Created in COMSOL Multiphysics 5.6

Dielectrophoretic Separation of Platelets from Red Blood Cells

Introduction

By exploiting the fact that platelets are the smallest cells in blood, it is possible to perform size-based fractionation of blood (that is, separate platelets from red blood cells) using dielectrophoresis, a force produced by a spatially nonuniform electric field that can even affect electrically neutral particles. This model demonstrates the continuous separation of platelets from red blood cells (RBCs) using the **Dielectrophoretic Force** feature available in the Particle Tracing for Fluid Flow interface.

Model Definition

Dielectrophoresis is the movement of particles in a nonuniform electric field due to the interaction of the particles' induced dipoles with the spatial gradient of the electric field norm.

When the electric field is computed in the frequency domain, the **Dielectrophoretic Force** feature adds the following contribution to the total force exerted on the particles:

$$\mathbf{F}_{\mathrm{dep}} = 2\pi r_{\mathrm{p}}^3\varepsilon_0\,\mathrm{real}(\varepsilon_{\mathrm{r}}^*)\,\mathrm{real}\left(\frac{\varepsilon_{\mathrm{r,\,p}}^* - \varepsilon_{\mathrm{r}}^*}{\varepsilon_{\mathrm{r,\,p}}^* + 2\varepsilon_{\mathrm{r}}^*}\right)\nabla|\mathbf{E}_{\mathrm{rms}}|^2$$

where

- r_{p} (SI unit: m) is the radius of a spherical particle in the field,
- $\varepsilon_0 = 8.854187817\cdot 10^{-12}$ F/m is the vacuum permittivity,
- $\varepsilon_{\mathrm{r}}^*$ (dimensionless) is the complex relative permittivity of the fluid,
- $\varepsilon_{\mathrm{r,\,p}}^*$ (dimensionless) is the complex relative permittivity of the particle, and
- $\mathbf{E}_{\mathrm{rms}}$ (SI unit: V/m) is the root mean square electric field.

For fields that are computed in the frequency domain, the complex permittivity can be expressed as

$$\varepsilon^* = \varepsilon - \frac{i\sigma}{\omega}$$

where ε (SI unit: F/m) is the permittivity, σ (SI unit: S/m) is the electrical conductivity, and ω (SI unit: Hz) is the angular frequency of the electric field.

The **Shell** subnode can be added to the **Dielectrophoretic Force** node to model the dielectrophoretic (DEP) force on particles with thin dielectric shells. The complex permittivity of the shell can differ from the complex permittivity of the rest of the particle.

When computing the dielectrophoretic force, the complex permittivity of the particle is replaced by the equivalent complex relative permittivity ε^*_{eq} of a homogeneous particle comprising both the shell and the interior of the particle:

$$\varepsilon^*_{eq} = \varepsilon^*_s \frac{\left(\frac{r_o}{r_i}\right)^3 + 2\left(\frac{\varepsilon^*_{r,p} - \varepsilon^*_{r,s}}{\varepsilon^*_{r,p} + 2\varepsilon^*_{r,s}}\right)}{\left(\frac{r_o}{r_i}\right)^3 - \left(\frac{\varepsilon^*_{r,p} - \varepsilon^*_{r,s}}{\varepsilon^*_{r,p} + 2\varepsilon^*_{r,s}}\right)}$$

where

- r_o and r_i (SI unit: m) are the outer and inner radii of the shell, respectively,
- $\varepsilon^*_{r,p}$ (dimensionless) is the complex relative permittivity of the particle, and
- $\varepsilon^*_{r,s}$ (dimensionless) is the complex relative permittivity of the outer shell.

For this model, the shell parameters for platelets and RBCs are respectively obtained from Ref. 2 and Ref. 3.

The present model is based on a lab-on-a-chip device described in detail in Ref. 1. It consists of two inlets, two outlets, and a separation region in which a nonuniform electric field created by an arrangement of electrodes of alternating polarity alter the particle trajectories. Figure 1 shows the schematic of the modeled geometry. As seen on the figure, the inlet velocity for the lower inlet is significantly higher (853 μm/s) than the upper inlet (154 μm/s) in order to focus all the injected particles toward the upper outlet.

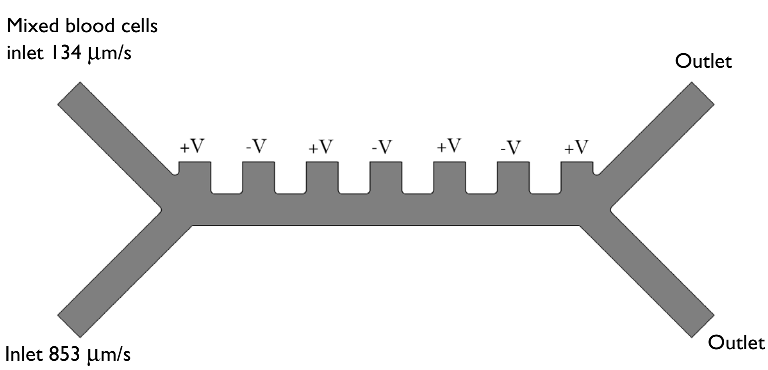

Figure 1: Two dimensional geometry of the modeled device. Details are presented in Ref. 1. The inlet velocity for the bottom inlet is significantly higher than the upper inlet to focus all the injected particles toward the upper outlet (Flow Focusing).

The model uses the following physics interfaces:

- Creeping Flow to model the fluid flow,
- Electric Currents to model the electric field in the microchannel, and
- Particle Tracing for Fluid Flow to compute the trajectories of RBCs and platelets under the influence of drag and dielectrophoretic forces

Three studies are also used:

1. Study 1 (**Stationary** and **Frequency Domain**) solves for the fluid velocity, pressure, and AC electric potential.
2. Study 2 (**Time Dependent**) estimates the particle trajectories in the flow without the DEP force, so that all particles (platelets and RBC) follow the same path.
3. Study 3 (**Time Dependent**) computes the particle trajectories including the DEP force.

Results and Discussion

Figure 2 shows the electric potential in the channel. When no dielectrophoretic force is applied, the red blood cells and platelets follow the same path and exit through the same outlet, as shown in Figure 3. When the dielectrophoretic force is applied, the two species are separated due to the differences in their dielectric properties, as shown in Figure 4.

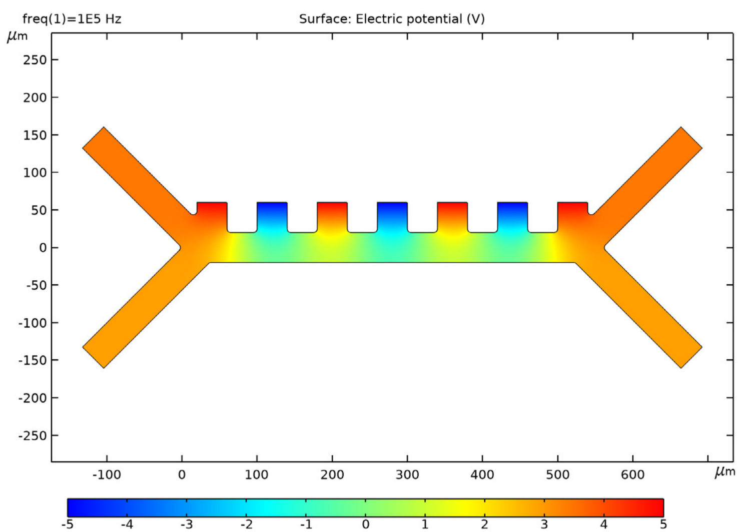

Figure 2: Spatial variation of the electric potential in the microfluidic channel.

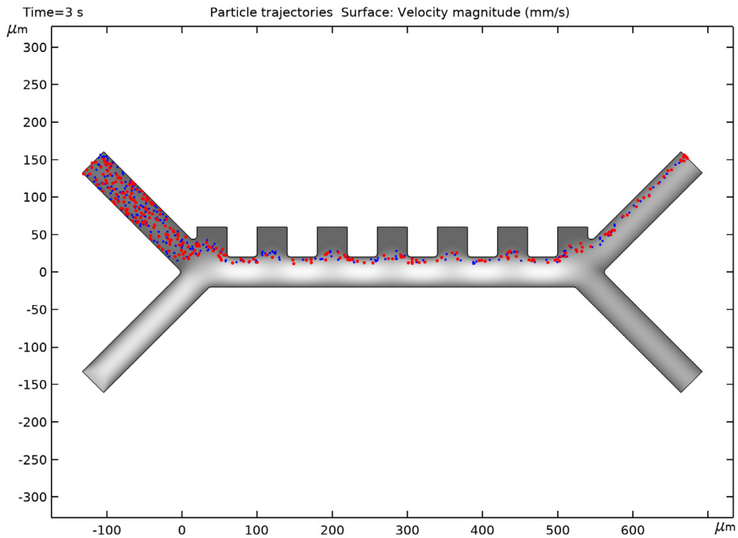

Figure 3: Particle trajectories without dielectrophoretic force applied. The RBCs are displayed in red and the platelets in blue. Since the particles are released at the same time and follow a similar path, the platelets are hidden behind the RBCs on the figure.

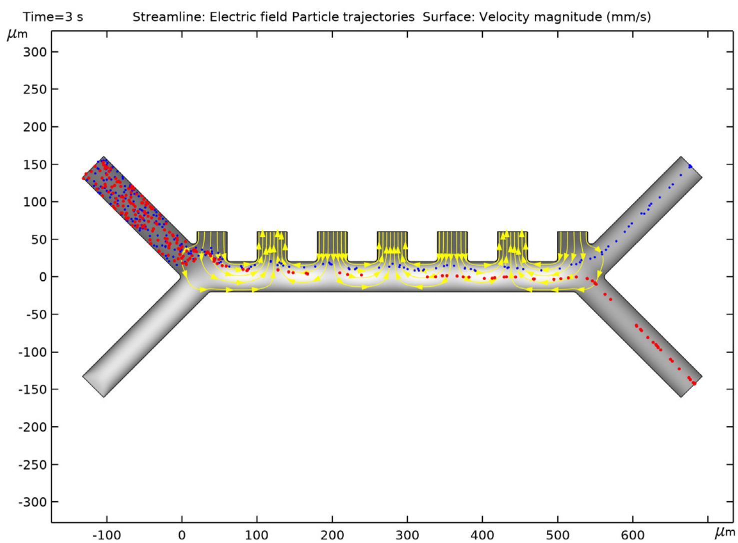

Figure 4: Particle trajectories with dielectrophoretic force applied. The RBCs are displayed in red and the platelets in blue. For sake of visualization, the relative size of the RBCs has been divided by two.

References

1. N. Piacentini, G. Mernier, R. Tornay, and P. Renaud, "Separation of platelets from other blood cells in continuous-flow by dielectrophoresis field-flow-fractionation," *Biomicrofluidics*, vol. 5, 034122, 2011.

2. M. Egger and E. Donath, "Electrorotation measurements of diamide-induced platelet activation changes," *Biophysical Journal*, vol. 68, pp. 364–372, 1995.

3. S. Park, Y. Zhang, T.H. Wang, and S. Yang, "Continuous dielectrophoretic bacterial separation and concentration from physiological media of high conductivity," Supplementary information, *Lab on a Chip*, vol. 11, pp. 2893–2900, 2011.

Application Library path: `Particle_Tracing_Module/Fluid_Flow/dielectrophoretic_separation`

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**.

2 In the **Select Physics** tree, select **AC/DC>Electric Fields and Currents>Electric Currents (ec)**.

3 Click **Add**.

4 In the **Select Physics** tree, select **Fluid Flow>Single-Phase Flow>Creeping Flow (spf)**.

5 Click **Add**.

6 In the **Select Physics** tree, select **Fluid Flow>Particle Tracing>Particle Tracing for Fluid Flow (fpt)**.

7 Click **Add**.

8 Click **Done**.

GEOMETRY 1

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in the appendix.

1 In the **Geometry** toolbar, click **Insert Sequence**.
2 Browse to the model's Application Libraries folder and double-click the file `dielectrophoretic_separation_geom_sequence.mph`.

GLOBAL DEFINITIONS

Parameters 1

Load the model parameters from a file.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `dielectrophoretic_separation_parameters.txt`.

ELECTRIC CURRENTS (EC)

Electric Potential 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Electric Currents (ec)** and choose **Electric Potential**.
2 In the **Settings** window for **Electric Potential**, locate the **Electric Potential** section.
3 In the V_0 text field, type `5`.
4 Select Boundaries 8, 17, 26, and 34 only.

Electric Potential 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Electric Potential**.
2 In the **Settings** window for **Electric Potential**, locate the **Electric Potential** section.
3 In the V_0 text field, type `-5`.
4 Select Boundaries 13, 21, and 30 only.

CREEPING FLOW (SPF)

In the **Model Builder** window, under **Component 1 (comp1)** click **Creeping Flow (spf)**.

Inlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Inlet**.

2 Select Boundary 3 only.

3 In the **Settings** window for **Inlet**, locate the **Velocity** section.

4 In the U_0 text field, type `134[um/s]`.

Inlet 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Inlet**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Inlet**, locate the **Velocity** section.

4 In the U_0 text field, type `853[um/s]`.

Outlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Outlet**.

2 Select Boundaries 40 and 41 only.

PARTICLE TRACING FOR FLUID FLOW (FPT)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Particle Tracing for Fluid Flow (fpt)**.

2 In the **Settings** window for **Particle Tracing for Fluid Flow**, locate the **Particle Release and Propagation** section.

3 From the **Formulation** list, choose **Newtonian, ignore inertial terms**.

This formulation is chosen because the Lagrangian response time of the particles is about six orders of magnitude smaller than the time for the particles to flow through the channel.

Platelets

1 In the **Model Builder** window, under **Component 1 (comp1)>** **Particle Tracing for Fluid Flow (fpt)** click **Particle Properties 1**.

2 In the **Settings** window for **Particle Properties**, type `Platelets` in the **Label** text field.

3 Locate the **Particle Properties** section. From the ρ_p list, choose **User defined**. In the associated text field, type `rho_p`.

4 In the d_p text field, type `dp1`.

Red Blood Cells

1 In the **Physics** toolbar, click **Global** and choose **Particle Properties**.

2 In the **Settings** window for **Particle Properties**, type `Red Blood Cells` in the **Label** text field.

3 Locate the **Particle Properties** section. From the ρ_p list, choose **User defined**. In the associated text field, type `rho_p`.

4 In the d_p text field, type `dp2`.

Inlet, Platelets

1 In the **Physics** toolbar, click **Boundaries** and choose **Inlet**.

2 In the **Settings** window for **Inlet**, type `Inlet, Platelets` in the **Label** text field.

3 Select Boundary 3 only.

4 Locate the **Release Times** section. In the **Release times** text field, type `range(0,0.01,3)`.

5 Locate the **Initial Position** section. From the **Initial position** list, choose **Random**.

Inlet, Red Blood Cells

1 Right-click **Inlet, Platelets** and choose **Duplicate**.

2 In the **Settings** window for **Inlet**, type `Inlet, Red Blood Cells` in the **Label** text field.

3 Click to expand the **Released Particle Properties** section. From the **Released particle properties** list, choose **Red Blood Cells**.

Outlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Outlet**.

2 Select Boundaries 40 and 41 only.

Drag Force 1

1 In the **Physics** toolbar, click **Domains** and choose **Drag Force**.

2 Select Domain 1 only.

3 In the **Settings** window for **Drag Force**, locate the **Drag Force** section.

4 From the $\mathbf{u}$ list, choose **Velocity field (spf)**.

5 Locate the **Additional Terms** section. Select the **Include virtual mass and pressure gradient forces** check box.

Dielectrophoretic Force, Platelets

1 In the **Physics** toolbar, click **Domains** and choose **Dielectrophoretic Force**.

2 In the **Settings** window for **Dielectrophoretic Force**, type `Dielectrophoretic Force, Platelets` in the **Label** text field.

3 Select Domain 1 only.

4 Locate the **Dielectrophoretic Force** section. From the $\mathbf{E}$ list, choose **Electric field (ec/cucn1)**.

5 Locate the **Advanced Settings** section. Select the **Use piecewise polynomial recovery on field** check box.

6 From the **Particles to affect** list, choose **Single species**.

Shell 1

1 In the **Physics** toolbar, click **Attributes** and choose **Shell**.

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

3 In the t_s text field, type `th_s1`.

4 In the $\varepsilon_{r,s}$ text field, type `epsilon_s1`.

5 In the σ_s text field, type `sigma_s1`.

Dielectrophoretic Force, Red Blood Cells

1 In the **Model Builder** window, right-click **Dielectrophoretic Force, Platelets** and choose **Duplicate**.

2 In the **Settings** window for **Dielectrophoretic Force**, type `Dielectrophoretic Force, Red Blood Cells` in the **Label** text field.

3 Locate the **Advanced Settings** section. From the **Affected particle properties** list, choose **Red Blood Cells**.

Shell 1

1 In the **Model Builder** window, expand the **Dielectrophoretic Force, Red Blood Cells** node, then click **Shell 1**.

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

3 In the t_s text field, type `th_s2`.

4 In the $\varepsilon_{r,s}$ text field, type `epsilon_s2`.

5 In the σ_s text field, type `sigma_s2`.

Platelets

1 In the **Model Builder** window, click **Platelets**.

2 In the **Settings** window for **Particle Properties**, locate the **Additional Material Properties** section.

3 From the $\varepsilon_{r,p}$ list, choose **User defined**. In the associated text field, type `epsilon_p1`.

4 From the σ_p list, choose **User defined**. In the associated text field, type `sigma_p1`.

Red Blood Cells

1 In the **Model Builder** window, click **Red Blood Cells**.

2 In the **Settings** window for **Particle Properties**, locate the **Additional Material Properties** section.

3 From the $\varepsilon_{r,p}$ list, choose **User defined**. In the associated text field, type `epsilon_p2`.

4 From the σ_p list, choose **User defined**. In the associated text field, type `sigma_p2`.

MATERIALS

Material 1 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	`sigma_f`	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`epsilon_f`	1	Basic
Density	rho	`rho_f`	kg/m³	Basic
Dynamic viscosity	mu	`mu_f`	Pa·s	Basic

Add a **Stationary** and a **Frequency Domain** study step to respectively solve the fluid flow and electric potential in the channel.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check boxes for **Electric Currents (ec)** and **Particle Tracing for Fluid Flow (fpt)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

5 Click **Add Study** in the window toolbar.

6 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 1

Frequency Domain

1 In the **Study** toolbar, click **Study Steps** and choose **Frequency Domain> Frequency Domain**.

2 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.

3 In the **Frequencies** text field, type `f0`.

4 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check boxes for **Creeping Flow (spf)** and **Particle Tracing for Fluid Flow (fpt)**.

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

RESULTS

Electric Potential (ec)

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

2 From the **Position** list, choose **Bottom**.

3 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot to Figure 2.

Velocity (spf)

1 In the **Model Builder** window, click **Velocity (spf)**.

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

3 From the **Position** list, choose **Bottom**.

Add a **Time Dependent** study to compute the trajectories of the particles without the **Dielectrophoretic Force** feature.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check boxes for **Electric Currents (ec)** and **Creeping Flow (spf)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies> Time Dependent**.

5 Click **Add Study** in the window toolbar.

6 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2, NO DIELECTROPHORETIC FORCE

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Study 2, no Dielectrophoretic Force` in the **Label** text field.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2, no Dielectrophoretic Force** click **Step 1: Time Dependent**.

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

3 In the **Output times** text field, type `range(0,0.05,3)`.

4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

5 In the **Physics and variables selection** tree, select **Component 1 (comp1)>Particle Tracing for Fluid Flow (fpt)>Dielectrophoretic Force, Platelets** and **Component 1 (comp1)>Particle Tracing for Fluid Flow (fpt)>Dielectrophoretic Force, Red Blood Cells**.

6 Click **Disable**.

Check the values of variables not solved for in order to get access to the velocity field and electric potential computed in the first study.

7 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

8 From the **Method** list, choose **Solution**.

9 From the **Study** list, choose **Study 1, Frequency Domain**.

Get the initial solution. The purpose is to generate a plot of the particule trajectories and use it to plot the particles while solving for them.

10 In the **Study** toolbar, click **Get Initial Value**.

RESULTS

Particle Trajectories (fpt)

Modify the plot to display the particle size and electric potential.

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

2 Clear the **Show legends** check box.

For clearer visualization use an `if` statement to display the RBCs with a diameter two times smaller than their real size.

Particle Trajectories 1

1 In the **Model Builder** window, expand the **Particle Trajectories (fpt)** node, then click **Particle Trajectories 1**.

2 In the **Settings** window for **Particle Trajectories**, locate the **Coloring and Style** section.

3 Find the **Point style** subsection. In the **Point radius expression** text field, type `if(fpt.sidx==2,dp2/2,dp1)`.

Color Expression 1

1 In the **Model Builder** window, expand the **Particle Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `fpt.dp`.

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

Surface 1

1 In the **Model Builder** window, right-click **Particle Trajectories (fpt)** 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 **Component 1 (comp1)>Creeping Flow>Velocity and pressure>spf.U - Velocity magnitude - m/s**.

3 Locate the **Expression** section. From the **Unit** list, choose **mm/s**.

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

Set a custom range to make the particles easier to see in the regions with slow-moving fluid.

5 Click to expand the **Range** section. Select the **Manual color range** check box.

6 In the **Minimum** text field, type `-1`.

7 In the **Maximum** text field, type `1.5`.

8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Plot the particle trajectories while solving. Note that the dielectrophoretic force is not applied in this study, so all of the particles appear follow approximately the same trajectory.

STUDY 2, NO DIELECTROPHORETIC FORCE

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2, no Dielectrophoretic Force** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, click to expand the **Results While Solving** section.

3 Select the **Plot** check box.

4 From the **Plot group** list, choose **Particle Trajectories (fpt)**.

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

RESULTS

Particle Trajectories (fpt)

Click the **Zoom Extents** button in the **Graphics** toolbar. The plot should look like Figure 3.

Now add another **Time Dependent** study to compute the effect of the dielectrophoretic force on the particle trajectories.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check boxes for **Electric Currents (ec)** and **Creeping Flow (spf)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies> Time Dependent**.

5 Click **Add Study** in the window toolbar.

6 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 3, DIELECTROPHORETIC FORCE

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Study 3, Dielectrophoretic Force` in the **Label** text field.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 3, Dielectrophoretic Force** click **Step 1: Time Dependent**.

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

3 In the **Output times** text field, type `range(0,0.05,3)`.

4 Locate the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

5 From the **Method** list, choose **Solution**.

6 From the **Study** list, choose **Study 1, Frequency Domain**.

Get the initial solution in order to view the particle trajectories while running the study.

7 In the **Study** toolbar, click **Get Initial Value**.

RESULTS

Particle Trajectories (fpt) 1

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

2 Clear the **Show legends** check box.

Particle Trajectories 1

1 In the **Model Builder** window, expand the **Particle Trajectories (fpt) 1** node, then click **Particle Trajectories 1**.

2 In the **Settings** window for **Particle Trajectories**, locate the **Coloring and Style** section.

3 Find the **Point style** subsection. In the **Point radius expression** text field, type `if(fpt.dp==dp2,dp2/2,dp1)`.

Color Expression 1

1 In the **Model Builder** window, expand the **Particle Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `fpt.dp`.

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

Surface 1

1 In the **Model Builder** window, right-click **Particle Trajectories (fpt) 1** 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 **Component 1 (comp1)>Creeping Flow>Velocity and pressure>spf.U - Velocity magnitude - m/s**.

3 Locate the **Expression** section. From the **Unit** list, choose **mm/s**.

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

Set a custom range to make the particles easier to see in the regions with slow-moving fluid.

5 Locate the **Range** section. Select the **Manual color range** check box.

6 In the **Minimum** text field, type `-1`.

7 In the **Maximum** text field, type `1.5`.

Streamline 1

1 Right-click **Particle Trajectories (fpt) 1** and choose **Streamline**.

2 In the **Settings** window for **Streamline**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Electric Currents>Electric>ec.Ex,ec.Ey - Electric field**.

3 Locate the **Streamline Positioning** section. From the **Entry method** list, choose **Coordinates**.

4 In the **x** text field, type `range(102.5,5,137.5) range(262.5,5,297.5) range(422.5,5,457.5)`.

5 In the **y** text field, type `60`.

6 Locate the **Coloring and Style** section. Find the **Point style** subsection. From the **Color** list, choose **Yellow**.

7 From the **Type** list, choose **Arrow**.

8 Select the **Number of arrows** check box.

9 In the associated text field, type `100`.

Moving the **Streamline** plot will make particles appear on top of the streamlines, rather than the other way around, whenever the two overlap.

10 Click the **Zoom Extents** button in the **Graphics** toolbar.

Plot the particle trajectories while solving. Note that the dielectrophoretic force separates the particles.

STUDY 3, DIELECTROPHORETIC FORCE

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 3, Dielectrophoretic Force** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Results While Solving** section.

3 Select the **Plot** check box.

4 From the **Plot group** list, choose **Particle Trajectories (fpt) 1**.

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

RESULTS

Particle Trajectories (fpt) 1

1 In the **Particle Trajectories (fpt) 1** toolbar, click **Plot**.

2 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot to Figure 4.

Appendix — Geometry Instructions

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **2D**.

GEOMETRY 1

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

2 From the **Length unit** list, choose **µm**.

Rectangle 1 (r1)

1 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 560/2.

4 In the **Height** text field, type 40.

5 Locate the **Position** section. In the **y** text field, type -20.

Rectangle 2 (r2)

1 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 40.

4 In the **Height** text field, type 200.

5 Locate the **Position** section. In the **x** text field, type 9.

6 In the **y** text field, type -9.

7 Locate the **Rotation Angle** section. In the **Rotation** text field, type 45.

Mirror 1 (mir1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

2 Select the object **r2** only.

3 In the **Settings** window for **Mirror**, locate the **Normal Vector to Line of Reflection** section.

4 In the **x** text field, type `0`.

5 In the **y** text field, type `1`.

6 Locate the **Input** section. Select the **Keep input objects** check box.

Mirror 2 (mir2)

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

2 Click in the **Graphics** window and then press Ctrl+A to select all objects.

3 In the **Settings** window for **Mirror**, locate the **Input** section.

4 Select the **Keep input objects** check box.

5 Locate the **Point on Line of Reflection** section. In the **x** text field, type `560/2`.

Square 1 (sq1)

1 In the **Geometry** toolbar, click **Square**.

2 In the **Settings** window for **Square**, locate the **Size** section.

3 In the **Side length** text field, type `40`.

4 Locate the **Position** section. In the **x** text field, type `20`.

5 In the **y** text field, type `20`.

Array 1 (arr1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 Select the object **sq1** only.

3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **x size** text field, type `7`.

5 Locate the **Displacement** section. In the **x** text field, type `80`.

Union 1 (uni1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

Use the select box icon to select all the geometry objects.

2 Click in the **Graphics** window and then press Ctrl+A to select all objects.

3 In the **Settings** window for **Union**, locate the **Union** section.

4 Clear the **Keep interior boundaries** check box.

Fillet 1 (fil1)

1 In the **Geometry** toolbar, click **Fillet**.

2 On the object **uni1**, select Points 5, 6, 8, 9, 11, 13, 15, 17, 19, 22, 24, 26, 28, 30, 32, 34, 35, and 37 only.

3 In the **Settings** window for **Fillet**, locate the **Radius** section.

4 In the **Radius** text field, type 5.

5 Click **Build All Objects**.