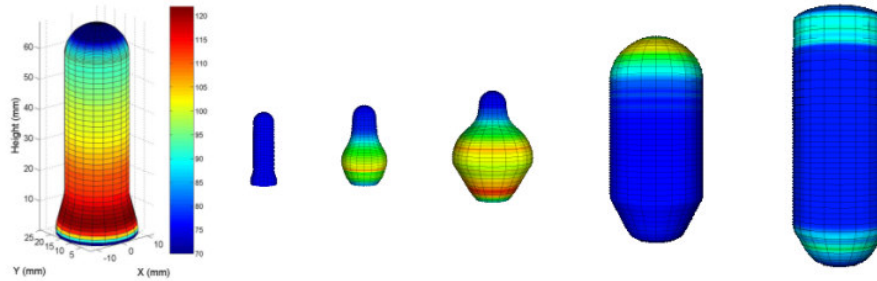




3rd Conference on Rotomoulding Thermoforming  
Stretch-Blow Moulding

Ecole des Mines d'Albi (France) - March, 11<sup>th</sup>-13<sup>th</sup>, 2009

<http://rts2009.enstimac.fr>



## Thickness Optimisation of Inflated Preforms by Varying Infrared Heating Coefficients



March 12, 2009

F.M. Schmidt

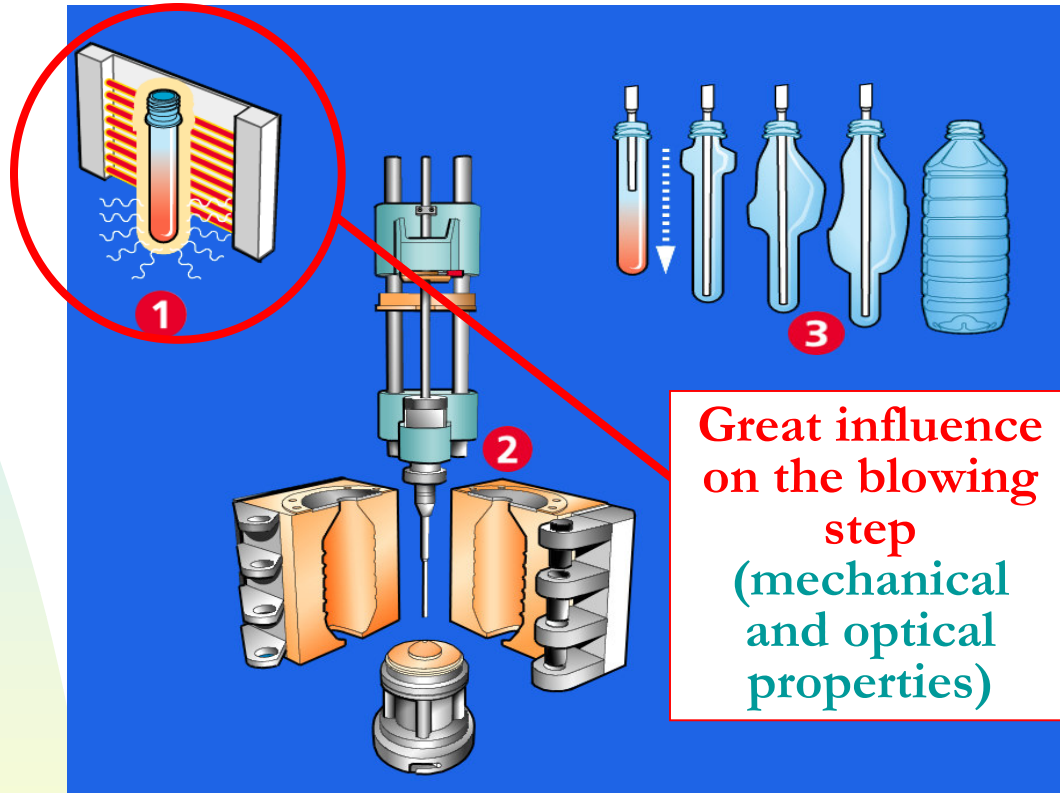
**École des Mines d'Albi**



# Stretch-blow molding process



**Infrared heating  
step** (from 20°C  
up to 110°C)



Oven efficiency:  $\approx 20\%$   
*[Monteix 1998]*

Heating time  $\gg$   
Blowing time  $\approx 1s$

- Radiative transfer modelling for **participating media** (PET polymer) using Ray tracing method
- Optimisation of the preform initial temperature distribution



# Global optimisation strategy



**Heating parameters  
(output parameters)**

**Blowing parameters  
(without stretch-rod)**

**Material parameters**

**Temperature profile along the preform length**

Temperature profile through the preform thickness

Mass flow rate  
Nominal pressure

Constitutive parameters  
Contact parameters friction & TCR

Simplex

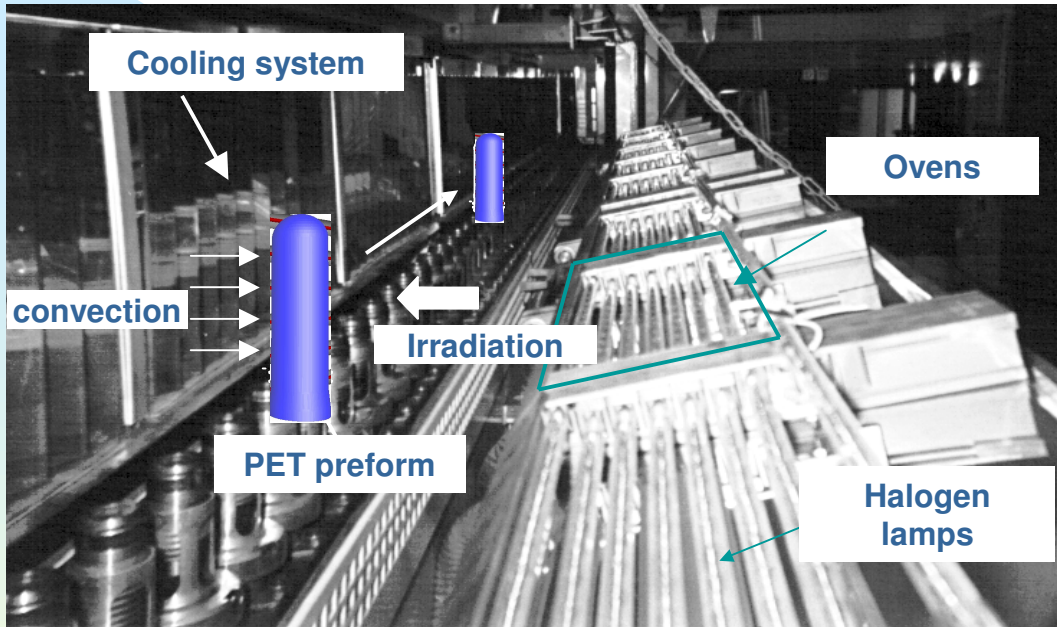
**Blowing simulation**

**Coupling between heating simulation & blowing simulation**

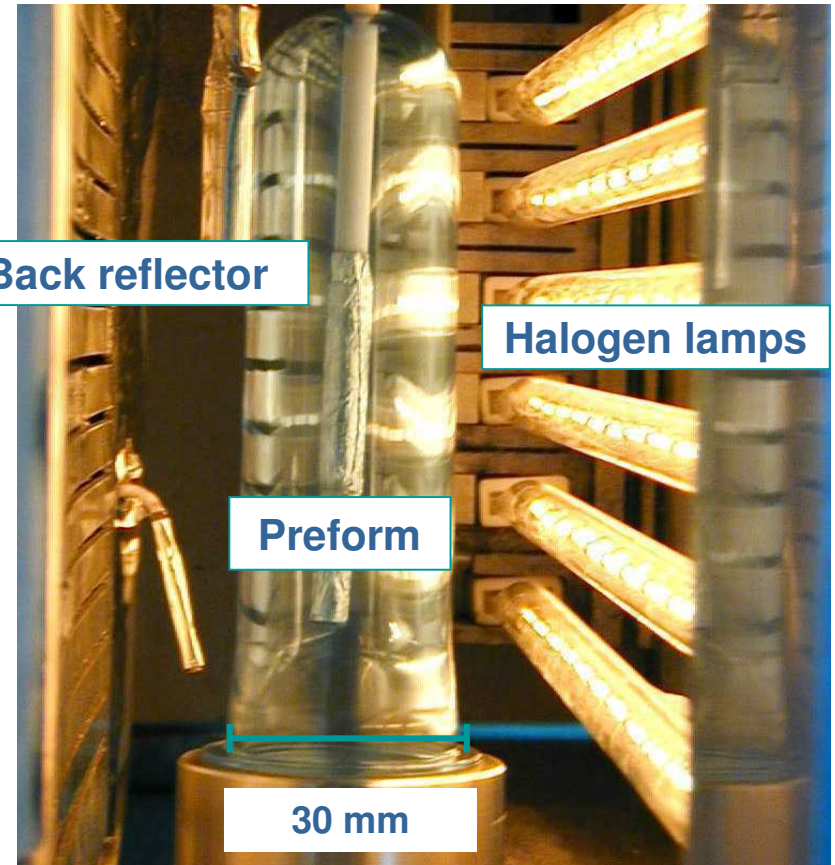
**Thickness distribution of the bottle**  
Evolution versus time of the air pressure



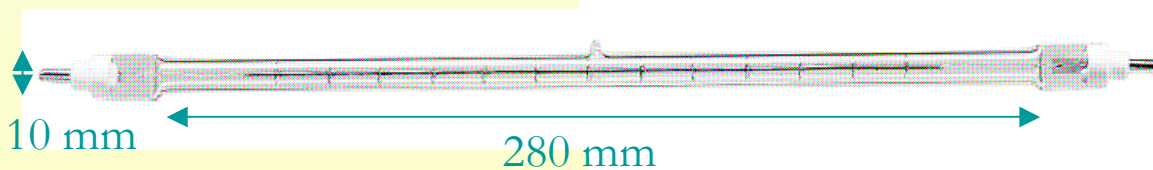
# In-lab infrared oven



Polymers = participating media



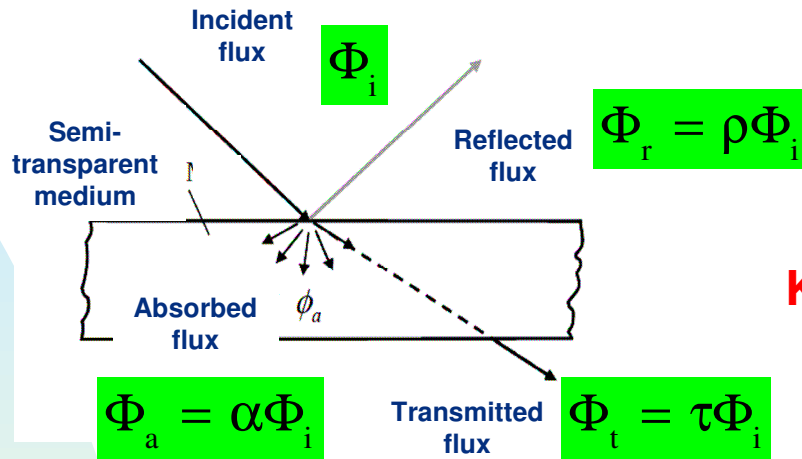
	T (K)	$\lambda_{max}$ ( $\mu m$ )	Spectral band ( $\mu m$ )
Halogen 1kW (IRC)	2400	1.2	0.6 - 6



Conductive, convective & radiative transfers

- Infrared heating modelling using ray tracing method
- Preform temperature distribution optimisation
- Future works

# Radiation heat balance equation



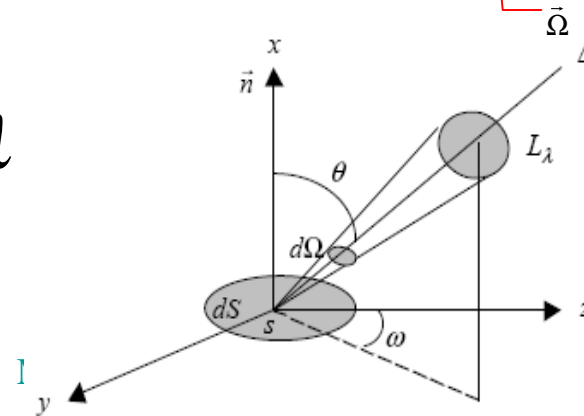
$$\rho c_p \frac{dT}{dt} = \vec{\nabla} \cdot (k \vec{\nabla} T) - \vec{\nabla} \cdot \vec{q}_r$$

**Radiation source term**

$$\vec{q}_r = \int_0^\infty \int_{S^2} \vec{\Omega} L_\lambda(\vec{s}, \vec{\Omega}) d\Omega d\lambda$$

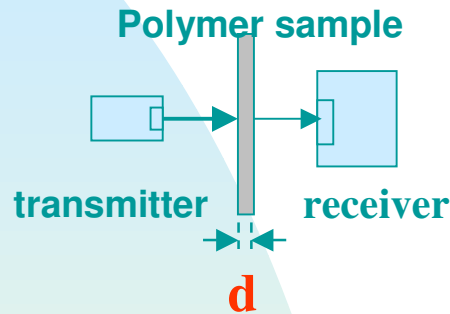
**Radiative flux**

**Radiation intensity**

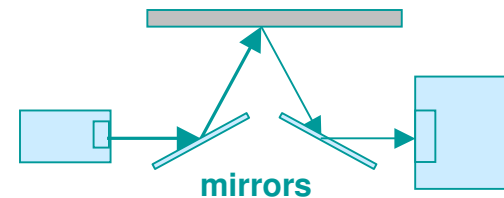


# PET optical properties measurement FT-IR 1.3-25 $\mu\text{m}$

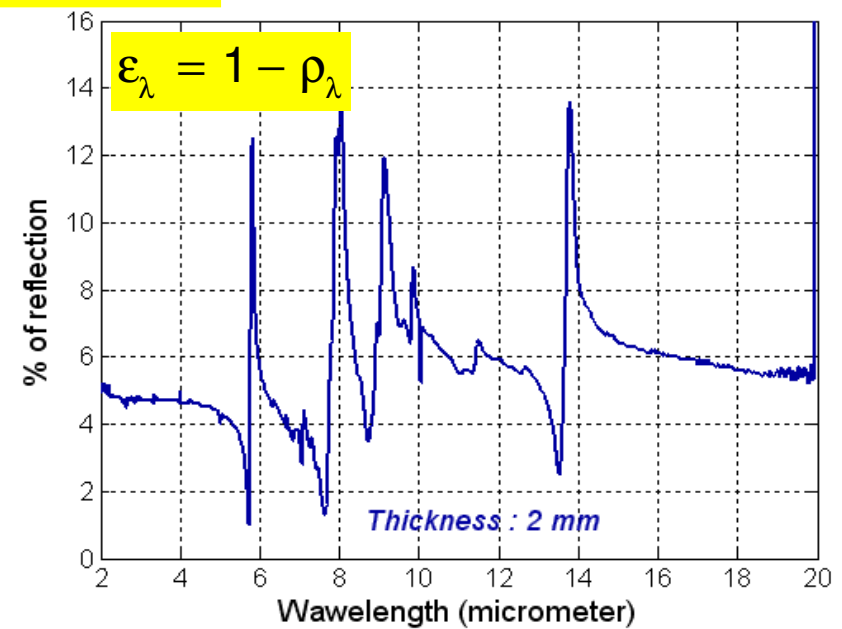
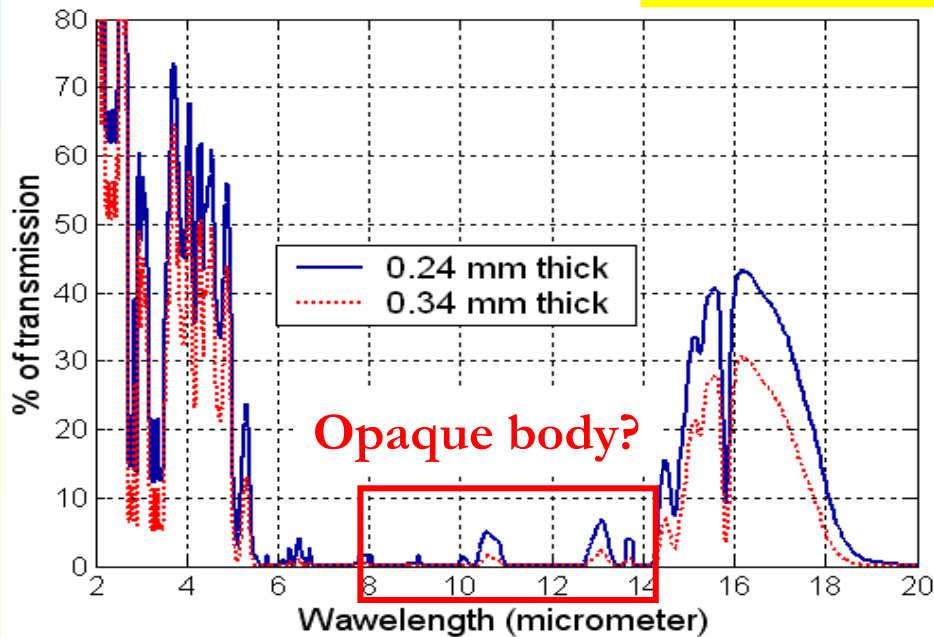
✓ Transmission mode:  $\kappa_\lambda$



✓ Specular reflection mode:  $\rho_\lambda$



PET Tergal T74F9 (IV=0.74)

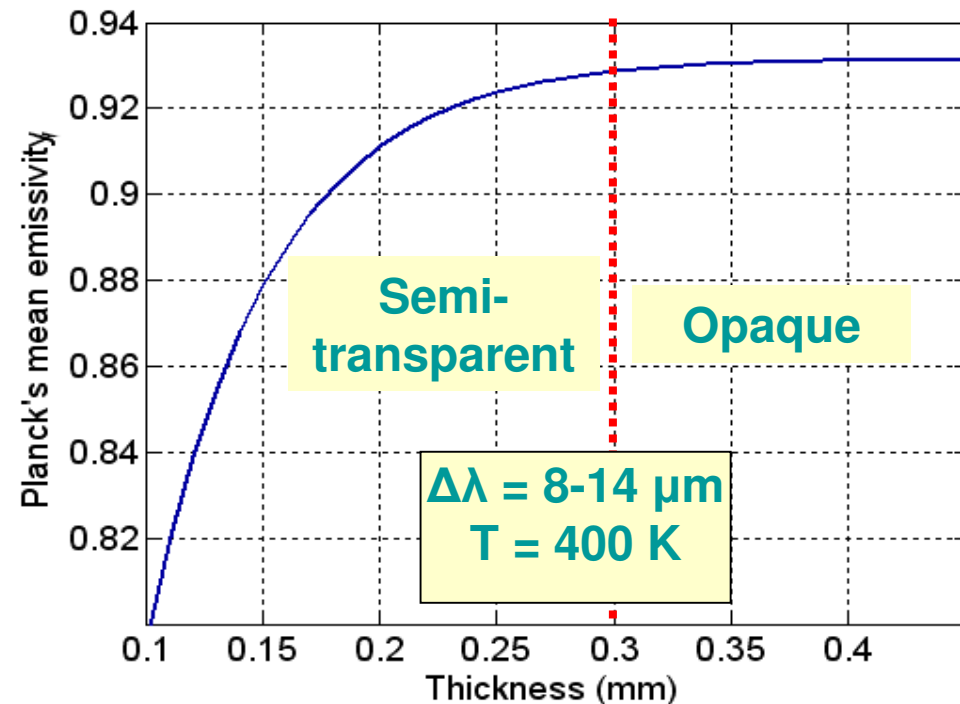




$$\varepsilon(T_{\text{PET}}) = \frac{\int_{\Delta\lambda} \varepsilon_{\lambda} L_{\lambda}^{\circ}(T_{\text{PET}}) d\lambda}{\int_{\Delta\lambda} L_{\lambda}^{\circ}(T_{\text{PET}}) d\lambda}$$

**Black body spectral  
intensity (Planck law)**

$$L_{\lambda}^{\circ} = \frac{c_1 \lambda^{-5}}{e\left(\frac{c_2}{\lambda T}\right) - 1}$$



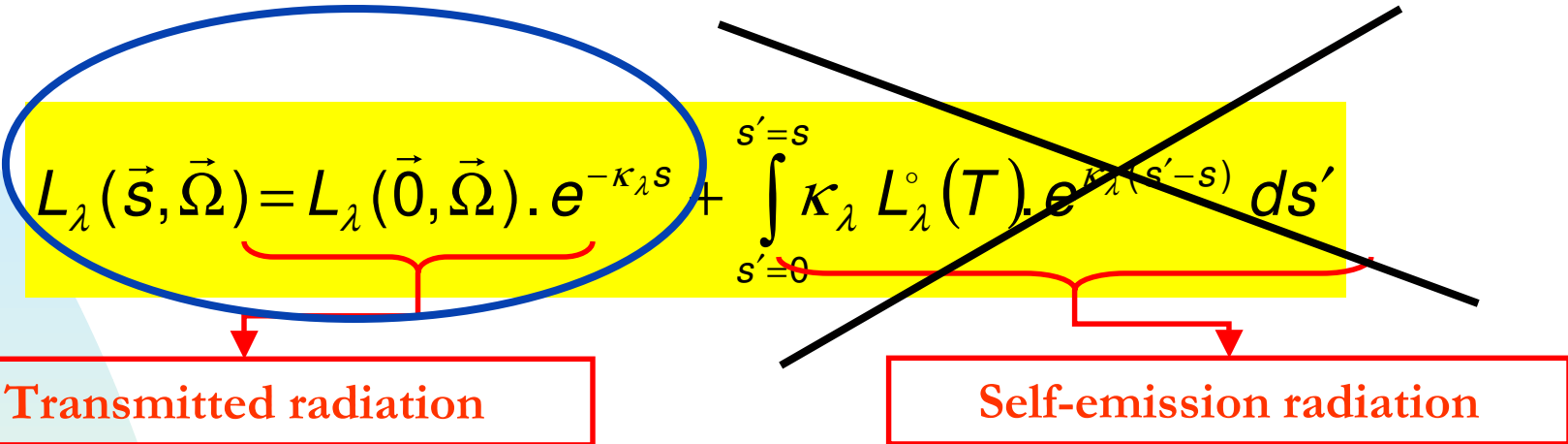
**Planck mean emissivity of PET T74F9  
versus thickness sample**



# Non-scattering cold medium assumption



Beer's law



	✓ Temperature	✓ Emissivity	✓ Spectral intensity	$\frac{\varepsilon_L \int_0^{\infty} L_{\lambda}^{\circ}(T_L) d\lambda}{\int_0^{\infty} L_{\lambda}^{\circ}(T_P) d\lambda} = \varepsilon_L \frac{T_L^4}{T_P^4}$
<b>✓ Cold medium assumption</b> ✓ Halogen emitters ✓ (blow moulding process)	✓ ≈ 2500 K	✓ 0.29	✓ ≈ $3,6 \cdot 10^5 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}$ ✓ (luminance incidente)	✓ $214 \gg 1$
✓ IRL emitters ✓ (thermoforming process)	✓ ≈ 970 K	✓ 0.96	✓ ≈ $3500 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}$ ✓ (luminance incidente)	✓ $16 \gg 1$
✓ PET	✓ ≈ 480 K	✓ /	✓ ≈ $100 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}$ ✓ (luminance du milieu)	✓ /

« Polymer self-radiation intensity is neglected regarding incident intensity »

# FEM formulation of radiation heat balance equation

$$[C] \frac{\partial \vec{T}}{\partial t} + [K] \cdot \vec{T} + \vec{F} = \vec{0}$$

$$C_{ij} = \int_{\Omega} \rho c_p \Psi_i \Psi_j d\Omega$$

Heat Capacity matrix

Heat conductivity matrix

$$K_{ij} = \int_{\Omega} k \vec{\nabla} \Psi_i \vec{\nabla} \Psi_j d\Omega + \int_{\Gamma} h_c \Psi_i \Psi_j d\Gamma$$

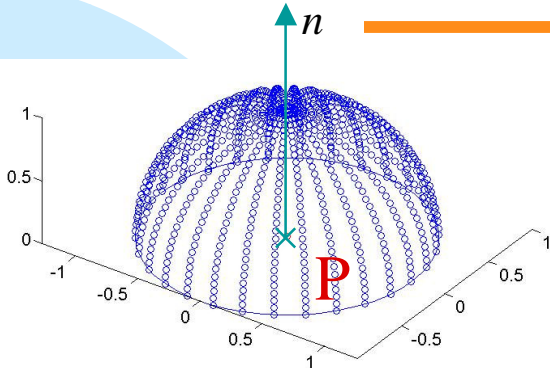
$$F_j = \int_{\Omega} (\vec{\nabla} \cdot \vec{q}_r) \Psi_j d\Omega + \int_{\Gamma} h_c T_a \Psi_j d\Gamma$$

Radiation source term

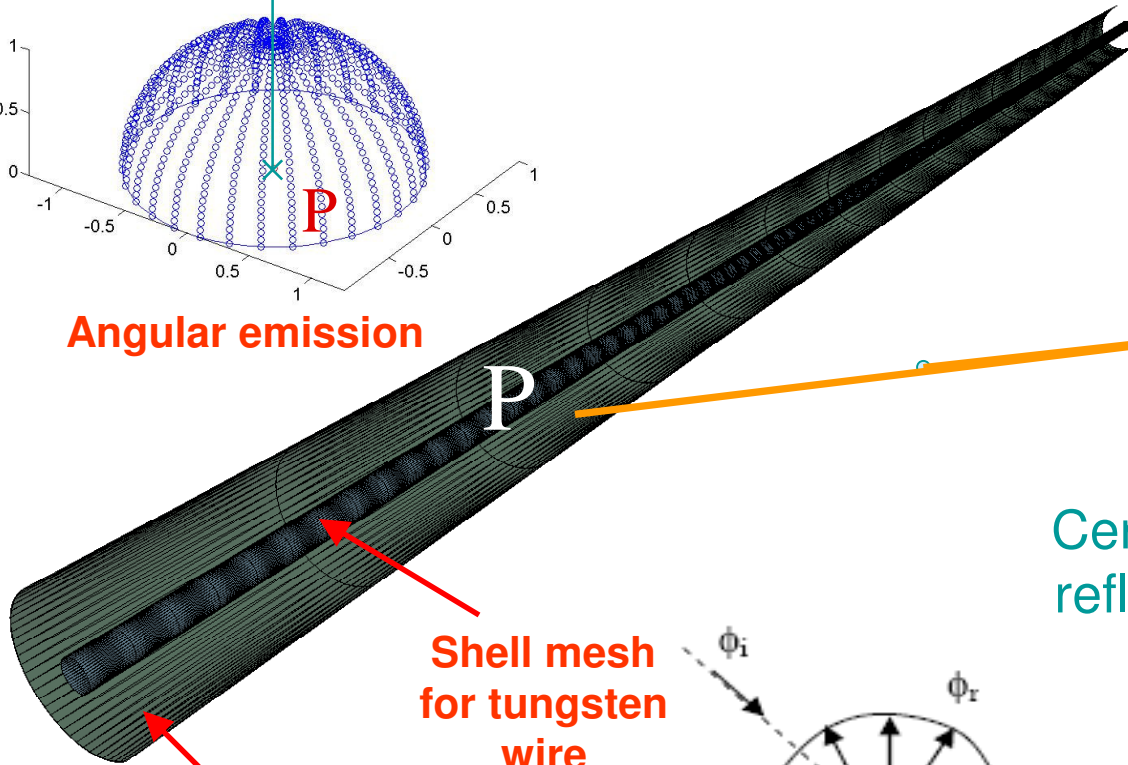
$$\int_0^{\infty} \kappa_{\lambda} M_{\lambda}(\vec{x}_P) e^{-\kappa_{\lambda} s} d\lambda$$



# Random ray tracing method

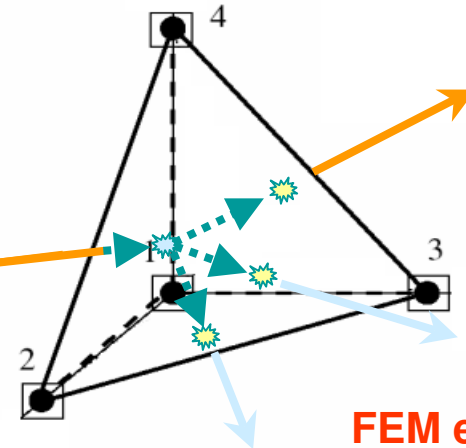


Angular emission

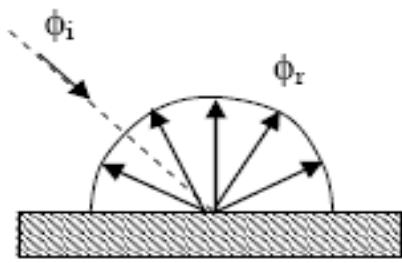


Shell mesh for tungsten wire

Shell mesh for ceramic reflector

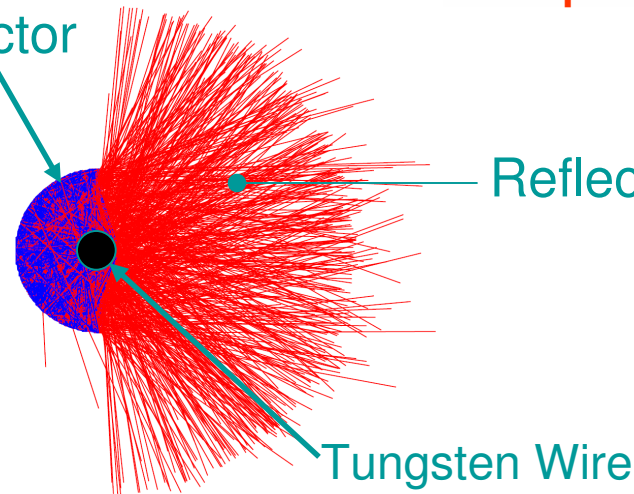


FEM element for preform



Diffuse reflection

Ceramic reflector

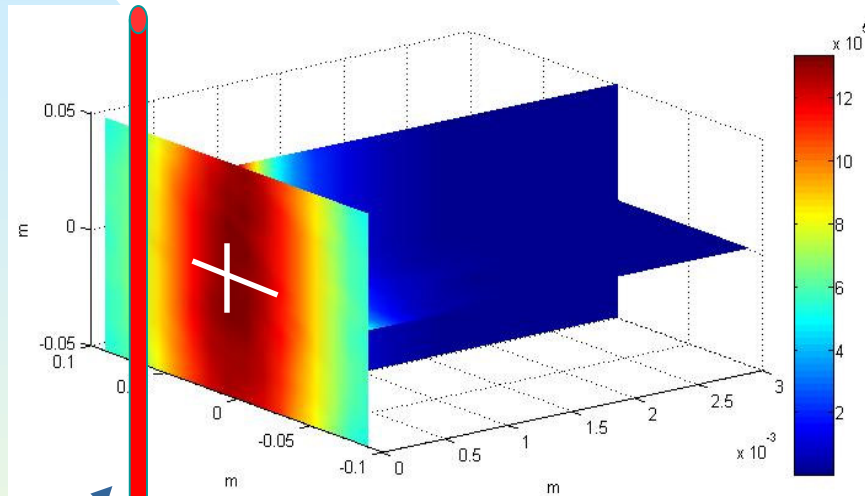


Reflected rays

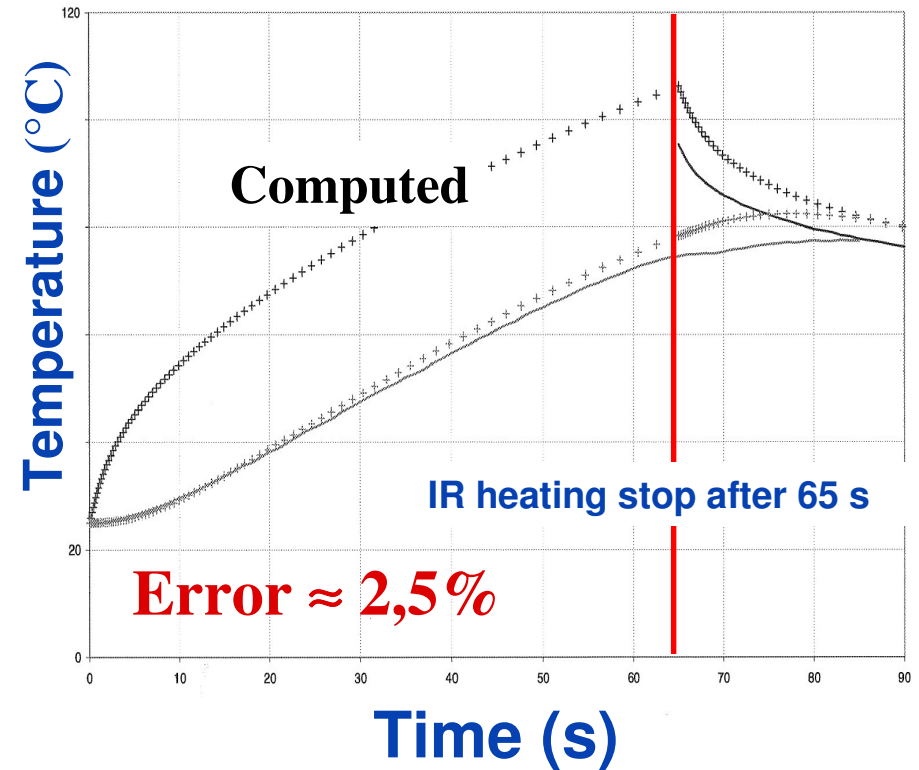
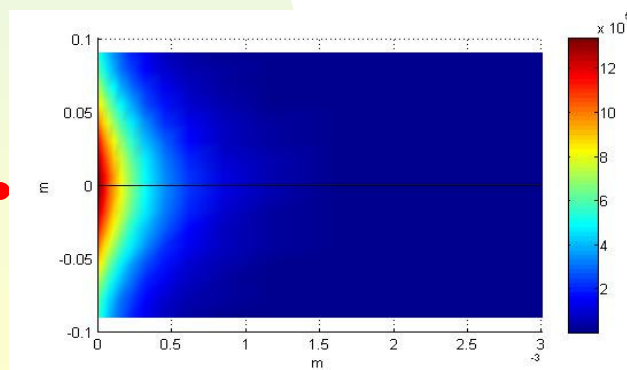
Tungsten Wire



# FEM computation vs experimental data (centre of PET plaque)

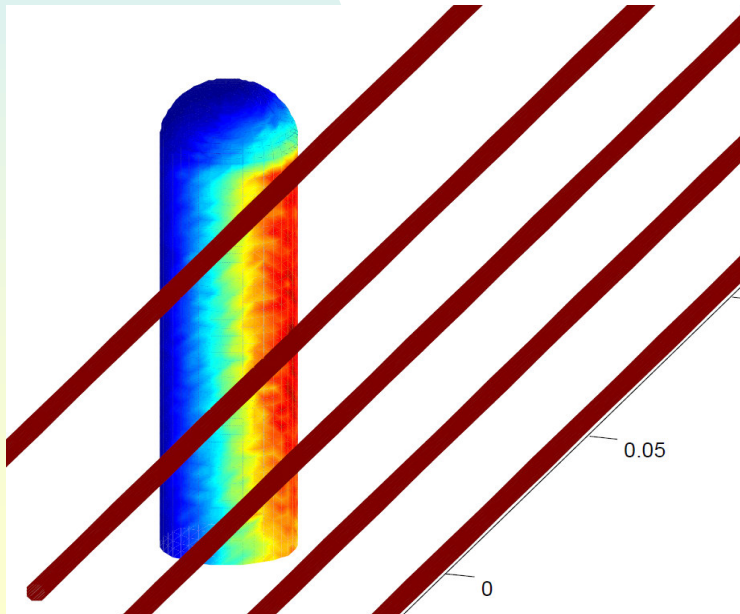


1kW lamp  
(2400 K)

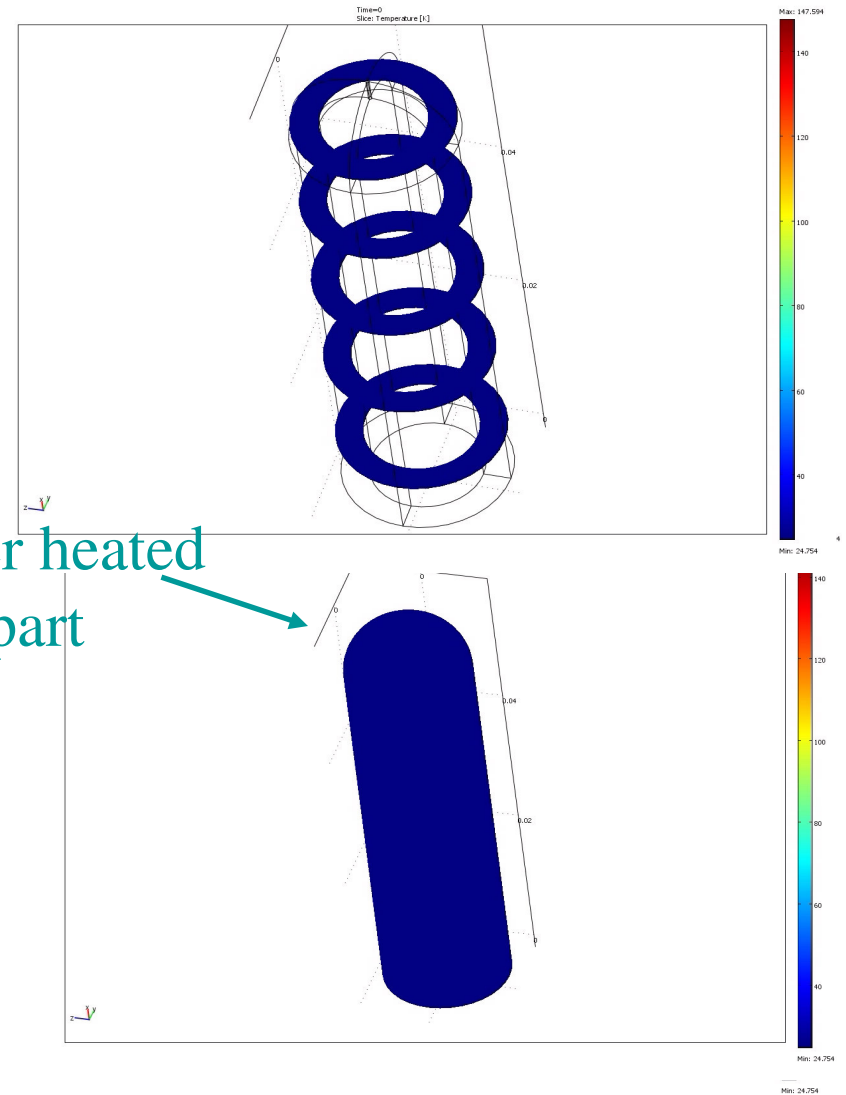


# Example of rotating preform IR heating simulation

- ✓ 1kW lamps  $\times$  5 – 100% power
- ✓ 15 s heating – 15 s cooling
- ✓ 2h45 mn CPU time



Under heated  
part



## ✓ Model

2D Axi-symmetric coupled temperature-displacement

## ✓ Material behaviour

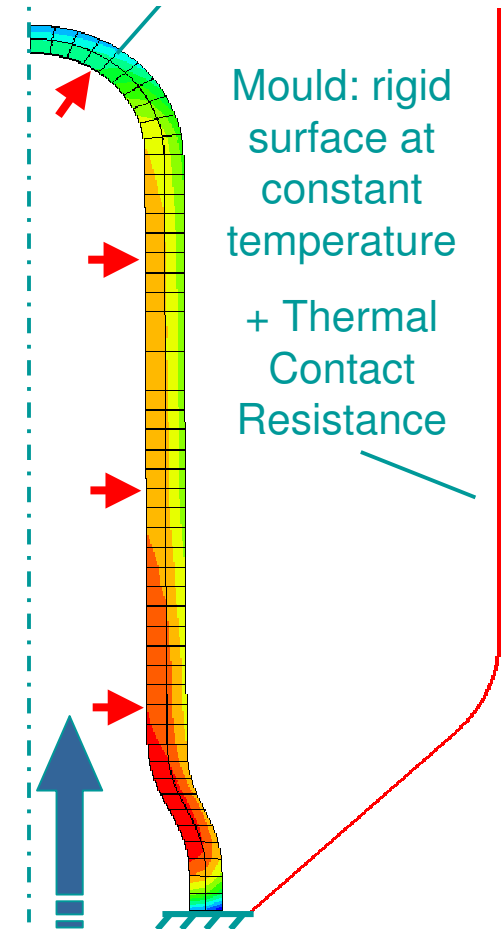
Viscoplastic G'sell law + WLF (user subroutine)

## ✓ Boundary conditions

- Preform initial temperature distribution
- **Mass Flow Rate (MFR)**  
→ **Air pressure automatically computed**
- Thermal Contact Resistance polymer/mold
- Sticking contact between polymer & mold:

} MEASURED

Preform: 100 quadratic solid elements (405 nodes)



Air mass flow rate

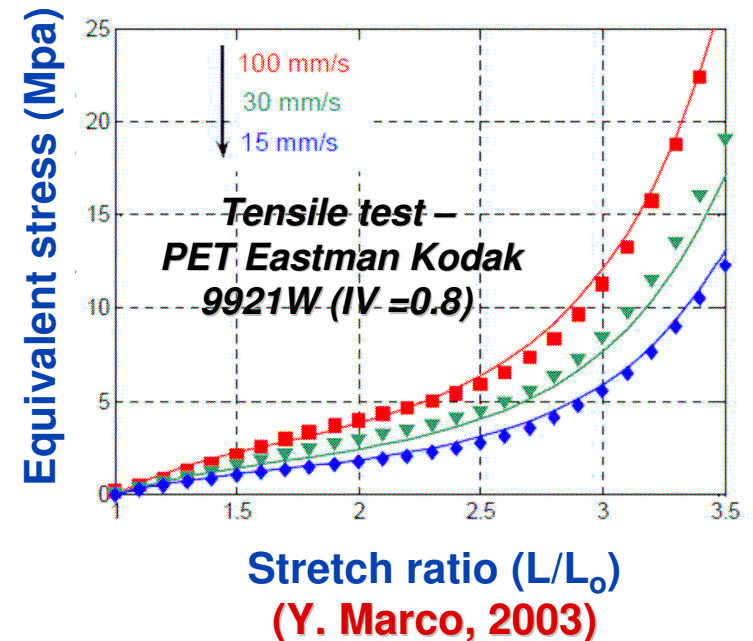


# G'Sell law + WLF thermodependency



$$\dot{\bar{\epsilon}} = \frac{\exp\left(\frac{B \bar{\epsilon}^C}{m}\right)}{K^{\frac{1}{m}} \sqrt{3}^{\frac{m+1}{m}} (1 - \exp(-A \bar{\epsilon}))^{\frac{1}{m}}} \bar{\sigma}^{\frac{1}{m}}$$

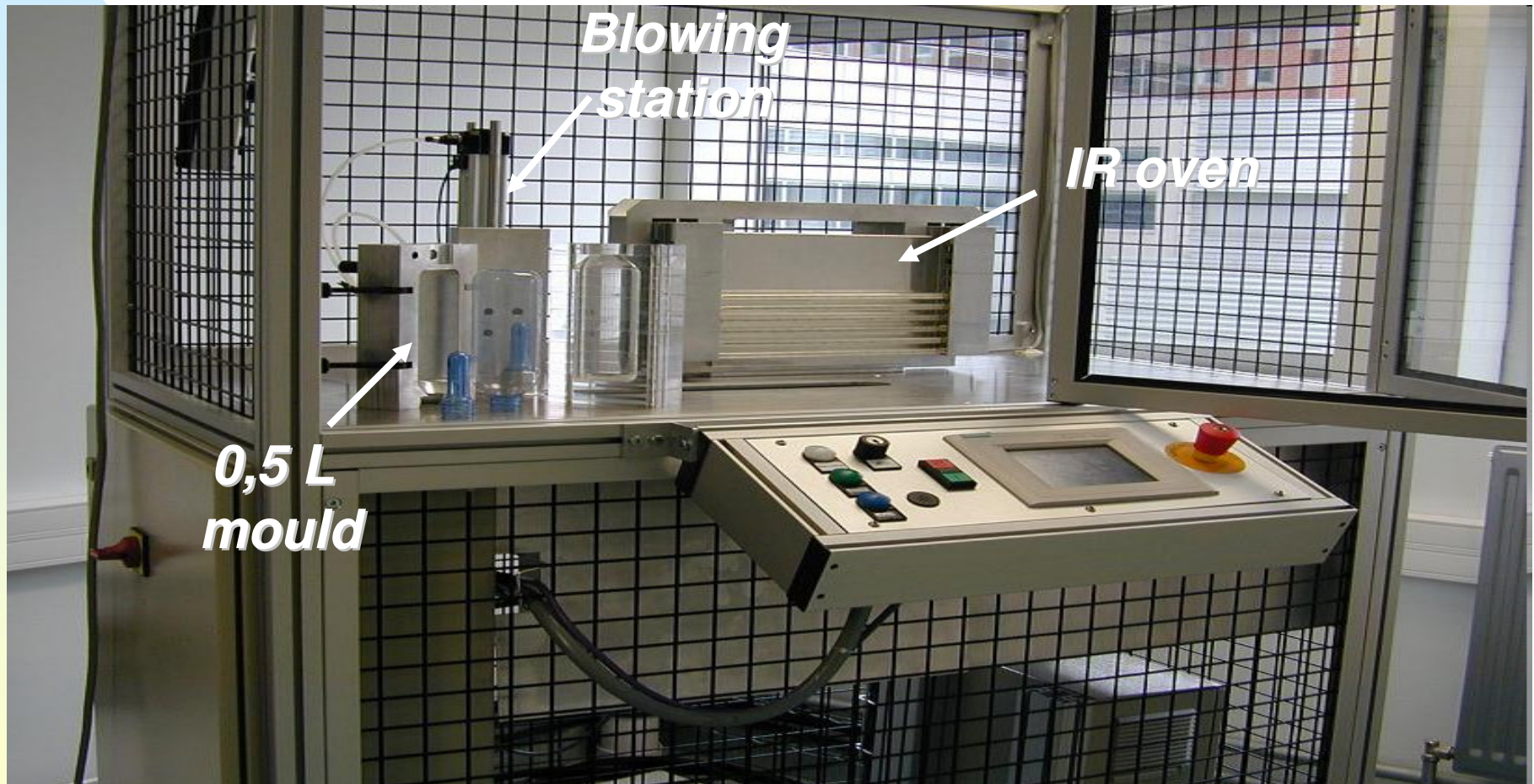
$$\text{with } K = K_0 \frac{-C_1 (T - T_0)}{C_2 + T - T_0}$$



- ✓ Takes into account strain rate dependence
- ✓ Good representation of the strain hardening
- ✓ Do not take into account the viscoelasticity

- ✓ Numerically stable
- ✓ Simple to implement
- ✓ Few constitutive parameters
- ✓ Small temperature and strain rate ranges

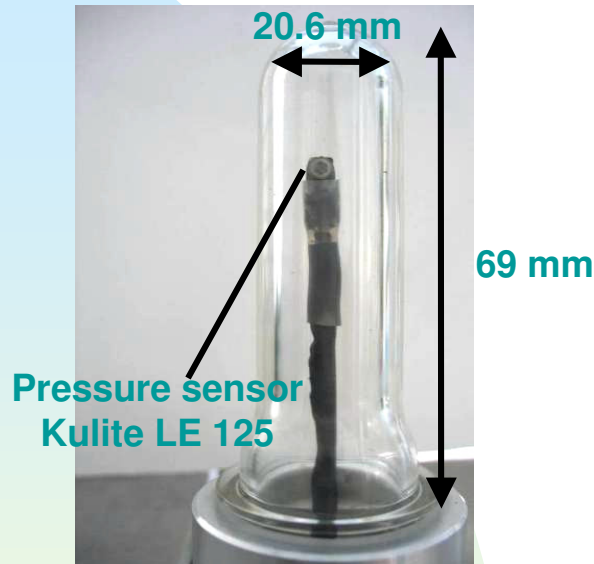






ECOLE DES MINES D'ALBI  
C A R M A U X

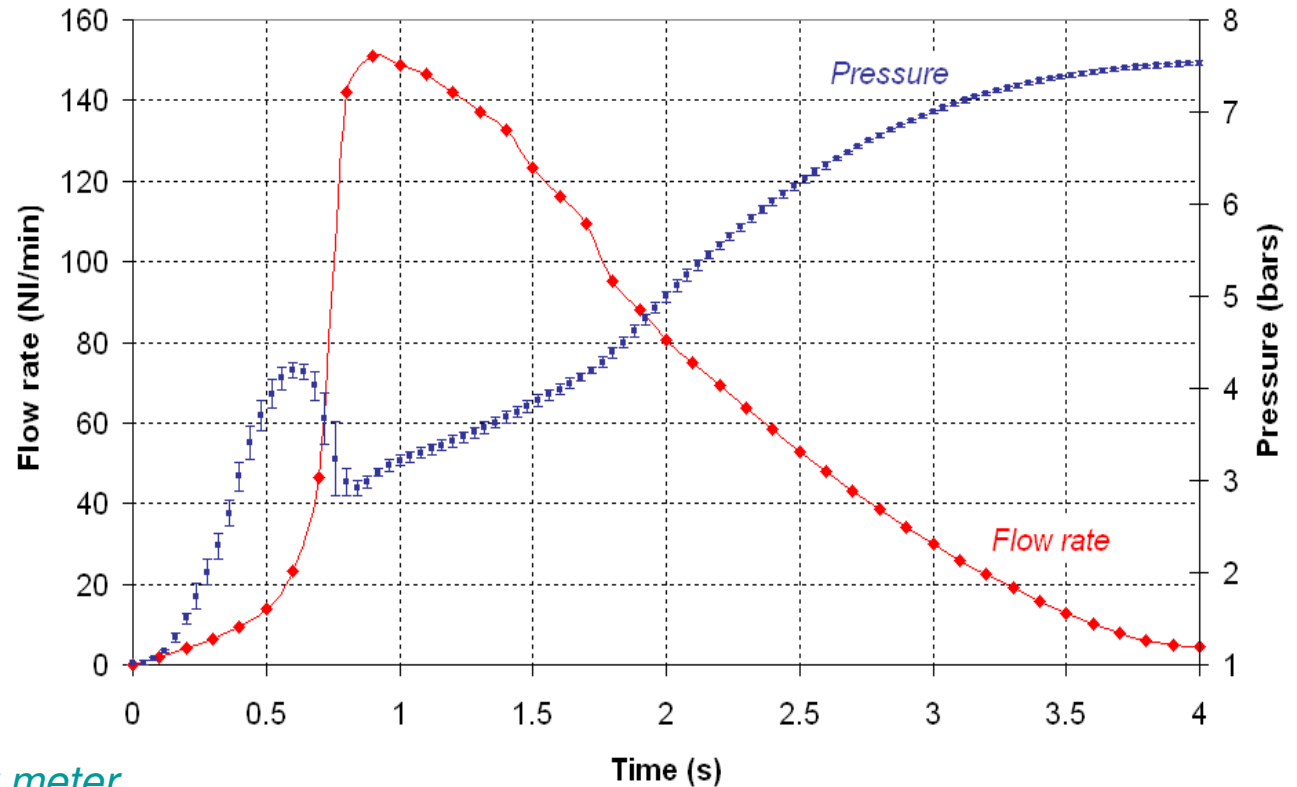
# Mass flow rate and air pressure inside preform



APT\_PACK 18.5g preform and  
pressure sensor

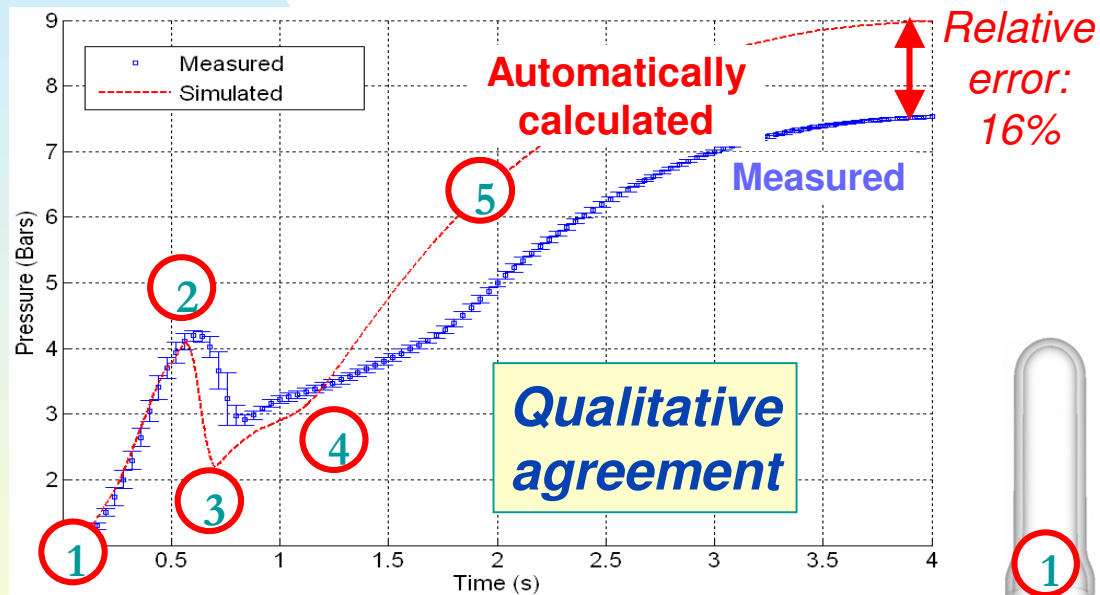


Bronkhorst mass flow meter  
(hot wire)

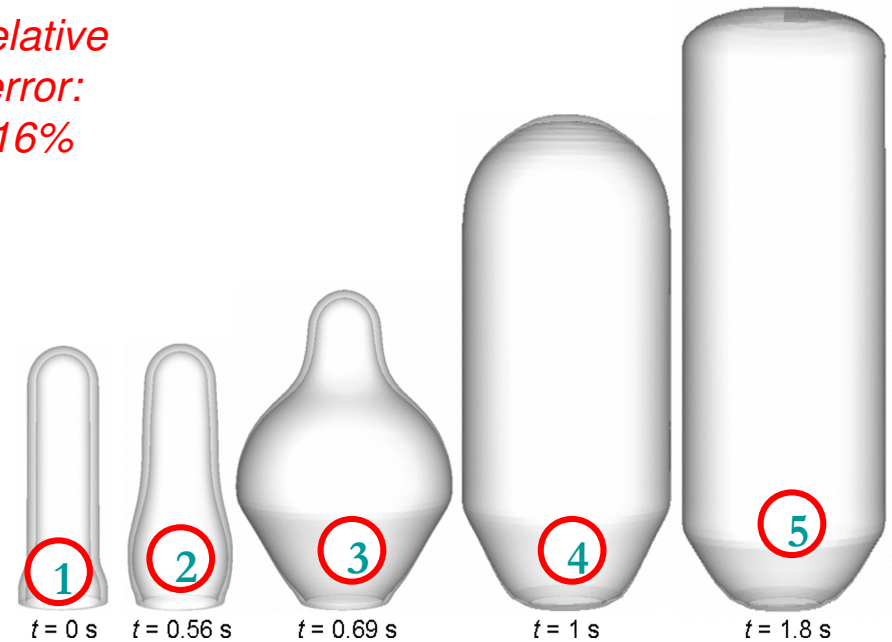


**Air pressure automatically calculated thanks to a  
thermodynamic model (ideal gas law)**

## Inflation pressure versus time



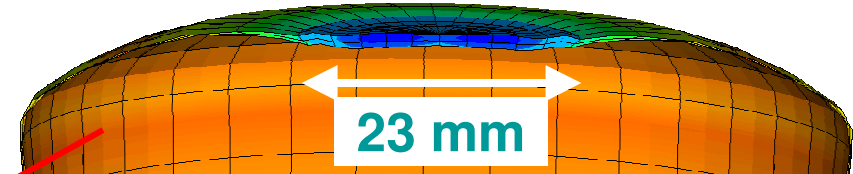
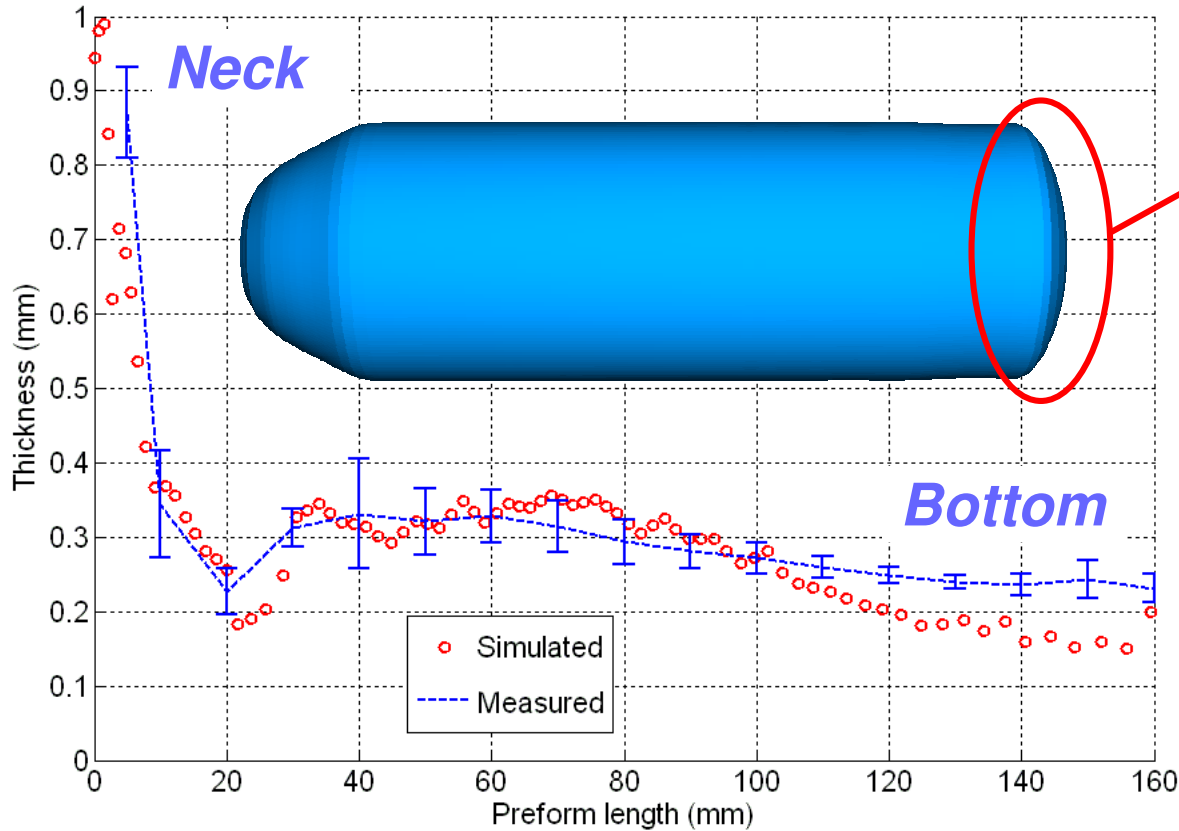
**CPU time: 26 min**  
**(Pentium 4 2.8 Ghz 512 Mo)**



Intermediate bottle shapes



# Thickness distribution & final preform shape



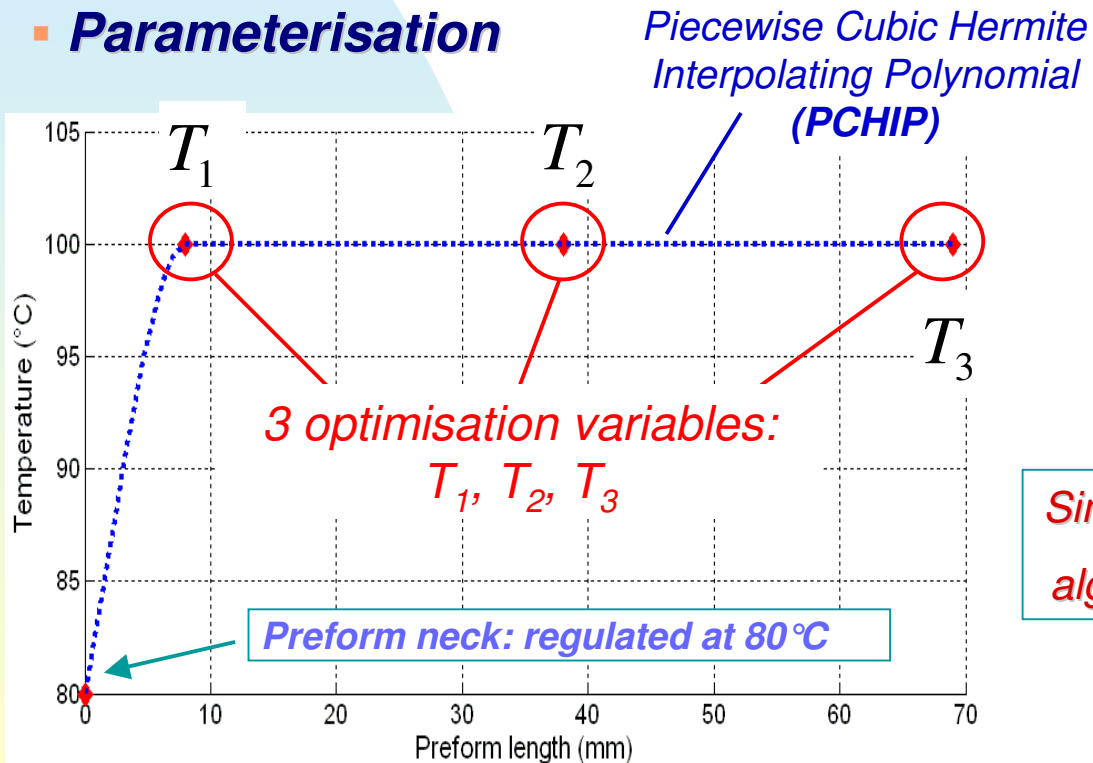
**Thickness distribution accurately predicted**

(The error bars show  $\pm 1$  standard deviation for a set of 3 trials)

# Optimisation of the preform temperature distribution

Objective: to achieve most **uniform thickness** for bottle by modifying temperature profile along preform length

## Parameterisation



Temperature profile along the preform length

## Optimisation procedure

- ✓ Automatic update of  $T_1, T_2, T_3$  at each iteration
- ✓ Rebuilding of the temperature profile using PCHIP
- Simplex algorithm**

  - ✓ Applying the temperature distribution as boundary condition
  - ✓ Blowing simulation
  - ✓ Cost function computation

# Cost function: standard deviation of the computed thickness

$$F(\vec{x}) = \left( \frac{1}{n-1} \sum_{i=1}^n (th_i - \overline{th})^2 \right)^{\frac{1}{2}}$$



**Thickness uniformity**

Mean thickness

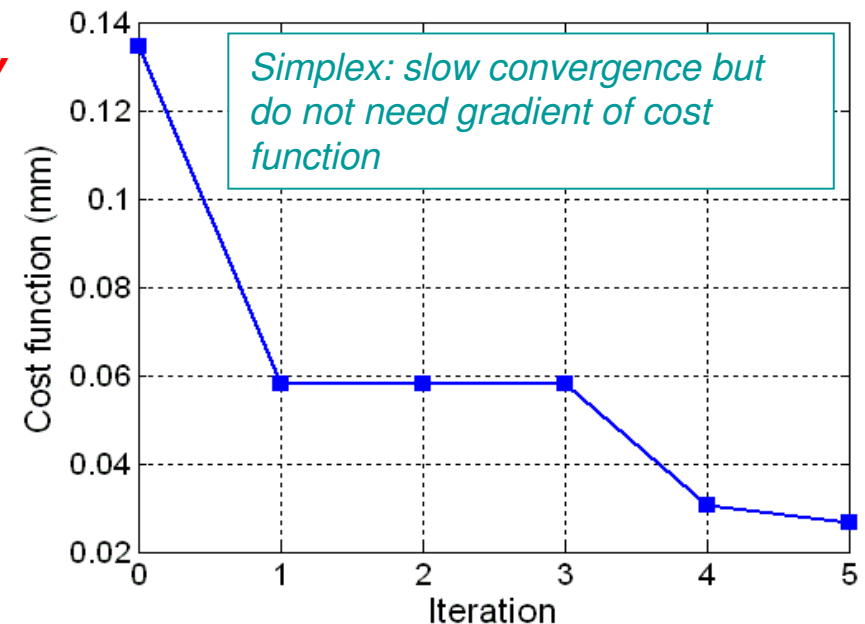
	T <sub>1</sub> (°C)	T <sub>2</sub> (°C)	T <sub>3</sub> (°C)	F (mm)
Initial	100	100	100	0.134
Final	110.7	98.9	92.9	0.026

**+ 80% of uniformity**

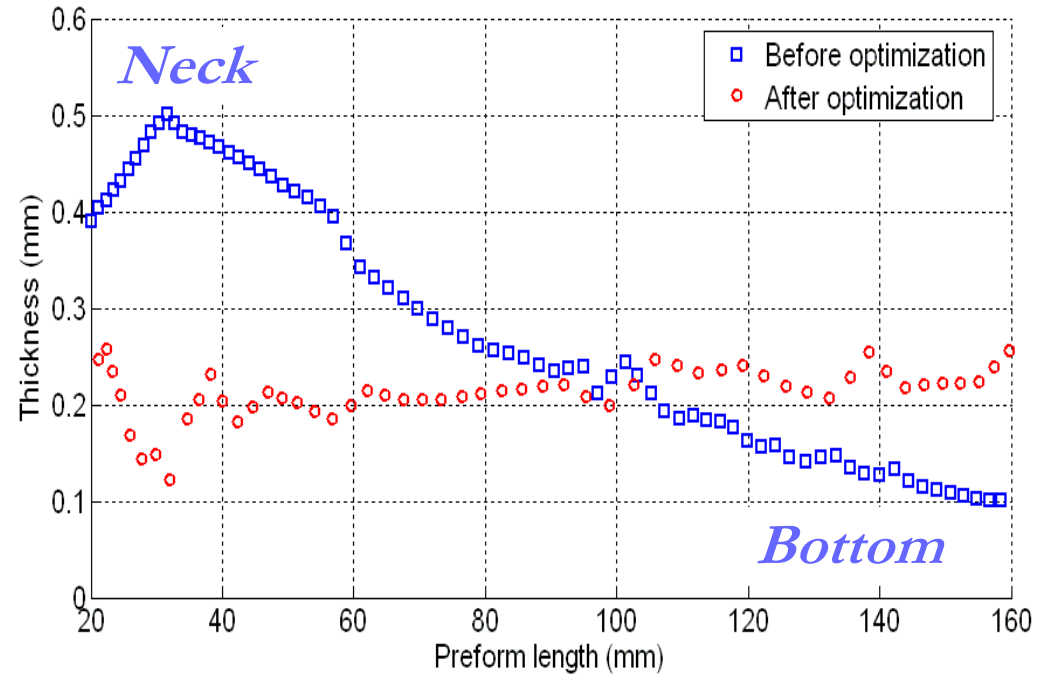
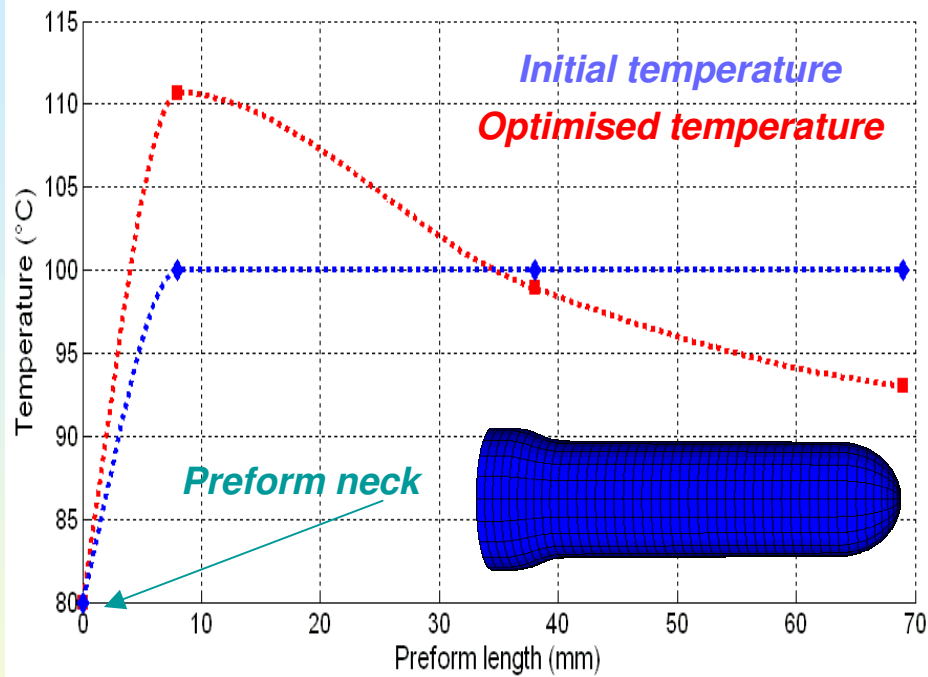


- Number of iterations: 5
- Number of cost function evaluations: 10
- CPU time: 3h 20 min**  
(Pentium 4 2.8 Ghz 512 Mo)

Cost function versus iteration



# Thickness distribution of the bottle vs Temperature profiles

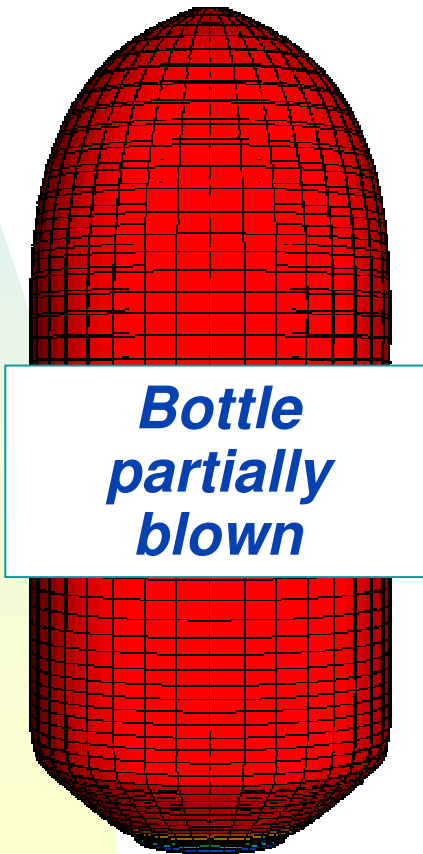
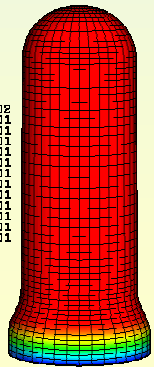
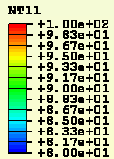


**(Assumption for the optimisation:  
uniform temperature through the preform  
thickness)**

**Thickness 80% more uniform**

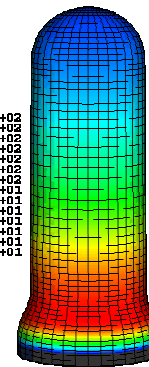
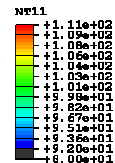
## Before optimisation

T (°C)



## After optimisation

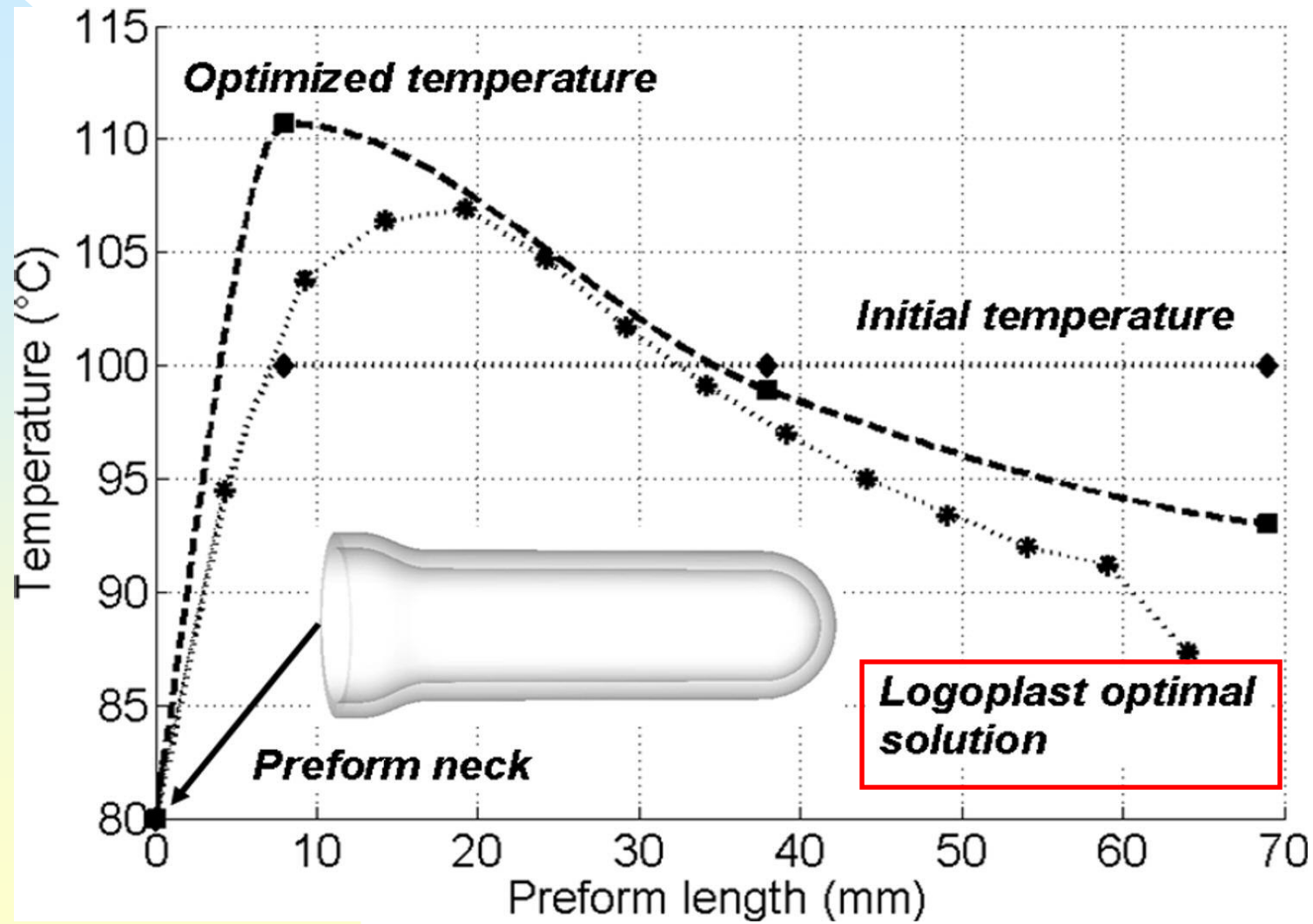
T (°C)







# Initial and optimised temperature profiles



## Future works

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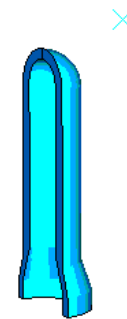
- Accurate validation of infrared heating of rotating preforms using ray tracing method
- Introduce temperature distribution through the wall thickness
- Full coupling between IR-heating and blowing optimisation

# Qualitative comparison (different preforms)



Blow moulding video  
(0,5 L bottle)

Step: Step-1 Frame: 0

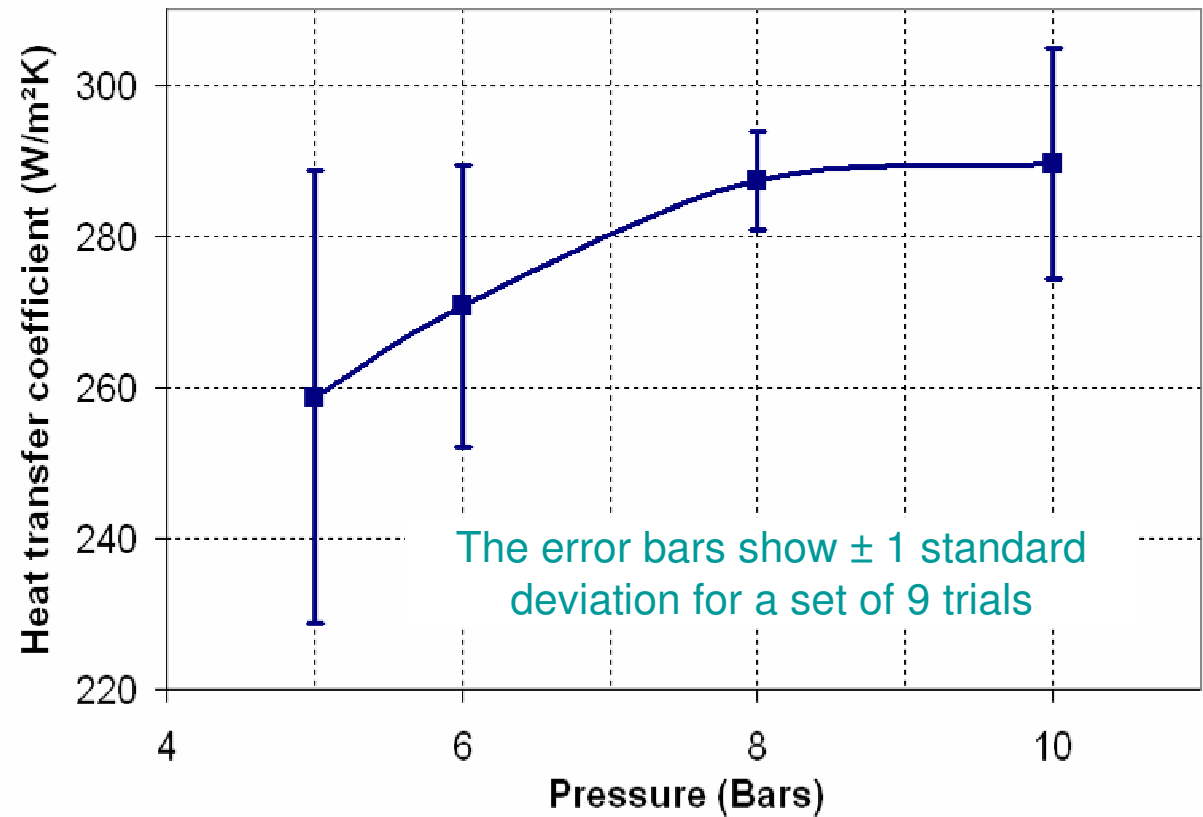
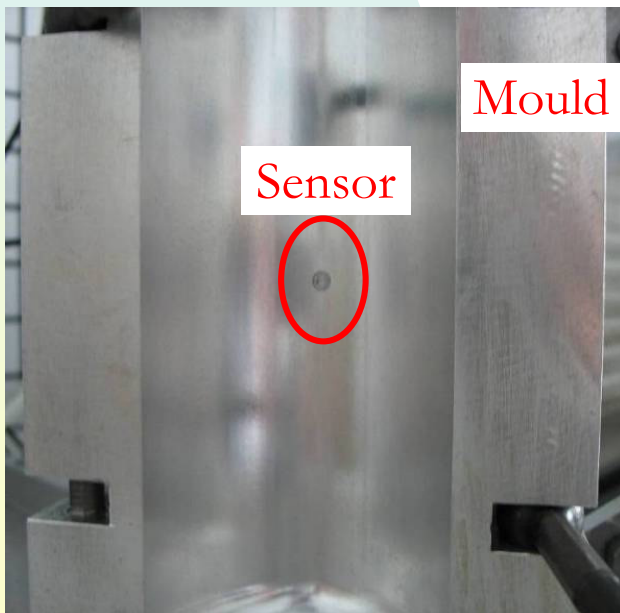
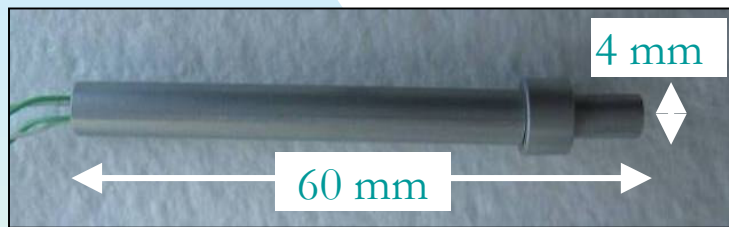


Typical blow moulding  
simulation



# Heat transfer coefficient polymer/mould

Sensor developed for thermal contact  
resistance measurement



*(Results fully presented in ESAFORM 2007)*