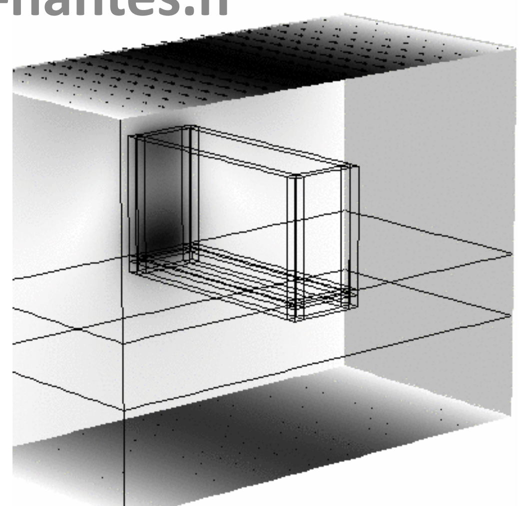
Modeling Microwave Heating During Batch Processing of Liquid Sample in a Single Mode Cavity

S. Curet[1], F. Bellincanta Begnini, O. Rouaud[1], L. Boillereaux[1]

[1]L'UNAM Université, ONIRIS, CNRS, GEPEA, UMR6144, Nantes, F-44322, France

sebastien.curet@oniris-nantes.fr



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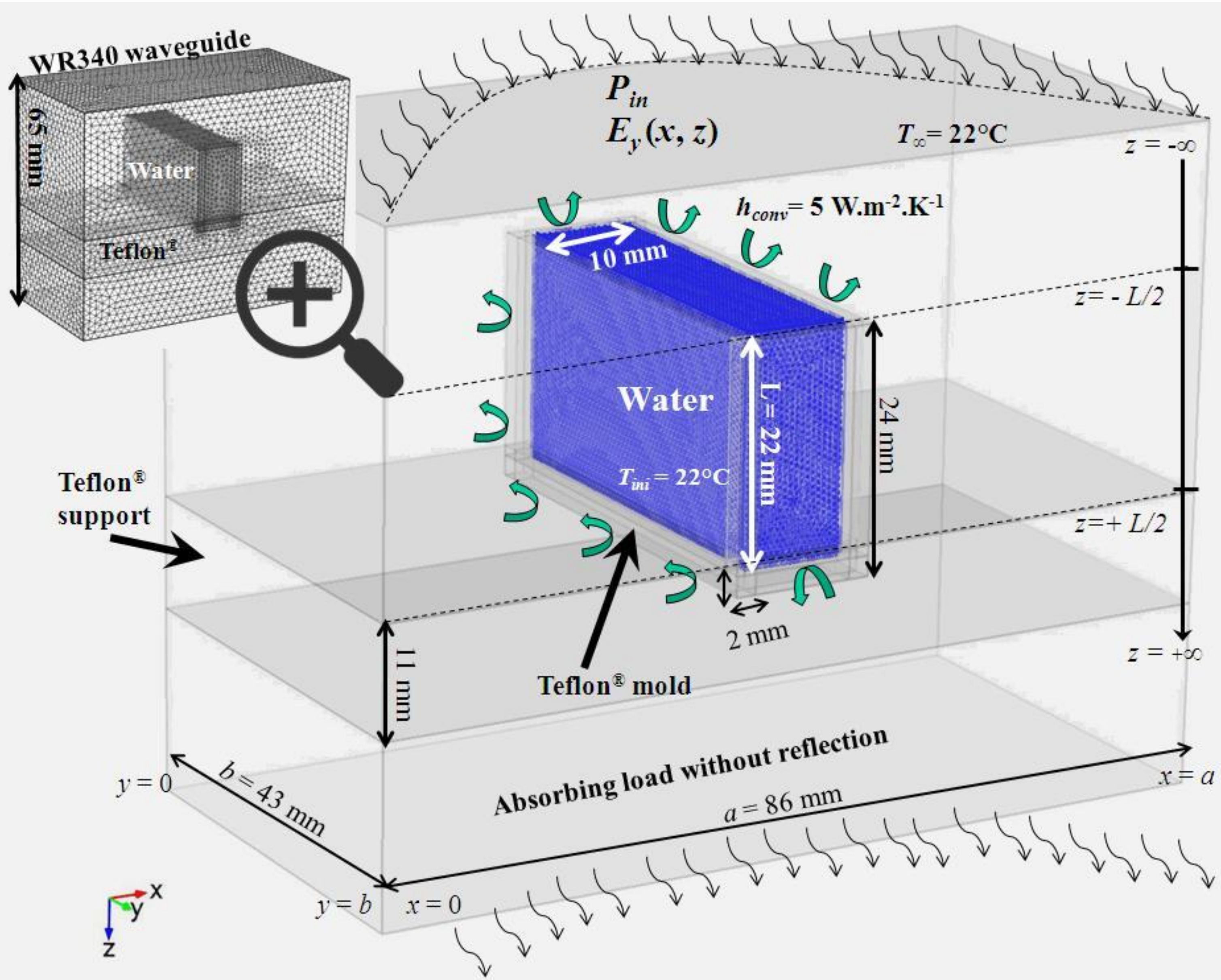
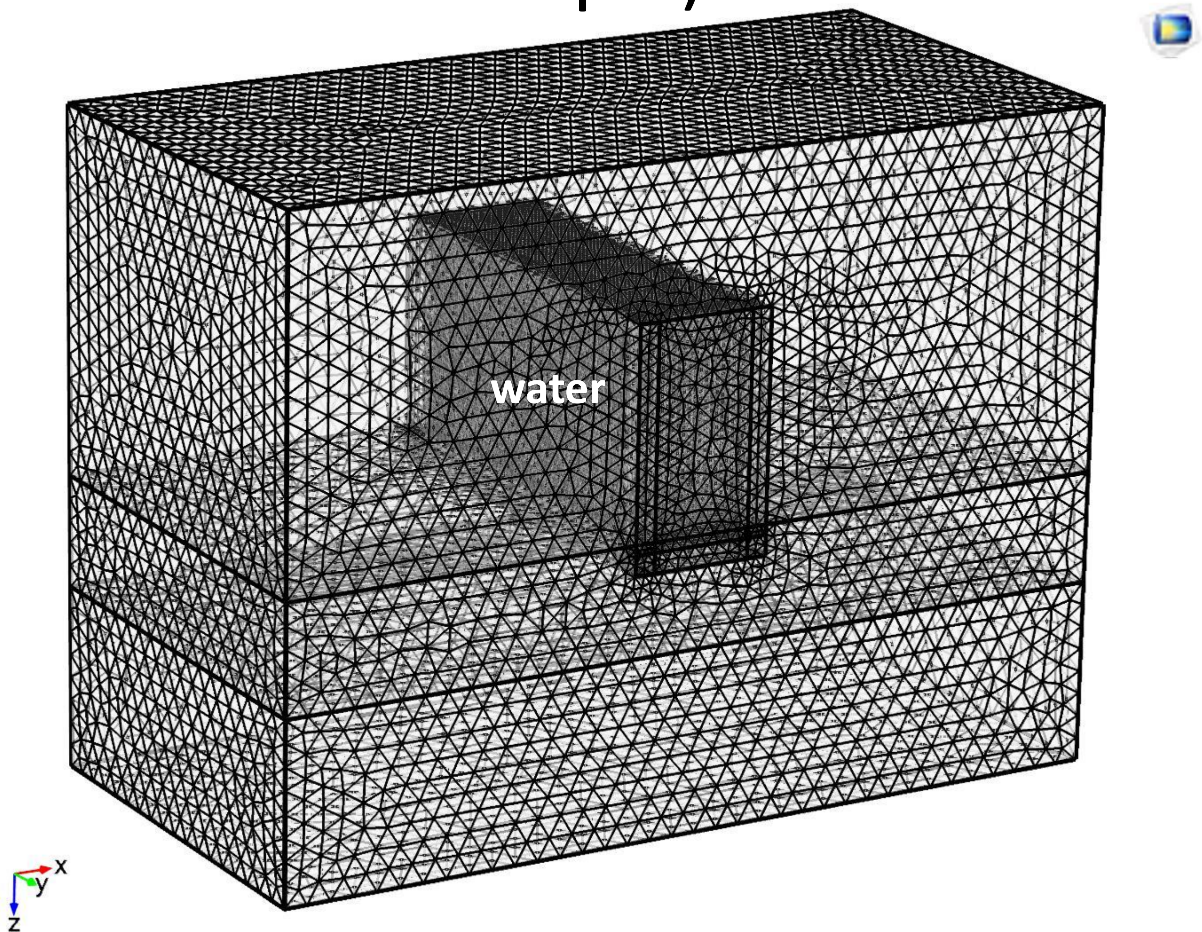


P_{in} = 50 W

t = 160 s

Mesh generation in COMSOL®

- **811 988** tetrahedral elements (**440 581** elements for the water sample).



Governing equations

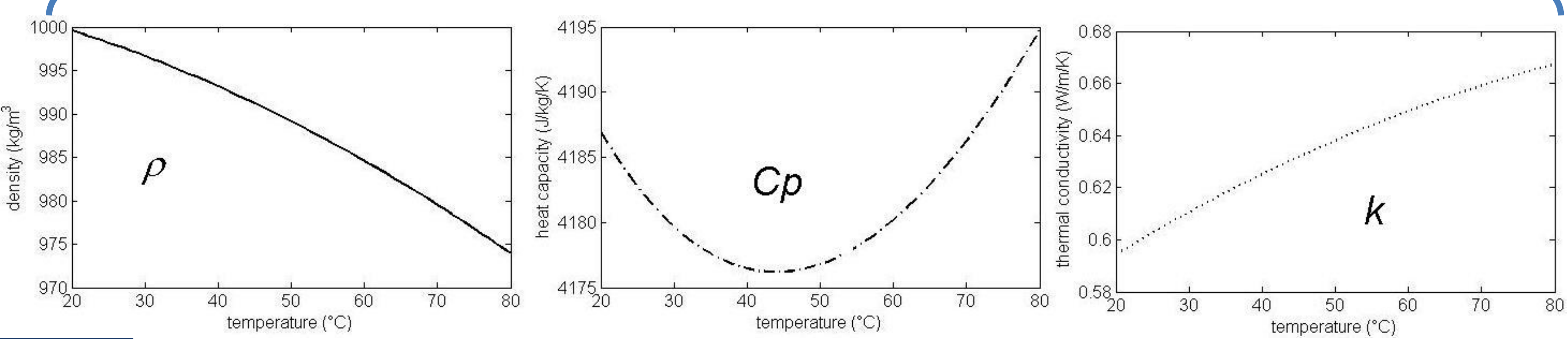
- Heat transfer equation *(HT module)*

$$\rho C_p \frac{\partial T}{\partial t} = div.(k \nabla T) + Q_{abs}$$

Thermophysical properties of pure water*

Microwave absorbed power ($W.m^{-3}$)

➔ Resolution of the Maxwell's equations



* From the COMSOL® material library

Governing equations

- Electric field propagation *(RF module)*

➔Maxwell's equations for a TE_{10} rectangular waveguide (sinusoidal time-varying fields with $\omega = 2\pi f$)

$$\nabla \times \mu_r^{-1}(\nabla \times E) - k_0^2\left(\varepsilon'_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \quad with \quad k_0 = \omega\sqrt{\varepsilon_0\mu_0}$$

Q_{abs} : volumetric heating rate (W.m^{-3}) ➔ $Q_{abs} = \frac{1}{2}\omega.\varepsilon_0.\varepsilon_r''|E_{local}|^2$

σ : Electrical conductivity (S/m)

f : frequency of microwaves **(2.45×10^9 Hz)**

ε_0 : permittivity of free space (F.m^{-1})

ε_r'' : relative dielectric loss factor

E_{local}: local electric field strength (V.m^{-1})

Governing equations

- Fluid flow modeling *(CFD module)*

➔Incompressible Navier-Stokes equations

$$\begin{cases} \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = 0 & (continuity) \\ \rho \dfrac{d\vec{U}}{dt} = \rho \vec{g} - \nabla P + \mu \Delta \vec{U} & (momentum) \end{cases} \qquad with\ \frac{d\vec{U}}{dt} = \frac{\partial \vec{U}}{\partial t} + \left(\vec{U}\nabla\right)\vec{U}$$

u, v, w : velocity field components following *x*, *y* and *z* directions

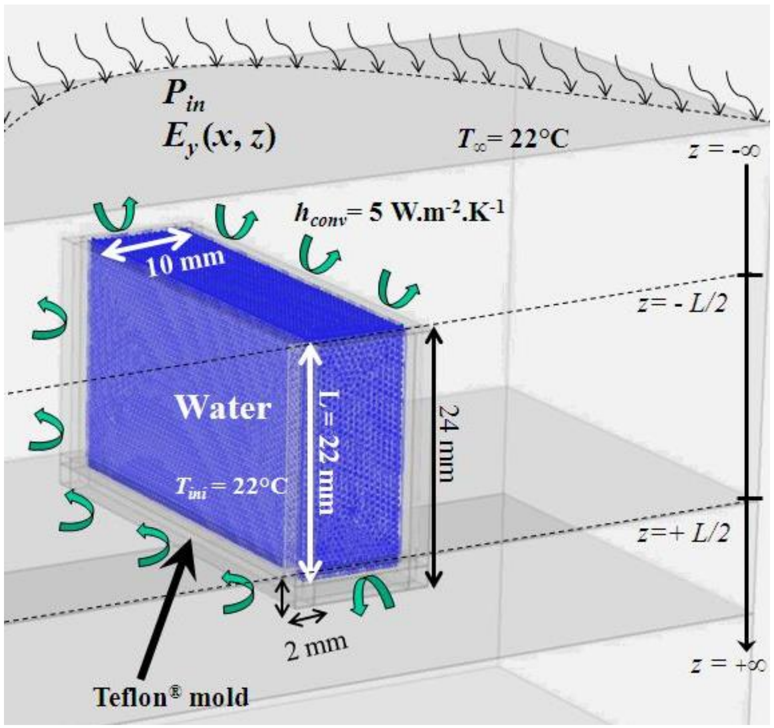
ρ: density of water (kg.m^{-3})

P: static pressure (Pa)

μ: dynamic viscosity of water (Pa.s)

Governing equations

- Initial & boundary conditions



HT

$$\begin{cases} T = T_0 & at\ t = 0, \forall x\ \forall y\ \forall z \\ k\nabla T = h(T - T_\infty) & at\ external\ boundary\ walls \end{cases}$$

RF

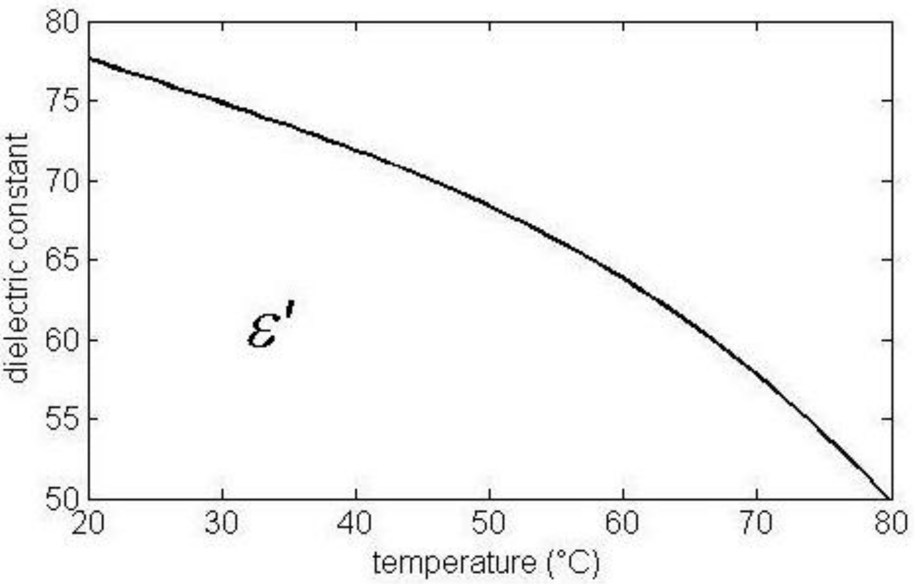
$$\begin{cases} E = 0 \quad at\ \ t = 0, \forall x\ y\ z \\ E_{in} = E_0 \cos\left(\frac{\pi x}{a}\right) with\ E_0 = 4Z_{TE}\frac{P_{in}}{ab} \quad at\ z = -\infty, \forall x \\ n \times (\mathbf{H}_{air} - \mathbf{H}_{sample}) = 0 \qquad at\ z = -L/2,\ z = L/2, \forall x \\ \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r - j\sigma/\omega}}\, n \times \mathbf{H} + E - (n.E)n = 0 \quad at \begin{cases} x = 0 \\ x = a \\ y = 0 \\ y = b \end{cases}, \forall z \end{cases}$$

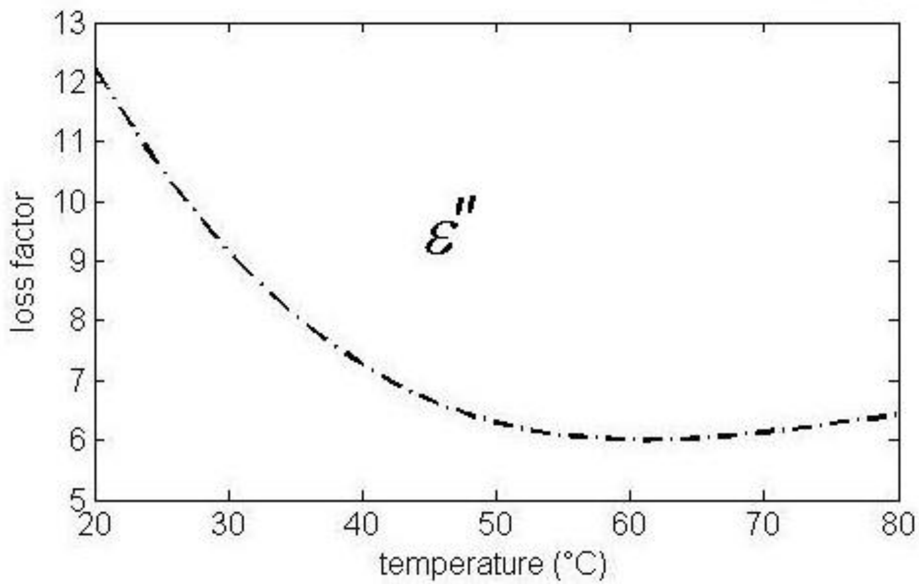
CFD

$$\begin{cases} U_0 = 0\ and\ P_0 = \rho g L \quad at\ \ t = 0, \forall x\ \forall y\ \forall z\ with\ 0 < L < 22mm \\ U = 0 \quad at\ \ the\ \text{liquid - container interfaces} \end{cases}$$

Material properties = $f(\theta\ °C)$

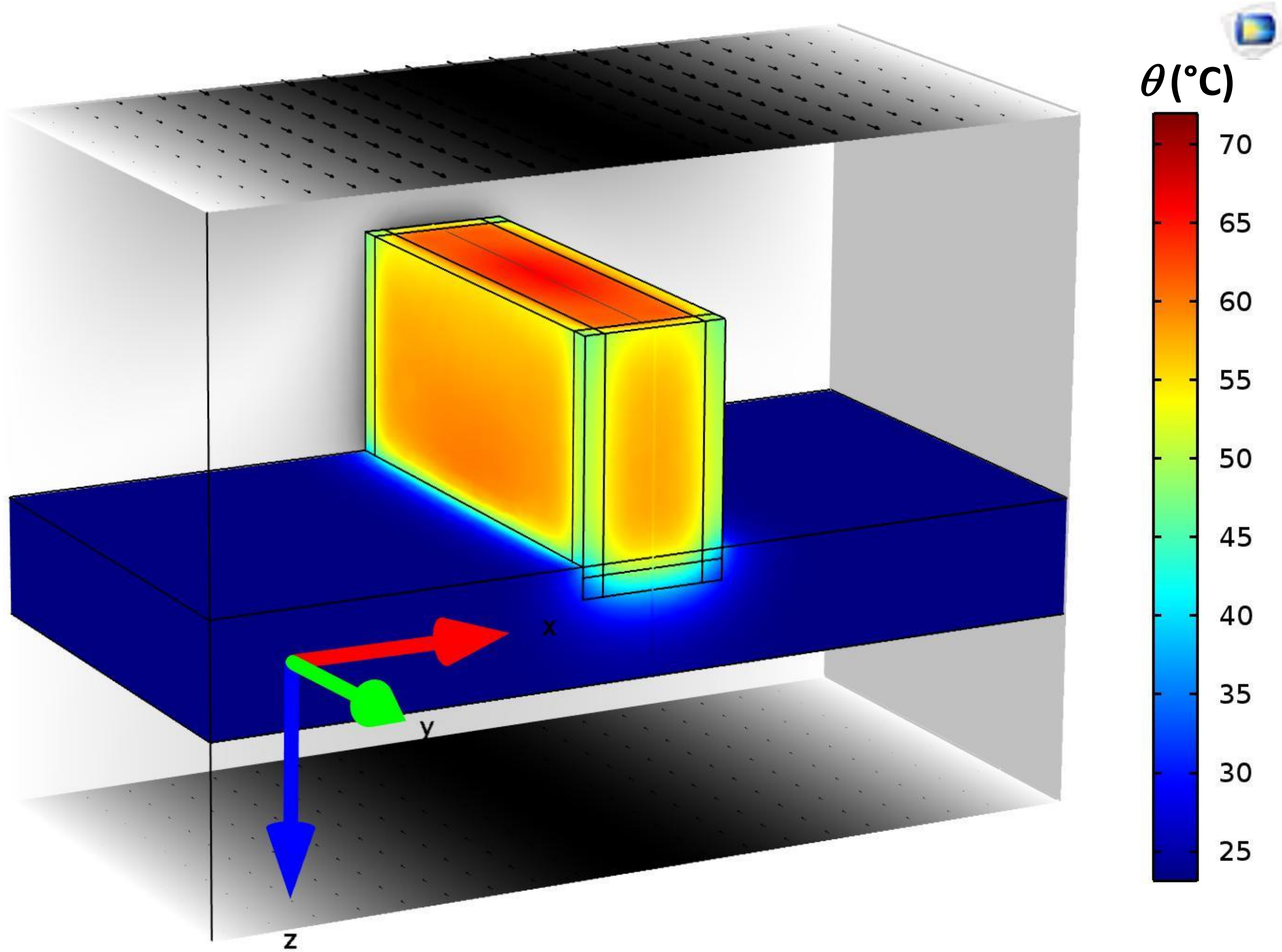
- Dielectric properties of pure water* (2.45 GHz)





* Zhang, Q., T. H. Jackson and A. Ungan. Numerical modeling of microwave induced natural convection. *International Journal of Heat and Mass Transfer* **43**: 2141-2154 (2000).

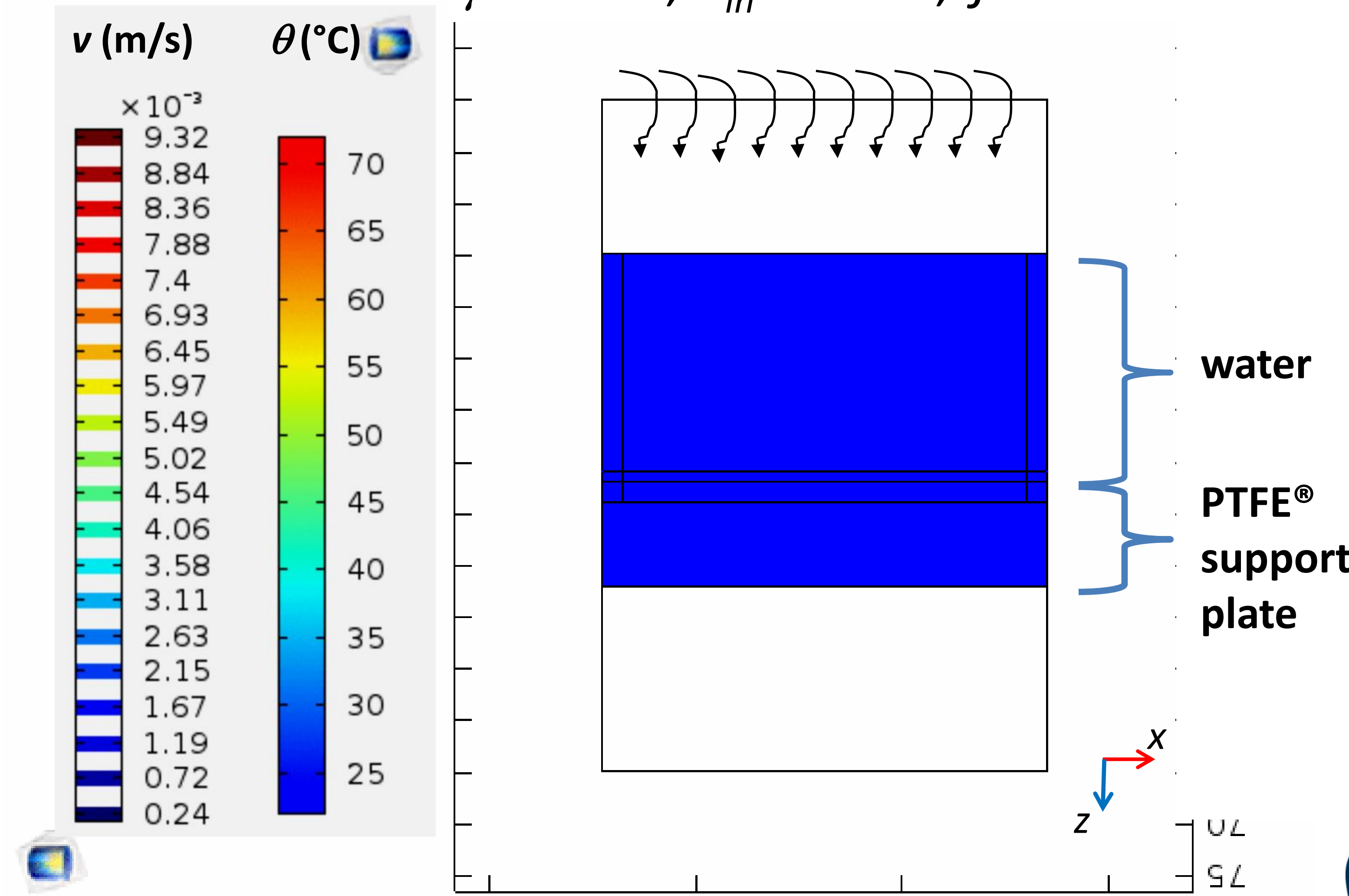
Temperature distribution at *t* =160 s



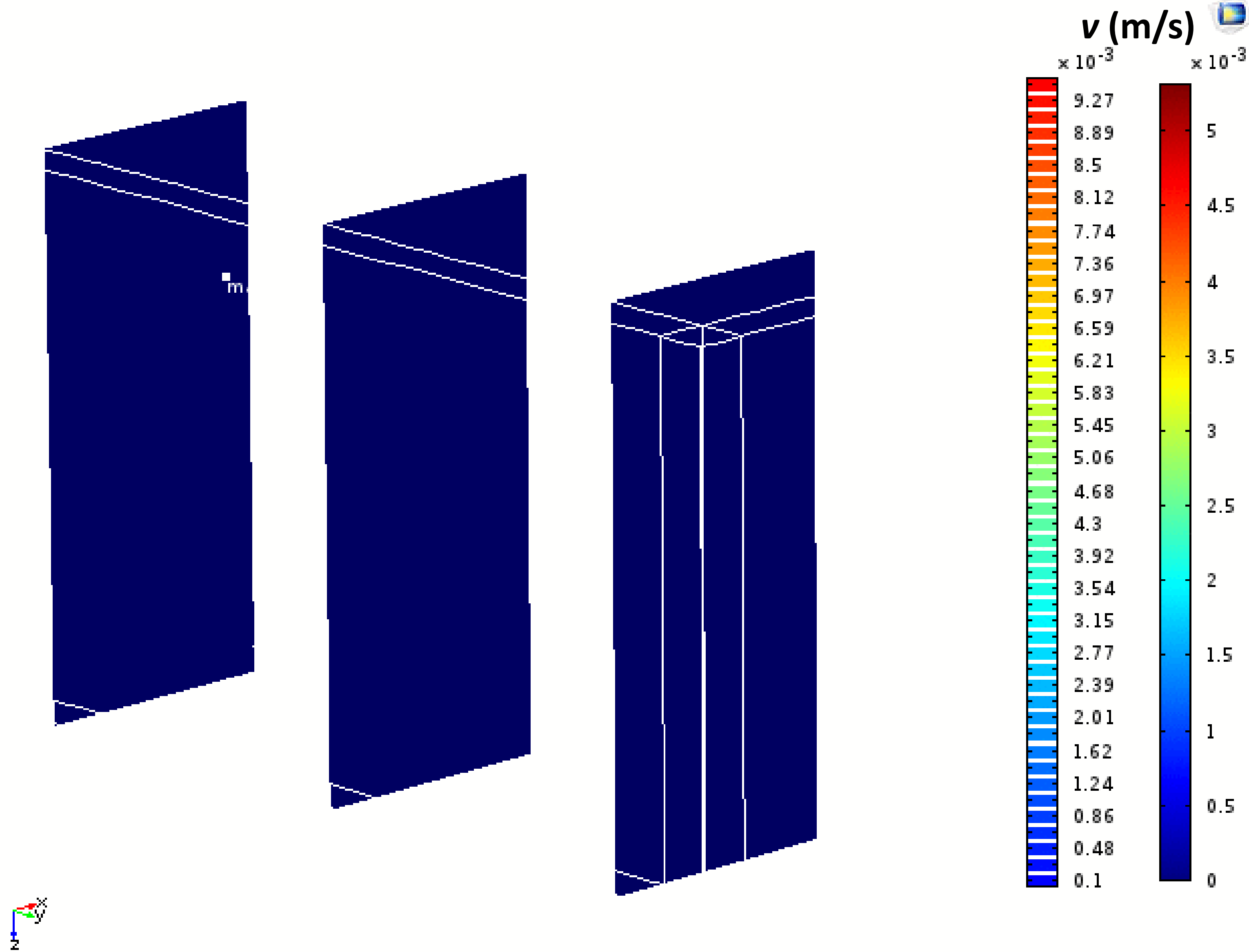
At the end of microwave processing, the surface of the water is close to 70 °C while the external temperatures of the walls range from 55 to 60 °C (*PTFE is only heated by conduction*)

Velocity fields and temperature variations = *f* (*t*)

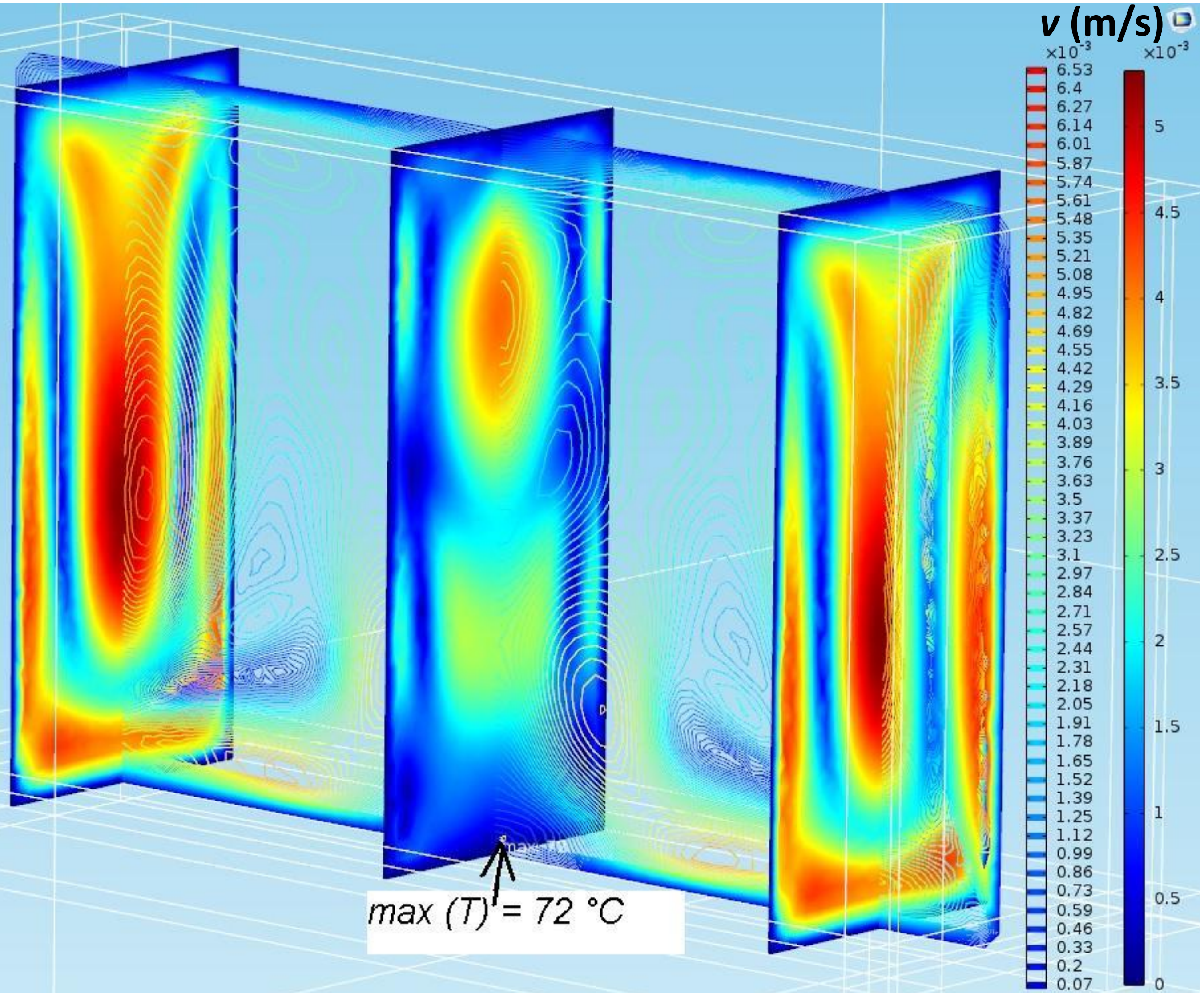
μ waves, $P_{in} = 50W$, $f = 2.45GHz$



Cross sections areas of velocity fields

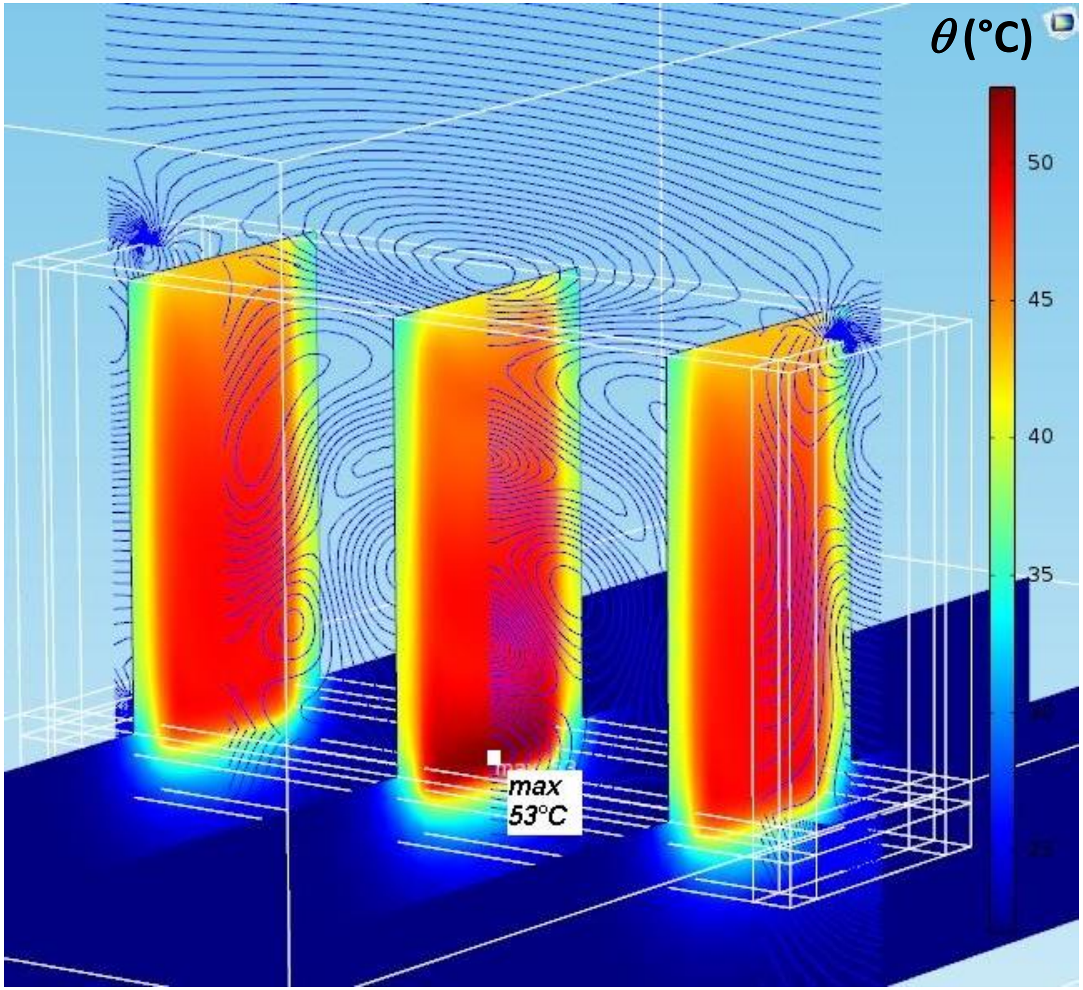


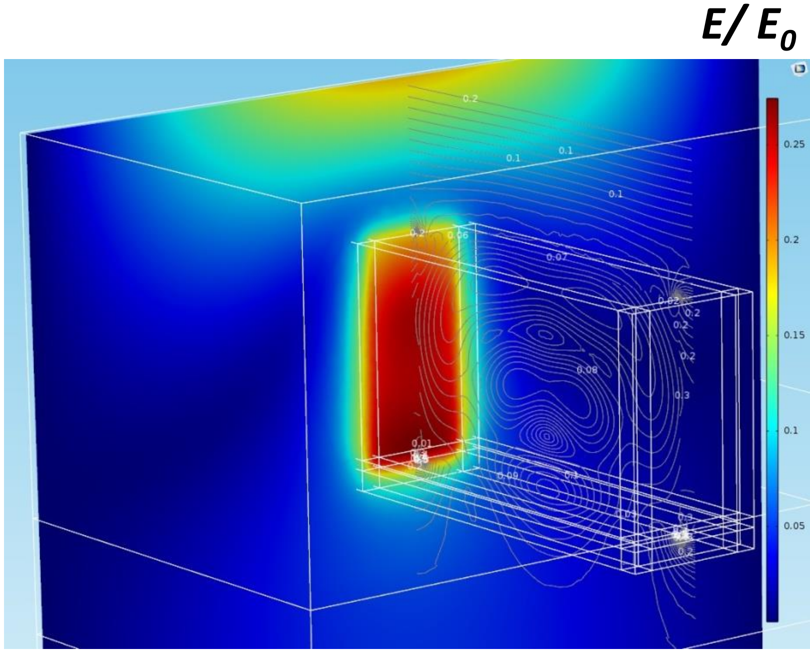
Cross sections areas of velocity fields at *t* = 160 s



At the end of processing, the gravitationally driven flow of water leads to max velocity gradients around ≈ 6 mm/s

Cross sections areas of temperature and electric field shape at *t* = 80 s

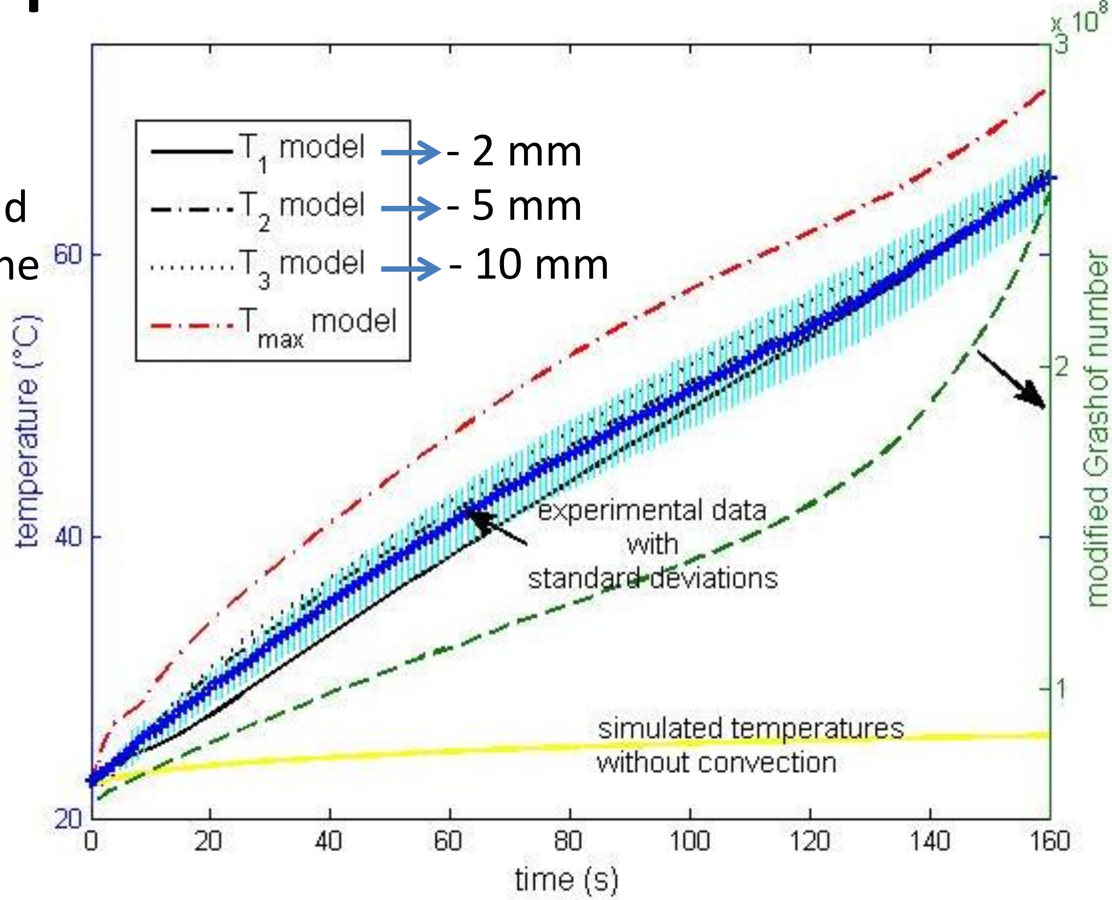




➔ The hot spots are depicted at the near bottom zone of the liquid-container interface

Experimental validation of numerical results

T_1, T_2 and T_3: 2 mm, 5 mm and 10 mm below the upper water surface



$$Gr^* = \frac{\rho^2 g \beta L^5 Q_{abs}}{\mu^2 k}$$

➔ fairly good agreement between exp. vs. numerical model

➔ As Gr* ↗, microwave induced natural convection ↗ as a function of processing time

Highlights

- *« Modeling microwave heating of a liquid sample in a static configuration »:*

➔Non uniform inner temperature distribution within a small liquid sample (8.5 mL)

➔Modeling enables to locate precisely the hot spots.

➔The Navier-Stokes equations must be coupled to the heat transfer and the Maxwell's equations in order to give realistic results.

➔High computational resources are needed for a strong coupling between the differential equations.

Future prospects

- Extension of this preliminary study to investigate the development of microwave applicators dedicated to liquid phase processing under continuous flows.

Thank you for your attention,