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Computational fluid dynamics (CFD) modelling and experimental validation of thermal processing of canned fruit salad in glass jar

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Abstract: In this study, samples of commercial fruit salad (five different fruits with various geometries and thermal properties) were used for the experiments in order (i) to study the thermal behaviour of fruits during the heat treatment and (ii) to develop a computational fluid dynamics model to investigate the temperature profiles during samples processing. Simulation data were validated with the experimental ones obtained by means of a pilot plant. Results showed a good fit between theoretical and experimental data, both for syrup and fruit pieces. Experimental F values varied as a function of the type of fruit, its position, dimension and thermal property and they were shown to be influenced by the natural convection motion of the syrup. The proposed model can be used for the simulation and prediction of thermal processes of canned fruit salad, though better reliability (by reducing the differences between theoretical and experimental data and by studying the influence of fruit position inside the jar during the thermal process) can be achieved.



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To: Editor-in-Chief of Journal of Food Engineering

Dear Professor,

I would like to submit to your attention a research paper on "Computational Fluid Dynamics (CFD) Modelling and Experimental Validation of Thermal Processing of Canned Fruit Salad in Glass Jar", by *M.Cordioli, M.Rinaldi, G.Copelli, P.Casoli and D.Barbanti*, for the publication in the Journal of Food Engineering.

As reported in the instruction for authors, the manuscript has been deeply reviewed by a native English speaker.

Each decision and suggestion from you and referees will be useful to us in order to improve the scientific quality of the paper.

Parma, 02.25.2014

With my Best Regards

Davide Barbanti

A handwritten signature in blue ink that reads "Barbanti Davide".

Highlights

Heat distribution was optimized during thermal treatment of fruit salad

A computational fluid dynamics model was used to investigate the temperature profiles

Simulation data were validated with those of experimental trials

The CFD model can be used for the simulation and prediction of thermal processes

1 **Computational Fluid Dynamics (CFD) Modelling and Experimental Validation of Thermal**
2 **Processing of Canned Fruit Salad in Glass Jar**

3

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15 **Abstract**

16 In this study, samples of commercial fruit salad (five different fruits with various geometries and
17 thermal properties) were used for the experiments in order (i) to study the thermal behaviour of
18 fruits during the heat treatment and (ii) to develop a computational fluid dynamics model to
19 investigate the temperature profiles during samples processing. Simulation data were validated with
20 the experimental ones obtained by means of a pilot plant. Results showed a good fit between
21 theoretical and experimental data, both for syrup and fruit pieces. Experimental *F values* varied as a
22 function of the type of fruit, its position, dimension and thermal property and they were shown to be
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24 simulation and prediction of thermal processes of canned fruit salad, though better reliability (by
25 reducing the differences between theoretical and experimental data and by studying the influence of
26 fruit position inside the jar during the thermal process) can be achieved.

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28

29

30 **Keywords:** CFD, Thermal processing, Canned fruit salad, Natural convection, Conduction.

31 **1.Introduction**

32 In the food industry, a great number of fruits and vegetables are packaged in cans or jars, filled with
33 an appropriate sugar syrup or brine, and thermally processed in order to increase their shelf life
34 through the inactivation of both spoilage microorganisms and enzymes (Kiziltas et al., 2010).

35 Heat transfer mechanisms in canned food are conduction for solid and high viscosity liquid foods,
36 natural convection for low viscosity liquid foods, convection plus conduction for liquid foods with
37 solid particles and convection followed by conduction for liquid foods containing starch or viscosity
38 modifiers (Chen and Ramaswamy, 2007).

39 Moreover, it is widely known that quality as well as nutritional characteristics of foods can be
40 dramatically reduced by the thermal stabilisation processes. Hence, time and temperature
41 combination during the heating and the cooling cycles must be properly assessed to guarantee both
42 effectiveness (inactivation of microorganisms and enzymes) and efficiency (retention of sensory
43 and nutritional characteristics as well as limiting of costs). As a consequence, the thermal process
44 must be properly designed by studying the thermal properties of foods and the mechanism of heat
45 transfer during the treatment. These purposes are normally achieved by a relevant number of
46 experimental trials with an increase in costs and time consumption thus reducing the possibility to
47 have fast, efficient and in-depth results (Sun, 2007).

48 In order to overcome these limits, in the last years, process design in the food industry has been
49 increasingly carried out by using numerical solutions of process governing equations, modelling
50 and calculation methods (Weng, 2005).

51 Among these, Computational Fluid Dynamics (CFD), has found widespread application in many
52 areas of food processing such as spray drying, baking, sterilization, heat exchangers design,
53 chilling, mixing, fermentation and in the agri-food industry (Sun, 2007).

54 CFD is a simulation tool which uses powerful computers and applied mathematics to model fluid
55 flow situations for the prediction of heat, mass, momentum transfer and optimal design in industrial

56 processes (Xia and Sun, 2002; Kuriakose and Anandharamakrishnan, 2010; Anandharamakrishnan,
57 2011; Chhanwal et al., 2012). Several works deal with CFD simulations of canned foods: Kumar et
58 al. (1990) simulated the natural convection in canned thick viscous liquid foods; Ghani et al.
59 (1999a, 2002) studied the natural convection heating of canned foods in vertical and horizontal
60 positions, showing faster heating in the vertical can, which is expected due to the enhancement of
61 natural convection caused by its greater height. The effect of the inclination of container walls and
62 geometry modification on the sterilization process was also investigated by Varma and Kannan
63 (2005).

64 A few works have been published on the CFD simulation studies of canned foods with solid/liquid
65 mixture. These include heat transfer and liquid flow prediction during the sterilization of large
66 particles in a cylindrical vertical can (Rabiey et al., 2007) and the heat transfer in canned peas under
67 pasteurization (Kiziltas et al., 2010). Ghani and Farid (2006) analysed and successfully modelled
68 the thermal sterilization process of canned solid-liquid food mixture (pineapple slices with
69 governing liquid) in metal cans, indicating that natural convection effects in the liquid played a
70 significant role in the evolution of temperature. In the same way, Dimous and Yanniotis (2011)
71 studied the temperature profile, the velocity profile and the slowest heating zone in a still can filled
72 with food items with cylindrical-conical shape such as asparagus. With regard to pineapples,
73 Padmavati and Anandharamakrishnan (2013) investigated the effect of size reduction of the product
74 (pineapple slices vs. tidbits) on the effectiveness of heat transfer during thermal processing.

75 However, the scientific literature still lacks a comprehensive simulation study for the prediction of
76 temperature changes of solid-liquid mixtures where solids with different shapes and thermal
77 characteristics are dispersed in the liquid phase.

78 In this paper, samples of commercial fruit salad (composed of five different fruits with various
79 geometries and thermal properties) were canned in glass jars and submitted to heat treatment.

80 The objectives of this work were (i) to study the temperature distribution and the thermal behaviour
81 of both fruit pieces and syrup during the process and (ii) to develop and experimentally validate a
82 computational fluid dynamics (CFD) model of the process itself.

83

84 **2. Materials and Methods**

85 *2.1 Plant and process details*

86 The thermal treatment of fruit salad and sugar syrup in a glass jar was carried out in a small scale
87 static pasteuriser (JBT FoodTech, Parma, Italy), controlled by PLC. Inside the pasteuriser (width =
88 550 mm; length = 730 mm) water was sprayed over the containers from two nozzles at a rate of
89 $2800 \text{ l}\cdot\text{h}^{-1}$ with a spread angle of 120° . Hot water temperature was set at 93°C and samples were
90 heated from 22 to 85°C at the slowest heating point (SHP). The water was heated and cooled
91 through a “tube in tube” heat exchanger where the heating and cooling media were water vapour
92 and icy water, respectively. The jar was positioned at the centre of the pasteuriser between the
93 nozzles and was surrounded with other jars (filled with the same product) in order to reproduce the
94 operating conditions of the industrial process.

95 During trials, only the heating phase of the thermal processing was studied.

96

97 *2.2 Sample characteristics*

98 The fruit salad was composed of five different fruits (percentage expressed by weight): peach
99 (52%), pear (38%), pineapple (5%), grape (3%) and cherry (2%). Peach and pear were cubic with
100 sides of 10 and 8 mm, respectively. Pineapple had a truncated pyramid geometry (such as a titbit,
101 with a thickness of 5 mm and major edge of 10 mm). Cherry had a hemispherical geometry with a
102 radius of 8 mm, with a spherical hole at the centre (due to destoning) with a radius of 4 mm. The
103 grape had an ellipsoidal geometry, with major and minor axis of 8 and 5 mm, respectively (**Figure**
104 **1**). The fruits were inserted into the jar simulating an industrial filling process in the order peach,

105 pear, pineapple, grape and cherry. The jar was then filled with 16.7% (w/w) sucrose solution
106 measured with an electronic refractometer (Sinotech, Fujian, China). The solid/liquid ratio was
107 61:39, the same as those of commercial samples. The jar used for the trials had a filling volume of
108 372 ml, diameter = 86.0 mm; height = 90.5 mm. Glass thickness was measured with a calliper at
109 different locations on the side and bottom surfaces of the container and resulted in an average value
110 of 3.5 mm. Prior to experiments, the jar was hermetically closed with a screw metal cap with a
111 diameter of 85 mm.

112

113 *2.3 Data acquisition*

114 The temperatures inside the jar were measured using thermocouples (K-type; Ni/Al-Ni/Cr)
115 connected to a multimeter acquisition system (Yokogawa Electric Corporation, Tokyo, Japan). A
116 stainless steel multipoint temperature probe was positioned along the central axis of the jar through
117 a hole made in the centre of the cap. This multipoint probe (length = 97.5 mm; diameter = 3.5 mm)
118 included four thermocouples spaced every 13 mm from the tip of the probe in order to record the
119 syrup temperature at four different heights (17.5, 30.5, 43.5 and 56.5 mm) from the bottom of the
120 jar. The temperature of fruit pieces was obtained by using five wire thermocouples (diameter = 0.9
121 mm) inserted at the core of each fruit. The temperature at half the height of the outer wall of the jar
122 was also measured. Both for multipoint probe and single thermocouples, an acquisition rate of 2 s
123 was used and time-temperature data were collected in an Excel® ASCII worksheet.

124

125 **3. CFD modelling**

126 *3.1 Geometry of fruit salad in the glass jar*

127 The process of thermal treatment of fruit salad in a glass jar was simulated by means of a
128 multidimensional CFD (Computational Fluid Dynamic) model. The observed spatial placement of
129 the fruit salad inside the container was replicated in a 3D CAD model. In order to reduce the

130 computational effort required by the solution of the CFD model, the spatial domain was assumed to
131 be symmetric with regard to two perpendicular planes through the vertical axis of the jar, hence
132 only a quarter of the jar needed to be simulated.

133 The fruit pieces were spatially arranged on a regular grid (8 rows evenly distributed over the full jar
134 height), and the spacing carefully chosen in order to obtain a solid/liquid content ratio as close as
135 possible to that measured in the experimental tests. The resulting spatial arrangement of the fruit
136 pieces in the model of the jar is depicted in **Figure 2**.

137 The model geometry was then imported into the ICEM CFD® software (Canonsburg, Pennsylvania,
138 USA) and discretized into an unstructured tetrahedral mesh. The maximum element dimension
139 was chosen taking into consideration the domain (solid, fluid and glass). The values of maximum
140 element edge dimension for the different fruit pieces inside the jar, together with syrup and glass are
141 reported in **Table 1**.

142 Following the approach used by Kiziltas et al. (2010) and Dimou et al. (2011), in order to reduce
143 the complexity of multiphase fluid calculation, the headspace was not considered in the simulation
144 assuming the jar completely filled with product.

145 In order to accurately calculate the flow field near the wall of the jar, six layers of flat prismatic
146 wedge element were used for the discretization of the fluid domain. The optimal number of wall
147 boundary layers needed to obtain an appropriate level of accuracy was identified by means of a
148 layer-independence analysis, which suggested a value for the dimension of the first element near the
149 wall equal to 0.04 mm with a height ratio of 1.2 between layers. The final mesh with solid and fluid
150 elements consists of 3×10^6 elements (**Figure 3**).

151

152 *3.2 Numerical model*

153 The evaluation of the field of fluid flow and thermal exchange occurring in the considered domain
154 due to natural convection required numerical solution of the generalized transport equations:

155 a) Continuity Equation

$$156 \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (1)$$

157 b) Momentum Equation

$$158 \quad \frac{\partial \rho V}{\partial t} + \nabla \cdot (\rho V \cdot V) = \nabla \cdot (-p \delta + \mu(\nabla V + (\nabla V)^t)) + S_M \quad (2)$$

159 c) Energy Equation

$$160 \quad \frac{\partial \rho h_{total}}{\partial t} - \frac{Dp}{Dt} + \nabla \cdot (\rho V h_{total}) = \nabla \cdot (k \Delta T) + S_E \quad (3)$$

161 Where t is the time, V is the velocity vector, ρ is the density, p is the pressure, μ is dynamic
162 viscosity, k is thermal conductivity, h_{total} is the specific total enthalpy.

163 The software Ansys® CFX 14.5 (Canonsburg, Pennsylvania, USA) was chosen for the calculation.

164 Natural convection was modelled using the Boussinesq approximation, which uses a constant
165 density fluid model, but applies a local body gravitational force throughout the fluid that is a linear
166 function of thermal expansivity β and of the local temperature difference. The buoyancy source is
167 added to the momentum equation as follows:

$$168 \quad S_M = -\rho_{REF} \beta (T - T_{REF}) \quad (4)$$

169 Where ρ_{ref} and T_{ref} are the density and temperature at the boundary wall condition and g is the
170 gravitational force.

171 No internal energy source terms (S_E) were taken into account.

172

173 3.3 Boundary conditions

174 A uniform time varying temperature condition was applied to all the external surfaces of the jar and
175 corresponded to that measured in the experimental tests. The value of initial temperature of fruit and
176 syrup was 22°C, while the variation of the outer wall temperature with time during the heat
177 treatment is showed in **Figure 4** (black dotted line).

178 Since the maximum Rayleigh number Ra , as estimated using the maximum temperature difference
179 and the maximum viscosity, remained lower than 10^6 during the whole thermal treatment, laminar
180 flow was adopted for all the simulations.

181 An adaptive time step option was used in order to maintain the Courant number lower than 1; the
182 maximum time step of 0.5 s was reached during heating phase. High resolution advection schemes
183 were adopted for all simulations, in order to achieve second order accuracy. The convergence
184 criterion was defined as residual root mean square (RMS) value lower than 10^4 .

185

186 *3.4 Thermal and physical properties*

187 Values of thermal and physical properties such as density (ρ), viscosity (μ), specific heat (Cp) and
188 thermal conductivity (k) of fruits, syrup and glass were needed for the definition of the model and
189 the values used are summarized in **Table 1**. The viscosity of the syrup was assumed to be a function
190 of temperature and a linear interpolation from experimental data was used.

191

192 *3.5 Model validation*

193 The developed model was validated by comparing experimental temperature measurements at
194 specific points inside the glass jar with predicted ones. The accuracy of the model prediction was
195 assessed by determining root mean square error ($RMSE$) and lethality (F_0). The equation for $RMSE$
196 determination can be expressed as:

$$197 \quad RMSE = \sqrt{\frac{\sum_{i=1}^n (T_E - T_P)^2}{N}} \quad (5)$$

198 where T_P is simulated temperature and T_E is measured temperature, at time t . The effect of heat
199 treatment and time with respect to the survival of a microorganism can be quantified by the
200 following F value equation (Holdsworth and Simpson, 2007):

$$F = \int_0^t 10^{(T-T_{ref})/z} dt \quad (6)$$

201

202 Lethality was calculated as an equivalent heating time at a constant temperature (T_{ref}) of 90°C and a
203 z value of 10°C as characteristic for pathogenic microorganisms and *Clostridium botulinum* spores
204 (Padmavati and Anandharamakrishnan, 2013).

205

206 **4. Results and discussion**

207 *4.1 Validation results*

208 The simulation results were in agreement with the experimental data for both the syrup and the
209 fruits, as shown in **Table 2**, where validation parameters at each measurement point are reported (4
210 and 5 points for syrup and fruits, respectively). No significant differences were observed between
211 experimental and simulated F values, confirming the accuracy of the developed model. In addition,
212 in **Figure 4** and **5** heating curves of the experimental treatment and simulation for syrup and fruit
213 pieces are compared, respectively. The small variations in the results of the model may be due to
214 the distribution of the fruit pieces, the combined effects of the experimental and model assumptions
215 such as Boussinesq approximation and the thermal properties of the materials. Furthermore, during
216 the experiment, the location of the temperature sensor may change the liquid flow pattern and
217 hence, affects the temperature profile of the sugar solution. In the simulation, small-scale
218 instabilities were produced by the buoyancy effect. The buoyancy-produced structures might have
219 directly interacted with the existing local turbulence with the strong coupling where laminar
220 modelling could not successfully predict this effect.

221

222 *4.2 Slowest heating point (SHP) and temperature profile*

223 The identification of the slowest heating point (SHP) inside the container was considered of basic
224 importance for the effectiveness of thermal processing of our samples. The temperature distribution

225 inside the jar was then measured at different time steps in order to describe the convective
226 movement of the SHP.

227 When a fluid is subjected to a rapid temperature increase adjacent to a solid wall, part of the fluid in
228 the wall neighbourhood expands resulting in an increase in the local pressure with significant
229 effects in heat transfer due to thermal buoyancy effects in a gravitational force field (Aktas and
230 Farouk, 2003). In a similar way, during thermal processing of solid-liquid mixtures in cans, such as
231 canned fruit salad, syrup closer to the can walls receives the heat (undergoes heat flux) thus
232 resulting in volume expansion and density decrease while the syrup far from the walls is still at
233 lower temperature. This phenomenon leads to development of an upward buoyancy force with a
234 motion due to density differences. This movement also carries the colder fluid upward by viscous
235 drag. The fluid flowing upward is deflected by the top surface of the can and starts moving in a
236 radial direction and, by becoming heavier, starts to move downwards through the stack of fruits.
237 Consequently, its temperature decreases as it comes in contact with colder pieces of fruits and
238 syrup, and a new cycle starts from the bottom. These convective movements create a recirculating
239 flow thus increasing the rate of heat transfer. This observation is similar to the results obtained by
240 other Authors for natural convection heating mechanism (Ghani et al., 1999a; Padmavati and
241 Anandharamakrishnan, 2013). The maximum value of liquid velocity was observed close to the
242 wall of the jar (due to the higher temperature gradient between the jar wall and the thin liquid layer
243 close to the wall). When solid and impermeable particles were distributed into the fluid, the velocity
244 profile changed due to the heat exchange and surface deflections: the flow was very slow through
245 the stack of solid particles in the horizontal direction while on the contrary it showed an increase
246 between solids in the vertical direction.

247 In the case of pure convection heating of liquids, the slowest heating point (SHP) is located at about
248 10-15% of the can height (Padmavati and Anandharamakrishnan, 2013), but in the case of solid-
249 liquid food mixtures heated by a combination of conduction and convection, SHP location is more

250 complex to determine. Under our experimental conditions, the SHP of the canned fruit salad was
251 not at the geometric centre of the can nor at a can height of 10-15% but at an intermediate position
252 between these (19-20% of the can height). The position of SHP is well shown by the *F value* of the
253 various fruits: pear pieces presented the lowest *F value* because this kind of fruit was positioned
254 closer to the SHP.

255 The natural convection effects also influenced the heating of the fruit pieces. As shown in **Table 2**,
256 the fruits positioned close to the top of the jar showed a simulated *F value* higher than those placed
257 close to the bottom: grape = 8.80 min, peach = 4.16 min.

258 When there is a marked effect of natural convection heating, thermal stratification takes place
259 (observation based on the fluid movement due to buoyancy effects explained above). **Figure 6**
260 shows temperature stratification for the syrup during heating phase, at 4 different time steps (5, 10,
261 20 and 30 min), while **Figure 7** reports the temperature stratification along the fruit pieces at the
262 same time steps (both figures come from the graphical representation of the mathematical model).

263

264 **5. Conclusions**

265 In this study, a 3D CFD model was developed in order to investigate the temperature profiles, to
266 identify the slowest heating point (SHP) and to describe the flow field during the heating processing
267 of canned fruit salad composed of five kinds of fruit canned in a glass jar and filled with sugar
268 syrup.

269 Experimental *F values* were different among the various fruits and in particular they were a
270 function of position, dimension and thermal properties; moreover, experimental *F values* were also
271 greatly influenced by the natural convection motion of the syrup.

272 Concerning the proposed model, an appreciable agreement between simulated and experimental
273 measurements of temperature both for syrup and fruit pieces was obtained: the model can be

274 considered successfully validated and applicable for the simulation and prediction of thermal
275 processes of canned fruit salad.
276 An increase in the reliability of the model by minimizing the differences with experimental data and
277 by studying the influence of fruit position inside the jar during the thermal process can be achieved.

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Figure 1
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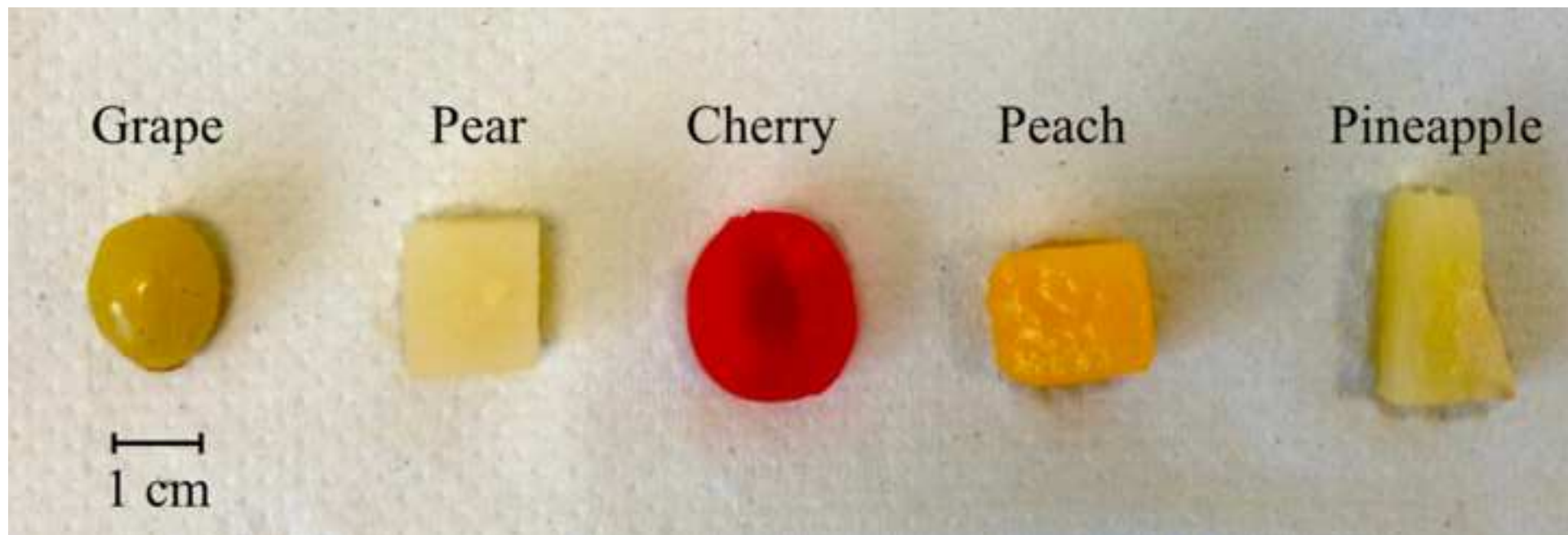


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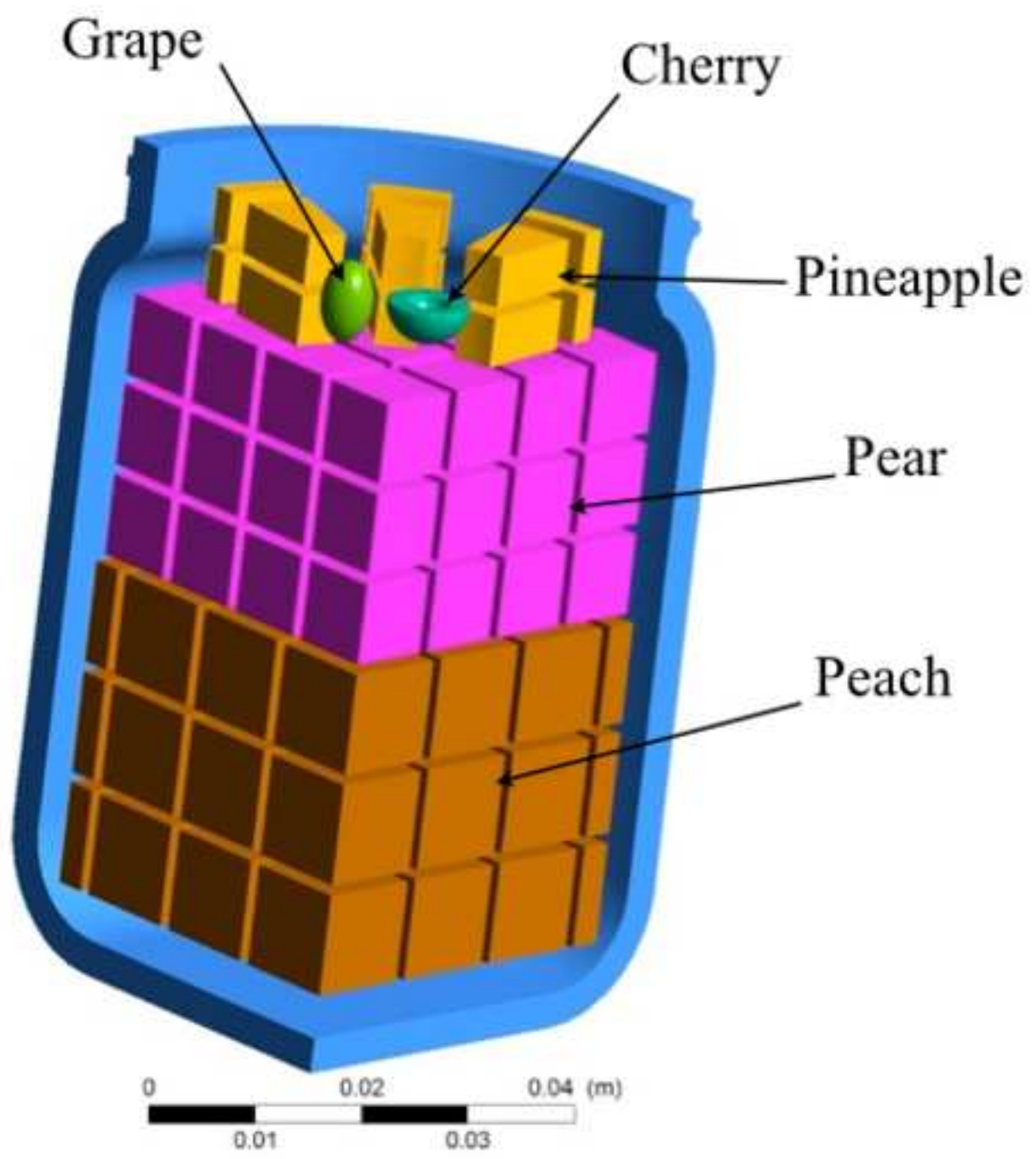


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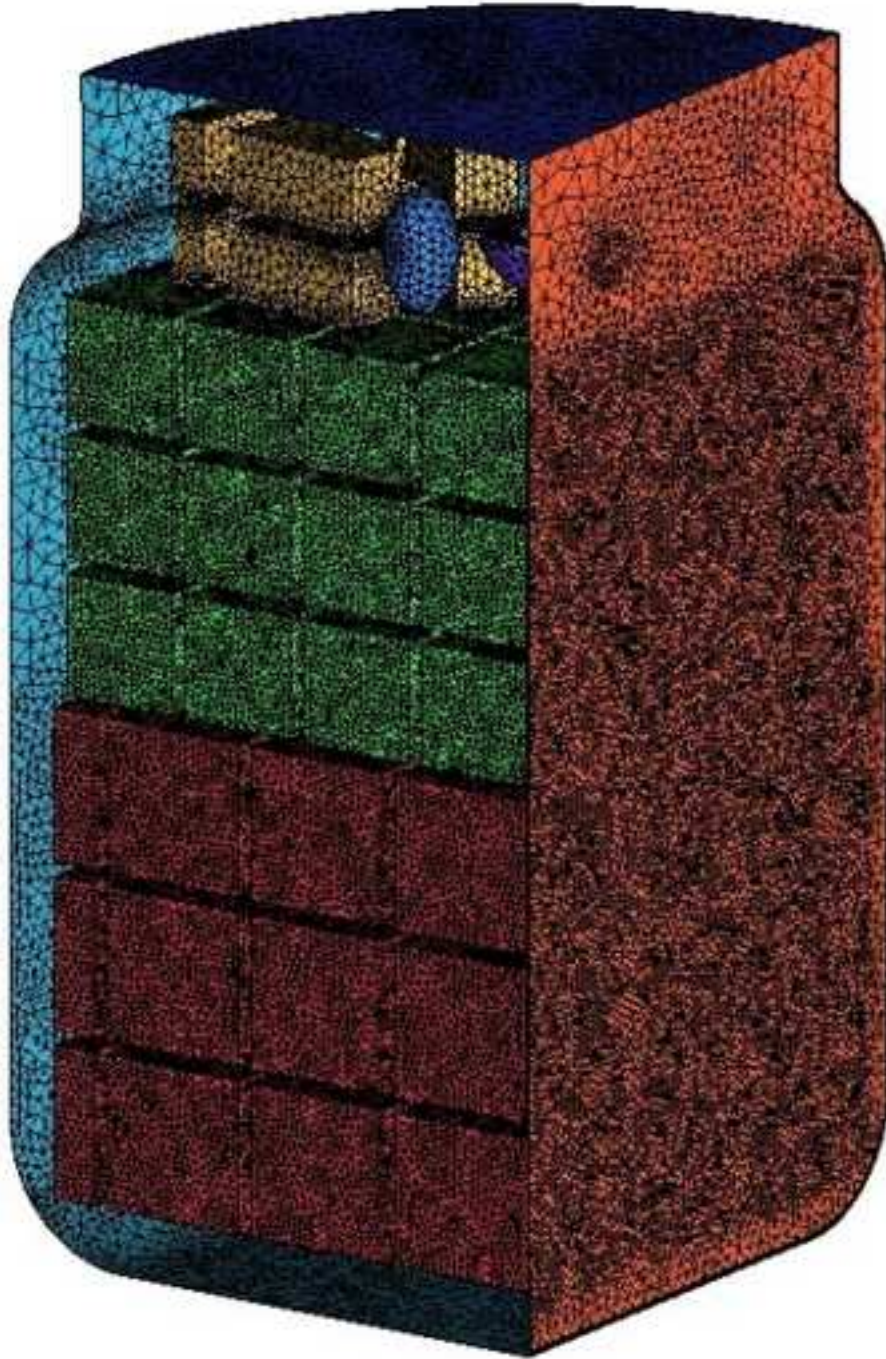


Figure 4
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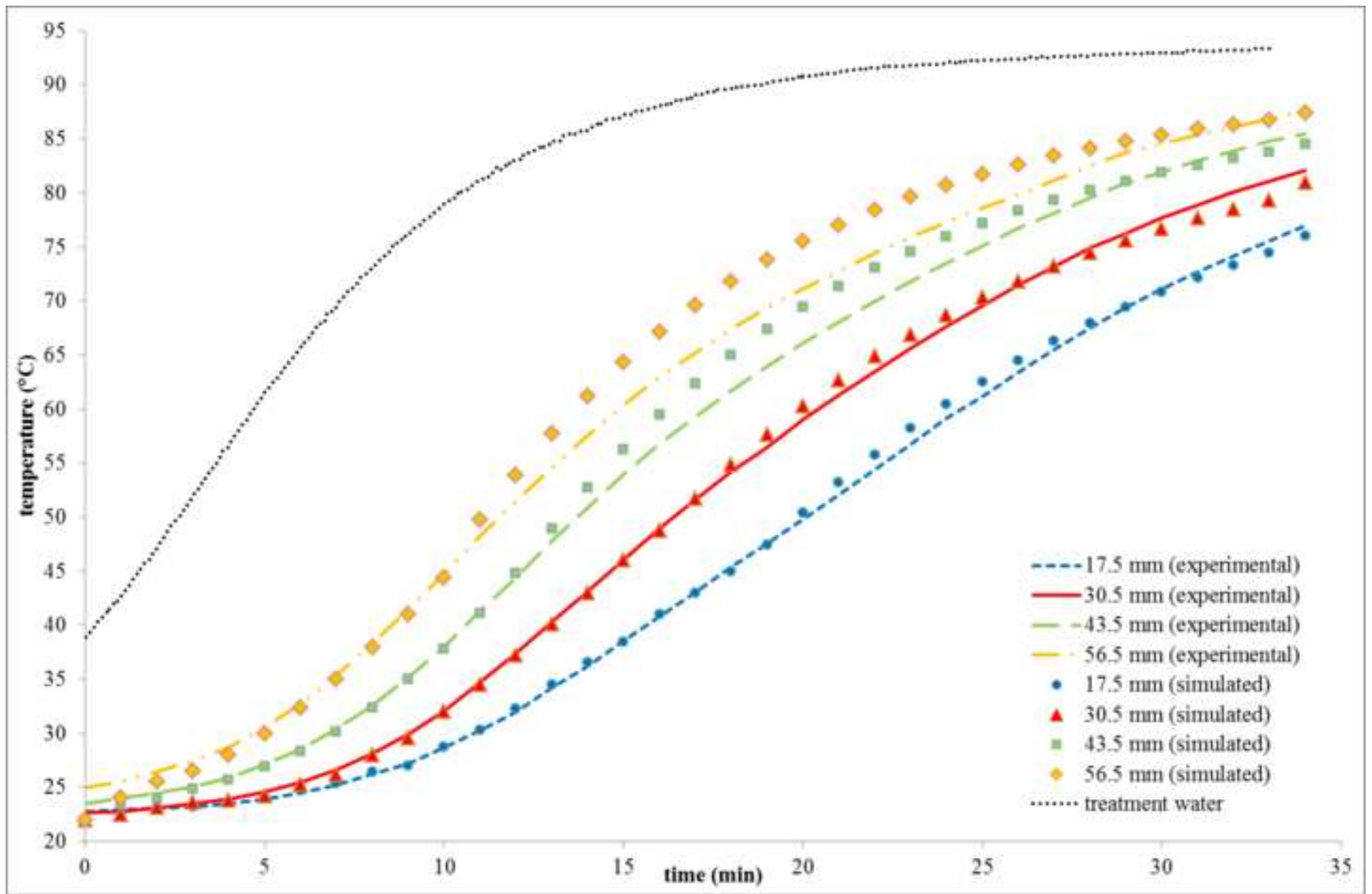


Figure 5
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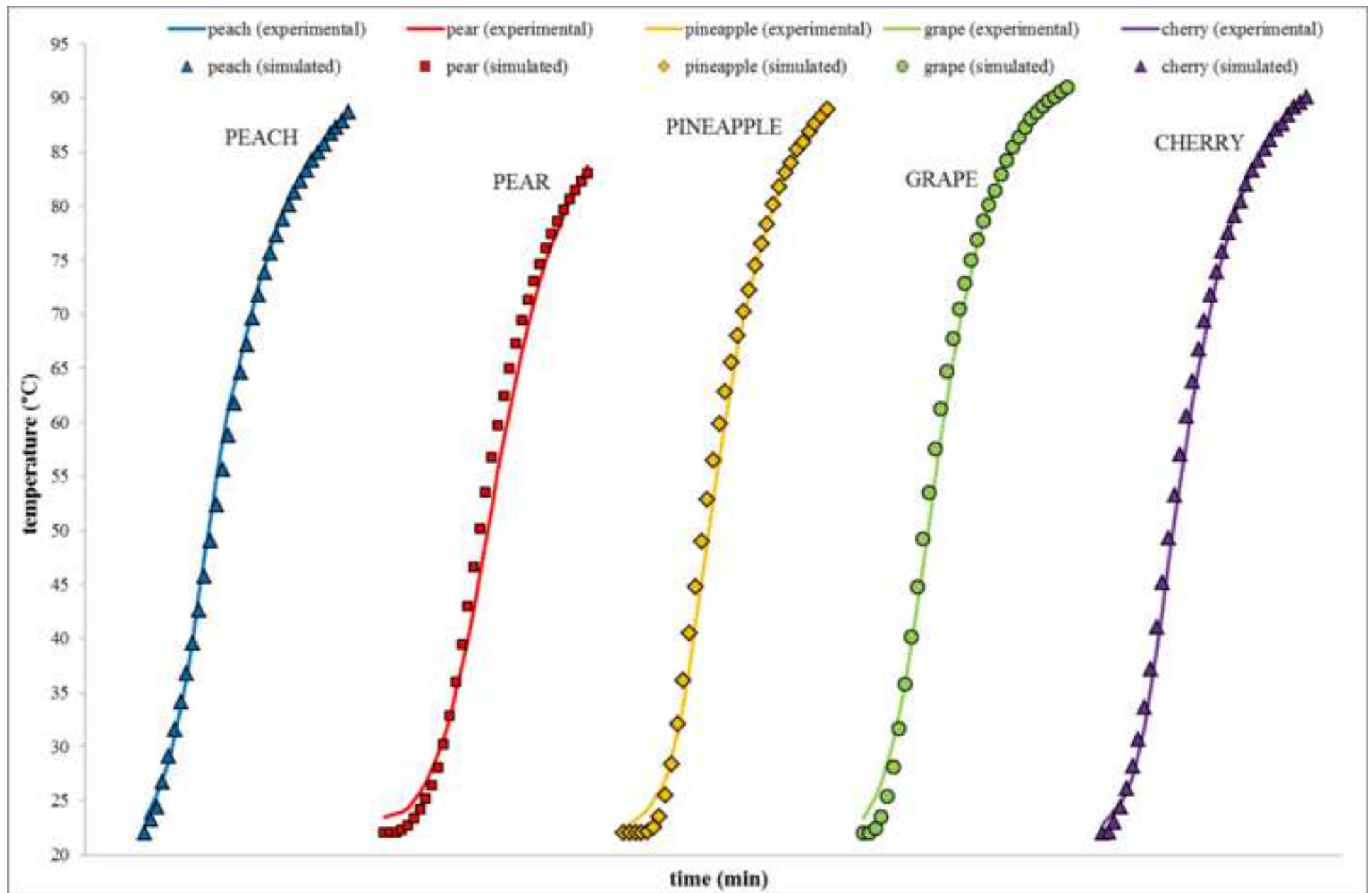


Figure 6
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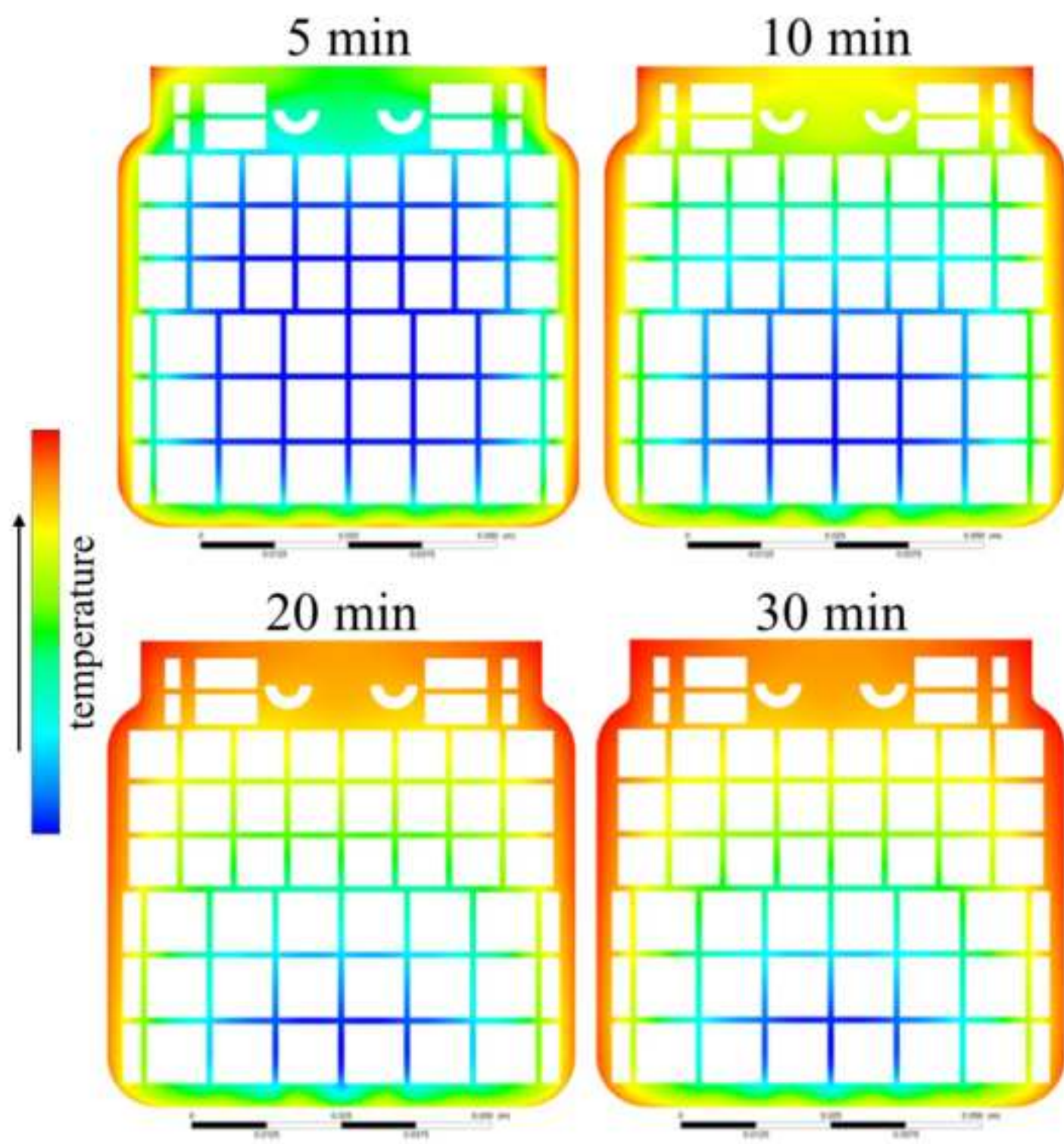
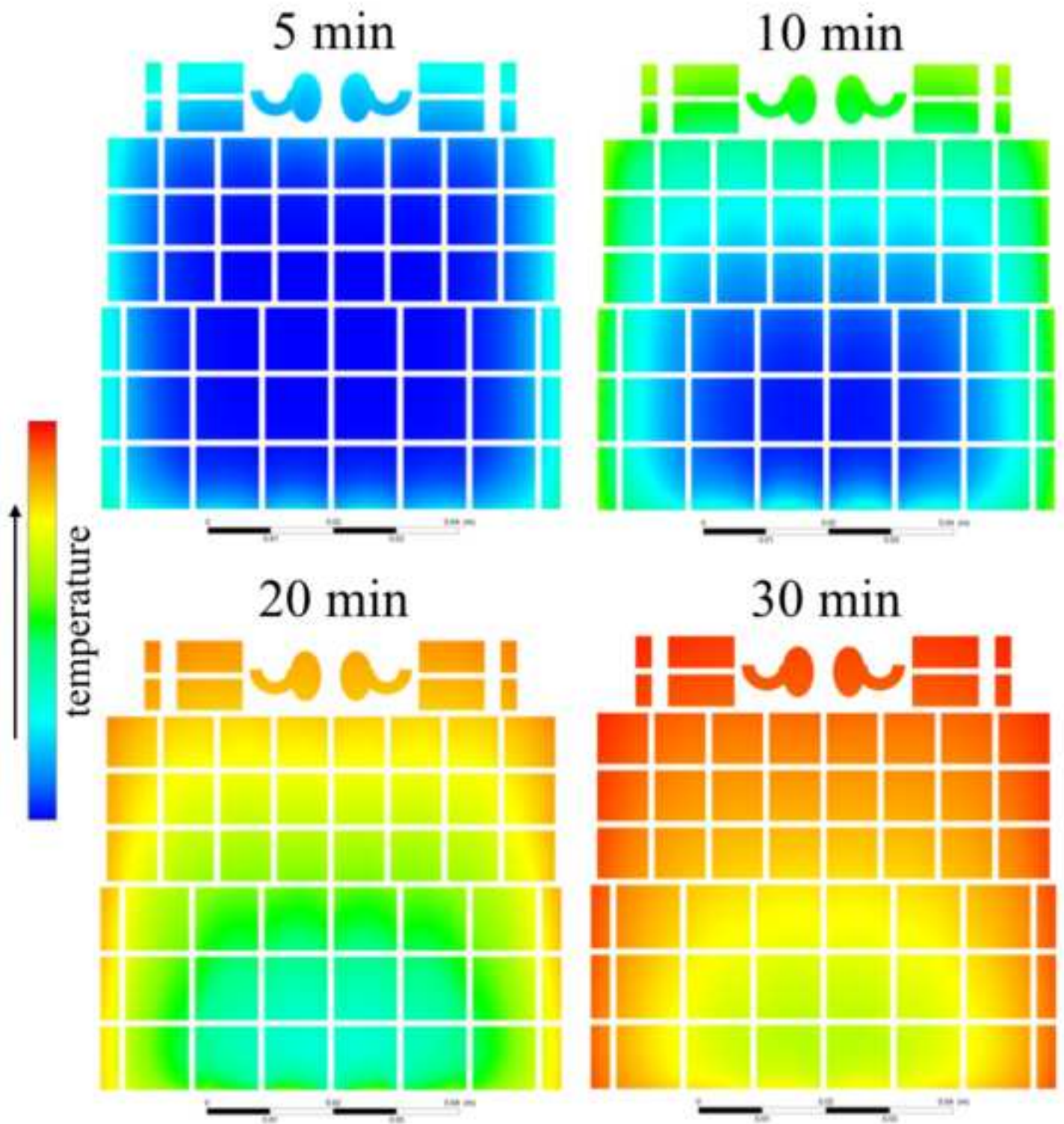


Figure 7
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Captions for Figures and Tables

Fig. 1 - Visual comparison of the different kind of fruits used in the experiments

Fig. 2 - 3D model of the distribution of the fruits inside the jar

Fig. 3 - 3D model of the fruits inside the jar with the mesh element

Fig. 4 - Comparison of temperature profile in syrup between experimental test and mathematical model

Fig. 5 - Comparison of the temperature profile in fruit pieces between experimental test and mathematical model

Fig. 6 - Temperature stratification of the syrup at 4 different time steps (from mathematical model)

Fig. 7 - Temperature stratification of the fruit pieces at 4 difference time steps (from mathematical model)

Table 1 - Thermal properties, rheological characteristic and maximum element edge dimension for all the different kinds of fruit inside the jar, together with syrup and glass

Table 2 - Validation results

Table 1

Food	ρ (kg/m ³)	μ (Pa s)	C_p (J/kg K)	k (W/m K)	Max edge length ^g (mm)
Syrup (16,7% sugar)	1074 ^g	0,0258-0,00023*T ^g	-	-	0.50
Peach	930 ^a	-	3700 ^a	0.581 ^b	1.70
Pear	1000 ^b	-	3800 ^c	0.595 ^b	1.50
Pineapple	1010 ^d	-	3490 ^d	0.549 ^d	0.80
Grape	1320 ^c	-	3325 ^e	0.273 ^e	0.45
Cherry	1049 ^b	-	3730 ^c	0.511 ^c	0.26
Glass	2500 ^f	-	750 ^f	1.400 ^f	2.00

^a from Whitelock et al. (1999);

^b from Rahman (2008);

^c from 2006 ASHRAE Handbook-refrigeration;

^d from Padmavati and Anandharamakrishnan (2013);

^e from Akhijahani and Khodaei (2013);

^f from Incropera et al. (2006);

^g experimental value.

Table 2

<i>Point of measurement</i>		<i>RMSE</i>	<i>Lethality ($F_{90,10}$)</i>		
			<i>Experimental</i>	<i>Simulated</i>	$\Delta F_{90,10}$
Syrup	17,5 mm	0.68	0.17	0.14	0.02
	30,5 mm	0.79	0.66	0.52	0.14
	43,5 mm	1.77	1.68	1.62	0.05
	56.5 mm	2.65	2.99	3.73	0.73
	Average	1.47			0.13
Peach		1.14	4.24	4.16	0.07
Pear		2.31	0.95	0.96	0.02
Pineapple		1.78	4.04	4.13	0.09
Grape		1.61	8.87	8.80	0.06
Cherry		1.31	6.24	6.27	0.03
Average		1.63			0.06