Microwave Inactivation of Bacteria under Dynamic Heating Conditions in Solid Media

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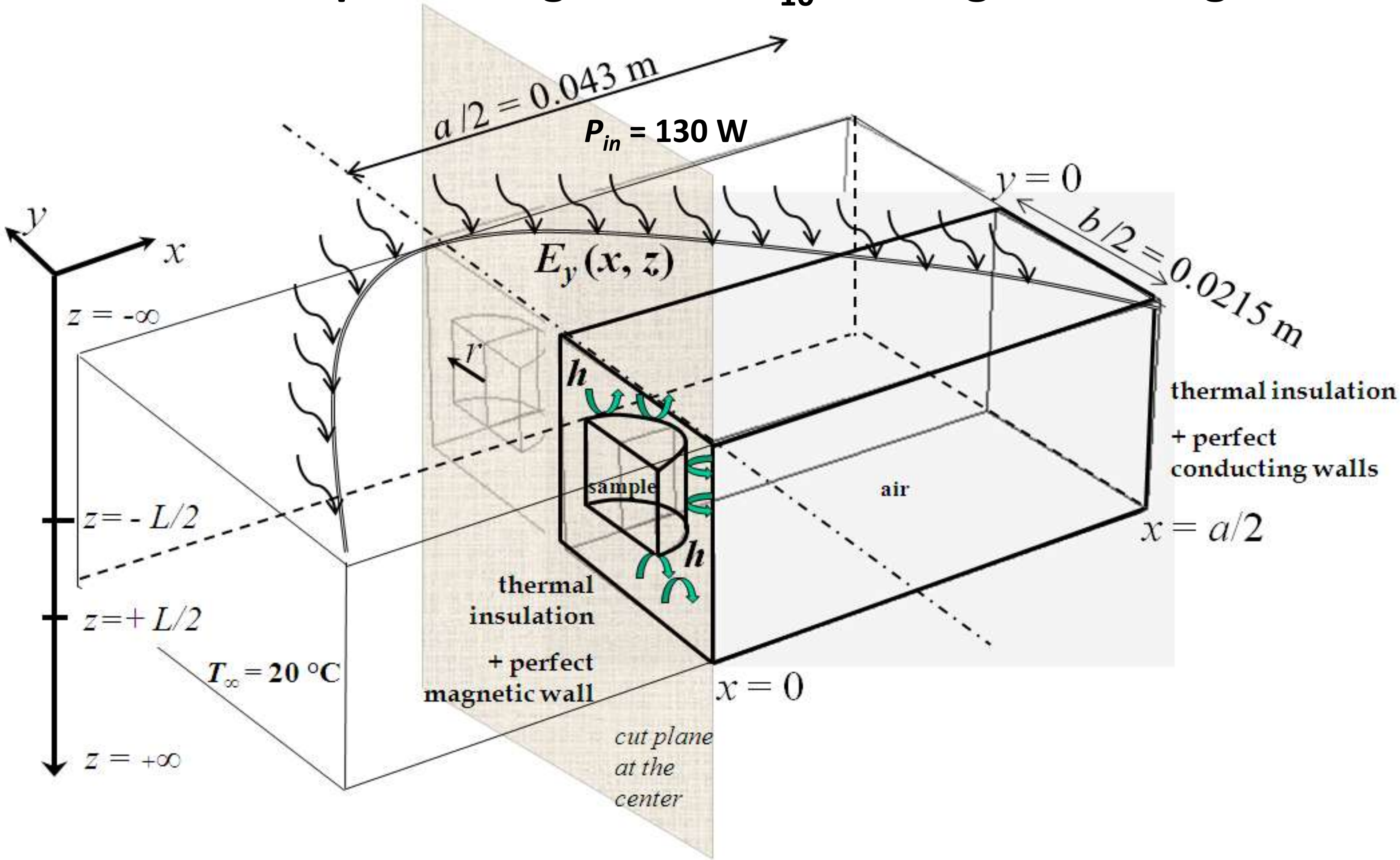
The microwave pasteurization process

- Application for prepacked food (yoghurt, pouch-packed meals, milk…)
- Difficulty in monitoring and predicting the microwave heating pattern during processing
- Few literature reviews concerning microwave inactivation process within a solid food products

- Objective: predicting microbial inactivation during microwave pasteurization

Microwave processing into a TE_{10} rectangular waveguide



Governing equations

- Heat transfer equation *(PDE from COMSOL®)*

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

Thermophysical properties of the Ca-alginate gel*

ρ (kg.m^{-3})	1010
C_p (J.kg^{-1}.K^{-1})	4120
k (W.m^{-1}.K^{-1})	0.84

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

Maxwell's equations

* Lin, Y. E., R. C. Anantheswaran, et al. (1995). "Finite element analysis of microwave heating of solid foods." Journal of Food Engineering 25(1): 85-112.

Governing equations

- Electric field propagation *(RF module)*

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

$$\left(\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2}\right) + \omega^2 \mu \varepsilon' \left(1 - j\frac{\sigma}{\omega \varepsilon'}\right) E_y = 0$$

Q_{abs} : volumetric heating rate ($W.m^{-3}$) ➔ $$Q_{abs} = \sigma |E_{rms}|^2 = 2\pi . f . \varepsilon_0 . \varepsilon_r'' |E_{rms}|^2$$

σ = Electrical conductivity (S/m)

$$E_{rms} = \frac{E_{local}}{\sqrt{2}}$$

f : frequency of microwaves **(2.45×10⁹ Hz)**

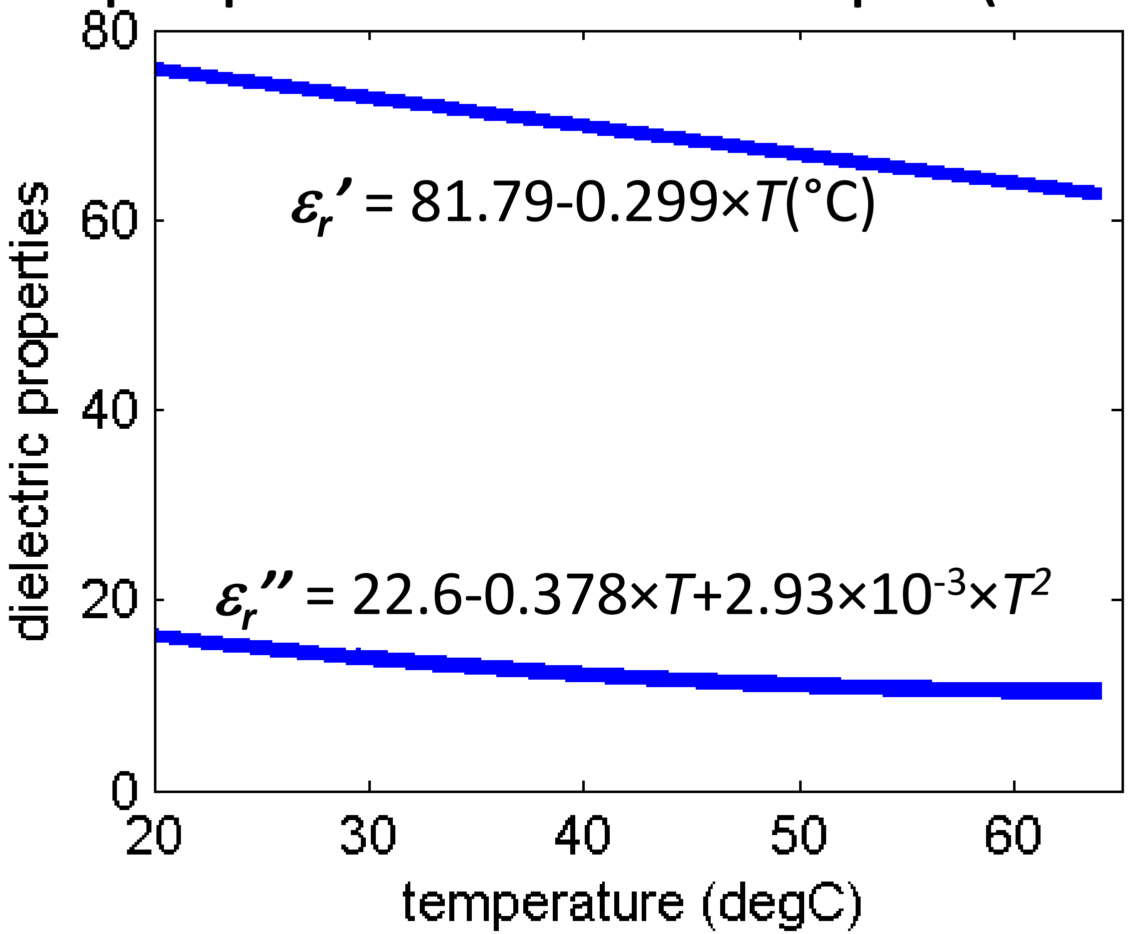
ε_0 : permittivity of free space ($F.m^{-1}$)

ε_r'' : relative dielectric loss factor

E_{rms}: root-mean-square average value of electric field at a location ($V.m^{-1}$)

Governing equations

- Dielectric properties of the sample (2.45 GHz)

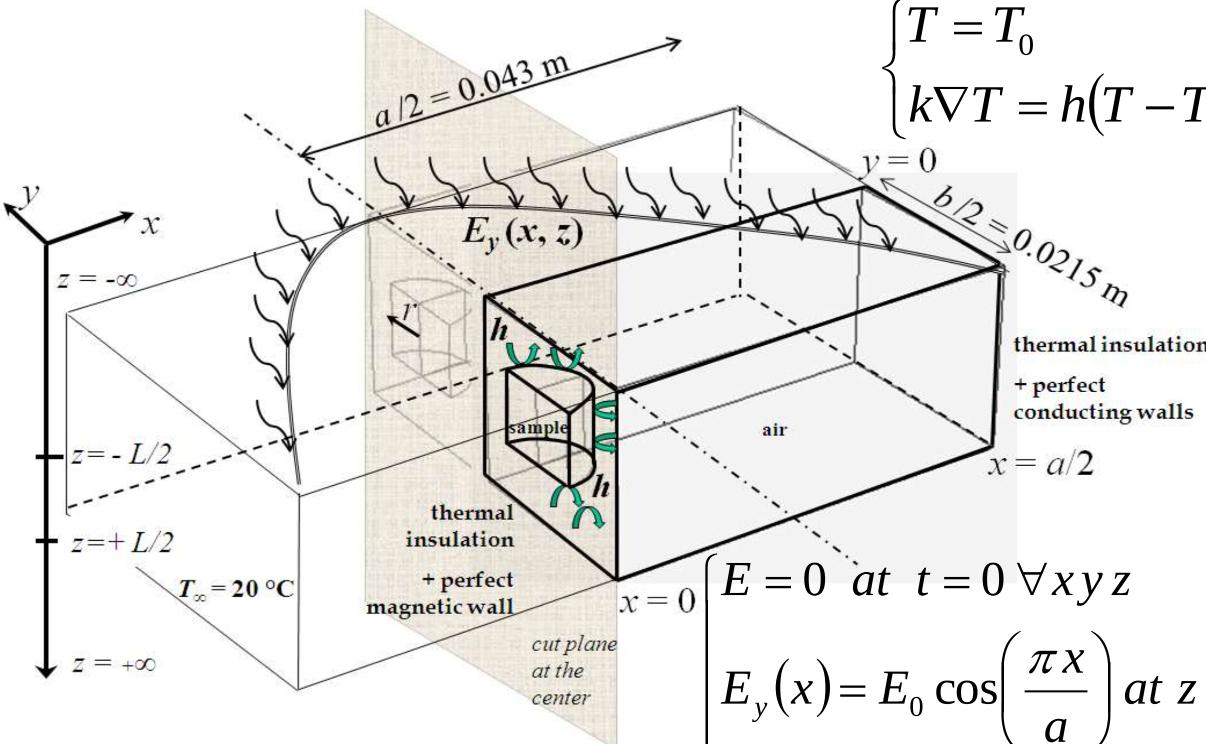


* Lin, Y. E., R. C. Anantheswaran, et al. (1995). "Finite element analysis of microwave heating of solid foods." Journal of Food Engineering 25(1): 85-112.

Governing equations

- Boundary conditions

$$\begin{cases} T = T_0 & at \;\; t = 0, \forall\, xyz \\ k\nabla T = h(T - T_\infty) & at \; r = R, \forall z \; and \;\; z = \pm L/2, \forall r \end{cases}$$



$$\begin{cases} E = 0 \;\; at \;\; t = 0 \; \forall\, x y z \\ E_y(x) = E_0 \cos\left(\dfrac{\pi x}{a}\right) at \;\; z = -\infty, \forall\, xy; \;\; E_0 = 4 Z_{TE} \dfrac{P_{in}}{ab} \\ E_y = E_{tan} = 0 \; at \;\; y = 0, \; y = b/2, \forall\, x z \;\; and \;\; at \;\; x = a/2, \forall y\, z \\ n \times H = 0 \; at \;\; x = 0, \forall y\, z \\ n \times (H_{air} - H_{sample}) = 0 \;\; at \;\; r = R, \forall z \; and \;\; z = \pm L/2, \forall r \end{cases}$$

Governing equations

- Microbial inactivation of *E. Coli K12* *(2 ODE equations)*

➔ Dynamic model from Geeraerd *et al.** (2000)

$$\begin{cases} \dfrac{dN}{dt} = -k_{\max} \cdot \left(\dfrac{1}{1+C_c} \right) . N \\ \dfrac{dC_c}{dt} = -k_{\max} \cdot C_c \end{cases}$$

N = microbial population (CFU/g)

C_c = physiological state of the cells (-)

➔ Inactivation kinetics during dynamic heating (Bigelow, 1921)

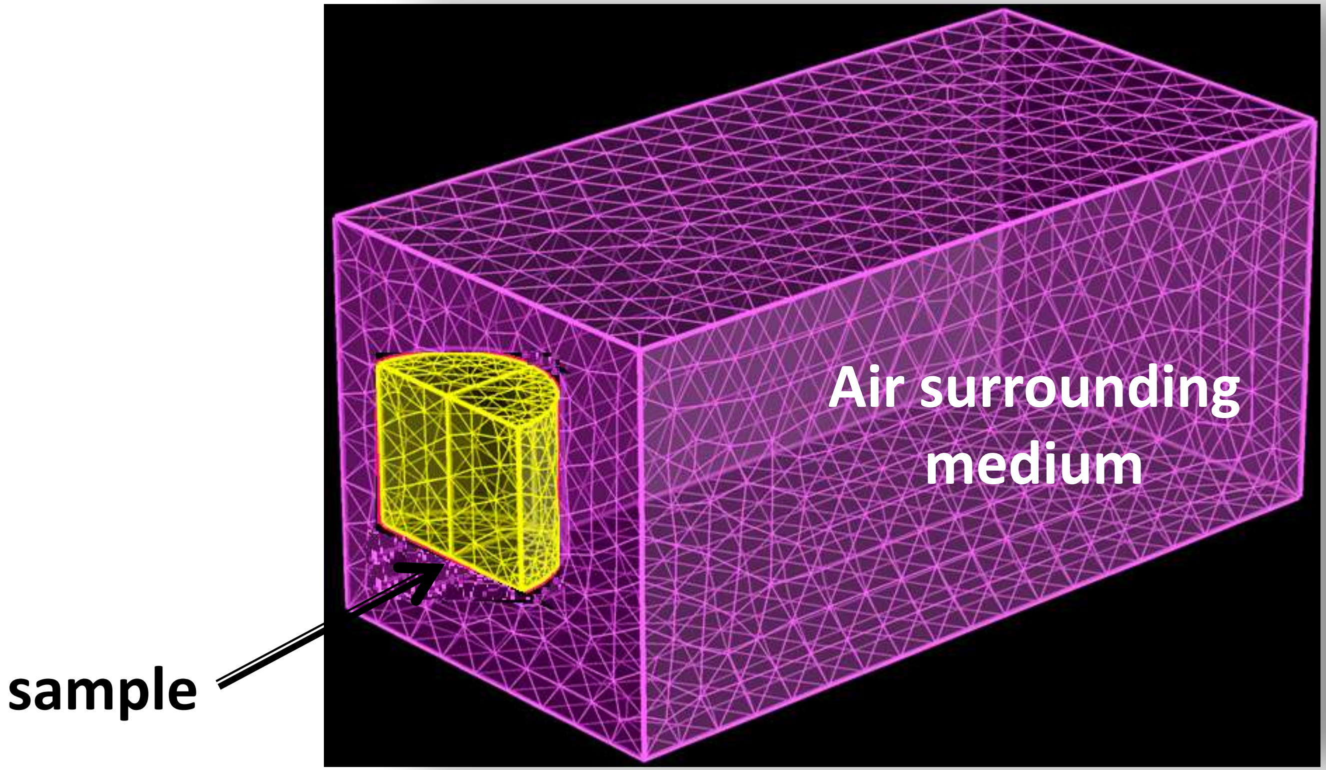
$$k_{\max}(T) = \frac{\ln 10}{D_{ref}} e^{\left(\frac{\ln 10}{z} .(T - T_{ref}) \right)}$$

D_{ref} is estimated at T_{ref} within the lethal temperature range

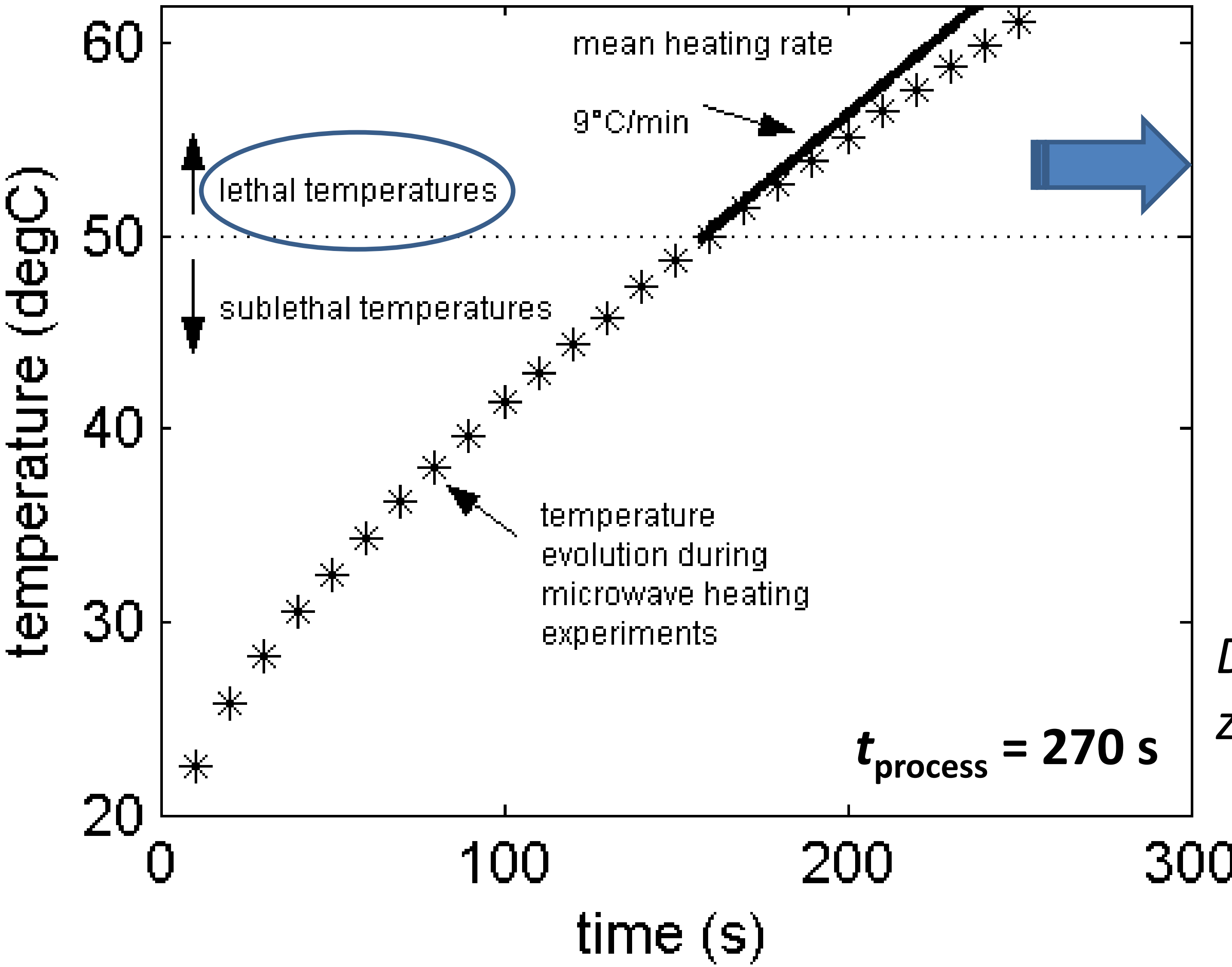
* Geeraerd, A. H., C. H. Herremans, et al. (2000). "Structural model requirements to describe microbial inactivation during a mild heat treatment." International Journal of Food Microbiology 59(3): 185-209.

Mesh generation

- 26750 tetrahedral elements



Dynamic temperature profile

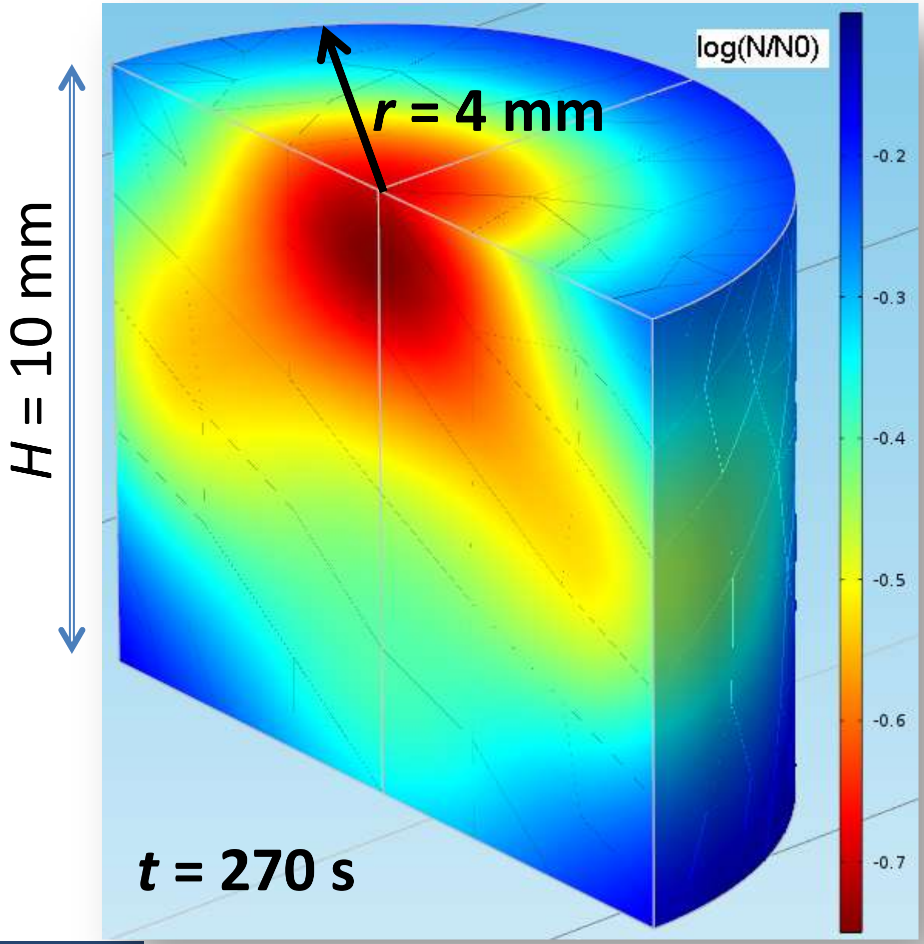


Estimation of *D* and z values from water bath experiments (9°C/min)

D_{ref} = 234 s at **57°C**,
z = 6.28°C

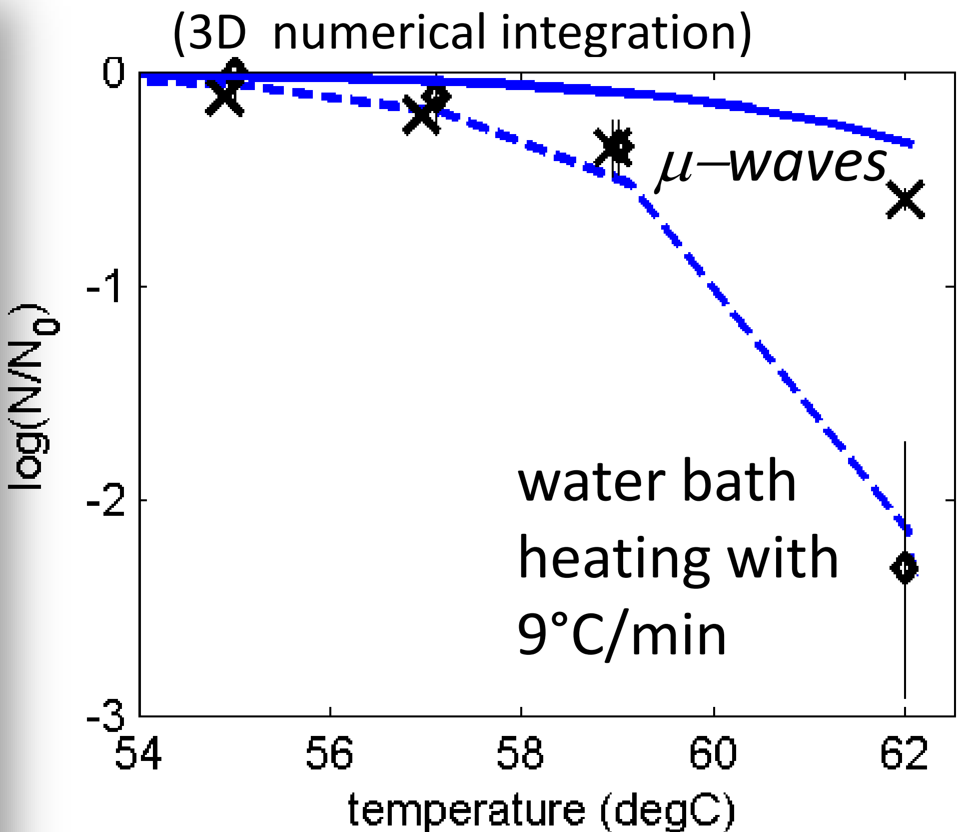
Microbial inactivation during microwave heating

➔ Local inactivation

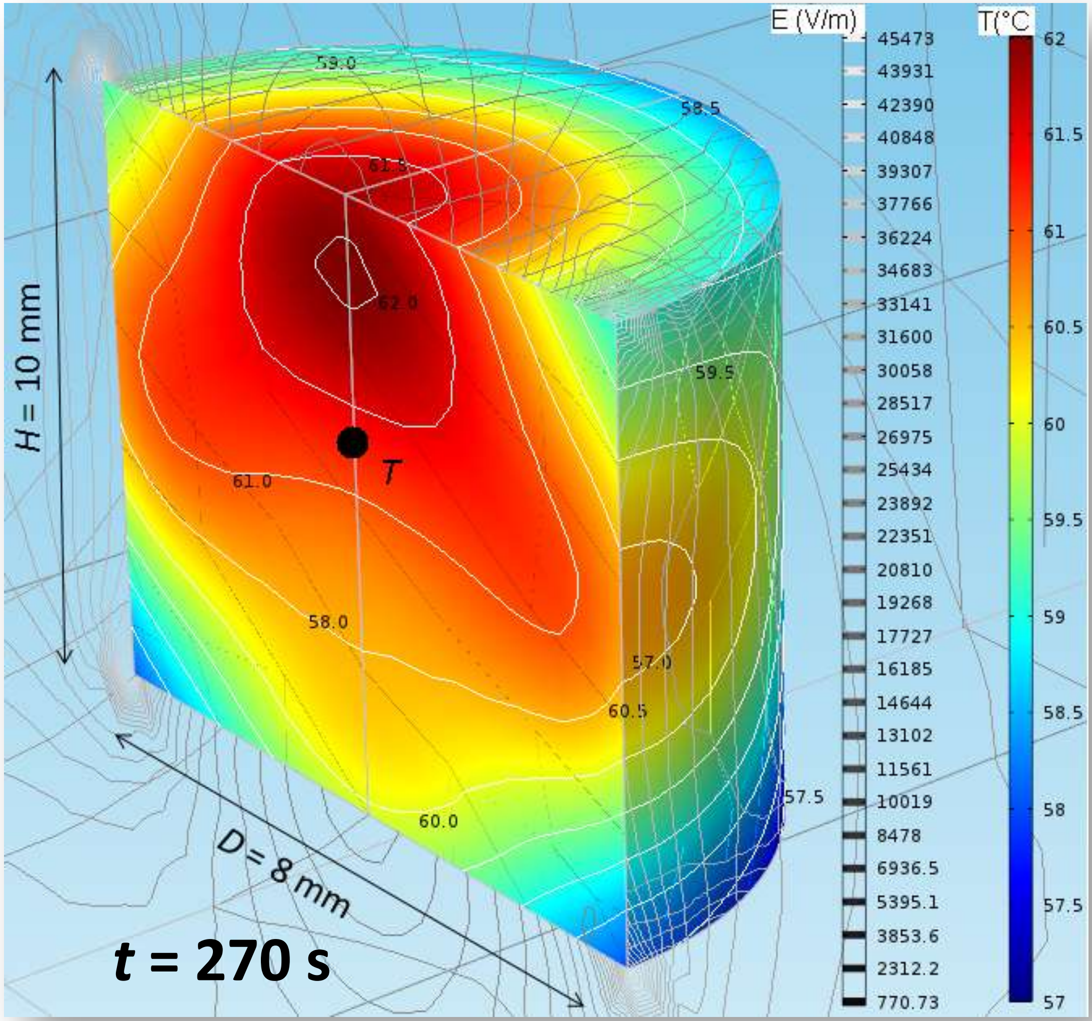


➔ Global inactivation

(3D numerical integration)



Temperature and electric field distribution



➔ thermal heterogeneities at the end of microwave processing (ΔT_{max} = 5°C between the hot and cold spots)

➔ local electric field concentrations around sample edges

Highlights

- Modelling microwave pasteurization process:

➔ Non-uniform temperature distribution into a 0.5 mL cylindrical sample (prediction of the cold point),

➔ Lower bacteria inactivation compared to conventional water bath thermal treatment,

➔ The global inactivation of bacteria under microwaves is successfully predicted from *D* and *z* values obtained from water bath experiments,

➔ Cells death during microwave heating is mainly due to a thermal effect.

Future prospects

- Validation of the numerical model with a time-temperature controlled loop:

  In order to insure better cells inactivation during microwave heating:

➔ Study on the inactivation efficiency by maintaining the temperature within the lethal range (*T* > 55 °C)

Thank you for your attention,

any questions ??

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