

# Convection Cooking of Chicken Patties

# Introduction

This example models the convection cooking of a chicken patty. The model was originally developed by H. Chen and others (Ref. 1).

To increase consumer convenience, many of today's food products are precooked so that you can quickly re-heat the product, for example in a microwave oven. One industrial precooking method is air-convection cooking. This example builds a time-dependent model of the convection cooking process for a chicken patty, and it shows the temperature rise over time in the patty.

This simulation also models the moisture concentration in the patty. From the viewpoint of product quality, it is of interest to minimize the loss of moisture during cooking. In this regard, cooking yield is a quantity that measures how much moisture, in percent, remains in the patty after the cooking process. Furthermore, the moisture concentration also influences the temperature field by heat loss due to vaporization and also by changing the patty's thermal conductivity.



Figure 1: Convection cooking of a chicken patty.

# Model Definition

This COMSOL Multiphysics example couples time-dependent interfaces describing the temperature and the moisture concentration, respectively. The simulation does not model the convective velocity field outside the patty because the coefficients for convective heat and moisture transfer to the surrounding air are given.

Inside the patty, diffusive processes describe both heat transfer and moisture transport.

The model assumes that the specific heat capacity increases with temperature according to the expression

$$C_p \,=\, 3017.2 + 2.05 \Delta T + 0.24 {(\Delta T)}^2 + 0.002 {(\Delta T)}^3 ~(\mathrm{J/(kg\cdot K)})$$

where  $\Delta T = (T - 0^{\circ} \text{C})$  and the dimensions of the numerical coefficients are such that the dimension of  $C_p$  is as stated.

Figure 2 depicts the patty's geometry, which is simple and allows for 2D axisymmetric modeling of its cross section. Additional symmetry in the cross section makes it possible to model just one quarter of the cross section.



Figure 2: Geometry of the chicken patty.

These simplifications result in a simple rectangular domain with the dimension 31 mm-by-5 mm. Figure 3 describes the boundary numbering used when specifying the boundary conditions.



Figure 3: Model domain and boundary numbering.

The equations describing moisture diffusion are coupled to the heat equation in the following two ways:

- The thermal conductivity, *k*, increases with moisture concentration according to  $k = (0.194 + 0.436(cM_{H2O}/\rho)) W/(m\cdot K)$ , where *c* is the concentration (mol/m<sup>3</sup>), M<sub>H2O</sub> the molar mass of water (kg/mol) and  $\rho$  is the density (kg/m<sup>3</sup>).
- The vaporization of water at the patty's outer boundaries generates a heat flux out of the patty. Represent this heat flux with the term λD∇c in the boundary conditions for Boundaries 3 and 4, where λ is the molar latent heat of vaporization (J/mol).

Assume symmetry for the temperature field on Boundaries 1 and 2. Air convection adds heat on Boundaries 3 and 34. According to the assumptions made earlier, add a term for the heat flux out of the patty due to moisture vaporization on Boundaries 3 and 4.

Summarizing, the boundary conditions for the heat transfer interface are

$$\begin{split} \mathbf{n} \cdot (-k \, \nabla T) &= 0 & \text{at } \partial \Omega_1 \text{ and } \partial \Omega_2 \\ \mathbf{n} \cdot (k \, \nabla T) &= h_T (T_{\text{air}} - T) + \lambda \mathbf{n} \cdot (D \nabla c) & \text{at } \partial \Omega_3 \text{ and } \partial \Omega_4 \end{split}$$

where  $h_T$  is the heat transfer coefficient (W/(m<sup>2</sup>·K)), and  $T_{air}$  is the oven air temperature. The boundary conditions for the diffusion are

$$\begin{split} \mathbf{n} \cdot (-D\nabla c) &= 0 & \text{at } \partial\Omega_1 \text{ and } \partial\Omega_2 \\ \mathbf{n} \cdot (D\nabla c) &= k_{\rm c}(c_{\rm b} - c) & \text{at } \partial\Omega_3 \text{ and } \partial\Omega_4 \end{split}$$

where *D* is the moisture diffusion coefficient in the patty  $(m^2/s)$ ,  $k_c$  refers to the mass transfer coefficient (m/s), and  $c_b$  denotes the outside air (bulk) moisture concentration  $(mol/m^3)$ . The diffusion coefficient and the mass transfer coefficient are given, respectively, by

$$D = \frac{k_{\rm m}}{\rho C_{\rm m}}, \qquad k_{\rm c} = \frac{h_{\rm m}}{\rho C_{\rm m}},$$

where  $C_{\rm m}$  equals the specific moisture capacity (kg moisture/kg meat),  $k_{\rm m}$  refers to the moisture conductivity (kg/(m·s)), and  $h_{\rm m}$  denotes the mass transfer coefficient in mass units (kg/(m<sup>2</sup>·s)).

Assume that the patty's temperature is  $22^{\circ}$ C at the start of the cooking process, and the moisture concentration in the patty at the air interface is  $1222 \text{ mol/m}^3 = 22 \text{ kg/m}^3$  on a wet basis, which means that the moisture is expressed in mass per volume of meat. Additional data are given in the modeling section below.

To obtain the temperature and moisture concentration over time, the model solves the equations with the boundary conditions discussed above.

# Results and Discussion

The most interesting result from this simulation is the time required to heat the patty from room temperature ( $22^{\circ}$ C) to at least 70°C throughout the entire patty. The section at the middle of the patty (at the lower-left corner of the modeling domain) takes the longest time to reach this temperature. It is also interesting to determine how much moisture remains in the patty after cooking. For this purpose, compute the cooking yield, defined as (initial moisture mass)/(final moisture mass).

The model shows that at an oven air temperature of 135°C, a cooking time of approximately 770 s is required to reach a center temperature of 70°C. Figure 4 shows how the temperature increases over time.



Figure 4: Temperature increase over time in the middle of the patty at an air temperature of 135°C.



Figure 5 illustrates the resulting temperature field after 770 s. The temperature at the lower-left corner is 70°C, and the temperature rises toward the outside boundaries.

Figure 5: Temperature field after 770 s at a cooking temperature of 135°C.

At this oven air temperature, the cooking yield is approximately 0.94 (94%). Figure 6 shows the resulting moisture concentration for these conditions. As expected, the



2

0 -2

-4 -6

-8-

0

5

convective loss of moisture at the boundaries results in a lower moisture concentration at the outer parts of the patty compared to its inner parts.

Figure 6: Moisture concentration after 770 s at a cooking temperature of 135°C.

15

10

Simulations show that an increased air temperature both shortens the time required to reach 70°C in the middle and increases the cooking yield. The drawback, however, is that the temperature gradients in the chicken patty increase. Figure 7 shows the temperature field obtained after 370 s at a cooking temperature of 219°C; the corresponding cooking yield is approximately 0.97 (97%).

20

25

30 mm

3

2.5

2

1.5



Figure 7: Temperature field after 370 s at a cooking temperature of 219°C.

## Reference

1. H. Chen, B.P. Marks, and R.Y. Murphy, "Modeling Coupled Heat and Mass Transfer for Convection Cooking of Chicken Patties," *J. Food Engineering*, vol. 42, pp. 139–146, 1999.

**Application Library path:** Heat\_Transfer\_Module/Phase\_Change/ chicken\_patties

# Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click 🙆 Model Wizard.

#### MODEL WIZARD

- I In the Model Wizard window, click 🚈 2D Axisymmetric.
- 2 In the Select Physics tree, select Chemical Species Transport> Transport of Diluted Species (tds).
- 3 Click Add.
- 4 In the Select Physics tree, select Heat Transfer>Heat Transfer in Solids (ht).
- 5 Click Add.
- 6 Click  $\bigcirc$  Study.
- 7 In the Select Study tree, select General Studies>Time Dependent.
- 8 Click **M** Done.

## GLOBAL DEFINITIONS

#### Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- **3** In the table, enter the following settings:

Name	Expression	Value	Description
T_air	135[degC]	408.15 K	Oven air temperature
то	22[degC]	295.15 K	Initial patty temperature
rho_p	1100[kg/m^3]	1100 kg/m³	Density of patty
h_T	25[W/(m^2*K)]	25 W/(m²·K)	Heat transfer coefficient
M_H20	18[g/mol]	0.018 kg/mol	Water molecular weight
c0	0.78*rho_p/M_H2O	47667 mol/m <sup>3</sup>	Initial moisture concentration
c_b	0.02*rho_p/M_H2O	1222.2 mol/m <sup>3</sup>	Air moisture concentration
C_m	0.003	0.003	Specific moisture capacity
k_m	1.29e-9[kg/(m*s)]	1.29E-9 kg/(m·s)	Moisture conductivity
h_m	1.67e-6[kg/(m^2* s)]	1.67E-6 kg/(m²·s)	Mass transfer coefficient in mass units
D	k_m/(rho_p*C_m)	3.9091E-10 m <sup>2</sup> /s	Diffusion coefficient

Name	Expression	Value	Description
k_c	h_m/(rho_p*C_m)	5.0606E-7 m/s	Mass transfer coefficient
lda	2.3e6[J/kg]*M_H20	41400 J/mol	Molar latent heat of vaporization

#### GEOMETRY I

I In the Model Builder window, under Component I (compl) click Geometry I.

- 2 In the Settings window for Geometry, locate the Units section.
- **3** From the **Length unit** list, choose **mm**.

Rectangle 1 (r1)

- I In the Geometry toolbar, click Rectangle.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- 3 In the Width text field, type 31.
- 4 In the **Height** text field, type 5.
- 5 In the Geometry toolbar, click 🟢 Build All.

## DEFINITIONS

Variables I

- I In the Home toolbar, click  $\partial =$  Variables and choose Local Variables.
- 2 In the Settings window for Variables, locate the Variables section.
- **3** In the table, enter the following settings:

Name	Expression	Unit	Description
k_T	(0.194+0.436*c*M_H2O/ rho_p)[W/(m*K)]	W/(m·K)	Thermal conductivity
dT	(T-0[degC])[1/K]		Temperature difference
C_p	(3017.2+2.05*dT+0.24*dT^2+ 0.002*dT^3)[J/(kg*K)]	J/(kg·K)	Specific heat

# MATERIALS

Chicken Meat

- I In the Materials toolbar, click 🚦 Blank Material.
- 2 In the Settings window for Material, type Chicken Meat in the Label text field.

**3** Locate the Material Contents section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	k_T	W/(m·K)	Basic
Density	rho	rho_p	kg/m³	Basic
Heat capacity at constant pressure	Ср	С_р	J/(kg·K)	Basic

#### TRANSPORT OF DILUTED SPECIES (TDS)

- I In the Model Builder window, under Component I (comp1) click Transport of Diluted Species (tds).
- **2** In the **Settings** window for **Transport of Diluted Species**, locate the **Transport Mechanisms** section.
- **3** Clear the **Convection** check box.

#### Transport Properties 1

- I In the Model Builder window, under Component I (compl)> Transport of Diluted Species (tds) click Transport Properties I.
- 2 In the Settings window for Transport Properties, locate the Diffusion section.
- **3** In the  $D_{\rm c}$  text field, type D.

#### Initial Values 1

- I In the Model Builder window, click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the c text field, type c0.

#### Flux I

- I In the Physics toolbar, click Boundaries and choose Flux.
- **2** Select Boundaries 3 and 4 only.
- 3 In the Settings window for Flux, locate the Inward Flux section.
- 4 Select the Species c check box.
- 5 From the Flux type list, choose External convection.
- **6** In the  $k_{c,c}$  text field, type k\_c.
- 7 In the  $c_{b,c}$  text field, type c\_b.

#### HEAT TRANSFER IN SOLIDS (HT)

Initial Values 1

- I In the Model Builder window, under Component I (comp1)>Heat Transfer in Solids (ht) click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the T text field, type TO.

#### Heat Flux 1

- I In the Physics toolbar, click Boundaries and choose Heat Flux.
- **2** Select Boundaries **3** and **4** only.
- 3 In the Settings window for Heat Flux, locate the Heat Flux section.
- 4 From the Flux type list, choose Convective heat flux.
- **5** In the *h* text field, type  $h_T$ .
- **6** In the  $T_{\text{ext}}$  text field, type T\_air.

Boundary Heat Source 1

- I In the Physics toolbar, click Boundaries and choose Boundary Heat Source.
- **2** Select Boundaries 3 and 4 only.
- **3** In the **Settings** window for **Boundary Heat Source**, locate the **Boundary Heat Source** section.
- 4 In the  $Q_{\rm b}$  text field, type lda\*k\_c\*(c\_b-c).

#### MESH I

Free Triangular 1

In the Mesh toolbar, click 🦳 Free Triangular.

Size 1

- I Right-click Free Triangular I and choose Size.
- 2 In the Settings window for Size, locate the Geometric Entity Selection section.
- 3 From the Geometric entity level list, choose Boundary.
- **4** Select Boundaries **3** and **4** only.
- 5 Locate the **Element Size** section. Click the **Custom** button.
- 6 Locate the Element Size Parameters section.
- 7 Select the Maximum element size check box. In the associated text field, type 0.1.
- 8 Click 📗 Build All.

#### STUDY I

- Step 1: Time Dependent
- I In the Model Builder window, under Study I click Step I: Time Dependent.
- 2 In the Settings window for Time Dependent, locate the Study Settings section.
- 3 In the **Output times** text field, type range(0,10,900).
- **4** In the **Home** toolbar, click **= Compute**.

## RESULTS

Concentration (tds)

The first two default plots visualize the moisture content at the last time step in 2D (compare with Figure 6) and 3D.

- I In the Settings window for 2D Plot Group, locate the Data section.
- 2 From the Time (s) list, choose 770.
- **3** In the **Concentration (tds)** toolbar, click **O Plot**.

#### Temperature, 3D (ht)

The third default plot shows the temperature in 3D, and the last plot shows the isothermal contours in 2D.

To plot the temperature in the middle of the patty (Figure 4), follow the steps given below.

Temperature Profile vs. Time

- I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Temperature Profile vs. Time in the Label text field.

Point Graph 1

- I In the Temperature Profile vs. Time toolbar, click 🗠 Point Graph.
- 2 Select Point 1 only.
- 3 In the Settings window for Point Graph, click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (compl)> Heat Transfer in Solids>Temperature>T Temperature K.
- 4 Locate the y-Axis Data section. From the Unit list, choose degC.
- 5 In the Temperature Profile vs. Time toolbar, click 💿 Plot.

#### Temperature Profile vs. Time

It takes 770 s to reach a temperature of 70°C in the center. Plot the temperature and moisture distributions in the patty for the time value 770 s (Figure 5 and Figure 6).

#### Temperature, 2D

- I In the Home toolbar, click 🚛 Add Plot Group and choose 2D Plot Group.
- 2 In the Settings window for 2D Plot Group, type Temperature, 2D in the Label text field.
- 3 Locate the Data section. From the Time (s) list, choose 770.

#### Surface 1

- I In the Temperature, 2D toolbar, click Surface.
- In the Settings window for Surface, click Replace Expression in the upper-right corner of the Expression section. From the menu, choose Component I (compl)>
  Heat Transfer in Solids>Temperature>T Temperature K.
- 3 Locate the Expression section. From the Unit list, choose degC.
- 4 Locate the Coloring and Style section. Click Change Color Table.
- 5 In the Color Table dialog box, select Thermal>HeatCameraLight in the tree.
- 6 Click OK.
- 7 In the Temperature, 2D toolbar, click 💿 Plot.
- 8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Now, compute the cooking yield.

#### Volume Average 1

- I In the Results toolbar, click <sup>8,85</sup><sub>e-12</sub> More Derived Values and choose Average> Volume Average.
- 2 In the Settings window for Volume Average, locate the Data section.
- **3** From the **Time selection** list, choose **From list**.
- 4 In the Times (s) list, select 370.
- **5** Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
c/c0	1	Cooking yield

6 Click **=** Evaluate.

#### STUDY I

To study the evolution of the temperature and the moisture in the patty for a range of oven temperatures, use the parametric solver.

## Parametric Sweep

- I In the **Study** toolbar, click **Parametric Sweep**.
- 2 In the Settings window for Parametric Sweep, locate the Study Settings section.
- 3 Click + Add.
- **4** In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
T_air (Oven air temperature)	range(135,42,219)	degC

**5** In the **Study** toolbar, click **= Compute**.

## RESULTS

Examine the temperature rise in the middle of the patty for the different oven temperature values.

#### Temperature Profile vs. Time

- I In the Model Builder window, under Results click Temperature Profile vs. Time.
- 2 In the Settings window for ID Plot Group, locate the Data section.
- 3 From the Dataset list, choose Study I/Parametric Solutions I (sol2).
- 4 Locate the Legend section. From the Position list, choose Lower right.

## Point Graph 1

- I In the Model Builder window, click Point Graph I.
- 2 In the Settings window for Point Graph, locate the x-Axis Data section.
- 3 From the Axis source data list, choose Inner solutions.
- 4 Click to expand the Legends section. Select the Show legends check box.
- 5 From the Legends list, choose Evaluated.
- 6 In the Legend text field, type Air temperature at eval(T\_air,degC)°C.

7 In the Temperature Profile vs. Time toolbar, click 🗿 Plot.



Follow these steps to see the temperature distribution inside the patty for the oven temperature 219°C. Compare the resulting plot with that in Figure 7.

#### Temperature, 2D

- I In the Model Builder window, under Results click Temperature, 2D.
- 2 In the Settings window for 2D Plot Group, locate the Data section.
- 3 From the Dataset list, choose Study I/Parametric Solutions I (sol2).
- 4 From the Time (s) list, choose 370.
- 5 In the Temperature, 2D toolbar, click 💽 Plot.
- 6 Click the + Zoom Extents button in the Graphics toolbar.

Finally, compute the cooking yield.

#### Volume Average 2

- I In the Results toolbar, click <sup>8,85</sup><sub>e-12</sub> More Derived Values and choose Average> Volume Average.
- 2 In the Settings window for Volume Average, locate the Data section.
- 3 From the Dataset list, choose Revolution 2D 2.

- 4 From the Parameter selection (T\_air) list, choose From list.
- 5 In the Parameter values (T\_air (degC)) list, select 219.
- 6 From the Time selection list, choose From list.
- 7 In the Times (s) list, select 370.
- 8 From the Table columns list, choose T\_air.

**9** Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
c/c0	1	Cooking yield

IO Click 🔳 Evaluate.