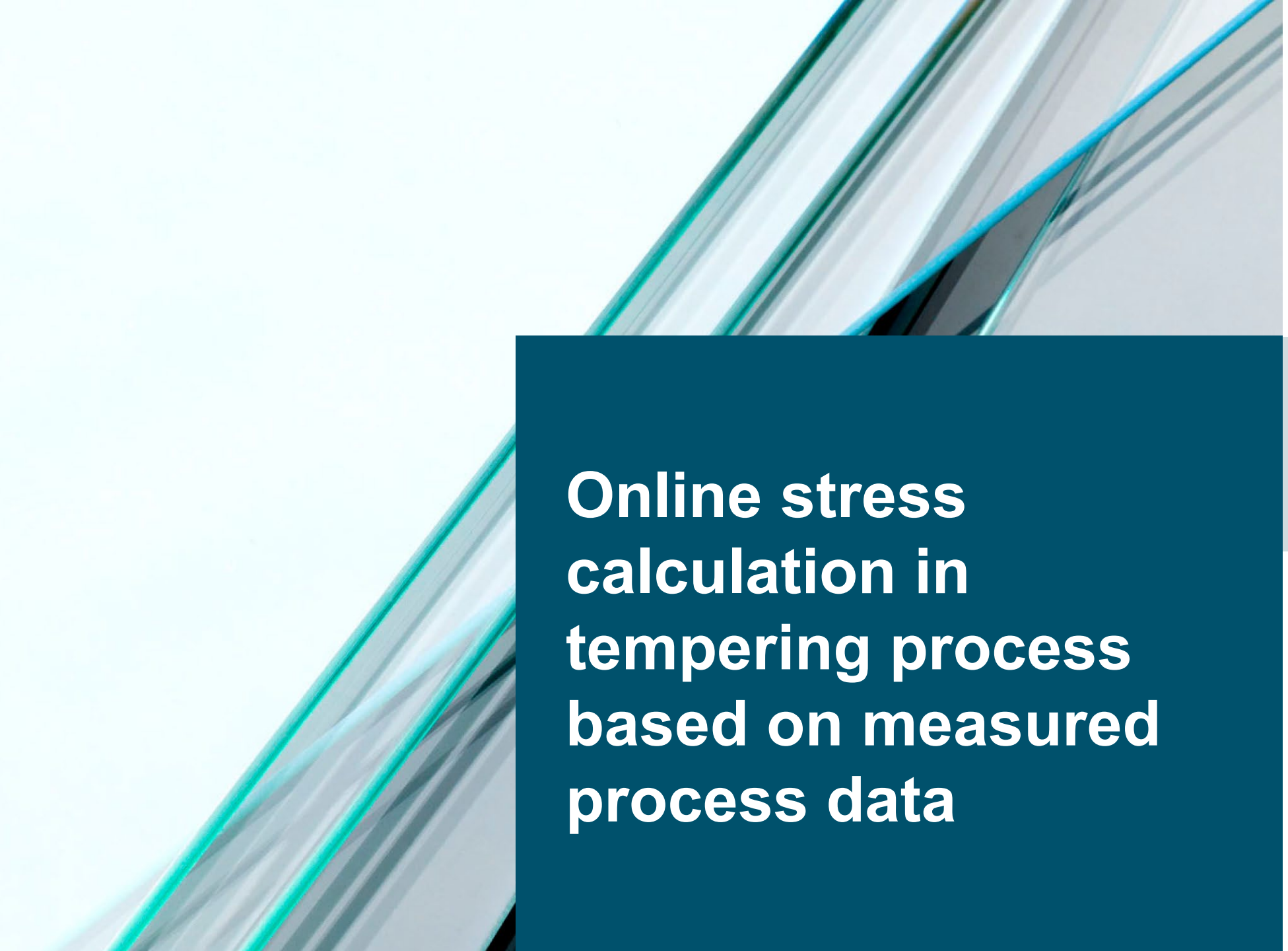

Online stress calculation in tempering process based on measured process data

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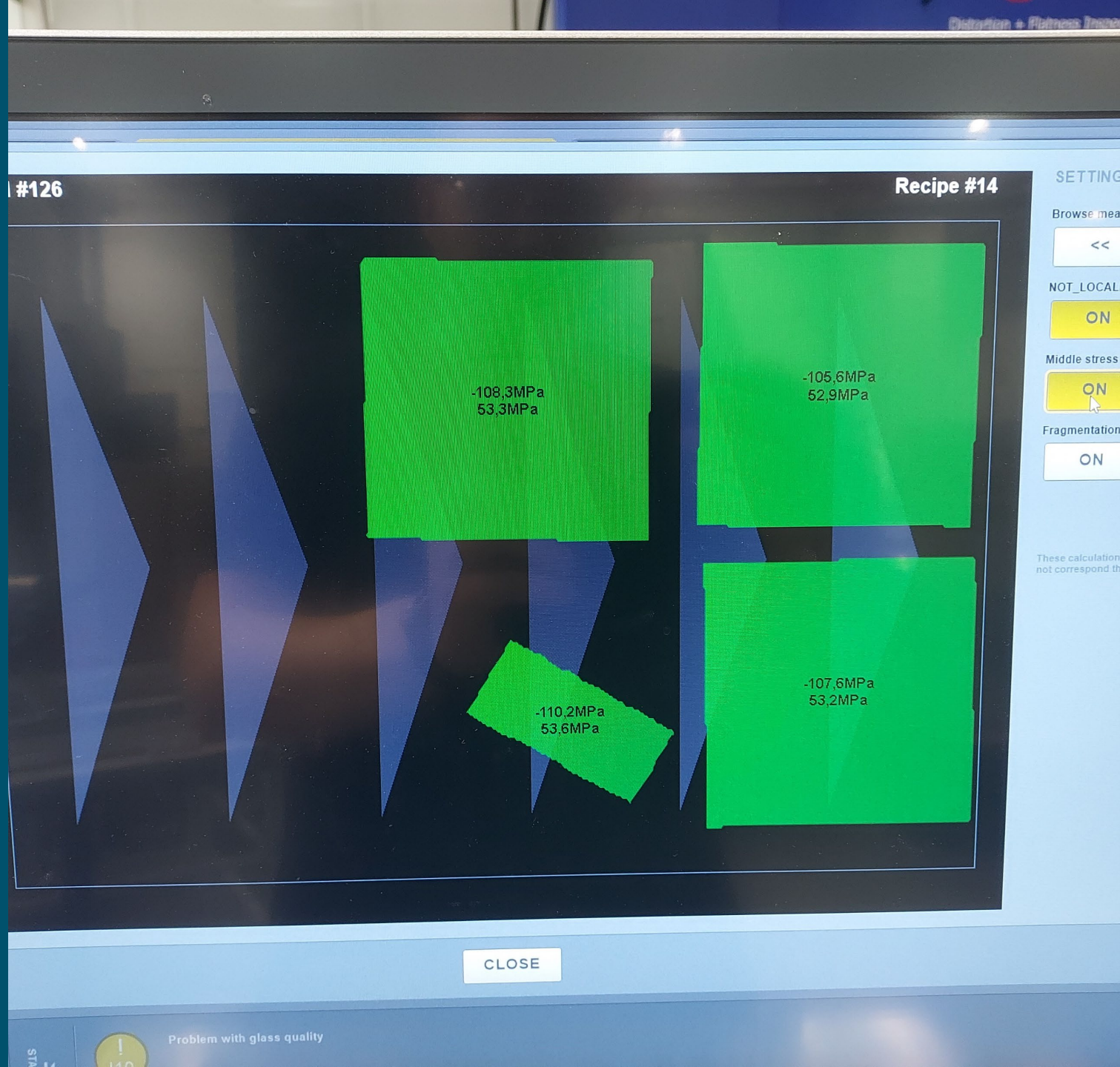
seeing it through®

Modelling/calculation of stresses in glass

- Modelling of stresses in glass tempering has been used for years
  - To develop new products
  - To design processes for different products.

- Now same model is used with measured data from process to calculate the stress level in glasses after heat treatment process

It is able to get value for stress level straight after tempering.



The stress level after tempering depends on…

Material

- Glass thickness
- Material properties of the glass
  - Thermal properties
  - Mechanical properties

Glass temperature

- Glass temperature after heating/before cooling
  - Thermal scanner/camera needed

Cooling effect

- Dimensions of cooling system
- Cooling air pressure
- Cooling air temperature

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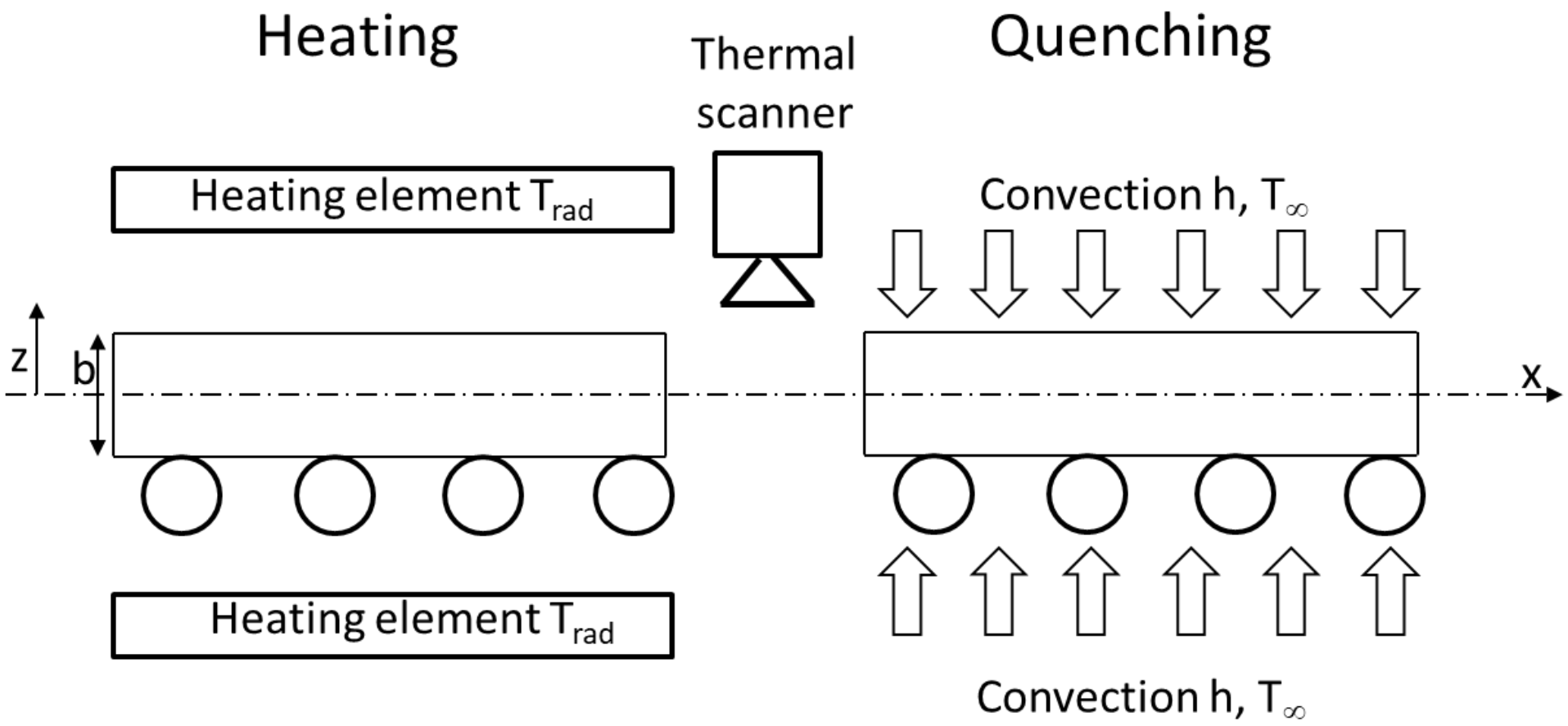
Glass tempering process



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Online glass stress calculation

Glass thickness and material information

Glass temperature from thermal scanner

Used quenching pressure at nozzles, nozzle-to-plate distance and cooling air temperature.

Time-dependent temperature calculation

Temperature distribution

Time-dependent stress calculation

Mid-plane stress

Calculation of number of fragments

Transient and residual stresses in glass surface and mid-plane

Amount of fragments in case of breakage

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Calculation model

Temperature

Solve
T, k, c_p, S

Solve
T_f, ϕ

Solve
ξ, G, K, ε^{th}

Strain

Solve
ε^0, κ, ε_z

Stresses

Solve
σ

$$\rho c_{pg}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+S(T,x)$$

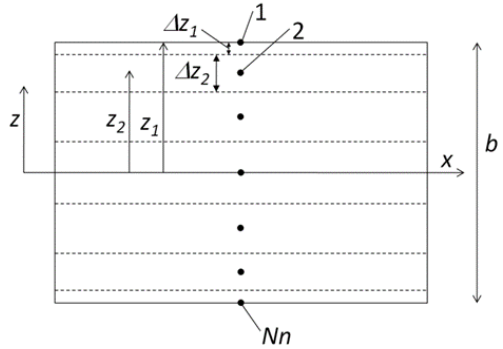
$$S(T,x)\approx\sum_{i=1,j=2}^{i=k,j=k+1}\left\{\begin{array}{c}\left[F_b(\lambda_i,\lambda_j,T_\infty)\sigma T_\infty^4-F_b(\lambda_i,\lambda_j,T_\infty)\sigma T^4\right]\cdot\frac{(1-\rho_m)}{1-\rho_m e^{-a(\Delta\lambda_i)L/\cos\alpha_m}}\cdot\\ \left[e^{-a(\Delta\lambda_i)x_1/\cos\alpha_m}-e^{-a(\Delta\lambda_i)x_2/\cos\alpha_m}+e^{-a(\Delta\lambda_i)(L-x_1)/\cos\alpha_m}-e^{-a(\Delta\lambda_i)(L-x_2)/\cos\alpha_m}\right]\end{array}\right\}$$

$$\bar{h}(T_S-T_\infty)=-k(T)\frac{\partial T}{\partial x}$$

$$\phi(t)=\exp\left(\frac{H}{R}\left(\frac{1}{T_{ref}}-\frac{x}{T(t)}-\frac{1-x}{T_f(t)}\right)\right)$$

$$T_{fi}(t)=\frac{\lambda_i T_{fi}(t-\Delta t)+\Delta t T(t)\phi(t)}{\lambda_i+\Delta t\phi(t)}$$

$$T_f(t)=\sum_{i=1}^{n}C_i T_{fi}(t)$$



$$\Delta\varepsilon^{th}(t)=(\alpha_l-\alpha_g)(T_f(t)-T_f(t-\Delta t))+\alpha_g(T(t)-T(t-\Delta t))$$

$$\xi(t)=\int_0^t\phi(t')dt'$$

$$G(\xi(t))=G_\infty+(G_0-G_\infty)\sum_{i=1}^{n}w_{1i}\exp\left(-\frac{\xi(t)}{\tau_{1i}}\right)$$

$$K(\xi(t))=K_\infty+(K_0-K_\infty)\sum_{i=1}^{n}w_{2i}\exp\left(-\frac{\xi(t)}{\tau_{2i}}\right)$$

$$\sigma_{ij}(t)=\delta_{ij}\int_0^t K(\xi(t)-\xi(t'))\frac{d\left(\varepsilon_{kk}(t')-3\varepsilon^{th}(t')\right)}{dt'}dt'+2\int_0^t G(\xi(t)-\xi(t'))\frac{d\left(\varepsilon_{ij}(t')-\frac{\delta_{ij}\varepsilon_{kk}(t')}{3}\right)}{dt'}dt'$$

$$\int_{-h/2}^{h/2}\sigma(z,t)dz=N$$

$$\int_{-h/2}^{h/2}\sigma(z,t)zdz=M$$

$$\varepsilon_x=\varepsilon_y=\varepsilon^0+\kappa z$$

Plane stress $\sigma_z=0$

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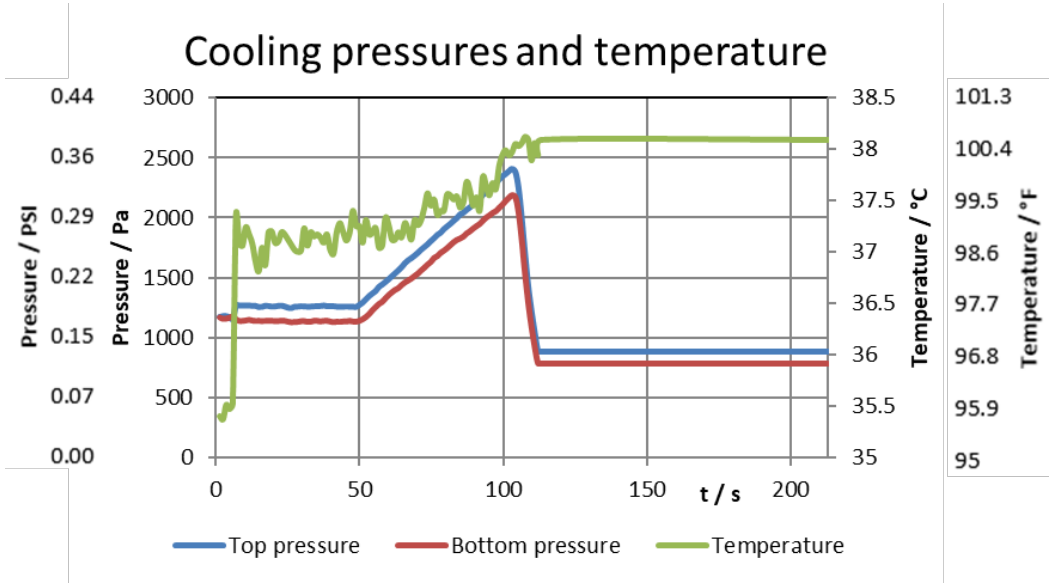
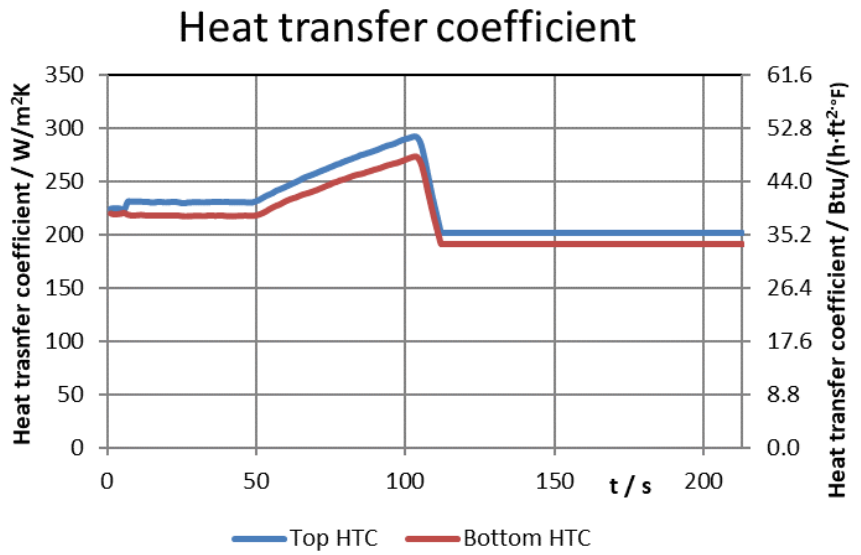
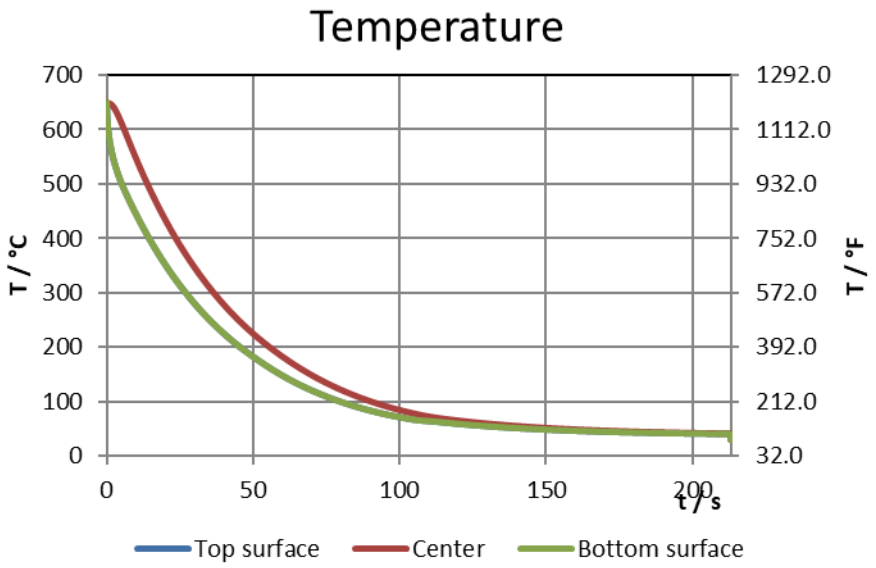
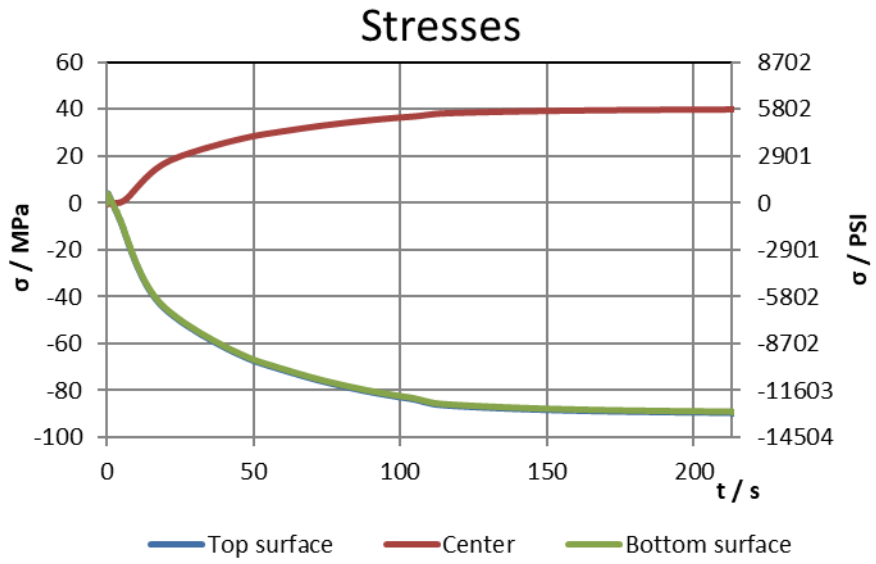
Calculation of stresses









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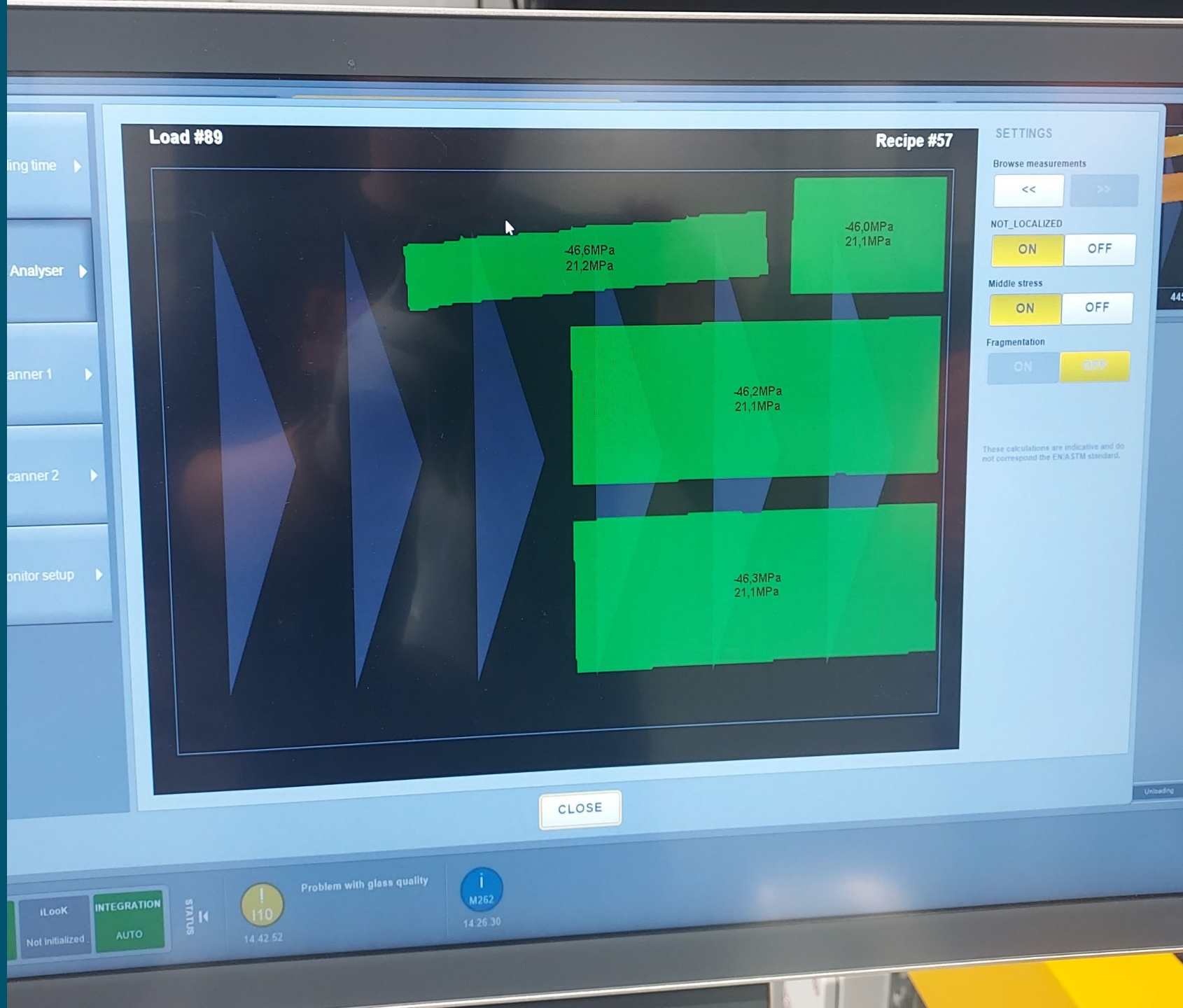
How about accuracy?



Which factors affect the accuracy of the results?

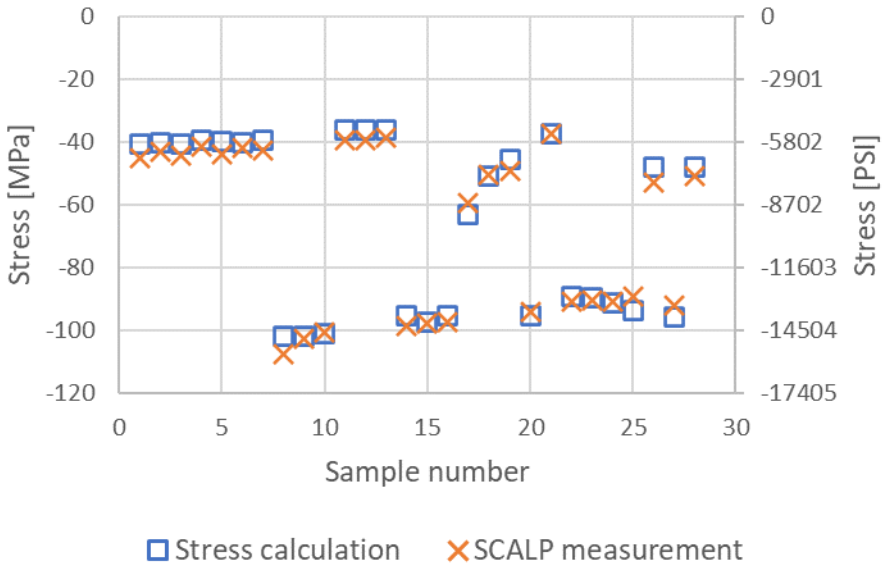
- Accuracy of thermal scanner measurement
- Uniformity of the glass temperature

- Pressure measurement
- Accuracy of the heat transfer coefficient calculation model

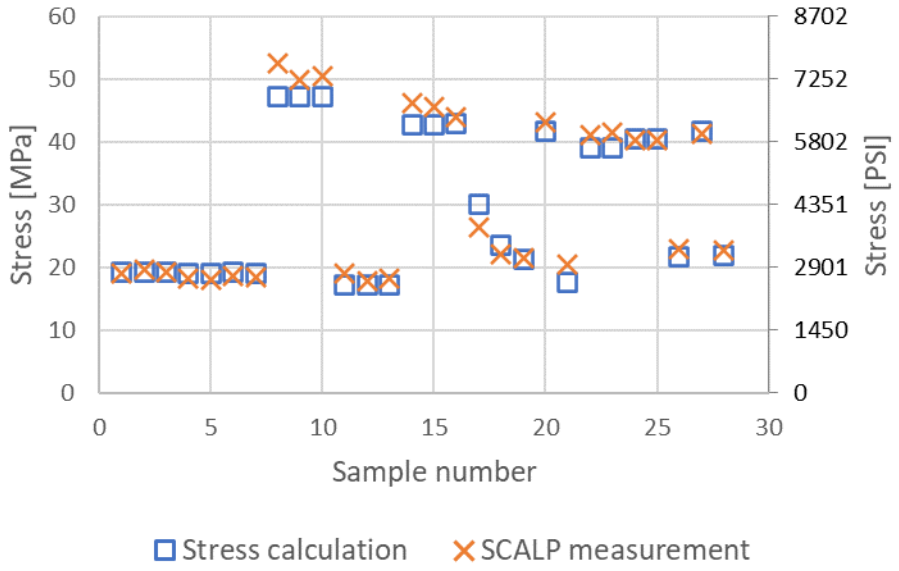
- Accuracy of the thermal and mechanical calculation model
- Material property values

Accuracy of stresses when comparing to SCALP

Surface stress



Mid-plane stress



- Test set with 3 - 6 mm glasses with tempered and heat strengthened, and clear and Low-E coated glasses
- For most of glasses the difference in this test set has been +/- 5% comparing stress calculation and SCALP measurements. All results within +/- 10 %.
- Stress calculation gives only one value for each glass, when SCALP is usually used in several position.

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What to do with stress results?

- **Stress level** in tempering production for **each glass** can be **monitored**.

- Stress levels can be compared to fragmentation results to find stress limits based on fragmentation
  → **The fragmentation level can be followed**

- Stress level can be used to follow the result for **tempered** and **heat strengthened** glass.

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This is the only way to get value for stress for each glass straight after tempering and heat strengthing with good accuracy without manual measurements.

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