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Materials Science and Technology

Monte Carlo Simulation To Model Natural Variability In Food Drying

Jörg Schemminger, Sharvari Raut, Barbara Sturm, Thijs Defraeye

27. October 2023

ATB
Leibniz-Institut für
Agrartechnik und Bioökonomie

HUMBOLDT-
UNIVERSITÄT
ZU BERLIN

Convective drying of fruits & vegetables…

… is widely used

… extends storage life

… makes foo available off season

… reduces energy consumption for transportation

Less food waste

Food security

get best use of our food resources

optimize towards …

best possible preservation of nutritional & sensorial quality

reduction energy consumption

… is energy consuming

… impacts quality aspects

… was often designed trial & error …

… decades ago

Defraeye, Thijs (2014): Advanced computational modelling for drying processes – A review (131). DOI: 10.1016/j.apenergy.2014.06.027
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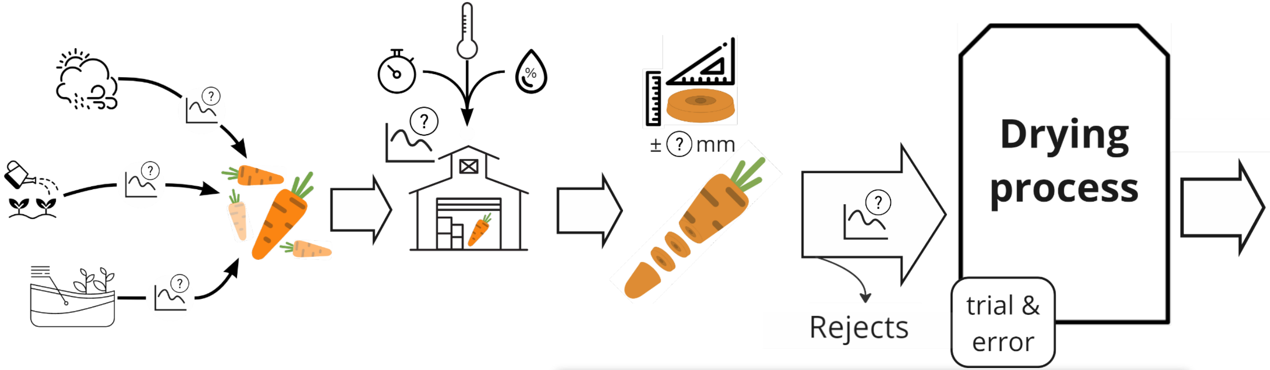
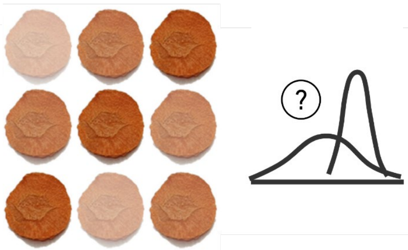
Dried carrot slices

Raut, Sharvari et al. (2021): Investigating the Effect of Different Drying Strategies on the Quality Parameters of Daucus carota L. Using Dynamic Process Control and Measurement Techniques. In: *Food Bioprocess Technol* 14 (6), S. 1067–1088. DOI: 10.1007/s11947-021-02609-y.

Hordentrockner | INNOTECH Ingenieursgesellschaft mbH (https://innotech-ing.com/site/de/hordentrockner.php)



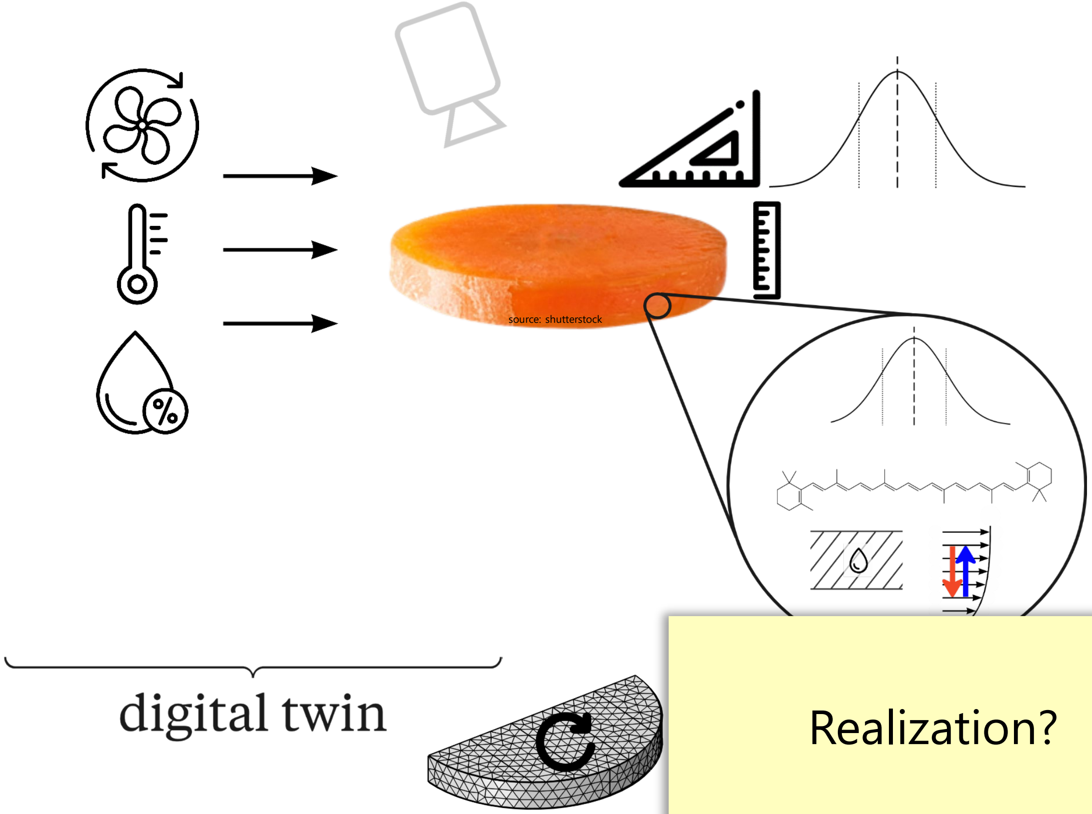


Modeling & simulation toolbox:

→ Hybrid Physics-Based Digital Twin

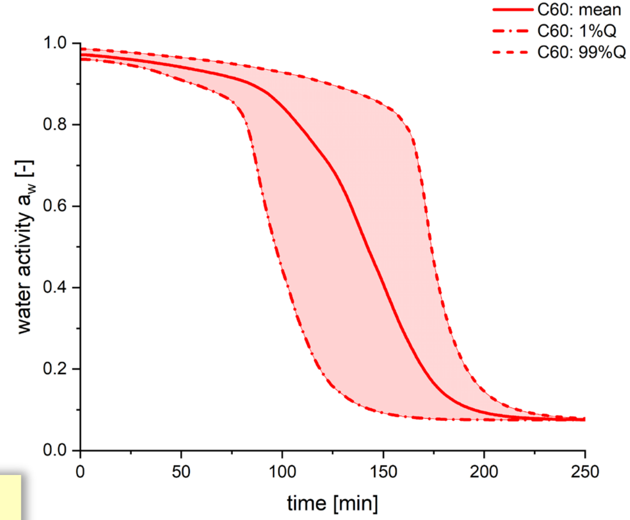
Werner Mühlbauer; Joachim Müller (2020): Drying Atlas. In: Drying Atlas. DOI: 10.1016/C2018-0-02312-9.

The *hybrid* physics-based digital twin

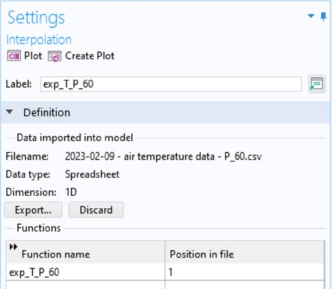


digital twin

Realization?



Implementation to COMSOL



Settings
Interpolation
Plot Create Plot

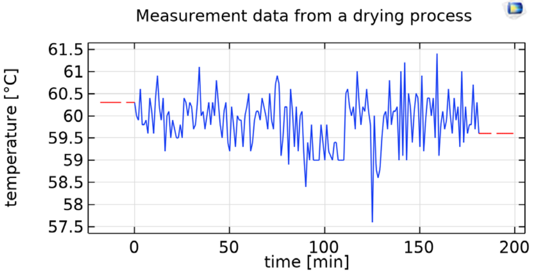
Label: exp_T_P_60

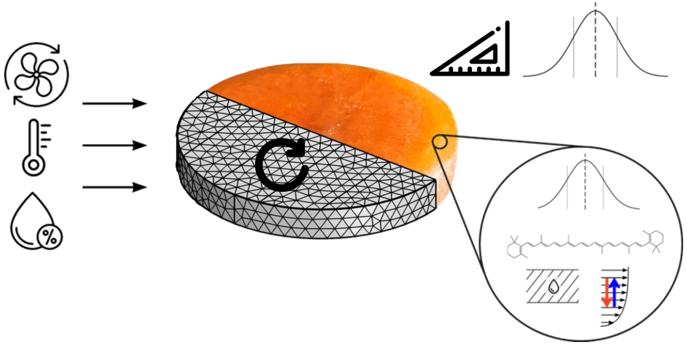
Definition

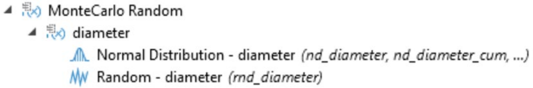
Data imported into model
Filename: 2023-02-09 - air temperature data - P_60.csv
Data type: Spreadsheet
Dimension: 1D

Functions

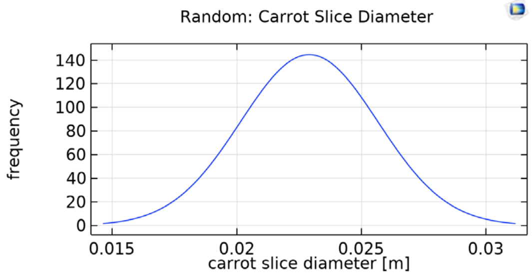
Function name	Position in file
exp_T_P_60	1

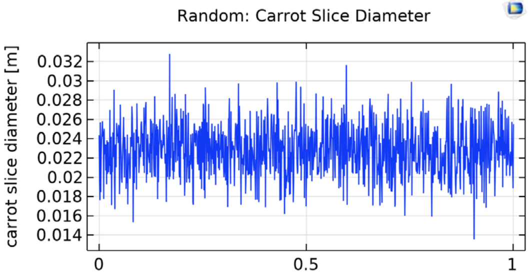


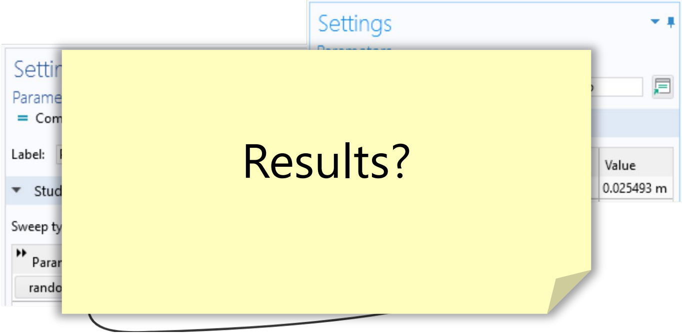




- MonteCarlo Random
  - diameter
    - Normal Distribution - diameter *(nd_diameter, nd_diameter_cum, ...)*
    - Random - diameter *(rnd_diameter)*







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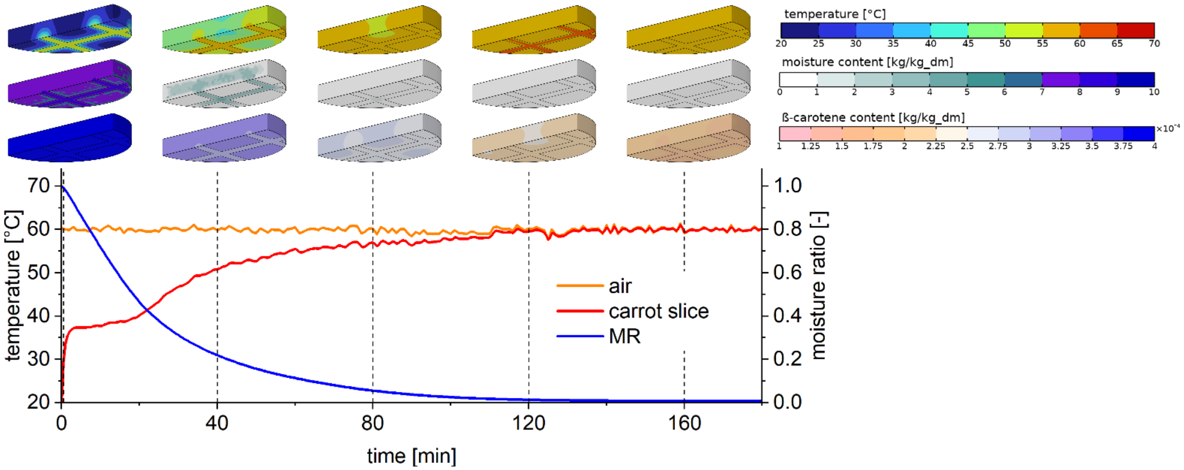
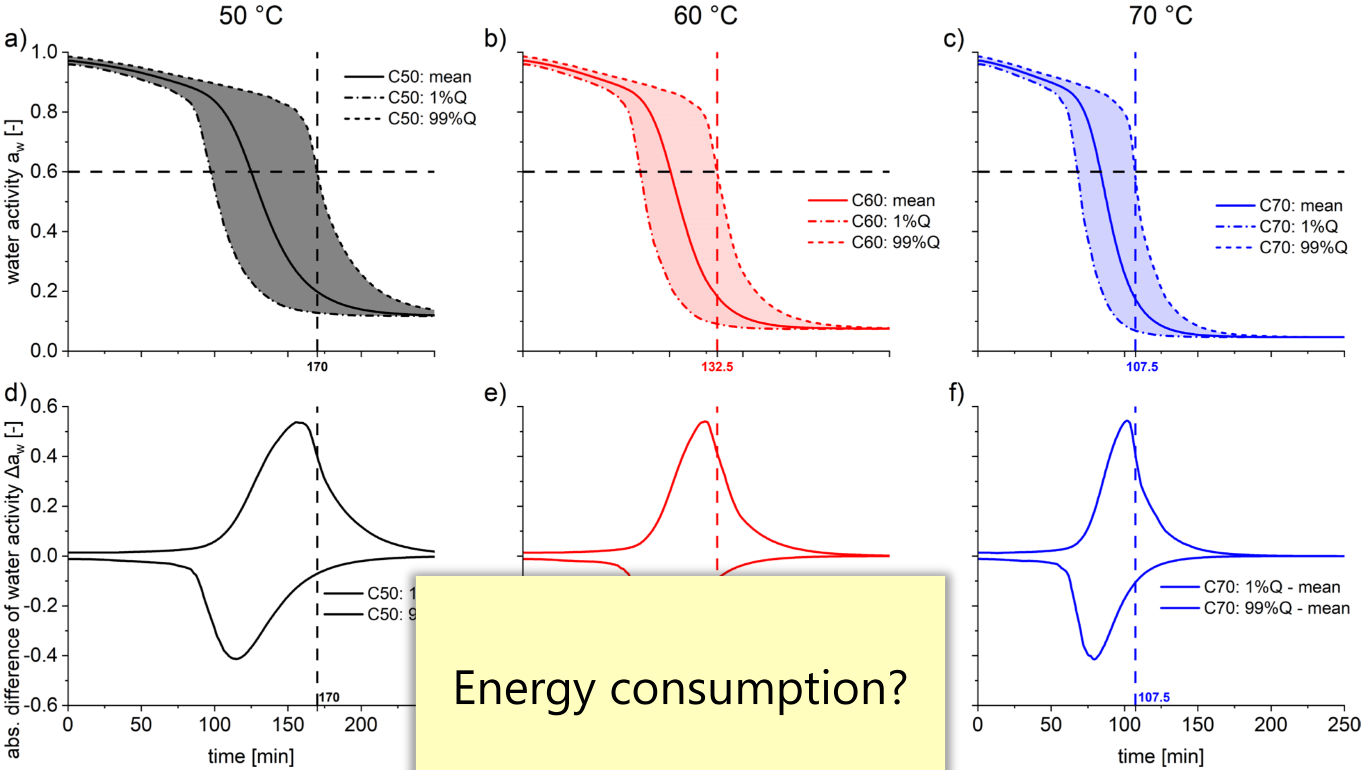
Results?

Actionable Metrics – Digital Twin



When to stop drying? – Hybrid Twin



Energy consumption?

When to stop drying?

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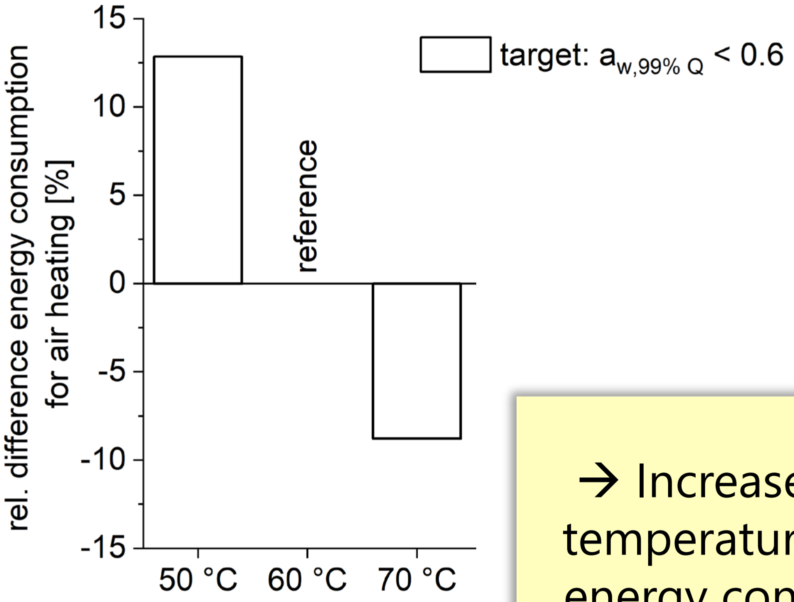
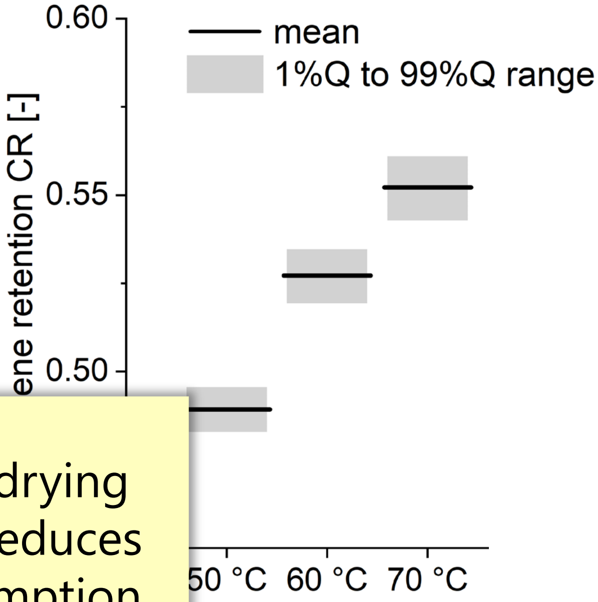
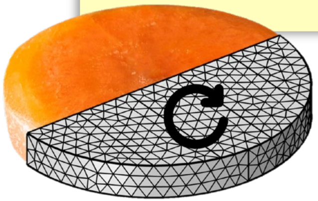


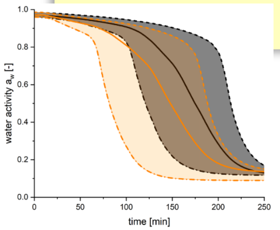


→ Increased drying temperature reduces energy consumption and increases carotene retention

Hybrid digital twin gives insights



Actionable metrics



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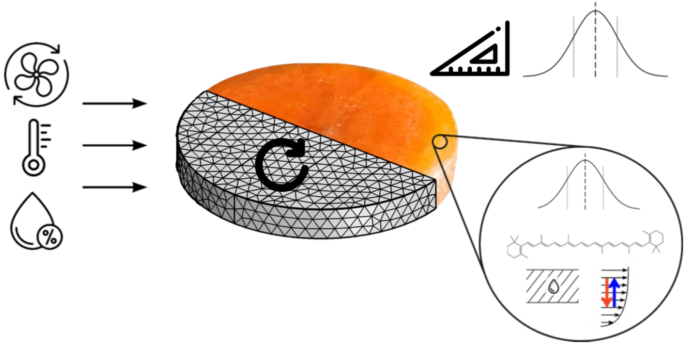
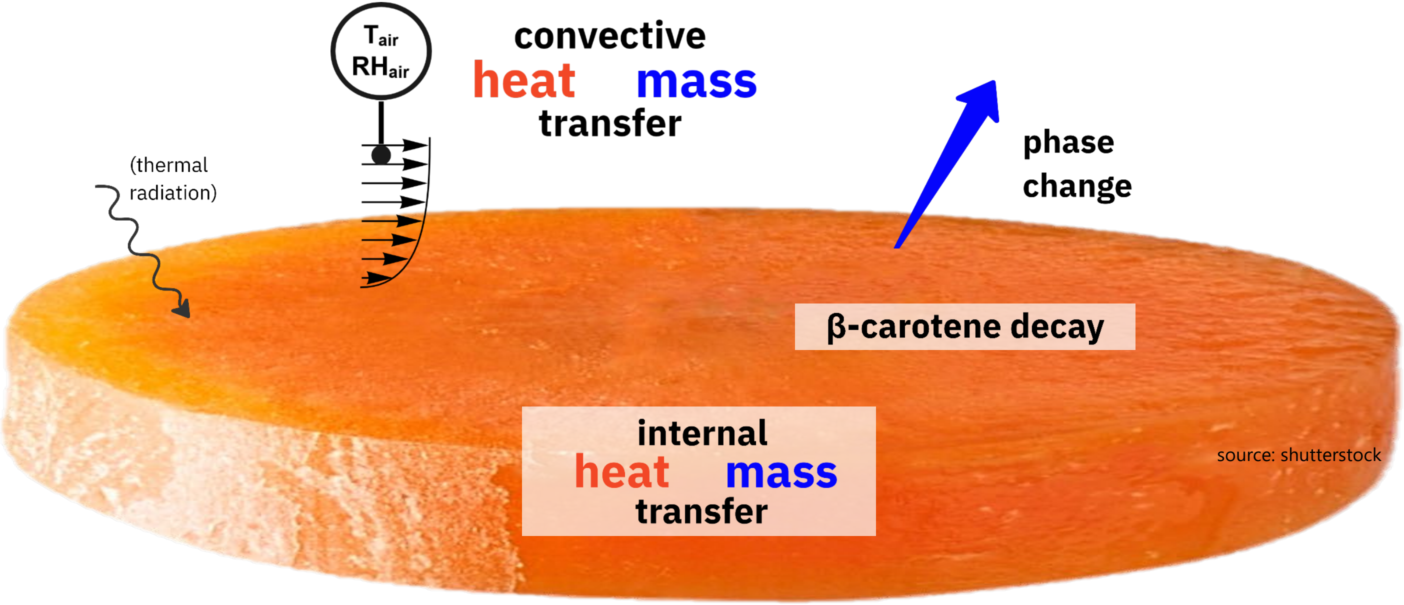


Thanks for your attention!

Icons by: https://www.iconfinder.com/

Backup Slides



T_{air}
RH_{air}

(thermal radiation)

convective
heat mass
transfer

phase change

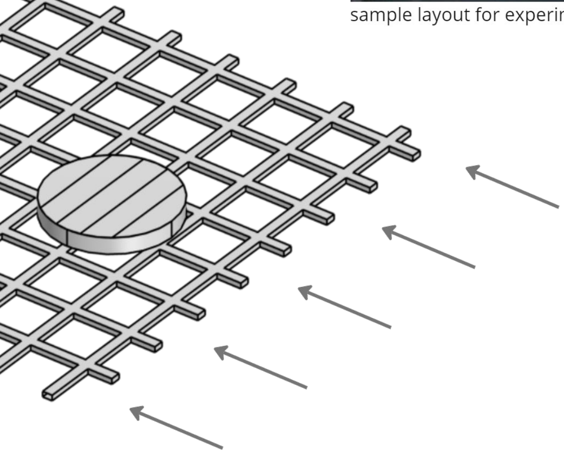
β-carotene decay

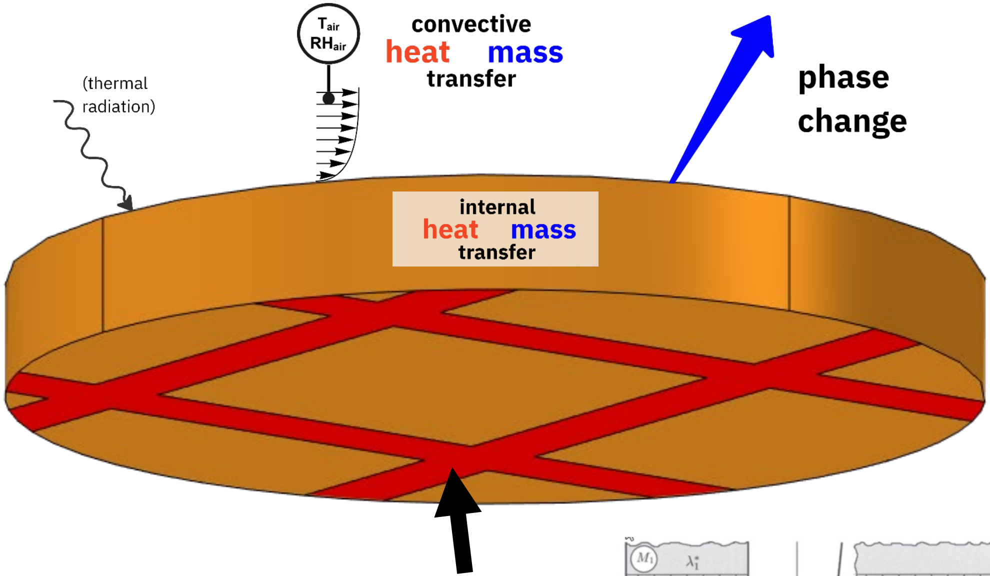
internal
heat mass
transfer

source: shutterstock

?

sample layout for experimental studies [1]





(thermal radiation)

T_{air}
RH_{air}

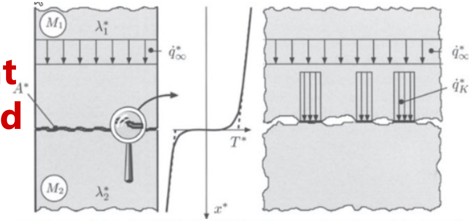
convective
heat **mass**
transfer

phase change

internal
heat **mass**
transfer

Conductive heat
ransfer, reduced
mass transfer

?



Langeheinecke, K., Jany, P. and Thieleke, G. (2011) Wärmeübertragung, Thermodynamik für Ingenieure. doi: 10.1007/978-3-8348-9903-3_10

[1] Raut, Sharvari; Md Saleh, Rosalizan; Kirchhofer, Phil; Kulig, Boris; Hensel, Oliver; Sturm, Barb strategies on the Quality Parameters of Daucus carota L. Using Dynamic Process Control and Measurement Techniques. In: *Food Bioprocess Technol* 14 (6), S. 1067–108

Backup: conductive heat flux

temperature:
- metal mesh
- carrot surface

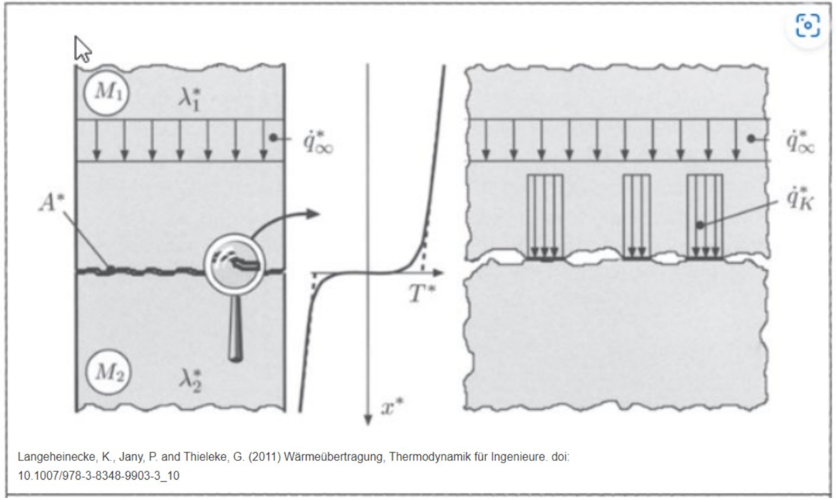
thermal gas conductivity

$$\dot{q}_C = \frac{\lambda_g}{l_g + l_T} \cdot (T_M - T_C)$$

gas gap thickness

temperature jump distance

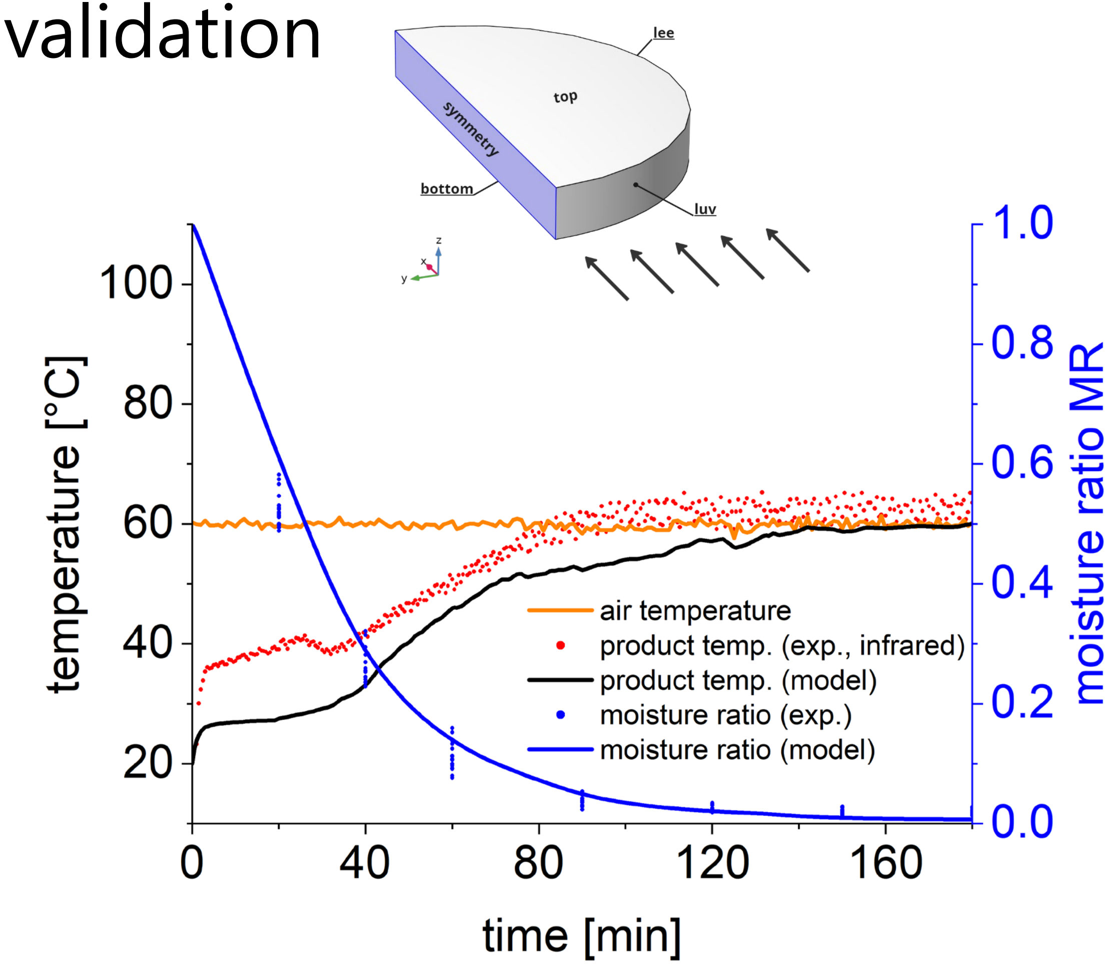
Chakravarti Madhusudana (2014): Thermal contact conductance: a review.



Langeheinecke, K., Jany, P. and Thieleke, G. (2011) Wärmeübertragung, Thermodynamik für Ingenieure. doi: 10.1007/978-3-8348-9903-3_10

Additional assumption: at the contact joints, the mass transfer is reduced by 80 %.

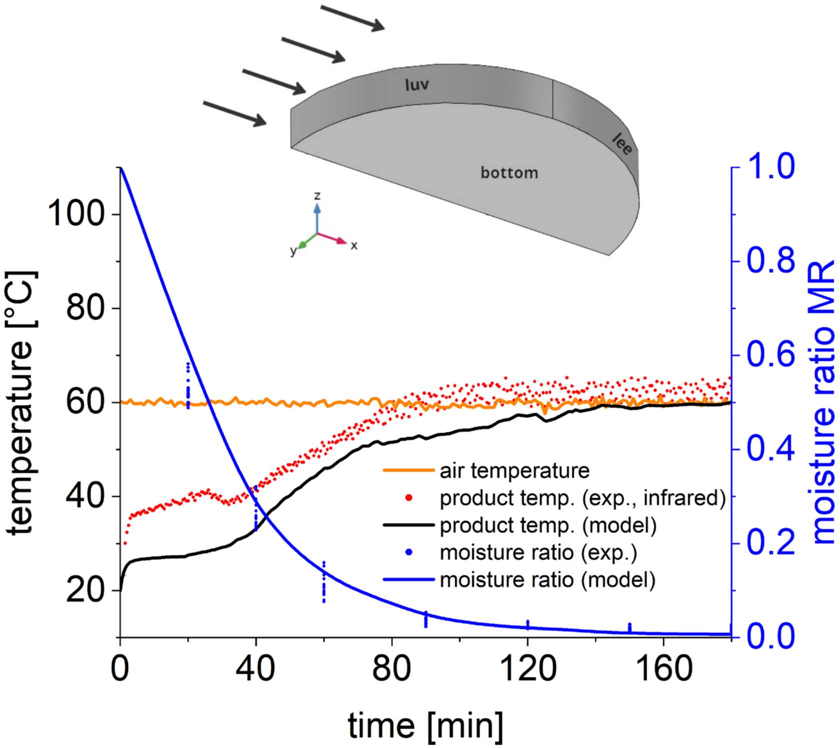
Backup: validation



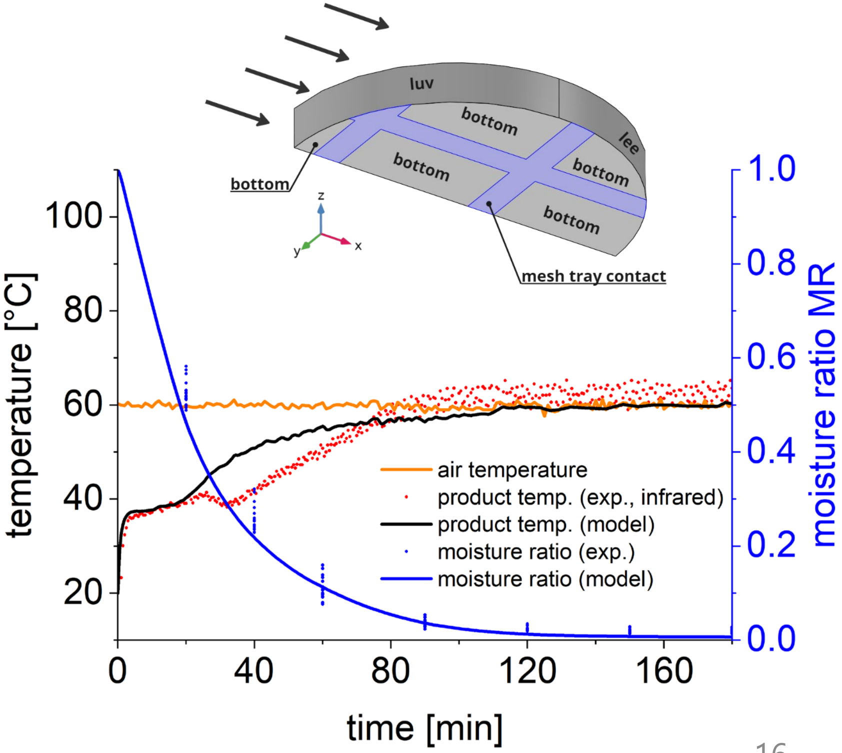
Exp. data from: Raut, Sharvari; Md Saleh, Rosalizan; Kirchhofer, Phil; Kulig, Boris; Hensel, Oliver; Sturm, Barbara (2021): Investigating the Effect of Different Drying Strategies on the Quality Parameters of Daucus carota L. Using Dynamic Process Control and Measurement Techniques. In: *Food Bioprocess Technol* 14 (6), S. 1067–1088. DOI: 10.1007/s11947-021-02609-y.

Backup: validation

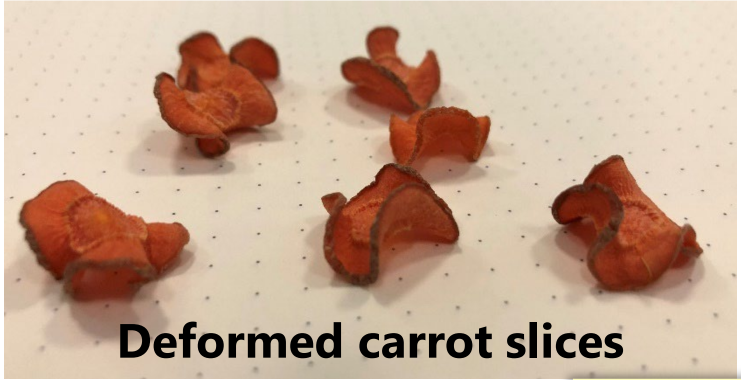
No tray contact



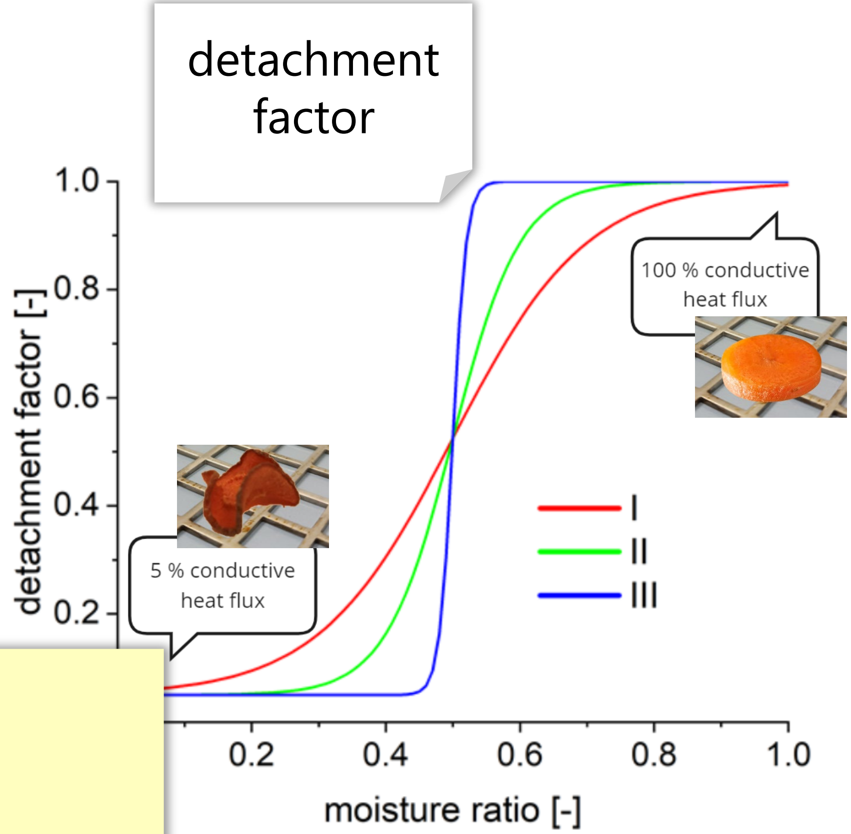
Permanent tray contact



Exp. data from: Raut, Sharvari; Md Saleh, Rosalizan; Kirchhofer, Phil; Kulig, Boris; Hensel, Oliver; Sturm, Barbara (2021): Investigating the Effect of Different Drying Strategies on the Quality Parameters of Daucus carota L. Using Dynamic Process Control and Measurement Techniques. In: *Food Bioprocess Technol* 14 (6), S. 1067–1088. DOI: 10.1007/s11947-021-02609-y.



Deformed carrot slices

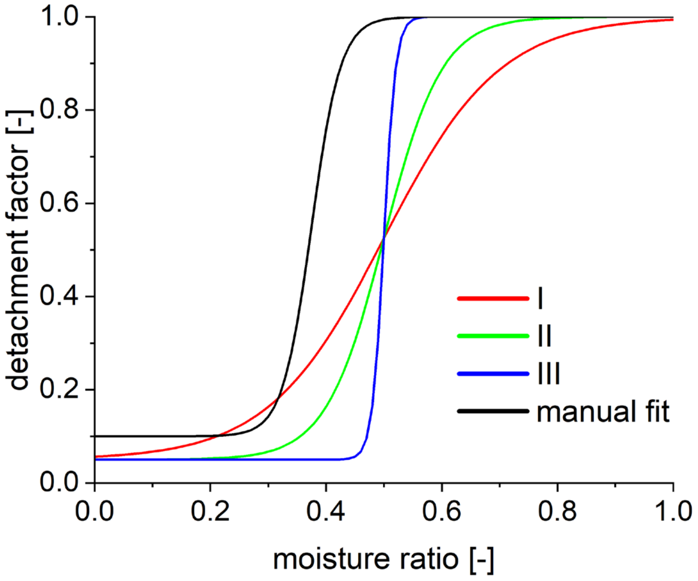


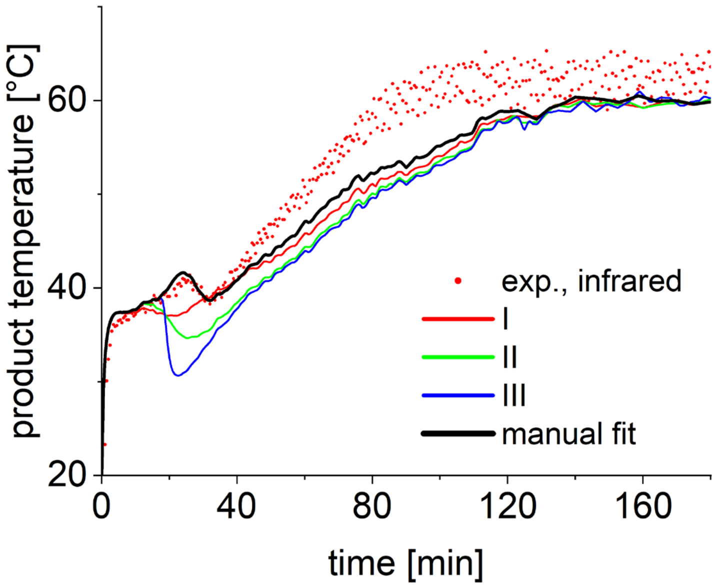
detachment factor

5 % conductive heat flux

100 % conductive heat flux

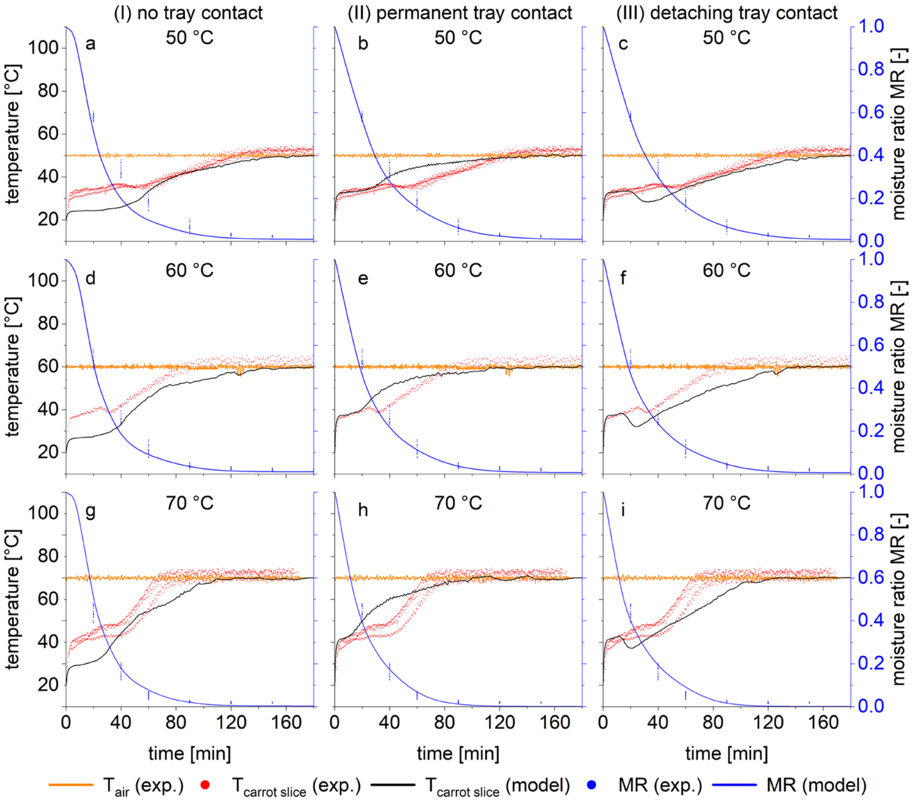
?

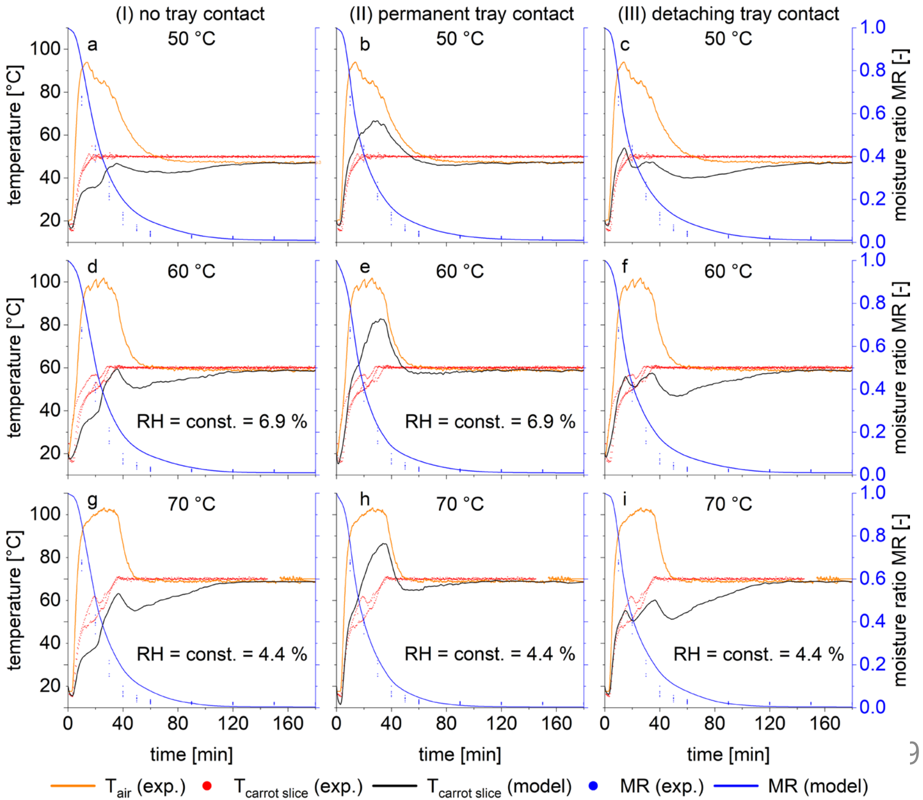




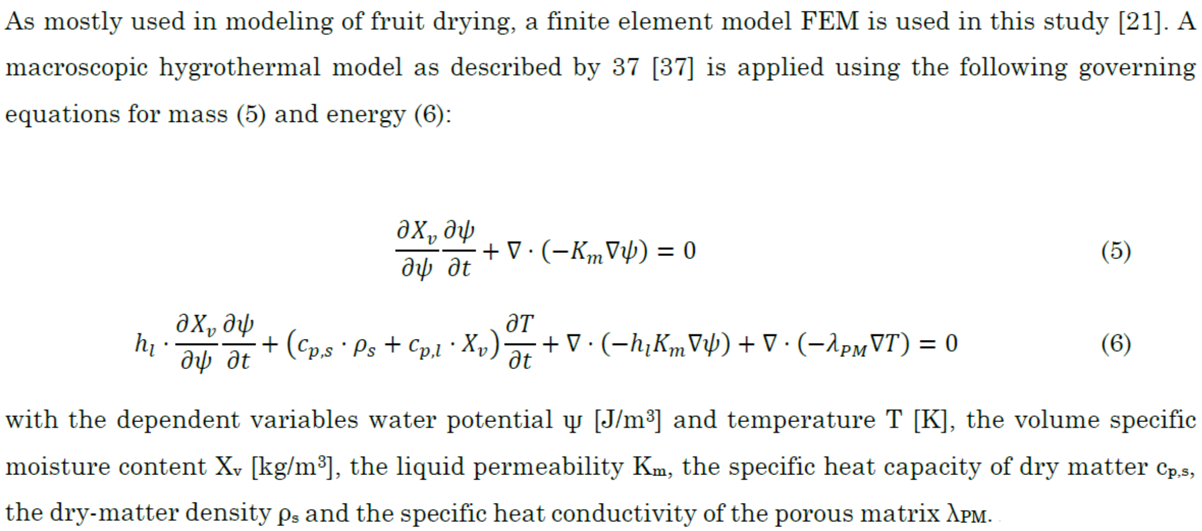
Exp. data from: Raut, Sharvari; Md Saleh, Rosalizan; Kirchhofer, Phil; Kulig, Boris; Hensel, Oliver; Sturm, Barbara (2021): Investigating the Effect of Different Drying Strategies on the Quality Parameters of Daucus carota L. Using Dynamic Process Control and Measurement Techniques. In: *Food Bioprocess Technol* 14 (6), S. 1067–1088. DOI: 10.1007/s11947-021-02609-y.

Validation


(I) no tray contact
(II) permanent tray contact
(III) detaching tray contact
a
b
c
50 °C
d
e
f
60 °C
g
h
i
70 °C
temperature [°C]
moisture ratio MR [-]
time [min]
0
40
80
120
160
20
60
100
0.0
0.2
0.4
0.6
0.8
1.0
T_air (exp.)
T_carrot slice (exp.)
T_carrot slice (model)
MR (exp.)
MR (model)


(I) no tray contact
(II) permanent tray contact
(III) detaching tray contact
a
b
c
50 °C
d
e
f
60 °C
RH = const. = 6.9 %
g
h
i
70 °C
RH = const. = 4.4 %
temperature [°C]
moisture ratio MR [-]
time [min]
0
40
80
120
160
20
60
100
0.0
0.2
0.4
0.6
0.8
1.0
T_air (exp.)
T_carrot slice (exp.)
T_carrot slice (model)
MR (exp.)
MR (model)

Backup: govering equations



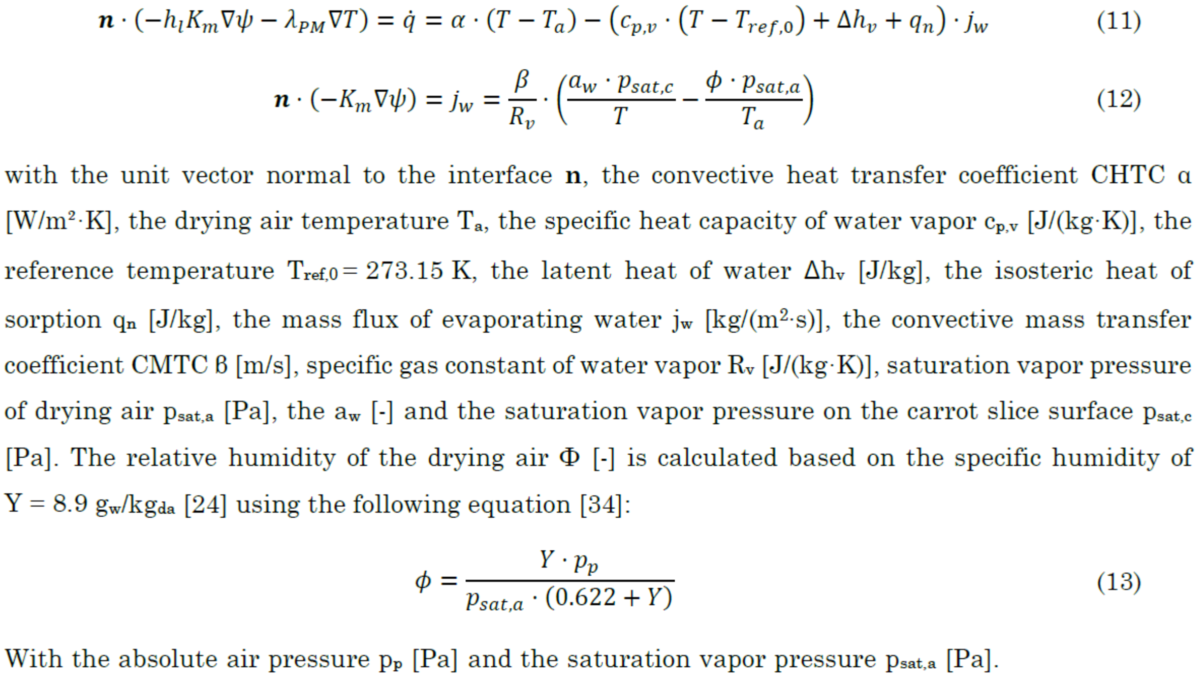
As mostly used in modeling of fruit drying, a finite element model FEM is used in this study [21]. A macroscopic hygrothermal model as described by 37 [37] is applied using the following governing equations for mass (5) and energy (6):

$$\frac{\partial X_v}{\partial \psi}\frac{\partial \psi}{\partial t} + \nabla \cdot (-K_m \nabla \psi) = 0 \tag{5}$$

$$h_l \cdot \frac{\partial X_v}{\partial \psi}\frac{\partial \psi}{\partial t} + \left(c_{p,s} \cdot \rho_s + c_{p,l} \cdot X_v\right)\frac{\partial T}{\partial t} + \nabla \cdot (-h_l K_m \nabla \psi) + \nabla \cdot (-\lambda_{PM} \nabla T) = 0 \tag{6}$$

with the dependent variables water potential ψ [J/m^3] and temperature T [K], the volume specific moisture content X_v [kg/m^3], the liquid permeability K_m, the specific heat capacity of dry matter $c_{p,s}$, the dry-matter density ρ_s and the specific heat conductivity of the porous matrix λ_{PM}.

Backup: boundary conditions



$$\boldsymbol{n}\cdot\left(-h_l K_m \nabla\psi - \lambda_{PM}\nabla T\right) = \dot{q} = \alpha\cdot\left(T - T_a\right) - \left(c_{p,v}\cdot\left(T - T_{ref,0}\right) + \Delta h_v + q_n\right)\cdot j_w \qquad (11)$$

$$\boldsymbol{n}\cdot\left(-K_m \nabla\psi\right) = j_w = \frac{\beta}{R_v}\cdot\left(\frac{a_w\cdot p_{sat,c}}{T} - \frac{\phi\cdot p_{sat,a}}{T_a}\right) \qquad (12)$$

with the unit vector normal to the interface **n**, the convective heat transfer coefficient CHTC α [W/m²·K], the drying air temperature T_a, the specific heat capacity of water vapor $c_{p,v}$ [J/(kg·K)], the reference temperature $T_{ref,0} = 273.15$ K, the latent heat of water Δh_v [J/kg], the isosteric heat of sorption q_n [J/kg], the mass flux of evaporating water j_w [kg/(m²·s)], the convective mass transfer coefficient CMTC ß [m/s], specific gas constant of water vapor R_v [J/(kg·K)], saturation vapor pressure of drying air $p_{sat,a}$ [Pa], the a_w [-] and the saturation vapor pressure on the carrot slice surface $p_{sat,c}$ [Pa]. The relative humidity of the drying air Φ [-] is calculated based on the specific humidity of Y = 8.9 g_w/kg_{da} [24] using the following equation [34]:

$$\phi = \frac{Y\cdot p_p}{p_{sat,a}\cdot(0.622 + Y)} \qquad (13)$$

With the absolute air pressure p_p [Pa] and the saturation vapor pressure $p_{sat,a}$ [Pa].