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A successful comparison between a non-invasive measurement of local profiles during drying of a highly shrinkable food material (eggplant) and the spatial reaction engineering approach

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1 **A successful comparison between a non-invasive measurement of local profiles during**
2 **drying of a highly shrinkable food material (eggplant) and the spatial reaction**
3 **engineering approach**

4
5
6 Abbreviated running title:

7 **Modeling local profiles inside of food materials by the spatial reaction engineering**
8 **approach**

9
10
11 Aditya Putranto^{1**}, Xiao Dong Chen^{2*}

12 ¹School of Chemistry and Chemical Engineering, Queen's University Belfast, David Keir
13 Building, Stranmilis Road, Belfast BT9 5AG, United Kingdom

14 ²School of Chemical and Environmental Engineering, College of Chemistry, Chemical
15 Engineering and Materials Science, Soochow University, Suzhou, Jiangsu Province, PR
16 China

26

27

Abstract

28 A reliable mathematical model is useful for predicting the internal profiles inside the materials
29 during drying. In this study, for the first time, the spatial reaction engineering approach (S-
30 REA) is used to model the local profiles of food materials during drying. The REA is applied
31 as the local rate of phase change and combined with a set of equations of conservation of heat
32 and mass transfer to yield the spatial temperature and concentration profiles during drying. The
33 S-REA predictions are benchmarked against the Magnetic Resonance Imaging (MRI) data. The
34 study indicates that the S-REA is applicable to model the internal profiles inside food materials
35 during drying. The S-REA predictions also show closer agreement towards the experimental
36 data than the effective diffusion model. While the S-REA predictions are accurate, it requires
37 minimum number of experiments to generate the drying parameters. The S-REA has
38 contributed to better analysis of transport phenomena inside food materials during drying
39 through generation of local profiles. The S-REA predictions are useful to interpret the sensory
40 and quality matters during drying such as hardness and crispiness.

41

42 **Key words:** drying, internal profiles, model, heat and mass transfer, spatial reaction
43 engineering approach

44

45 Corresponding authors' emails: *Professor Xiao Dong Chen (xdchen@mail.suda.edu.cn), **

46 Dr. Aditya Putranto (a.putranto@qub.ac.uk)

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50 **1. Introduction**

51 Drying is commonly employed in food and bioproduct processing to remove moisture
52 to extend the shelf life and to minimise transportation costs (Chou et al., 2000). It is an energy
53 intensive process since large amount of heat needs to be supplied for vaporising water. Drying
54 may also alter the product structure, impacting on the quality. For fruits and vegetables, drying
55 may lead to non-enzymatic browning, loss of ascorbic acid, loss of beta carotene content, color
56 changes and many other chemical changes (Pan et al., 1999; Cnossen et al., 2002).

57

58 Tailoring drying schemes and conditions are feasible to ensure good product quality is
59 met. The internal profiles of moisture content and temperature along with the microstructures
60 are essential information. This understanding is useful to systematically fine-tune the drying
61 schemes. The ability to manage average moisture content and average temperature seems not
62 sufficient these days. The antioxidant capacity, phenolic content, loss of vitamin C and color
63 changes during drying of fruits and vegetables can be related to the local moisture content and
64 the local temperature (Fan et al., 2017; Horuz et al., 2017). For rice, high temperature and
65 moisture content gradients may induce fissuring and breakage. Drying under time-varying
66 conditions has shown to minimise the fissuring since it allows the moisture and heat to
67 equilibrate inside the samples (Aqueretta et al., 2007; Dong et al., 2010). In baking, the
68 understanding of local variables assists in optimising crispness, softness and color changes due
69 to browning reactions, starch gelatinisation and protein denaturation (Hadiyanto et al., 2008).
70 Since evaporation/condensation occurs inside bread, the temperature gradients inside the
71 samples need to be studied (De Vries et al., 1989).

72

73 Reliable drying models can be used assist in predicting the internal profiles during
74 drying. For this purpose, the spatial drying models are useful. The diffusion-based models are
75 commonly implemented to describe drying with a wide range of accuracy is shown (Vaquiro

76 et al., 2009; Brasiello et al., 2013; 2017). Most of the models use the effective diffusivity to
77 lump the capillary and water vapor diffusivity (Mariani et al., 2007; Vaquiro et al., 2009;
78 Brasiello et al., 2011; 2017). In addition, Luikov's based models (Luikov, 1975) based on
79 classical thermodynamics are used to represent the spatial profiles. The models postulate that
80 the thermal and moisture potential gradient within a porous body cause the vapor and liquid
81 water transfer so that the flux of liquid water and water vapor is proportional to the thermal
82 gradient and moisture potential gradient. The two-way coupled system of Luikov's approach
83 was implemented to model timber drying and a reasonable agreement towards the experimental
84 data is shown (Thomas et al., 1980; Kulasiri and Samarasinghe, 1986). Similarly, Whitaker's
85 approach (Whitaker, 1977) can be implemented to generate the spatial profiles during drying.
86 Darcy's law is usually used to describe the momentum transfer in liquid and gas phases while
87 the mass transfer considers capillary action as well as evaporation/condensation. This approach
88 has been used to model several drying process well (Hager et al., 2000; Torres et al., 2011).

89

90 The reaction engineering approach (REA) is basically a 'middle-path' approach to
91 model drying. The major physics of drying is captured by the relative activation energy of the
92 REA. The relative activation energy is essentially material characteristics which describe the
93 difficulty to remove moisture from materials being dried. At the beginning of drying, the
94 relative activation energy is zero and it keeps increasing as drying progresses. When the
95 equilibrium condition is achieved, the relative activation energy is one. The REA requires
96 minimum number of experiments to generate the relative activation energy since the one
97 generated from one accurate drying run is applicable to project drying the same materials at
98 other conditions provided the similar initial moisture content (Chen and Putranto, 2013). When
99 compared to characteristics drying rate curve (CDRC), the REA gives advantages in yielding
100 natural transition during drying since it does not depend on the critical moisture content (Baini

101 and Langrish, 2007). Therefore, it is applicable to describe the heat and mass transfer processes
102 under time-varying conditions (Putranto et al, 2011^{a-c}). Benchmarks against diffusion-based
103 models also showed that the REA result in closer agreement towards experimental data
104 (Putranto and Chen, 2011^{a-b}).

105

106 The REA in its lumped format is further called as the lumped reaction engineering
107 approach (L-REA) and it has been combined with a set of equations of conservation of heat
108 and mass transfer to yield a spatial model labelled as the spatial reaction engineering approach
109 (S-REA) (Chen and Putranto, 2013). The S-REA is non-equilibrium multiphase model in
110 which the REA is used as the local evaporation/condensation rate. The use of non-equilibrium
111 multiphase model is suggested as it is more general and can be used to assess the applicability
112 of the equilibrium multiphase drying model (Zhang and Datta, 2004; Chen, 2007). It also yields
113 better understanding of transport phenomena during drying since the profiles of concentration
114 of water vapor can be established. In S-REA, the moisture content inside the solid matrix is not
115 assumed to be in equilibrium with the concentration of water vapor inside pore spaces. The S-
116 REA has been used so far to describe a number of heat and mass transfer processes including
117 convective drying, intermittent drying, baking and water vapor sorption (Putranto and Chen,
118 2015^{a-c}). In these studies, the S-REA is shown to be able to model well the average moisture
119 content.

120

121 However, it is not certain whether the S-REA can be used to model the internal profiles
122 inside food materials during drying. In this study, for the first time, the S-REA is applied to
123 model the local profiles during drying. The capability of the S-REA is tested by benchmarking
124 the S-REA predictions against a set of Magnetic Resonance Imaging (MRI) data. The eggplant
125 is chosen as a shrinkable vegetable that present reasonable challenges to model. The outline of

126 this paper is as follows. The experimental details are reviewed briefly followed by the
127 mathematical modelling using S-REA. The reported results of modelling are then discussed.

128

129 **2. Review of experimental details**

130 The experimental data for validating the results of modelling are derived from previous
131 study (Brasiello et al., 2017). For better understanding of the modelling, the experimental
132 details are reviewed briefly here. The fresh eggplant is firstly stored in the fridge at 4 °C before
133 processing. The samples are then washed, cut longitudinally around the centre from left to right
134 and shaped using a steel mould to give an initial diameter of 2 cm. The samples are randomised
135 before processing to avoid unavoidable difference in material structure. The initial sample
136 moisture content is 12.75 ± 0.96 kg water.kg dry solids⁻¹ (Brasiello et al., 2017). Drying is
137 conducted in a forced convective dryer (Espec Corp SU221) at drying air temperature of 50 °C
138 and air velocity of 1.2 m.s⁻¹. During drying, the weight loss is measured at particular timings
139 using gravimetric method and the moisture content is analysed using the AOAC standards
140 (Helrich, 1990). For the measurement of the internal moisture content distribution at different
141 timings, Magnetic Resonance Imaging (MRI) is implemented (Brasiello et al., 2017).

142

143 **3. Mathematical modelling using the spatial reaction engineering approach (S-REA)**

144 The spatial reaction engineering approach (S-REA) is used to model the convective
145 drying of eggplant in this study. The details of the reaction engineering approach (REA) have
146 been published previously (Chen and Putranto, 2013; Putranto and Chen, 2015^{a,b}; 2016;
147 Putranto et al., 2017). The S-REA consists of a set of equations of conservation of heat and
148 mass transfer in which the REA is used to describe the local evaporation rate. In S-REA, the
149 moisture content inside the solid matrix is not assumed to be in equilibrium with the

150 concentration of water vapor inside pore spaces. The REA serves as a source and depletion
151 term for equation of conservation of water vapour and liquid water, respectively.

152

153 The mass balance of liquid water can be represented as (Chen and Putranto, 2013; Putranto and
154 Chen, 2015^{a-c}):

$$155 \quad \frac{\partial(C_s X)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (D_w r \frac{\partial(C_s X)}{\partial r}) - \dot{I} \quad (1)$$

156 where t is the time (s), r is the sample radius (m), X is the concentration of liquid water (kg
157 H₂O kg dry solids⁻¹), D_w is the capillary diffusivity (m² s⁻¹), C_s is the solids concentration (kg
158 dry solids m⁻³), \dot{I} is the local evaporation or condensation rate (kgm⁻³s⁻¹) and \dot{I} is >0 when
159 evaporation occurs locally.

160

161 The mass balance of water vapor can be written as (Chen and Putranto, 2013; Putranto and
162 Chen, 2015^{a-c}):

$$163 \quad \frac{\partial C_v}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (D_v r \frac{\partial C_v}{\partial r}) + \dot{I} \quad (2)$$

164 where C_v is the concentration of water vapor (kg H₂O m⁻³) and D_v is the water vapor diffusivity
165 (m² s⁻¹).

166

167 In addition the heat balance can be represented as (Chen and Putranto, 2013; Putranto and
168 Chen, 2015^{a-c}):

$$169 \quad \rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (kr \frac{\partial T}{\partial r}) - \dot{I} \Delta H_v \quad (3)$$

170 where T is the sample temperature (K). ρ is the sample density (kg m⁻³), C_p is the sample specific
171 heat capacity (J kg⁻¹ K⁻¹), ΔH_v is the water vaporization enthalpy (J kg⁻¹) and k is the sample
172 thermal conductivity (W m⁻¹ K⁻¹).

173

174 The initial and boundary conditions of equations (1) to (3) are:

175 $t=0, X=X_o, C_v=C_{vo}, T=T_o$ (initial condition, uniform initial concentrations and temperature)

176 (4)

177 $r=0, \frac{dX}{dr} = 0, \frac{dC_v}{dr} = 0, \frac{dT}{dr} = 0$ (symmetrical condition) (5)

178 $r=R,$

179 $-C_s D_w \frac{dX}{dr} = h_m \varepsilon_w \left(\frac{C_{v,s}}{\varepsilon} - \rho_{v,b} \right)$ (convective boundary for liquid water transfer) (6)

180 where ε_w is the fraction of surface area covered by liquid water.

181 $-D_v \frac{dC_v}{dr} = h_m \varepsilon_v \left(\frac{C_{v,s}}{\varepsilon} - \rho_{v,b} \right)$ (convective boundary for water vapor transfer) (7)

182 where ε_v is the fraction of surface area covered by water vapor.

183

184 $k \frac{dT}{dr} = h(T_b - T)$ (convective boundary for heat transfer) (8)

185

186 \dot{I} is the local drying or wetting rate within the solid structure described as (Putranto and Chen,

187 2015^{a-c}):

188 $\dot{I} = h_{m,in} A_{in} (C_{v,s} - C_v)$ (9)

189 where $h_{m,in}$ is the internal mass transfer coefficient (m s^{-1}), A_{in} is the total internal surface area

190 available for phase change ($\text{m}^2 \text{m}^{-3}$), $C_{v,s}$ is the internal-solid-surface water vapor concentration

191 (kg m^{-3}).

192

193 By implementing the REA, internal-surface water vapor concentration can be written as (Chen
194 and Putranto, 2013):

$$195 \quad C_{v,s} = \exp\left(\frac{-\Delta E_v}{RT}\right) C_{v,sat} \quad (10)$$

196 where ΔE_v is the activation energy ($\text{J mol}^{-1} \text{K}^{-1}$) and $C_{v,sat}$ is the internal-saturated water vapour
197 concentration (kg m^{-3})

198 Therefore, the local drying or wetting rate can be expressed as (Chen and Putranto, 2013):

$$199 \quad \dot{I} = h_{m_in} A_{in} \left(\exp\left(\frac{-\Delta E_v}{RT}\right) C_{v,sat} - C_v \right) \quad (11)$$

200 The relative activation energy of convective drying of eggplant, as fingerprint of the
201 REA, is established from eggplant drying at drying air temperature of 60 °C (Adiletta et al,
202 2014). Only one temperature data set is used to generate the relate activation energy function.
203 Based on the experimental data set of drying at 60 °C, the activation energy is calculated.
204 Dividing the activation energy (ΔE_v) with the equilibrium activation energy ($\Delta E_{v,b}$) yields the
205 relative activation energy ($\Delta E_v/\Delta E_{v,b}$). The detailed equations to evaluate the activation energy
206 and equilibrium activation energy have been presented previously (Putranto and Chen, 2015^{s-}
207 °). The relationship between the relative activation energy and average moisture content can be
208 represented by simplified mathematical equation obtained by least square method. The relative
209 activation energy ($\Delta E_v/\Delta E_{v,b}$) of eggplant during convective drying can be represented as:

$$210 \quad \frac{\Delta E_v}{\Delta E_{v,b}} = -7.69 \times 10^{-4} (\bar{X} - X_b)^3 + 2.32 \times 10^{-2} (\bar{X} - X_b)^2 - 2.48 \times 10^{-1} (\bar{X} - X_b) + 1 \quad (12)$$

211 The good agreement between the fitted and experimental relative activation energy is shown
212 by R^2 of 0.999 and plotted in Figure 1. The format of equation (12) can be varied to be the best

213 fit but in this case, equation (12) is sufficient to describe the relative activation energy of
214 eggplant.

215

216 For modelling using S-REA, equation (12) is implemented to describe the ‘local’
217 relative activation energy by substituting the average moisture content (\bar{X}) with the local
218 moisture content (X). This is to say that the kinetics obtained for average parameters can also
219 be used as the local kinetics. Combining the ‘local’ relative activation energy with the
220 equilibrium activation energy results in the ‘local’ activation energy which represents the
221 ‘local’ behavioural changes of eggplant as affected by the local variables and structures. The
222 ‘local’ activation energy is then implemented to represent the local evaporation and
223 condensation rate shown in equation (11). The determination of transport properties used in the
224 modelling is presented in Appendix A while the calculation of internal surface area (A_{in}) is
225 shown in Appendix B.

226

227 In order to yield the spatial profiles of moisture content, concentration of water vapor
228 and temperature, equations (1) to (3) are solved simultaneously in conjunction with the initial
229 and boundary conditions (equations (4) to (8)) as well as the relative and equilibrium activation
230 energy. Matlab® is used to solve the equations simultaneously and the results of modelling are
231 validated towards the Magnetic Resonance Imaging (MRI) data of convective drying of
232 eggplant at drying air temperature of 50 °C.

233

234 **4. Results and Discussion**

235 Figure 2 indicates the average moisture content during drying modelled by the S-REA.
236 A very good agreement with the experimental data is resulted by the modelling. It is further

237 confirmed by R^2 of 0.999. When benchmarking against the diffusion-based model (Brasiello
238 et al., 2017), the S-REA results in closer agreement with experimental data. The diffusion-
239 based model gives R^2 of 0.92 (Brasiello et al., 2017). This indicates that the S-REA describes
240 accurately the average moisture content during drying. The applicability of the S-REA may be
241 because the relative activation energy is accurate to represent the structural changes inside the
242 eggplant samples during drying.

243

244 The distribution of moisture content inside the samples at drying time of 1800s is shown
245 in Figure 3. The S-REA predicts accurately the spatial profiles of moisture content at this initial
246 drying period. At the sample edge, the moisture content is lower than that at the core since the
247 moisture is transferred from the centre to the drying air via convection. This also indicates that
248 the moisture migrates outwards during drying. Although the modelling implemented by
249 Brasiello et al. (2017) represents the parabolic profiles, the other model seems to overestimate
250 the drying rate.

251

252 For drying time of 3600 s, the spatial profiles of moisture content inside the eggplant
253 samples are represented in Figure 4. Similar to Figure 3, the S-REA predictions match well
254 with the experimental data and confirmed by R^2 of 0.98. As drying progresses, the moisture
255 content at this drying period is lower than that at 3600 s. Similar to the profiles at drying time
256 of 1800 s, the maximum moisture content is located at the centre of the eggplant samples. Both
257 the MRI data and the S-REA show the similar behaviors. The other model (Brasiello et al.,
258 2017) shows the lower predictions of the moisture content at this drying time.

259

260 Figure 5 shows the distribution of moisture content at drying time of 5400 s. The S-
261 REA also represents accurately the internal profiles of moisture content at this drying period.

262 Compared to the modelling by the other modelling, a better agreement towards the
263 experimental data is shown by the S-REA. Similar results are also found during drying at
264 drying time of 7200 s as indicated in Figure 6. As drying progresses, the gradient of moisture
265 content inside the eggplant samples decreases in line with the depletion of moisture inside the
266 samples.

267

268 As a whole, the S-REA outlined in this paper has performed very well in predicting the
269 local behaviour of moisture transfer. It is in fact quite precise, which is a nice surprise
270 considering it is based on the lumped model to obtain the kinetics data. For better representation
271 of transport processes inside the materials, the spatial concentration of water vapor during
272 drying time is generated and shown in Figure 7. At the beginning of drying, the distribution of
273 concentration of water vapor is not large but this increases until drying time of 8000s. More
274 plateau-like profiles are then observed in the later drying period. This seems to correspond well
275 with a relatively uniform moisture content and temperature profiles. The maximum
276 concentration of water vapor is attained at the sample core which may be due to the maximum
277 local moisture content at this location. The water vapor at the sample core diffuses outwards
278 during drying since the concentration of water vapor in the drying air is lower than that at the
279 sample surface.

280

281 Figure 8 indicates the spatial profiles of the local evaporation rate during drying inside
282 the eggplant samples. At the beginning of drying, the local evaporation rate seems to be
283 relatively uniform although the moisture content at the sample core is higher. The initial
284 porosity of the samples is 0.72. As drying progresses, the local evaporation rate at the inner
285 part becomes higher than that that at the outer part which may bedue to the higher local pore
286 surface relative humidity at the inner part of the samples as shown in Figure 9. The higher

287 moisture content at the core of the samples as indicated in Figure 2 to 5 seems to correspond
288 to this condition. This also corresponds to the profiles of water vapour concentration as shown
289 in Figure 7. Along drying, the local evaporation rate increases because of the increase of
290 temperature. Nevertheless, this only lasts until drying time of 5000 s. After this period, the
291 moisture content inside the samples decreases and the equilibrium condition is approached.
292 The gradient of local evaporation rate also decreases towards the end of drying. In agreement
293 with this, as shown in Figure 10, the local pore surface relative humidity inside the samples
294 decreases as drying progresses. It has been shown here that the REA serves well as the local
295 evaporation rate.

296

297 The spatial temperature profiles during drying are shown in Figure 10. The sample
298 temperature increases as moisture being reduced to approach to the drying air temperature. The
299 temperature at the outer part of the eggplant sample is slightly higher than that at the sample
300 core. This is reasonable since the sample receives heat from the surrounding and the heat is
301 mostly used for vaporizing the moisture. Any heat left is then penetrated inwards via
302 conduction to increase the sample temperature. Nevertheless, the gradient temperature inside
303 the eggplant samples is essentially small which is also indicated by Ch_{Bi} (Chen and Peng,
304 2005) which is found to be about 0.002. The low gradients of temperature during drying of
305 food materials are also reported previously (Putranto and Chen, 2015^{a-c}; Putranto et al., 2017).
306 As drying progresses, the temperature gradient actually decreases and no noticeable of
307 temperature difference is observed at the end of drying. This is in line with plateau profiles of
308 moisture content, concentration of water vapor and local evaporation rate at the end of drying
309 as discussed above. No temperature profiles are published by the other model (Brasiello et al.,
310 2017).

311

312 In this study, the S-REA has been shown to be able to model the internal profiles of
313 eggplant during drying. The capability is probably because of the accuracy of ‘local’ activation
314 energy, resulted from combination of both ‘local’ relative and equilibrium activation energy.
315 The ‘local’ activation energy seems to be flexible to represent the ‘local’ drying behaviours at
316 micro-scale as affected by local structure and drying conditions. As the local evaporation rate,
317 the REA is useful not only to link equations of conservation of liquid water and water vapor
318 but also to interpret the complex interrelationships of moisture content, concentration of water
319 vapor and temperature during drying.

320

321 Since the S-REA is applicable to model the internal profiles of food materials during
322 drying, the S-REA can be implemented to evaluate the local mechanical properties. These
323 predictions are useful to interpret the sensory and quality matters such as hardness and
324 crispiness. These sensory properties cannot yet be predicted even with the most comprehensive
325 models (Wang et al., 2012; Kharaghani et al., 2013). In addition, it is interesting to see the S-
326 REA applications in predicting the local profiles of more challenging drying cases including
327 intermittent drying, infrared-heating, microwave and ultrasonic-assisted drying.

328

329

330 **Conclusions**

331 In this study, for the first time, the S-REA is used to model the internal profiles inside
332 food materials during drying. The REA is used as the local evaporation/condensation rate and
333 coupled with a set of equations of conservation of heat and mass transfer. When benchmarked
334 against the available MRI data, the S-REA shows excellent predictions. The local evaporation
335 rate has also been plotted to provide an insight to the transport phenomena. The understanding
336 of local profiles during drying of food materials can be gained by the S-REA. The S-REA is

337 readily implemented as a tool to analyse the transport phenomena inside food materials during
338 drying. The S-REA framework can be used to fine-tune the drying schemes to yield food
339 materials with the desirable product characteristics.

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355 **Nomenclatures**

356

357	A	surface area of samples	(m^2)
358	A_{in}	internal surface area	$(\text{m}^2 \text{ m}^{-3})$
359	A_p	cell surface area	(m^2)
360	C_p	specific heat of sample	$(\text{J kg}^{-1}\text{K}^{-1})$
361	C_s	solids concentration	(kg m^{-3})
362	C_v	water vapor concentration	(kg m^{-3})
363	$C_{v,s}$	internal-surface vapor concentration	(kg m^{-3})
364	$C_{v,sat}$	internal-saturated vapor concentration	(kg m^{-3})
365	D_v	effective water vapor diffusivity	$(\text{m}^2\text{s}^{-1})$
366	$D_{v,o}$	water vapor diffusivity	$(\text{m}^2\text{s}^{-1})$
367	D_w	liquid diffusivity	$(\text{m}^2\text{s}^{-1})$
368	h	heat transfer coefficient	$(\text{W m}^{-2}\text{K}^{-1})$

369	h_m	mass transfer coefficient	(m s ⁻¹)
370	$h_{m,in}$	internal mass transfer coefficient	(m s ⁻¹)
371	I	local evaporation/condensation rate	(kg m ⁻³ s ⁻¹)
372	k	thermal conductivity of sample	(W m ⁻¹ K ⁻¹)
373	m_p	dry mass of cell	(kg)
374	m_s	dried mass sample of material	(kg)
375	m_w	mass of liquid water	(kg)
376	n	constant	
377	N	number of cell in samples	
378	n_p	number of cell per unit volume	(m ⁻³)
379	r	radial position	(m)
380	RH_b	relative humidity of drying air	
381	r_p	cell radius	(m)
382	T	sample temperature	(K)
383	T_s	surface sample temperature	(K)
384	t	time	(s)
385	T_b	drying air temperature	(K)
386	V	volume of sample	(m ³)
387	V_0	initial volume of sample	(m ³)
388	V_p	cell volume	(m ³)
389	v_w	mass fraction of water	
390	X	moisture content on dry basis	(kg kg ⁻¹)
391	\bar{X}	average moisture content on dry basis	(kg kg ⁻¹)
392	X_b	equilibrium moisture content on dry basis	(kg kg ⁻¹)
393	X_o	initial moisture content	(kg kg ⁻¹)
394	ΔE_v	apparent activation energy	(J mol ⁻¹)
395	$\Delta E_{v,b}$	equilibrium activation energy	(J mol ⁻¹)
396	$\Delta E_v/\Delta E_{v,b}$	relative activation energy	
397	ΔH_v	vaporization enthalpy of water	(J kg ⁻¹)
398	ε	porosity	
399	ε_w	fraction of surface area covered by liquid water	
400	ε_v	fraction of surface area covered by water vapor	
401	ε_o	initial porosity	
402	ρ	sample density	(kg.m ⁻³)
403	ρ_s	density of solids	(kg.m ⁻³)
404	$\rho_{v,b}$	vapor concentration in drying medium	(kg. m ⁻³)
405	$\rho_{v,s}$	surface vapor concentration	(kg.m ⁻³)
406	$\rho_{v,sat}$	saturated vapor concentration	(kg m ⁻³)
407	ρ_w	density of water	(kg m ⁻³)
408	τ	turtuosity	
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Appendix A. The physical and transport properties used in the modeling

$$\rho = 670 \text{ kg m}^{-3} \tag{B1}$$

where ρ is the density of eggplant (kg m^{-3}) (Llave et al, 2016).

$$C_p = 1470 + 2720X \tag{B2}$$

where C_p is the specific heat of eggplant ($\text{J kg}^{-1} \text{K}^{-1}$) (Lamb, 1976).

$$k = 14.8 + 49.3X \tag{B3}$$

439 where k is the thermal conductivity of eggplant ($\text{W m}^{-1} \text{K}^{-1}$) (Sweat, 1974).

$$440 \quad D_v = D_{v_0} \frac{\varepsilon}{\tau} \quad (\text{B4})$$

441 where D_v is the effective water vapour diffusivity (m^2s^{-1}) (Bird et al, 2002).

$$442 \quad D_{v_0} = 2.09 \times 10^{-5} + 2.137 \times 10^{-7} (T - 273.15) \quad (\text{B5})$$

443 where D_{v_0} is the vapour diffusivity (m^2s^{-1}) (Slattery and Bird, 1958).

$$444 \quad \tau = \varepsilon^{-n} \quad (\text{B6})$$

445 where τ is the tortuosity, ε is the porosity and n is the value between 0 to 0.5 (Audu and Jeffreys,
446 1975).

$$447 \quad C_s = \frac{1 - \varepsilon}{\frac{1}{\rho_s} + \frac{X}{\rho_w}} \quad (\text{B7})$$

448 where C_s is the solid concentration (kg m^{-3}), ρ_s is the solid density (kg m^{-3}) and ρ_w is the water
449 density (Putranto and Chen, 2015^{a-c}).

$$450 \quad \varepsilon = 1 - \frac{V_0}{V} (1 - \varepsilon_0) \left(\frac{\frac{\rho_s}{\rho_w} X + 1}{1 + \frac{\rho_s}{\rho_w} X_0} \right) \quad (\text{B8})$$

451 where ε is the porosity, V is the sample volume (m^3), V_0 is the initial sample volume (m^3) and
452 X_0 is the initial moisture content ($\text{kg water kg dry solids}^{-1}$) (Madiouli et al, 2007).

$$453 \quad \varepsilon_w = \frac{C_s X}{\rho_w} \quad (\text{B9})$$

454 where ε_w is the fraction of surface area covered by liquid water (Ousegui et al., 2010).

455
$$\varepsilon_v = \frac{C_v}{\rho_v} \quad (\text{B10})$$

456 where ε_v is the fraction of surface area covered by water vapour (Ousegui et al., 2010).

457
$$D_w = 1.05 \times 10^{-4} \exp\left(-\frac{3265.91}{T}\right) \quad (\text{B11})$$

458 where D_w is the capillary diffusivity ($\text{m}^2 \text{s}^{-1}$) (Brasiello et al, 2017).

459
$$R = R_0 \left(0.1817 + 0.9185 \frac{X}{X_0}\right)^{0.5} \quad (\text{B12})$$

460 where R is the sample radius (m) and R_0 is the initial sample radius (m) (Adiletta et al, 2014).

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466 **Appendix B. Evaluation of internal surface area (A_{in})** (Kar and Chen, 2010; Putranto and

467 Chen, 2015^{a-c})

468
$$A_p = 4\pi r_p^2 \quad (\text{C1})$$

469 where A_p is the cell surface area (m^2) and r_p is the cell diameter (m).

470
$$V_p = \frac{4}{3} \pi r_p^3 \quad (\text{C2})$$

471 where V_p is the cell volume (m^3)

472
$$m_p = \rho_p V_p (1 - v_w) \quad (\text{C3})$$

473 where m_p is the cell mass (kg) and v_w is the volume fraction of water

$$474 \quad N = \frac{m_s}{m_p} \quad (C4)$$

475 where N is the number cell in samples and m_s is the dried mass of the samples (kg)

$$476 \quad n_p = \frac{N}{V_s} \quad (C5)$$

477 where n_p is the number of cell per unit volume and V_s is the dried cell volume (m^3)

$$478 \quad A_{in} = n_p A_p \quad (B6)$$

479 where A_{in} is the internal surface area ($m^2 m^{-3}$)

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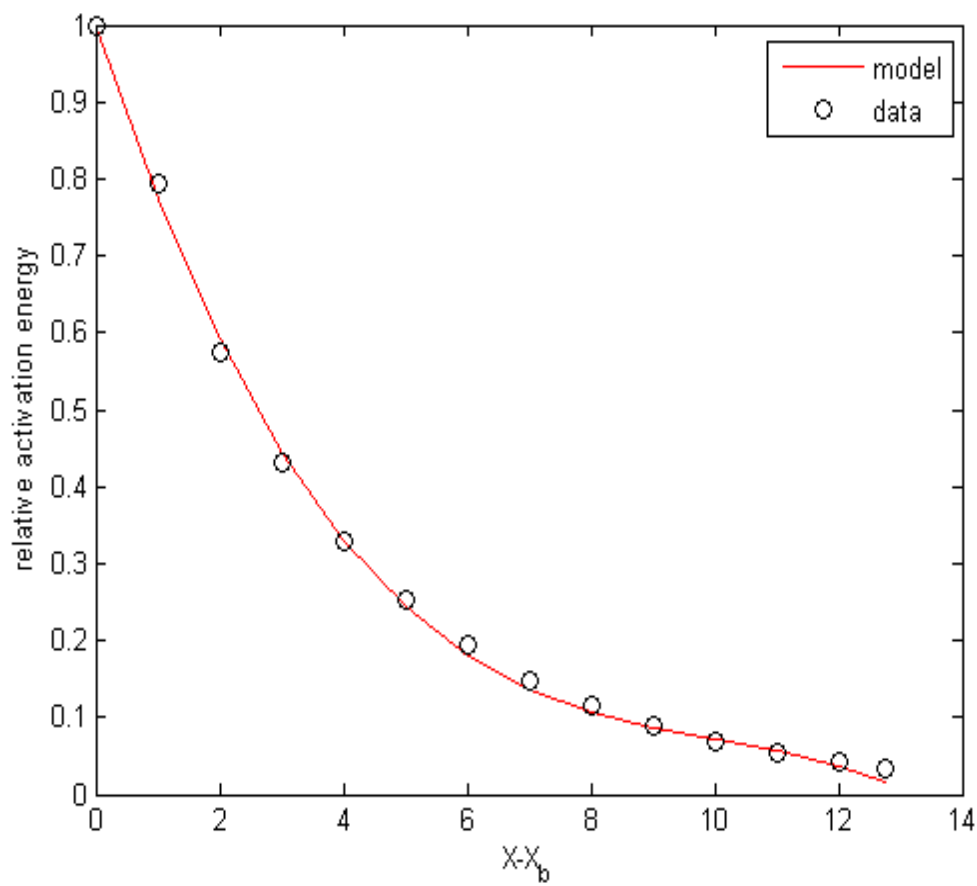
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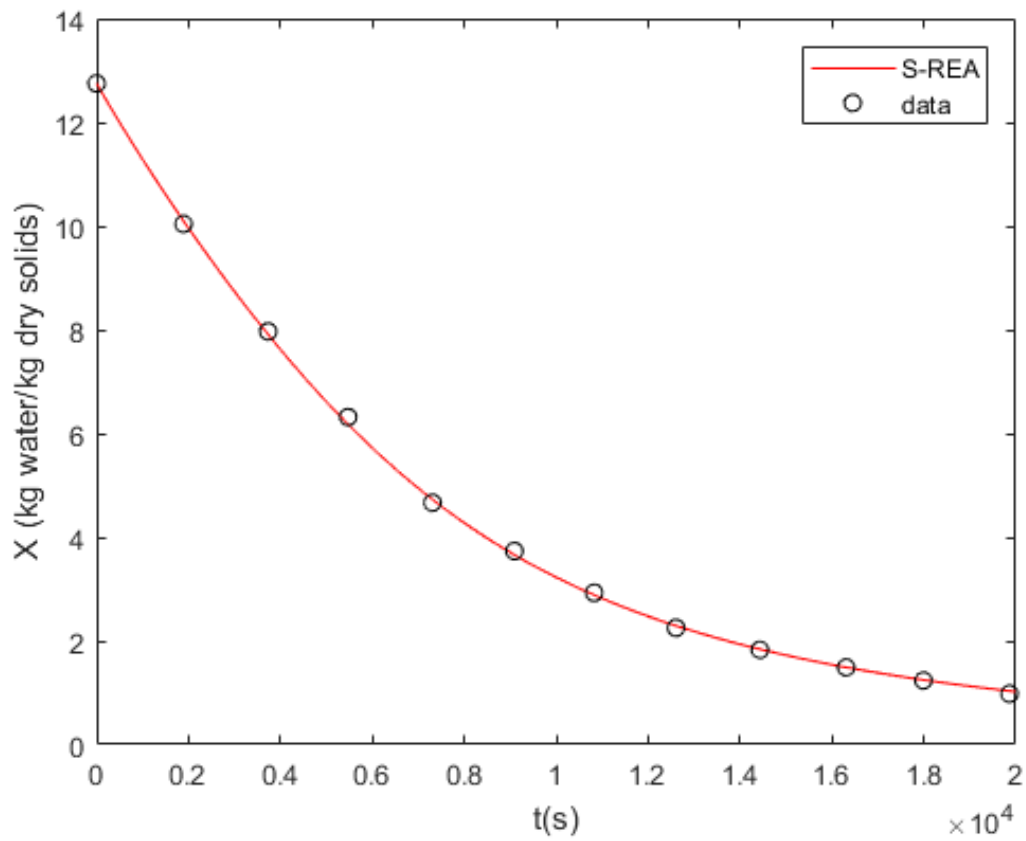
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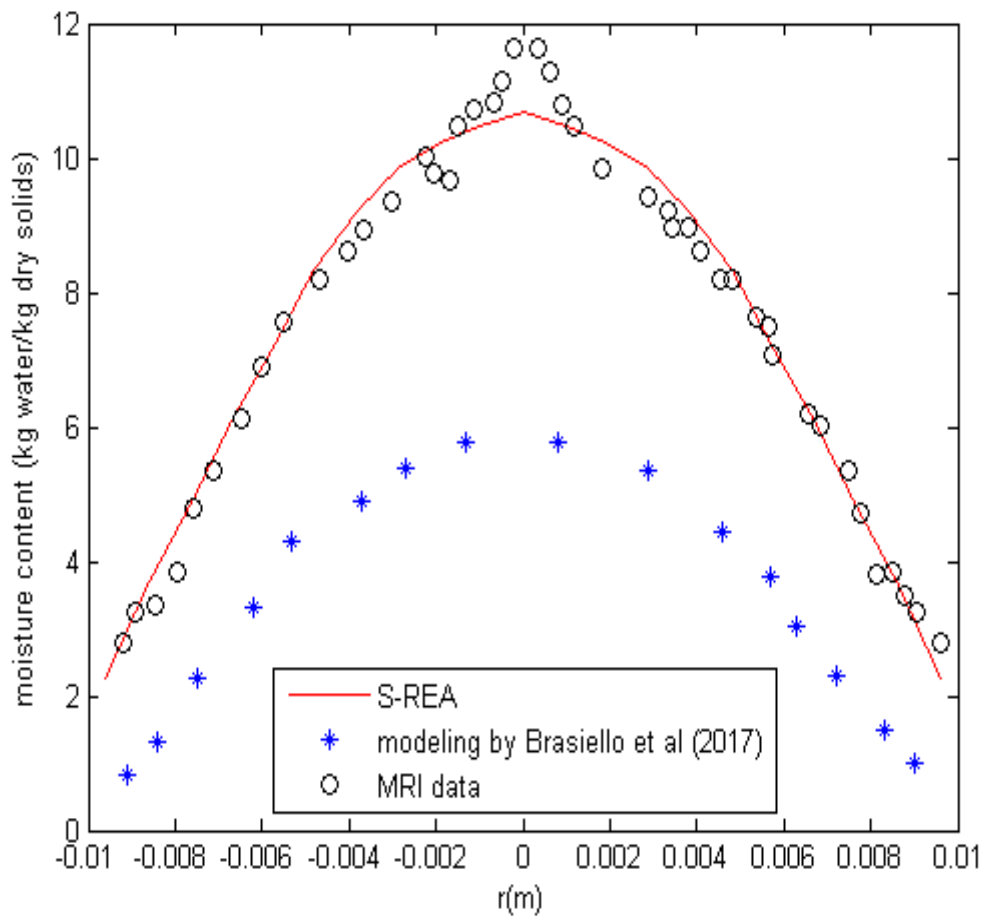
Figure 1. The relative activation energy of eggplant during convective drying at drying air temperature of 60 °C



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Figure 2. The average moisture content during convective drying at drying air temperature of 50 °C

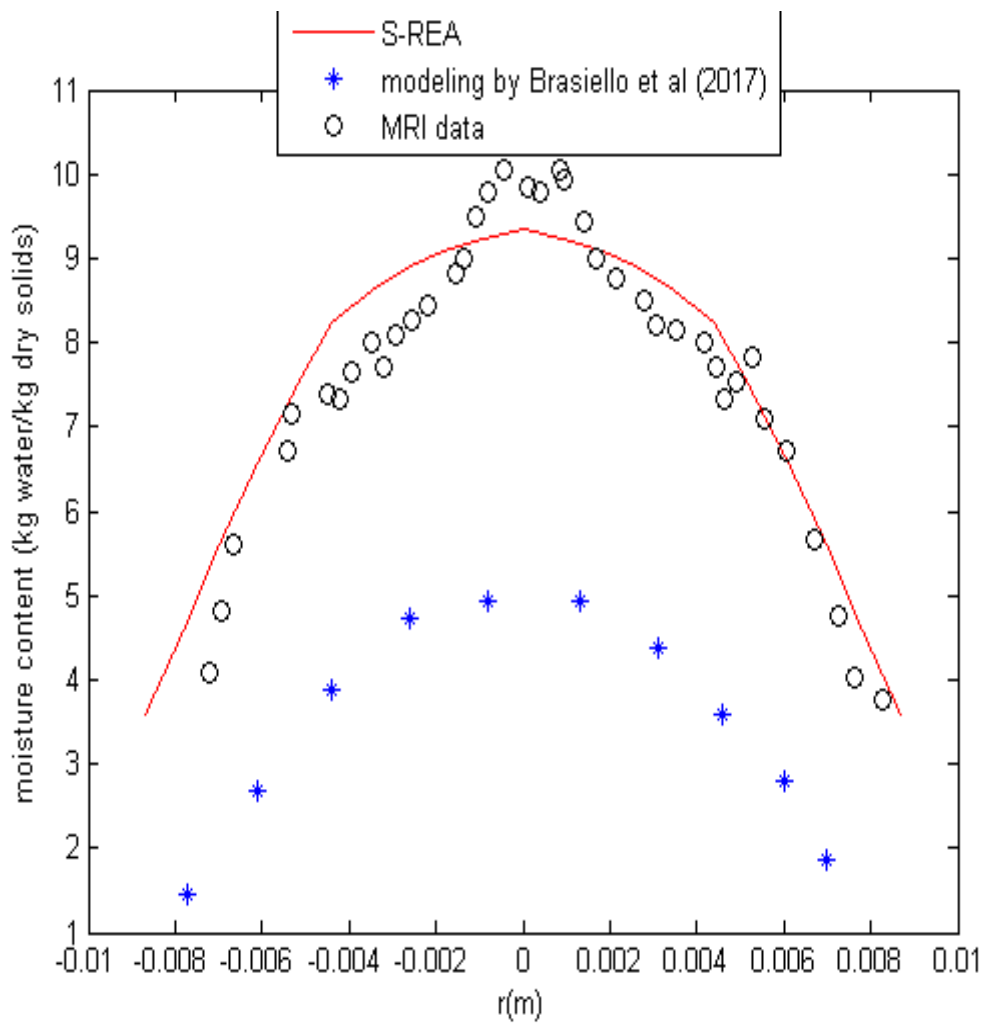
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Figure 3. The internal moisture content profiles during convective drying of eggplant at drying time of 1800 s

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679 **Figure 4. The internal moisture content profiles during convective drying of eggplant at**
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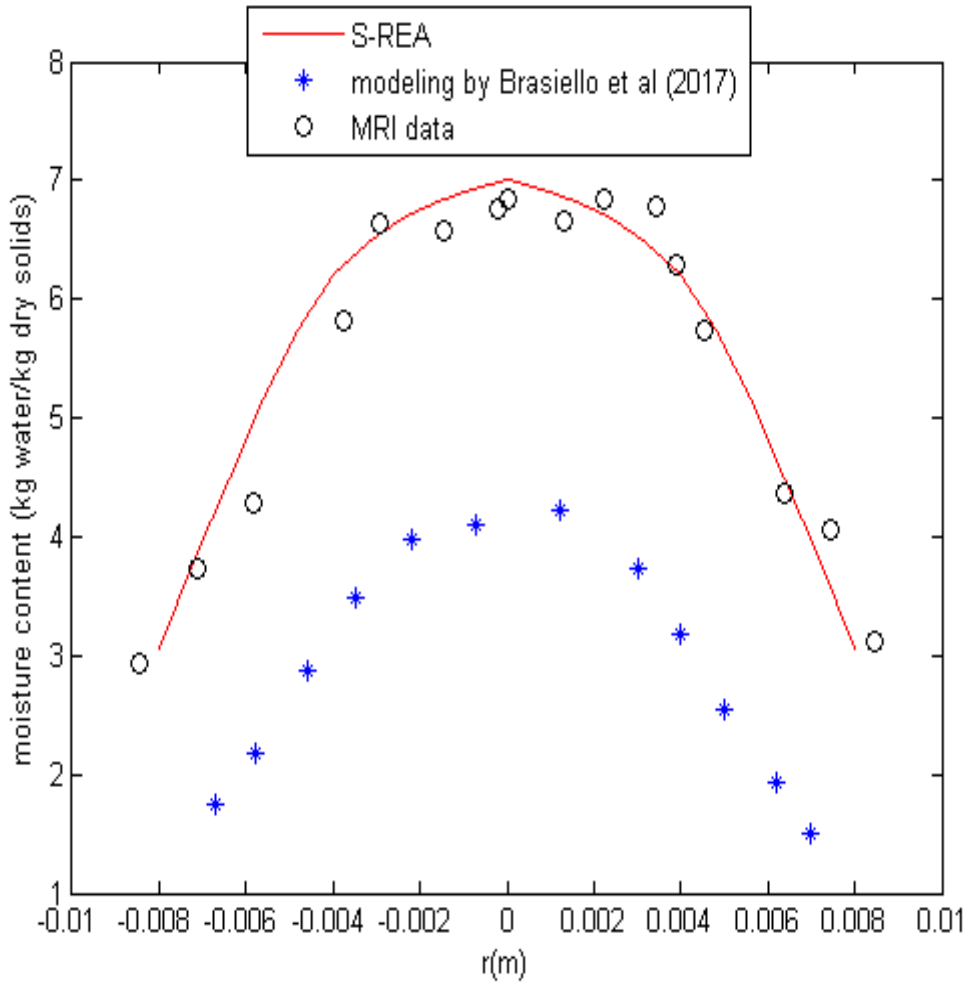
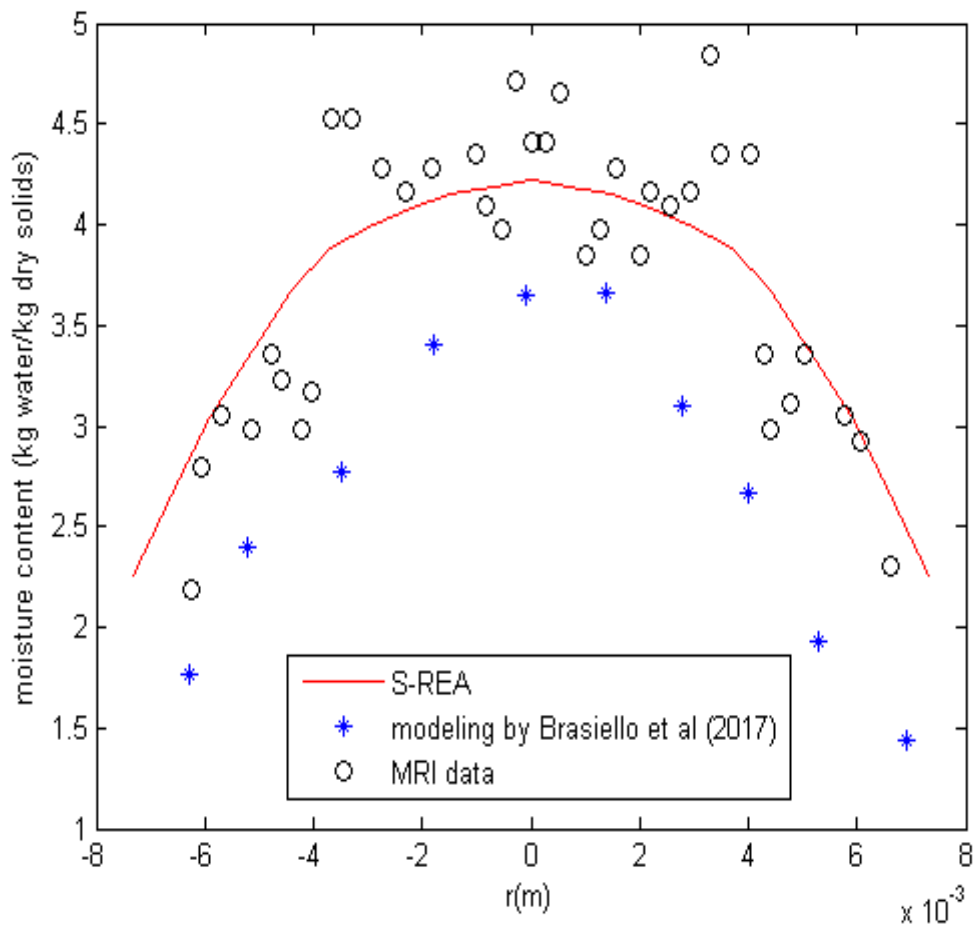


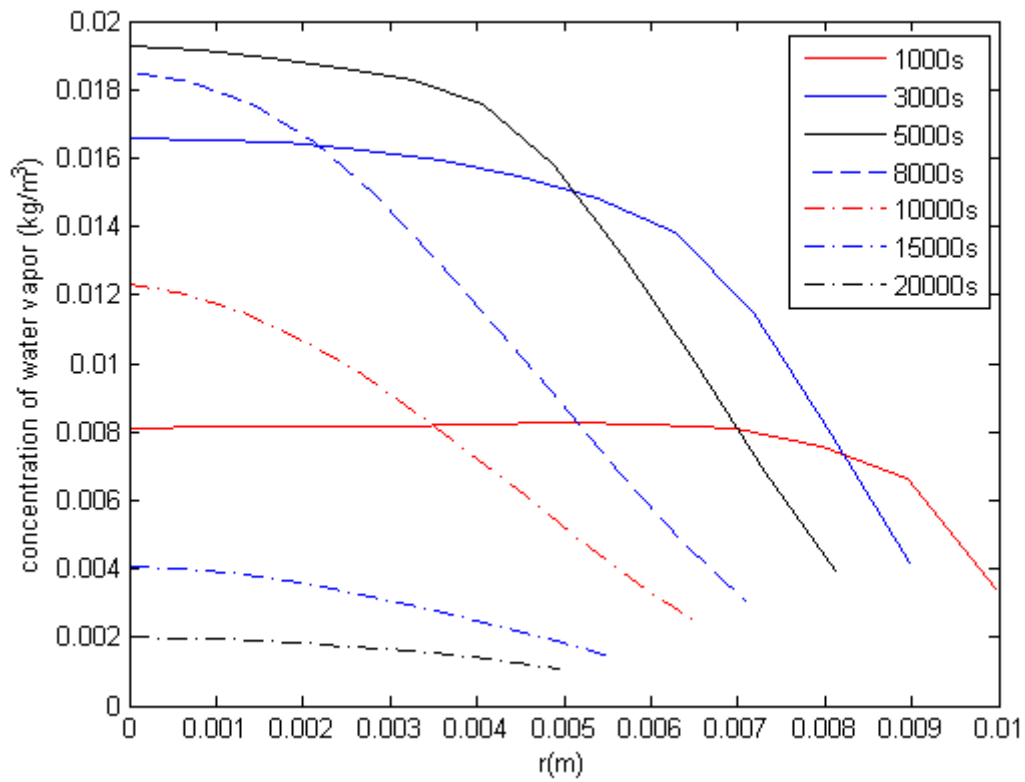
Figure 5. The internal moisture content profiles during convective drying of eggplant at drying time of 5400 s

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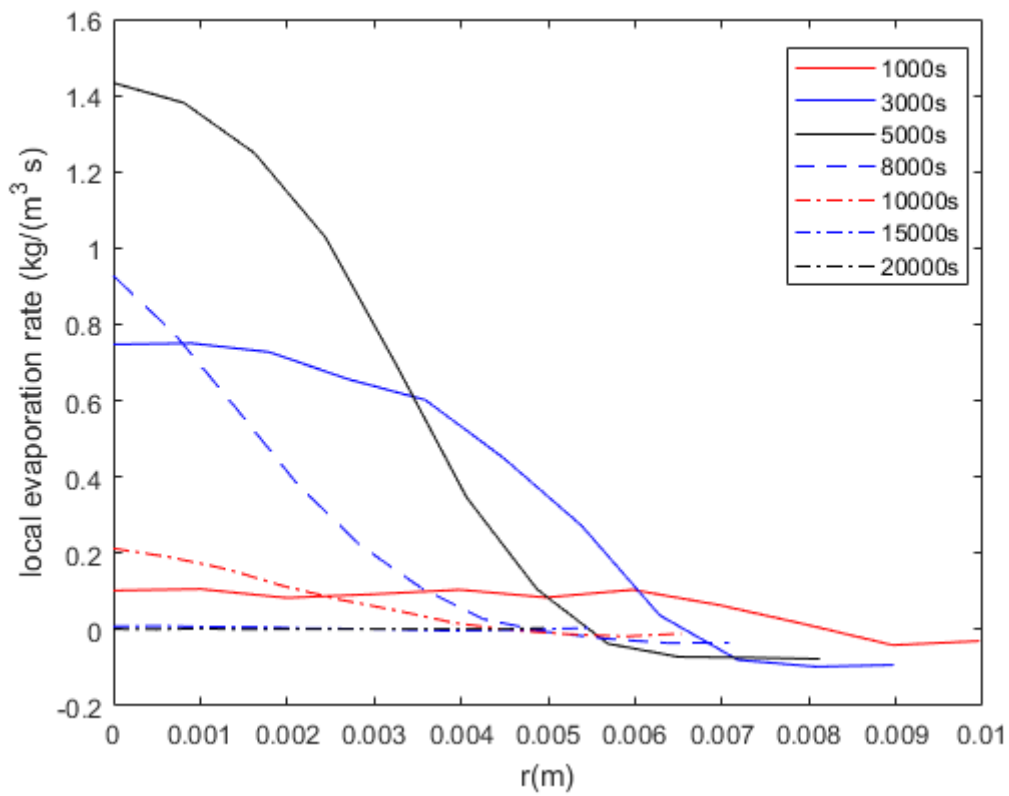


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Figure 6. The internal moisture content profiles during convective drying of eggplant at drying time of 7200 s

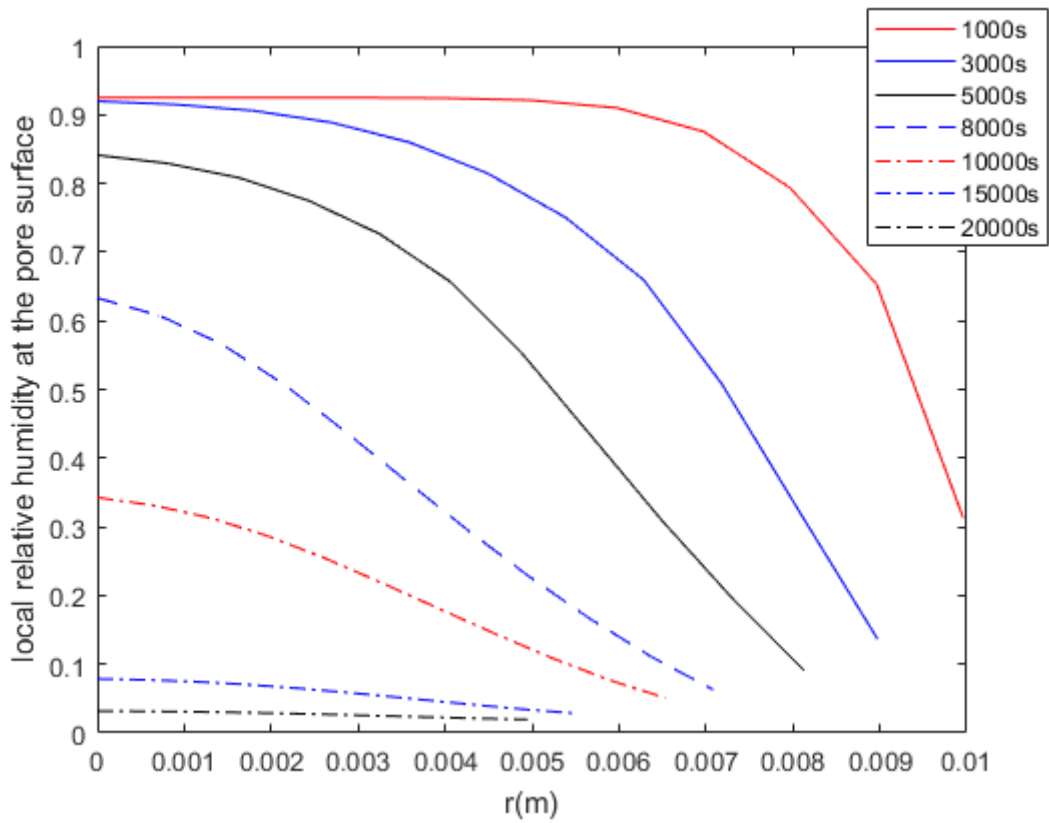


739 **Figure 7. The spatial profiles of concentration of water vapor during convective drying**
 740 **of eggplant at drying air temperature of 50 °C**
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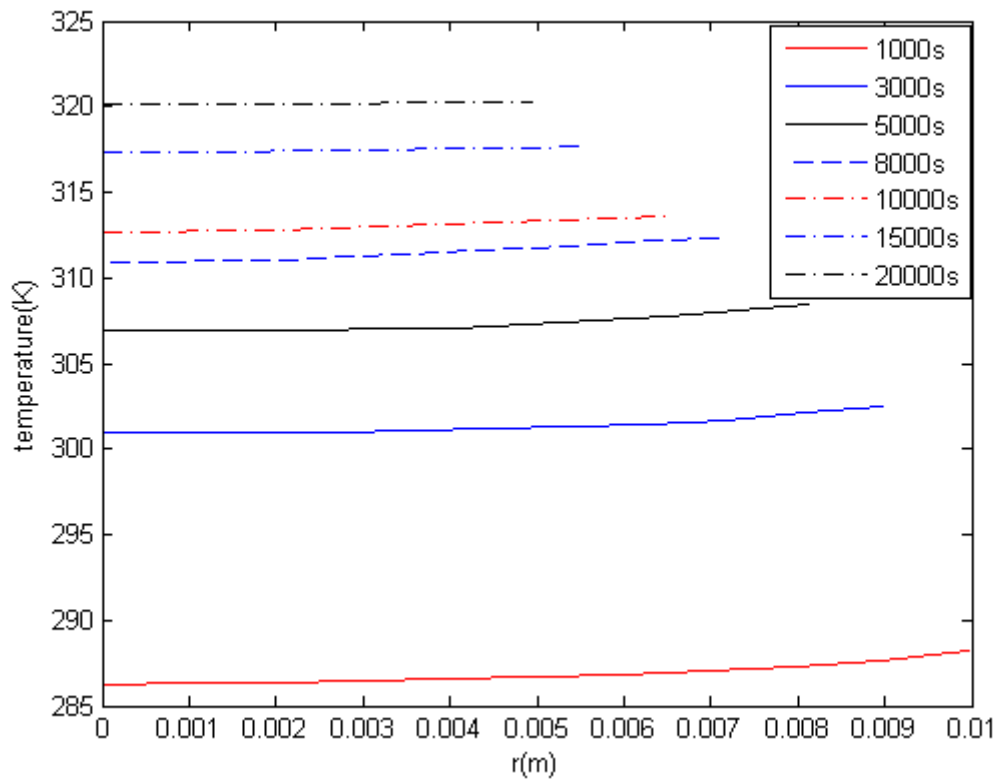


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Figure 8. The spatial profiles of local evaporation rate convective drying of eggplant at drying air temperature of 50 °C



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 772 **Figure 9. The spatial profiles of local pore surface relative humidity during convective**
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Figure 10. The spatial profiles of temperature during convective drying of eggplant at drying air temperature of 50 °C