



Model created in COMSOL Multiphysics 6.4

Nonisothermal Laminar Flow in a Circular Tube

Introduction

This validation model of laminar airflow through a tube validates the heat transfer coefficient obtained from the simulation against Nusselt-number-based correlation functions. The simulation results are in good agreement with experimental measurements.

Model Definition

The tube is modeled as a 2D axisymmetric geometry. The tube has a diameter of 0.05 m and a length of 3 m. A coupled heat transfer and fluid flow problem is solved using the Nonisothermal Flow interface.

At the inlet, a laminar velocity profile U with an average velocity U_{av} of 0.1 m/s is applied using the normal inflow option:

$$U = 1,5U_{av}\left(1 - 4\left(\frac{r}{b}\right)^2\right)$$

where r denotes the radial distance from the tube center and b the tube's diameter. The expression gives the typical parabolic velocity profile for fully developed laminar flow. The air enters with a temperature T_0 of 283 K.

At the cylinder wall, a constant heat flux q_w of 10 W/m² is applied.

NUSSELT NUMBER CORRELATIONS

Two different Nusselt number correlations are used to validate the numerical results.

First, in regions with fully developed laminar flow with a radial temperature profile, a constant Nusselt number Nu_c can be defined as follows:

$$Nu_c = \frac{hD_h}{k}$$

where k (SI unit: W/(m·K)) denotes the thermal conductivity, D_h (SI unit: m) the hydraulic diameter, and h (SI unit: W/(m²·K)) the heat transfer coefficient. In the case of a tube with uniform surface heat flux, $Nu = 4.36$ (Ref. 1, p. 507).

Alternatively, a local Nusselt number Nu_l can be defined, based on the z -position along the cylinder, to describe both the entrance and fully developed regions of the flow (Ref. 2, p. 304):

$$\frac{Nu_1}{4.364 \left[1 + \left(\frac{Gz}{29.6} \right)^2 \right]^{1/6}} = \left[1 + \left(\frac{Gz/19.04}{\left[1 + \left(\frac{Pr}{0.0207} \right)^{2/3} \right]^{1/2} \left[1 + \left(\frac{Gz}{29.6} \right)^2 \right]^{1/3}} \right)^{3/2} \right]^{1/3}$$

where Pr is the Prandtl number, and the Graetz number Gz is defined by:

$$Gz = \frac{\pi}{4} \cdot \frac{Re_b \cdot Pr \cdot b}{z}$$

with Re_b the Reynolds number associated to the tube diameter b .

Results and Discussion

The velocity field is shown in Figure 1 and the temperature field in Figure 2. Both are plotted in a scaled view to get a clearer visualization of the results.

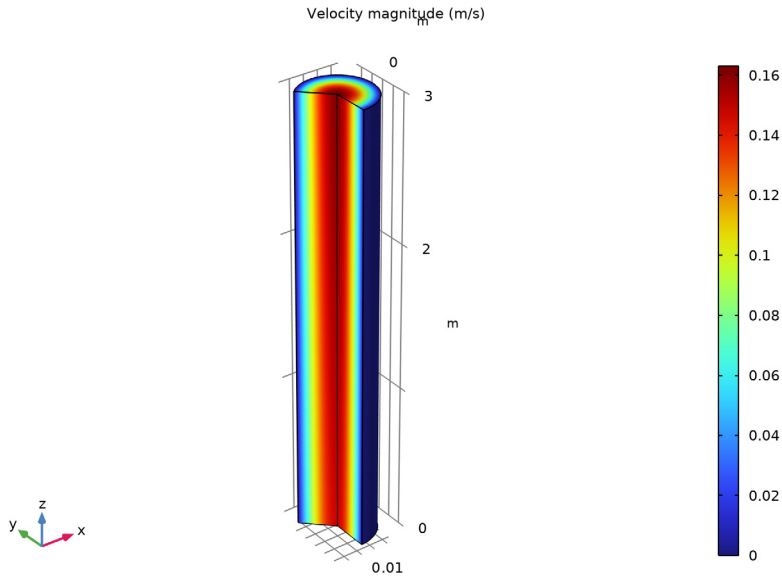


Figure 1: Velocity field.

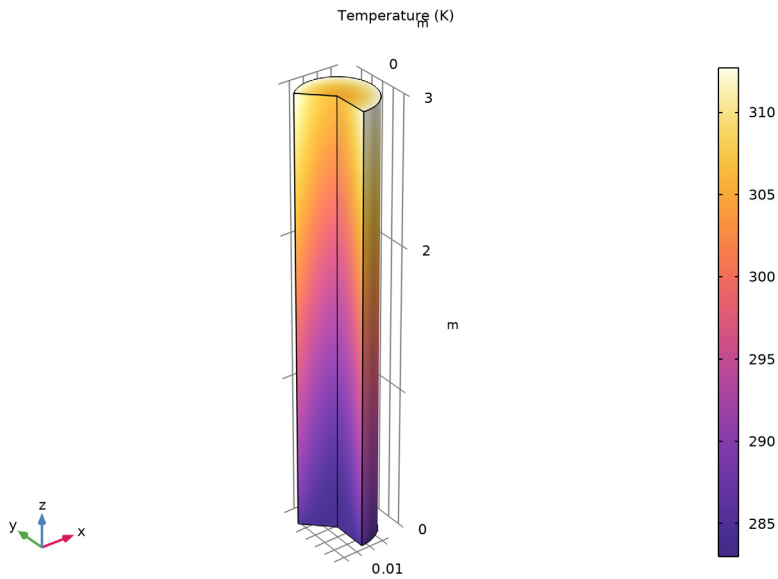


Figure 2: Temperature field.

The comparison of the computed heat transfer coefficient with the Nusselt number correlations shows that the Local Nusselt number provides a good approximation over the whole cylinder. On the other hand, constant Nusselt number represents the region where velocity and temperature profile are fully developed ([Figure 3](#)).

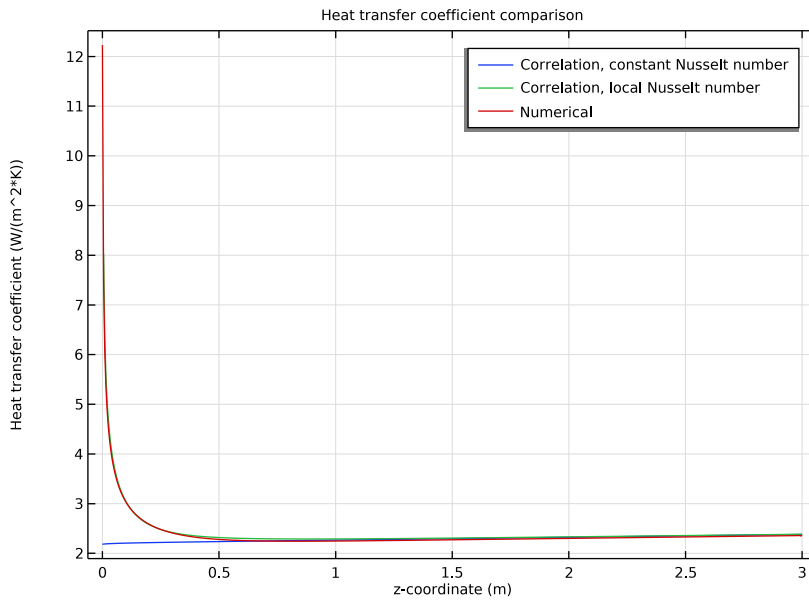


Figure 3: Comparison of the computed heat transfer coefficient with the heat transfer coefficient estimation based on Nusselt number correlations.

References


1. F.P. Incropera, D.P. DeWitt, T.L. Bergman, and A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th Edition, John Wiley & Sons, 2006.
2. A. Bejan and others, *Heat Transfer Handbook*, John Wiley & Sons, 2003.

Application Library path: Heat_Transfer_Module/Verification_Examples/
circular_tube_nitf_laminar




Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click  **Model Wizard**.

MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D Axisymmetric**.
- 2 In the **Select Physics** tree, select **Fluid Flow** > **Nonisothermal Flow** > **Laminar Flow**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **General Studies** > **Stationary**.
- 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
L	3[m]	3 m	Length
b	0.05[m]	0.05 m	Height
T0	283[K]	283 K	Inlet temperature
U_av	0.1[m/s]	0.1 m/s	Average inlet velocity
qw	10[W/m^2]	10 W/m ²	Wall heat flux
Tw	293[K]	293 K	Wall temperature

DEFINITIONS

Variables I

Define several variables: A variable for the inlet velocity profile, a variable for the bulk temperature which is a radial weighted temperature, and similarly a variable for the bulk velocity. Finally, add variables to compare the simulation results with the literature values.


- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.
- 2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
U	$1.5*U_{av}*(1-4*(r/b)^2)$	m/s	Inlet velocity
Tb	$\text{integrate}(\text{comp1.at2}(r,z,2*\pi*r*w*T),r,0,b/2)/\text{integrate}(\text{comp1.at2}(r,z,2*\pi*r*w),r,0,b/2)$	K	Bulk temperature
Ub	$\text{integrate}(\text{comp1.at2}(r,z,2*\pi*r*w),r,0,b/2)/(\pi*(b/2)^2)$	m/s	Bulk velocity
Tc	$\text{comp1.at2}(0,z,T)$	K	Center line temperature
Pr	$ht.Cp*spf.mu/ht.kmean$		Prandtl number
Re_D	$\text{nitf1.rho}*Ub*b/spf.mu$		Reynolds number
Gz	$b*Re_D*Pr/z*\pi/4$		Graetz number
Nu_D	$(1+(Gz/19.04/((1+(Pr/0.0207)^2/3)^{1/2}*(1+(Gz/29.6)^2)^{1/3}))^{3/2})^{1/3}*4.364*(1+(Gz/29.6)^2)^{1/6}$		Local Nusselt number

GEOMETRY I

Rectangle I (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 $b/2$.

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

5 Click  **Build All Objects**.

ADD MATERIAL

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

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


3 In the tree, select **Built-in > Air**.

4 Click the **Add to Component** button in the window toolbar.

5 In the **Materials** toolbar, click  **Add Material** to close the **Add Material** window.

LAMINAR FLOW (SPF)

Inlet 1


- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Inlet**.
- 2 Select Boundary 2 only.
- 3 In the **Settings** window for **Inlet**, locate the **Velocity** section.
- 4 In the U_0 text field, type U.

Outlet 1


- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Outlet**.
- 2 Select Boundary 3 only.

HEAT TRANSFER IN FLUIDS (HT)


Inflow 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Inflow**.
- 2 Select Boundary 2 only.
- 3 In the **Settings** window for **Inflow**, locate the **Upstream Properties** section.
- 4 In the T_{ustr} text field, type T0.

Outflow 1


- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Outflow**.
- 2 Select Boundary 3 only.

Heat Flux 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Heat Flux**.
- 2 Select Boundary 4 only.
- 3 In the **Settings** window for **Heat Flux**, locate the **Heat Flux** section.
- 4 In the q_0 text field, type qw.

MESH 1

Mapped 1

In the **Mesh** toolbar, click  **Mapped**.


Distribution 1

- 1 Right-click **Mapped 1** and choose **Distribution**.
- 2 Select Boundary 4 only.
- 3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type 600.

Distribution 2

1 In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.

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

3 Select Boundaries 2 and 3 only.

4 In the **Settings** window for **Distribution**, locate the **Distribution** section.


5 From the **Distribution type** list, choose **Predefined**.

6 In the **Number of elements** text field, type 33.

7 In the **Element ratio** text field, type 5.

8 Click  **Build All**.

STUDY 1

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

RESULTS

Velocity, 3D (spf)

For better visualization of the results, use a scaled the view.

View 3D 2

In the **Model Builder** window, expand the **Results > Views** node.

Camera

1 In the **Model Builder** window, expand the **View 3D 2** node, then click **Camera**.

2 In the **Settings** window for **Camera**, locate the **Camera** section.

3 From the **View scale** list, choose **Manual**.

4 In the **z scale** text field, type 0.1.


5 Click  **Update**.


Velocity, 3D (spf)

1 In the **Model Builder** window, under **Results** click **Velocity, 3D (spf)**.

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



3 From the **View** list, choose **View 3D 2**.

4 In the **Velocity, 3D (spf)** toolbar, click  **Plot**.

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



Add a plot from the **Result Templates** to see the temperature distribution in 3D.

RESULT TEMPLATES


- 1 In the **Results** toolbar, click  **Result Templates** to open the **Result Templates** window.
- 2 Go to the **Result Templates** window.
- 3 In the tree, select **Study 1/Solution 1 (sol1) > Heat Transfer in Fluids > Temperature (ht)**.
- 4 Click the **Add Result Template** button in the window toolbar.
- 5 In the **Results** toolbar, click  **Result Templates** to close the **Result Templates** window.

RESULTS

Temperature 3D

- 1 In the **Settings** window for **3D Plot Group**, type **Temperature 3D** in the **Label** text field.
- 2 Locate the **Plot Settings** section. From the **View** list, choose **View 3D 2**.
- 3 In the **Temperature 3D** toolbar, click  **Plot**.
- 4 Click the  **Zoom Extents** button in the **Graphics** toolbar.

Heat Transfer Coefficient

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Heat Transfer Coefficient** in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 4 In the **Title** text area, type **Heat transfer coefficient comparison**.
- 5 Locate the **Plot Settings** section.
- 6 Select the **y-axis label** checkbox. In the associated text field, type **Heat transfer coefficient (W/(m^2*K))**.

Line Graph 1

- 1 Right-click **Heat Transfer Coefficient** and choose **Line Graph**.
- 2 Select **Boundary 4** only.
- 3 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 4 In the **Expression** text field, type **4.36*ht.krr/b**.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type **z**.
- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends

Correlation, constant Nusselt number

Line Graph 2

- 1 In the **Model Builder** window, right-click **Heat Transfer Coefficient** and choose **Line Graph**.
- 2 Select Boundary 4 only.
- 3 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 4 In the **Expression** text field, type $Nu_D \cdot ht.k_{mean}/b$.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type z .
- 7 Locate the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.
- 9 In the table, enter the following settings:

Legends

Correlation, local Nusselt number


Line Graph 3

- 1 Right-click **Heat Transfer Coefficient** and choose **Line Graph**.
- 2 Select Boundary 4 only.
- 3 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 4 In the **Expression** text field, type $qw/(T-T_b)$.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type z .
- 7 Locate the **Legends** section. Select the **Show legends** checkbox.
- 8 From the **Legends** list, choose **Manual**.
- 9 In the table, enter the following settings:

Legends

Numerical

Heat Transfer Coefficient

- 1 In the **Model Builder** window, click **Heat Transfer Coefficient**.
- 2 In the **Heat Transfer Coefficient** toolbar, click  **Plot**.

