Simulating the Coupled Mass and Heat Transport in Package Material during Induction Sealing

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COMSOL Conference - Florence, Italy, 22 October 2024

Tetra Pak®
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Outline

- Introduction
  - Tetra Pak, Tetra Pak® Package Material, Induction Sealing
- Package material model: heat and mass transport
- Induction heating device model
- Results & discussion

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Tetra Pak

A world leading food processing and packaging company

Packaging technology: design and engineering of Filling Machines

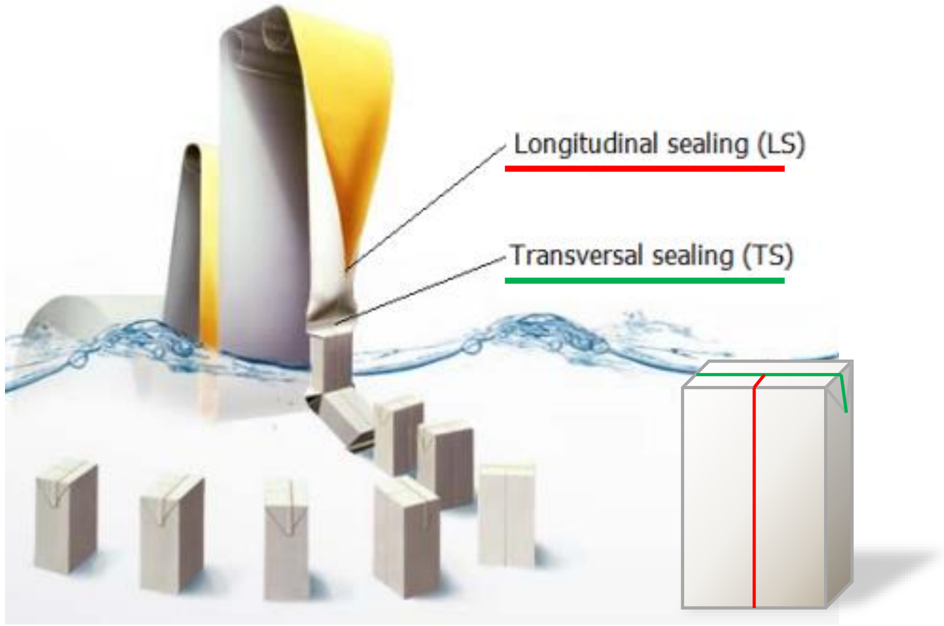
- Automated machines; from package material reels to liquid food containers in the order of *thousands-per-hour*
- Stored food must stay *fresh and safe for consumption for 1 year* without the need for preservatives or refrigeration

> 8k Filling Machines in operation

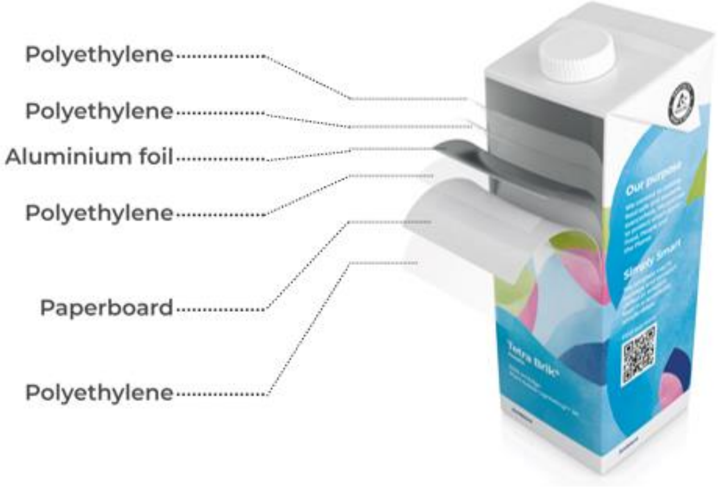
≈ $200 \cdot 10^9$ Tetra Pak® packages produced 2023

Filling machines, package material, induction sealing

Sterilization, Forming, Filling, Sealing, Cutting



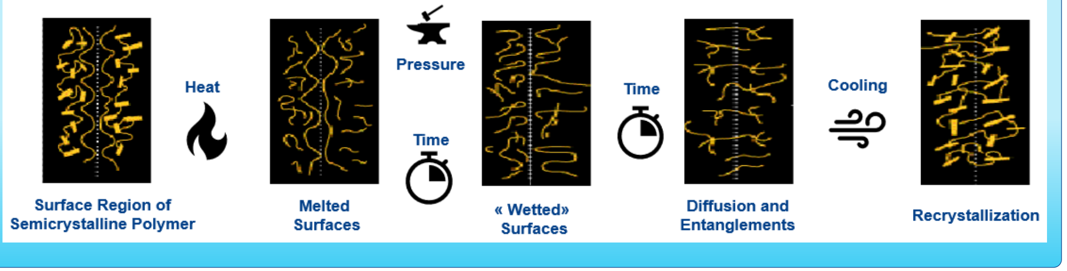
Package Material: multi-layered



Induction sealing process

Exploit high electrical conductivity of Al-foil (eddy current) to heat-up the polyethylene for polymer welding.

Typically: up to 150 ℃ in < 1 s.



Paperboard: Porous, Hygroscopic

Induction sealing is deeply impacted by paperboard physics

- Heating → Drying → Energy
- Heating → Vapour → Pressure

Next

- How is induction heating of package material affected by board properties?

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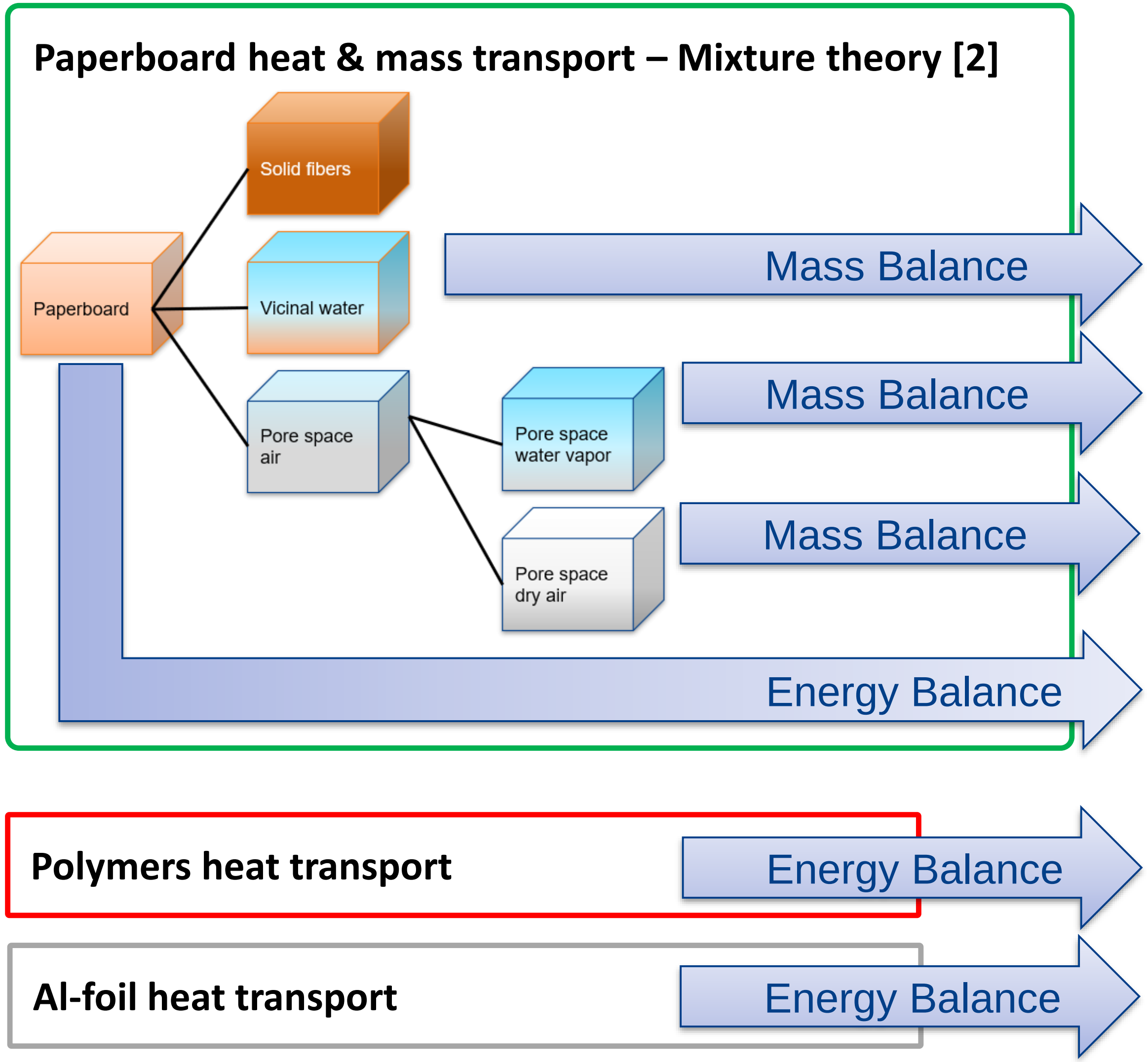
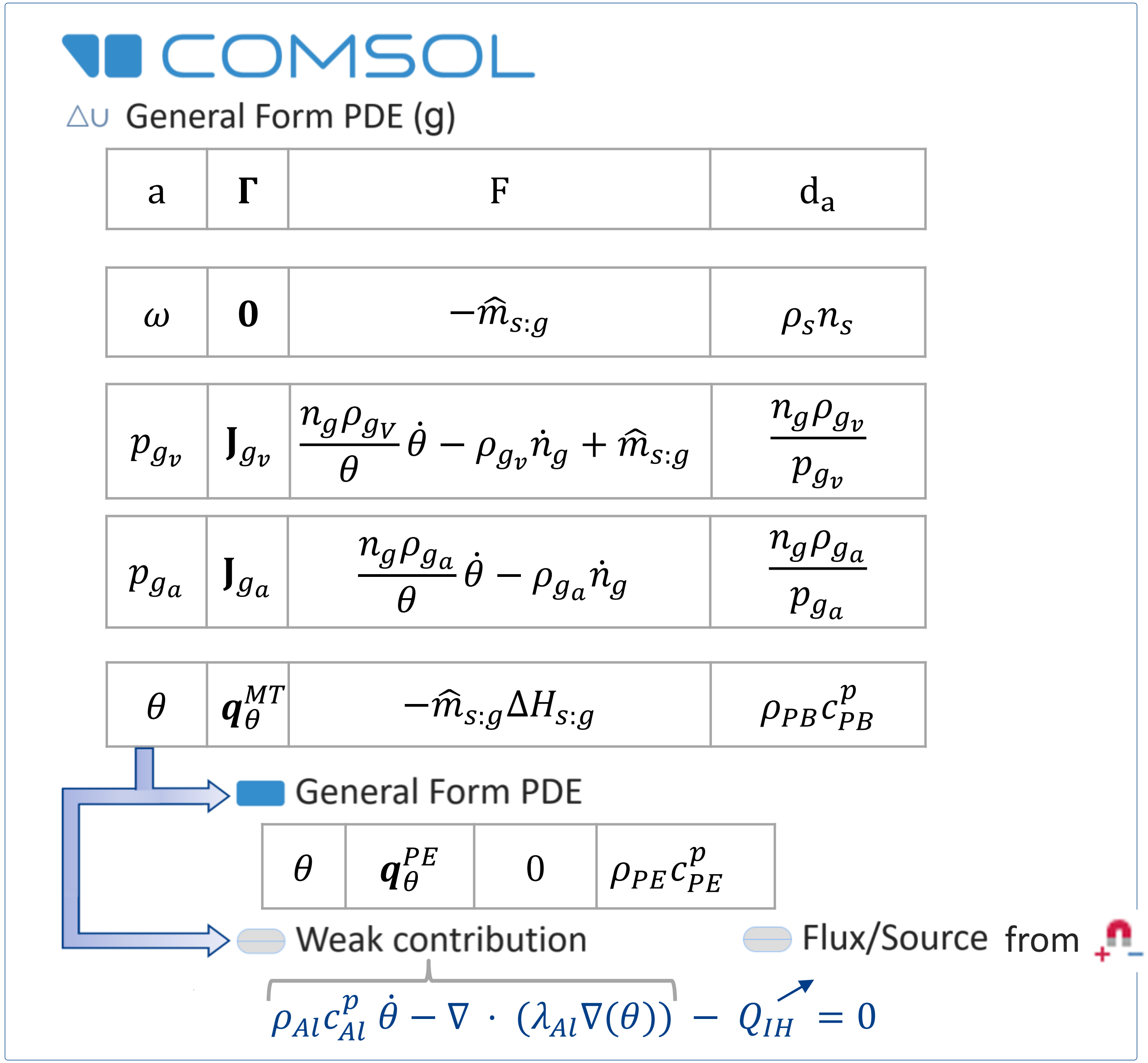
Package material model: heat and mass transport



Paperboard heat & mass transport – Mixture theory [2]

Polymers heat transport

Al-foil heat transport



COMSOL

ΔU General Form PDE (g)

a	Γ	F	da
ω	$\mathbf{0}$	$-\hat{m}_{s:g}$	$\rho_s n_s$
p_{g_v}	$\mathbf{J}_{g_v}$	$\frac{n_g \rho_{g_V}}{\theta}\dot{\theta} - \rho_{g_v}\dot{n}_g + \hat{m}_{s:g}$	$\frac{n_g \rho_{g_v}}{p_{g_v}}$
p_{g_a}	$\mathbf{J}_{g_a}$	$\frac{n_g \rho_{g_a}}{\theta}\dot{\theta} - \rho_{g_a}\dot{n}_g$	$\frac{n_g \rho_{g_a}}{p_{g_a}}$
θ	$\boldsymbol{q}_{\theta}^{MT}$	$-\hat{m}_{s:g}\Delta H_{s:g}$	$\rho_{PB} c_{PB}^{p}$

General Form PDE

θ	$\boldsymbol{q}_{\theta}^{PE}$	0	$\rho_{PE} c_{PE}^{p}$

Weak contribution

Flux/Source from

$$\overbrace{\rho_{Al} c_{Al}^{p}\,\dot{\theta} - \nabla \cdot (\lambda_{Al}\nabla(\theta))} - Q_{IH} = 0$$

[2] H. Askfelt and M. Ristinmaa, "Experimental and numerical analysis of adhesion failure in moist packaging material during excessive heating," International Journal of Heat and Mass Transfer, vol. 108, pp. 2566 - 2580, 2017

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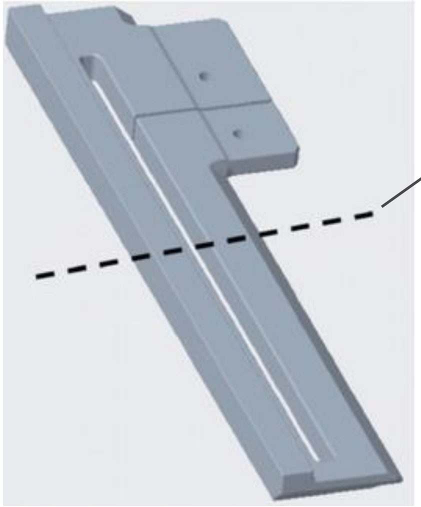
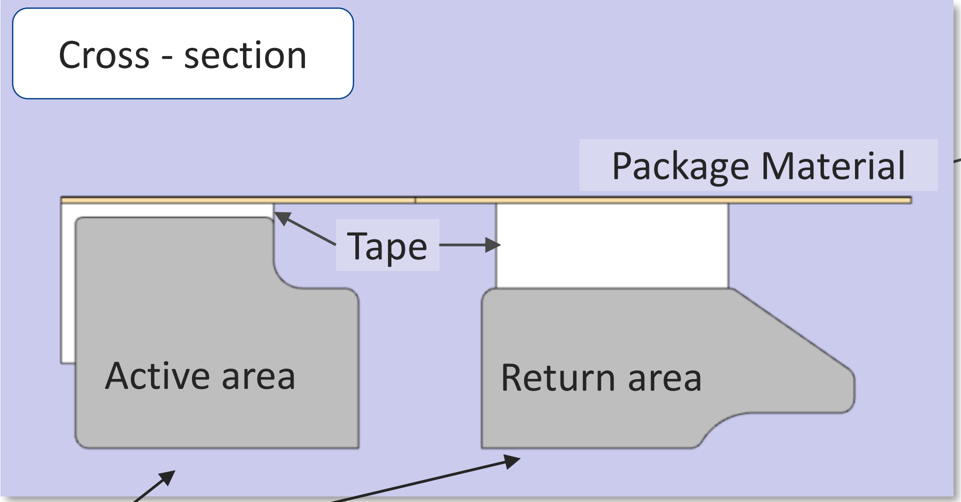
Induction heating device model (2-D)

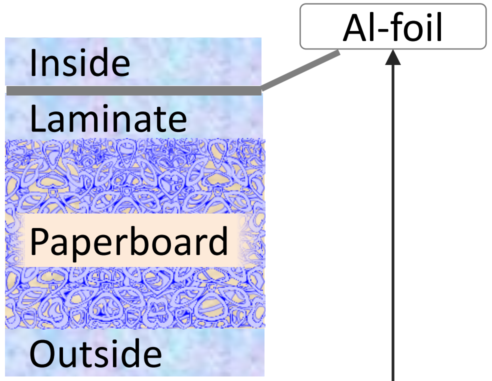
Test setup [1]



aluminum coil
ac current (f ~ 500 kHz)

COMSOL Magnetic Fields (mf)





Single-Conductor Boundary Coil

Coil excitation – Current $I \equiv 0$

Single-Conductor Domain Coil

- Reversed Current Direction

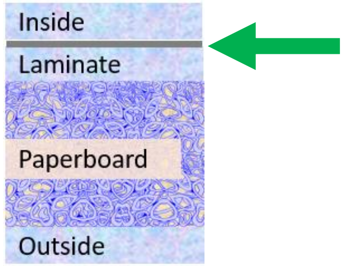
Coil excitation – Current I_{rms}

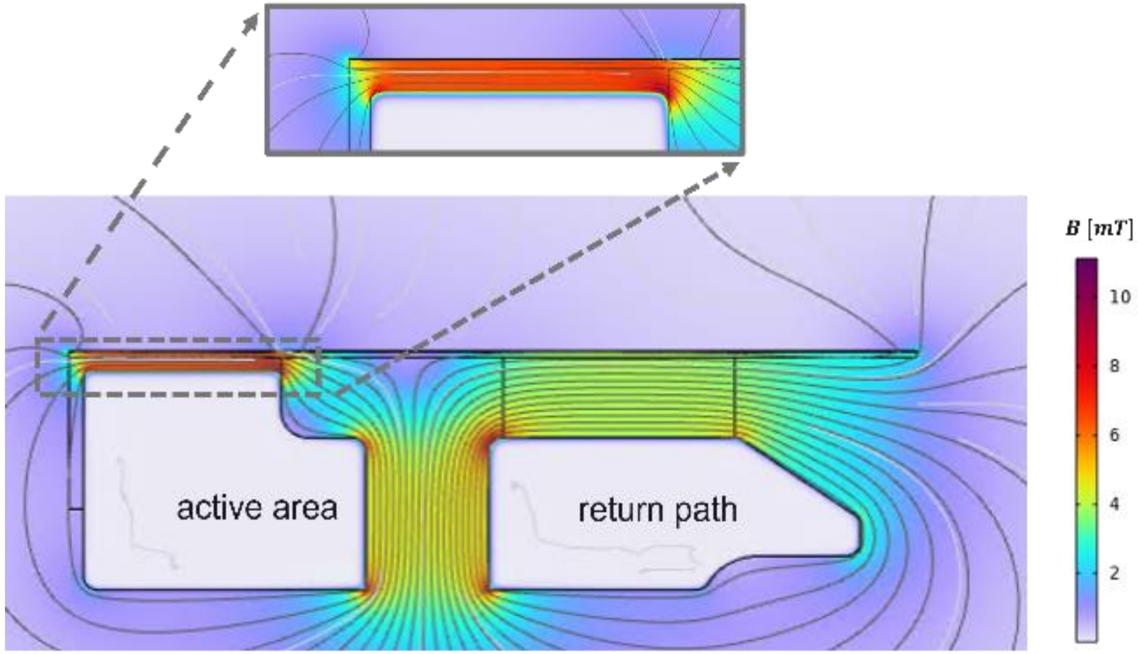
Global Equations

I_{rms} → Total load power fixed

[1] M. Giangolini, G. Betti Beneventi and A. Babini, "Assessment of thermographic tools for the validation of physics-based models of an induction sealing process," International Journal of Applied Electromagnetics and Mechanics, vol. 75, no. 2, pp. 179-191, 2024.

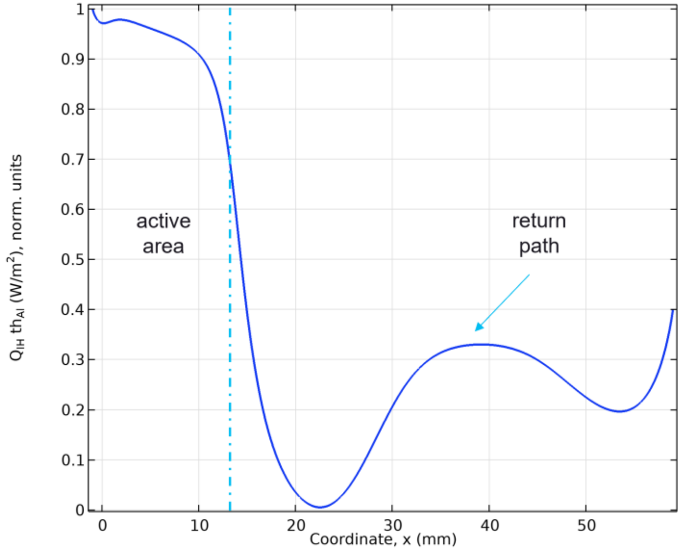
Induction heating device model (2-D)





Colorbar: norm(**B**) [mT]

Contour lines: Az $[\mathrm{Wb} \cdot \mathrm{m}^{-2}]$



Normalized electromagnetic surface loss. density vs. coordinate

Excitation: load power (~650 W) ; 600 ms of on-time (Frequency –Transient)

- Next: sensitivity analysis vs. board initial moisture ratio and density

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Model results

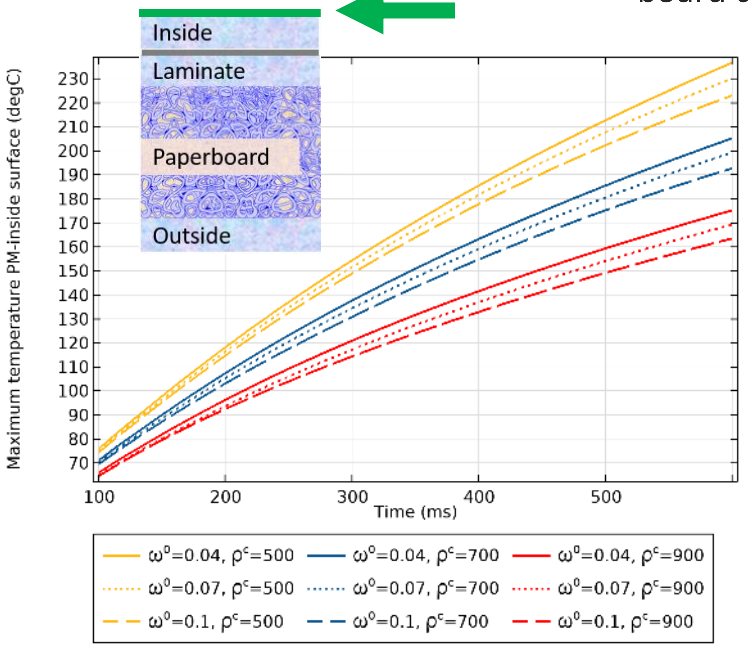
- Sensitivity analysis

Parametric sweep

Parameter	Value list	Unit
ω^0	0.04, 0.07, 0.1	1
ρ^c	500, 700, 900	$\mathrm{kg} \cdot \mathrm{m}^{-3}$

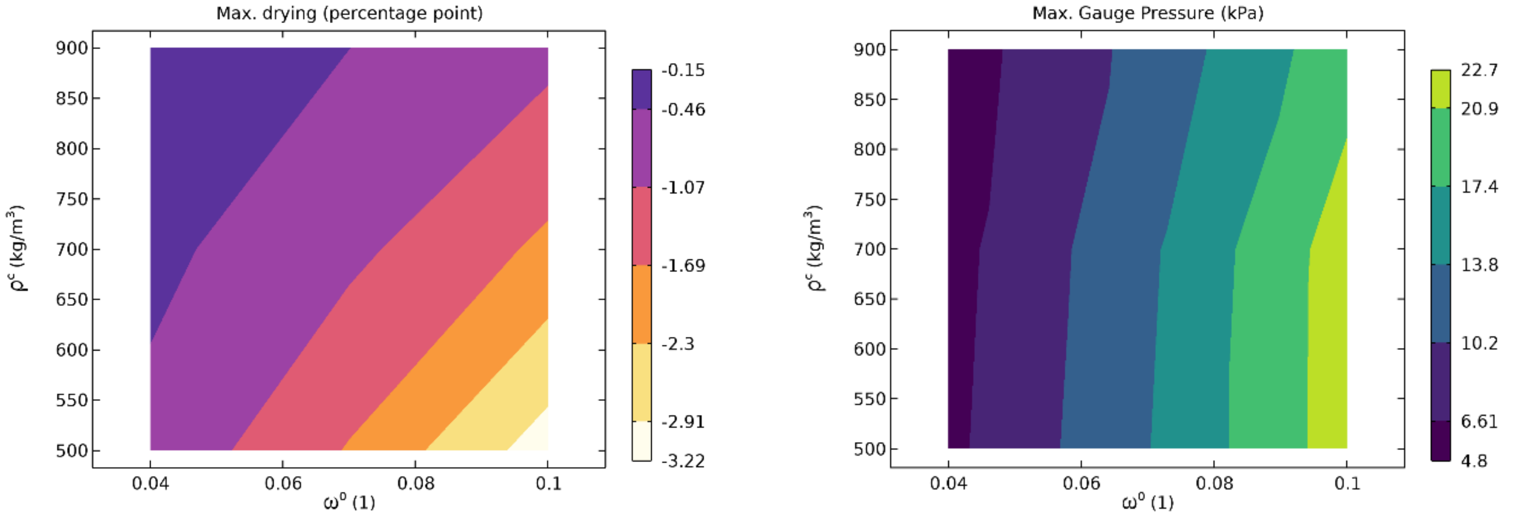
initial moisture ratio

initial board density

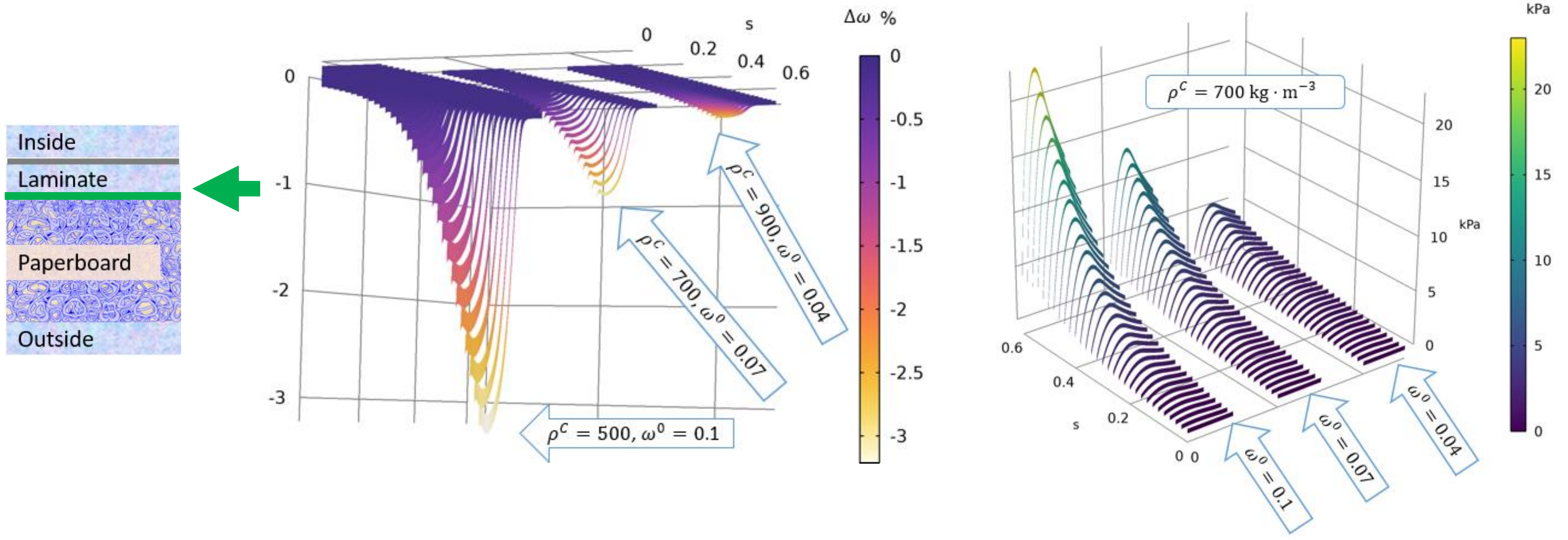


Evolution of the maximum temperature of the package material inside top surface

Maximum of drying and internal pressure over paperboard domain

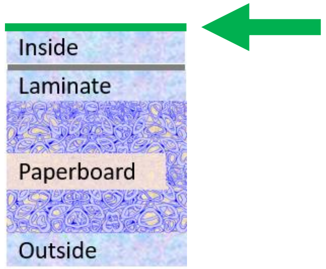


Time-evolution at the board/laminate interface, above the coil active area

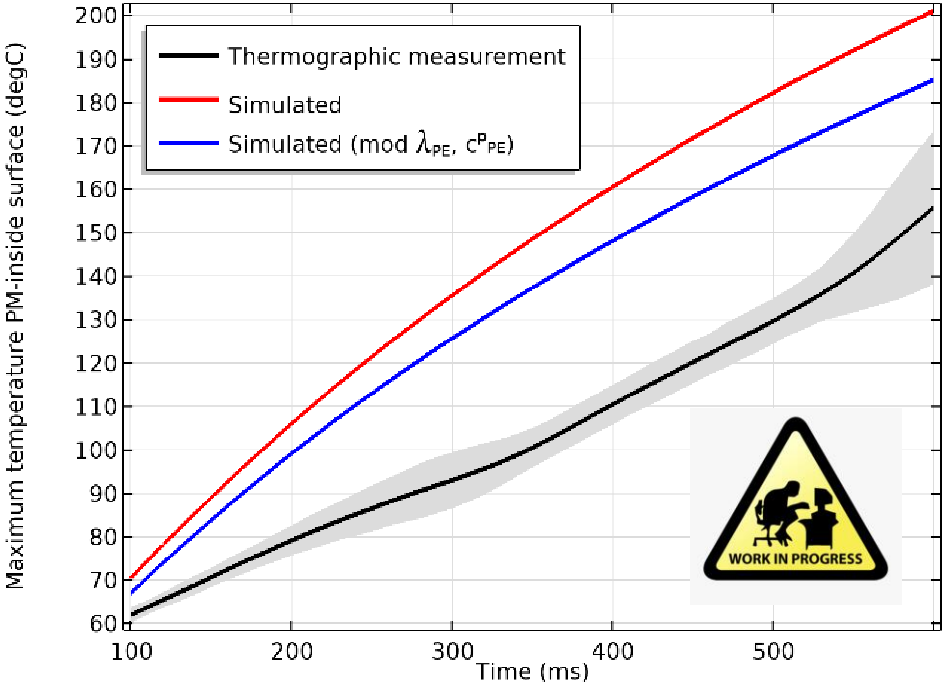


Discussion

- Model vs. experimental data carried out on a given board grade



Max. temperature on inside top surface vs. time



FLIR cooled camera

- Matching between model and data [1] currently is **not** satisfactory
- Prediction improved with temperature-dependent heat transport parameters of PE
- The model can be used in its present state for **relative comparisons** and to study **interplay of physical parameters**

- COMSOL Multiphysics® as **enabling technology** to allow the collaboration of modeling engineers having different expertise (e.g., paperboard physics / electromagnetic modeling)

[1] M. Giangolini, G. Betti Beneventi and A. Babini, "Assessment of thermographic tools for the validation of physics-based models of an induction sealing process," International Journal of Applied Electromagnetics and Mechanics, vol. 75, no. 2, pp. 179-191, 2024.

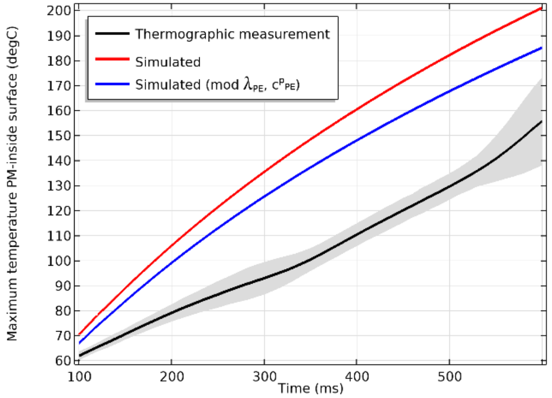
Recap

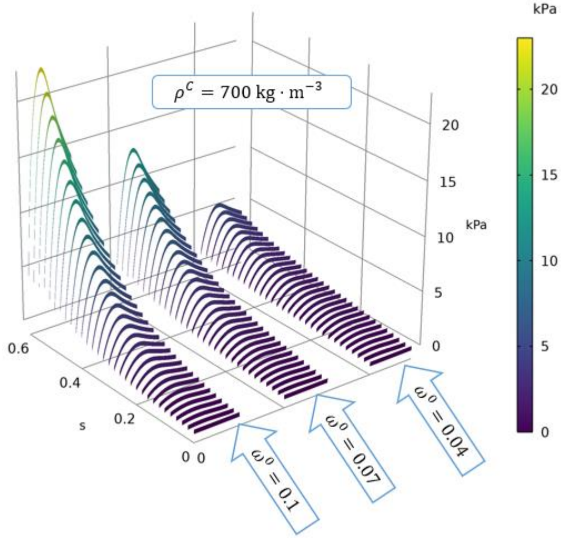
Key takeaways

With COMSOL we are able to simulate the package material response during induction heating.

The model is able to capture complex multiphysical couplings such as gauge pressure build up and drying

The model may be used to understand how different attributes of the board will affect the package material behavior





Next step

Improve polymer model
- Heat transport & phase transformation

Backup Slides

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Model Results

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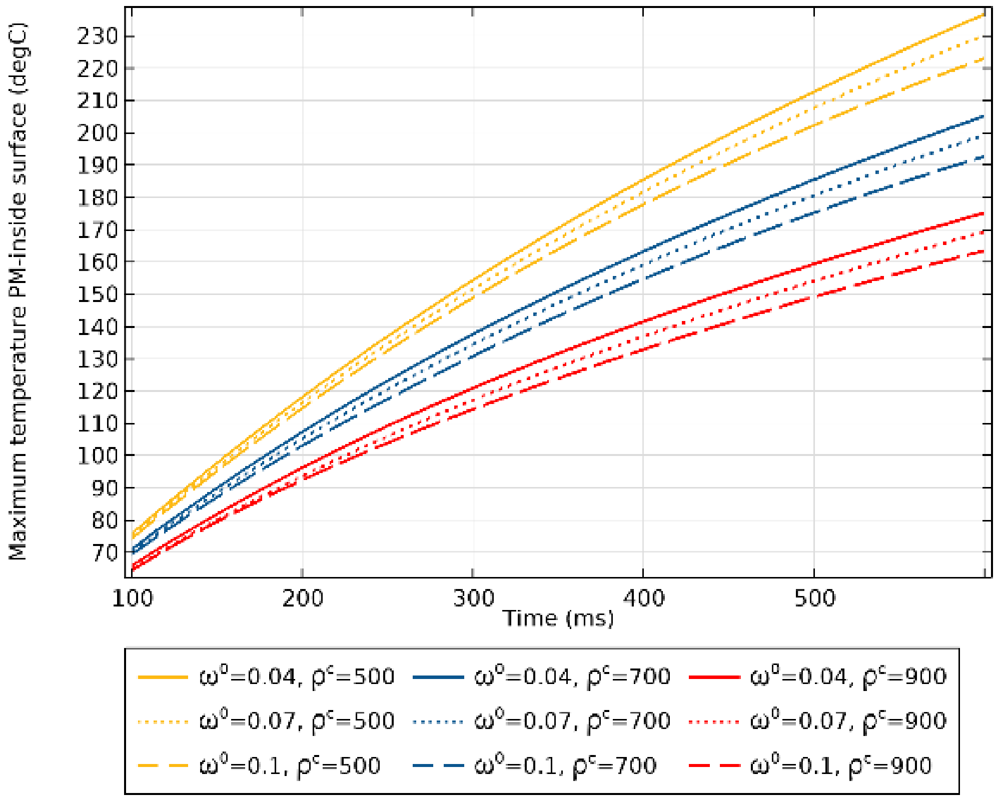
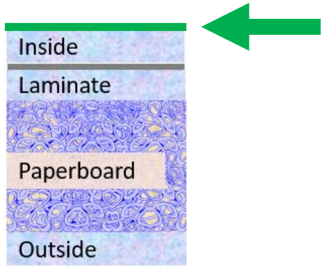
Parametric sweep

Parameter	Value list	Unit
ω^0	0.04, 0.07, 0.1	1
ρ^c	500, 700, 900	$\mathrm{kg} \cdot \mathrm{m}^{-3}$

← initial moisture ratio

← initial density





Max. temperature on inside top surface vs. time

- Lower PE temperature for higher density board
  - higher specific heat
  - higher thermal conductivity
- Lower PE temperature the higher the moisture content
  - higher specific heat
  - higher thermal conductivity
  - more energy required to dry

PE = polyethylene

Model Results

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Parametric sweep

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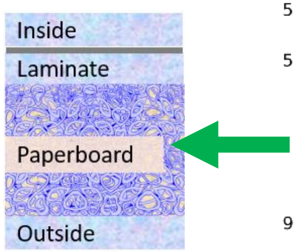
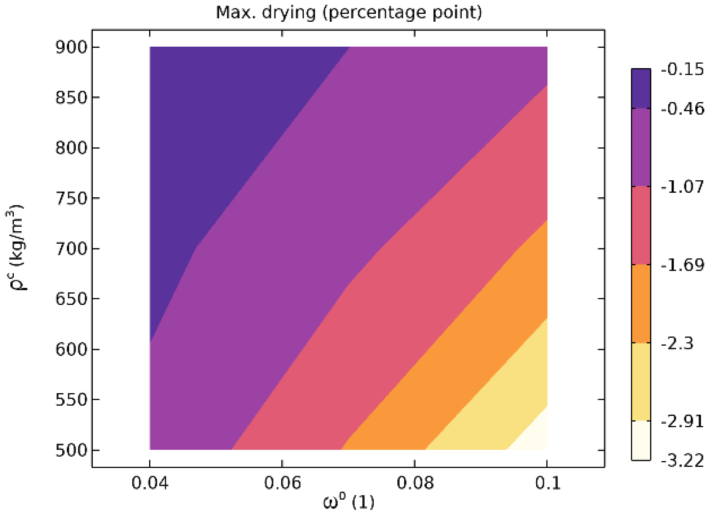
ω^0	0.04, 0.07, 0.1	1
ρ^c	500, 700, 900	$\mathrm{kg \cdot m^{-3}}$

← initial moisture ratio

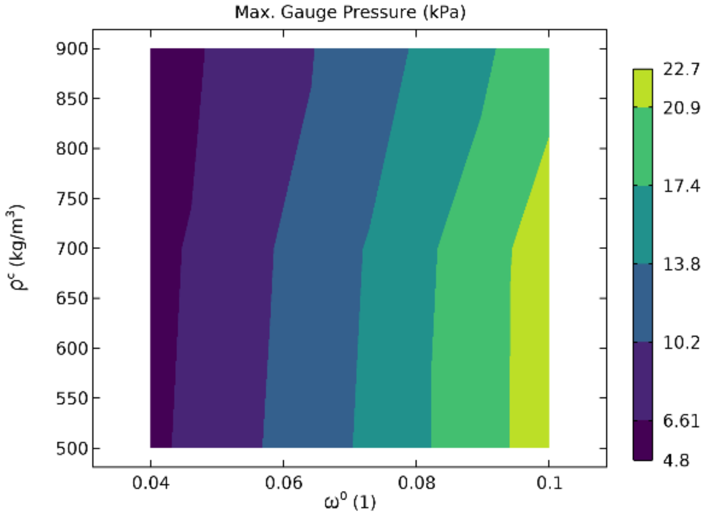
← initial density





Max drying over paperboard domain (end of heating phase)

- located on top left corner of board below Al-foil nearby active area
- higher for higher initial moisture ratio → more desorption
  - increased driving force for drying
- higher for decreased density → increased gas volume
  - gas accumulates more water
  - ease for vapor to flow within the board



Max internal pressure build-up over paperboard domain (end of heating phase)

- higher initial moisture → more desorption
- increased density → less desorption
  - increase resistance for gas to flow→ higher pressure → higher desorption

  BUT
  - increased density → lower temperature → lower pressure → lower desorption

➢ decreased temperature dominates over higher mass flux resistivity

Model Results

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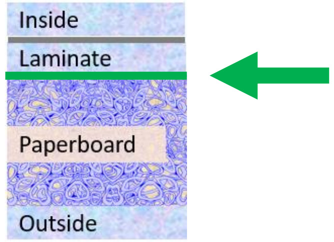
Parametric sweep

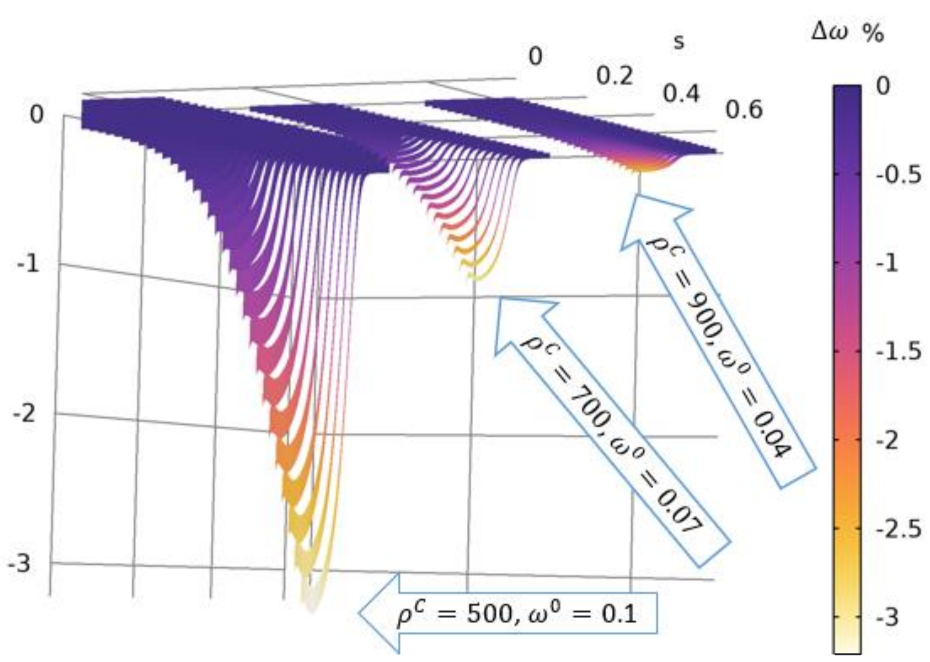
Parameter	Value list	Unit
ω^0	0.04, 0.07, 0.1	1
ρ^c	500, 700, 900	$\mathrm{kg} \cdot \mathrm{m}^{-3}$

← initial moisture ratio

← initial density



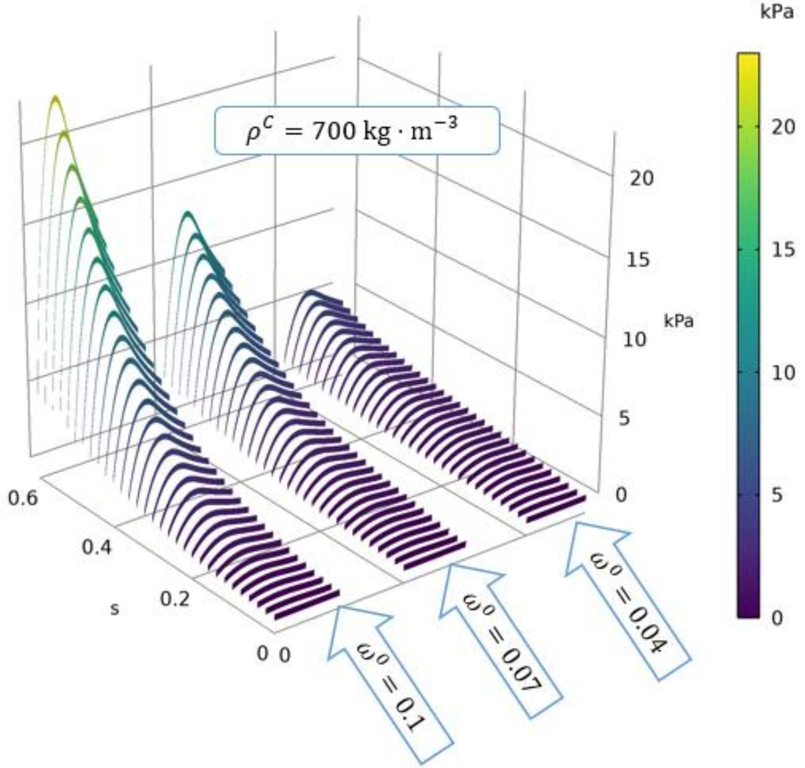
Drying and internal pressure time evolution at the board/laminate interface, above the active area coil



$\rho^c = 900, \omega^0 = 0.04$

$\rho^c = 700, \omega^0 = 0.07$

$\rho^c = 500, \omega^0 = 0.1$



$\rho^c = 700\ \mathrm{kg} \cdot \mathrm{m}^{-3}$

$\omega_0 = 0.1$

$\omega_0 = 0.07$

$\omega_0 = 0.04$

Boundary conditions

The mass fluxes, $J_{g_j}^{n}$, of the gas constituents, through the free edges of the board (vertical edges in Figure 3), are approximated by stagnant-film models with the incorporation of Stefan correction factors, as described in [7]. No heat flux is assumed on the contact between the biadhesive tape and the aluminum coil. All boundaries between polymers and ambient air assume a Newton cooling format with the heat convection coefficient, h_α, retrieved from classic boundary layer theory. The heat flux, q_θ^n, through the free edges of the board, incorporates the mass flux and is given by

$$q_\theta^n = h_\alpha(\theta - \theta^*) + J_{g_v}^n \cdot h_{g_v} + J_{g_a}^n \cdot h_{g_a}$$

where h_{g_j} [J/kg] is the specific enthalpy of g_v.