Created in COMSOL Multiphysics 5.2a

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.

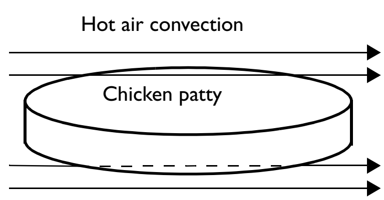


Figure 1: Convection cooking of a chicken patty.

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

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

where $\Delta T = (T - 0\ °\mathrm{C})$ 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.

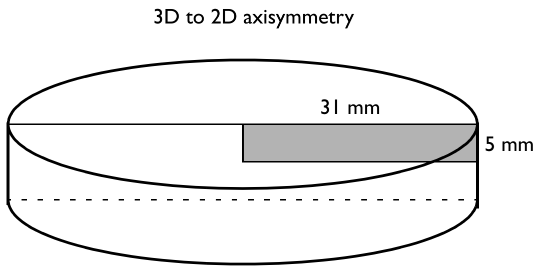


Figure 2: Geometry of the chicken patty.

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.

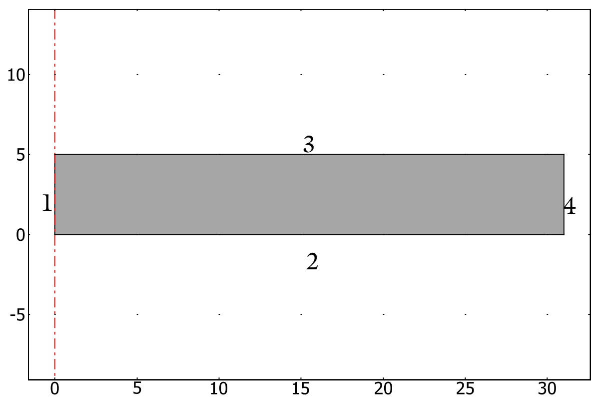


Figure 3: Model domain and boundary numbering.

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·K), where c is the concentration (mol/m^3), M_{H2O} the molar mass of water (kg/mol) and ρ is the density (kg/m^3).
- 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 $\lambda D\nabla c$ 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

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

where h_T is the heat transfer coefficient (W/(m^2·K)), and T_{air} is the oven air temperature.

The boundary conditions for the diffusion are

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

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

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

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

Assume that the patty's temperature is 22 °C at the start of the cooking process, and the moisture concentration in the patty at the air interface is 1222 mol/m^3 = 22 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 °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 840 s is required to reach a center temperature of 70 °C. Figure 4 shows how the temperature increases over time.

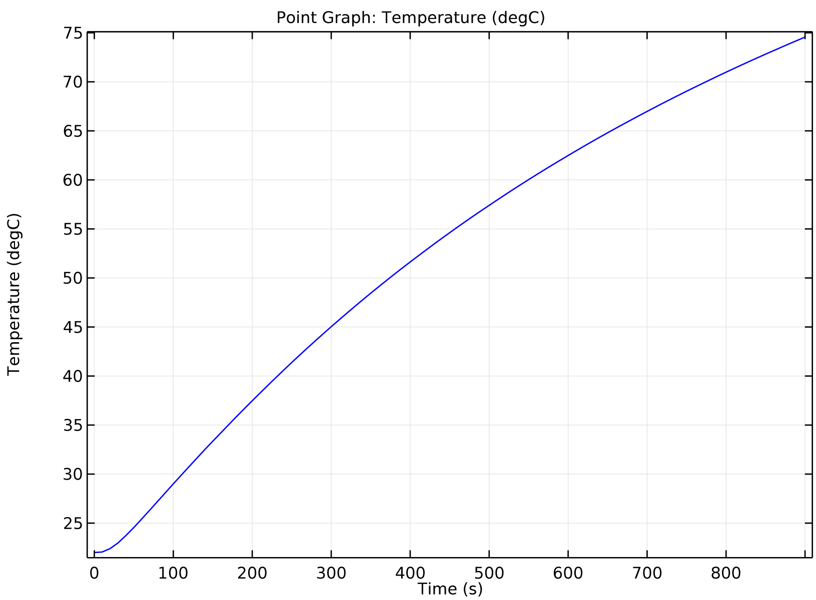


Figure 4: Temperature increase over time in the middle of the patty at an air temperature of 135 °C.

Figure 5 illustrates the resulting temperature field after 840 s. The temperature at the lower-left corner is 70 °C, and the temperature rises toward the outside boundaries.

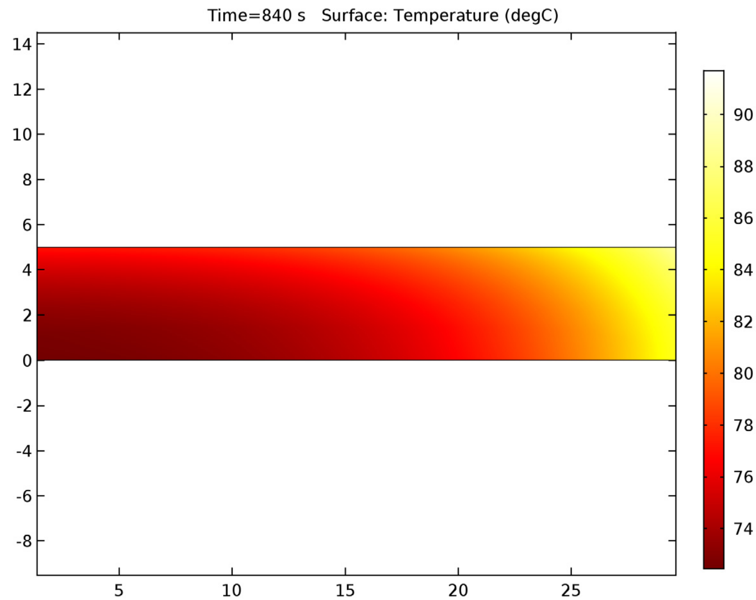


Figure 5: Temperature field after 840 s at a cooking temperature of 135 °C.

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 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.

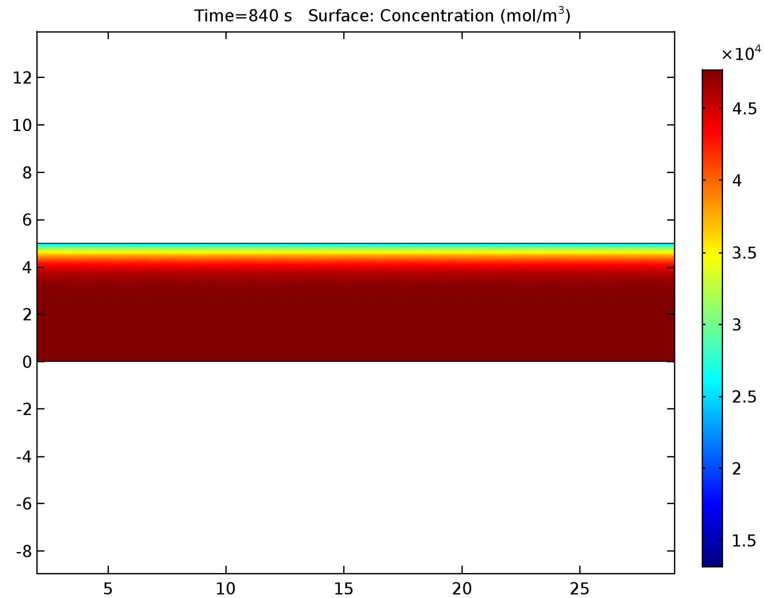


Figure 6: Moisture concentration after 840 s at a cooking temperature of 135 °C.

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%).

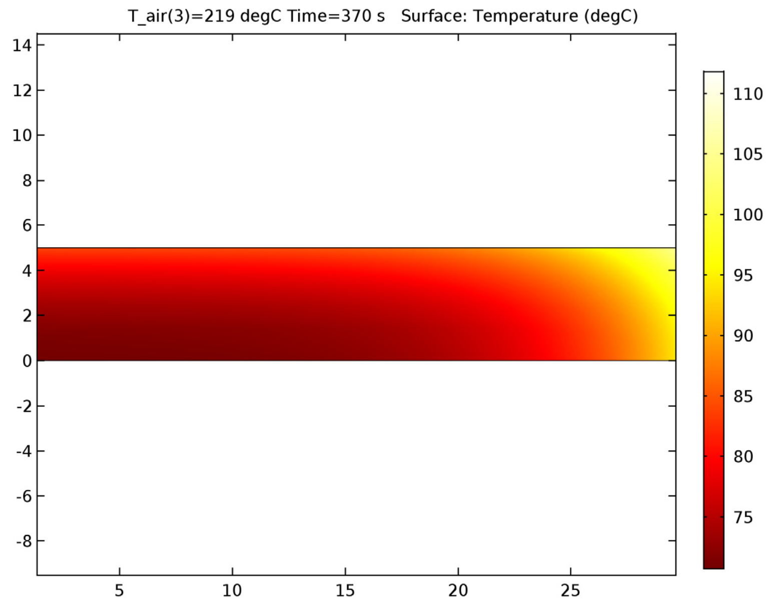


Figure 7: Temperature field after 370 s at a cooking temperature of 219°C.

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

1 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 **Study**.
7 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Time Dependent**.
8 Click **Done**.

GLOBAL DEFINITIONS

Parameters

1 On the **Home** toolbar, click **Parameters**.
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
T0	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_H2O	18[g/mol]	0.018 kg/mol	Water molecular weight
c0	0.78*rho_p/M_H2O	47667 mol/m³	Initial moisture concentration
c_b	0.02*rho_p/M_H2O	1222.2 mol/m³	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

Name	Expression	Value	Description
D	k_m/(rho_p*C_m)	3.9091E-10 m²/s	Diffusion coefficient
k_c	h_m/(rho_p*C_m)	5.0606E-7 m/s	Mass transfer coefficient
lda	2.3e6[J/kg]*M_H2O	41400 J/mol	Molar latent heat of vaporization

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for Geometry, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

Rectangle 1 (r1)

1 On the **Geometry** toolbar, click **Primitives** and choose **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 On the **Geometry** toolbar, click **Build All**.

DEFINITIONS

Variables 1

1 On the **Home** toolbar, click **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

Material 1 (mat1)

1 On 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	Name	Value	Unit	Property group
Thermal conductivity	k	k_T	W/(m·K)	Basic
Density	rho	rho_p	kg/m³	Basic
Heat capacity at constant pressure	Cp	C_p	J/(kg·K)	Basic

TRANSPORT OF DILUTED SPECIES (TDS)

1 In the **Model Builder** window, under **Component 1 (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

1 In the **Model Builder** window, under **Component 1 (comp1)>Transport of Diluted Species (tds)** click **Transport Properties 1**.

2 In the **Settings** window for Transport Properties, locate the **Diffusion** section.

3 In the D_c text field, type `D`.

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Transport of Diluted Species (tds)** click **Initial Values 1**.

2 In the **Settings** window for Initial Values, locate the **Initial Values** section.

3 In the c text field, type `c0`.

Flux 1

1 On 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 forced 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

1 In the **Model Builder** window, under **Component 1 (comp1)>Heat Transfer in Solids (ht)** click **Initial Values 1**.

2 In the **Settings** window for Initial Values, type `T0` in the T text field.

3 In the **Model Builder** window, click **Heat Transfer in Solids (ht)**.

Heat Flux 1

1 On 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 Click the **Convective heat flux** button.

5 In the h text field, type `h_T`.

6 In the T_{ext} text field, type `T_air`.

Boundary Heat Source 1

1 On 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_{b} text field, type `lda*k_c*(c_b-c)`.

MESH 1

On the **Mesh** toolbar, click **Free Triangular**.

Free Triangular 1

In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Free Triangular 1** and choose **Size**.

Size 1

1 In the **Settings** window for Size, locate the **Geometric Entity Selection** section.

2 From the **Geometric entity level** list, choose **Boundary**.

3 Select Boundaries 3 and 4 only.

4 Locate the **Element Size** section. Click the **Custom** button.

5 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

6 In the associated text field, type `0.1`.

7 Click **Build All**.

STUDY 1

Step 1: Time Dependent

1 In the **Settings** window for Time Dependent, locate the **Study Settings** section.

2 In the **Times** text field, type `range(0,10,900)`.

3 On the **Home** toolbar, click **Compute**.

RESULTS

Concentration (tds)

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

1 In the **Model Builder** window, under **Results** click **Concentration (tds)**.

2 In the **Settings** window for 2D Plot Group, locate the **Data** section.

3 From the **Time (s)** list, choose **840**.

4 On the **Concentration (tds)** toolbar, click **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.

1D Plot Group 5

1 On the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for 1D Plot Group, type `Temperature Profile vs Time` in the **Label** text field.

Point Graph 1

1 On 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 **Model>Component 1>Heat Transfer in Solids>Temperature>T - Temperature**.

4 Locate the **y-Axis Data** section. From the **Unit** list, choose **degC**.

5 On the **Temperature Profile vs Time** toolbar, click **Plot**.

Temperature Profile vs Time

It takes 840 s to reach a temperature of 70 °C in the center. Plot the temperature and moisture distributions in the patty for the time value 840 s (Figure 5 and Figure 6).

2D Plot Group 6

1 On 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 **840**.

Surface 1

1 Right-click **Temperature, 2D** and choose **Surface**.

2 In the **Settings** window for Surface, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Model>Component 1>Heat Transfer in Solids>Temperature>T - Temperature**.

3 Locate the **Expression** section. From the **Unit** list, choose **degC**.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalLight**.

5 On the **Temperature, 2D** toolbar, click **Plot**.

6 Click the **Zoom Extents** button on the **Graphics** toolbar.

Now, compute the cooking yield.

Volume Average 1

1 On the **Results** toolbar, click **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 1

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

1 On 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	range(135,42,219)	degC

5 On the **Study** toolbar, click **Compute**.

RESULTS

Concentration (tds) 2

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

Temperature Profile vs Time

1 In the **Model Builder** window, under **Results** click **Temperature Profile vs Time**.

2 In the **Settings** window for 1D Plot Group, locate the **Data** section.

3 From the **Data set** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Point Graph 1

1 In the **Model Builder** window, under **Results>Temperature Profile vs Time** click **Point Graph 1**.

2 In the **Settings** window for Point Graph, locate the **x-Axis Data** section.

3 From the **Axis source data** list, choose **Inner solutions**.

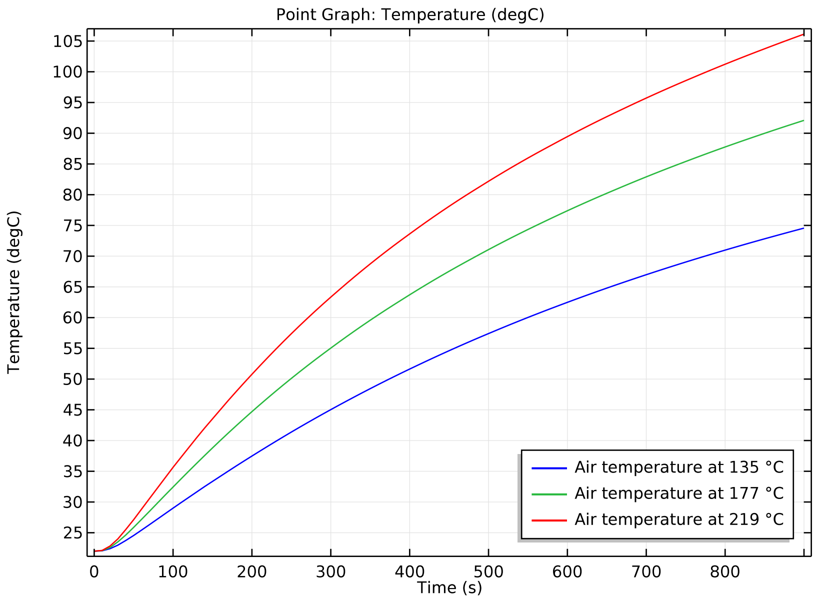
4 Click to expand the **Legends** section. Select the **Show legends** check box.

5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
Air temperature at 135 °C
Air temperature at 177 °C
Air temperature at 219 °C

7 On 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

1 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 **Data set** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 From the **Time (s)** list, choose **370**.

5 On the **Temperature, 2D** toolbar, click **Plot**.

6 Click the **Zoom Extents** button on the **Graphics** toolbar.

Finally, compute the cooking yield.

Volume Average 2

1 On the **Results** toolbar, click **More Derived Values** and choose **Average>Volume Average**.

2 In the **Settings** window for Volume Average, locate the **Data** section.

3 From the **Data set** list, choose **Revolution 2D 1**.

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

10 Click **Evaluate**.