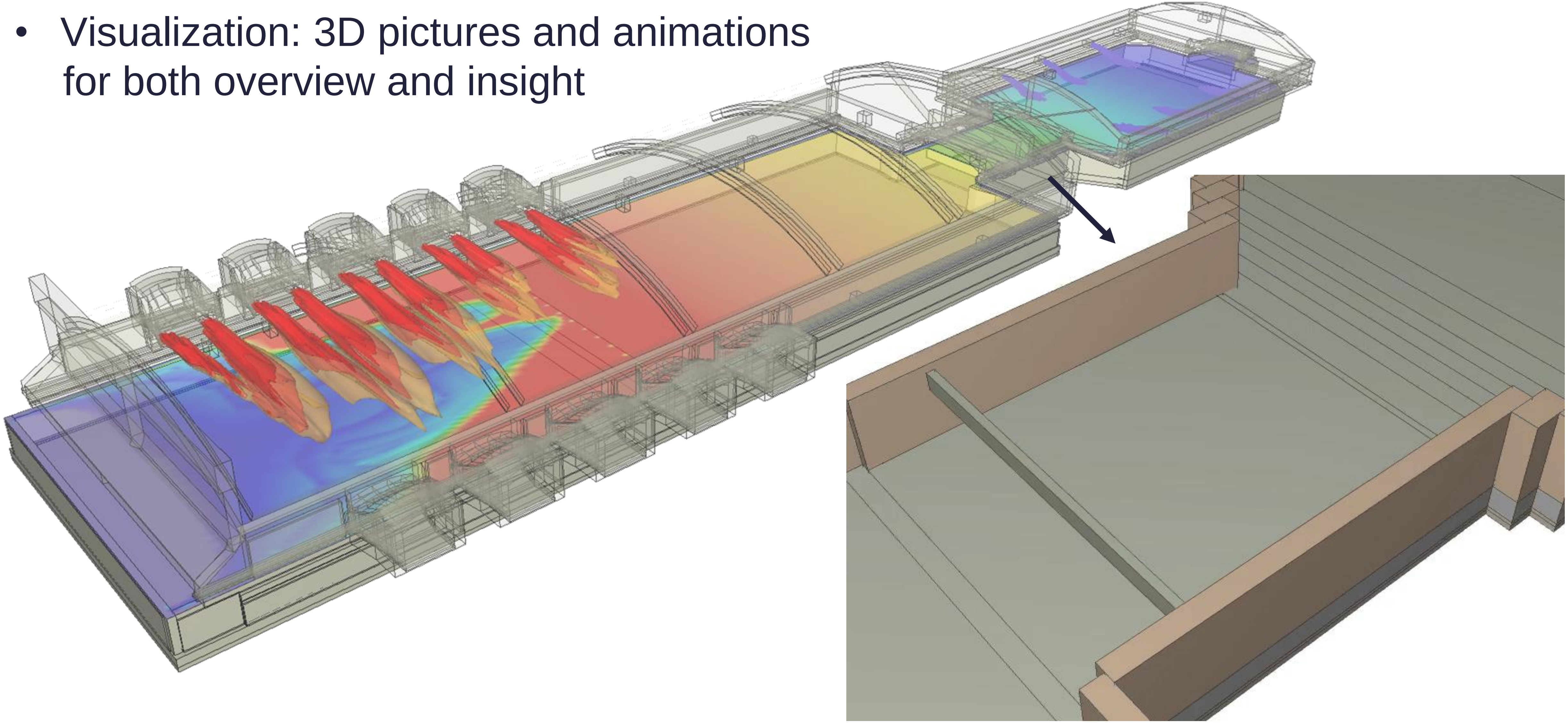
- Visualization: 2D pictures and animations for detailed insight and general overview



Temperature, flame luminosity, and heat fluxes to glass in a flat glass model

GFM – Modeling Workflow – Postprocessing – Visualization

- Visualization: 3D pictures and animations for both overview and insight

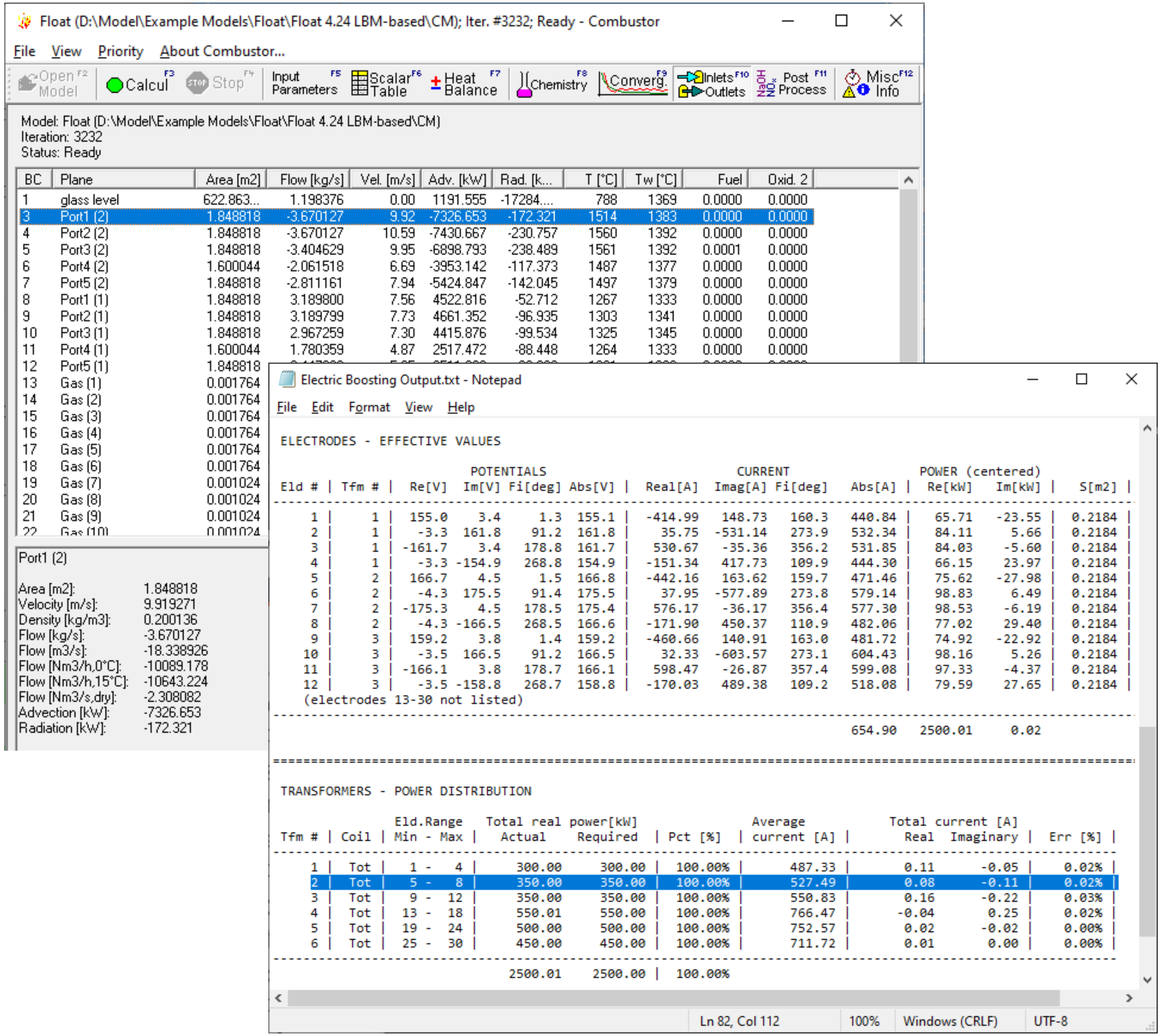


Glass flow from melter to working end, mixed by stirrers

GFM – Modeling Workflow – Postprocessing – Evaluation

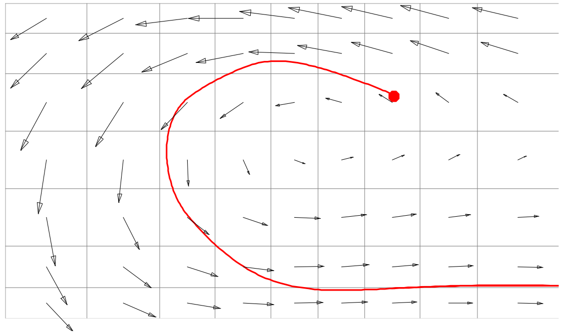
- **Heat balance**: combustion space, batch, glass, solids
  - Heat fluxes and sources / losses (water cooling, air cooling)
- **Inlets/outlets**: burners, ports, exhausts, batch chargers, glass pull
  - Temperature, energy, flow rates, composition
- **Electric boosting**: electrodes, transformers
  - Voltage, current (density), resistance, power (Joulean heat), Lorentz force
- **Bubbling**

- Evaluation can be done / statistics can be calculated in any part of the model to get required information



GFM – Modeling Workflow – Postprocessing – Quality Indicators

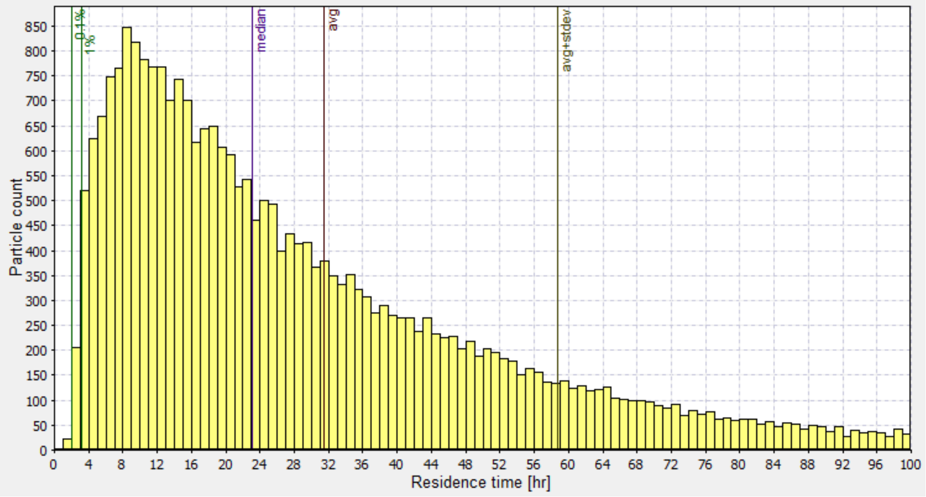
- **Particle tracing**: the basic idea is to calculate trajectories of particles in glass melt velocity field and evaluate variables characterizing glass along the trajectories
- Massless particles just follow glass flow and are used to calculate **glass quality indicators**
  - **Bubble growth index**: “how good is glass at removing bubbles”
  - **Sand dissolution index**: “how good is glass at dissolving sand grains”
  - **Mixing index**: mixing capabilities of glass, e.g., cords
  - Residence time distribution
- Glass quality indicators are **not absolute** – they are used to **compare** various **cases** of a model

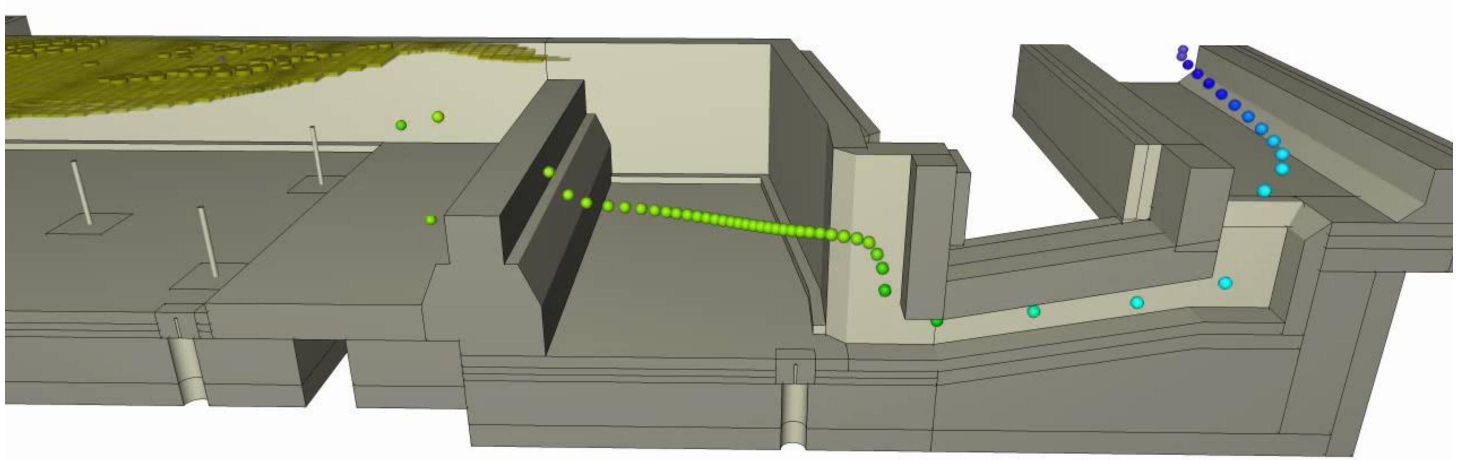


27777 particles calculated (161.6 per second); done 2023-09-19 09:07

	Minimum	Least 0.1%	Least 1%	Median	Average	Std. deviation	
Residence time [hr]:	1.45545	2.08776	3.1242	23.1076	31.4917	27.2623	
Sand dissolution index:	1.43874	2.24354	3.37352	29.9931	41.4018	36.9824	
Bubble growth index:	1.41559	2.1732	3.32184	30.0456	41.515	37.1588	
Mixing index:	1.29238	2.20493	3.68029	47.3725	67.2386	63.6302	
Melting index:	724838	1.1385e+06	1.7424e+06	1.46482e+07	2.01904e+07	1.78737e+07	
Fining index:	330642	456466	697945	7.48607e+06	1.04429e+07	9.56713e+06	(1400

Residence time distribution | Cumulative | Chart column width [hours] 1 | Copy to clipboard

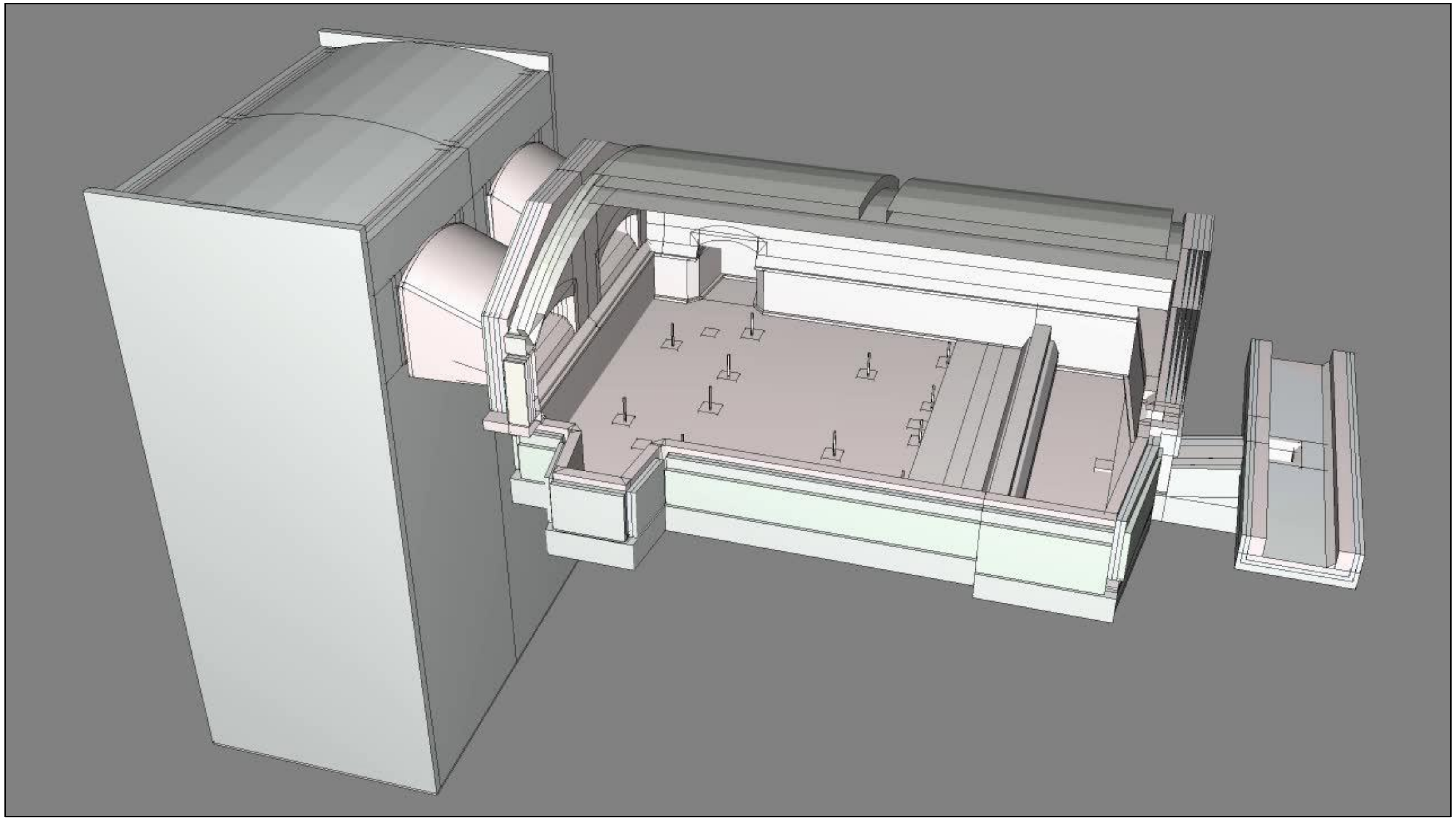




Trajectory with least bubble growth index

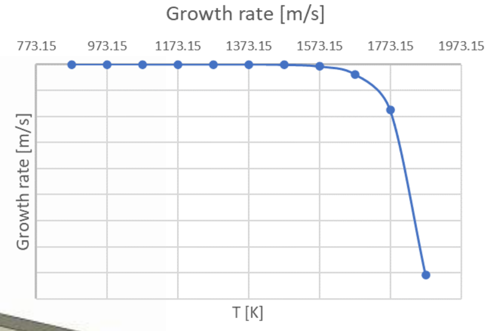
GFM – Modeling Workflow – Postprocessing – Bubble Tracing

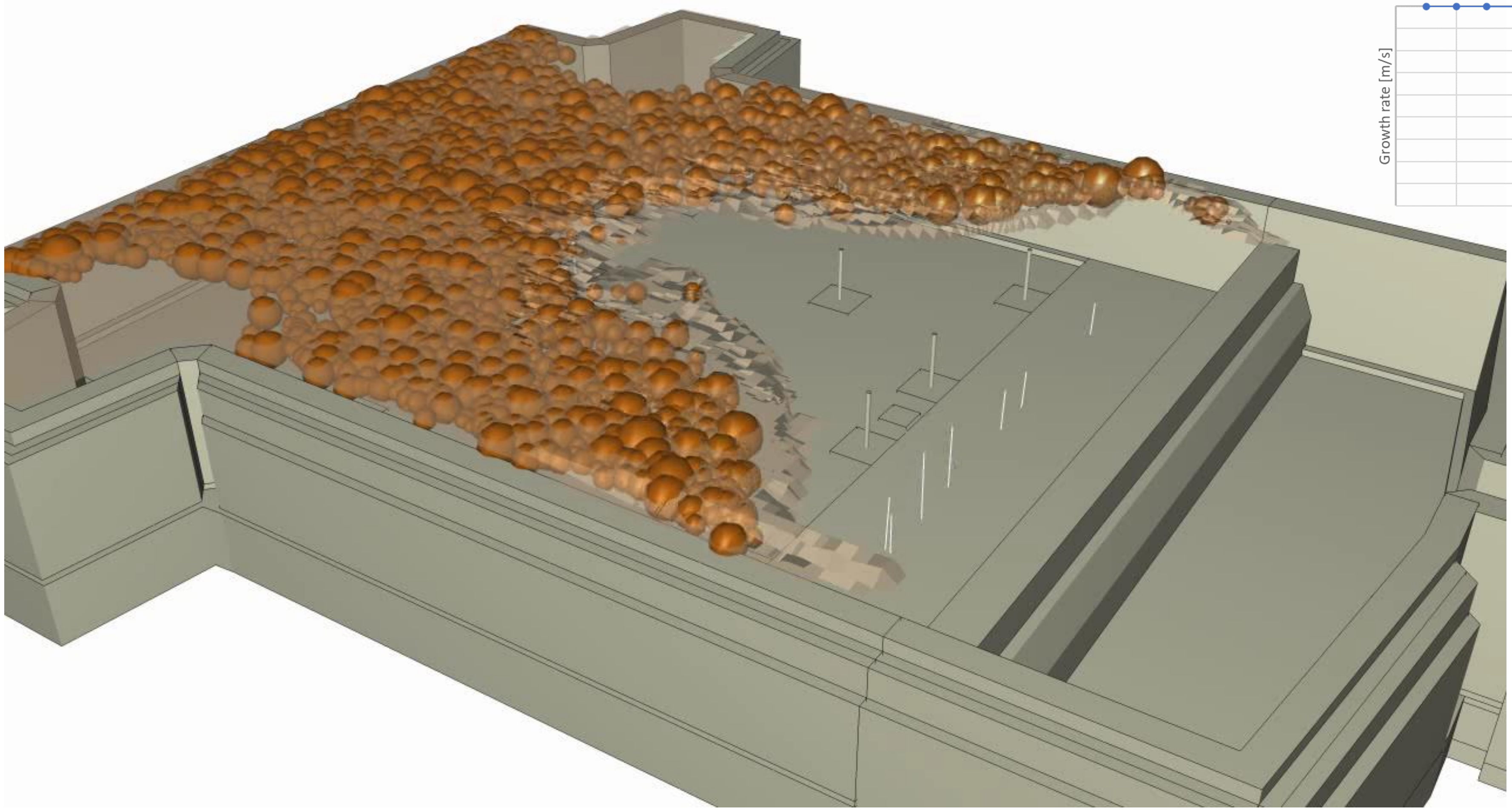
- Bubbles from batch melting and refractories are typically simulated using either experimental bubble growth model (bubble growth speed is measured in laboratory as function of temperature) or using redox model, to see what percentage reaches glass output / exit



AZS refractory bubbles in a container glass furnace

- Dissolution of sand grains released from batch is simulated using either three stage dissolution model by Hrma and Němec or using experimental growth rate model (sand dissolution speed is measured in laboratory as a function of temperature)

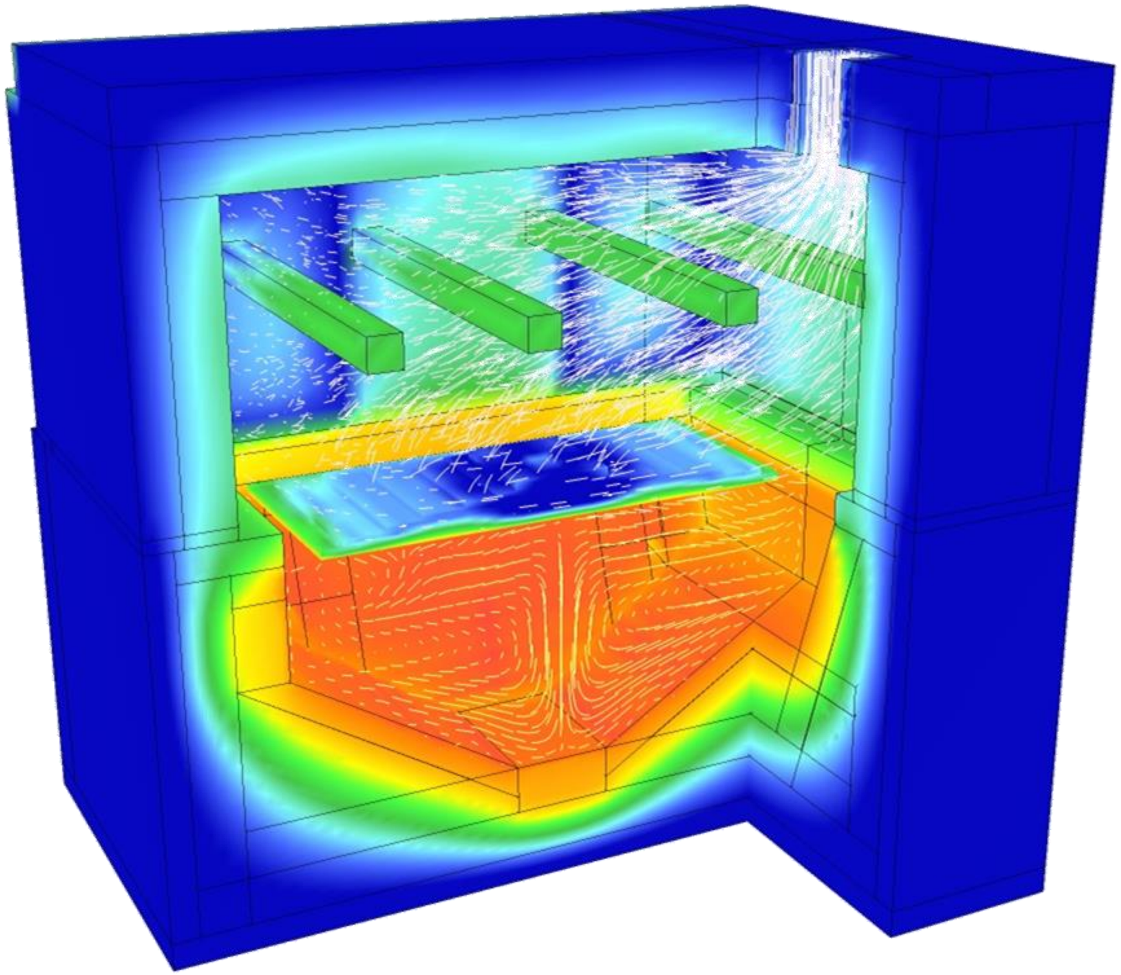




Sand grains dissolution in a container glass furnace

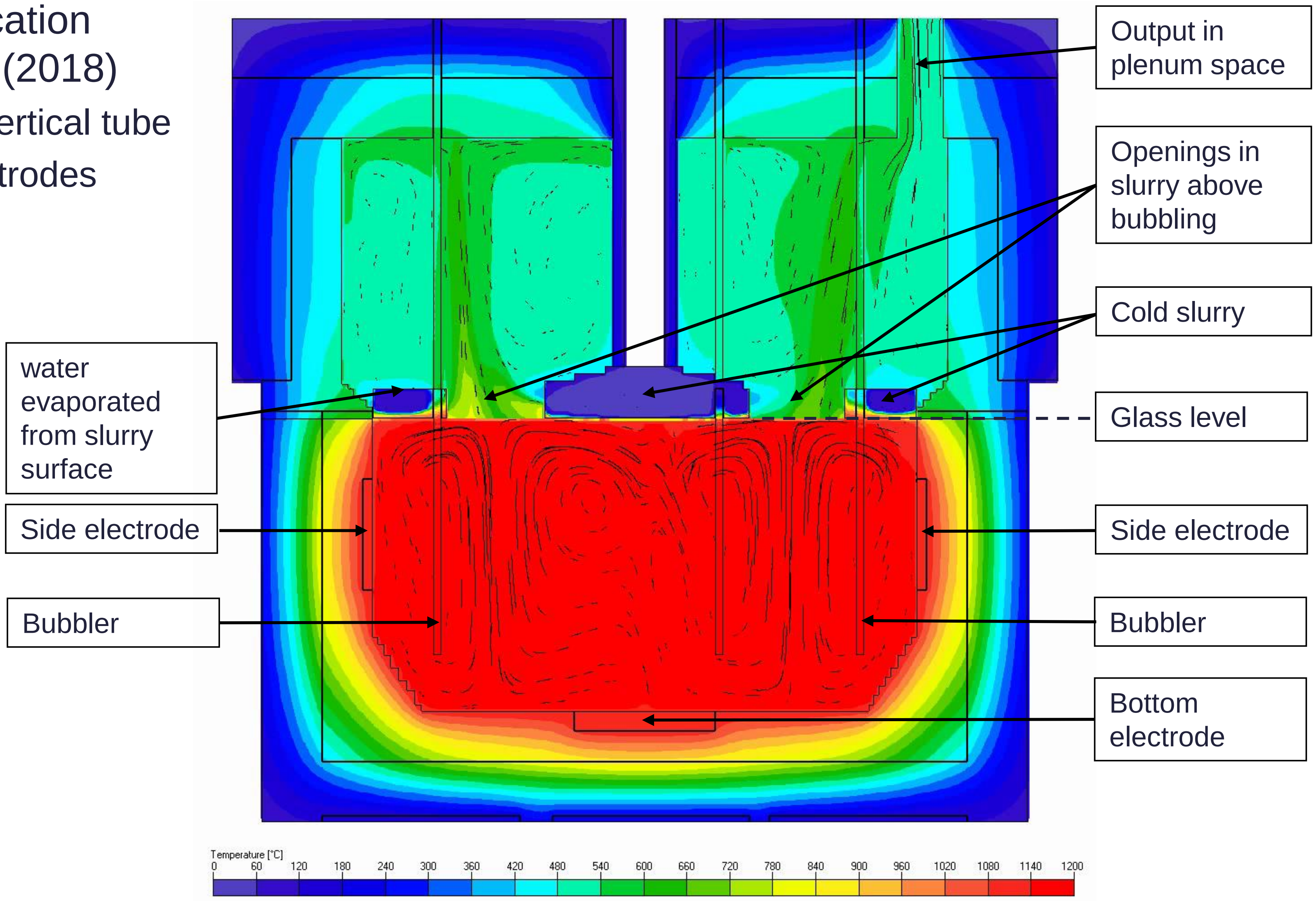
GFM Application – Waste Vitrification

- 3 modeling studies of waste glass vitrification melters calculated with GFM in GS
- The first one: Slurry-Fed Ceramic Melter
  - Simulation included precipitation, growth, dissolution, motion and settling of spinel
  - Settling of RuO_2 was simulated too
  - Glass properties were functions of concentration of solid particles and temperature
  - Heating: 3 block electrodes, 4 lid heaters
  - Output rate: 45 kg/h



GFM Application – Waste Vitrification

- The latest waste vitrification melter modeling study (2018)
  - Slurry feeding from vertical tube
  - Heating: 3 block electrodes
  - Output rate: 50 kg/h



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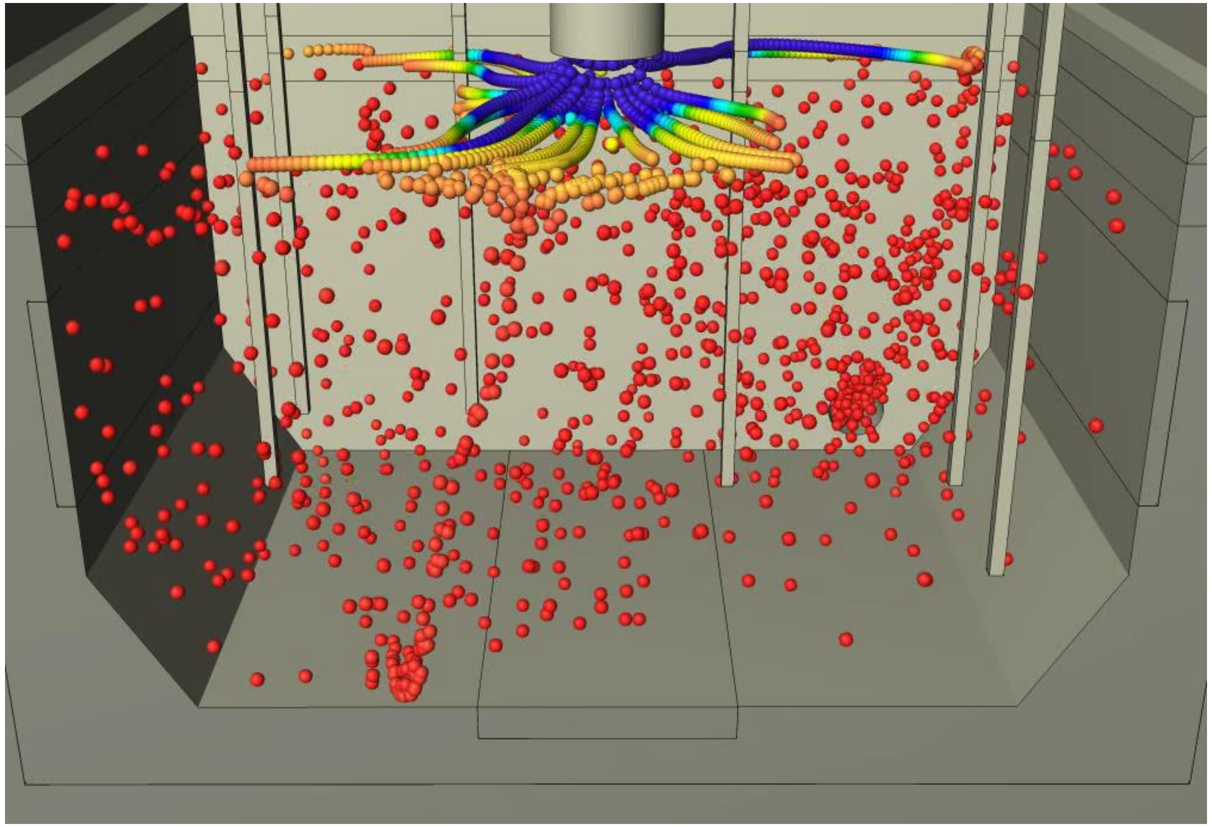
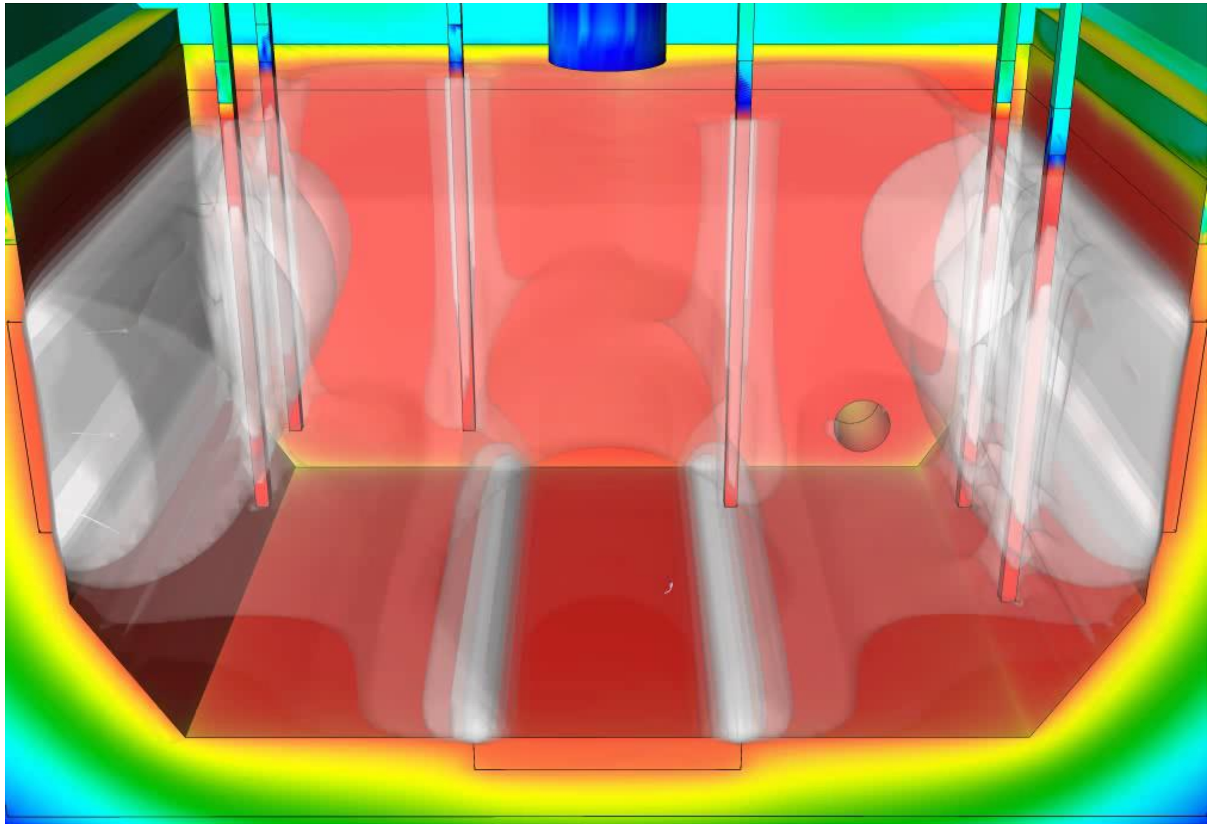
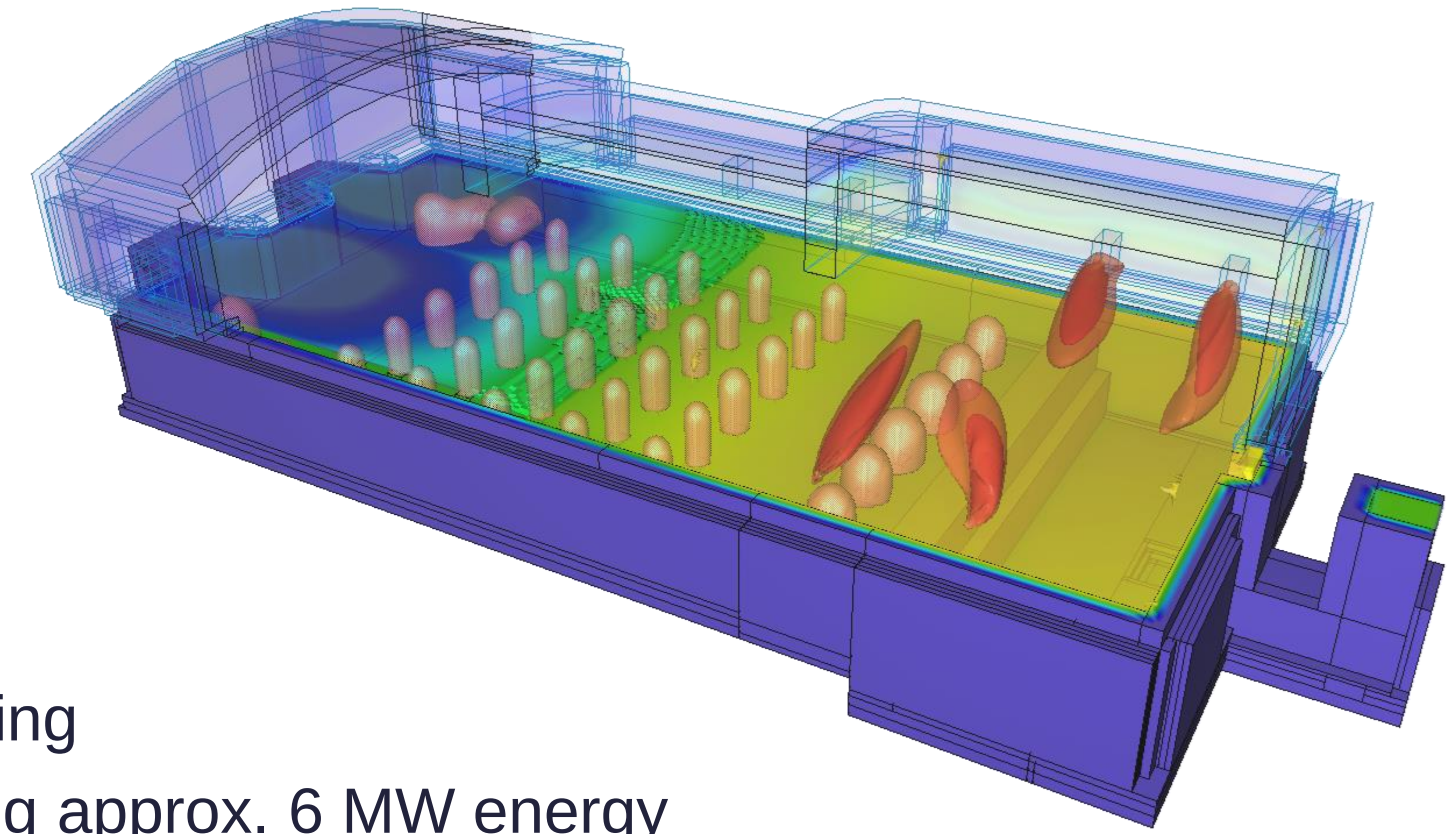


Slurry feeding and glass flow



Joulean heat iso-surfaces and electric current streamlines

GFM Application – GS H^2EM Concept Furnace Design

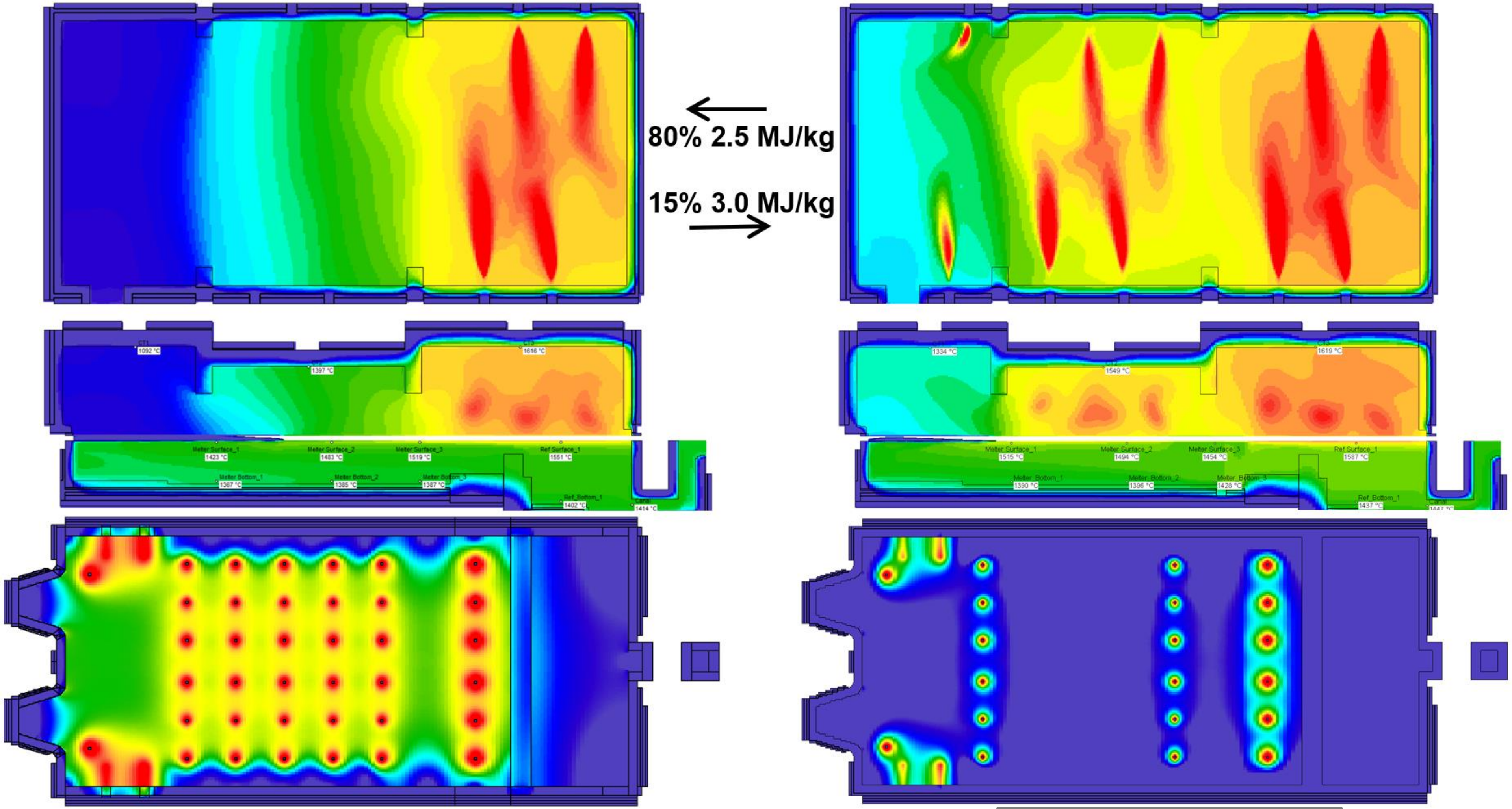


- 350 TPD concept design
- 80% renewable electric melting
- About 60 electrodes providing approx. 6 MW energy
- Natural gas / oxygen burners (NG could be replaced by hydrogen)

- **Such concept in currently being realized in EU (4 MW already exists)**

GFM Application – GS H^{2}EM Concept Furnace Design

- 350 TPD H^{2}EM concept working in 80% electric mode (left) and 15% electric mode (right)



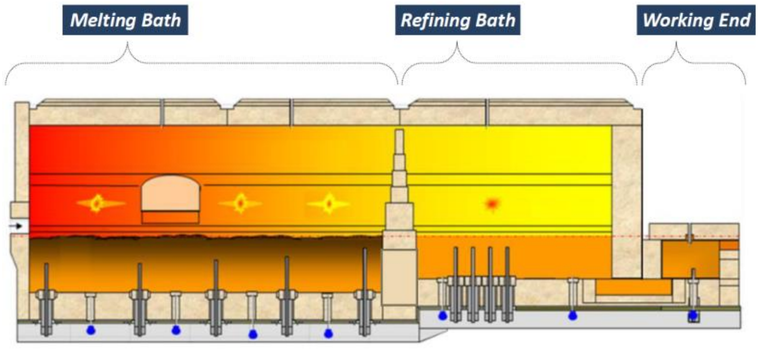
80% electric mode

15% electric mode

GFM Application – GS & LMFV Cooperation

- Optimization of LMFV (La Maison Française du Verre)'s furnace
- Presented on 16th International Seminar On Furnace Design – Operation & Process Simulation, Velké Karlovice, Czech Republic, 2023

Base Case : Our Furnace in 2018

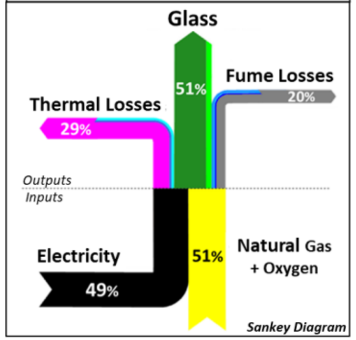


- 6 Oxy-Gas Burners
- 5 Rows of Electrodes
- Separating Crosswall

- 2 Oxy-Gas Burners
- 2 Rows of Electrodes
- Max Temp : 1550°C

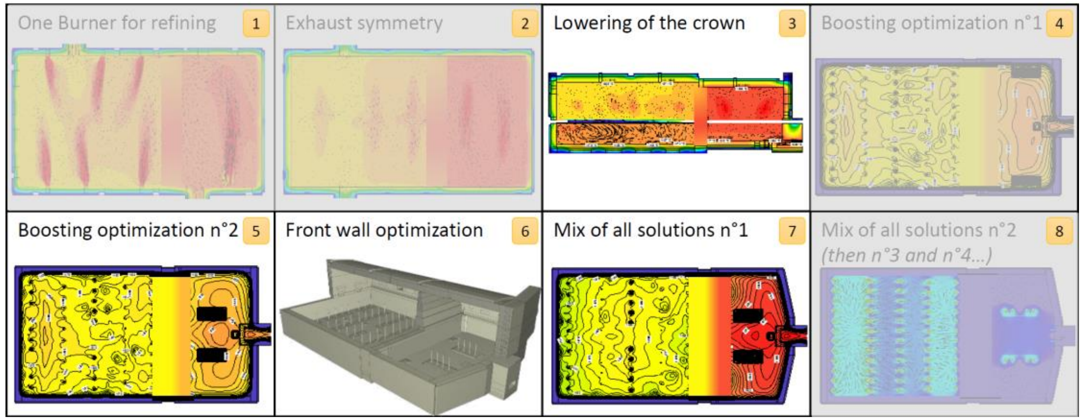
Almost no CO_2 from batch

Max Pull (Borosilicate)	≈ 160 t/d
Average Cullet	≈ 25 %
Natural Gas (Fossil)	620 kWh/t (LHV)
Electricity	600 kWh/t
CO_2 Emission	186 kg CO2e/t



Base case

From 2018 to 2022 : Partnerships for a new design



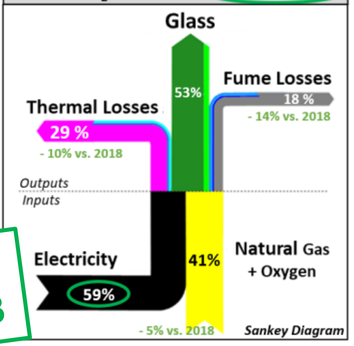
The Result : Our Furnace in 2023

- Crown & Tank Design (FIC Ger)
- Boosting Optimizations (GS & FIC)
- Insulations & Refractories review

- Near IR Camera (GS)
- Tank Blocs Monitoring (SEFPRO)
- ESIII (GS)

-60% CO2 versus before 2018

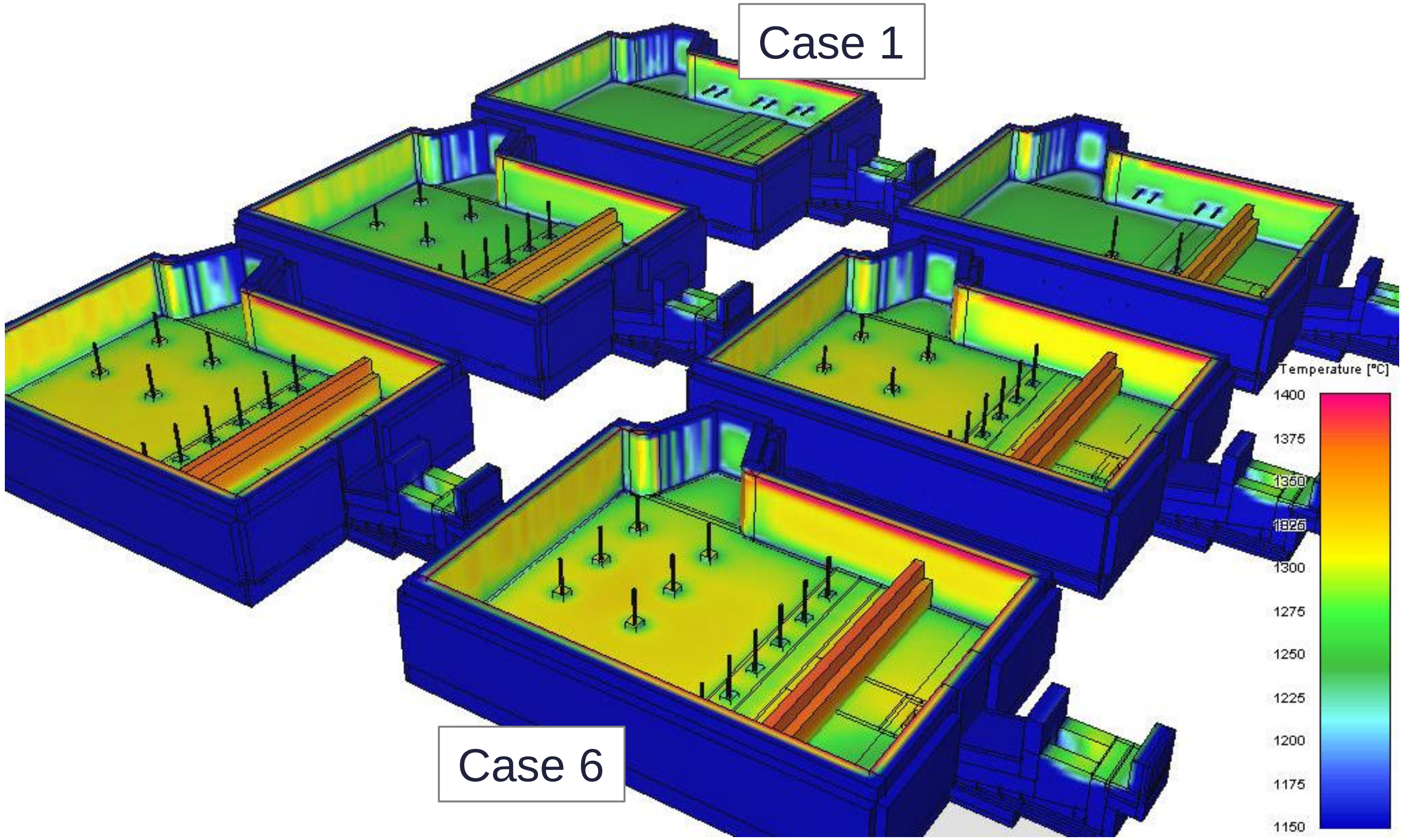
Max Pull (Borosilicate)	≈ 160 t/d
Average Cullet	≈ 25 %
Natural Gas (Fossil)	475 kWh/t (LHV)
Electricity	687 kWh/t
CO_2 Emission	157 kg CO2e/t



Result

GFM Application – Electric Boosting Optimization

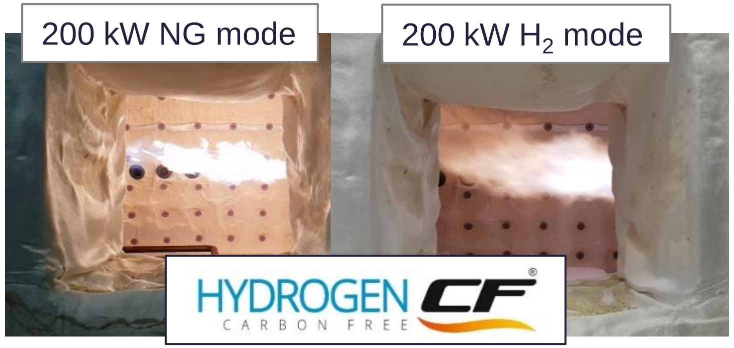
- **Goal: keep glass quality** after changing glass from flint to amber, by changing electric boosting configuration
- Case 1
  - Flint glass
  - 12 side electrodes
- Cases 2-6
  - Amber glass
  - Various electric boosting configurations
- Case 6
  - Target glass quality
  - 14 bottom electrodes



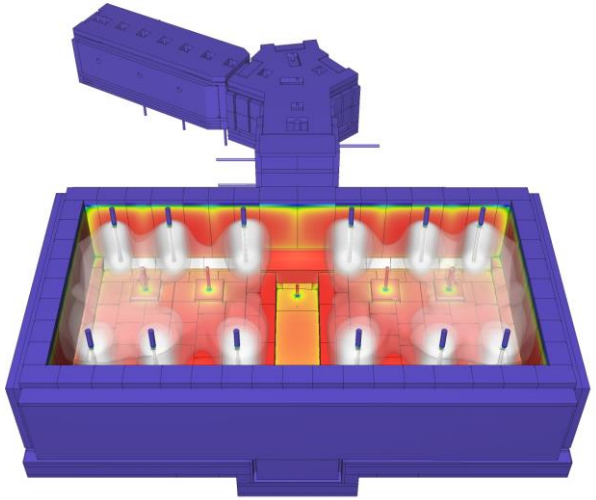
	CASE 1 FLINT	CASE 1 AMBER	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
INSERTED BUBBLES [pcs]	3 577	3 441	3 453	3 750	3 750	3 750	3 750
REFINED BUBBLES [pcs]	3 496	2 971	2 871	3 198	3 252	3 287	3 400
DISSOLVED BUBBLES [pcs]	64	203	298	321	415	337	331
CIRCULATED BUBBLES [pcs]	0	2	2	0	6	8	1
BUBBLES IN THE GOAL [pcs]	17	265	282	231	77	118	18
BUBBLES IN THE PRODUCT [%]	**0.47**	**7.7**	**8.16**	**6.16**	**2.0**	**3.1**	**0.48**

Conclusions

- Current global situation (environmental / economical) pushes (not only) glass producers to dramatically change production processes, especially to:
  - Decrease and optimize energy consumption
  - Decrease production of pollutants (CO_2, NO_x, etc.)



Big pressure for production transformation and decarbonization



- Any change in the furnace operation and design can be difficult and expensive

Great opportunity for mathematical modeling!

- Glass Service Glass Furnace Model (GFM) software is a great tool which can be used to tackle current glass production challenges

Thank Your For Your Attention !