

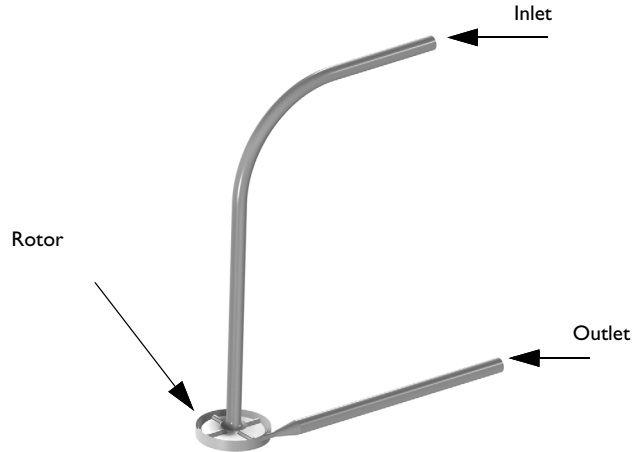


# FDA Benchmark Blood Pump

## Introduction

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Centrifugal pumps are widely used in medical applications. Fluid-structure interaction is a vital aspect of a variety of medical devices. A centrifugal blood pump is one such device that uses a rotating impeller to pump blood.



*Figure 1: Geometry of the centrifugal blood pump.*

This model features a centrifugal blood pump with 4 filleted blades (3 mm tall and 3 mm wide) placed at 90° angle on a 4 mm thick rotor base; see [Figure 1](#). The CAD geometry used in this model is taken from [Ref. 1](#).

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### Model Definition

Following the FDA guidelines, the blood is assumed to be a Newtonian fluid. The k-ε turbulence model is used to obtain an initial flow solution for the shear stress transport (SST) model, which is subsequently used to obtain flow solutions with higher accuracy. Inlet flow rates of 2.5–7 L/min at a pump speed of 3500 rpm are simulated. A frozen rotor approach is used to compute the (pseudo) steady-state solution.

### Results and Discussion

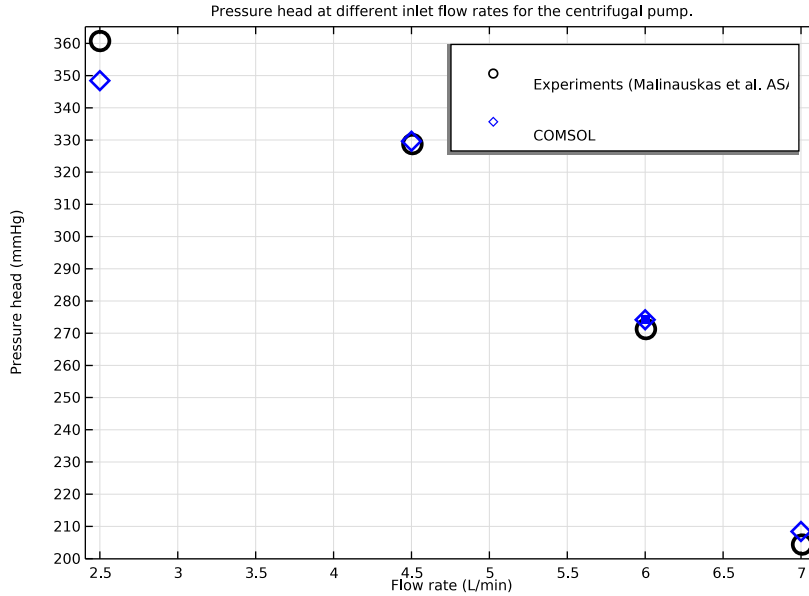
Table 1 shows a summary of wall shear stress and torque values. The maximum wall shear stress magnitude is computed over the housing rim (the 180° segment nearest the outlet) and also wall maximum shear stress magnitude is computed over the fillet around cutwater. The shaft torque value is computed from the integral of the total stress.

TABLE 1: PRESSURE HEAD (BETWEEN INLET AND OUTLET), WALL SHEAR STRESS MAGNITUDE OVER THE HOUSING RIM, AND SHAFT TORQUE FOR ALL SIMULATION CASES.

Case	Inlet flow rate (L/m)	Maximum wall shear stress, housing rim (N·m <sup>2</sup> )	Maximum wall shear stress, fillet (N·m <sup>2</sup> )	Shaft torque (nN·m)
1	2.5	318.59	302.82	28480
2	4.5	562.24	282.27	33841
4	7	668.15	270.06	36281

In Ref. 2, FDA published its benchmark centrifugal blood pump study, reporting results from computational studies as well as the data from its experiments. The experimental data is extracted from the graphs in the publication and compared with the results of the centrifugal benchmark blood pump model in order to validate the CFD results.

The pressure head across the pump is computed at a pump speed of 3500 rpm for several flow rates. The computed results show good agreement with the experimental results from Ref. 2, as is shown in Figure 2.



*Figure 2: Pressure head at different inlet flow rates for the centrifugal pump operating at 3500 rpm.*

The velocity magnitude at pump condition of 6 L/min and 3500 rpm is computed at the upper blade plane. The velocity magnitude, inside the blood pump model, based on the  $x$ - and  $y$ -velocity components along the radial cut line (see [Figure 3](#)) match the measurements qualitatively and are consistent with what is reported in other CFD studies [Ref. 2](#). The results of the comparison are presented in [Figure 4](#).

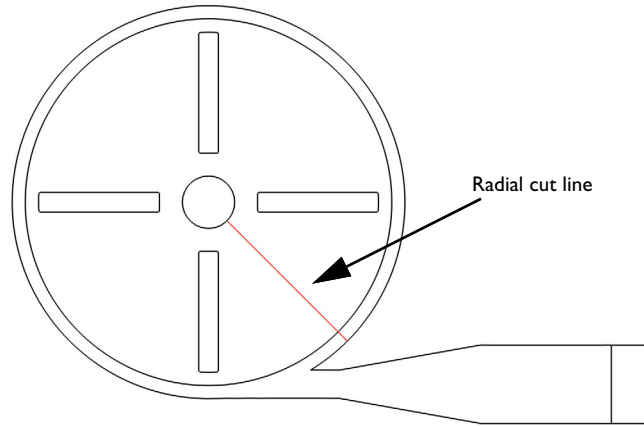


Figure 3: Radial cut line at upper blade plane.

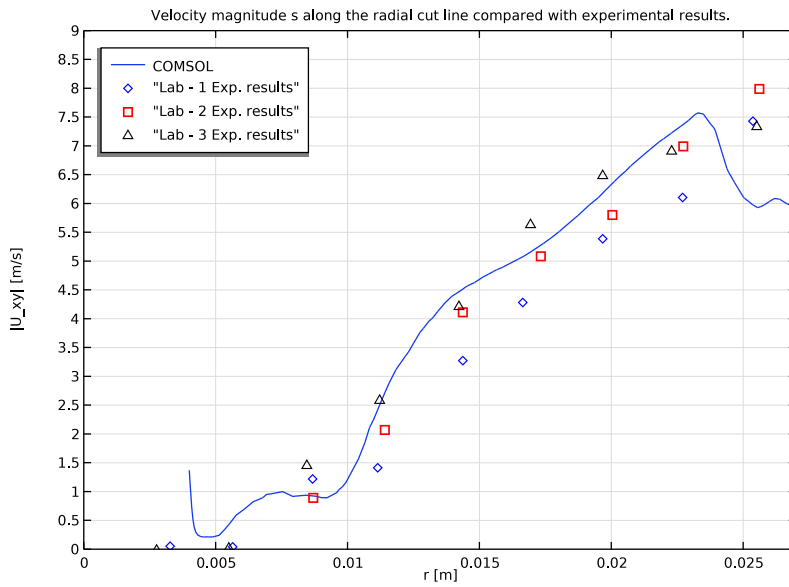
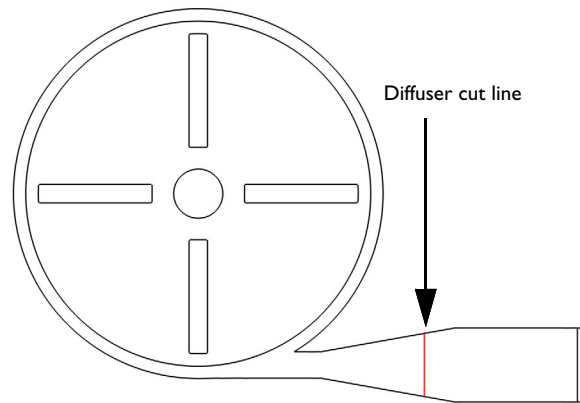
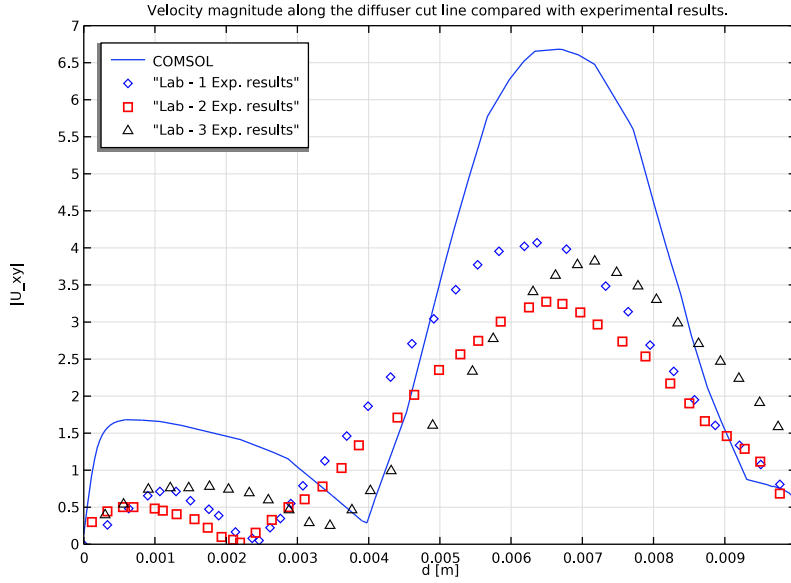


Figure 4: The velocity magnitude based on the  $x$ - and  $y$ -velocity components along the radial cut line compared with experimental data [Ref. 2](#).

Similarly, the velocity profile was computed at  $x = 0.035$  m in the diffuser region [Figure 5](#) at a pump condition of 6 L/min and 3500 rpm. [Figure 6](#) shows that the computed velocity magnitudes match the measurements qualitatively and are consistent with what is reported in [Ref. 2](#).



*Figure 5: Diffuser cut line.*



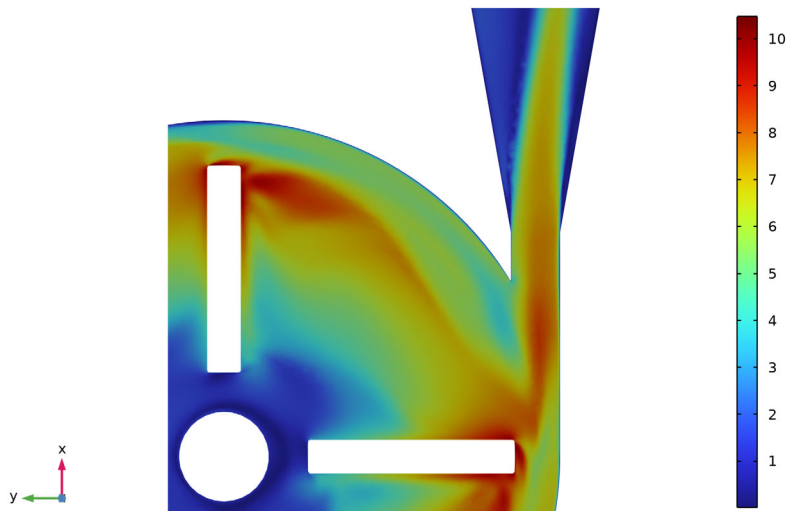
*Figure 6: Velocity magnitude inside the blood pump based on the  $x$ - and  $y$ -velocity components along the diffuser cut line compared with experimental results from [Ref. 2](#).*

The interpolated contours of the three-dimensional velocity magnitude for the upper-blade passage plane under operating condition of 3500 rpm and an inlet flow rate of 6 L/min are plotted in [Figure](#) . The results qualitatively match those in [Ref. 2](#).

?

Qb(2)=6 L/min

Velocity magnitude at the blade passage plane



Velocity magnitude at the blade passage plane under operating condition of 3500 rpm and an inlet flow rate of 6 L/min.

## References

1. Computational Fluid Dynamics Round Robin Study:  
[https://ncihub.cancer.gov/wiki/FDA\\_CFD](https://ncihub.cancer.gov/wiki/FDA_CFD).
2. R.A. Malinauskas and others, “FDA benchmark medical device flow models for CFD validation,” *ASAIO Journal*, vol. 63, no. 2, pp. 150–160, 2017.

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**Application Library path:** CFD\_Module/Verification\_Examples/fda\_benchmark\_blood\_pump


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## 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  **3D**.
- 2 In the **Select Physics** tree, select **Fluid Flow>Single-Phase Flow>Turbulent Flow>Turbulent Flow, k-ε (spf)**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **Empty Study**.
- 6 Click  **Done**.

**GLOBAL DEFINITIONS**


*Parameters I*

- 1 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
TIME	0[s]	0 s	
rho_f	1035[kg/m^3]	1035 kg/m³	Blood density
mu_f	0.0035[Pa*s]	0.0035 Pa·s	Blood viscosity
Qb	6.0[L/min]	1E-4 m³/s	Inlet flow rate
rp	3500[rpm]	58.333 1/s	Impeller rpm

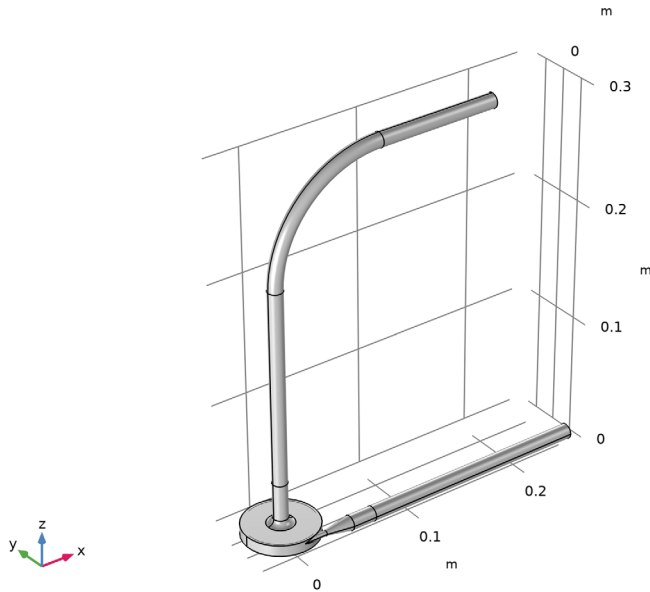
**GEOMETRY I**

Create the geometry. To simplify this step, insert a prepared geometry sequence.

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
- 2 In the **Settings** window for **Geometry**, locate the **Advanced** section.
- 3 From the **Geometry representation** list, choose **CAD kernel**.
- 4 In the **Geometry** toolbar, click  **Insert Sequence**.
- 5 Browse to the model's Application Libraries folder and double-click the file `fda_benchmark_blood_pump_geom_sequence.mph`.

Full geometry instructions can be found at the end of the document.

6 In the **Geometry** toolbar, click  **Build All**.



## MATERIALS

### Blood

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, type Blood in the **Label** text field.
- 3 Locate the **Material Contents** section. In the table, enter the following settings:



Property	Variable	Value	Unit	Property group
Density	rho	rho_f	kg/m <sup>3</sup>	Basic
Dynamic viscosity	mu	mu_f	Pa·s	Basic

## COMPONENT 1 (COMP1)

a Moving Mesh is used to rotate the impeller/rotor.

### Rotating Domain 1

- 1 In the **Physics** toolbar, click  **Moving Mesh** and choose **Rotating Domain**.
- 2 In the **Settings** window for **Rotating Domain**, locate the **Domain Selection** section.


- 3 Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 2 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Rotating Domain**, locate the **Rotation** section.
- 8 From the **Rotation type** list, choose **Specified rotational velocity**.
- 9 From the **Rotational velocity expression** list, choose **Constant revolutions per time**.
- 10 In the  $f$  text field, type  $rp$ .

The turbulent flow in the pump is resolved using a RANS model. To obtain initial values for the SST model, a  $k$ - $\epsilon$  model is first solved in Study 1.



#### **TURBULENT FLOW, K- $\epsilon$ - PRELIM**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Turbulent Flow, k- $\epsilon$  (spf)**.
- 2 In the **Settings** window for **Turbulent Flow, k- $\epsilon$** , type **Turbulent Flow, k-[epsilon] - Prelim** in the **Label** text field.

##### *Wall 2*



- 1 In the **Model Builder** window, expand the **Component 1 (comp1)>Turbulent Flow, k- $\epsilon$  - Prelim (spf)** node.
- 2 Right-click **Component 1 (comp1)>Turbulent Flow, k- $\epsilon$  - Prelim (spf)** and choose **Wall**.
- 3 In the **Settings** window for **Wall**, click to expand the **Wall Movement** section.
- 4 From the **Translational velocity** list, choose **Zero (Fixed wall)**.
- 5 Locate the **Boundary Selection** section. Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog box, type 7 in the **Selection** text field.
- 7 Click **OK**.

##### *Inlet 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Inlet**.
- 2 In the **Settings** window for **Inlet**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog box, type 54 in the **Selection** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Inlet**, locate the **Boundary Condition** section.
- 7 From the list, choose **Fully developed flow**.

- 8 Locate the **Fully Developed Flow** section. Click the **Flow rate** button.
- 9 In the  $V_0$  text field, type Qb.

#### *Outlet 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Outlet**.
- 2 In the **Settings** window for **Outlet**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog box, type 55 in the **Selection** text field.
- 5 Click **OK**.

#### **MESH 1**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.
- 2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.
- 3 From the list, choose **User-controlled mesh**.

#### *Size*

- 1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.
- 2 In the **Settings** window for **Size**, click to expand the **Element Size Parameters** section.
- 3 Locate the **Element Size** section. From the **Predefined** list, choose **Fine**.
- 4 Locate the **Element Size Parameters** section. In the **Minimum element size** text field, type 0.000004.



#### *Size 1*

In the **Model Builder** window, right-click **Size 1** and choose **Delete**. Click **Yes** to confirm.


#### *Corner Refinement 1*

In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Corner Refinement 1** and choose **Delete**. Click **Yes** to confirm.

#### *Free Triangular 1*

- 1 In the **Mesh** toolbar, click  **More Generators** and choose **Free Triangular**.
- 2 In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.
- 3 Click  **Paste Selection**.
- 4 In the **Paste Selection** dialog box, type 9-13, 28-33 in the **Selection** text field.
- 5 Click **OK**.
- 6 Right-click **Free Triangular 1** and choose **Move Up**.
- 7 Right-click **Free Triangular 1** and choose **Move Up**.

#### *Size 1*

- 1 Right-click **Free Triangular 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 From the **Calibrate for** list, choose **Fluid dynamics**.
- 4 From the **Predefined** list, choose **Finer**.
- 5 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  $1e-3$ .
- 8 Select the **Minimum element size** check box. In the associated text field, type  $4e-4$ .
- 9 Click  **Build Selected**.

#### *Free Triangular 2*

- 1 In the **Mesh** toolbar, click  **More Generators** and choose **Free Triangular**.
- 2 Select Boundary 40 only.

#### *Distribution 1*

- 1 Right-click **Free Triangular 2** and choose **Distribution**.
- 2 Select Edges 70 and 72 only.
- 3 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 4 From the **Distribution type** list, choose **Predefined**.
- 5 In the **Number of elements** text field, type 800.
- 6 In the **Element ratio** text field, type 4.
- 7 Select the **Reverse direction** check box.


#### *Free Triangular 2*

Right-click **Free Triangular 2** and choose **Distribution**.



#### *Distribution 2*

- 1 Select Edges 69 and 71 only.
- 2 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 3 From the **Distribution type** list, choose **Predefined**.
- 4 In the **Number of elements** text field, type 800.
- 5 In the **Element ratio** text field, type 4.



### *Free Tetrahedral 1*


- 1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Free Tetrahedral 1**.
- 2 In the **Settings** window for **Free Tetrahedral**, locate the **Domain Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 1-2 in the **Selection** text field.
- 6 Click **OK**.

### *Size 1*



- 1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
- 3 Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 2 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Size**, locate the **Element Size** section.
- 8 From the **Calibrate for** list, choose **Fluid dynamics**.
- 9 Click the **Custom** button.
- 10 Locate the **Element Size Parameters** section.
- 11 Select the **Maximum element size** check box. In the associated text field, type  $1\text{e-}3$ .
- 12 Select the **Minimum element size** check box. In the associated text field, type  $4\text{e-}4$ .

### *Size 2*



- 1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
- 3 Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 1 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Size**, locate the **Element Size** section.
- 8 From the **Calibrate for** list, choose **Fluid dynamics**.
- 9 Click the **Custom** button.

- 10 Locate the **Element Size Parameters** section.
- 11 Select the **Maximum element size** check box. In the associated text field, type  $1e-3$ .
- 12 Select the **Minimum element size** check box. In the associated text field, type  $1e-7$ .
- 13 Select the **Maximum element growth rate** check box. In the associated text field, type 1.4.
- 14 Select the **Curvature factor** check box.
- 15 Select the **Resolution of narrow regions** check box.
- 16 Click  **Build Selected**.

#### *Swept 1*



- 1 In the **Mesh** toolbar, click  **Swept**.
- 2 Drag and drop below **Free Tetrahedral 1**.
- 3 In the **Settings** window for **Swept**, locate the **Domain Selection** section.
- 4 From the **Geometric entity level** list, choose **Domain**.
- 5 Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog box, type 3 4 5 6 in the **Selection** text field.
- 7 Click **OK**.

#### *Distribution 1*



- 1 In the **Model Builder** window, right-click **Swept 1** and choose **Distribution**.
- 2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.
- 3 Click  **Clear Selection**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 3 in the **Selection** text field.
- 6 Click **OK**.
- 7 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 8 From the **Distribution type** list, choose **Predefined**.
- 9 In the **Number of elements** text field, type 60.
- 10 In the **Element ratio** text field, type 3.
- 11 Select the **Symmetric distribution** check box.

#### *Distribution 2*



- 1 In the **Model Builder** window, right-click **Swept 1** and choose **Distribution**.
- 2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.

- 3 Click  **Clear Selection.**
- 4 Click  **Paste Selection.**
- 5 In the **Paste Selection** dialog box, type 4 in the **Selection** text field.
- 6 Click **OK.**
- 7 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 8 From the **Distribution type** list, choose **Predefined.**
- 9 In the **Number of elements** text field, type 70.
- 10 In the **Element ratio** text field, type 1.

#### *Distribution 3*

- 1 Right-click **Swept 1** and choose **Distribution.**
- 2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.
- 3 Click  **Clear Selection.**
- 4 Click  **Paste Selection.**
- 5 In the **Paste Selection** dialog box, type 5 in the **Selection** text field.
- 6 Click **OK.**
- 7 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 8 From the **Distribution type** list, choose **Predefined.**
- 9 In the **Number of elements** text field, type 100.
- 10 In the **Element ratio** text field, type 2.

#### *Distribution 4*


- 1 Right-click **Swept 1** and choose **Distribution.**
- 2 In the **Settings** window for **Distribution**, locate the **Domain Selection** section.
- 3 Click  **Clear Selection.**
- 4 Click  **Paste Selection.**
- 5 In the **Paste Selection** dialog box, type 6 in the **Selection** text field.
- 6 Click **OK.**
- 7 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 8 From the **Distribution type** list, choose **Predefined.**
- 9 In the **Number of elements** text field, type 30.
- 10 In the **Element ratio** text field, type 2.



### *Boundary Layers I*


- 1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Boundary Layers 1**.
- 2 In the **Settings** window for **Boundary Layers**, locate the **Geometric Entity Selection** section.
- 3 In the list, select **1**.
- 4 From the **Geometric entity level** list, choose **Entire geometry**.
- 5 Click to expand the **Corner Settings** section. From the **Handling of sharp edges** list, choose **Splitting**.

### *Boundary Layer Properties I*

- 1 In the **Model Builder** window, expand the **Boundary Layers 1** node, then click **Boundary Layer Properties 1**.
- 2 In the **Settings** window for **Boundary Layer Properties**, locate the **Layers** section.
- 3 In the **Number of layers** text field, type 8.
- 4 In the **Thickness adjustment factor** text field, type 1.1.
- 5 Clear the **Adjust directions for each layer** check box.
- 6 Click  **Build All**.

## **STUDY 1**

### *Step 1: Frozen Rotor*

- 1 In the **Study** toolbar, click  **Study Steps** and choose **Stationary>Frozen Rotor**.  
A Frozen Rotor study is used to compute the steady-state flow involving the rotating machinery.
- 2 In the **Model Builder** window, click **Study 1**.
- 3 In the **Settings** window for **Study**, locate the **Study Settings** section.
- 4 Clear the **Generate default plots** check box.
- 5 In the **Label** text field, type Study 1 - k-epsilon.


### *Solution 1 (sol1)*

- 1 In the **Study** toolbar, click  **Show Default Solver**.
- 2 Click  **Compute**.




## **DEFINITIONS**

### *Wall Boundaries*




- 1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

- 2 Right-click **Definitions** and choose **Selections>Explicit**.
- 3 In the **Settings** window for **Explicit**, type Wall Boundaries in the **Label** text field.
- 4 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.
- 5 Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog box, type 1-4, 7, 9-19, 22, 23, 28-33, 40-51 in the **Selection** text field.
- 7 Click **OK**.

#### *Inlet Pressure*

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, locate the **Source Selection** section.
- 3 From the **Selection** list, choose **Manual**.
- 4 Click  **Clear Selection**.
- 5 Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog box, type 54 in the **Selection** text field.
- 7 Click **OK**.
- 8 In the **Settings** window for **Boundary Probe**, type Inlet Pressure in the **Label** text field.
- 9 In the **Variable name** text field, type p\_in.
- 10 Locate the **Expression** section. In the **Expression** text field, type spf2.pA.
- 11 In the **Table and plot unit** field, type Pa.






#### *Outlet Pressure*

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, type Outlet Pressure in the **Label** text field.
- 3 In the **Variable name** text field, type p\_out.
- 4 Locate the **Source Selection** section. Click  **Clear Selection**.
- 5 Click  **Paste Selection**.
- 6 In the **Paste Selection** dialog box, type 55 in the **Selection** text field.
- 7 Click **OK**.
- 8 In the **Settings** window for **Boundary Probe**, locate the **Expression** section.
- 9 In the **Expression** text field, type spf2.pA.
- 10 In the **Table and plot unit** field, type Pa.




11 Click to expand the **Table and Window Settings** section. Click  **Add Plot Window**.

An important indicator of less trauma to red blood cells and a lower systemic inflammatory response is shear stress.





#### *Maximum Wall Shear Stress - Housing Rim*

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, type Maximum Wall Shear Stress - Housing Rim in the **Label** text field.
- 3 In the **Variable name** text field, type tau\_housing\_max.
- 4 Locate the **Probe Type** section. From the **Type** list, choose **Maximum**.
- 5 Locate the **Source Selection** section. Click  **Clear Selection**.
- 6 Click  **Copy Selection**.
- 7 Click  **Paste Selection**.
- 8 In the **Paste Selection** dialog box, type 1 in the **Selection** text field.
- 9 Click **OK**.
- 10 In the **Settings** window for **Boundary Probe**, locate the **Expression** section.
- 11 In the **Expression** text field, type  $\sqrt{\text{spf2.K\_stressx}^2 + \text{spf2.K\_stressy}^2 + \text{spf2.K\_stressz}^2}$ .
- 12 In the **Table and plot unit** field, type N/m<sup>2</sup>.
- 13 Click to expand the **Table and Window Settings** section. Click  **Add Plot Window**.



#### *Maximum Wall Shear Stress - Fillet*

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, type Maximum Wall Shear Stress - Fillet in the **Label** text field.
- 3 In the **Variable name** text field, type tau\_fillet\_max.
- 4 Locate the **Probe Type** section. From the **Type** list, choose **Maximum**.
- 5 Locate the **Source Selection** section. From the **Selection** list, choose **Manual**.
- 6 Click  **Clear Selection**.
- 7 Select Boundary 40 only.
- 8 Locate the **Expression** section. In the **Expression** text field, type  $\text{spf2.K\_stressx} \cdot n_x + \text{spf2.K\_stressy} \cdot n_y + \text{spf2.K\_stressz} \cdot n_z$ .
- 9 Click to expand the **Table and Window Settings** section. Click  **Add Plot Window**.



### Shaft Torque

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, type Shaft Torque in the **Label** text field.
- 3 In the **Variable name** text field, type shaft\_torque.
- 4 Locate the **Probe Type** section. From the **Type** list, choose **Integral**.
- 5 Locate the **Source Selection** section. Click  **Clear Selection**.
- 6 Click  **Paste Selection**.
- 7 In the **Paste Selection** dialog box, type 28-31 in the **Selection** text field.
- 8 Click **OK**.
- 9 In the **Settings** window for **Boundary Probe**, locate the **Expression** section.
- 10 In the **Expression** text field, type  $x*spf2.T\_stressy-y*spf2.T\_stressx$ .
- 11 In the **Table and plot unit** field, type  $nN*m$ .
- 12 Locate the **Table and Window Settings** section. Click  **Add Plot Window**.

### Average 1 (aveop1)


- 1 In the **Definitions** toolbar, click  **Nonlocal Couplings** and choose **Average**.
- 2 In the **Settings** window for **Average**, locate the **Source Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 21 in the **Selection** text field.
- 6 Click **OK**.

### Average 2 (aveop2)

- 1 In the **Definitions** toolbar, click  **Nonlocal Couplings** and choose **Average**.
- 2 In the **Settings** window for **Average**, locate the **Source Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 Click  **Paste Selection**.
- 5 In the **Paste Selection** dialog box, type 55 in the **Selection** text field.
- 6 Click **OK**.

## TURBULENT FLOW, K-ε - PRELIM (SPF)

### Generate New Turbulence Model Interface 1

- 1 In the **Physics** toolbar, click  **Global** and choose **Generate New Turbulence Model Interface**.


- 2 In the **Settings** window for **Generate New Turbulence Model Interface**, locate the **Study** section.
- 3 From the **Initial value from study** list, choose **Study 1 - k-epsilon**.
- 4 Locate the **Turbulence Model Interface** section. From the list, choose **Turbulent Flow, SST**.
- 5 Locate the **Model Generation** section. Click **Create**.

## **TURBULENT FLOW, SST 2 (SPF2)**

### *Wall 1*



- 1 In the **Model Builder** window, expand the **Turbulent Flow, SST 2 (spf2)** node, then click **Wall 1**.
- 2 In the **Settings** window for **Wall**, click to expand the **Wall Movement** section.
- 3 From the **Translational velocity** list, choose **Automatic from frame**.

## **STUDY 2 - SST**

- 1 In the **Model Builder** window, click **Study 2**.
- 2 In the **Settings** window for **Study**, type Study 2 - SST in the **Label** text field.
- 3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.
- 4 In the **Home** toolbar, click  **Compute**.


The **Generate New Turbulence Model** option is used to create a turbulent flow interface using the SST model solved with Study 2. This also generates initial values for the new interface based on the solution from Study 1.

## **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 **Studies** subsection. In the **Select Study** tree, select **Empty Study**.
- 4 Click **Add Study** in the window toolbar.
- 5 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

## **STUDY 3**

### *Step 1: Frozen Rotor*

- 1 In the **Study** toolbar, click  **Study Steps** and choose **Stationary>Frozen Rotor**.
- 2 In the **Settings** window for **Frozen Rotor**, locate the **Physics and Variables Selection** section.

3 In the table, enter the following settings:

Physics interface	Solve for	Equation form
Turbulent Flow, k-ε - Prelim (spf)		Automatic (Stationary)

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

5 In the **Settings** window for **Study**, type Study 3 - SST - Qb Sweep in the **Label** text field.

6 In the **Model Builder** window, click **Step 1: Frozen Rotor**.

7 In the **Settings** window for **Frozen Rotor**, click to expand the **Values of Dependent Variables** section.

8 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

10 From the **Study** list, choose **Study 2 - SST, Frozen Rotor**.

11 Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

12 From the **Study** list, choose **Study 2 - SST, Frozen Rotor**.

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

14 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

15 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Qb (Inlet flow rate)	7 4.5 2.5	L/min

16 In the table, click to select the cell at row number 1 and column number 1.

*Solution 4 (sol4)*

1 In the **Study** toolbar, click  **Show Default Solver**.

2 Click  **Compute**.

## RESULTS

*Exterior Walls, Study 3 - SST - Qb Sweep/Solution 4*


1 In the **Model Builder** window, expand the **Results>Datasets** node, then click **Exterior Walls**.

- 2 In the **Settings** window for **Surface**, type Exterior Walls, Study 3 - SST - Qb Sweep/Solution 4 in the **Label** text field.
- 3 Locate the **Selection** section. From the **Selection** list, choose **Wall Boundaries**.
- 4 Right-click **Results>Datasets>Exterior Walls, Study 3 - SST - Qb Sweep/Solution 4** and choose **Duplicate**.


#### *Exterior Walls, Study 2 - SST/Solution 2*

- 1 In the **Model Builder** window, under **Results>Datasets** click **Exterior Walls, Study 3 - SST - Qb Sweep/Solution 4.1**.
- 2 In the **Settings** window for **Surface**, type Exterior Walls, Study 2 - SST/Solution 2 in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Selection** section. From the **Selection** list, choose **Wall Boundaries**.


#### *Blade Passage Plane*

- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type Blade Passage Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.
- 5 In the **z-coordinate** text field, type 0.006562.

#### *Lower Gap Plane*

- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type Lower Gap Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.
- 5 In the **z-coordinate** text field, type 0.0005.

#### *zx Outlet Plane*


- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type zx Outlet Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.
- 5 In the **y-coordinate** text field, type -0.027805.

#### *Upper Gap Plane*


- 1 In the **Results** toolbar, click  **Cut Plane**.

- 2 In the **Settings** window for **Cut Plane**, type Upper Gap Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.
- 5 In the **z-coordinate** text field, type 0.0085.


#### *zx Inlet Plane*

- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type zx Inlet Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.


#### *yz Inlet Plane*

- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type yz Inlet Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.


#### *Upper Blade Plane*

- 1 In the **Results** toolbar, click  **Cut Plane**.
- 2 In the **Settings** window for **Cut Plane**, type Upper Blade Plane in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.
- 5 In the **z-coordinate** text field, type  $8[\text{mm}] - 1.2[\text{mm}]$ .

#### *Radial Cut Line 2D*

- 1 In the **Results** toolbar, click  **Cut Line 2D**.
- 2 In the **Settings** window for **Cut Line 2D**, type Radial Cut Line 2D in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Upper Blade Plane**.
- 4 Locate the **Line Data** section. In row **Point 2**, set **x** to  $0.03 \cdot \cos(45[\text{deg}])$ .
- 5 In row **Point 2**, set **y** to  $-0.03 \cdot \cos(45[\text{deg}])$ .

#### *Diffuser Cut Line 2D*


- 1 In the **Results** toolbar, click  **Cut Line 2D**.
- 2 In the **Settings** window for **Cut Line 2D**, type Diffuser Cut Line 2D in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Upper Blade Plane**.
- 4 Locate the **Line Data** section. In row **Point 1**, set **x** to 0.0367.




5 In row **Point 2**, set **x** to 0.0367.

6 In row **Point 2**, set **y** to -0.04.

#### *Imported Experimental Results - Radial Cut Line 1*

1 In the **Results** toolbar, click  **Table**.

2 In the **Settings** window for **Table**, type Imported Experimental Results - Radial Cut Line 1 in the **Label** text field.


3 Locate the **Data** section. Click  **Import**.

4 Browse to the model's Application Libraries folder and double-click the file fda\_benchmark\_blood\_pump\_uxy\_1\_lab1.txt.


5 Locate the **Column Headers** section. In the table, enter the following settings:

Column	Header
1	r [m]
2	U_xy  [m/s]

#### *Imported Experimental Results - Radial Cut Line 2*

1 In the **Results** toolbar, click  **Table**.

2 In the **Settings** window for **Table**, type Imported Experimental Results - Radial Cut Line 2 in the **Label** text field.


3 Locate the **Data** section. Click  **Import**.

4 Browse to the model's Application Libraries folder and double-click the file fda\_benchmark\_blood\_pump\_uxy\_1\_lab2.txt.


5 Locate the **Column Headers** section. In the table, enter the following settings:

Column	Header
1	r [m]
2	U_xy  [m/s]

#### *Imported Experimental Results - Radial Cut Line 3*

1 In the **Results** toolbar, click  **Table**.

2 In the **Settings** window for **Table**, type Imported Experimental Results - Radial Cut Line 3 in the **Label** text field.



3 Locate the **Data** section. Click  **Import**.

4 Browse to the model's Application Libraries folder and double-click the file fda\_benchmark\_blood\_pump\_uxy\_1\_lab3a.txt.

5 Locate the **Column Headers** section. In the table, enter the following settings:



Column	Header
1	$r$ [m]
2	$ U_{xy} $ [m/s]

*Imported Experimental Results -Diffuser Cut Line 1*

- 1 In the **Results** toolbar, click  **Table**.
- 2 In the **Settings** window for **Table**, type Imported Experimental Results -Diffuser Cut Line 1 in the **Label** text field.
- 3 Locate the **Data** section. Click  **Import**.
- 4 Browse to the model's Application Libraries folder and double-click the file fda\_benchmark\_blood\_pump\_uxy\_2\_lab1.txt.
- 5 Locate the **Column Headers** section. In the table, enter the following settings:



Column	Header
1	$d$ [m]
2	$ U_{xy} $ [m/s]

*Imported Experimental Results -Diffuser Cut Line 2*

- 1 In the **Results** toolbar, click  **Table**.
- 2 In the **Settings** window for **Table**, type Imported Experimental Results -Diffuser Cut Line 2 in the **Label** text field.
- 3 Locate the **Data** section. Click  **Import**.
- 4 Browse to the model's Application Libraries folder and double-click the file fda\_benchmark\_blood\_pump\_uxy\_2\_lab2.txt.
- 5 Locate the **Column Headers** section. In the table, enter the following settings:

Column	Header
1	$d$ [m]
2	$ U_{xy} $ [m/s]



*Imported Experimental Results -Diffuser Cut Line 3*

- 1 In the **Results** toolbar, click  **Table**.
- 2 In the **Settings** window for **Table**, type Imported Experimental Results -Diffuser Cut Line 3 in the **Label** text field.
- 3 Locate the **Data** section. Click  **Import**.

- 4 Browse to the model's Application Libraries folder and double-click the file `fda_benchmark_blood_pump_uxy_2_lab3a.txt`.
- 5 Locate the **Column Headers** section. In the table, enter the following settings:


Column	Header
1	d [m]
2	U_xy  [m/s]

#### *Imported - Experimental Results - Pressure Head*

- 1 In the **Results** toolbar, click  **Table**.
- 2 In the **Settings** window for **Table**, type Imported - Experimental Results - Pressure Head in the **Label** text field.
- 3 Locate the **Data** section. Click  **Import**.
- 4 Browse to the model's Application Libraries folder and double-click the file `fda_benchmark_blood_pump_pressure_head_exp.txt`.
- 5 Locate the **Column Headers** section. In the table, enter the following settings:

Column	Header
1	Flow rate(L/min)
2	Pressure Head(mmHg)

#### *Pressure Head - Study 3*

- 1 In the **Results** toolbar, click  **Global Evaluation**.
- 2 In the **Settings** window for **Global Evaluation**, type Pressure Head - Study 3 in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 3 - SST - Qb Sweep/Solution 4 (sol4)**.
- 4 Locate the **Expressions** section. In the table, enter the following settings:


Expression	Unit	Description
<code>abs(aveop1(p2) - aveop2(p2))</code>	mmHg	

- 5 Click  next to  **Evaluate**, then choose **New Table**.

#### *Pressure Head - Study 3*

- 1 In the **Model Builder** window, under **Results>Tables** click **Table 9**.
- 2 In the **Settings** window for **Table**, type Pressure Head - Study 3 in the **Label** text field.

#### Pressure Head - Study 2

- 1 In the **Results** toolbar, click  **Global Evaluation**.
- 2 In the **Settings** window for **Global Evaluation**, type Pressure Head - Study 2 in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 4 Locate the **Expressions** section. In the table, enter the following settings:


Expression	Unit	Description
Qb	L/min	Inlet flow rate
abs(aveop1(p2) - aveop2(p2))	mmHg	

- 5 Click  next to  **Evaluate**, then choose **New Table**.

#### Pressure Head - Study 2


- 1 In the **Model Builder** window, under **Results>Tables** click **Table 10**.
- 2 In the **Settings** window for **Table**, type Pressure Head - Study 2 in the **Label** text field.

#### Surface Integration 1 - Inflow

- 1 In the **Results** toolbar, click  **More Derived Values** and choose **Integration>Surface Integration**.
- 2 In the **Settings** window for **Surface Integration**, type Surface Integration 1 - Inflow in the **Label** text field.
- 3 Select Boundary 52 only.
- 4 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 5 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
spf2.rho*(u2*nx+v2*ny+w2*nz)	kg/s	

#### Surface Integration 1 - Outflow

- 1 In the **Results** toolbar, click  **More Derived Values** and choose **Integration>Surface Integration**.
- 2 In the **Settings** window for **Surface Integration**, type Surface Integration 1 - Outflow in the **Label** text field.
- 3 Select Boundary 53 only.
- 4 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.

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

Expression	Unit	Description
$\text{spf2}.\text{rho}*(\text{u2}*\text{nx}+\text{v2}*\text{ny}+\text{w2}*\text{nz})$	kg/s	

#### *Probe Plot Group 1*

- 1 In the **Model Builder** window, under **Results** click **Probe Plot Group 1**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 Clear the **Show legends** check box.
- 4 Locate the **Plot Settings** section.
- 5 Select the **y-axis label** check box. In the associated text field, type Absolute pressure (Pa).
- 6 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type Inlet Pressure.


#### *Probe Plot Group 2*

- 1 In the **Model Builder** window, click **Probe Plot Group 2**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 Clear the **Show legends** check box.
- 4 Locate the **Plot Settings** section.
- 5 Select the **y-axis label** check box. In the associated text field, type Absolute pressure (Pa).
- 6 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type Outlet Pressure.

#### *Probe Plot Group 3*

- 1 In the **Model Builder** window, expand the **Probe Plot Group 2** node, then click **Results> Probe Plot Group 3**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 Clear the **Show legends** check box.
- 4 Locate the **Plot Settings** section.
- 5 Select the **y-axis label** check box. In the associated text field, type Maximum Wall Shear Stress ( $\text{N/m}^2$ ).
- 6 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type Maximum Wall Shear Stress on Housing Rim.

#### *Probe Plot Group 4*

- 1 In the **Model Builder** window, click **Probe Plot Group 4**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 Clear the **Show legends** check box.
- 4 Locate the **Plot Settings** section.
- 5 Select the **y-axis label** check box. In the associated text field, type Maximum Wall Shear Stress.
- 6 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type Maximum Wall Shear Stress on Fillet.
- 8 In the **Probe Plot Group 4** toolbar, click  **Plot**.

#### *Probe Plot Group 5*


- 1 In the **Model Builder** window, click **Probe Plot Group 5**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 Clear the **Show legends** check box.
- 4 Locate the **Plot Settings** section.
- 5 Select the **y-axis label** check box. In the associated text field, type Shaft Torque (nN\*m).

### **DEFINITIONS**

#### *View 8*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **View**.
- 2 In the **Settings** window for **View**, locate the **View** section.
- 3 Select the **Show axis units** check box.
- 4 Clear the **Show grid** check box.

#### *Hide for Geometry 1*

- 1 Right-click **View 8** and choose **Hide for Geometry**.
- 2 In the **Settings** window for **Hide for Geometry**, locate the **Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 Click the  **Paste Selection** button for **Selection**.
- 5 In the **Paste Selection** dialog box, type 4-6, 8, 14, 16, 18, 20-22, 24-27, 34-37, 39, 42, 45, 47, 48, 50-52, 54, 55 in the **Selection** text field.

6 Click **OK**.

## RESULTS

### *Velocity (spf2)*

- 1 In the **Model Builder** window, under **Results** click **Velocity (spf2)**.
- 2 In the **Settings** window for **3D Plot Group**, click to expand the **Title** section.
- 3 From the **Title type** list, choose **None**.
- 4 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.
- 5 From the **View** list, choose **View 8**.
- 6 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.

### *Slice*

- 1 In the **Model Builder** window, expand the **Velocity (spf2)** node.
- 2 Right-click **Slice** and choose **Disable**.

### *Surface 1*

- 1 In the **Model Builder** window, right-click **Velocity (spf2)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Blade Passage Plane**.
- 4 Locate the **Expression** section. In the **Expression** text field, type `spf2.U`.

### *Transparency 1*

Right-click **Surface 1** and choose **Transparency**.

### *Surface 2*

- 1 In the **Model Builder** window, right-click **Velocity (spf2)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **zx Outlet Plane**.
- 4 Locate the **Expression** section. In the **Expression** text field, type `spf2.U`.
- 5 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

### *Transparency 1*

Right-click **Surface 2** and choose **Transparency**.

### *Surface 3*

- 1 In the **Model Builder** window, right-click **Velocity (spf2)** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.

- 3 From the **Dataset** list, choose **zx Inlet Plane**.
- 4 Locate the **Expression** section. In the **Expression** text field, type `spf2.U`.
- 5 Locate the **Coloring and Style** section. Clear the **Color legend** check box.


#### *Transparency 1*

Right-click **Surface 3** and choose **Transparency**.

#### *Velocity (spf2)*

Right-click **Surface 3>Transparency 1** and choose **Surface**.

#### *Surface 4*

- 1 In the **Settings** window for **Surface**, locate the **Data** section.
- 2 From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.
- 3 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.
- 4 From the **Color** list, choose **Gray**.
- 5 In the **Velocity (spf2)** toolbar, click  **Plot**.

#### *Pressure (spf2)*

- 1 In the **Model Builder** window, under **Results** click **Pressure (spf2)**.
- 2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Exterior Walls, Study 2 - SST/Solution 2**.


#### *Surface*

- 1 In the **Model Builder** window, expand the **Pressure (spf2)** node, then click **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Blade Passage Plane**.
- 4 Locate the **Expression** section. In the **Expression** text field, type `p2`.

#### *Pressure (spf2)*

Right-click **Surface** and choose **Surface**.

#### *Surface 2*

- 1 In the **Settings** window for **Surface**, locate the **Data** section.
- 2 From the **Dataset** list, choose **zx Outlet Plane**.
- 3 Locate the **Expression** section. In the **Expression** text field, type `p2`.
- 4 In the **Pressure (spf2)** toolbar, click  **Plot**.

#### *Wall Resolution (spf2)*

- 1 In the **Model Builder** window, under **Results** click **Wall Resolution (spf2)**.



2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.

#### *Turbulent Viscosity*

1 In the **Home** toolbar, click  **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type **Turbulent Viscosity** in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - SST/Solution 2 (sol2)**.

#### *Surface 1*

1 Right-click **Turbulent Viscosity** and choose **Surface**.

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

3 From the **Dataset** list, choose **Blade Passage Plane**.

4 Locate the **Expression** section. In the **Expression** text field, type `spf2.muT`.

#### *Surface 2*

1 In the **Model Builder** window, right-click **Turbulent Viscosity** and choose **Surface**.

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

3 From the **Dataset** list, choose **zx Outlet Plane**.

4 Locate the **Expression** section. In the **Expression** text field, type `spf2.muT`.

5 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

#### *Turbulent Viscosity*

1 In the **Model Builder** window, click **Turbulent Viscosity**.

2 In the **Turbulent Viscosity** toolbar, click  **Plot**.

#### *Magnitude of Uxy - Radial*

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

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

3 Select the **x-axis label** check box.

4 Select the **y-axis label** check box.

5 In the **x-axis label** text field, type `r [m]`.

6 In the **y-axis label** text field, type `|U_xy| [m/s]`.

7 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

8 In the **Title** text area, type **Velocity magnitude s along the radial cut line compared with experimental results..**

- 9 In the **Label** text field, type **Magnitude of Uxy - Radial**.
- 10 Locate the **Data** section. From the **Dataset** list, choose **Radial Cut Line 2D**.
- 11 Locate the **Plot Settings** section. Select the **x-axis label** check box.
- 12 Select the **y-axis label** check box.
- 13 In the **x-axis label** text field, type  $r \text{ [m]}$ .
- 14 In the **y-axis label** text field, type  $|U_{xy}| \text{ [m/s]}$ .
- 15 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 16 In the **Title** text area, type **Velocity magnitude s along the radial cut line compared with experimental results..**
- 17 Locate the **Axis** section. Select the **Manual axis limits** check box.
- 18 In the **x minimum** text field, type 0.
- 19 In the **x maximum** text field, type 0.027.
- 20 In the **y minimum** text field, type 0.
- 21 In the **y maximum** text field, type 9.
- 22 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

#### *Line Graph 1*

- 1 Right-click **Magnitude of Uxy - Radial** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type  $\sqrt{u^2+v^2}$ .
- 4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 5 In the **Expression** text field, type  $\sqrt{x^2+y^2}$ .
- 6 Click to expand the **Legends** section. Select the **Show legends** check box.
- 7 From the **Legends** list, choose **Manual**.
- 8 In the table, enter the following settings:

Legends
COMSOL

- 9 In the **Magnitude of Uxy - Radial** toolbar, click  **Plot**.

#### *Table Graph 1*

- 1 In the **Model Builder** window, right-click **Magnitude of Uxy - Radial** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.

- 3 From the **Table** list, choose **Imported Experimental Results - Radial Cut Line 1**.
- 4 From the **x-axis data** list, choose **r [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Blue**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 1 Exp. results"

- 12 In the **Magnitude of Uxy - Radial** toolbar, click  **Plot**.

*Table Graph 2*

- 1 Right-click **Magnitude of Uxy - Radial** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported Experimental Results - Radial Cut Line 2**.
- 4 From the **x-axis data** list, choose **r [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Red**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Square**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 2 Exp. results"

- 12 In the **Magnitude of Uxy - Radial** toolbar, click  **Plot**.


### Table Graph 3

- 1 Right-click **Magnitude of Uxy - Radial** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported Experimental Results - Radial Cut Line 3**.
- 4 From the **x-axis data** list, choose **r [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Black**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Triangle**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 3 Exp. results"

- 12 In the **Magnitude of Uxy - Radial** toolbar, click  **Plot**.

### Magnitude of Uxy - Diffuser

- 1 In the **Home** toolbar, click  **Add Plot Group** and choose **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Magnitude of Uxy - Diffuser** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Diffuser Cut Line 2D**.
- 4 Locate the **Plot Settings** section. Select the **x-axis label** check box.
- 5 Select the **y-axis label** check box.
- 6 In the **x-axis label** text field, type **d [m]**.
- 7 In the **y-axis label** text field, type **|U<sub>xy</sub>|**.
- 8 Locate the **Title** section. From the **Title type** list, choose **Manual**.
- 9 In the **Title** text area, type **Velocity magnitude along the diffuser cut line compared with experimental results..**
- 10 Locate the **Axis** section. Select the **Manual axis limits** check box.
- 11 In the **x minimum** text field, type **0**.
- 12 In the **x maximum** text field, type **0.01**.

- 13 In the **y minimum** text field, type 0.
- 14 In the **y maximum** text field, type 7.
- 15 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

*Line Graph 1*

- 1 Right-click **Magnitude of Uxy - Diffuser** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type  $\sqrt{u^2+v^2}$ .
- 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
COMSOL

- 7 In the **Magnitude of Uxy - Diffuser** toolbar, click  **Plot**.

*Table Graph 1*

- 1 In the **Model Builder** window, right-click **Magnitude of Uxy - Diffuser** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported Experimental Results -Diffuser Cut Line 1**.
- 4 From the **x-axis data** list, choose **d [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Blue**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 1 Exp. results"

- 12 In the **Magnitude of Uxy - Diffuser** toolbar, click  **Plot**.

### Table Graph 2

- 1 Right-click **Magnitude of Uxy - Diffuser** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported Experimental Results -Diffuser Cut Line 2**.
- 4 From the **x-axis data** list, choose **d [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Red**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Square**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 2 Exp. results"

- 12 In the **Magnitude of Uxy - Diffuser** toolbar, click  **Plot**.


### Table Graph 3

- 1 Right-click **Magnitude of Uxy - Diffuser** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported Experimental Results -Diffuser Cut Line 3**.
- 4 From the **x-axis data** list, choose **d [m]**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Black**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Triangle**.
- 8 From the **Positioning** list, choose **In data points**.
- 9 Click to expand the **Legends** section. Select the **Show legends** check box.
- 10 From the **Legends** list, choose **Manual**.
- 11 In the table, enter the following settings:

Legends
"Lab - 3 Exp. results"

12 In the **Magnitude of Uxy - Diffuser** toolbar, click  **Plot**.

*Pressure Head - Exp. Comparison*

- 1 In the **Home** toolbar, click  **Add Plot Group** and choose **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Pressure Head - Exp. Comparison** in the **Label** text field.
- 3 Locate the **Title** section. From the **Title type** list, choose **Manual**.
- 4 In the **Title** text area, type **Pressure head at different inlet flow rates for the centrifugal pump**.
- 5 Locate the **Plot Settings** section.
- 6 Select the **x-axis label** check box. In the associated text field, type **Flow rate (L/min)**.
- 7 Select the **y-axis label** check box. In the associated text field, type **Pressure head (mmHg)**.

*Table Graph 1*

- 1 Right-click **Pressure Head - Exp. Comparison** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Imported - Experimental Results - Pressure Head**.
- 4 From the **x-axis data** list, choose **Flow rate(L/min)**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 6 From the **Color** list, choose **Black**.
- 7 From the **Width** list, choose **6**.
- 8 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.
- 9 Locate the **Legends** section. From the **Legends** list, choose **Manual**.
- 10 Select the **Show legends** check box.
- 11 In the table, enter the following settings:

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**Legends**

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Experiments (Malinauskas et al. ASAI0 Journal 2017)

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*Table Graph 2*

- 1 In the **Model Builder** window, right-click **Pressure Head - Exp. Comparison** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Pressure Head - Study 3**.


- 4 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
- 5 From the **Color** list, choose **Blue**.
- 6 From the **Width** list, choose **6**.
- 7 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.
- 8 Locate the **Legends** section. Select the **Show legends** check box.
- 9 From the **Legends** list, choose **Manual**.
- 10 In the table, enter the following settings:

Legends
COMSOL

*Table Graph 3*

- 1 Right-click **Pressure Head - Exp. Comparison** and choose **Table Graph**.
- 2 In the **Settings** window for **Table Graph**, locate the **Data** section.
- 3 From the **Table** list, choose **Pressure Head - Study 2**.
- 4 From the **x-axis data** list, choose **Inlet flow rate (L/min)**.
- 5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Solid**.
- 6 From the **Color** list, choose **Blue**.
- 7 From the **Width** list, choose **6**.
- 8 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.
- 9 In the **Pressure Head - Exp. Comparison** toolbar, click  **Plot**.

*Velocity magnitude at the blade passage plane*

- 1 In the **Home** toolbar, click  **Add Plot Group** and choose **3D Plot Group**.
- 2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Blade Passage Plane**.
- 4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 5 In the **Title** text area, type Velocity magnitude at the blade passage plane under operating condition of 3500 [rpm] and an inlet flow rate of 6 [L/min]..
- 6 In the **Label** text field, type Velocity magnitude at the blade passage plane.
- 7 Locate the **Title** section. In the **Title** text area, type Velocity magnitude at the blade passage plane.




- 8 In the **Parameter indicator** text field, type  $Qb(2)=6 \text{ L/min}$ .
- 9 Click to expand the **Plot Settings** section. Clear the **Plot dataset edges** check box.
- 10 From the **View** list, choose **New view**.

#### Surface 1

- 1 Right-click **Velocity magnitude at the blade passage plane** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type  $spf2.U$ .

#### Filter 1

- 1 Right-click **Surface 1** and choose **Filter**.
- 2 In the **Settings** window for **Filter**, locate the **Element Selection** section.
- 3 In the **Logical expression for inclusion** text field, type  $x > -0.005 \ \&\& \ x < 0.04 \ \&\& \ y < 0.005$ .
- 4 In the **Velocity magnitude at the blade passage plane** toolbar, click  **Plot**.

