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COMSOL MULTIPHYSICS®

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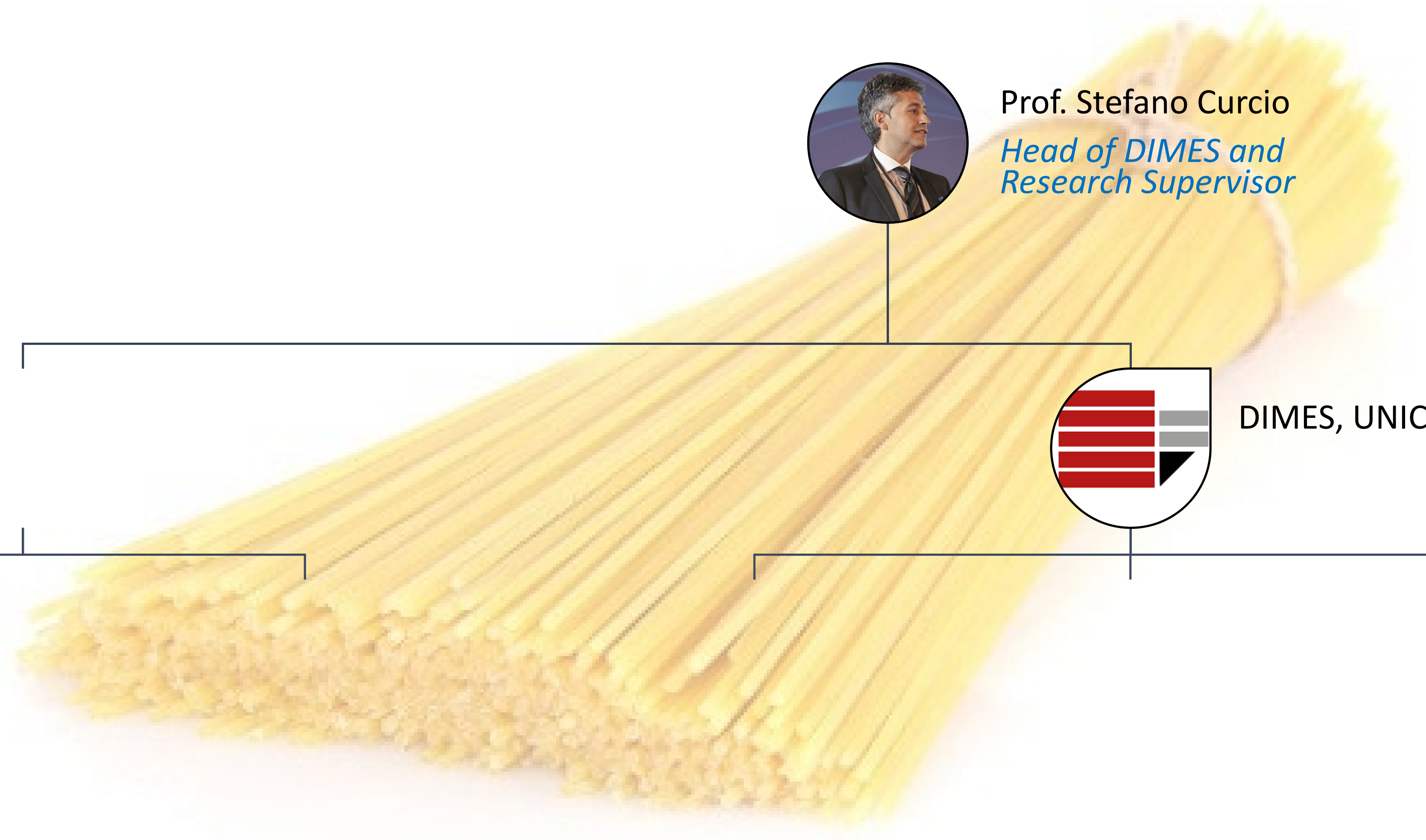
Modeling and Simulation of the Pasta Drying Process via Comsol Multiphysics

Gaetano Adduci



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Outline

1. Engineering Modeling & Simulation
2. Problem Formulation
3. Transport Equations
    - 3.1. Heat / Mass Transfer
    - 3.2. Momentum Transfer
4. Model Structure
5. Implemented Conditions
    - 5.1. Initial Conditions
    - 5.2. Boundary Conditions – Fluid Domain
    - 5.3. Boundary Conditions – Solid Domain / Interface
6. Glass Transition Phenomena
7. Geometry
8. Study and Results
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    - 8.2. Model 2 – X/RH Space Evolution - DIP
    - 8.3. Model 2 - X - Parameterization of $T_{a,in}$ and RH_{in}
    - 8.4. Model 1 – GLT Space Evolution - DIP
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2. Problem Formulation

I. Pre-Drying

$X_{in_I} \rightarrow X_{out_I}$

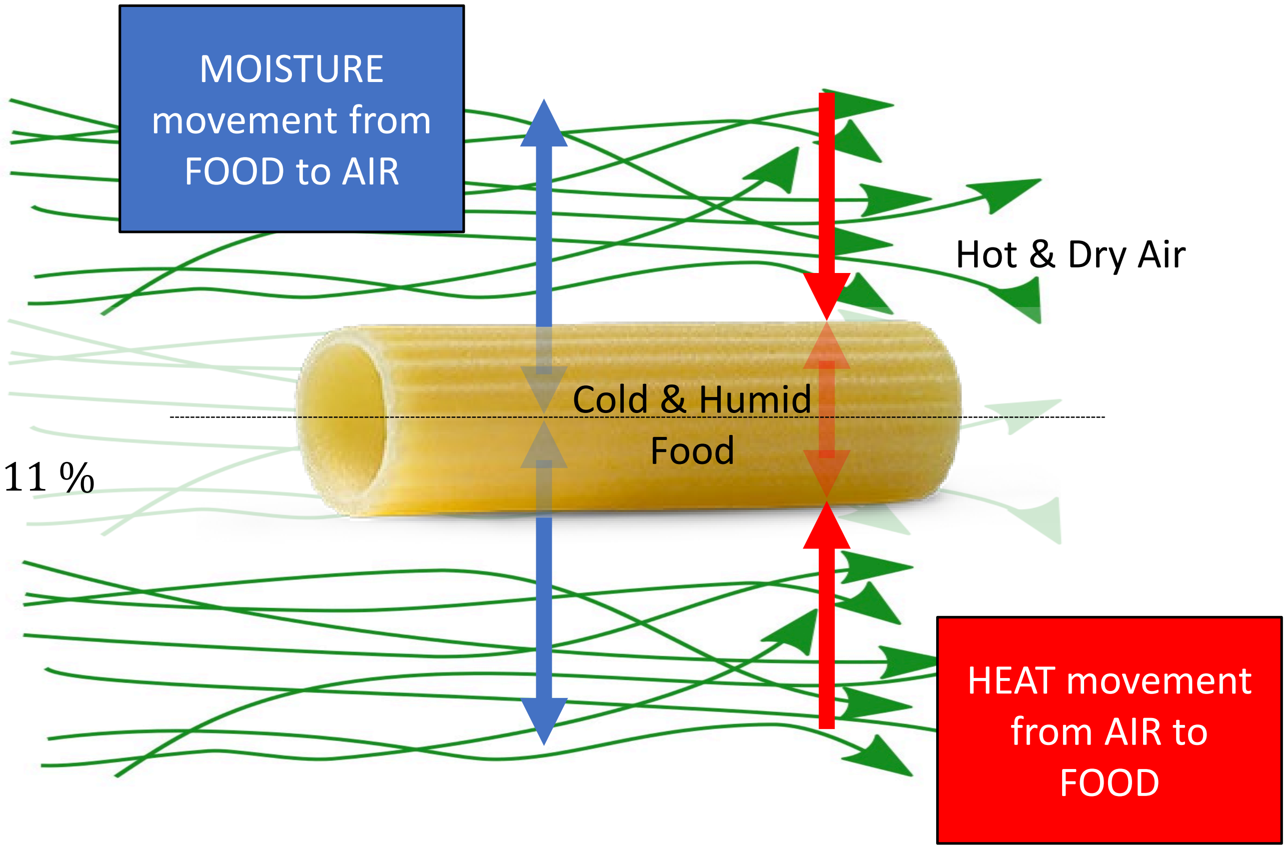
II. Drying

$X_{in_{II}} = X_{out_I} \rightarrow X_{out_{II}}$

III. Stabilization

$X_{in_{III}} = X_{out_{II}} \rightarrow X_{out_{III}} = 11\ \%$

$X_{in_i}\left[\frac{kg_{water}}{kg_{dry}}\right]$	Water content on a dry basis at the beginning of the stage i
$X_{out_i}\left[\frac{kg_{water}}{kg_{dry}}\right]$	Water content on a dry basis at the end of the stage i
$i = I, II, III$	Stage number



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1. Physical-Mathematical model

- **Heat** Transfer Balance

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3.1. Heat / Mass Transfer

	Solid Domain 	Fluid Domain 
Heat	$\rho_d\, C_{pd}\, \partial T_s/\partial t = \boldsymbol{\nabla}\cdot(k_d\, \boldsymbol{\nabla} T_s)$	$\rho_a\, C_{pa}\, \partial T_a/\partial t - \boldsymbol{\nabla}\cdot(k_a\, \boldsymbol{\nabla} T_a) + \rho_a\, C_{pa}\, \boldsymbol{u}\, \boldsymbol{\nabla} T_a = 0$
	• By **conduction** exclusively • **Fourier's Law** • **Evaporation** only occurs at **food surface**	• By both **convection** and **conduction**
Mass	$\partial c_l/\partial t = \boldsymbol{\nabla}\cdot(D_d\, \boldsymbol{\nabla} c_l)$	$\partial c_v/\partial t + \boldsymbol{\nabla}\cdot(-D_a\, \boldsymbol{\nabla} c_v) + \boldsymbol{u}\, \boldsymbol{\nabla} c_v = 0$
	• By **diffusion** exclusively • **Fick's Law** • **Liquid** species only • **Evaporation** only occurs at **food surface**	• By both **convection** and **diffusion** • **Vapour** species only

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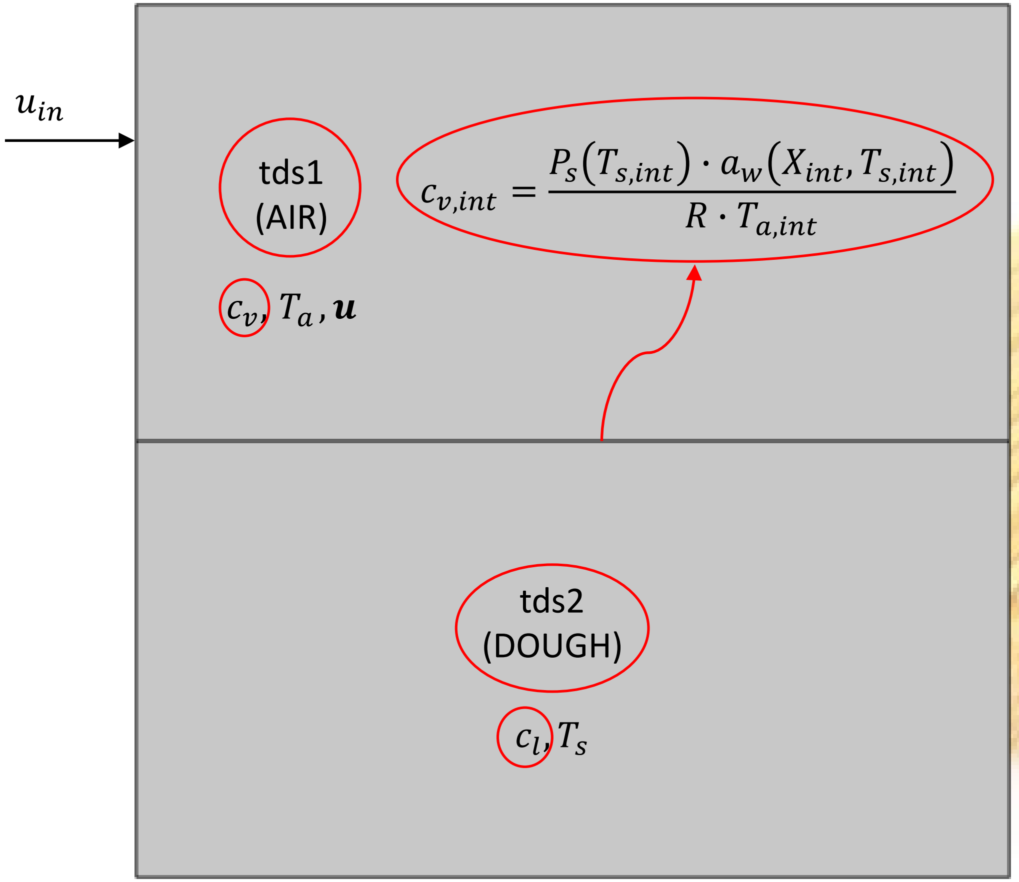
4. Model Structure



- **2 different species**, each for each domain (c_v, c_l)
- **2 "Transport of Diluted Species" modules**, each for each domain (AIR/DOUGH)
- The **vapour concentration** at the interface is derived from the **thermodynamic equilibrium condition**

$$y_v \cdot p = P_s \cdot a_w; \quad c_T \cdot R \cdot T_a = p; \quad \Longrightarrow$$

$$c_v = y_v \cdot c_T = \frac{P_s \cdot a_w}{R \cdot T_a};$$

$a_w\ [-]$	Water activity	$P_s\ [Pa]$	Water saturation pressure
$c_l\ \left[\frac{mol}{m^3}\right]$	Liquid concentration	$R\ \left[\frac{J}{mol \cdot K}\right]$	Gas constant
$c_v\ \left[\frac{mol}{m^3}\right]$	Vapour concentration	$T_a\ [K]$	Air temperature
$c_T\ \left[\frac{mol}{m^3}\right]$	Air-vapour mixture concentration	$T_s\ [K]$	Dough temperature
$p\ [Pa]$	Total pressure of air-vapour mixture	$\boldsymbol{u}\ \left[\frac{m}{s}\right]$	Air velocity vector

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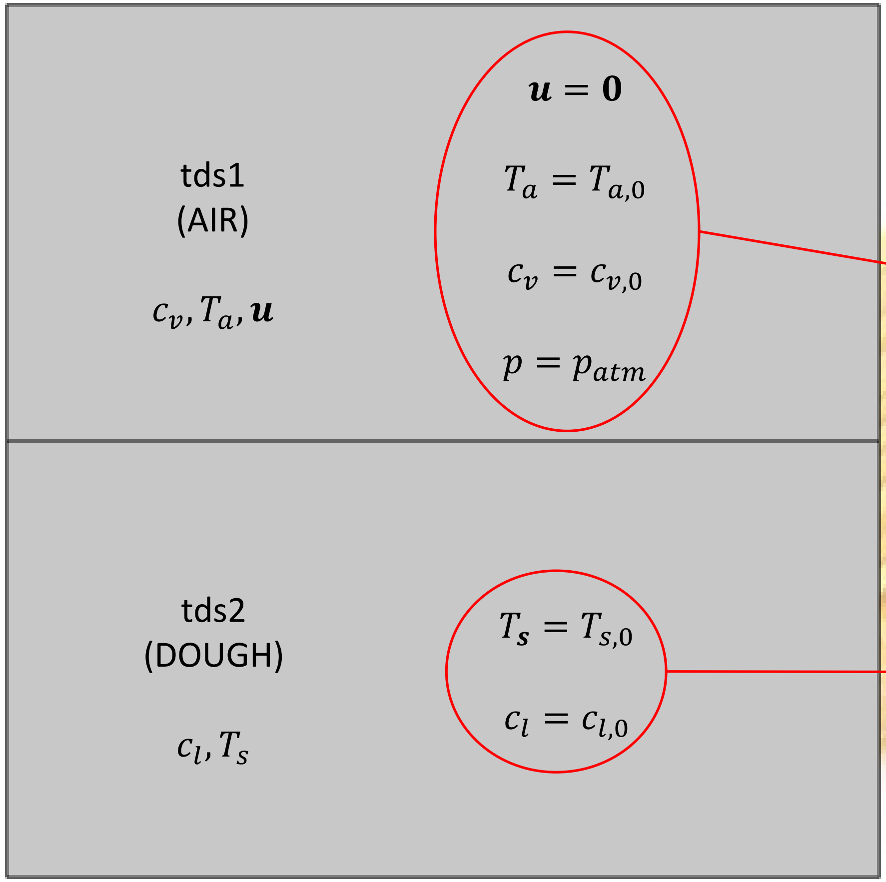
5.1. Initial Conditions



Fluid	$\boldsymbol{u} = \boldsymbol{0}$	Initial air velocity field equal to 0 along both components
	$T_a = T_{a,0}$	Initial air-vapour mixture temperature
	$c_v = c_{v,0}$	Initial concentration of vapour within the fluid
	$p = p_{atm}$	Initial pressure inside the drying chamber
Solid	$T_s = T_{s,0}$	Initial dough temperature
	$c_l = c_{l,0}$	Initial water concentration within the solid matrix

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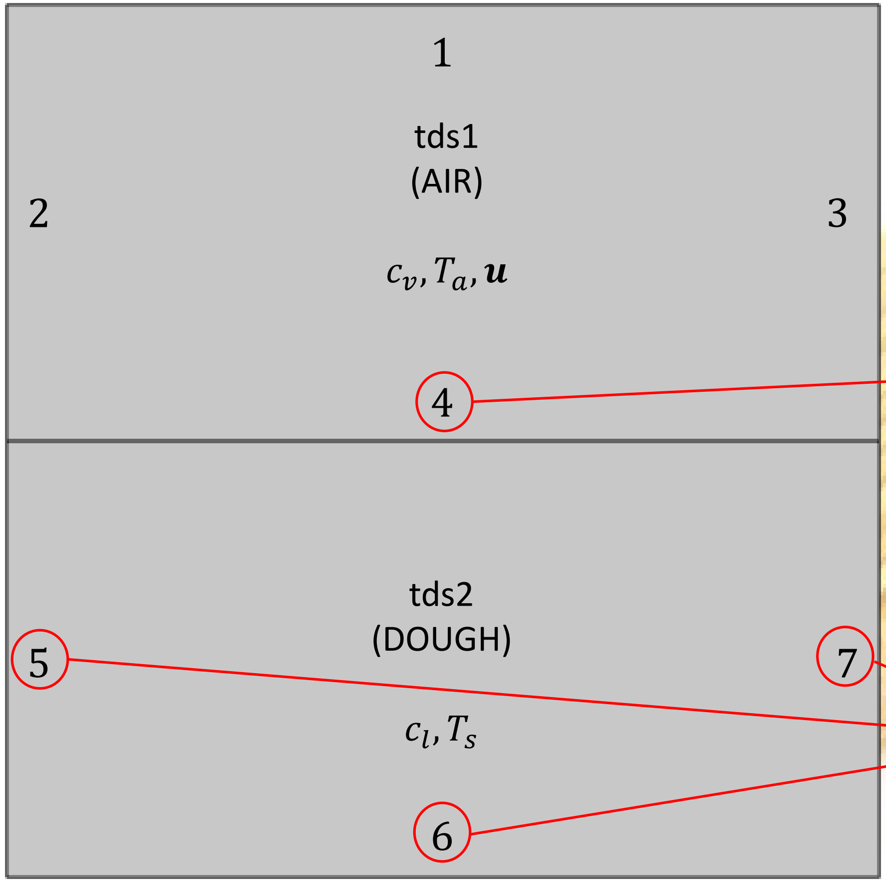
5.3. Boundary Conditions – Solid Domain / Interface



4	$\boldsymbol{u} \cdot \boldsymbol{n} = \boldsymbol{0}$	"No slip" condition
	$T_a = T_s$	Temperature continuity
	$\boldsymbol{n} \cdot (-k_a\, \boldsymbol{\nabla} T_a + \rho_a\, C_{pa}\, \boldsymbol{u}\, T_a) = \boldsymbol{n} \cdot (-k_d\, \boldsymbol{\nabla} T_s) - \lambda_{ev}\, \boldsymbol{n} \cdot (-D_d\, \boldsymbol{\nabla} c_l)$	Heat flux continuity
	$\boldsymbol{n} \cdot (-D_a\, \boldsymbol{\nabla} c_v + c_v\, \boldsymbol{u}) = \boldsymbol{n} \cdot (-D_d\, \boldsymbol{\nabla} c_l)$	Mass flux continuity
	$y_v \cdot p = P_s \cdot a_w$	Thermodynamic equilibrium
5, 6, 7	$\boldsymbol{n} \cdot (-k_d\, \boldsymbol{\nabla} T_s) = 0$	Thermal insulation
	$\boldsymbol{n} \cdot (-D_d\, \boldsymbol{\nabla} c_l) = 0$	No mass flux

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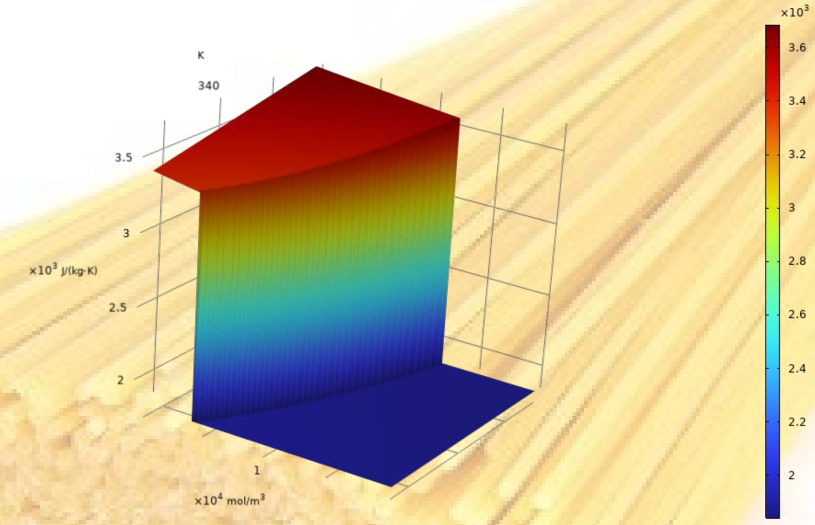
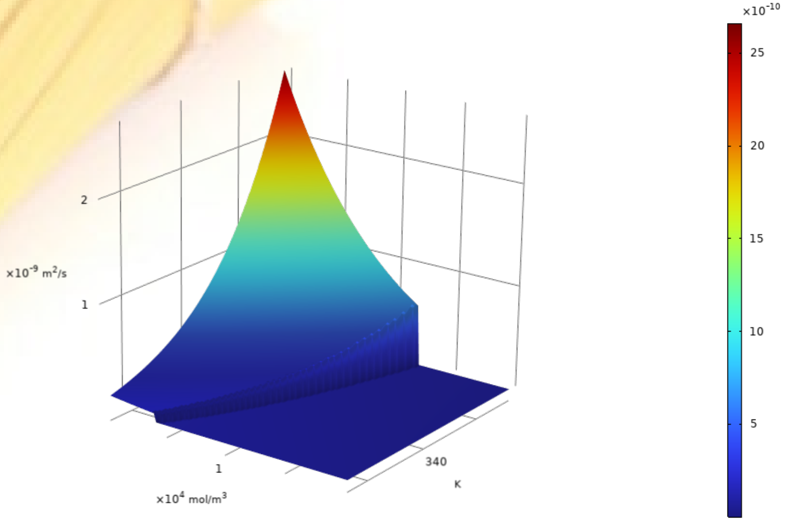
6. Glass Transition Phenomena

Kwei’s Model for deriving Glass Transition Temperature (T_g)

Adjusted pasta Specific Heat
$C_{pd} = f(X,T)$ [=] $[J/(kg \cdot K)]$



Adjusted Water Diffusion Coefficient within pasta
$D_d = f(X,T)$ [=] $[m^2/s]$



- $T_g = f(X)$
- Rubbery State above,
  Glassy State below
- T_g

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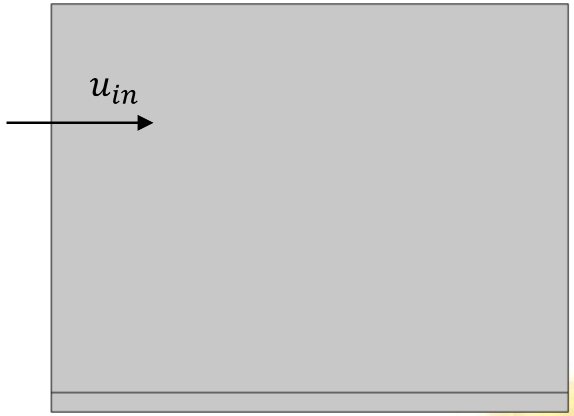
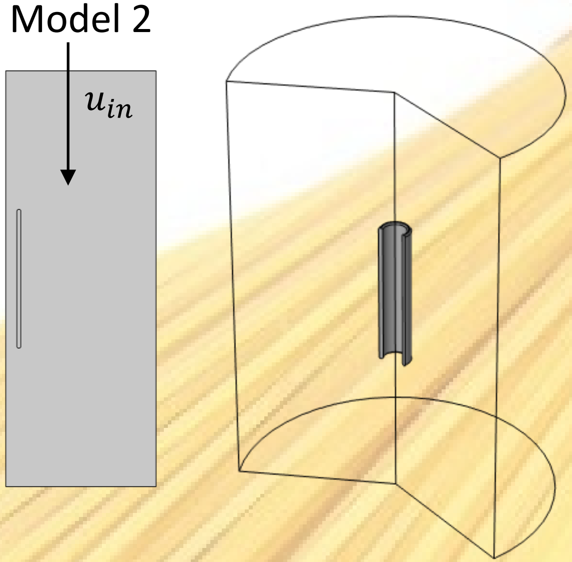
7. Geometry

Model 1



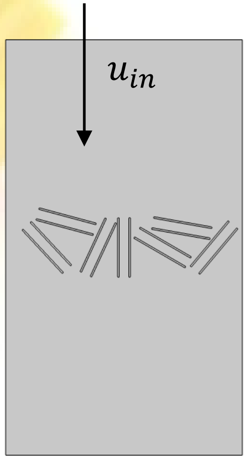
- Basic geometry
- 2 stacked blocks
- 'Tagliatella' pasta (3 mm thick, 80 mm long)
- Mainly used to study effects at the interface

Model 2



- Axisymmetric geometry
- 3 concentric cylinders
- 'Rigatone' pasta (1.3 mm thick, 46 mm long, 5 mm outer radius)
- Dryer duct dimensions fitted to a single piece

Model 3



- More complex geometry
- 7 randomly placed sections placed witihin a block
- 'Rigatone' pasta (1.3 mm thick, 46 mm long, 5 mm outer radius)
- Attempt to approach real system geometry

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8.1. DIP, Output Variables, Study

$u_{in}\left[\frac{m}{s}\right]$	$T_{s,0}\ [°C]$	$T_{a,in}\ [°C]$	$RH_{in}\ [\%]$	$c_{v,in}\left[\frac{mol}{m^3}\right]$	$X_0\left[\frac{kg_w}{kg_{dry}}\right]$	$c_{l,0}\left[\frac{mol}{m^3}\right]$	$t\ [min]$
1	45	90	30	6.96	0.3	17913	60

Default Input Parameters (DIP)

- Applied to both initial and boundary conditions
- Adapted on Barilla ''Pre-Drying'' stage
- $T_{a,in}$ and RH_{in} set $c_{v,in}$ equal to 6.96 mol/m^3
- X_0 sets $c_{l,0}$ equal to 17913 mol/m^3

Variable	$X\left[\frac{kg_w}{kg_{dry}}\right]$	$T_s\ [°C]$	$T_{int}\ [°C]$	$c_{l,int}\left[\frac{mol}{m^3}\right]$
Location	Dough domain		Air-dough interface	
Type of measure	Average			

Output Variables

- Parametric study of a single input while everything else is left at Default Input Parameters

Inlet Air Temperature	$T_{a,in}\ [°C]$	60 70 80 90
Inlet Air Relative Humidity	$RH_{in}\ [\%]$	30 40 50 60
Initial Dough Humidity	$X_0\ [kg_w/kg_{dry}]$	0.2 0.25 0.3 0.35 0.4

Study

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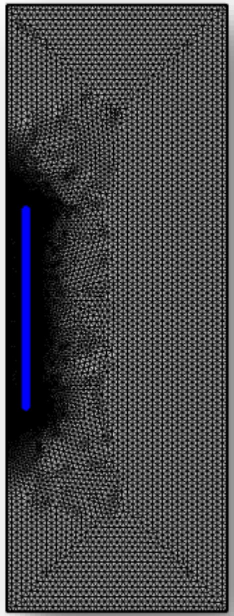
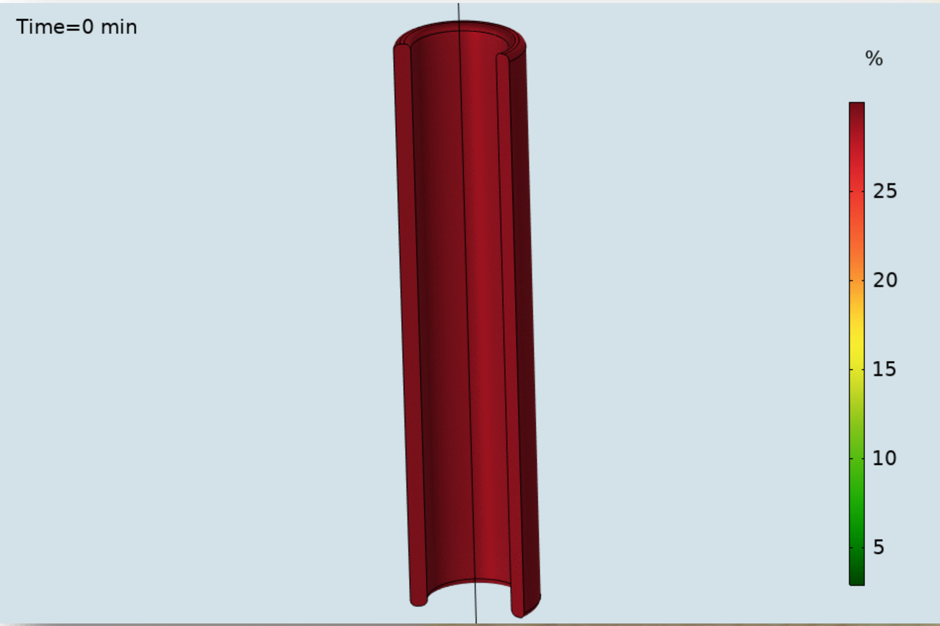
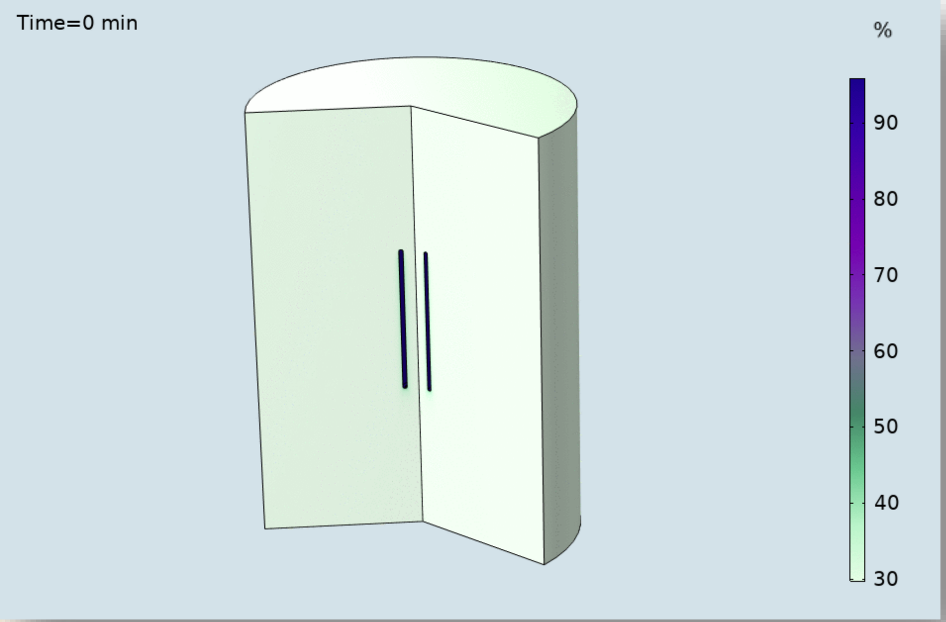
8.2. Model 2 – X/RH Space Evolution - DIP



Pasta X



Air RH



- Mesh Vertices 1181
- Number of Elements 2012
- Average Element Quality 0.8884
- Mesh Area 59.58 mm^2

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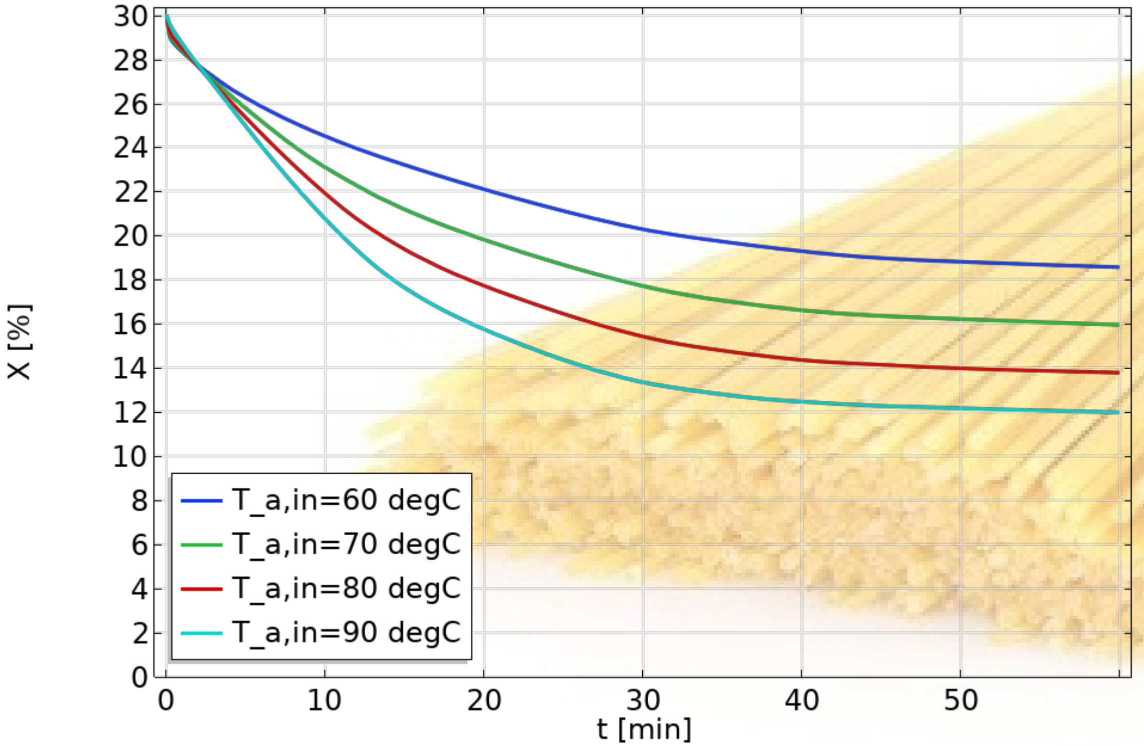
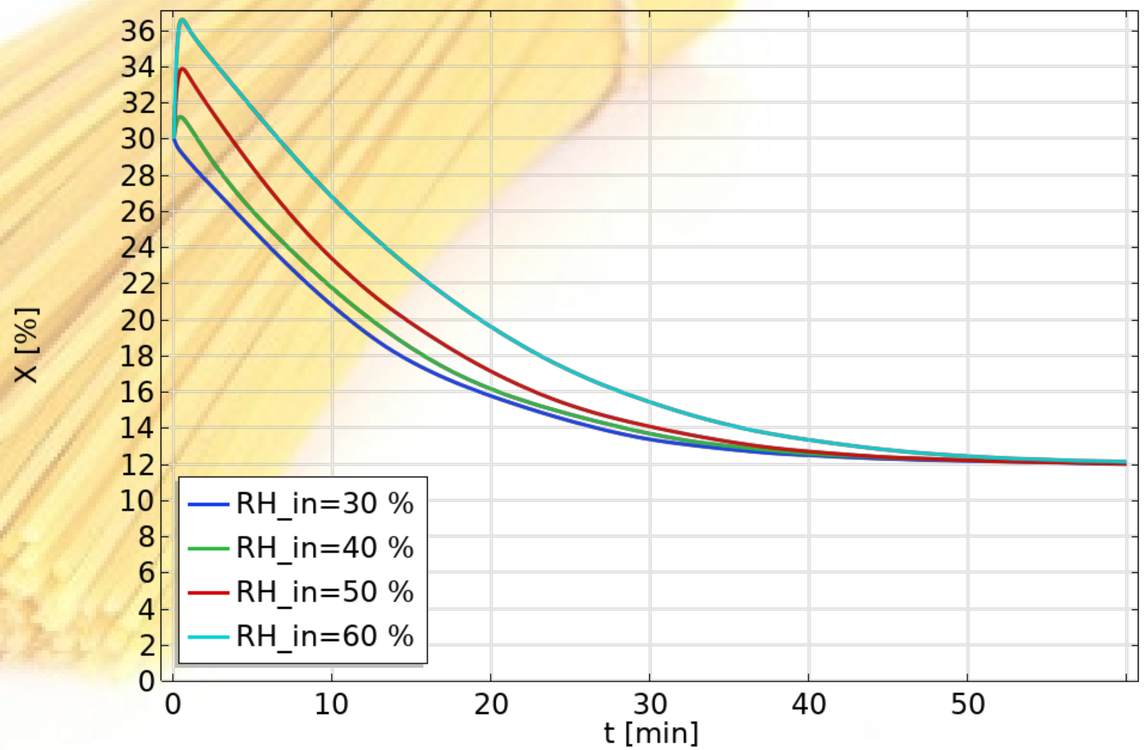
8.3. Model 2 - X - $T_{a,in}$ and RH_{in} Parameterization

$T_{a,in}$ Parameterization



RH_{in} Parameterization



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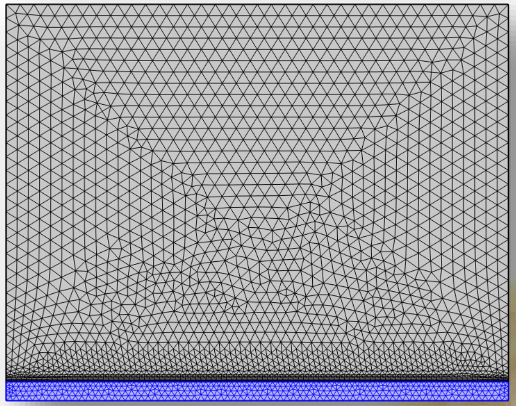
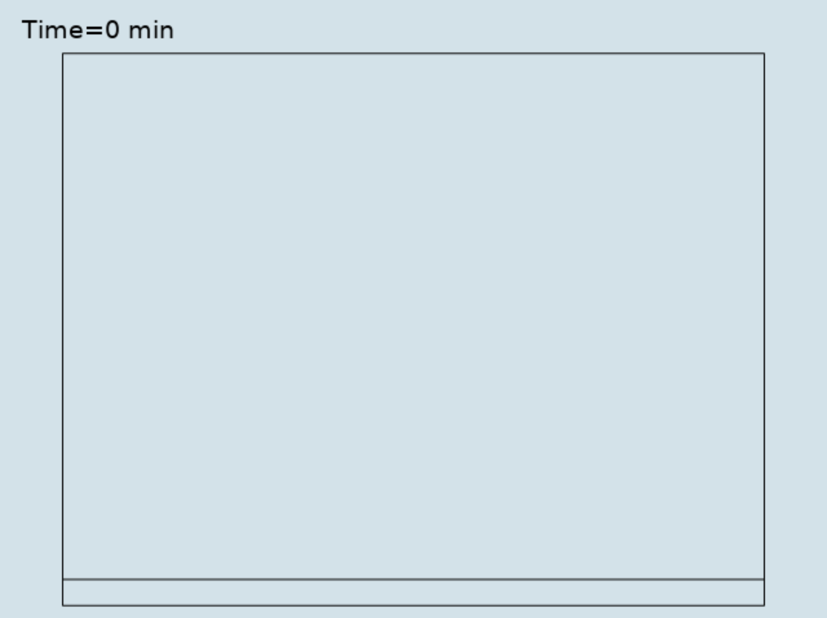
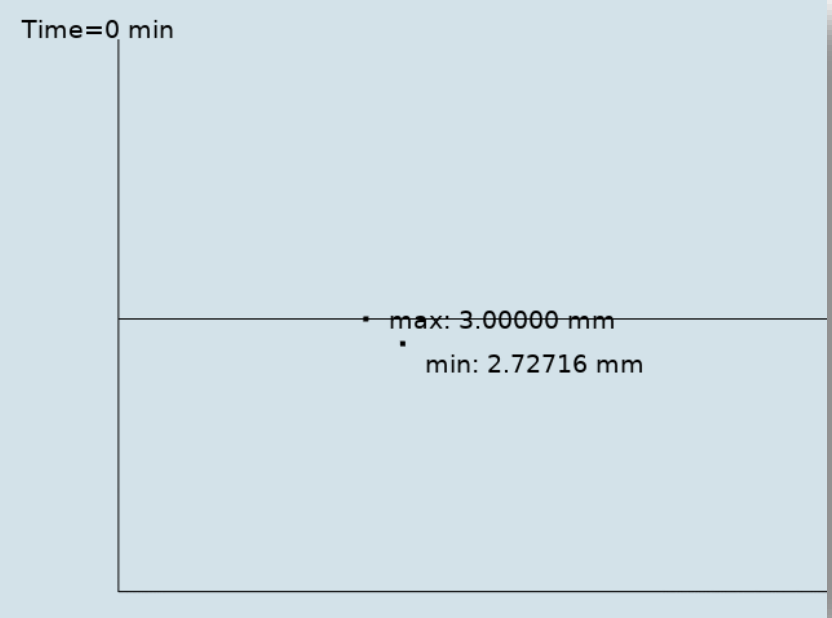
8.4. Model 1 - GLT Space Evolution – DIP







- Mesh Vertices 453
- Number of Elements 722
- Average Element Quality 0.9041
- Mesh Area 240 mm^2

9. Conclusions

- **Transport phenomena** within a drying chamber were first **modelled** and then **simulated** via Comsol Multiphysics.
- **Fourier's** / **Fick's Laws** have been implemented for heat / mass transfer within the solid.
- Comsol implementation of **2 tds** modules, each for each domain.
- The proposed model totally **disregards** the use of the **transport coefficients** of matter and heat at the interface between the samples to be dried and the drying air.
- **Glass transition phenomena** were also taken into account.
- Various **less** or **more complex** geometries.
- Simulations uphold the underlying physics of the process, **matching validation tests** quite well.
- **No shrinkage phenomena** at present stage.

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Thanks for your attention!