IMI-NFG Course on Processing in Glass

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Lecture 3: Basics of industrial glass melting furnaces

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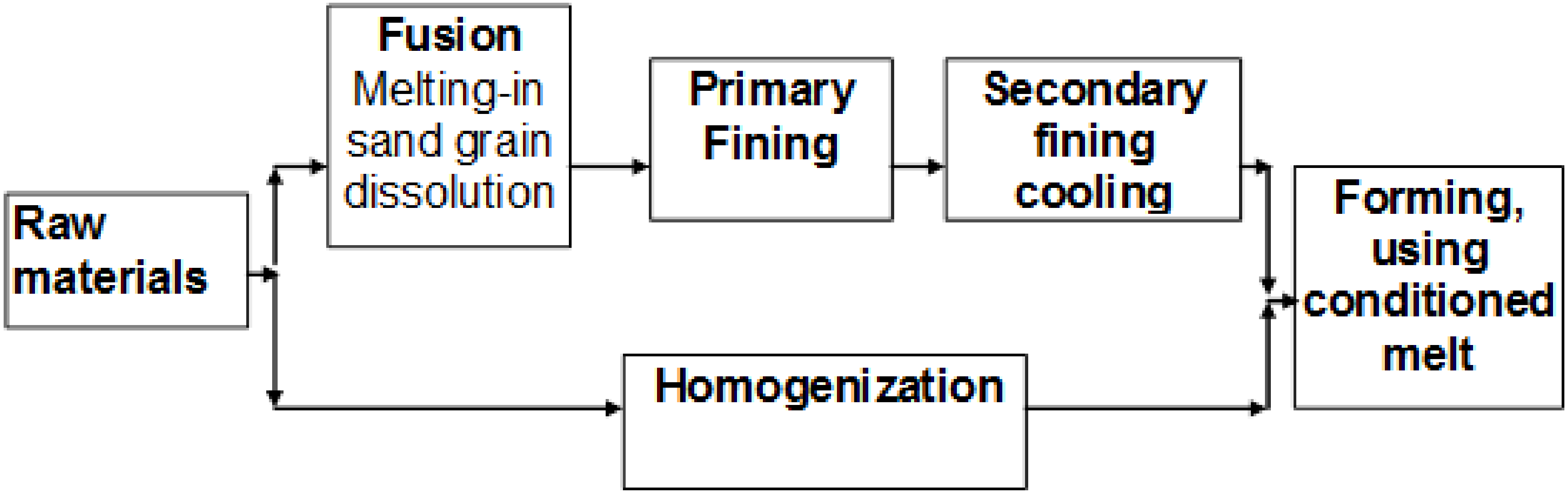
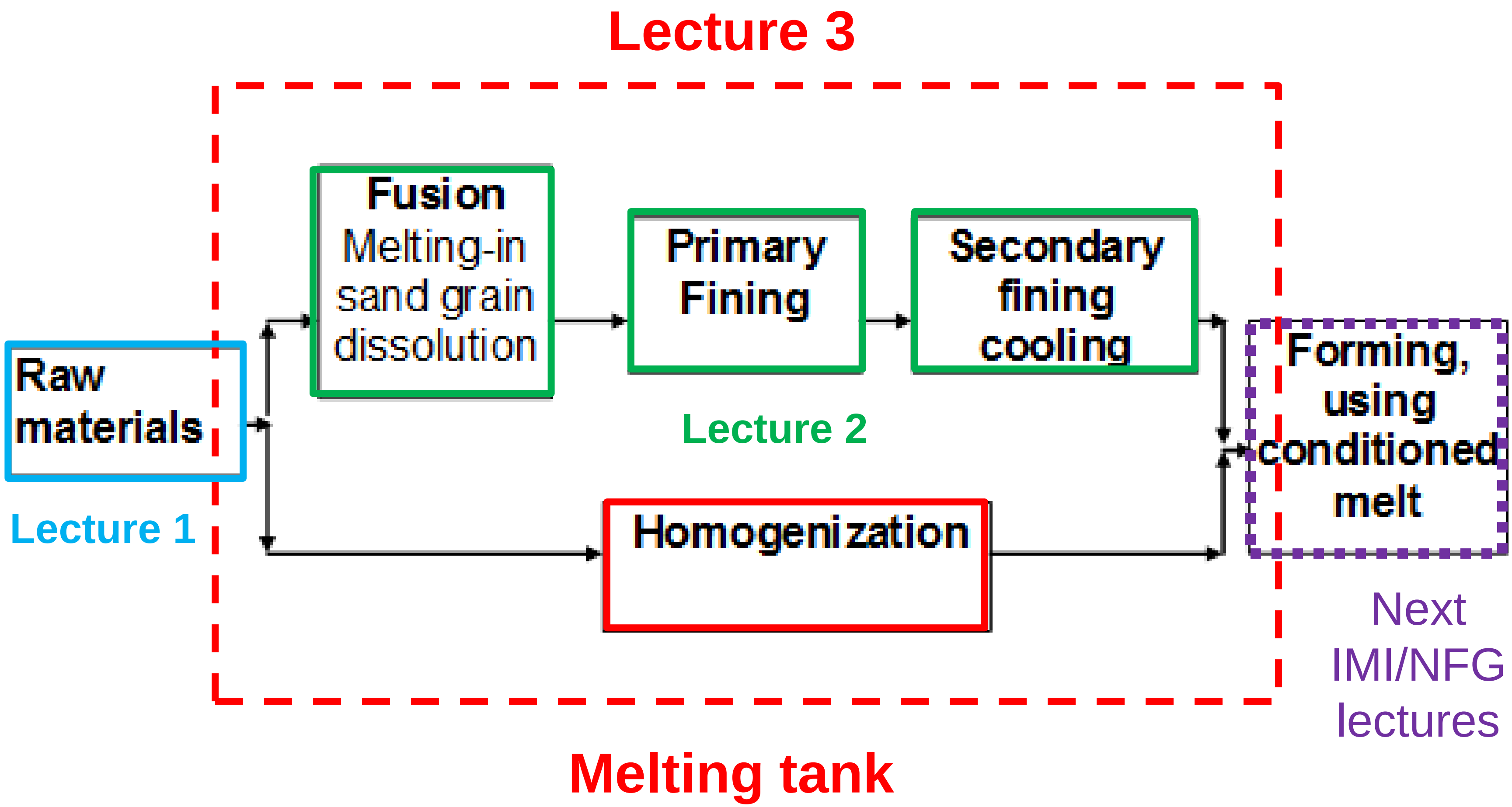
Introduction

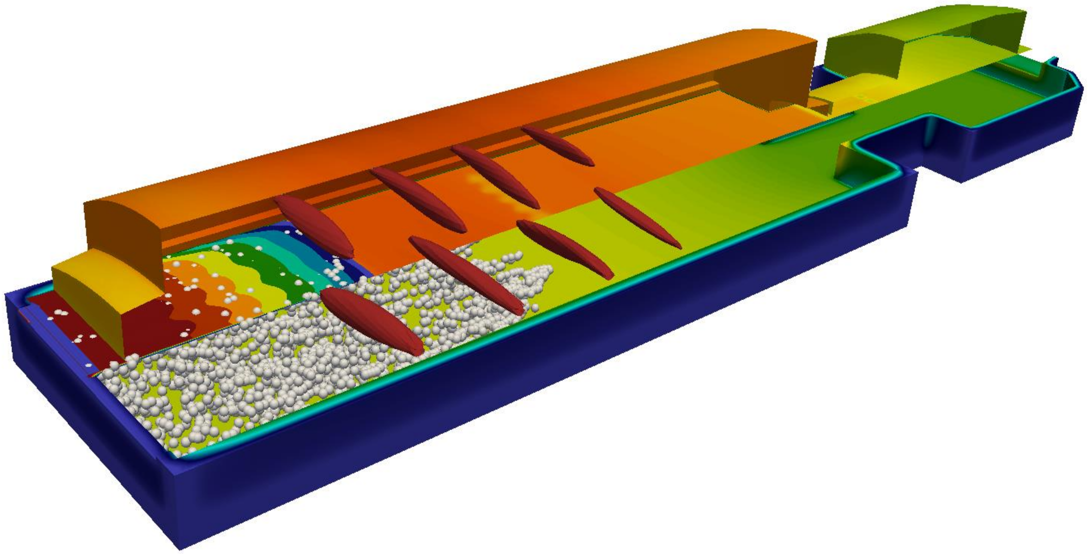


Introduction



Outline of this lecture

1. **Glass melting furnaces**
   - Furnace design (focus on continuous melting tanks)
   - Process steps
   - Furnace operation



2. **Heat transfer**

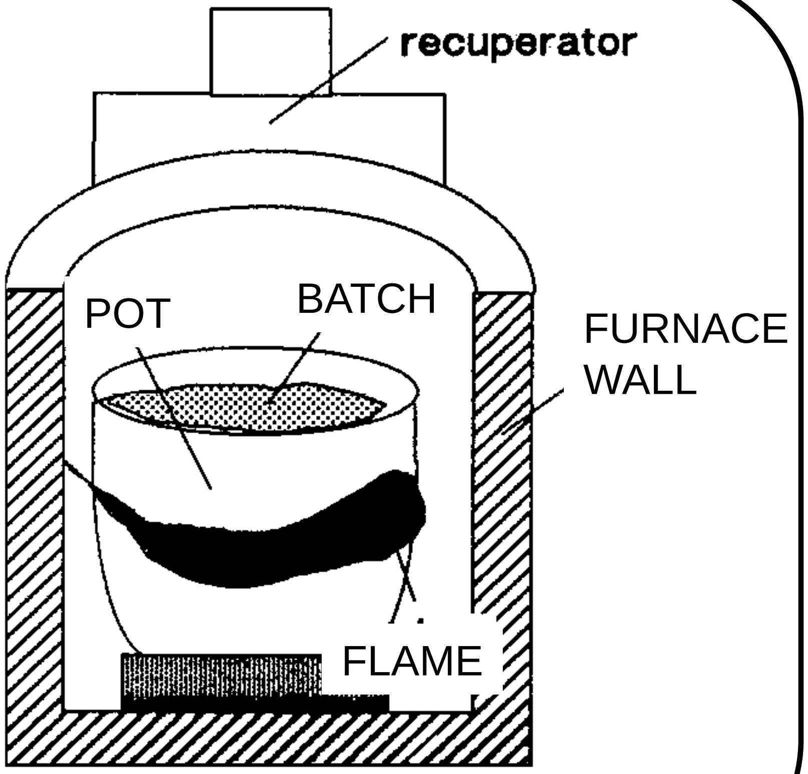
3. **Refractories**

Furnace types

- Different furnace types and designs exist, depending on the quantity of glass to be produced, the type of glass production, plus economic (and logistic) factors
- The main types of furnaces include:
  - ✓ Pot furnaces (discontinuous)
  - ✓ Day tanks (semi-continuous)
  - ✓ **Recuperative** / unit type melters
  - ✓ **Cross-fired regenerative** furnaces – *throat or neck/waist design*
  - ✓ **End-port fired regenerative** furnaces – *throat design*
  - ✓ **Oxygen-fired** unit melters
  - ✓ Special (segmented) melter (LoNOx®, Flex® melters)
  - ✓ All-electric furnaces

Discontinuous furnace (day tanks and pot furnaces)

- The following actions take place (generally in a one-day cycle) within discontinuous melting furnaces:



Example of a pot furnace

✓ Melting tank or pot is charged with mixed raw material batch

✓ This batch is heated to the desired temperature

✓ The glass is melted, fined, homogenized and subsequently cooled down to the working temperature to allow forming by the craftsman or semi-automatic machines taking portions (gobs) of glass from the glass melt pot.

Continuous glass furnaces

- Usual synonyms for a continuous furnace are **glass-melting tank** or **tank furnace**.
- These furnaces are applied for
  - ✓ Container glass production
  - ✓ Flat glass (Float & Rolled) production
  - ✓ Most tableware glass production
  - ✓ Fiber & glass wool production
  - ✓ Most specialty glass production (tubes, display glass, glass-ceramics, lighting bulbs,..)
- *These furnaces not applied for:*
  - ✓ *Most hand-made glass*
  - ✓ *Vitreous silica*
  - ✓ *Optical glass fibers*

Continuous glass furnaces characteristics

- Tank of refractory material, **continuously charged** with mixed batch
- **Heat transfer from combustion chamber** using fossil fuel (mostly natural gas) firing with preheated air or oxygen
- All basis process steps in **different zones** or sections of furnace
- Continuous operation, during campaigns 5-15 years
- Indefinite number of trajectories from batch charger to exit of furnace (throat or canal).
- These furnace types are suitable for the **mass production** of glass
- The furnace melting capacity (**glass pull**) usually is expressed in the number of (metric) tons of glass melted per day (24 hours)
- Depending on the furnace and type of glass produced, the pull can vary from ~ 20 tons per day (TPD) up to > 700 TPD

Continuous glass furnaces characteristics

- Within the melt, currents (**glass melt flow patterns**) are being generated, both by pull & by free convection
- Extra mixing by the application of **bubbling or electrodes**
- Possibility to **boost** energy input using **electrodes**
- Electric current in melt will release latent energy
- Large number of trajectories of material in tank: **wide residence time distribution** & **quality** differences depending on route
- **Temperature gradients** in melt: higher levels (close to the surface) are generally hotter than bottom glass melt
- Weirs or dams are optionally applied to bring bottom glass to upper glass melt layers
- Using air preheating (**regenerators/recuperators**) or pure oxygen

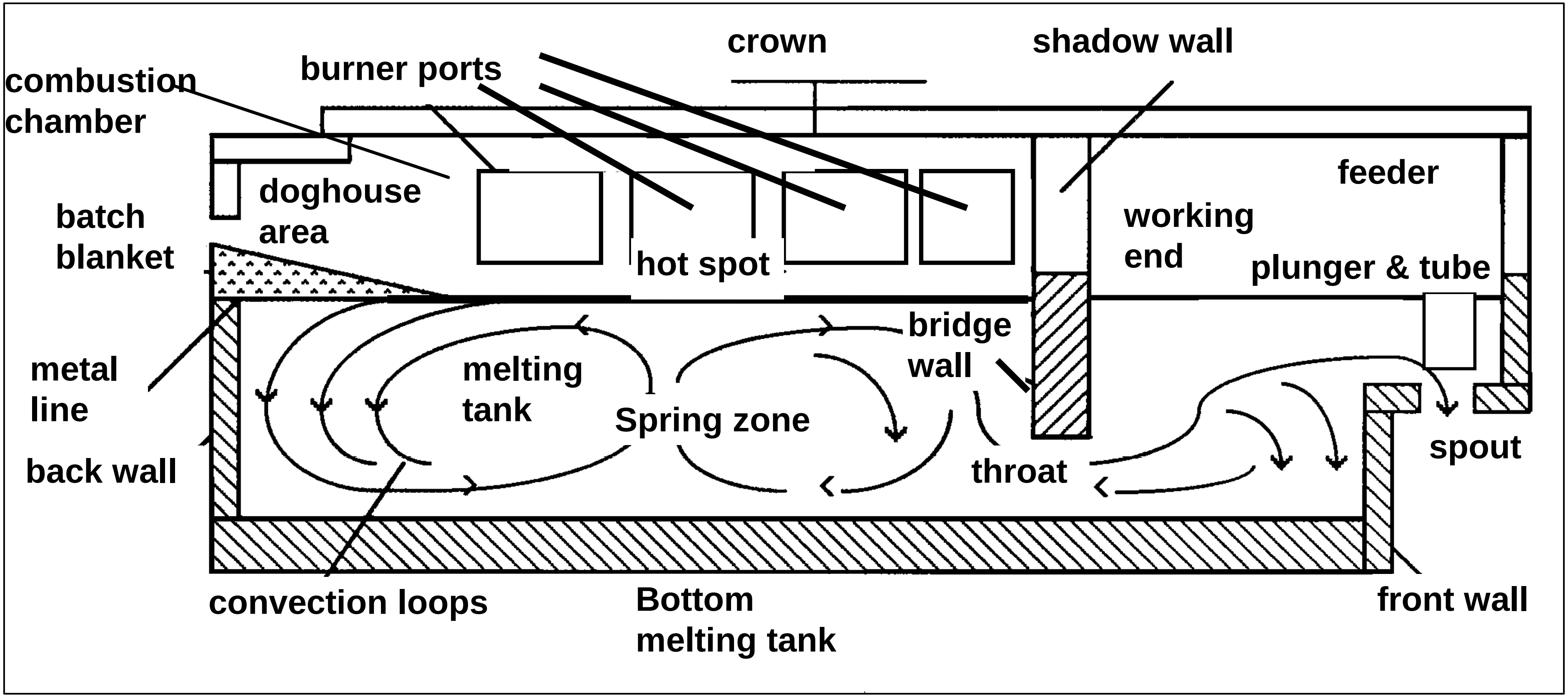
Continuous glass furnaces characteristics

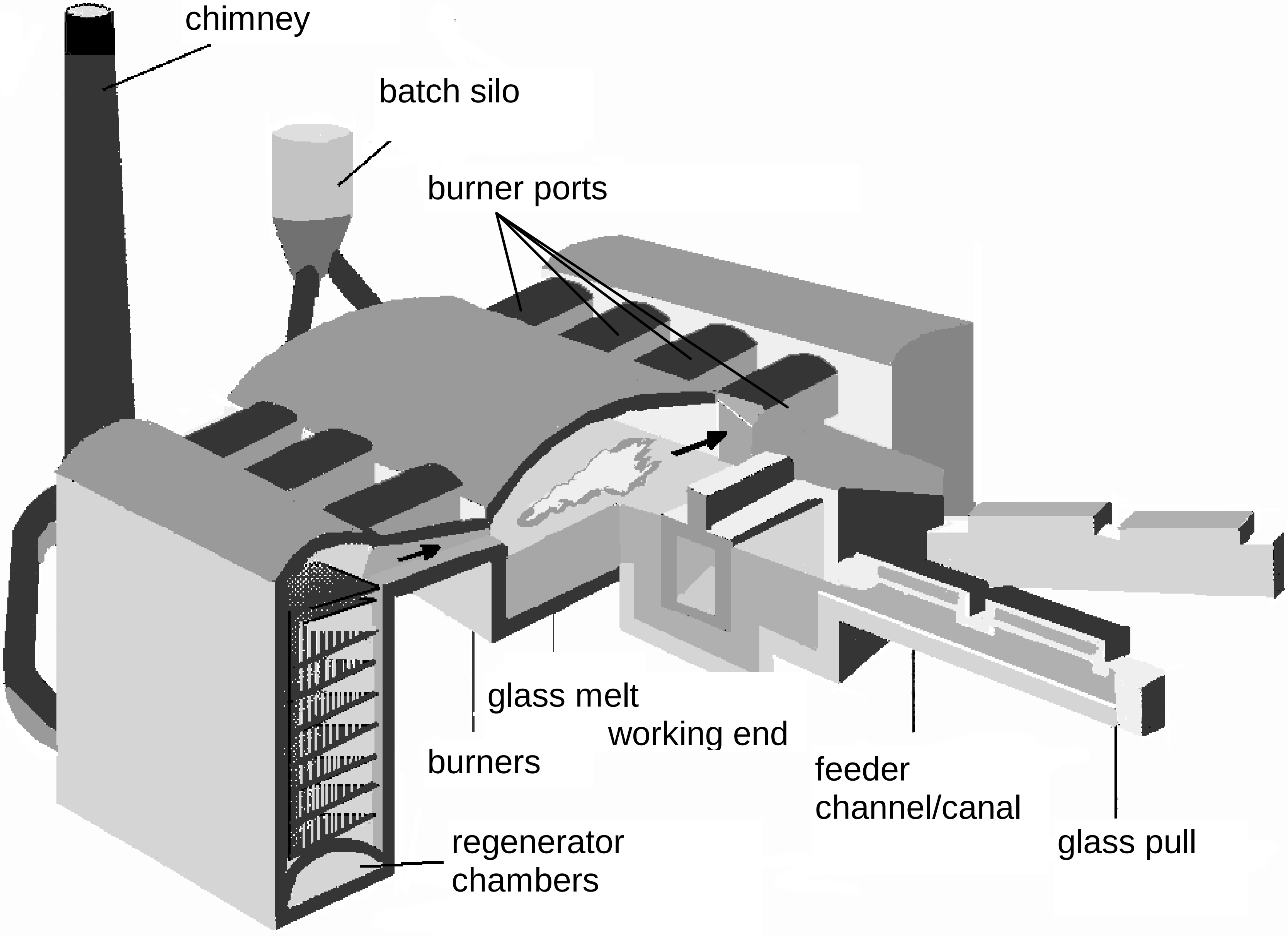
A melting furnace consists of :

- **Melting tank** (glass melt bath)
- **Superstructure** (combustion chamber)
- **Throat** as connection between the melting end and the riser that brings the molten glass in the **refiner, working end or distributor**
- **Neck** in case of float glass production, between the melting end and working end
- **Working chamber** (working end, gathering end, nose, refiner)
- **Heat exchangers**: regenerators or recuperators

Continuous glass furnace components

Designations of glass furnace components (tank furnace, cross fired, dimension scale is not meant to be correctly presented).



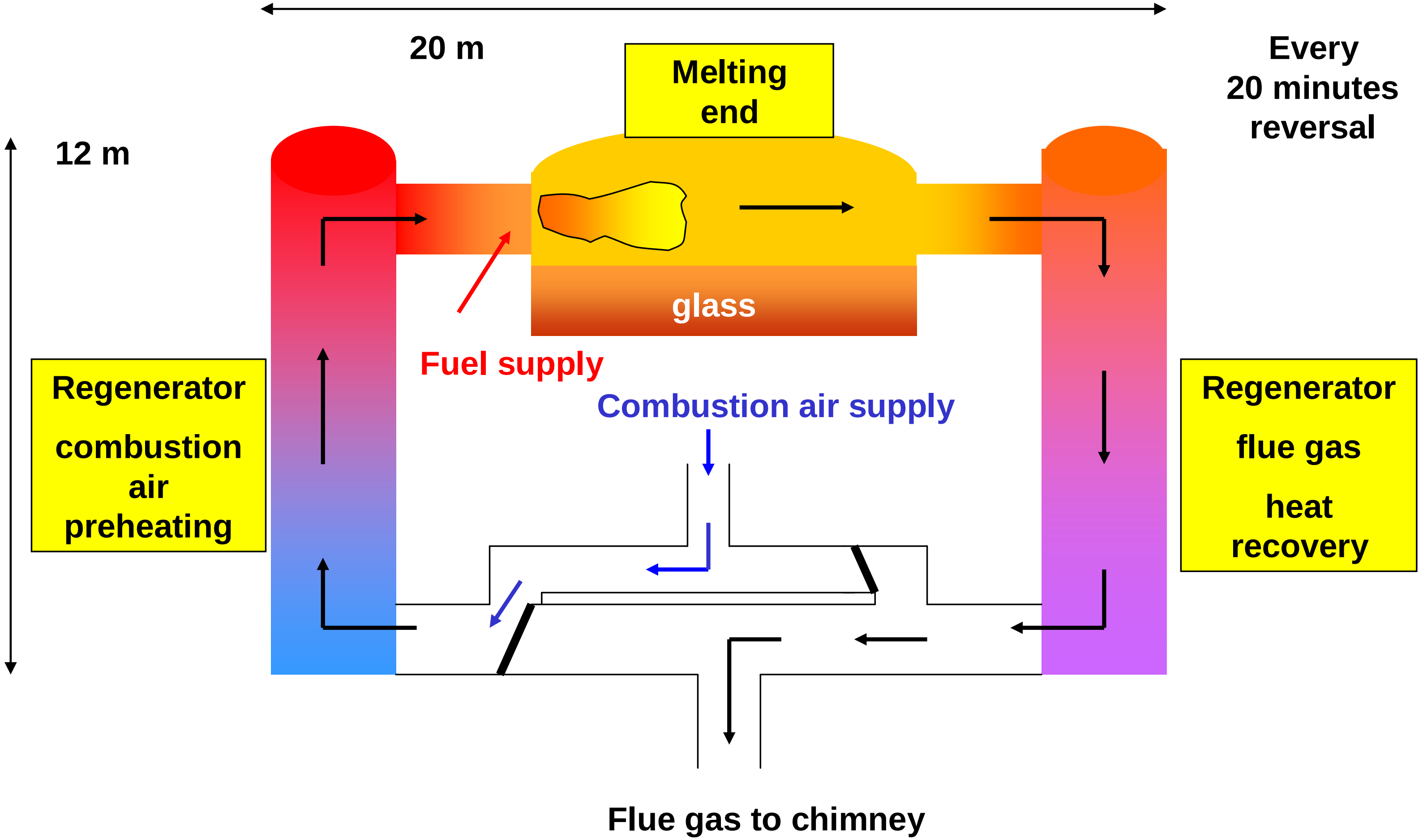

chimney
batch silo
burner ports
glass melt
working end
burners
feeder
channel/canal
regenerator
chambers
glass pull

Regenerative furnaces

- A regenerator consists of a **regenerator chamber** in which a **checkerwork** (or just **checkers**) of **refractory bricks** has been stacked.
- In one cycle the checker is heated up by flue gases, subsequently in the following stage (20-30 minutes) the heat is transferred to combustion air
- These furnaces are provided with 2 or more (an even number) regenerators
- In principle the optimum **half-cycle time** depends on the pull of the melting tank (**thermal load**)
- During the **burner reversal**, lasting about 30 - 60 seconds, there are no flames within the furnace.
- The reversal period (no-firing interval) should be as short as possible to avoid too much cooling down of the furnace.

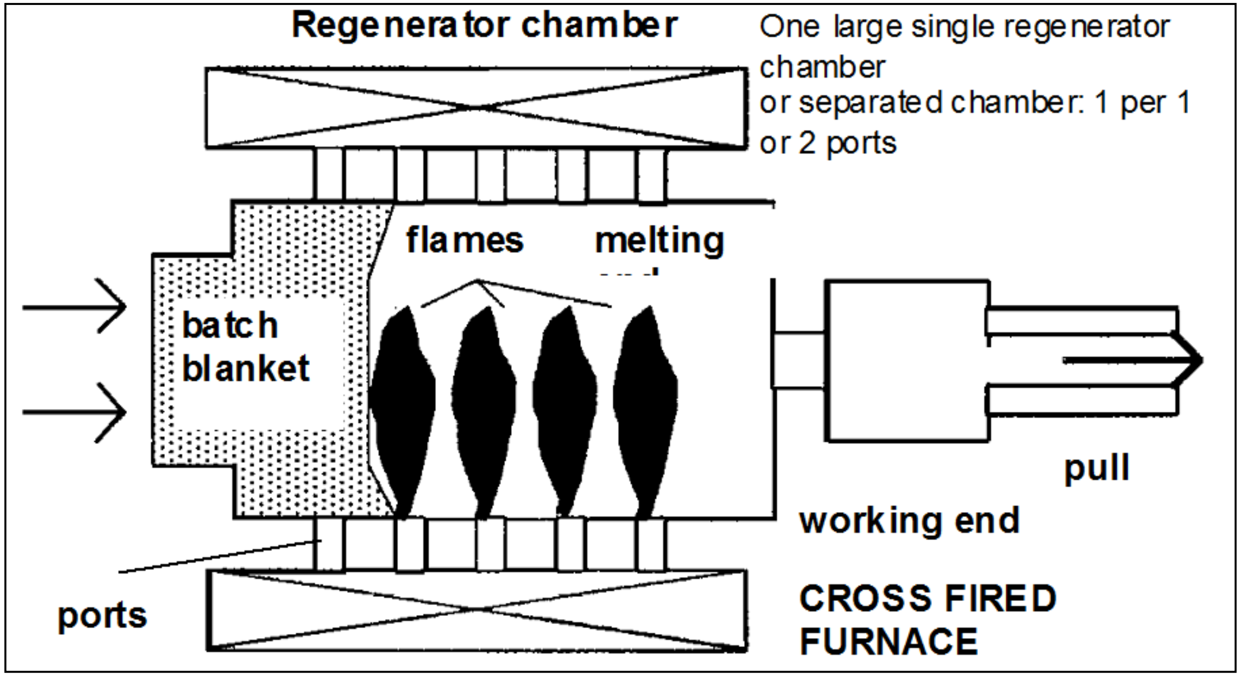
Regenerative furnaces

Melting end, regenerative, cross section



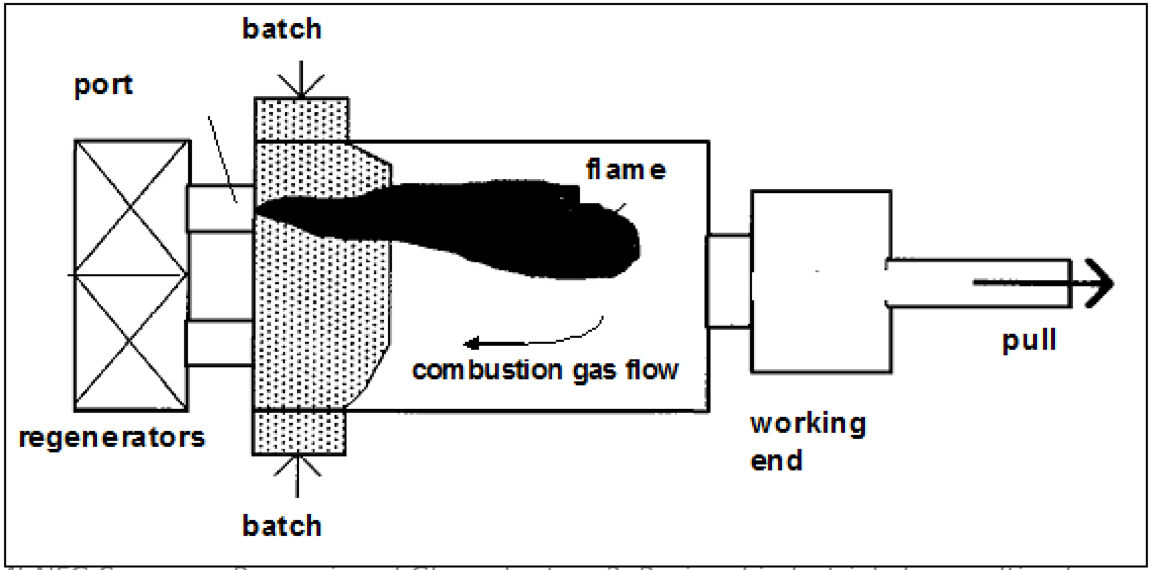
Cross-fired regenerative furnaces

- The regenerators are placed on the **side of the furnace**
- The furnace can be equipped on both sides with **4 up to 8 burner ports (per side)** depending on furnace size.
- The **profile of heating** (fuel distribution among the burners located along the sidewalls) determines location and size of the hot spot area (primary fining zone) in the glass melt.



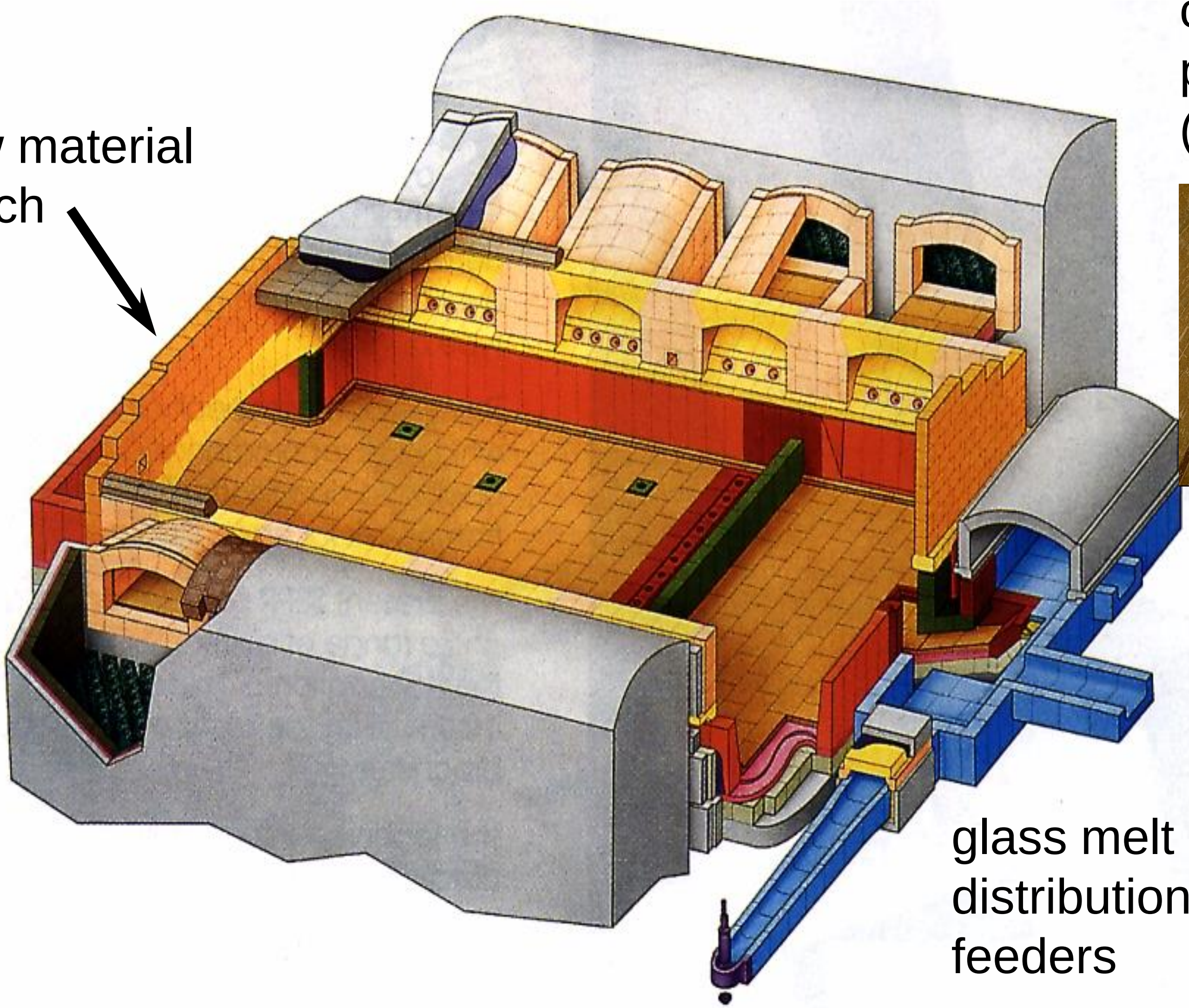
End port-fired (or U-flame) regenerative furnaces

- Burners (2 to 4 burners at each port) and the regenerator chambers are connected **at the back wall side** of the superstructure.
- The combustion of fuel & preheated air from one regenerator chamber takes place: flames starting from the burner nozzles and extending almost over the length of the furnace
- **Flame / Combustion direction turns at front wall**
- Less structural heat losses compared to cross fired regenerative furnaces (combustion gases have longer residence time)



Typical air-fired container furnace (source: SEPR)

raw material batch

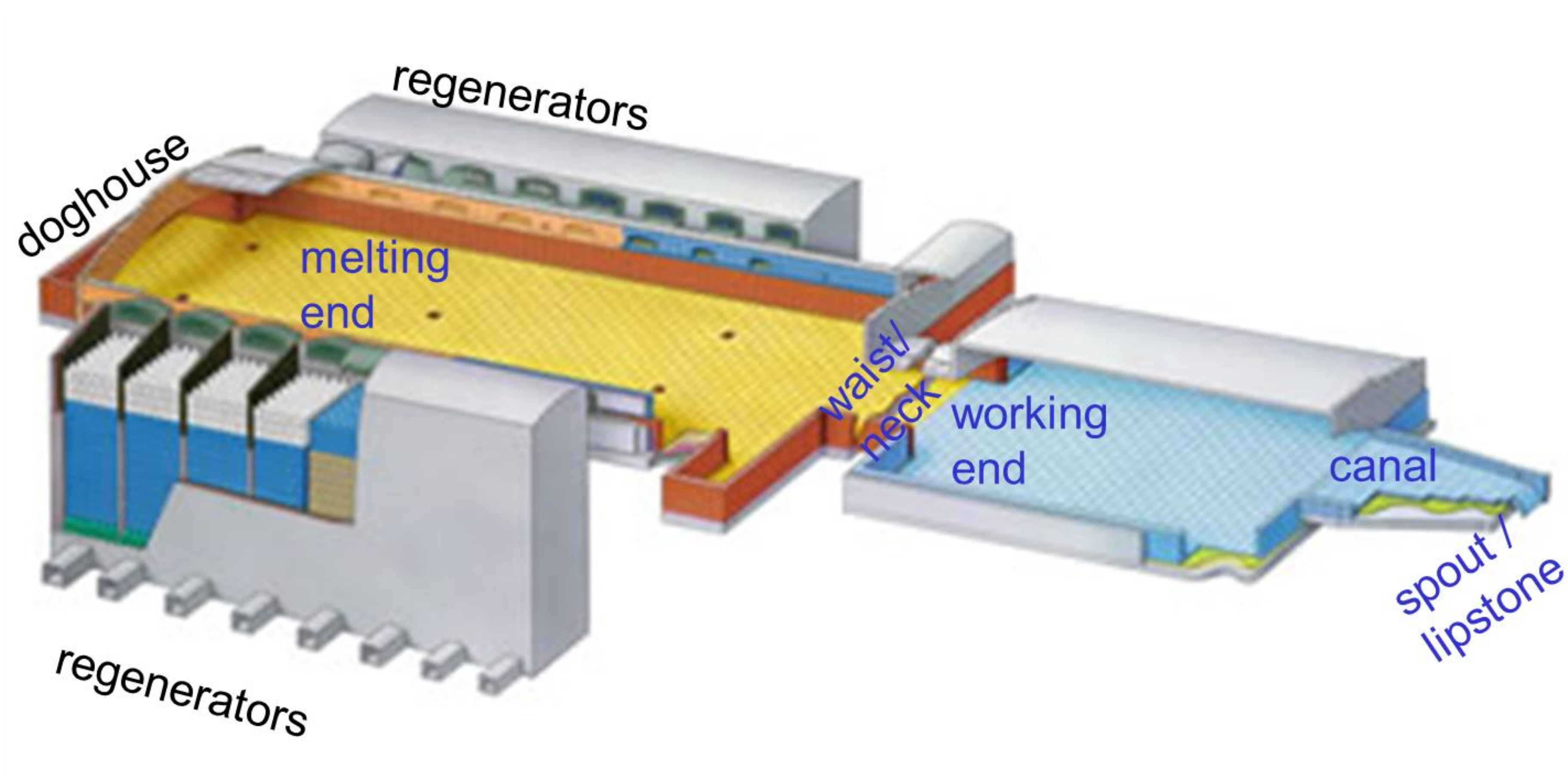


combustion air preheating (regenerators)

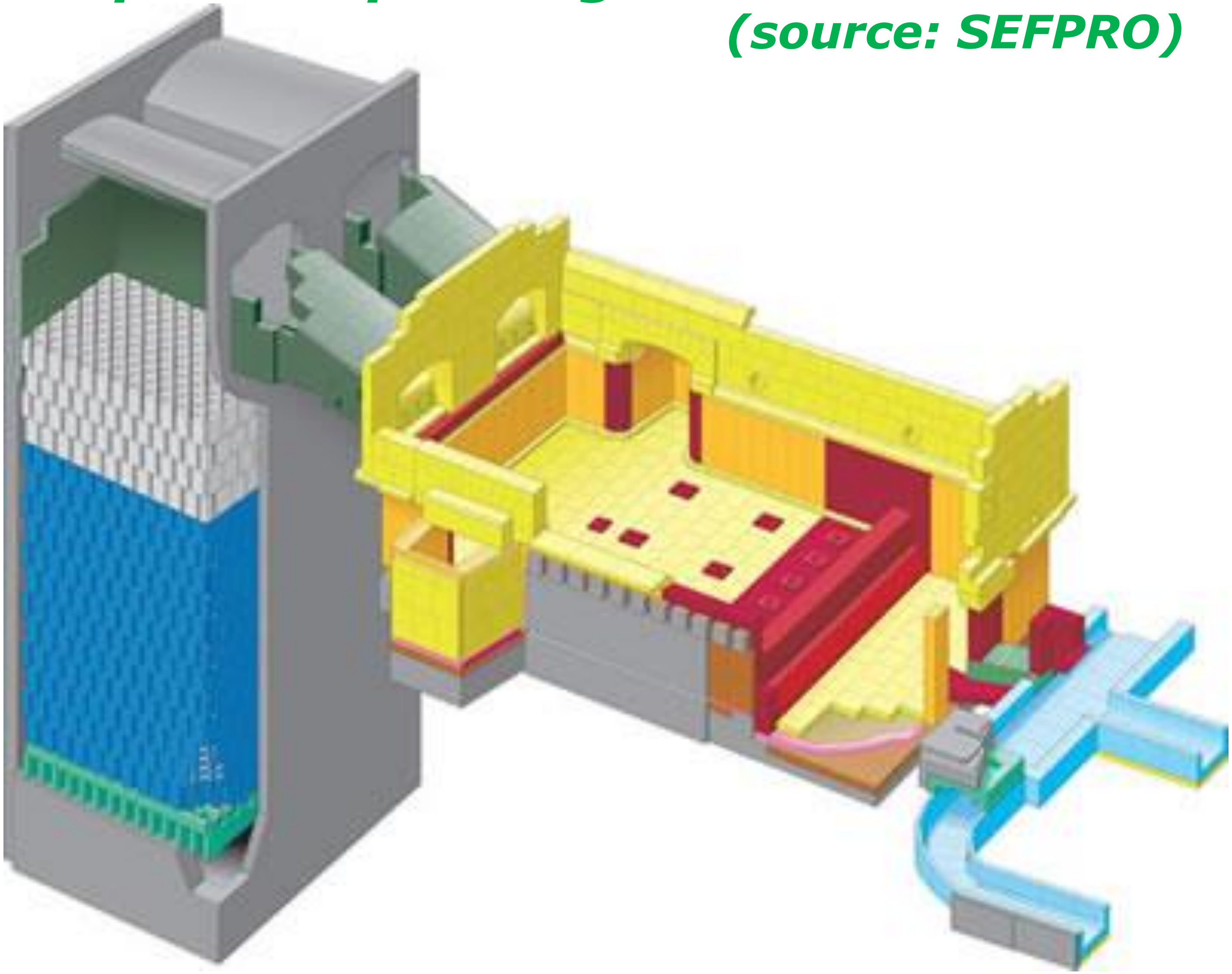
glass melt distribution feeders

Cross-fired furnace

Example flat glass furnace (source: SEFPRO)



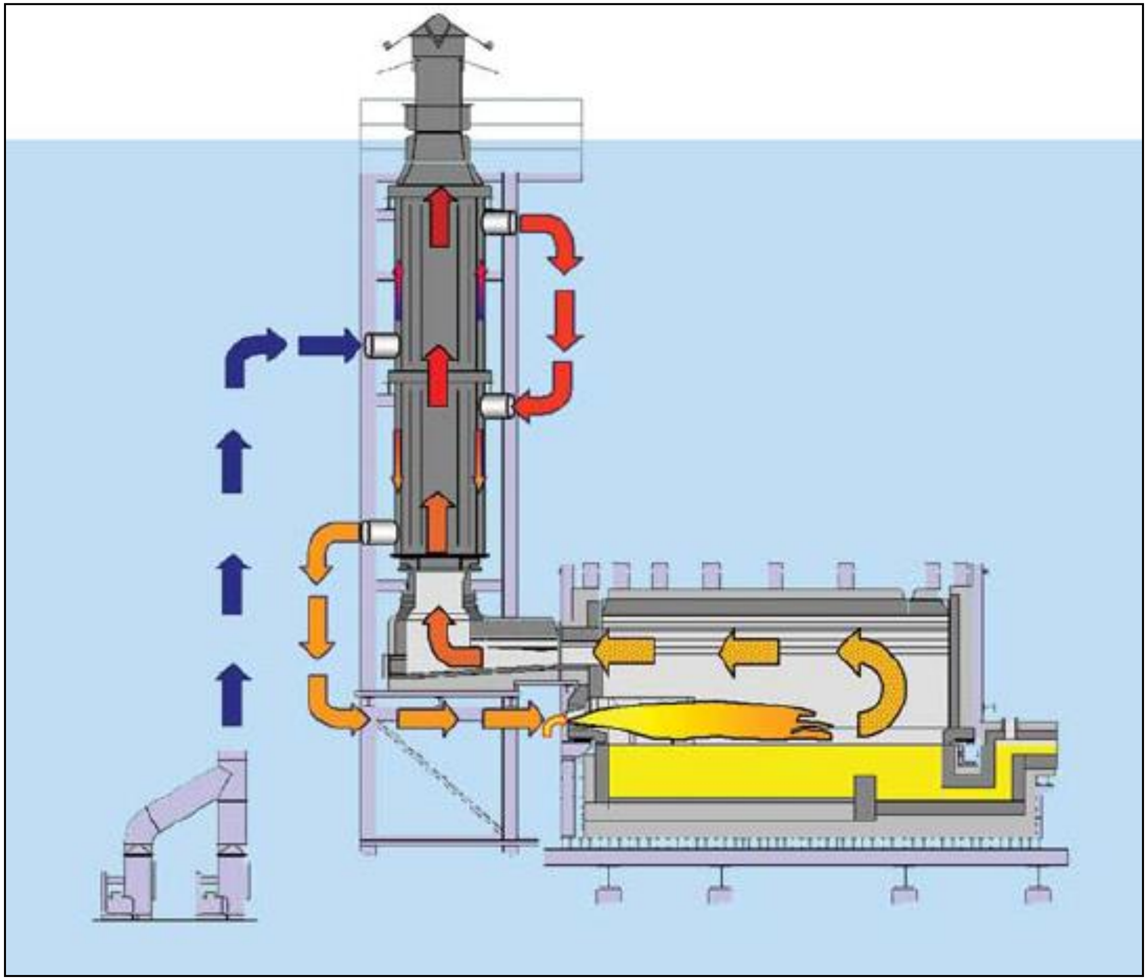
Example end-port regenerative furnace (source: SEFPRO)



Recuperative furnaces

- Recuperators are used to pre-heat the combustion air

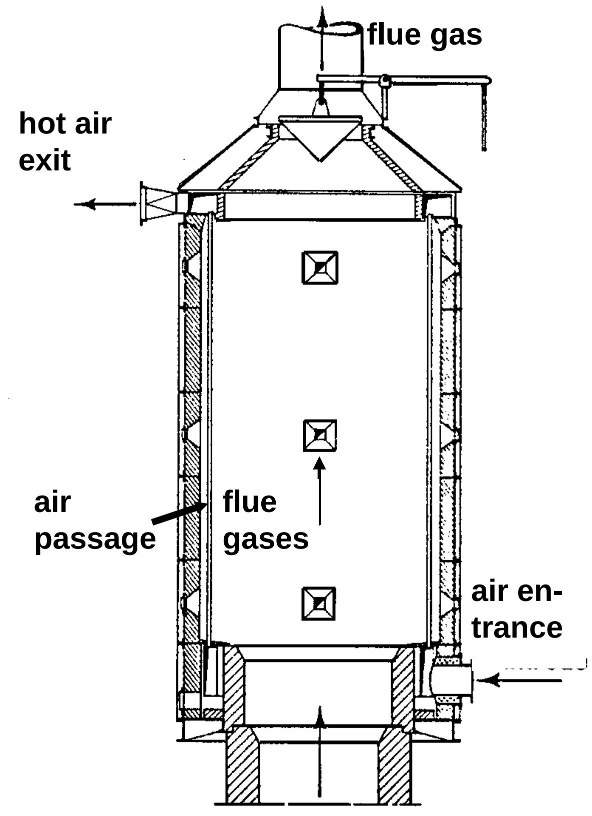
- The hot flue gases are send through the recuperator to heat the combustion air



Picture from Sorg, report "Glass melting technology", available online

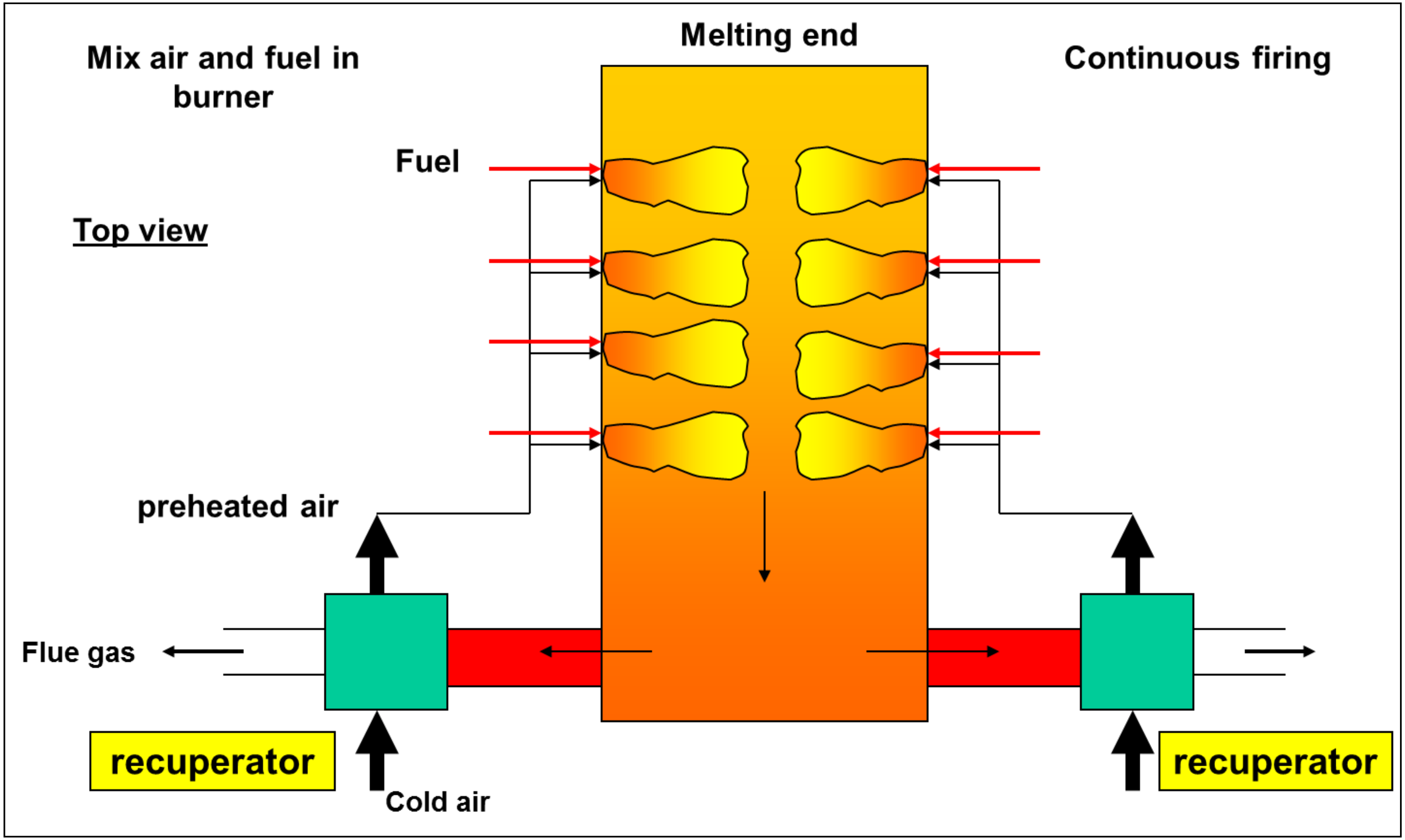
Recuperative furnaces

- Recuperator: **heat exchanger** in which heat is transferred from the flue gases to the combustion air in co-current or in counter-current flow
- **Recuperative furnaces** are provided with one or two recuperators
- Most recuperators are made from high temperature resistant steels, like chrome nickel steel (or chromium-nickel-aluminum steels)
- Because heat transmission in this type of recuperators is based mainly on radiation, these heat exchangers are called **radiation recuperators**



A. radiation recuperator

Recuperative furnaces



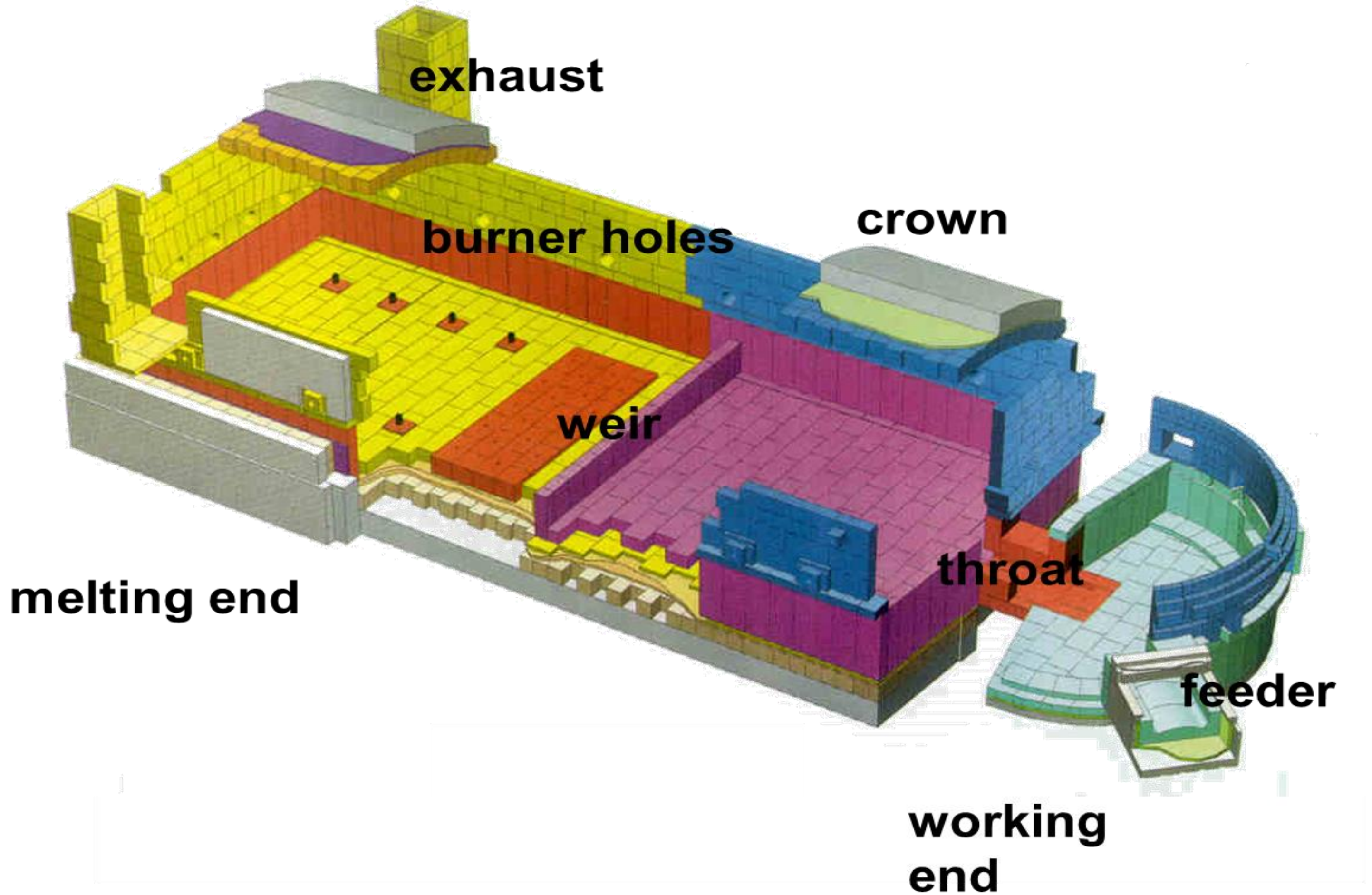
Recuperative furnaces

- **Investment costs** are relatively low
- **No cycle** (firing reversal) system, therefore continuous process conditions
- Controllable temperature profile along the length, due to the large number of burners which might be controlled independently (5-15 burners per side)
- The furnace is easily accessible (also for an end-port fired regenerative furnace the side-walls can easily provided with peepholes)
- The combustion chamber has a relatively simple construction and it can be sealed reasonably well (no large burner port)
- But: preheating of the combustion air is less efficient than for regenerative furnaces

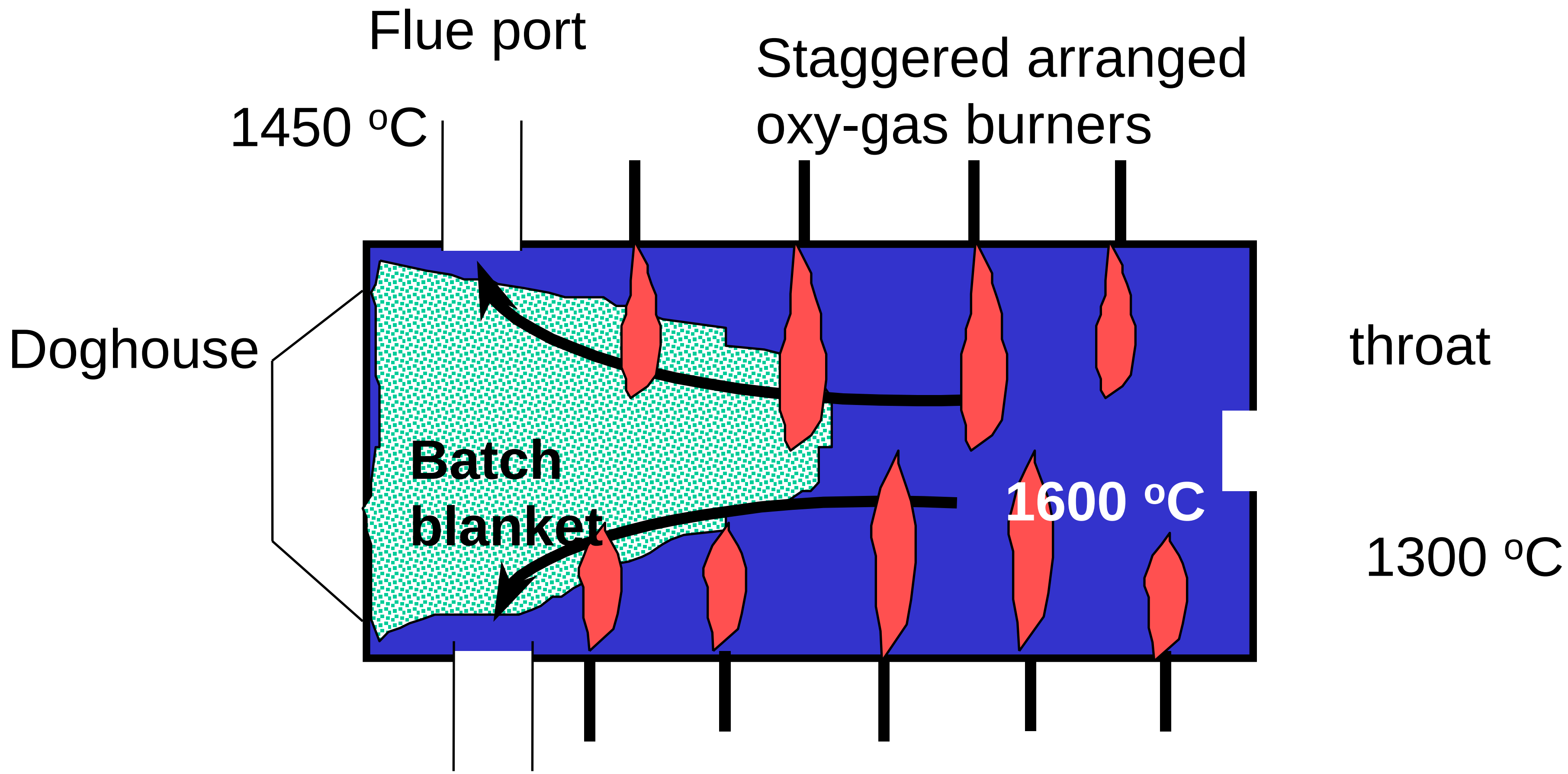
Oxygen-fuel fired furnaces (Oxy-fuel)

- The fuel is fired without nitrogen in the applied oxidant (pure oxygen) (lower volumes of flue gases, less diluted)
- In general, oxy-fuel glass furnaces have the same basic design as recuperative glass melters, with multiple lateral burners and a limited number of exhaust port(s).
- Most oxygen fired glass furnaces hardly utilise heat recovery systems to pre-heat the oxygen supply to the burners *(there are some developments in **oxygen and natural gas preheating** using the heat contents of the flue gases)*
- Burners positioned in special burner blocks in the sidewalls
- Typically only **4 to 6 burners per sidewall** are installed.
- NB: Burners from opposite sidewalls are preferably not placed in one line. This would lead to instable flame tips influencing each other.

Oxygen-fuel fired furnaces (Oxy-fuel)
(source: SEPR)



Oxygen-fuel fired furnaces (Oxy-fuel)



Optionally multiple exhaust ports

Oxygen-fuel fired furnaces (Oxy-fuel)

- **Advantages**
  - ✓ cheaper furnace designs
  - ✓ lower specific NOx emissions (in kg NOx/ton molten glass);
  - ✓ smaller flue gas volumes
  - ✓ smaller footprints for furnace system
  - ✓ reduction in fuel consumption

- **Drawbacks**
  - ✓ oxygen costs may exceed the reduction in fuel costs
  - ✓ oxygen-firing require higher refractory quality superstructures

Melting tanks dimensions

Typical melting tank dimensions for continuous glass furnaces	
Length Width Glass depth Length/width ratio	8 – 40 m 5 - 15 m 0.6 - 1.8 m (deep refiner > 1.5 m) 1.25:1 - 5:1

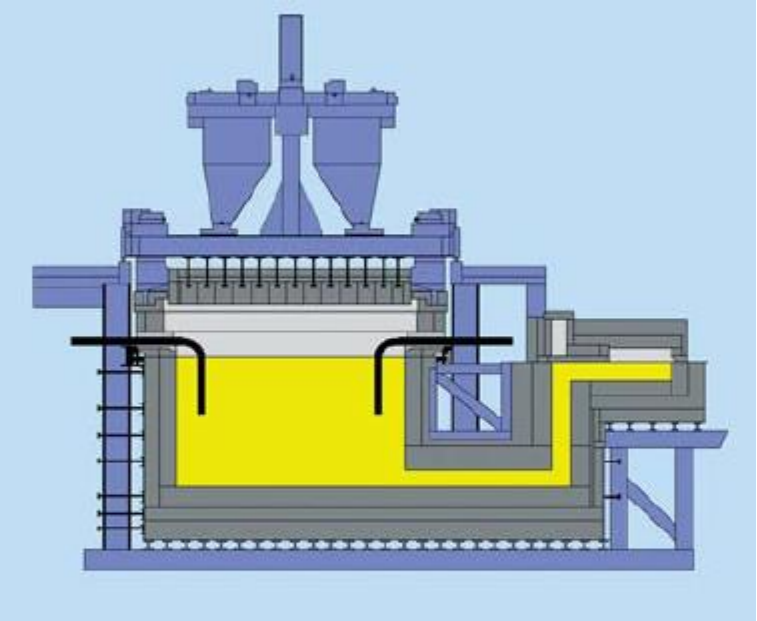
Extension of tank for charging the raw material batch: **doghouse**

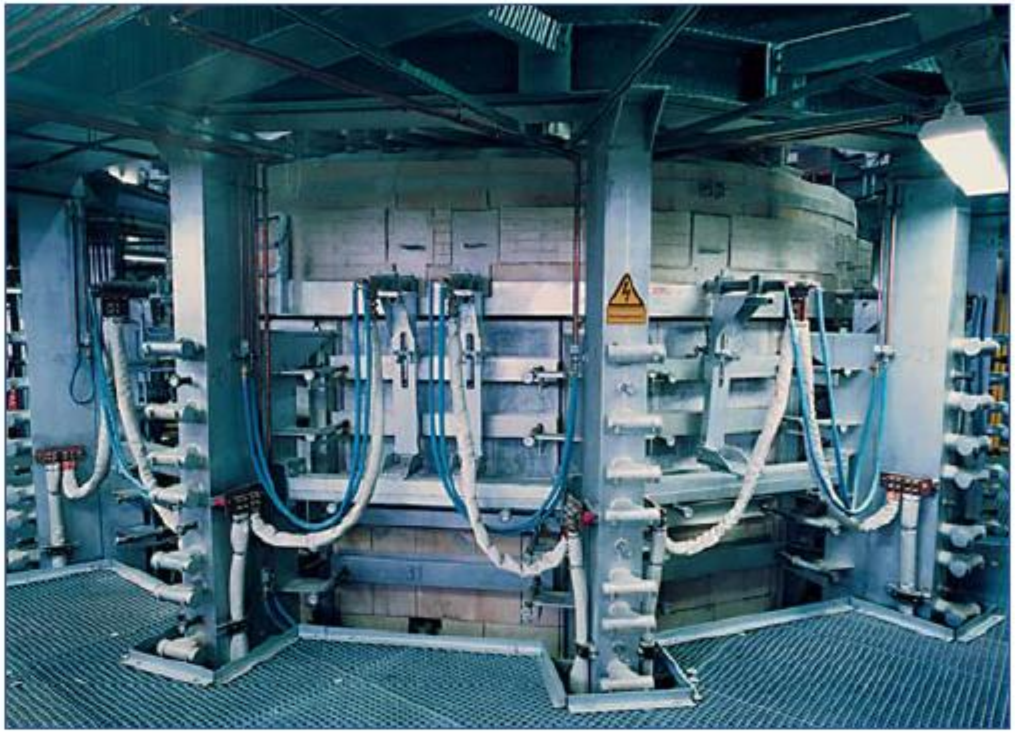
Summary / overview furnace types

Furnace type	Glass type	Glass pull range (TPD)	Melting area Range (m^2)
Regenerative cross fired (open connection to working end)	- Float-glass	500 - 1000	300 - 400
Regenerative Cross fired (with throat)	- Container glass - TV-CRT glass - Lighting glass - Tableware	100 - 600	20 - 200
Regenerative End port fired (with throat)	- Container Glass - Tableware	100 - 400	50 - 140
Recuperative cross-fired	- Fiber glass - Technical glass - Tableware - Container glass (small)	20 - 400	15 - 140
Oxy-fuel (cross-fired)	- Fiber glass - Technical & Special glass - Tableware - Glass wool - Container glass - Float Glass	1 - 400 500 - 800	1 - 100 250 - 400

All-electric melting

- The heating is not provided by combustion systems, but by electric energy provided by electrodes plunging in the melt
- Below is an example of an all-electric furnace with top electrodes (Sorg)



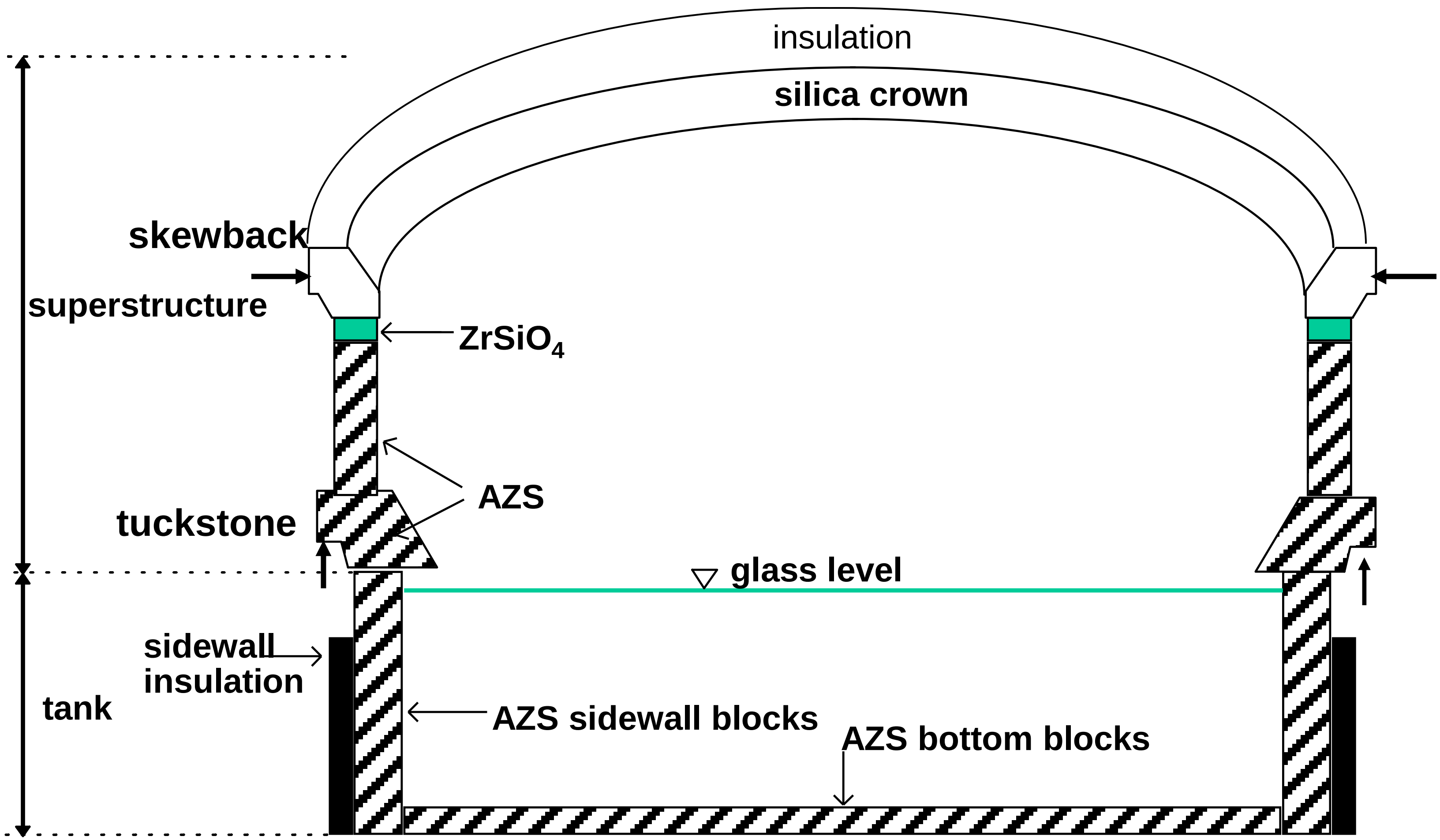


Pictures from Sorg, report "Glass melting technology", available online

Furnace superstructure

Melt tank and superstructure construction

Arrows indicate supports of superstructure by steel construction



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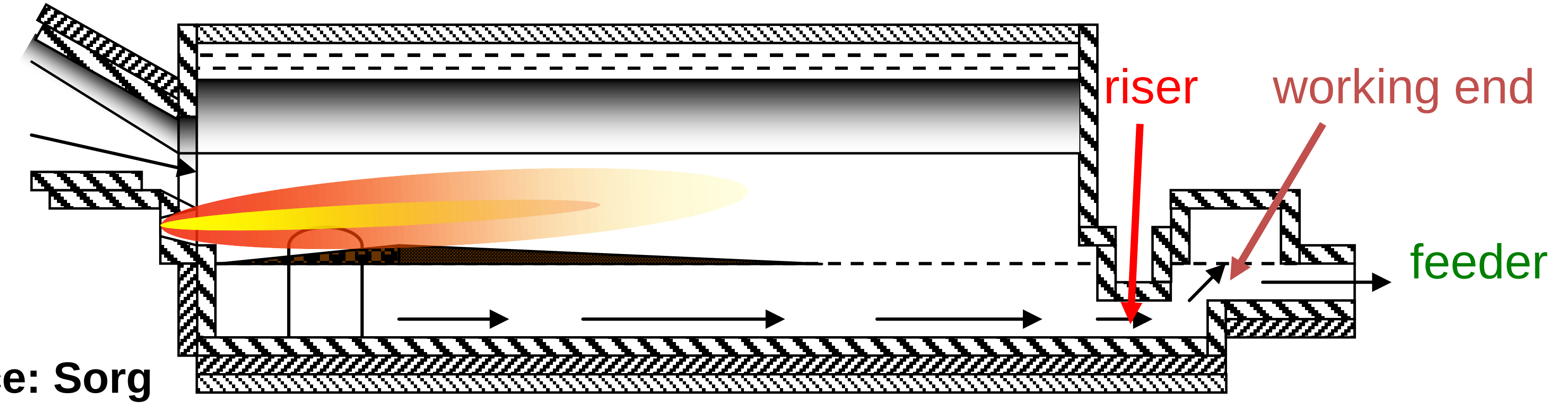
Downstream glass melting tank

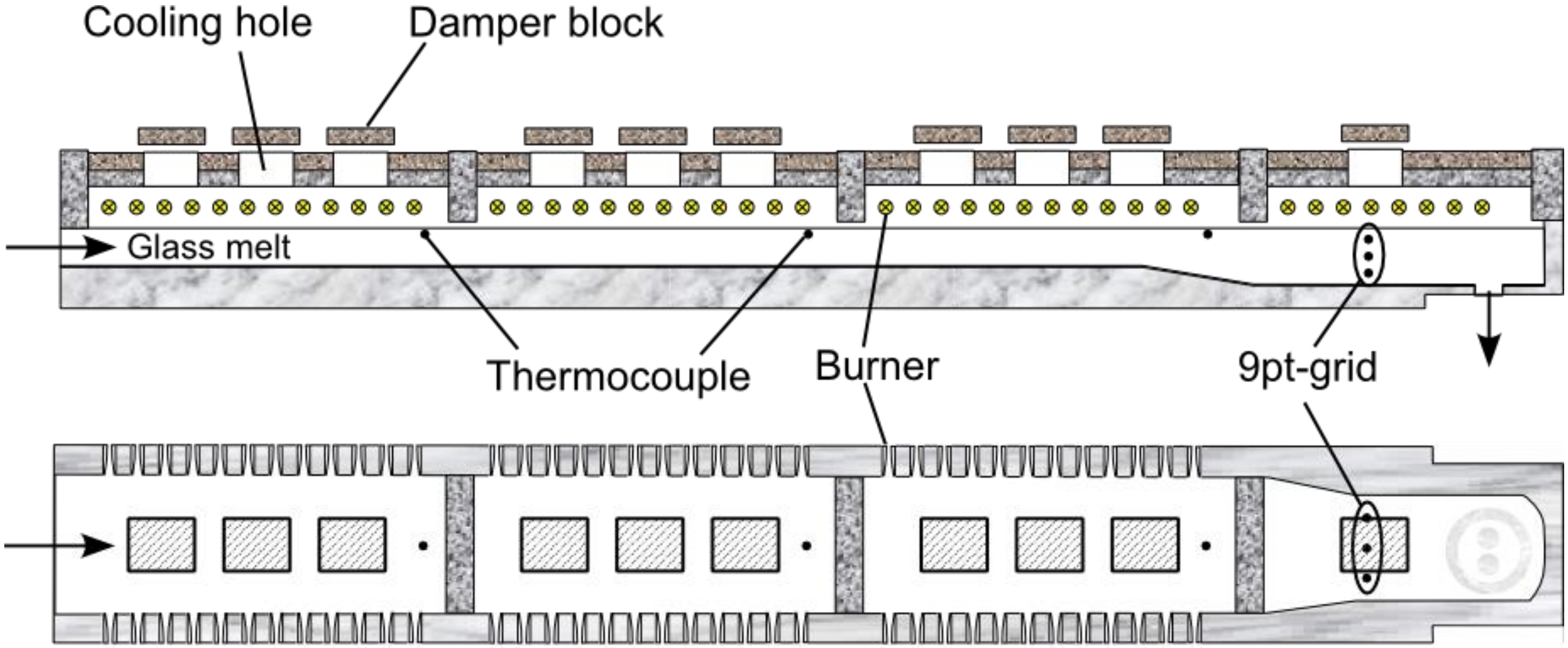
- Temperature of the glass melt, flowing from the **melting- end** through the throat into the **riser** and then into the **distributor/working-end/refiner**, is too hot for **forming.**
- Required cooling: by **refiner and feeders** by 200 to 300ºC to approximately the working temperature.
- Glass portions or gobs or a continuous flow of glass at this lower temperature level are required for a well performing forming process.



Source: Sorg

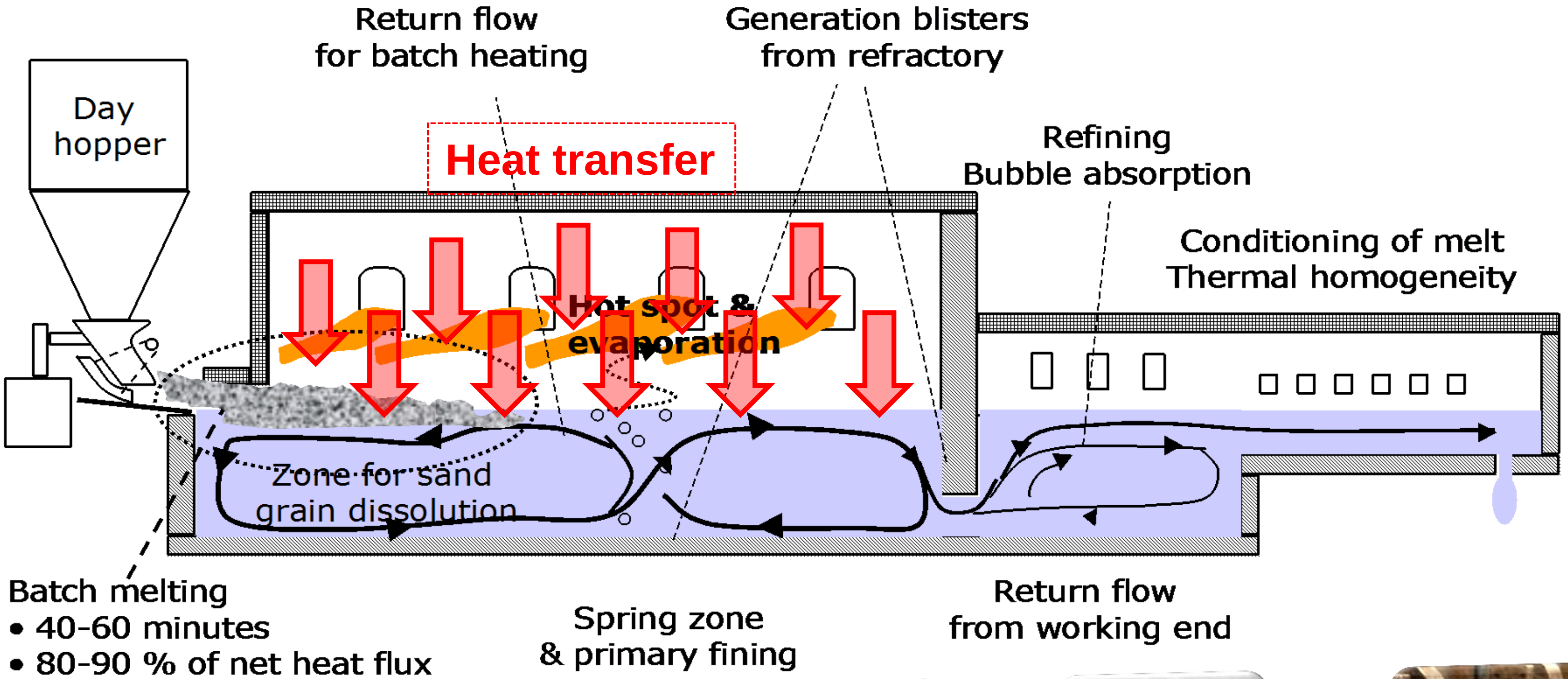
Example of a feeder canal (container glass)

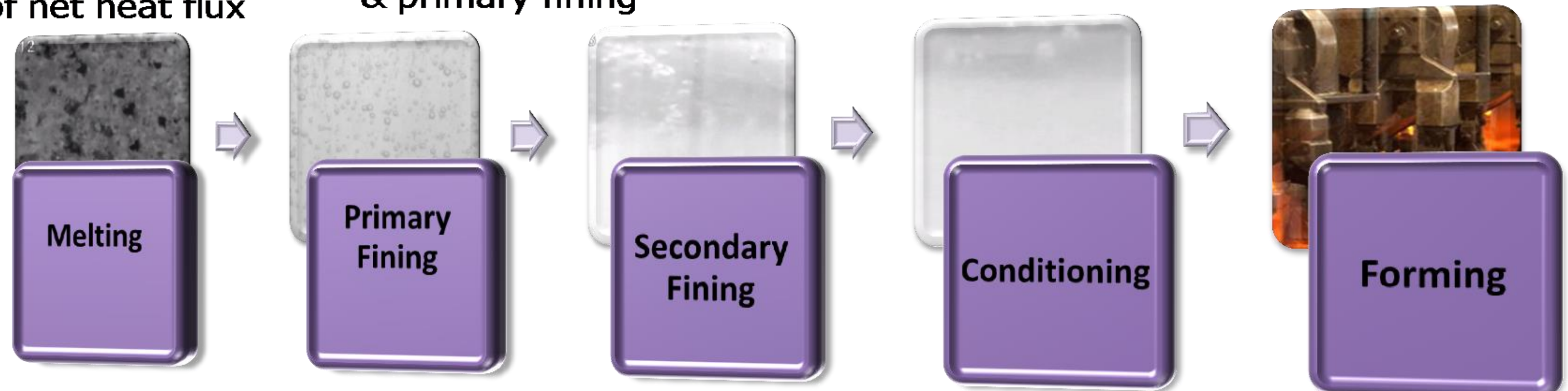
- **Heating** of relatively cold glass flowing **at the sides** and
- **Cooling** of glass melt flow **in center** axis of canal



Process steps

Process steps

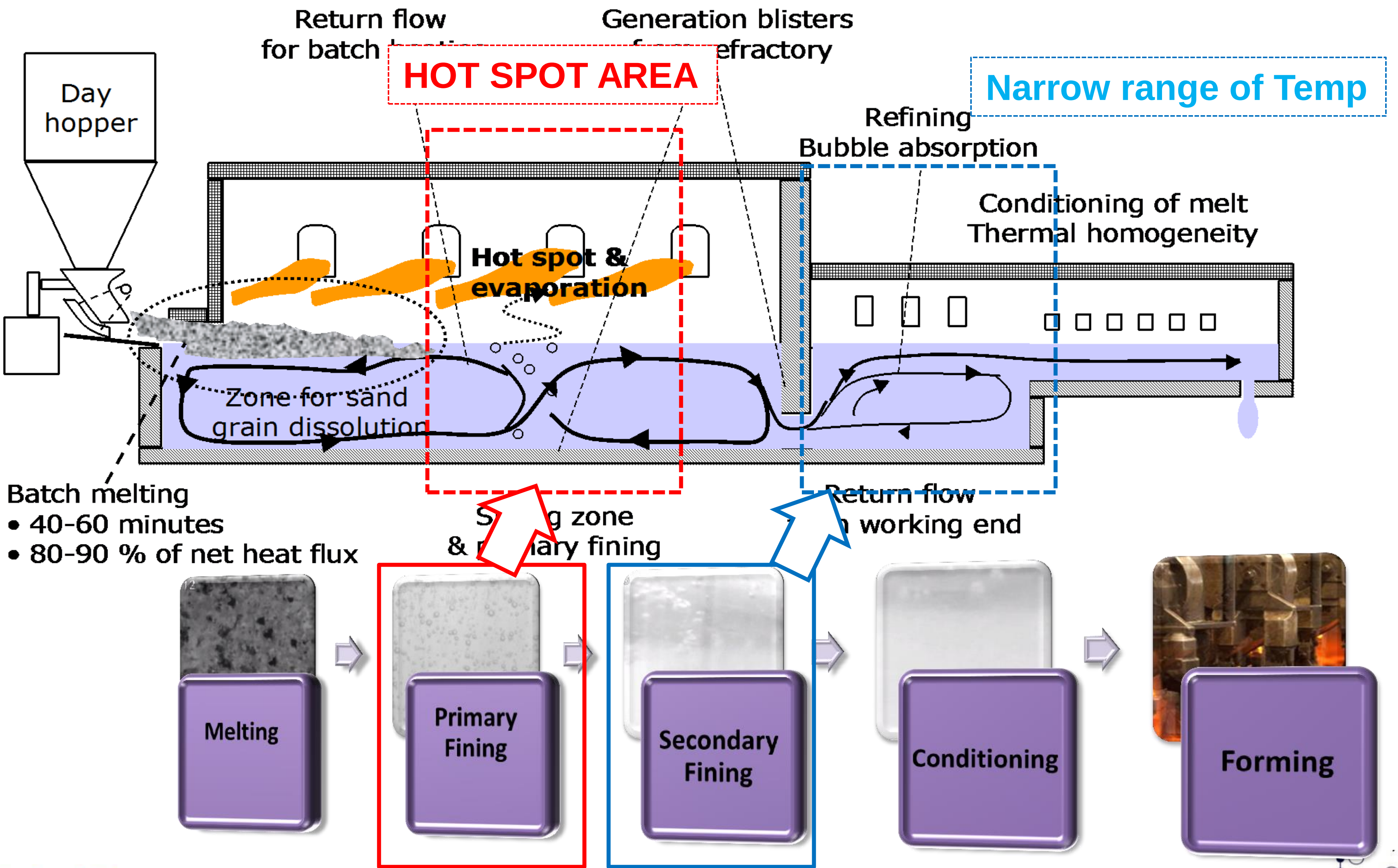




Process steps

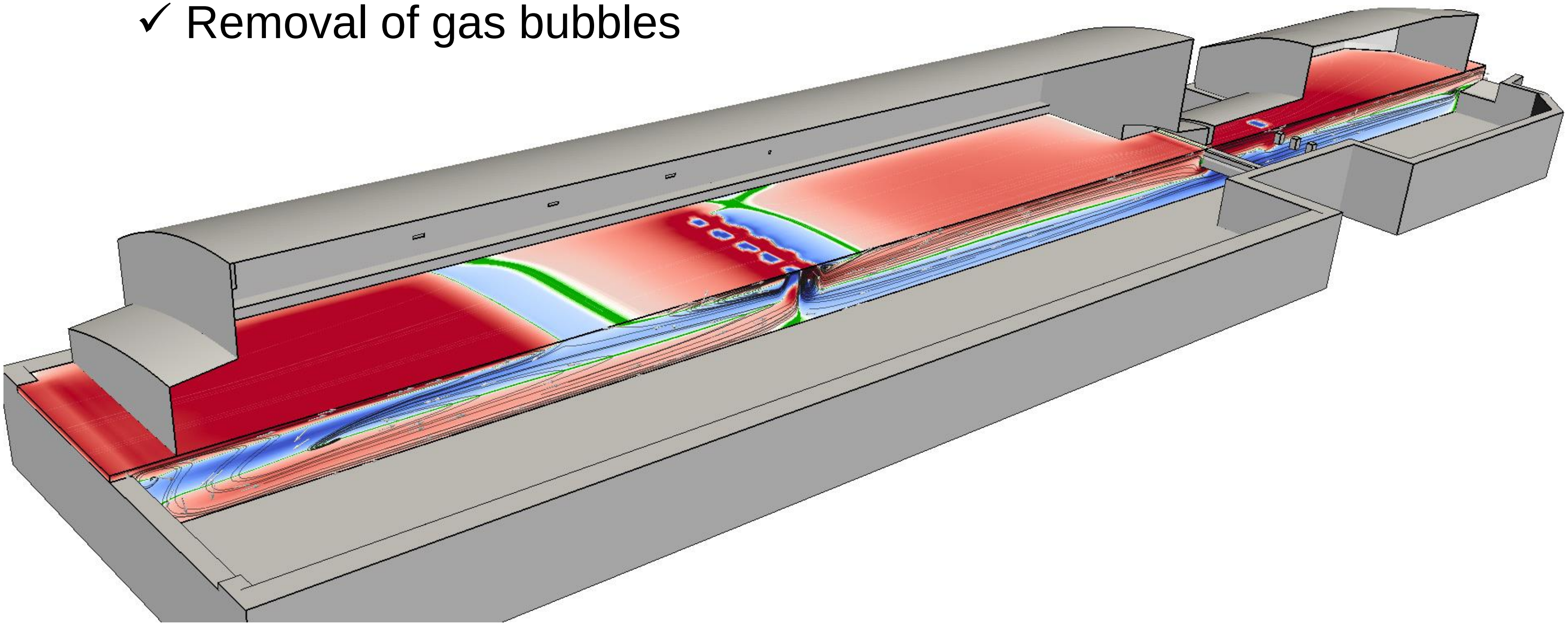
- During melting of batch, new bubbles are generated
- Primary fining should start after last new bubble has been created
- During all stages of melting, fining and conditioning: **homogenization**
- For each process step, requirements have to be fulfilled with respect to **local temperature**, **residence time** and **mixing characteristics**
- This is not the only reason why the process steps preferably should be passed successively
    - ➢ During the melting process bubbles are generated
    - ➢ These bubbles can only be removed effectively from the melt by the fining process, when the fusion process has been completed and no new bubbles are being formed anymore at the interfaces non-dissolved raw material grains.

Process steps



Flow patterns

- The **glass melt flow patterns** in glass melting tanks are decisive for the **residence times** and the exposure of the melt to sufficiently high temperatures for:
  - ✓ Melting of batch
  - ✓ Complete dissolution of sand grains
  - ✓ Removal of gas bubbles

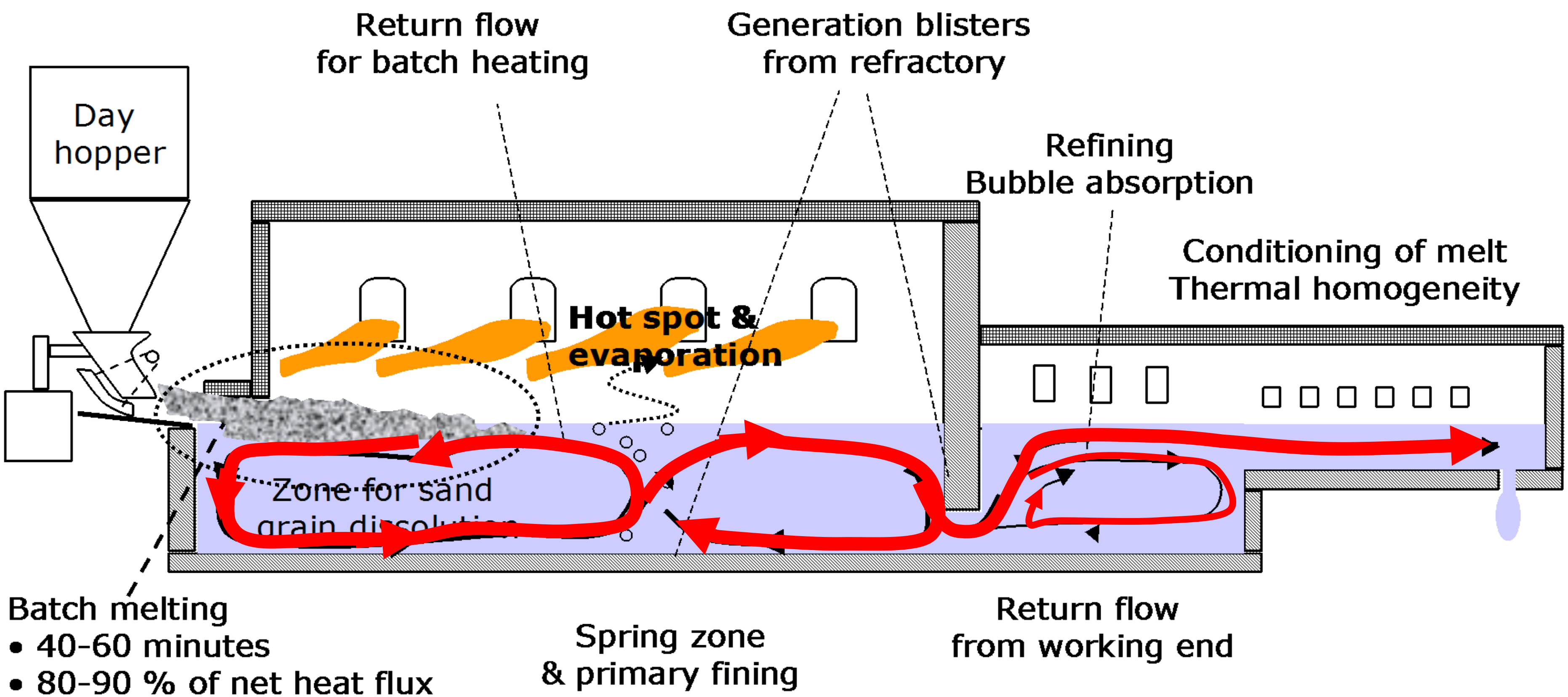


Heating and flows

- The melt is heated by gas or oil **flames directed over the glass melt** bath. Within the melt, glass **melt flow patterns**, are being generated, both by the **pull & free convection**.
- **Free convection** flow arises from **density differences within the melt**
- Due to the **temperature profiles**, density differences are generated within the melt which will create free convection (density difference driven) flow.
- The **free convection flow is generated on purpose** in order to obtain enough mixing and homogenization and to avoid short cut flows

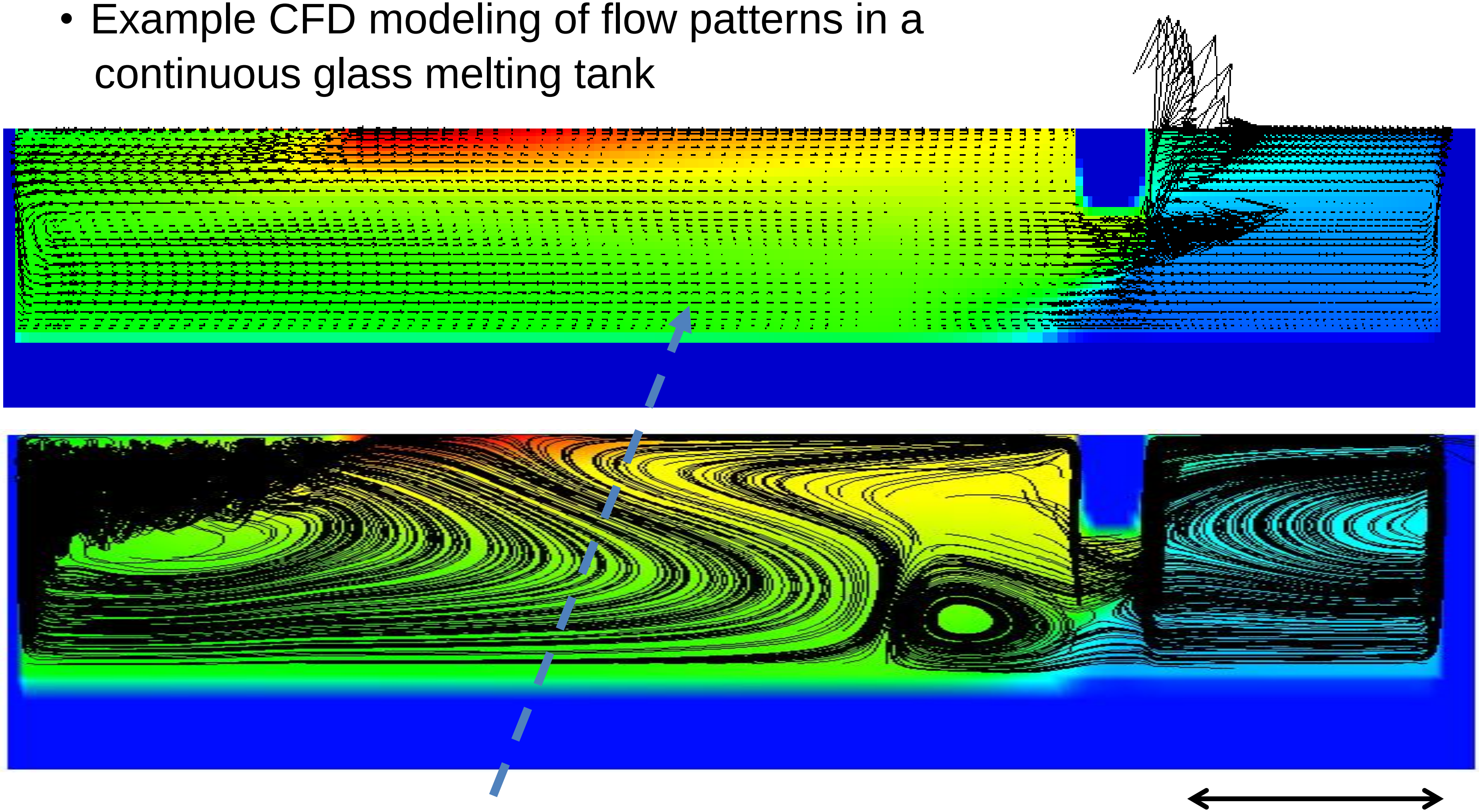
Convections loops

Goal: force all the glass melt to the area with the highest temperature and to avoid a short cut flow in the melt tank



Characteristic flows and temperatures

- Example CFD modeling of flow patterns in a continuous glass melting tank

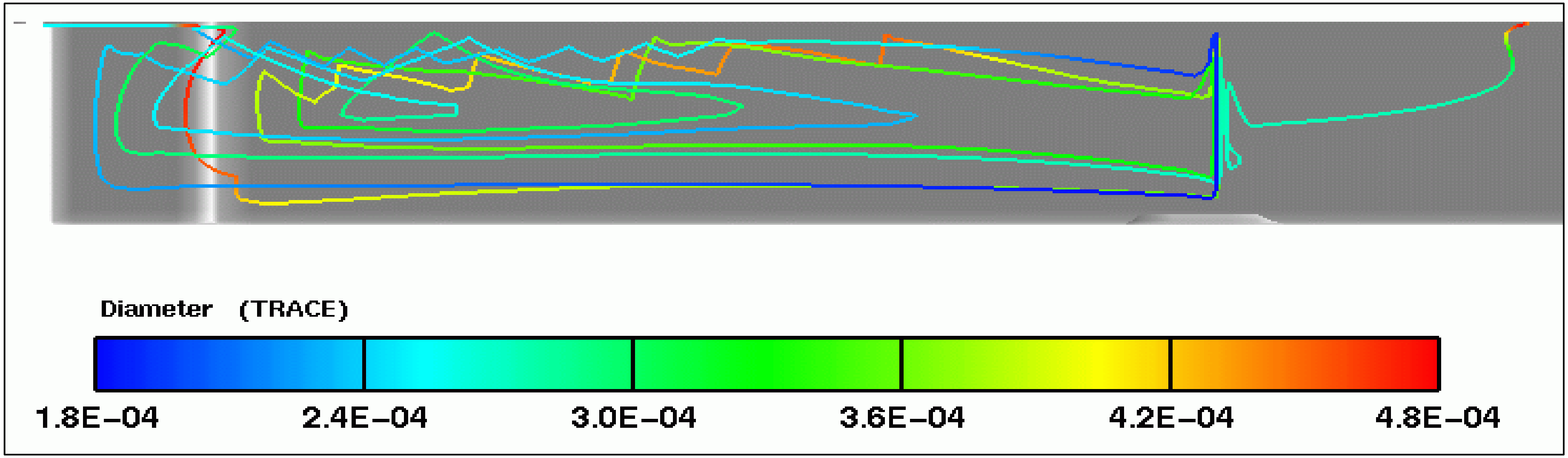


Tendency for short cut flow!

Residence time

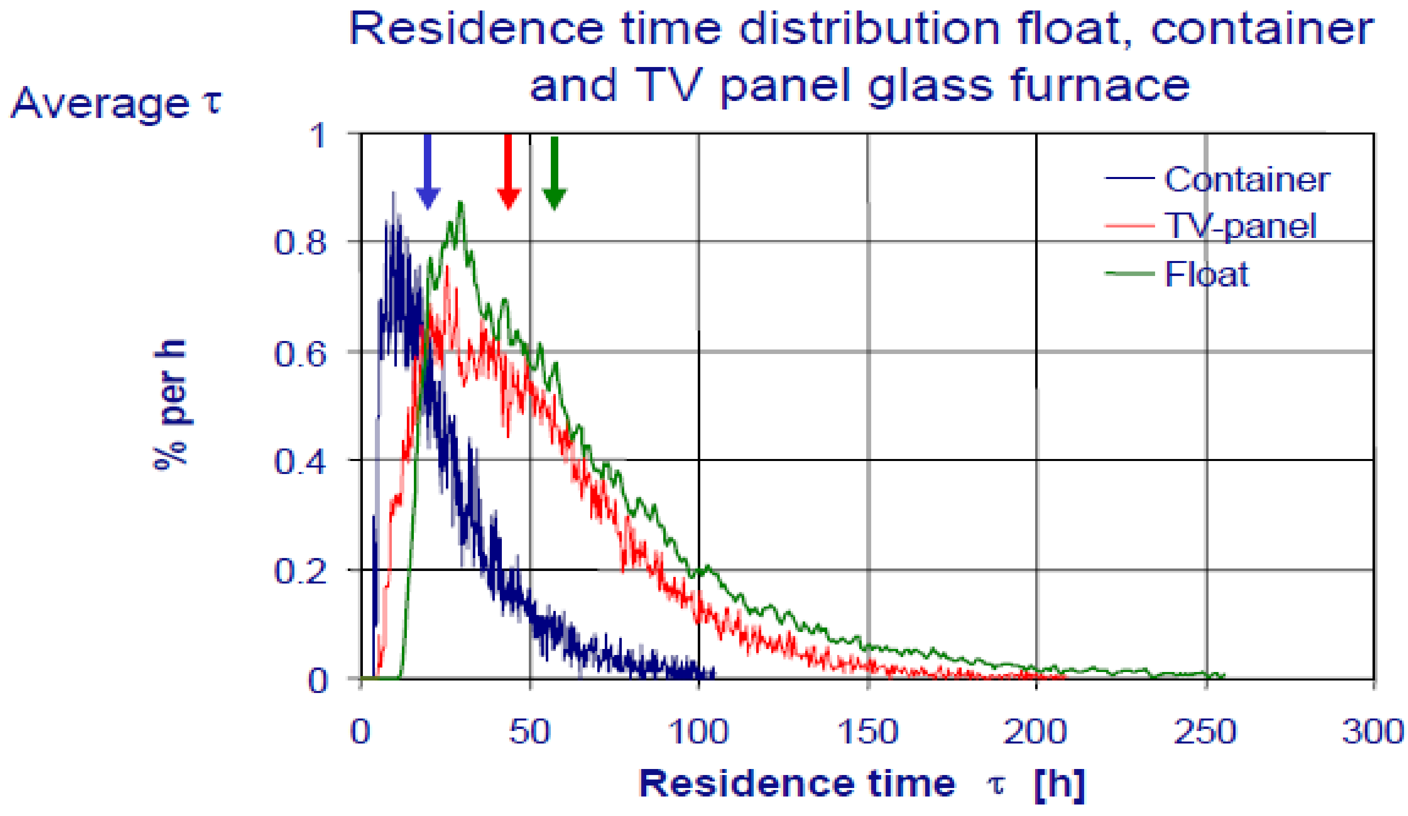
- Not all particles (notably sand grains) will have similar residence time inside the furnace
- To avoid defects, it is important to ensure that all particles remain in the furnace long enough to allow good dissolution and homogenization
- **Minimum residence time** is thus a very important factor for a good glass quality and homogeneity

Example: many different trajectories (paths) in tank



Residence time

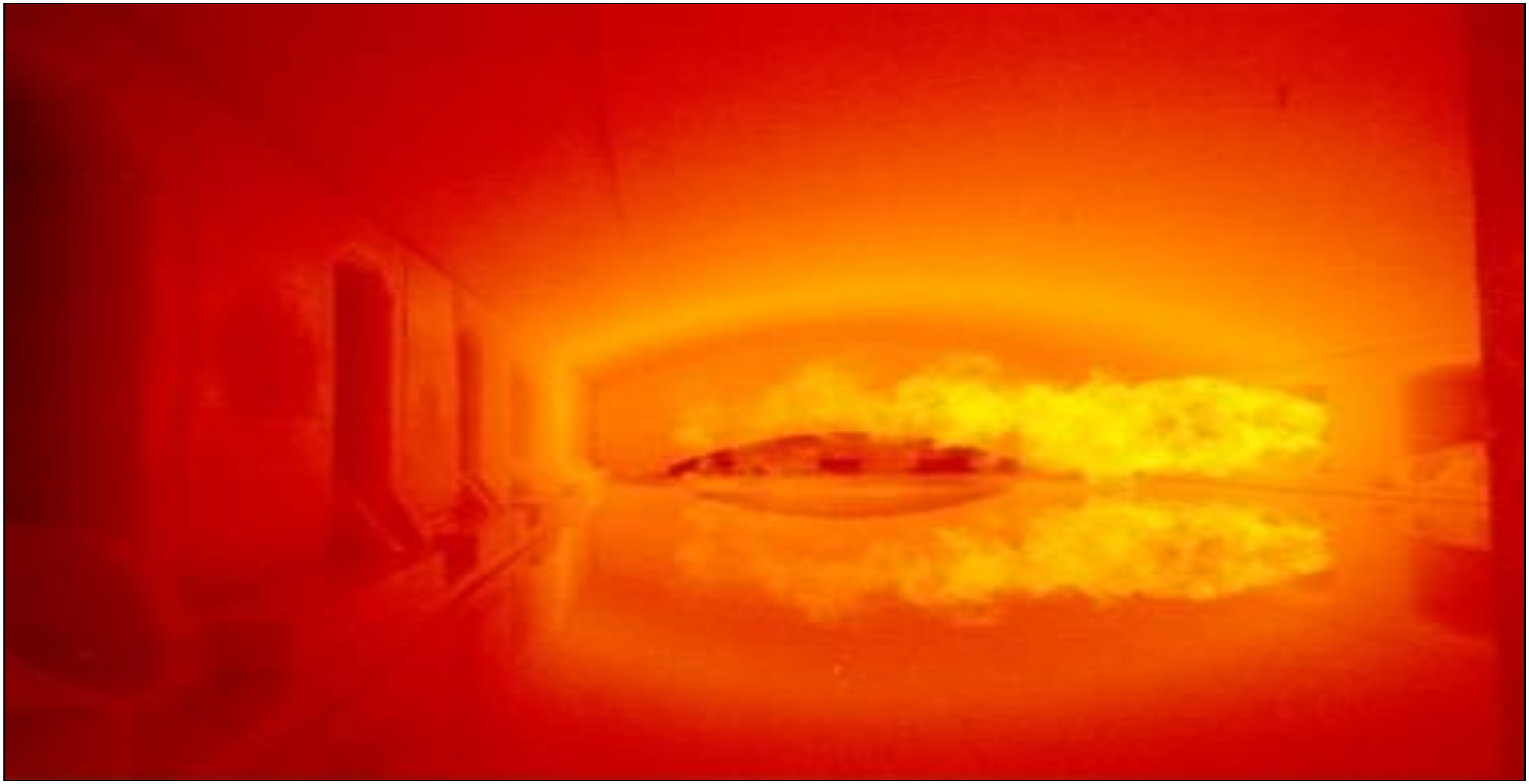
This **minimum residence time** is the **shortest reaction time** of the glass product on changes in batch composition



min. residence time/average residence time = 0.15-0.20

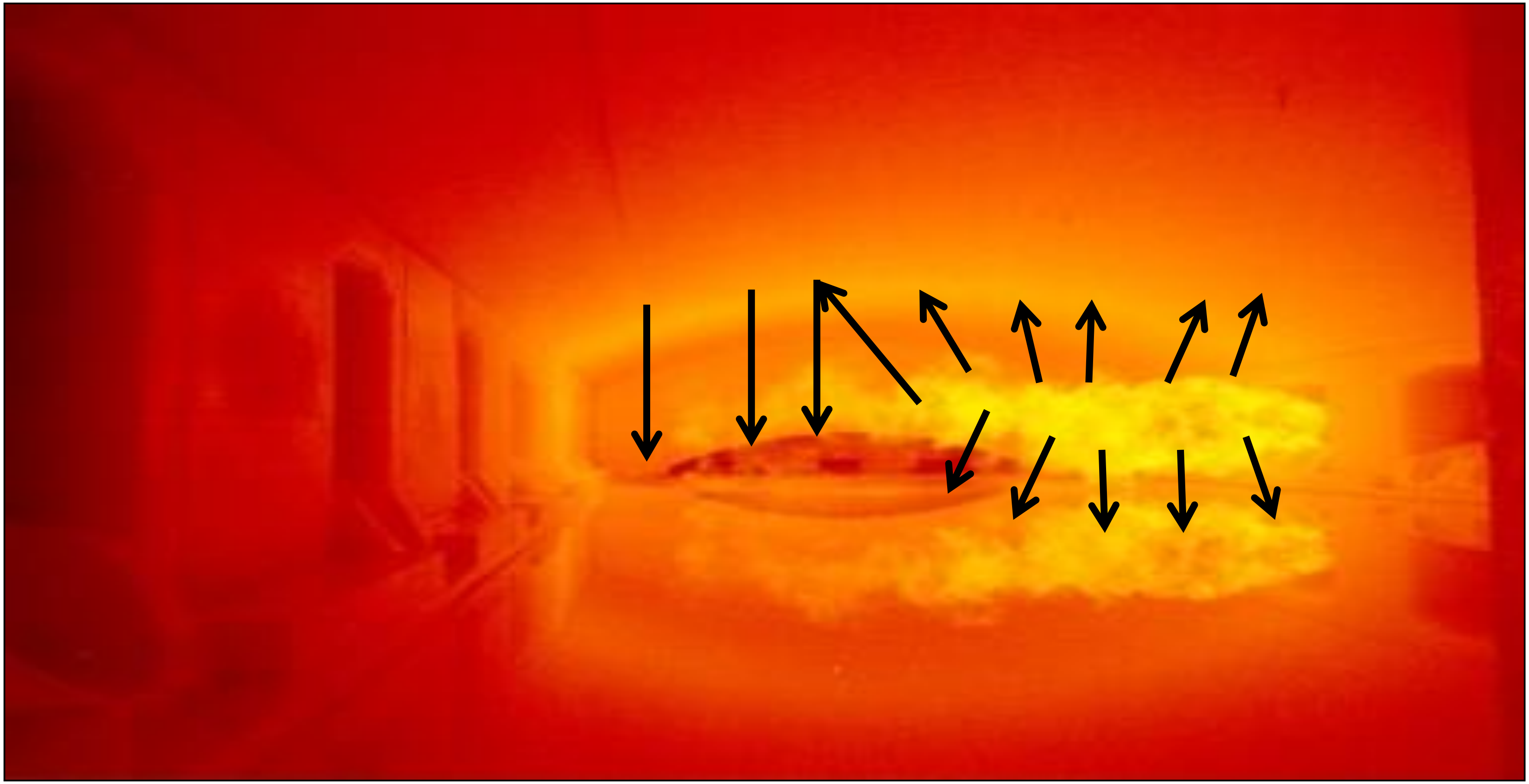
Heat transfer

- Example of a flame above the glass melt in a side-port regenerative furnace



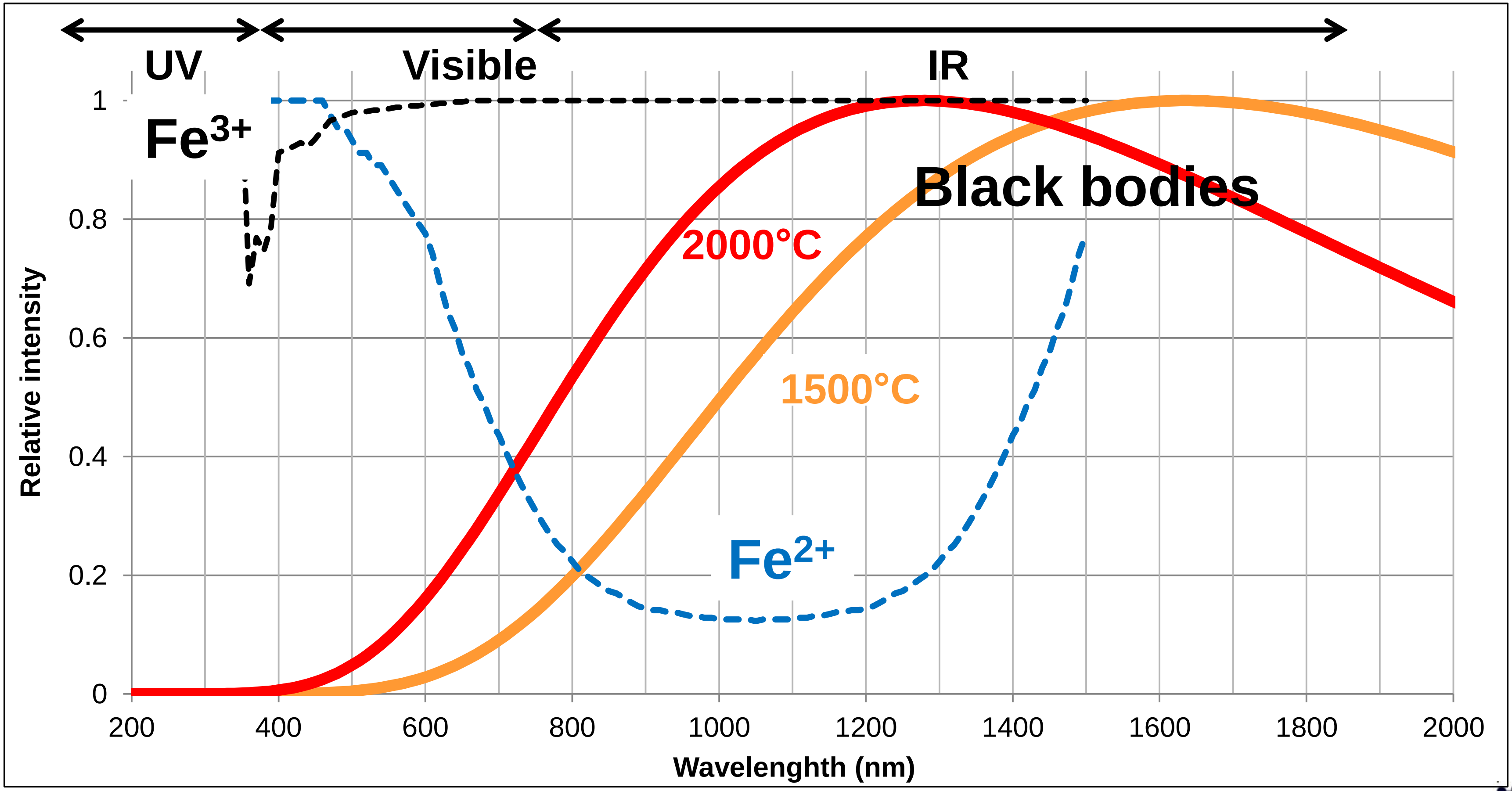
Heat transfer

- The heat is transferred from the flames to the melt by radiation
- The flames also heat up the **crown**, which also radiates towards the melt

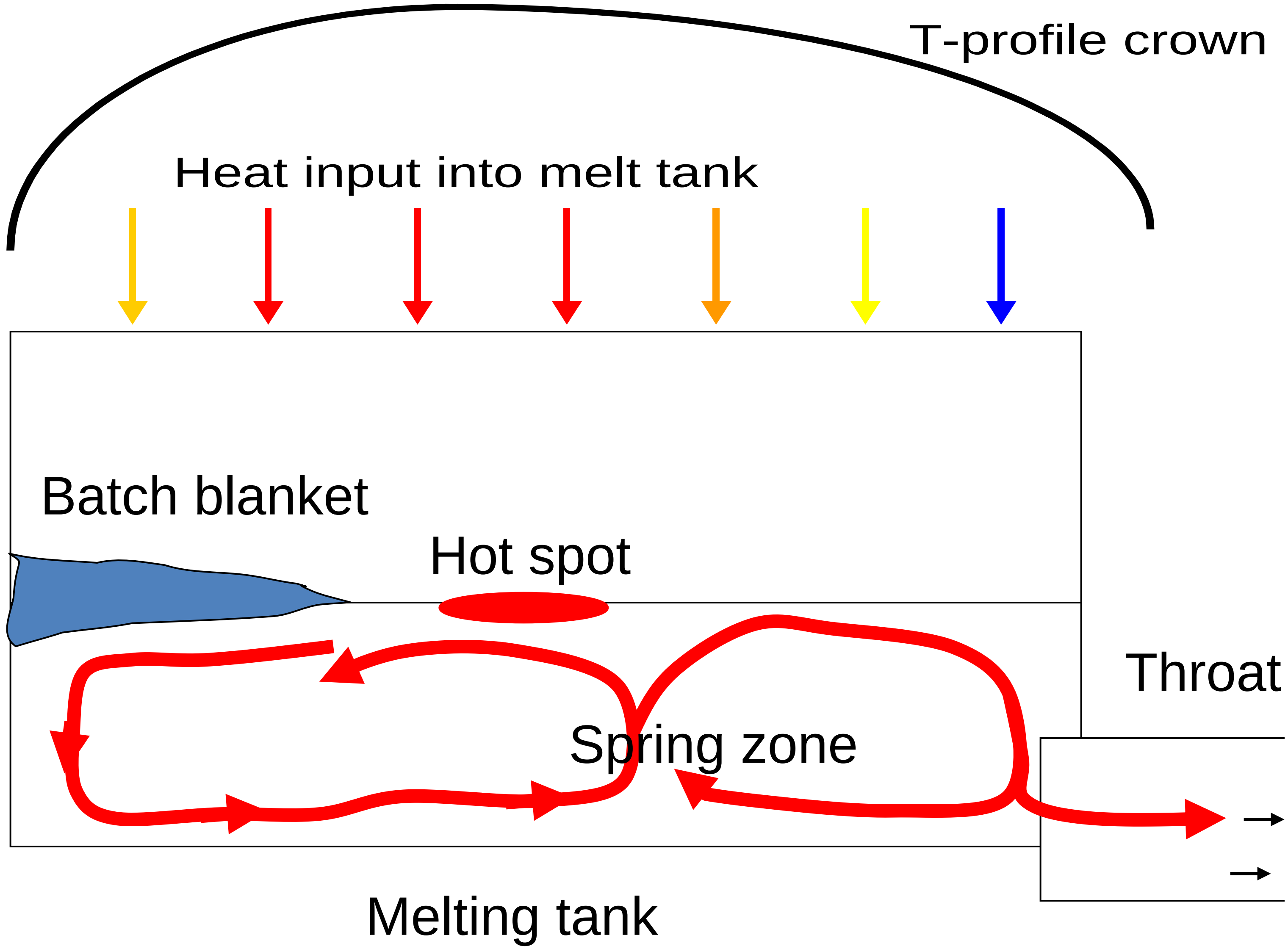


Redox of the glass and heat transfer

- The absorption in the **infrared** is very important for heat transfer
- The **redox state of the melt** (notably iron ratio Fe^{2+} / Fe^{3+}) plays a major role in the amount of heat absorbed by the melt

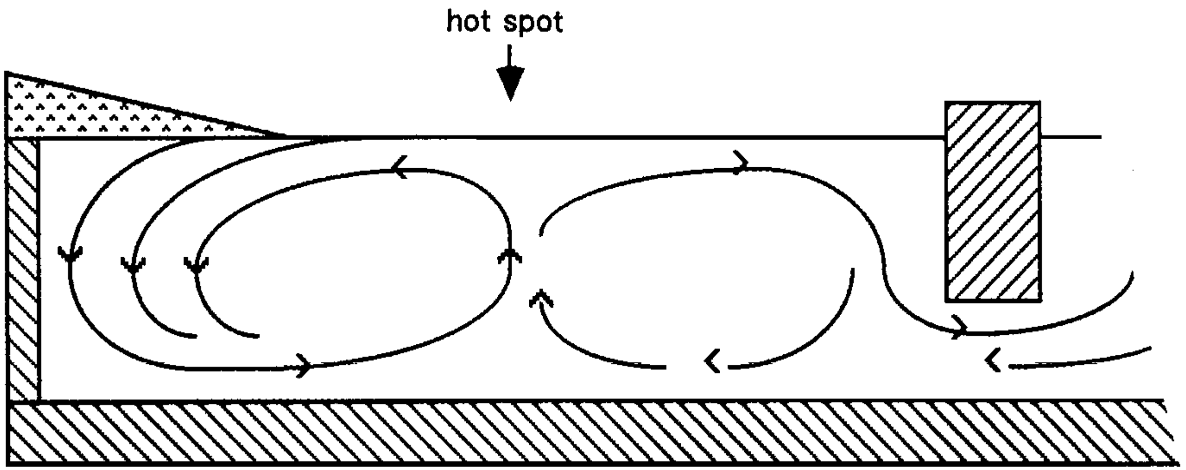


Temperature profile in the crown

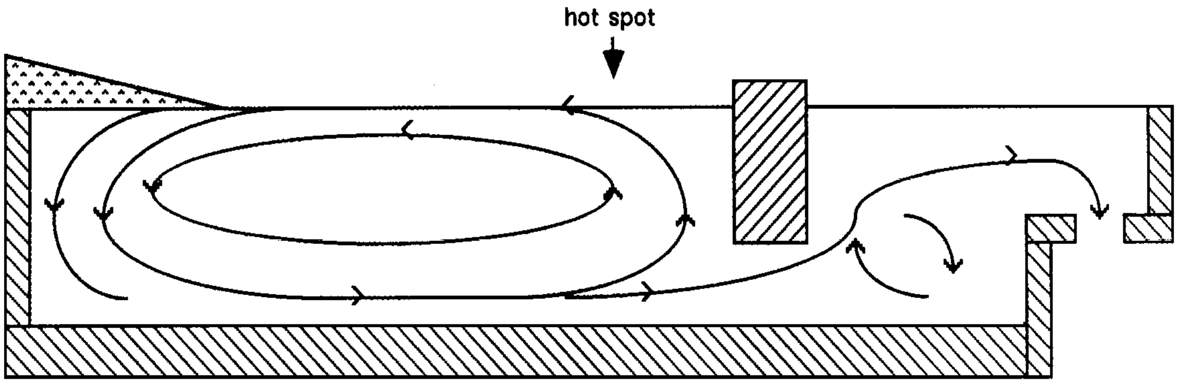


Convection flows by temperature differences in the glass melt

Hot spot in position in the middle of the furnace



Hot spot at the end of the furnace, only one large loop is created (like in most U-flame furnaces)



Additional means to influence flows

- Besides adjusting the settings of the burners (fuel distribution) to modify the temperature profile in the melting tank, additional means can be implemented in the furnace to promote the flows
- These include:
  - ✓ Forced bubbling (via bubblers)
  - ✓ Electric boosting
  - ✓ Weirs/dams

- NB: the presence of foam on top of the melt may disturb the heat transfer from the flames to the melt

Bubblers

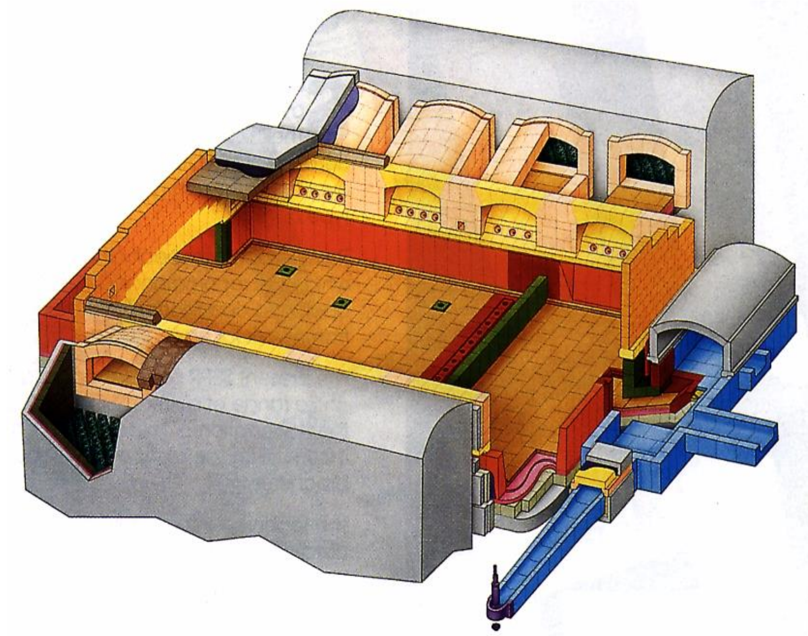
- Bubbling improves the heat transfer by bringing the relatively **colder glass melt** from the bottom to the **surface** of the melt.
- In many cases, **bubbling** in the molten glass is applied in the melting tank, especially in the hot spot sections of the melting tank.
- Proper bubbler positioning and operation can improve the spring zone performance:
  - ✓ bringing the relatively cold bottom glass to the hot glass melt surface
  - ✓ preventing cold glass melt flowing along the bottom directly to the working end section
  - ✓ separation between melting-in zone and fining zone.

Electric boosting

- **Electrodes** in the melt can be applied to rise the glass melt to the surface
- Vertical electrodes positioned over the width of the melting tank, sometimes in combination with horizontal electrodes, are used to heat the glass melt by electric currents.
- The glass melt passing the zone with the electrodes is heated up at this position in the tank, and the decreasing glass melt density brings this melt to the surface area
- NB: Special precautions must be taken when using electrodes and/or bubblers: construction, material employed, oxidation, cooling systems for the electrode…

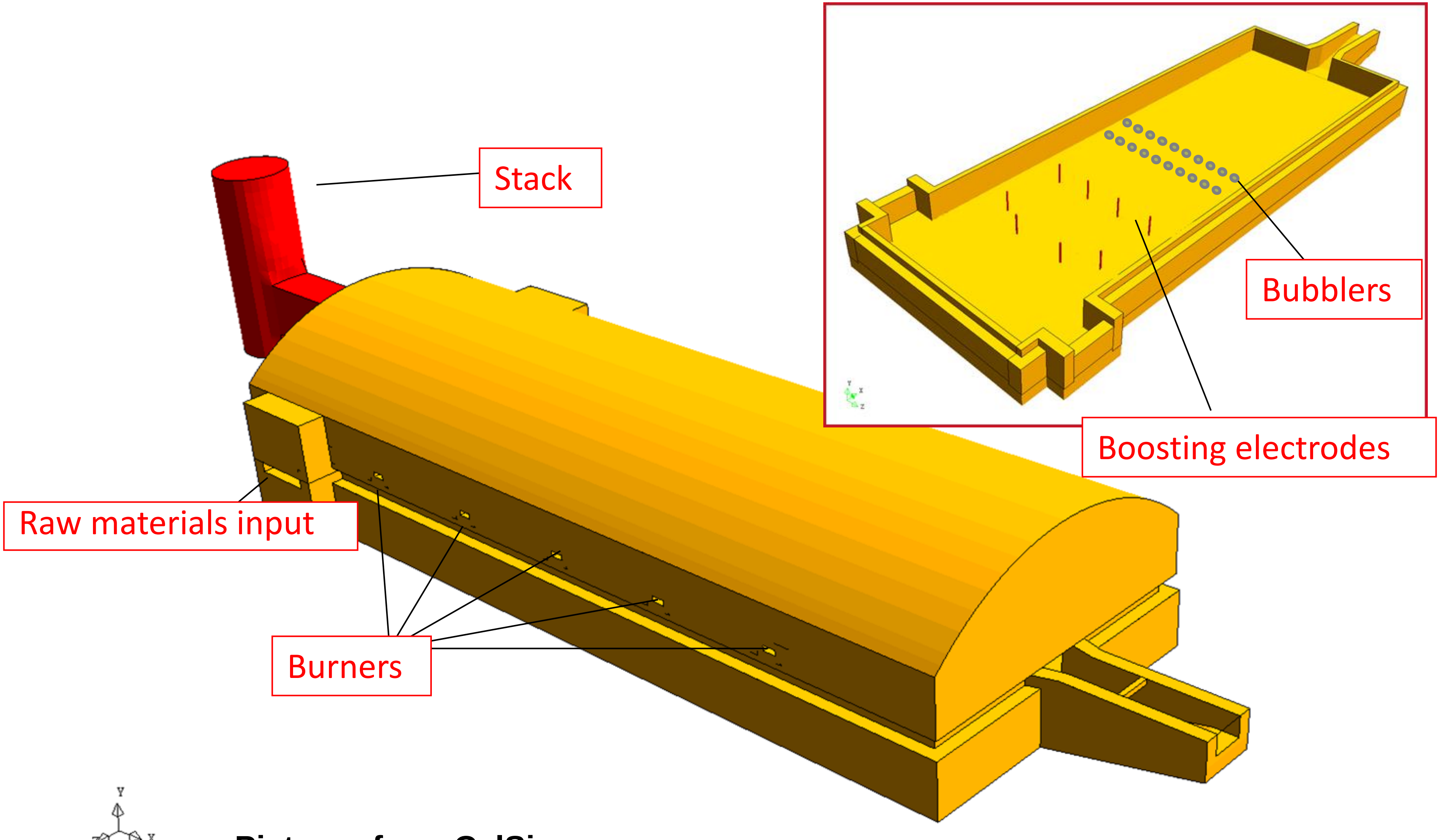
Weirs/dams

- The application of a weir (cross wall, flow barrier, dam) will influence the glass melt flow (mostly applied in the area of the hot-spot)
- This will force the cold bottom glass to move upwards over the weir to be heated and fined before leaving the melting tank
- Such a cross wall is subjected to severe wear (due to high temperatures in the top sections and due to high glass melt velocities)
- For improved fining, a longer weir or fining shelf is more efficient, exposing the glass melt for a longer time to a shallow tank depth.



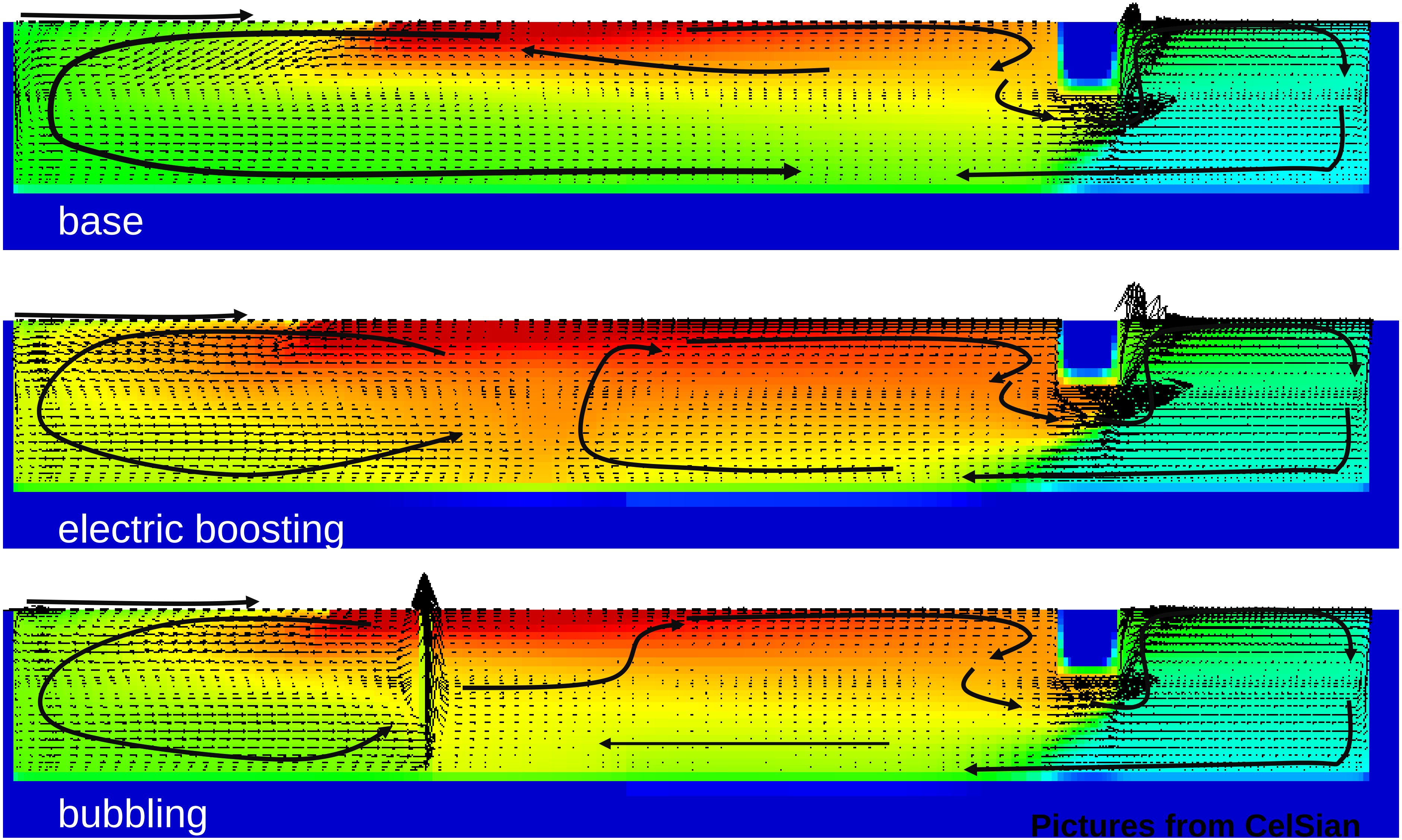
Source: SEPR

Furnace equipped with boosters and bubblers



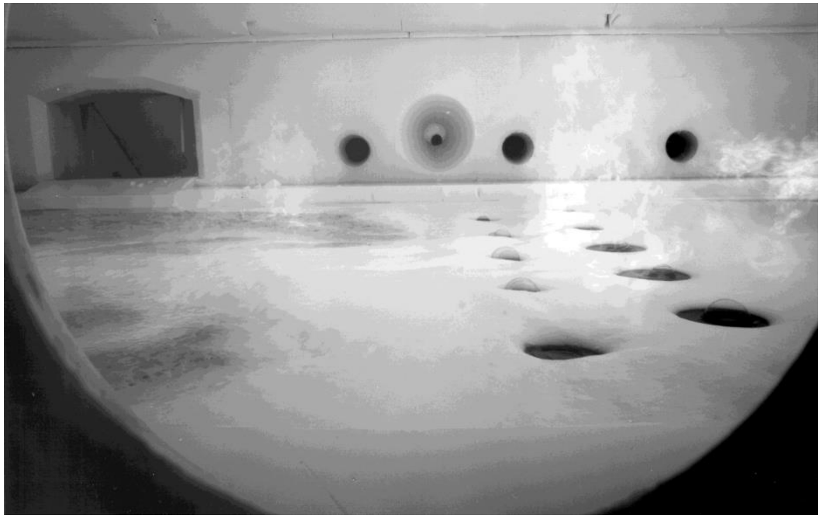
Pictures from CelSian

Example – effect of boosting and bubbling



Foaming

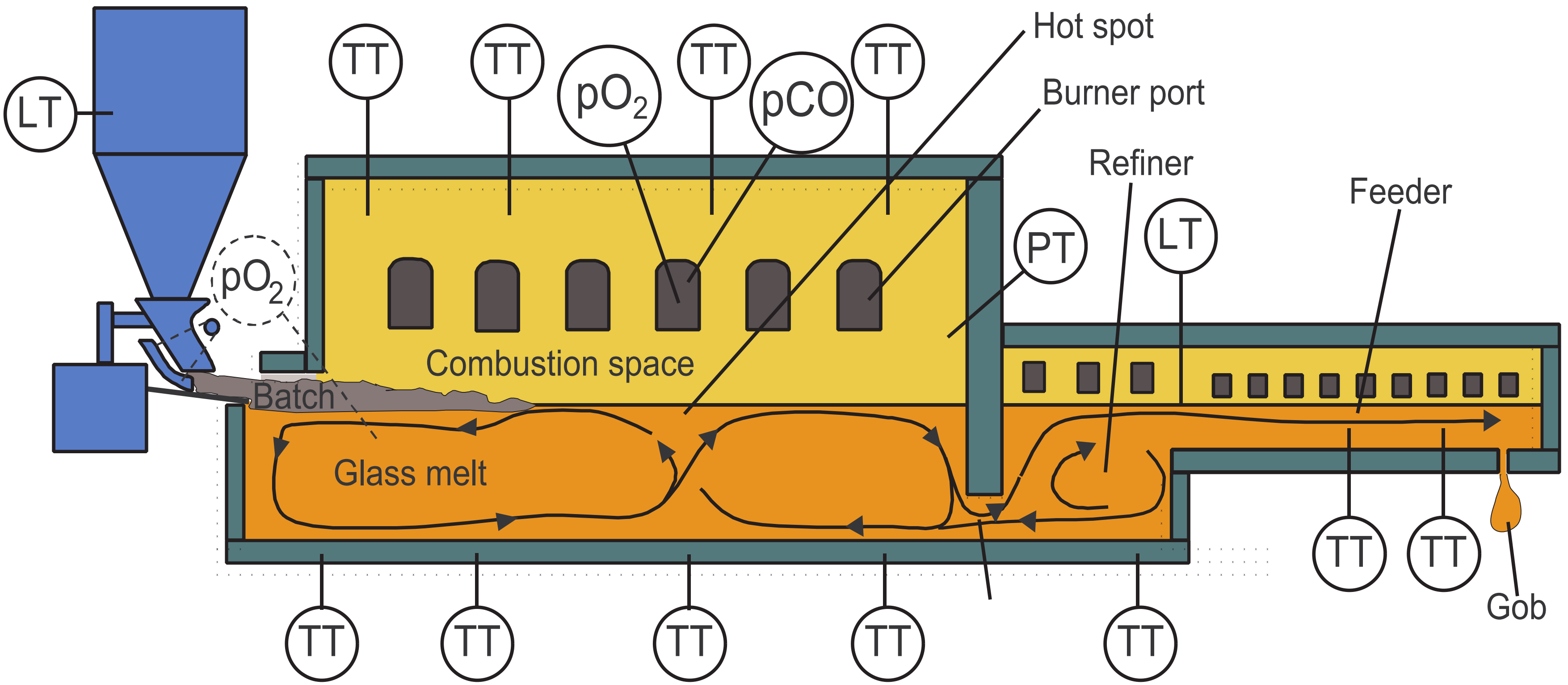
- Due to the release of gas bubbles and certain lifetime of the bubbles at the glass melt surface, a foam layer may arise
- Foaming is caused by degassing of the glass melt during fusion of the batch blanket (**primary foam**) and/or during fining process (**secondary foam**).



- Foam has a strong **insulation** effect.
- It prevents the radiative heat penetration from the combustion chamber into the melt.
- This is unfavorable for the fining process, because especially the primary fining process needs a high temperature

Furnace control and sensors

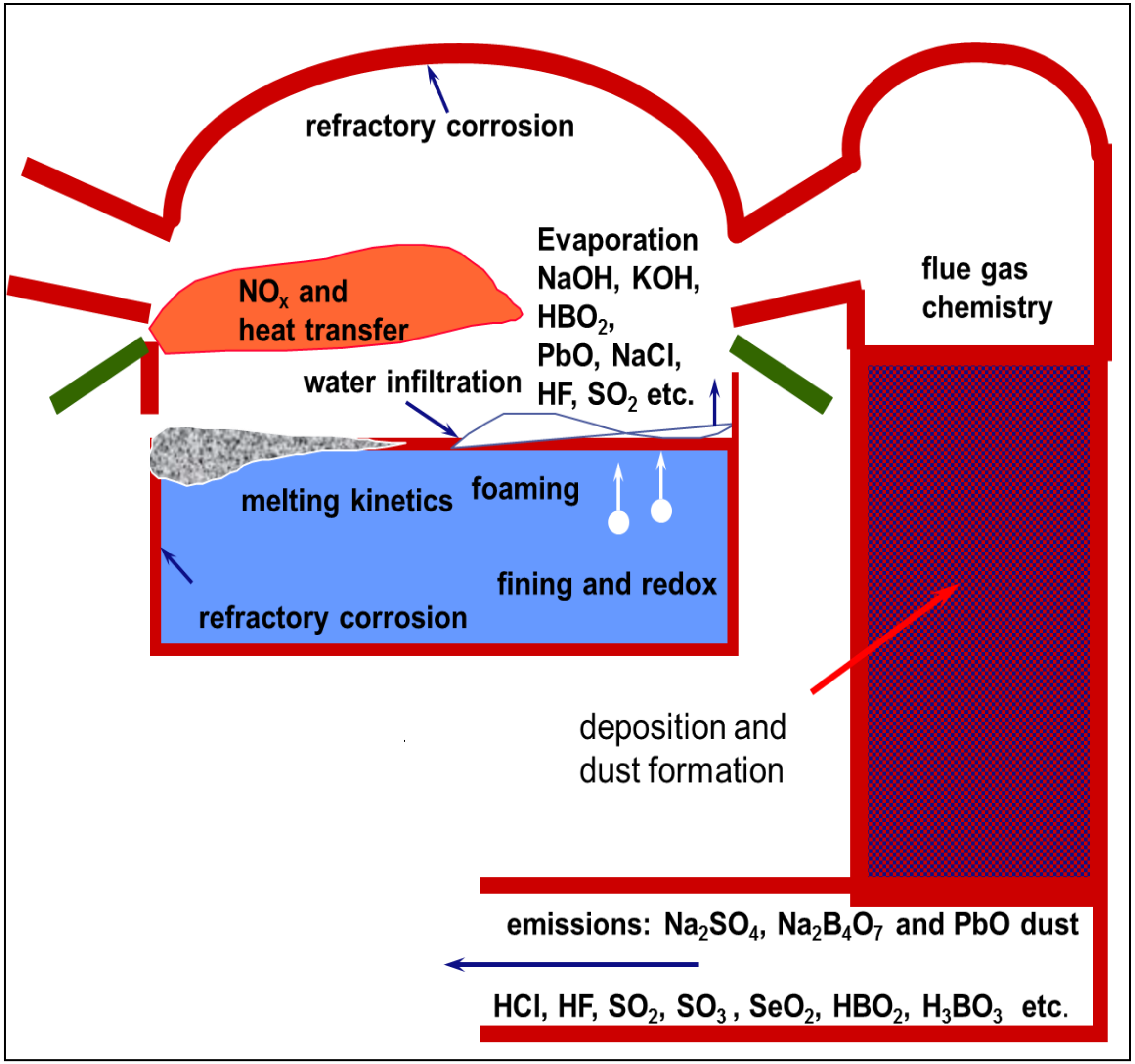
Drawing of a cross fired glass furnace with indicative positions for temperature sensors (TT), gas concentration measurements (pCO, pO_2), glass melt / batch level (LT), pressure level (PT)



Emissions from glass furnaces

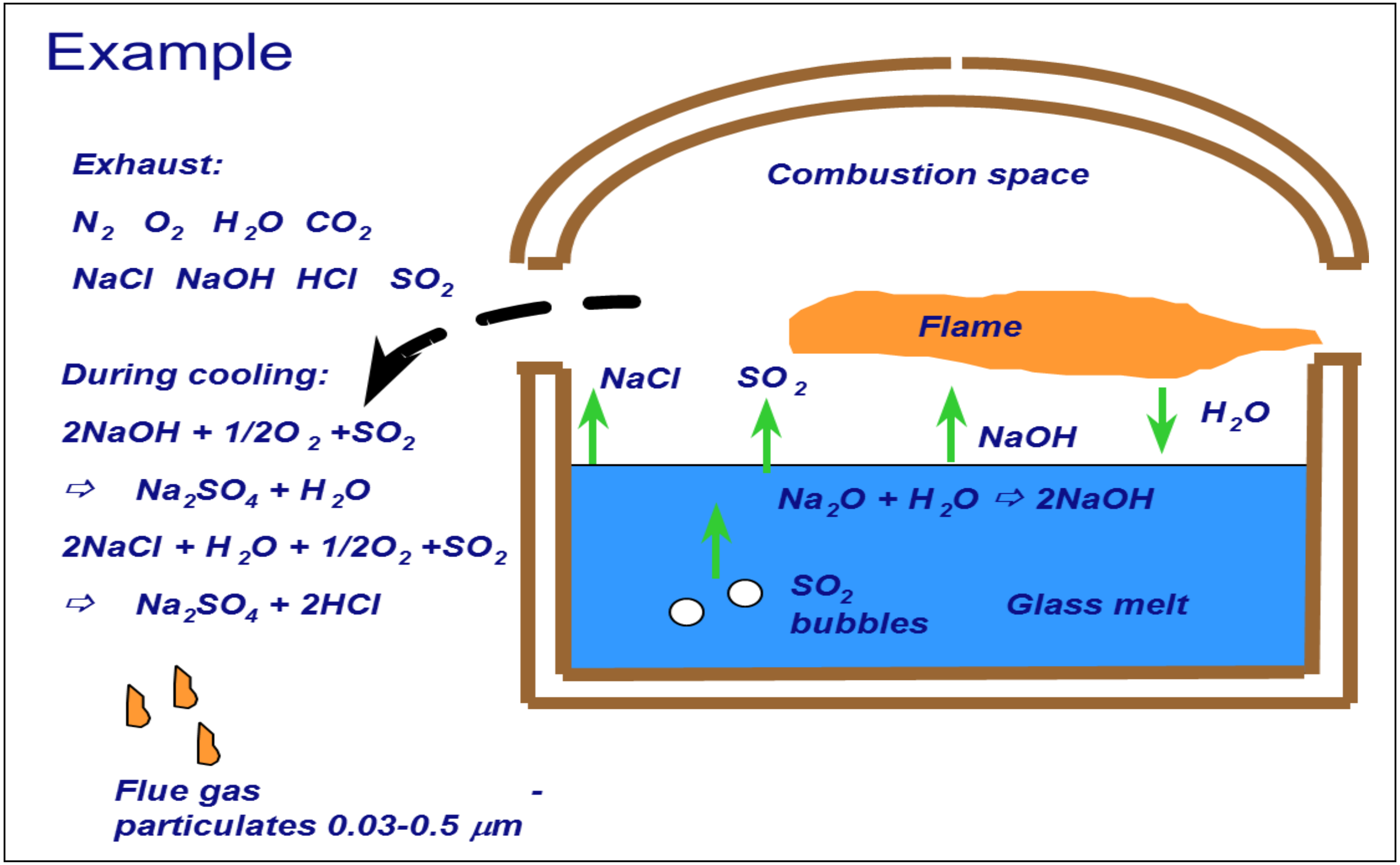
Important factors:

- **Temperature of the glass melt surface**
- **Composition of the glass melt**, especially the contents of volatile components
- **Sodium sulfate** added
- Composition of the **furnace combustion atmosphere**,
- **Gas velocity** at the melt surface
- **Residence time** of the glass melt in the furnace or the **specific surface area** of the melt
- **Foaming** of the glass melt



Evaporation processes

Evaporation processes are the main cause of **fine dust emissions** of most glass melting furnaces.



Refractories

Refractories and furnace lifetime

- **The furnace lifetime depends directly on refractory quality**
- Lifetimes for melting tanks based on AZS fused cast (Alumina Zircon Silica) refractories

✓Container glass furnaces:	12 - 16 years*
✓Float glass:	14 - 18 years*
✓Tableware soda-lime-silica glass:	6 - 8 years

- **Selection of appropriate refractories is crucial**

* Hot repairs included during campaign:

- plates of AZS or Chromium oxide covering soldier blocks
- repairs of open joints & holes with patch
- ceramic welding by metal/metal oxide powder (oxytherm)

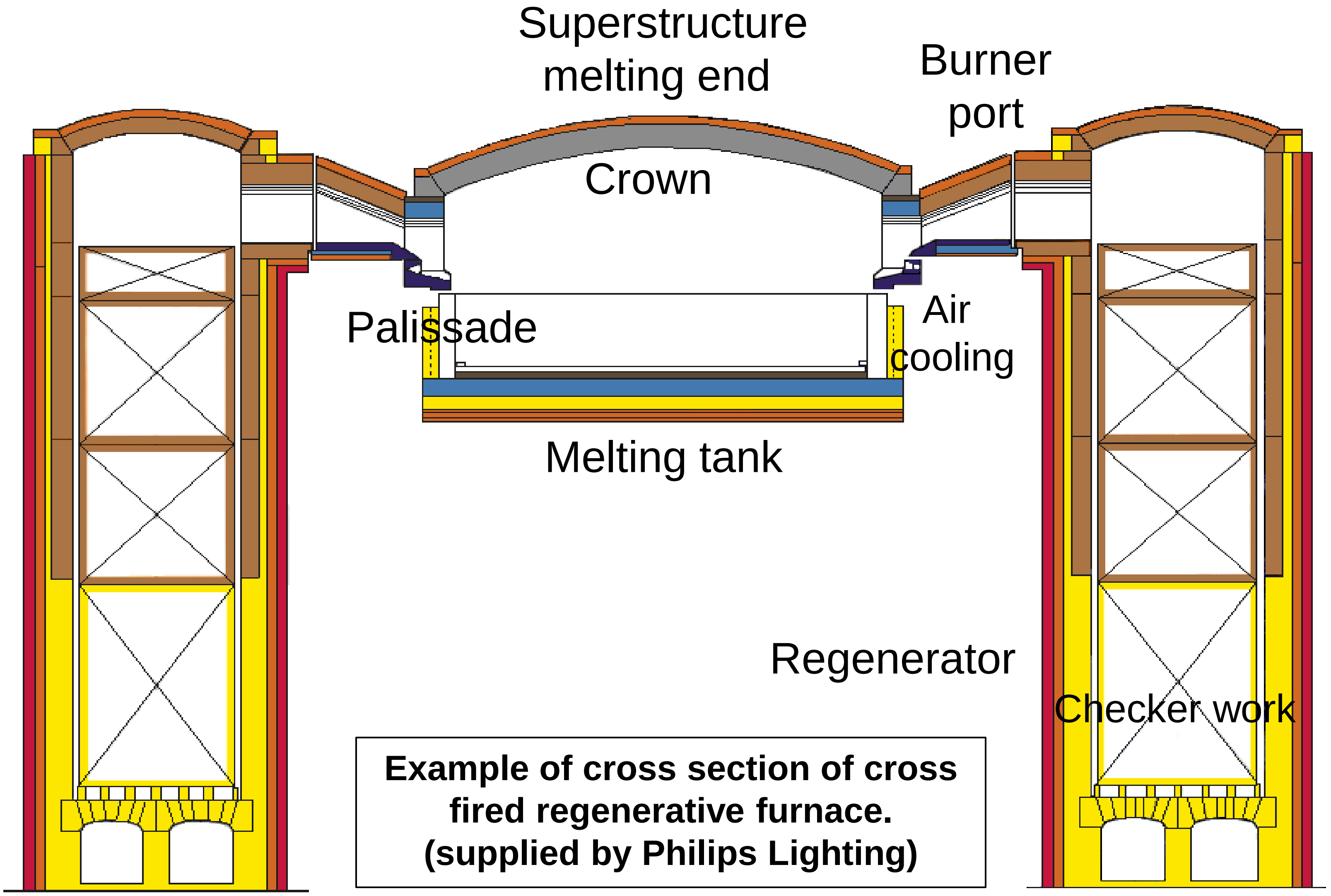
Refractory selection – General aspects

- Not only the **chemical composition**, but the **microstructure** and **macrostructure** of the material (grain sizes, binding phases) determine refractory behavior
- **Impurities** generally decrease the refractory quality
- For combustion chamber applications refractory (crown) temperatures may reach levels between 1550 and 1700°C (higher temperatures typically observed in furnaces for borosilicate glasses or glass-ceramics)
- The refractory materials, exposed to molten glass, are operated at about 1100-1550°C in most cases.
- In regenerators temperatures levels between 1550°C (at the top) and 500°C (at the bottom) can be observed

Refractory selection – General aspects

- Important factors to consider include:
  - ✓ Temperature resistance and stability at high temperatures
  - ✓ Thermal shock resistance (especially during first heating)
  - ✓ Thermal expansion
  - ✓ Thermal conductivity
  - ✓ Mechanical resistance / Deformation under load
  - ✓ Corrosion resistance (e.g. different behavior in acid or basic environments)
  - ✓ Costs!

Application of refractories in melting furnaces



Example of cross section of cross fired regenerative furnace.
(supplied by Philips Lighting)

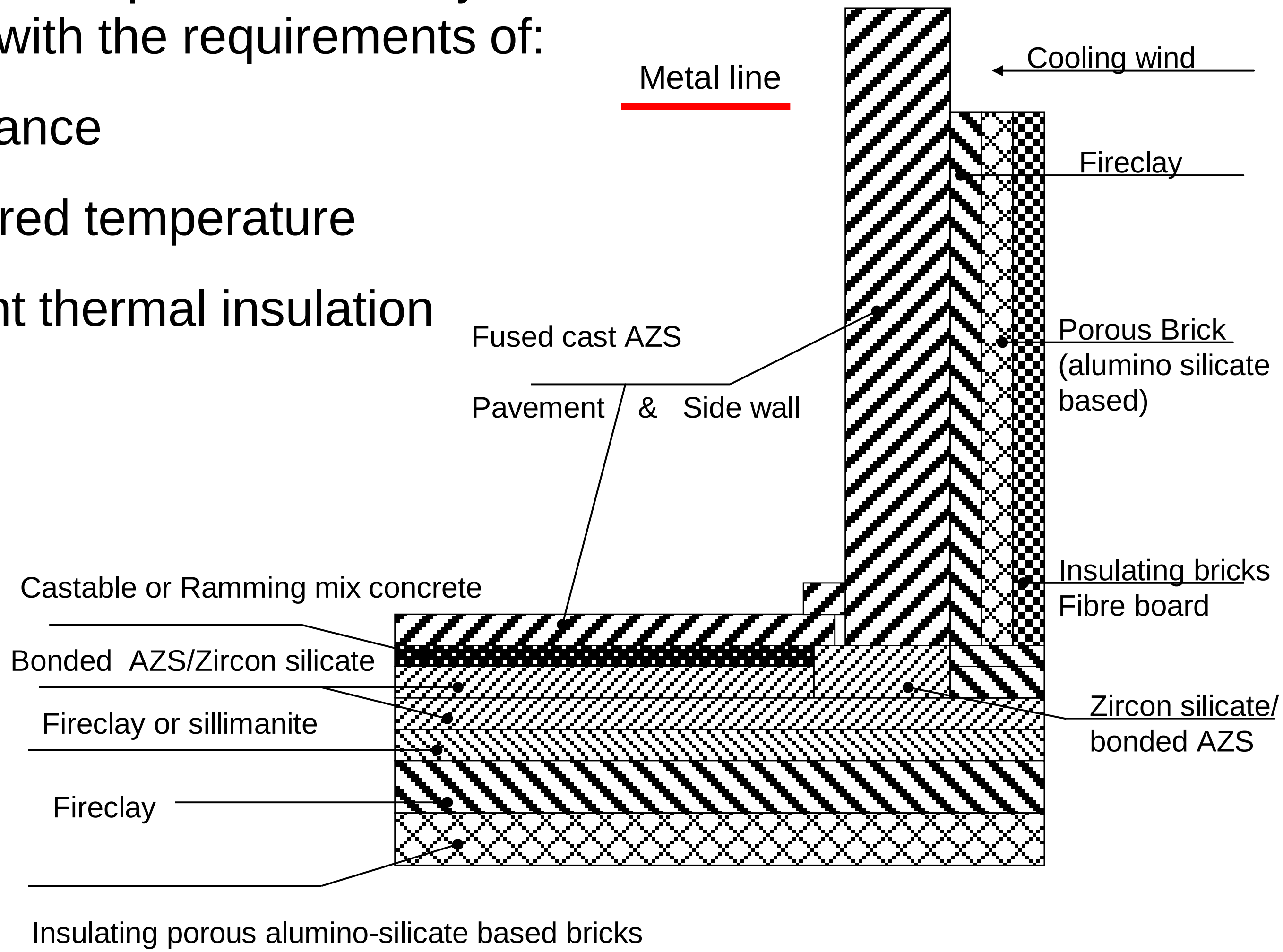
Bottom and sidewall of a furnace

Furnace walls are built up in different layers, in order to comply with the requirements of:

a) Corrosion resistance

b) Obtain the required temperature

c) Achieve sufficient thermal insulation



Refractory corrosion

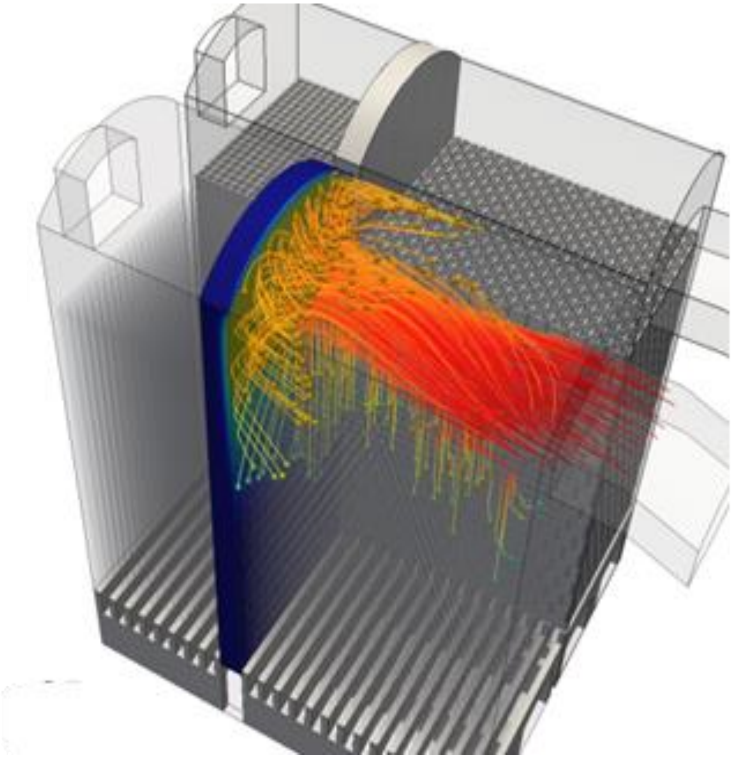
- The selected refractory material should not react with the environment to which it is exposed.
- In contact with glass melt: hardly any parts of the refractory materials may dissolve or detach into the melt (resulting in inhomogeneity, cords, undesired colorization of the glass) & no reactions should occur, that create bubbles.
- Release of the gases entrapped within the refractory should be limited by selecting refractory with low amounts of gaseous inclusions.
- Refractory materials in contact with molten glass should not contain nitrides or carbon impurities, the contents of polyvalent ions (Fe^{3+}/Fe^{2+}, Ti^{4+}/Ti^{2+}) should be low to avoid redox reactions and gas formation

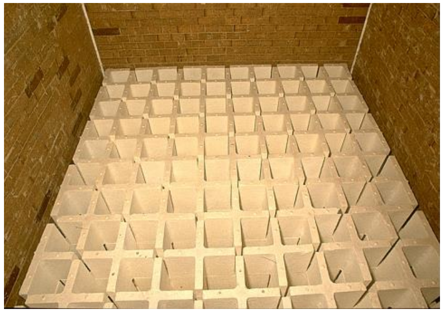
Corrosion of refractories

Example of corrosion of refractories at the metal line

Regenerator refractories

- The top layers of the checkers are exposed to high temperatures and carry-over
- Volatile products from the cooling flue gases, originating from the glass melt, condense and are deposited on the surfaces of the checker work.
- Corrosion & damage to porous refractory is often severe, due to repeated solidifying & melting of the sodium sulfate.
- Dust (from **carry-over** of sand, glass dust, dolomite, limestone, or condensed material) can be captured in the top layers of the checkers
- Avoid corrosion problems by the **selection of refractory materials**

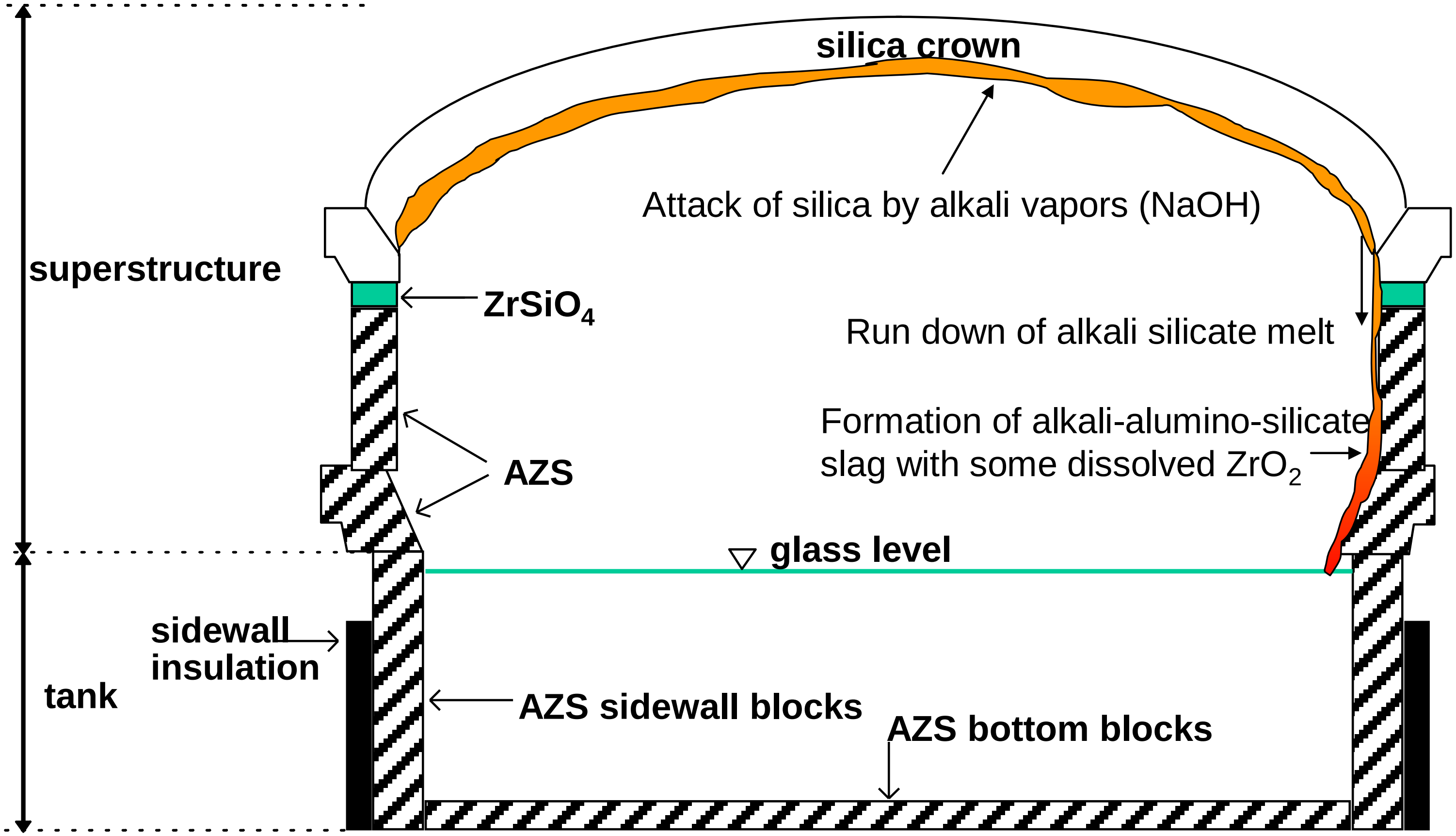




Typical regenerator chimney block packing during construction

Examples of refractory corrosion mechanisms

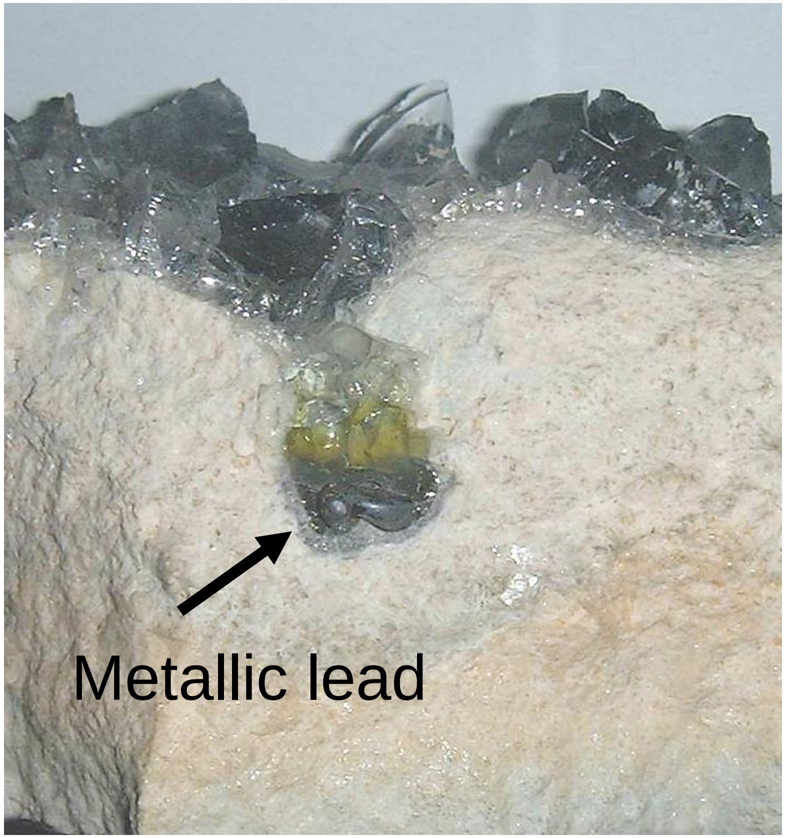
Process of silica attack and breast wall corrosion by alkali silicate run down



Effect of metals contamination on furnace lifetime

- Metal (such as lead) may form drops which fall at the bottom of the furnace and provoke accelerated corrosion. This is called **downward drilling**

Downward drilling of liquid lead



Conclusions – 1/2

- A continuous glass melting tank is designed to ensure a series of processes (melting, fining, homogenization…) essential for the quality of the glass produced
- **Minimum residence time** of the particles (from the batch) is crucial
- Good homogenization is directly dependent on the **convection flows** in the melting tank, shortcuts should be avoided
- **Different designs** of continuous furnaces exist (cross-fired or end-port fired regenerative, recuperative, oxy-fuel, all-electric…), and the choice depends notably on the type of glass produced
- Good heat transfer from the combustion chamber (flames) to the melt is essential. Once again, **redox** plays a major role in the absorption behavior of the glass melt

Conclusions – 2/2

- Several strategies can be applied to promote convection flows in the furnace (adjustment of fuel distribution, weirs, bubblers, boosting…)
- The lifetime of a furnace is highly dependent on the **quality of the refractories** used
- **Refractory corrosion** may be particularly detrimental to the furnace lifetime

In this lecture, we reviewed the processes happening in the melting tank, up to the working end, where glass is "conditioned" to present the best properties (homogeneity, absence of defects, temperature/viscosity) for the forming process (may it be for bottles, plate glass, fibers…)

These aspects will be presented during this IMI/NFG Spring 2015 course on Glass Processing

Home assignment

- A multiple choice questionnaire (MCQ) including questions on industrial glass melting tanks, process steps and refractories is provided with this lecture
- The MCQ will be available online on IMI's website

References and further reading

- Book "Introduction to Glass Science and Technology", J. Shelby (RSC publishing, 2nd edition 2005)
- Book "Fundamentals of Inorganic Glasses", A. Varshneya (Elsevier, 1993)
- Book "Glass Furnaces: Design, Construction and Operation", W. Trier and K. Loewenstein (Society of Glass Technology, 1987)
- Glass Technology journals (e.g. Eur. J. of Glass Science and Technology)
- NCNG's Glass Technology course and handbook 2013
- Proceedings of GlassTrend meetings and seminars (www.glasstrend.nl)
- Proceedings of "Glass Problem Conferences" (Wiley, every year)
- Youtube video: Production of Glass Bottles - How it's made

Thank you for your attention

Questions ?

Visit us in Eindhoven

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