Shear Stress and Shear Rate Calculations for the µ-Slide y-shaped Based on Computational Fluid Dynamics (CFD)

This Application Note provides instructions on how to calculate the wall shear stress (WSS) in the µ-Slide y-shaped. For simplicity reasons, the term "shear stress" used here will always refer to wall shear stress. Further, the shear rate is calculated.

The µ-Slide y-shaped was designed for studies of non-uniform laminar shear stress. Under flow conditions, the shear stress levels depend on the region on the slide: The prevalent shear stress in the branched regions is approximately half of the regions with only the single channel.

Due to the standardized Luer adapters, the µ-Slide y-shaped can easily be combined with any flow system (e.g., the ibidi Pump System). The shear stress calculations apply equally for all systems.

For a detailed explanation on how to calculate shear stress and shear rates in the ibidi µ-Slides, including a glossary and considerations before setting up an experiment, please have a look at: AN 11 “Shear Stress and Shear Rates for ibidi µ-Slides Based on Numerical Calculations”

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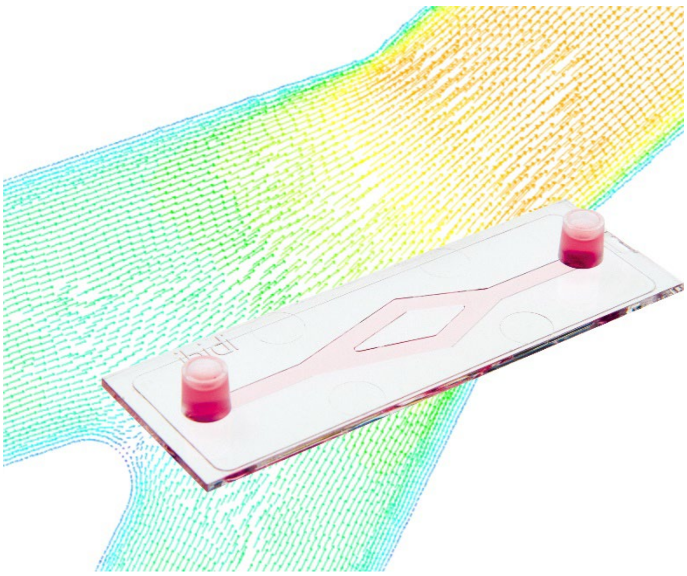


1 Flow Regions in the µ-Slide y-shaped

The µ-Slide y-shaped provides regions of **uniform laminar flow** and **non-uniform laminar flow**.

Laminar flow is defined as the movement of liquids without turbulences. The fluid flows in parallel layers with no disruption between them. Furthermore, a uniform laminar shear stress has a constant direction and velocity over time.

In the case of non-uniform laminar flow, the flow direction is constant, whereas the velocity spatially varies across the cell layer. Non-uniform laminar flow is characterized by flow velocity gradients in small sub millimeter regions.

Please note: The flow pattern in the µ-Slide y-shaped is always laminar! Therefore, it is experimentally impossible to generate turbulences with aqueous solutions in the µ-Slide y-shaped.

2 Shear Stress and Shear Rate Calculations in Uniform Laminar Flow Regions

The shear stress is uniform in the straight parts of the channel. This applies for the single channel region as well as for the branched parts of the channel. The flow rate and shear stress in the orange regions are twice as high as in the green regions (Figure 1).

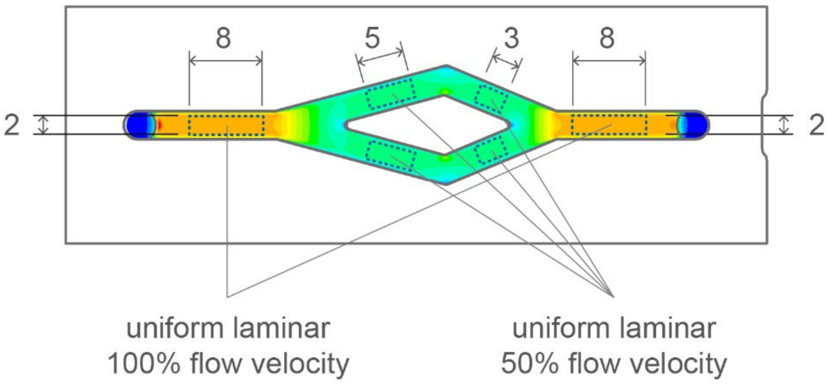


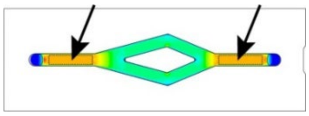
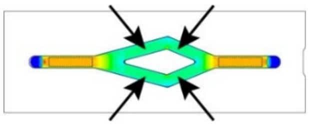
Figure 1: Bottom view of the µ-Slide y-shaped. The dashed rectangles indicate zones of uniform laminar flow and, therefore, also uniform laminar shear stress. Measures in mm indicate the size of the zones.

Nomenclature and units:

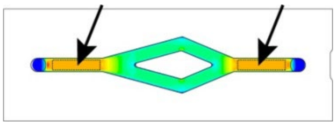
Φ	flow rate	ml/min
τ	shear stress	dyn/cm²
η	dynamical viscosity	dyn·s/cm²

To use the following equations, insert the flow rate, shear stress, and viscosity values in the indicated units. For simplicity reasons, the calculations include all unit conversions (not shown). To calculate the wall shear stress correctly, you need to know the viscosity of the perfused medium (for details, see Application Note 11).

cells in focus ibidi

	Shear Stress	Shear Rate	
Single channel area (100% flow velocity)	$\boxed{\tau = \eta \cdot 227.4 \cdot \Phi}$	$\boxed{\gamma = 227.4 \cdot \Phi}$	
Branched area (50% flow velocity)	$\boxed{\tau = \eta \cdot 113.7 \cdot \Phi}$	$\boxed{\gamma = 113.7 \cdot \Phi}$	

2.1 Reference Table for Shear Stress Values in the Single Channel Area

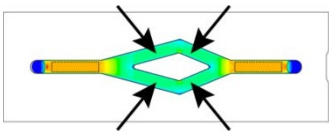


These tables are suitable for a quick determination of the needed flow rate. The shear stress is calculated for medium at 37°C with viscosity η = 0.0072 dyn·s/cm².

$$\boxed{\tau = \eta \cdot 227.4 \cdot \Phi}$$

τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]
0.1	0.06	3.5	2.14	25	15.27
0.2	0.12	4	2.44	30	18.32
0.3	0.18	4.5	2.75	35	21.38
0.4	0.24	5	3.05	40	24.43
0.5	0.31	5.5	3.36	45	27.48
0.6	0.37	6	3.66	50	30.54
0.7	0.43	7	4.28	55	33.59
0.8	0.49	8	4.89	60	36.65
0.9	0.55	9	5.50	65	39.70
1	0.61	10	6.11	70	42.75
1.2	0.73	11	6.72	75	45.81
1.4	0.86	12	7.33	80	48.86
1.6	0.98	13	7.94	85	51.92
1.8	1.10	14	8.55	90	54.97
2	1.22	15	9.16	95	58.02
2.2	1.34	16	9.77	100	61.08
2.4	1.47	18	10.99	105	64.13
2.6	1.59	20	12.22	110	67.18
2.8	1.71	22	13.44	115	70.24
3	1.83	24	14.66	120	73.29

2.2 Reference Table for Shear Stress Values in the Branched Channel Area



These tables are suitable for a quick determination of the needed flow rate. The shear stress is calculated for medium at 37°C with viscosity η = 0.0072 dyn·s/cm².

$$\boxed{\tau = \eta \cdot 113.7 \cdot \Phi}$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.12
0.2	0.24
0.3	0.37
0.4	0.49
0.5	0.61
0.6	0.73
0.7	0.86
0.8	0.98
0.9	1.10
1	1.22
1.2	1.47
1.4	1.71
1.6	1.95
1.8	2.20
2	2.44
2.2	2.69
2.4	2.93
2.6	3.18
2.8	3.42
3	3.66

τ [dyn/cm²]	Φ [ml/min]
3.5	4.28
4	4.89
4.5	5.50
5	6.11
5.5	6.72
6	7.33
7	8.55
8	9.77
9	10.99
10	12.22
11	13.44
12	14.66
13	15.88
14	17.10
15	18.32
16	19.54
18	21.99
20	24.43
22	26.87
24	29.32

τ [dyn/cm²]	Φ [ml/min]
25	30.54
30	36.65
35	42.75
40	48.86
45	54.97
50	61.08
55	67.18
60	73.29
65	79.40
70	85.51
75	91.62
80	97.72
85	103.83
90	109.94
95	116.05
100	122.15
105	128.26
110	134.37
115	140.48
120	146.58

3 Shear Stress and Shear Rate Calculations in Non-Uniform Laminar Flow Regions

In the kink and branching regions of the µ-Slide y-shaped (Figure 2), the laminar flow and thus also the shear stress are non-uniform and need to be calculated based on the velocity distribution.

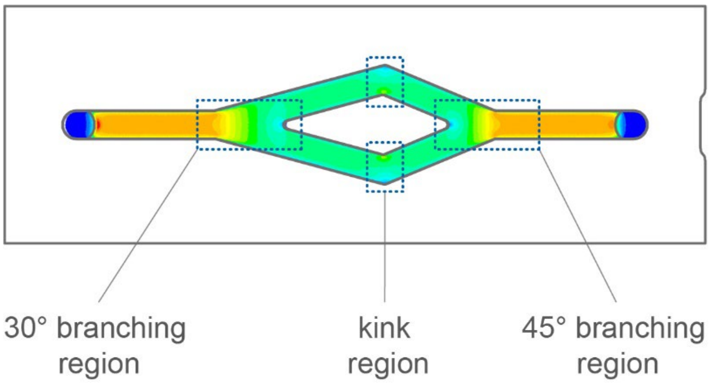


Figure 2: Bottom view of the µ-Slide y-shaped. The dashed rectangles indicate zones of non-uniform laminar flow and, therefore, non-uniform laminar shear stress. The branching region on the left provides an opening angle of 30°. The branching region on the right provides a 45° opening angle.

The shear stress is assumed to be proportional to the calculated velocity at 1 µm distance from the bottom. The value of 100 % velocity is defined as 0.00024 m/s, which is the velocity in the uniform flow region of the single channels. In this region, the shear stress is 2.274 dyn/cm² at a 1 ml/min flow rate.

Further, for calculating the shear stress at a specific location within a non-uniform flow region, the correspondent flow velocity and the viscosity of the used medium are required. Detailed flow velocities for every spot on the µ-Slide y-shaped were simulated by computational fluid dynamics (CFD) and can be looked up in Figures 3–5.

The shear stress in the non-uniform regions of the µ-Slide y-shaped is calculated as follows:

$$\tau = \frac{velocity\ (color\ scale)}{100\%\ velocity} \cdot 2.274 \frac{dyn \cdot min}{cm^2 \cdot ml} \cdot \Phi \cdot \frac{viscosity}{viscosity\ water\ at\ 20°C}$$

Calculation Example

1. Define the spot where you want to calculate the shear stress. The spot used in this example is marked in Figure 3.
2. Determine the color at the desired position and look up the corresponding flow velocity in the legend. The spot in this example lies in the yellow region of Figure 3, with a corresponding flow velocity of 0.00018 m/s.
3. In this example, the flow rate is assumed at 2 ml/min. The viscosity is assumed at 0.0072 dyn·s/cm².

The shear stress at the spot used in this example is calculated as follows:

$$\tau = \frac{0.00018\frac{m}{s}}{0.00024\frac{m}{s}} \cdot 2.274\frac{dyn \cdot min}{cm^2 \cdot ml} \cdot 2\frac{ml}{min} \cdot \frac{0.0072\frac{dyn \cdot s}{cm^2}}{0.01\frac{dyn \cdot s}{cm^2}} = 2.46\frac{dyn}{cm^2}$$

The velocity distribution in non-uniform laminar flow regions shown in Figures 3–5 was determined with a computational fluid dynamic (CFD) simulation (ANSYS FLUENT Flow Modeling Software) with the following parameters and assumptions: stationary, isothermal, laminar, water assumed to be incompressible, density of water 1000 kg/m³, viscosity 0.001 kg/(m·s), and at given flow of mass = 1.001 ml/min. Calculated is the velocity in 1 µm distance from the bottom.

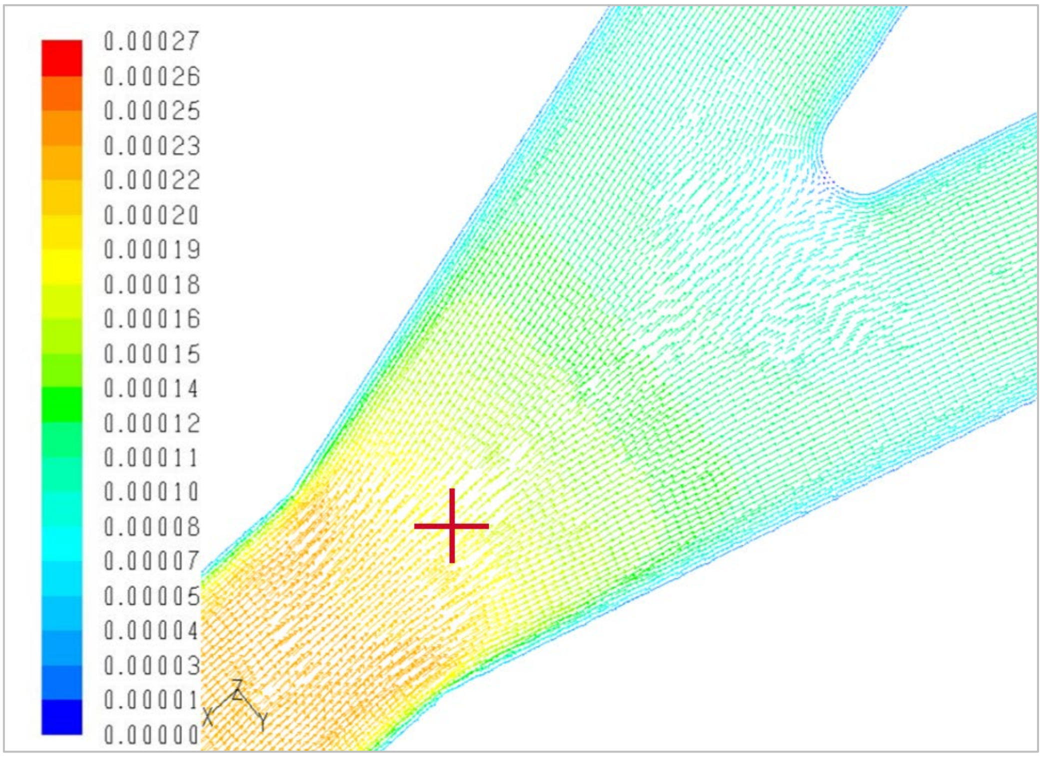


Figure 3: Calculated data for the 30° branching region. The arrows indicate the flow direction. The color scale gives the velocity [m/s]. The spot used in the calculation example is marked with a red cross.

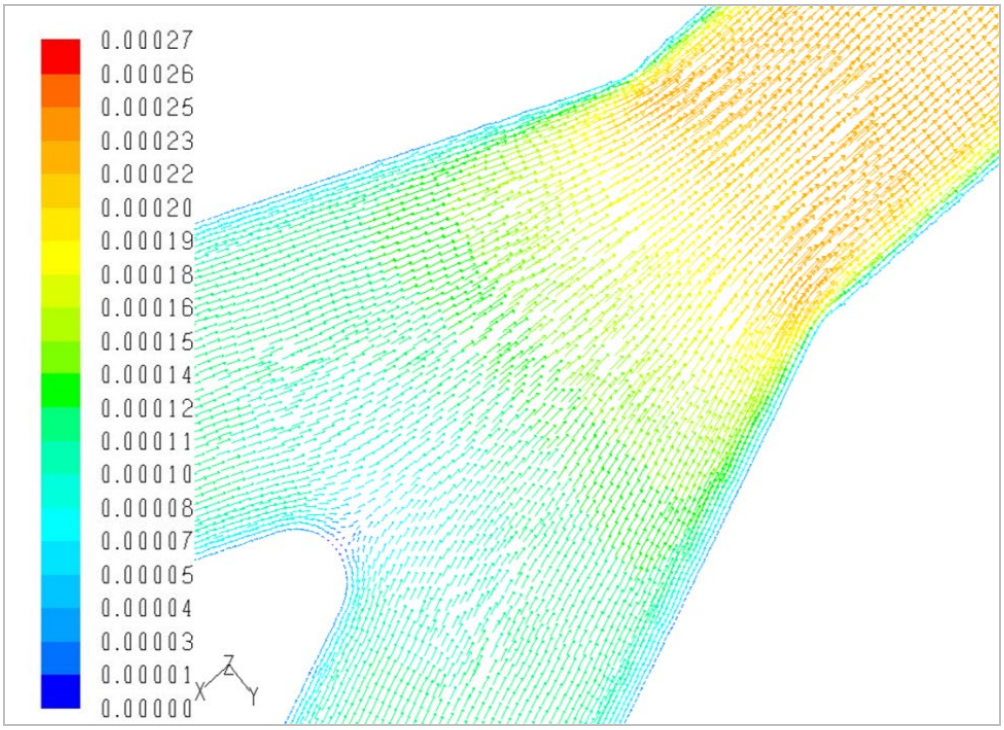


Figure 4: Calculated data for the 45° branching region. The arrows indicate the flow direction. The color scale gives the velocity [m/s].

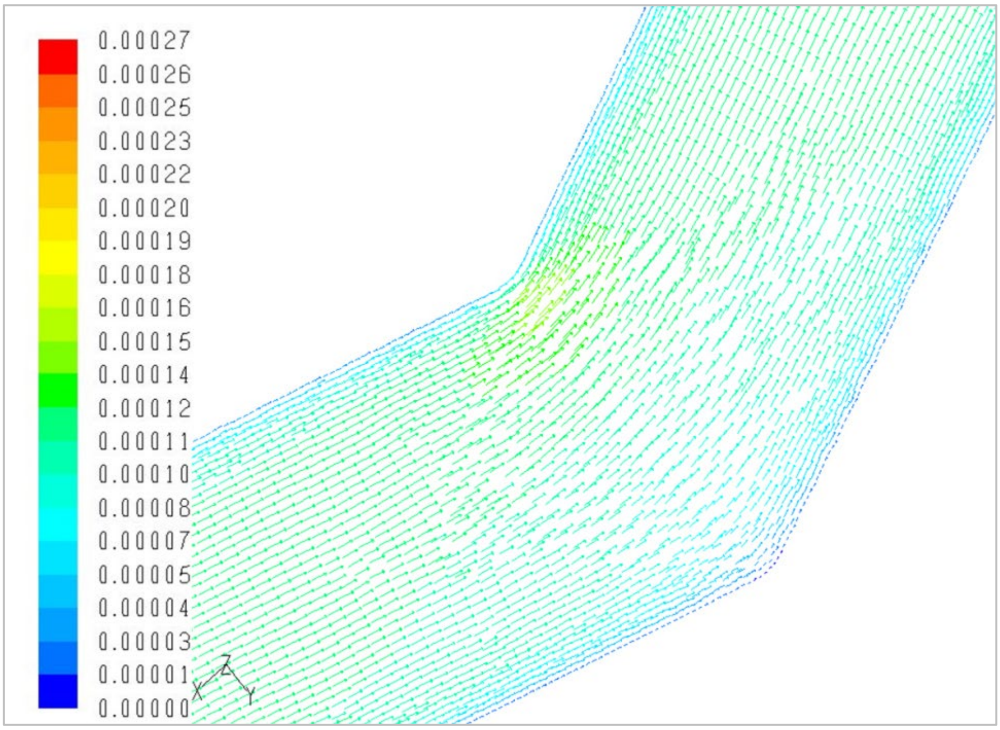


Figure 5: Calculated data for the kink region. The arrows indicate the flow direction. The color scale gives the velocity [m/s].