Heat and Mass Transfer Modelling during Freezing of Foodstuffs

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Objectives

- To develop a mathematical model dedicated to the determination of freezing rate and weight loss during the freezing of food (*in very cold environment*).

  - 2 freezing conditions studied:
    - Cryogenic device with Nitrogen gas at -80°C
    - Classical process with cold air at -30°C

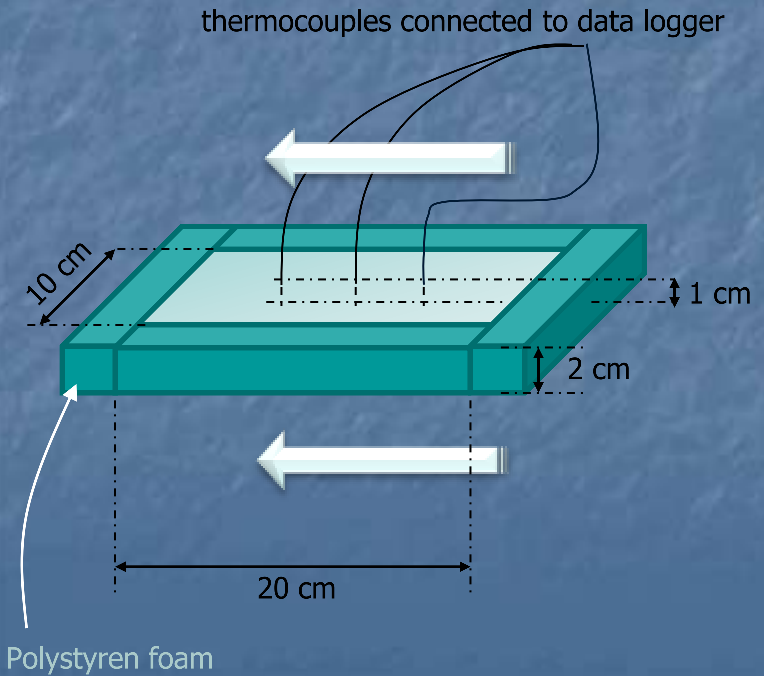
  - Comparisons with experimental data (cryogenic freezing)

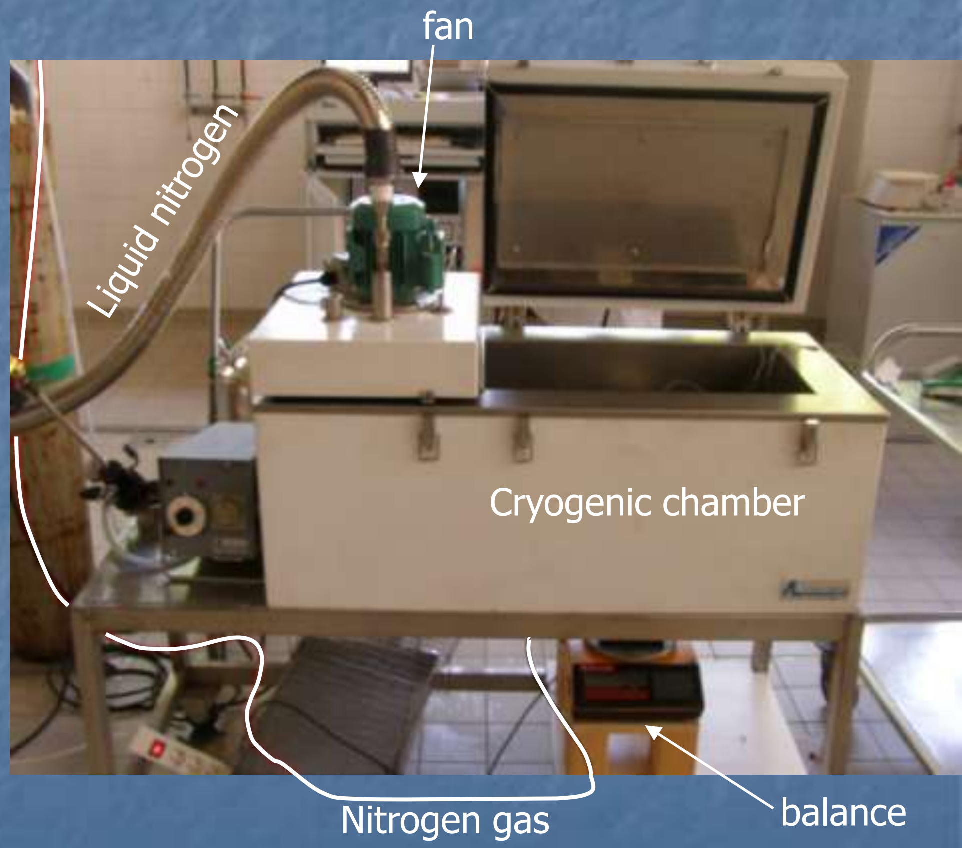
  - Focus on the influences of the external temperature and on the heat transfer coefficient

Material

- Experiments
  - Freezing of flat plate in an air-blast freezer
  - Freezing of plate in a cryogenic chamber (-80°C)

Flat plate of methylcellulose gel
with 3 thermocouples inside:





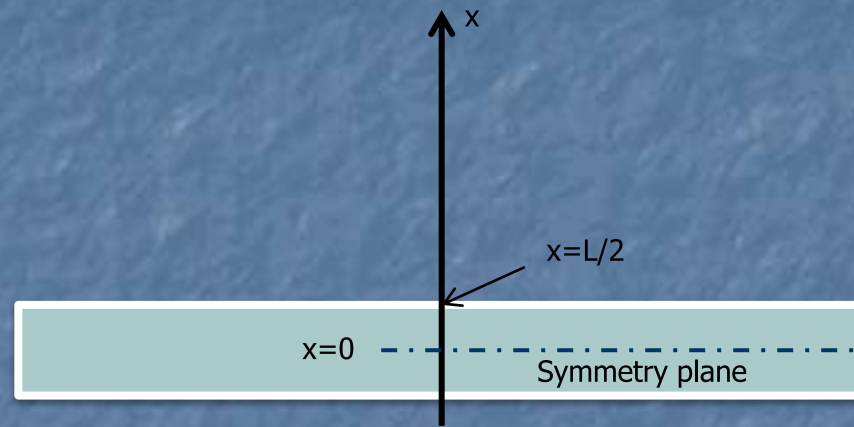
Experimental set-up

Model

- 1D Heat Transfer

1) $$\rho_{s,app} C_{p,app} \frac{\partial T}{\partial t} = \nabla.\left(k_{eff} \nabla T\right)$$

2) $$C_{p,app} = C_s + X_l C_l + X_{ice} C_{ice} - H_{li} \frac{\partial X_{ice}}{\partial T}$$



- 1D Mass Transfer

3) $$\rho_{s,app} \frac{\partial X}{\partial t} = \nabla.\left(\rho_{s,app} D_{eff} \nabla X_l\right)$$ with $X_l = X - X_{ice}$ and $X_{ice} = \left(X - X_b\right).f(T)$

$$\Rightarrow \rho_{s,app} \frac{\partial X}{\partial t} = \nabla.\left(\rho_{s,app} D_{eff} \left[\left(1 - f(T)\right)\nabla X + \left(X_b - X\right)\frac{df}{dT} \nabla T\right]\right)$$

- Function that takes into account the ice formation:

$$f(T) = 1 - \left(\frac{T_f - 273.15}{T - 273.15}\right)\left(\frac{T - T_{ff}}{T_f - T_{ff}}\right)$$ if $T_{ff} \leq T \leq T_f$; 0 if $T>0$; 1 if $T<T_{ff}$

Model

- Boundary conditions:
  - Evaporation (and sublimation) at the surface of food (x=L/2)
  - 1 plane of symmetry (x=0)

$$\left(-k_{eff}\nabla T\right)=0 \qquad \text{at } x=0$$

$$\left(-k_{eff}\nabla T\right)=h\left(T-T_{amb}\right)+F_w\left(H_{vl}+f_{ice}H_{li}\right) \qquad \text{at } x=L/2$$

$$\left(\rho_{s,app}D_{eff}\nabla X\right)=0 \qquad \text{at } x=0$$

$$\left(\rho_{s,app}D_{eff}\nabla X\right)=-h_m\left(P_{sat}a_w-P_{sat\_amb}RH\right) \qquad \text{at } x=L/2$$

- Initial and external conditions:
  - Initial temperature and water content homogeneous inside the food
  - External temperature (T_{amb}) and heat transfer coefficient (h) constant

Model

- Implementation in Comsol 4.2
  - Comsol interface: PDE interface chosen for the mass transfer

$$X \equiv u$$

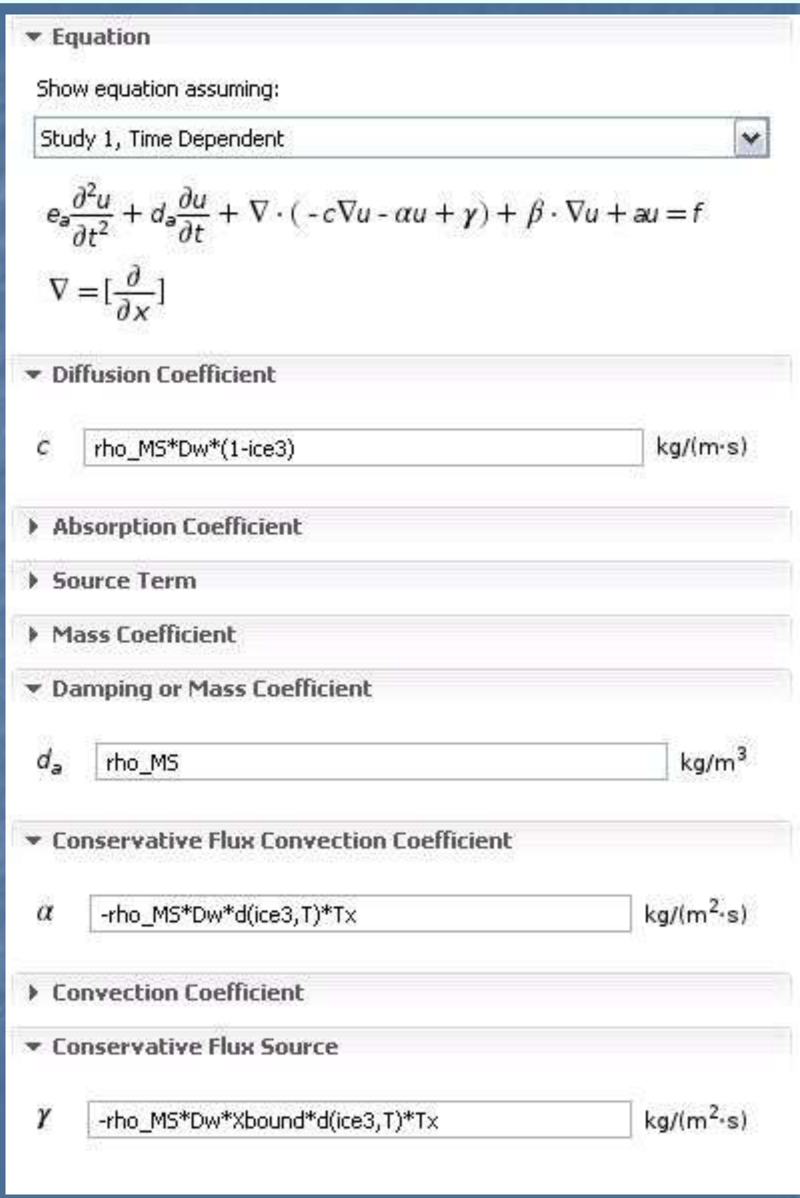
$$f(T) \equiv ice3 \equiv ice(T)$$

$$D_{eff} \equiv Dw$$

$$\rho_{s,app} \equiv rho\_MS$$

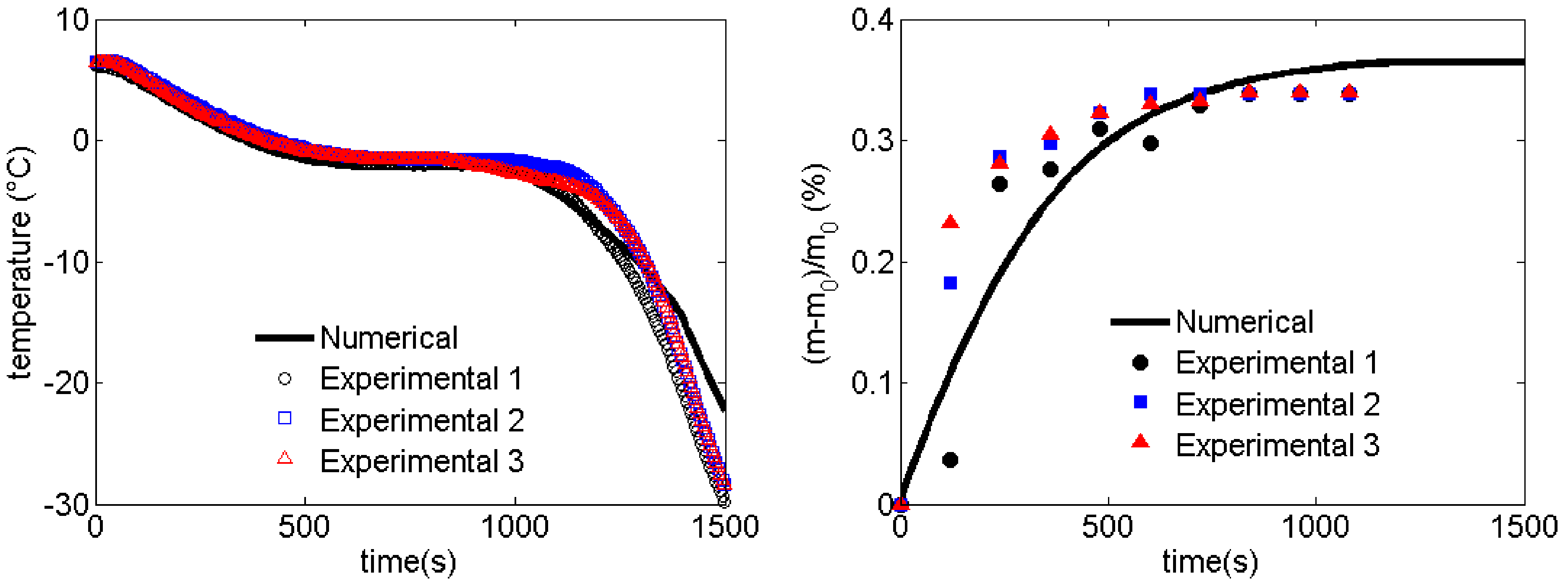
- ice(T) defined as analytic function in Model/Definitions
- Derivative of f(T) computed by Comsol:

$$\frac{df}{dT} \equiv d(ice3, T)$$



Results

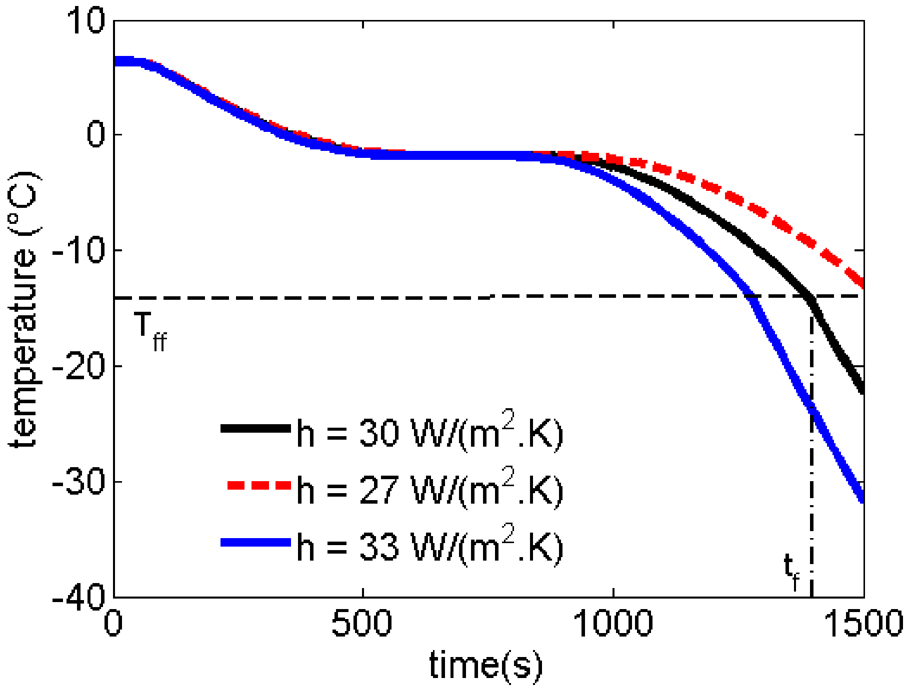
- Comparison between numerical and experimental results in the cryogenic system (T_{amb} = -80°C, h = 30 $W.m^{-2}.K^{-1}$)

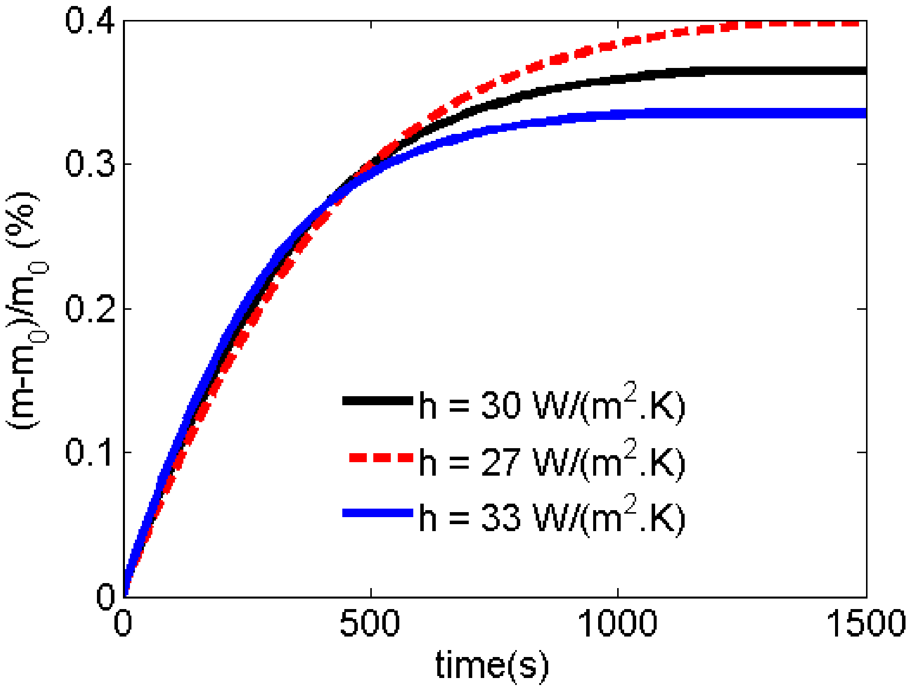


- Temperature well predicted despite freezing time slightly underestimated
- Good agreement between simulated and experimental weight loss

Results

- Influence of the heat transfer coefficient

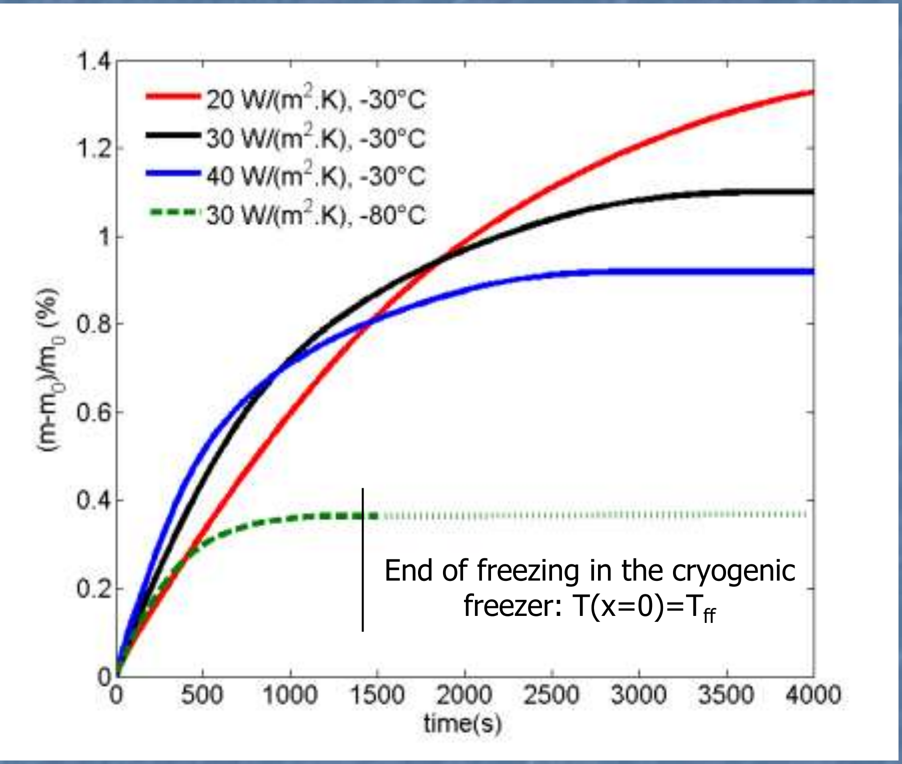




- Increasing h by 10% decreases the effective freezing time t_f by 9% (t_f: from T_i to T_{ff})
- Increasing h by 10% decreases the mass loss by 8%.

Results

- Cryogenic freezing vs air-blast freezing

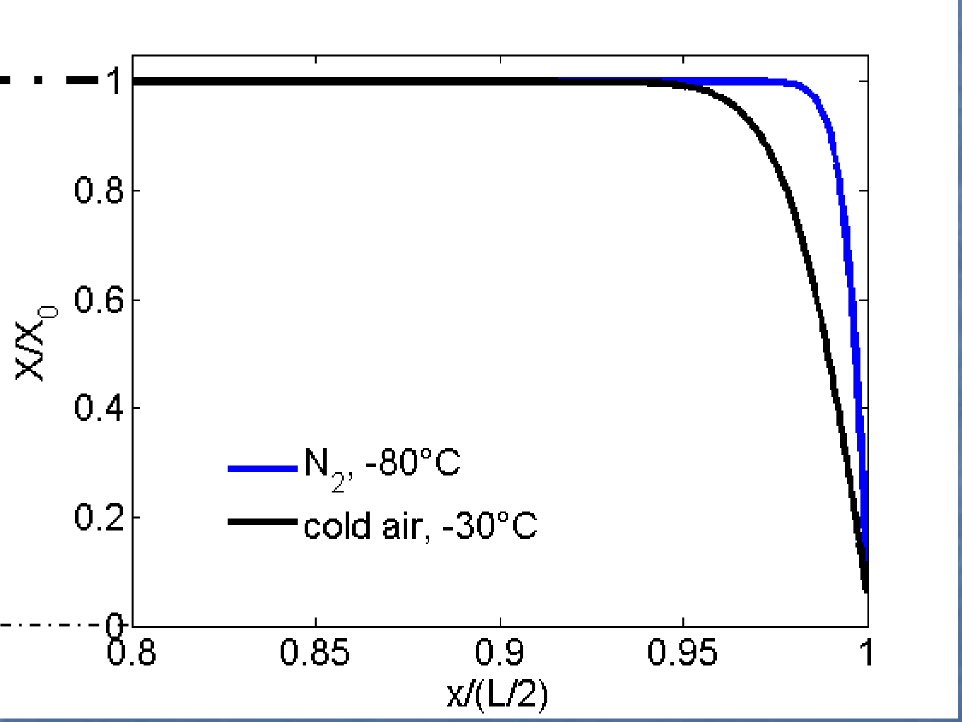


- Effective freezing time in cold air is 3 times higher than in the cryogenic freezer for the same h (4000 s vs 1400 s)
- Air-blast freezing: the weight loss is higher at the beginning (chilling) if h is higher
- The total weight loss at the end of freezing is less for high heat transfer coefficient because T_f is reached sooner

- The weight loss is reduced in cryogenic freezer due to the very low temperature (less than 0.4% vs 1.1% for air-blast freezing)

Discussion

- Strong water content gradient at the surface:
  - Finer grid essential close to the surface ($\delta x \approx$ 1.e-5 m)



- Phase change characterized by a sharp peak ($C_{p,app}(T)$):
  - Using the time dependent solver with free time steps limited to 1s to ensure the recognition of the phase change.

- Problems with discontinuities at $T = T_{ff}$ due to the function f(T)

- Experiments: strong influence of experimental conditions (h, central temperature…)

Conclusion

- Development of a mathematical model to predict the freezing time and the weight loss of food during freezing

- Model developed for non-porous food, well suited for freezing in very low ambient temperatures (high heat and mass transfer):
  - Agreement between experimental and numerical results

- Using very cold environment reduces the freezing time and the weight loss

- High degree of dehydration at the beginning (chilling) – sublimation negligible

- Perspectives:
  - Model will be developed for porous food
  - The function f(T) has to be improved

Thank you for your attention