
Small is the next
big thing

Micro Process Engineering – An Interdisciplinary Approach

Micro Process Engineering, the science of enhanced transport process in microstructured devices

Basic Understandings

Scaling down to micrometer dimensions changes not only the length or volume of a device, but also influences the performance of unit operations.

Relevant Books

Microflows and Nanoflows - Fundamentals and Simulation by George Karniadakis, Ali Beskok, Narayan Aluru; Springer, 2005.

MICRODROPS AND DIGITAL MICROFLUIDICS by Jean Berthier, William Andrew Inc. 2008.

Transport Phenomena in Micro Process Engineering, by Norbert Kockmann, Springer, 2006.

Topics to be covered

Overview – length and time scales

Manufacturing practices – top down and bottom up

Transport in microchannels – heat pipes

Continuum, scaling

Balance and transport equations, convective flow and heat transfer in microchannels

Microfluidic networks

Electrowetting and digital microfluidics

Differences between fluid mechanics at microscales and in the macrodomain :

- ***Non-continuum effects:*** Both viscosity and the no-slip condition are concepts developed under the framework of continuum. Slip / Contact line motion?

- ***Surface-dominated effects:*** Friction, electrostatic forces, viscous effects

- ***Low Reynolds number effects:***

- ***Multiscale and multiphysics effects.***

Microdevices tend to behave differently from the objects we are used to handling in our daily life.

The inertial forces tend to be quite small, and surface effects tend to dominate the behavior of these small systems.

Friction, electrostatic forces, and viscous effects due to the surrounding air or liquid become increasingly important as the devices become smaller.

Example: Forces present in a thin film of liquid

Navier Stokes Equation

$$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=$$

$$-\frac{\partial P}{\partial z}+\mu\left[\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho g_z$$

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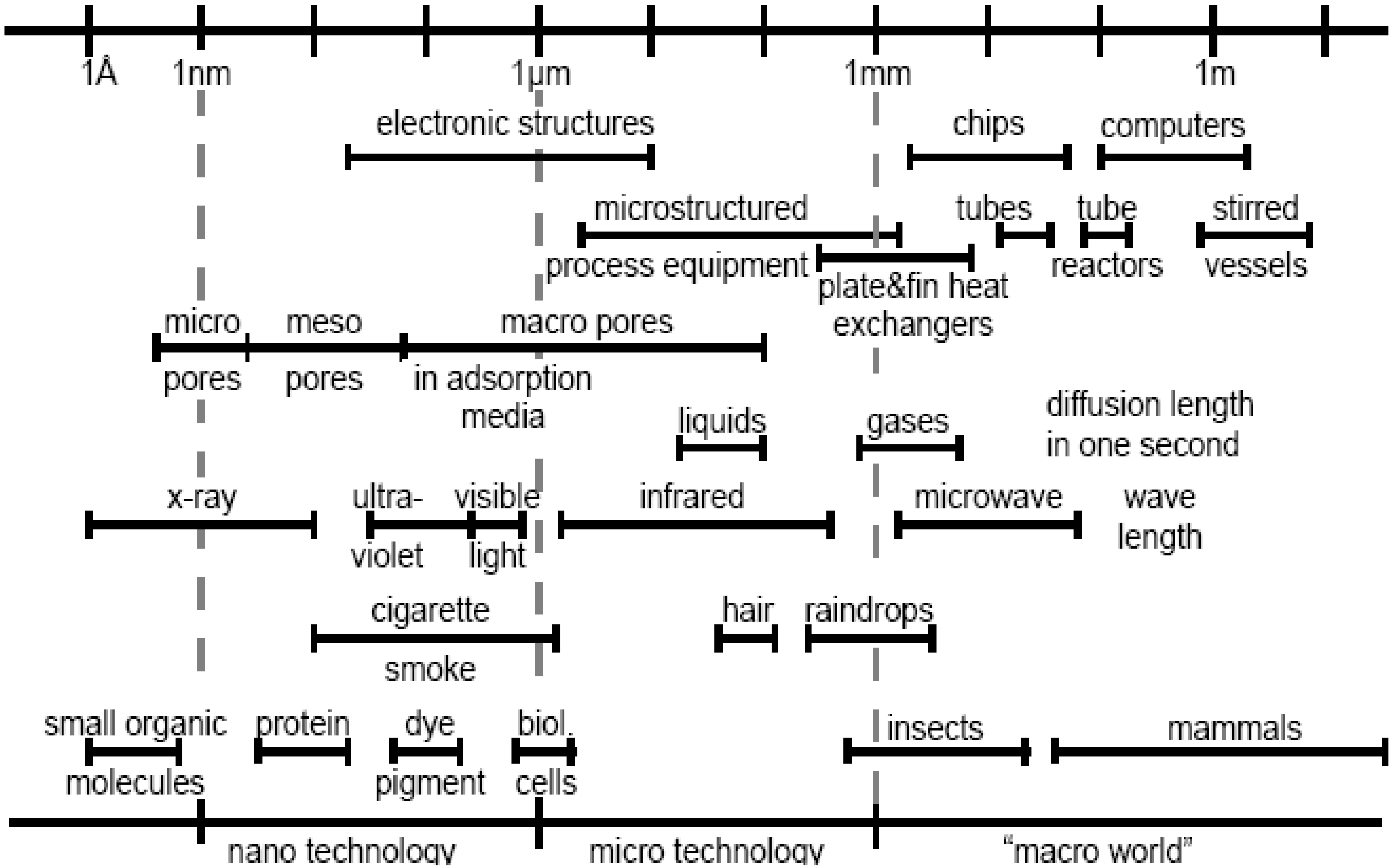
the z - momentum equation

$$v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}=-\frac{\partial p}{\partial z^*}+\frac{\partial}{\partial y^*}\left[\eta^*\frac{\partial w^*}{\partial y^*}\right]+\frac{1}{\mathrm{Re}^2}\frac{\partial}{\partial z^*}\left[\eta^*\frac{\partial w^*}{\partial z^*}\right],$$

Micromechanical systems started to enter technical systems in the 80s and 90s, enabling fluidic systems to be developed.

Starting from data processing, microsystems have now integrated mechanical, optical, fluid mechanical, and chemical functions for tasks like sensing and analyzing, controlling larger systems, or producing suitable goods and growing application fields for therapeutics and diagnostics.

Due to the reduced length scale of microstructured process equipment, the transfer lengths are short and precisely defined, and the areas are small, but high surface-to-volume ratios and tiny volumes dominate everything.



Characteristics lengths of important processes and equipment in chemical engineering and microsystems technology

Overview of miniaturization effects and beneficial phenomena e.g. in microchannels with characteristic dimensions from 10 to 1000 µm.

Process intensification in chemical engineering benefits from the miniaturization of channels and ducts within devices, where the characteristic lengths reach into the scale of boundary layers.

The higher transport rates can be used for many different purposes such as rapid mixing, temperature-sensitive reactions, temperature homogenization, nanoparticle precipitation.

Square-Cube Law

When an object undergoes a proportional increase in size, its new volume is proportional to the cube of the multiplier and its new surface area is proportional to the square of the multiplier.

Example from Biology

If an animal were scaled up by a considerable amount, its relative muscular strength would be severely reduced, since the cross section of its muscles would increase by the ***square*** of the scaling factor while its mass would increase by the ***cube*** of the scaling factor.

Cardiovascular and respiratory functions would be severely burdened.

In general, properties (p) that are a function of the area of interaction (A) decrease more slowly than properties that depend on the volume (V), as expressed by the ***"square-cube" law***:

$$\frac{p_1(A)}{p_2(V)} \propto \frac{L^2}{L^3} \propto \frac{1}{L}$$

L is the characteristic dimension of the microdevice. This has interesting application in microdevices.

A typical order of magnitude of the ratio is 10^6 m^2/m^3.

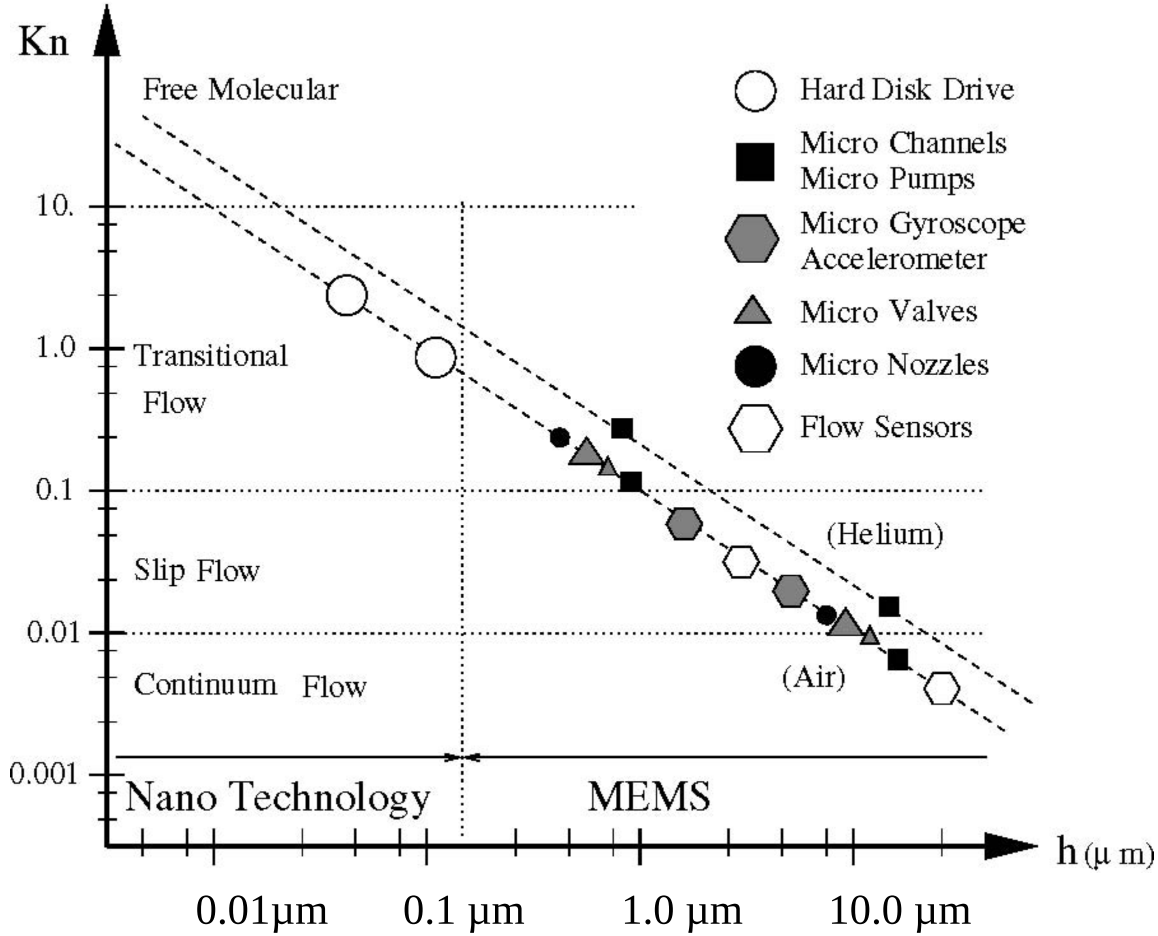
Surface tension effects are dominant at these scales, and micropumps and microvalves have been fabricated taking advantage of this principle

Early applications in computer components – the Winchester-type hard disk drive mechanism, where the read/write head floats 50 nm above the surface of the spinning platter. Smaller the gap - greater the recording capacity.

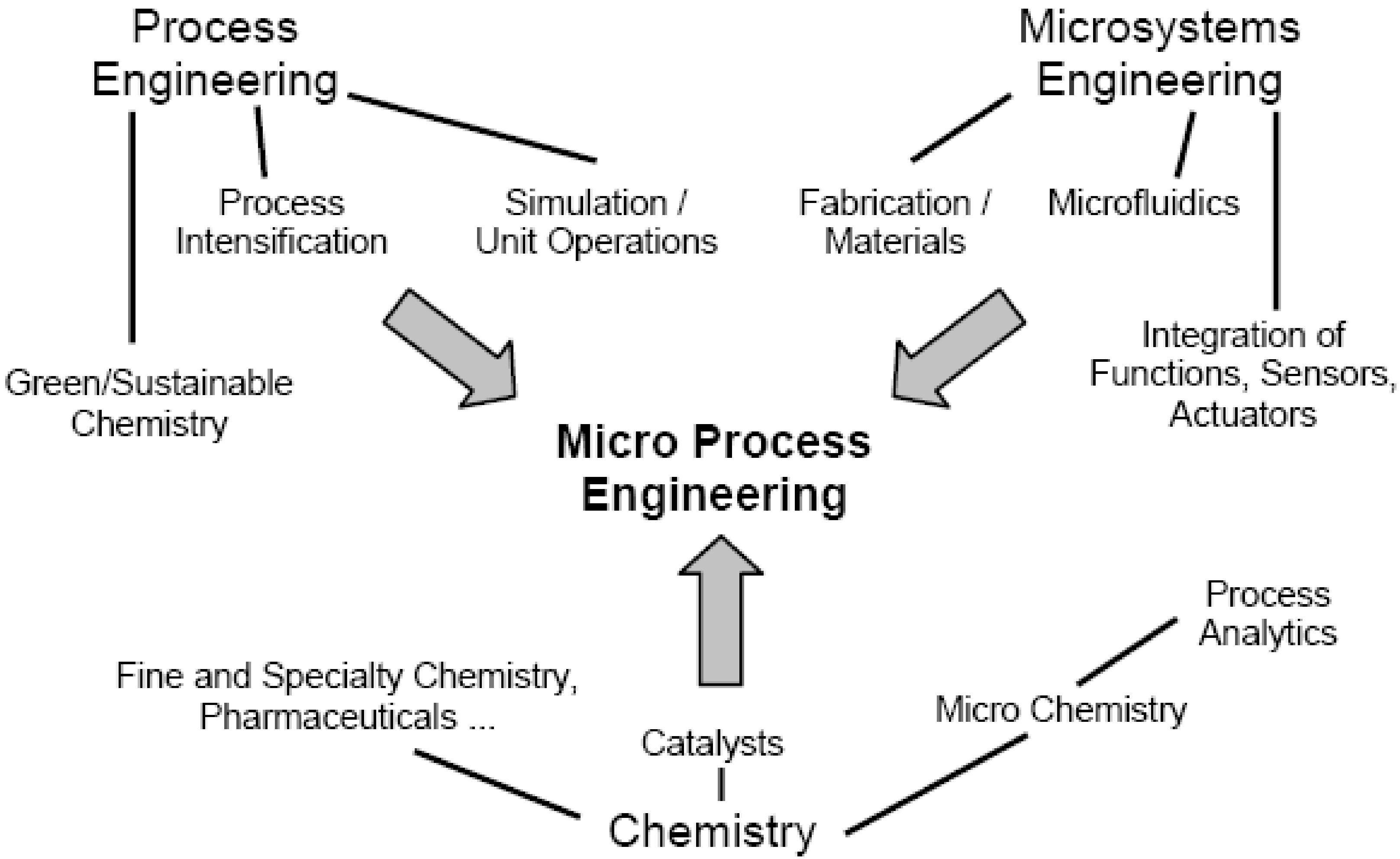
Correspond to low Reynolds and Mach number, e.g., less than 0.*6 and 0.3, respectively.*

The corresponding Knudsen number, (λ / L), is relatively large. –

Continuum Limit?



Typical MEMS and nanotechnology applications in standard atmospheric conditions span the entire Knudsen regime (Continuum, slip, transition, and free-molecular flow). Here h denotes a characteristic length scale for the microflow.



Microprocess Engineering – an interdisciplinary field with inputs from various disciplines

Issues to be looked into

Characteristic length and time scales

Transport phenomena in microstructures

Continuum range

Micro process engineering

Momentum and heat transfer in microchannels
- Micromixers, Micro heat pipes

Coupled transport processes

Micro fabrication technology – process intensification

Transfer lengths are short, areas are small but <u>high surface-to volume ratios and tiny volumes dominate everything</u>

Small channels allow short transport lengths for heat and mass transfer.

This results in high transfer rates, as described for diffusive mass transfer with the mean transport length from the

Einstein-Smoluchovski equation

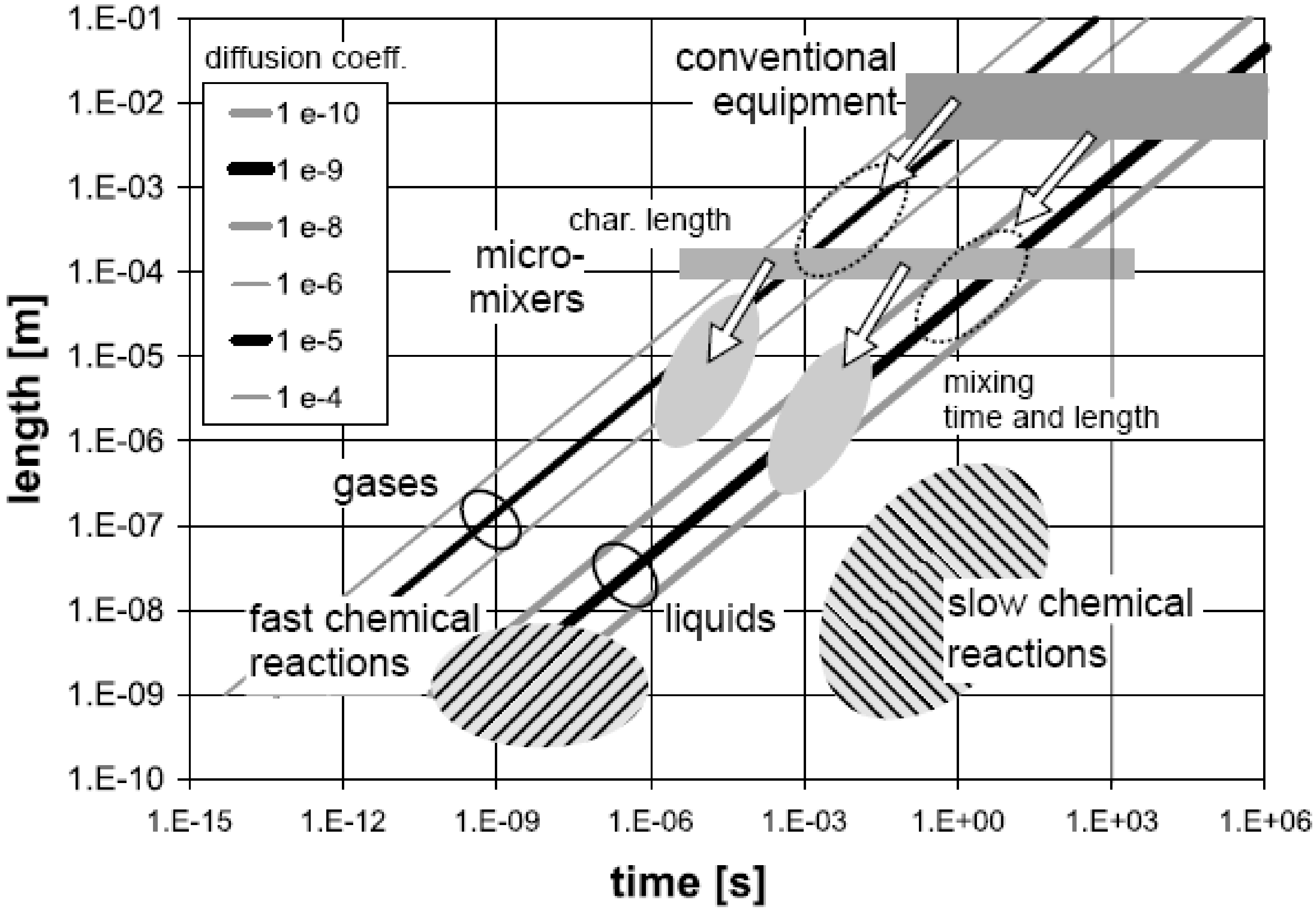
$$x^2 = 2\,D\,t$$

The transport lengths by diffusive mixing in gases ($D = 10^{-6}\ m^2/s$) and in liquids with low viscosity ($D = 10^{-10}\ m^2/s$) are shown in the next figure.

In general, the shorter the length, the shorter the characteristic time for transport processes will be, and the higher the transformation frequencies.

$$x^2 = 2\,D\,t$$

For diffusion of a species in a surrounding fluid, the typical diffusion length within one second is approx. 7 mm in gases (air) and approx. 70 µm in liquids such as water.



Characteristics length and time scales for mixing in microstructured devices with chemical reaction

Conventional equipment has typical geometries in the range of centimeters and produces fluid structures in the range from 100 μm to 1 mm. The corresponding diffusion time in gases is approx. 1 ms and in liquids in the range of 1 s.

Microstructured devices with typical length scales from 100 μm to 1 mm provide fluid structures with length scales of approx. 1 μm. These small fluid structures lead to mixing times shorter than 100 μs in gases and approx. 1 ms in liquids.

This is the main reason for the enhanced selectivity and high yield of chemical reactions in microreactors.

The conduction length - from the basic balance equation

momentum $x_p = \sqrt{2\nu t}$ heat transfer $x_q = \sqrt{2\alpha t}$

Thermal diffusivity $\alpha = k / \rho c_p$ m^2/s

k = Thermal conductivity

ν = Kinematic viscosity = μ / ρ , m^2/s

Einstein-Smoluchovski equation

$$x^2 = 2 D t$$

The characteristic time is proportional to the square of the length variation and to the transport coefficient

Information about typical length and time scales for fast chemical reactions like neutralizations or slow chemical reactions such as polymerization are required to compare the processes.

The mass transfer in micromixers acts on a length scale of a few microns within milliseconds or less.

Different time scales are typical for partial reactions in complex reaction systems.

With properly designed micromixers and an adjustment of the component concentration, the selectivity of a complex reaction can be increased.

Important - the scale of fluid residence time within the device.

Within small devices, the fluids rest only briefly (seconds or less), which can be detrimental to slow reactions. A slow reaction may be incomplete at the channel outlet.

Fast reactions require short and small channels and a sufficiently high number of channels. They benefit from the rapid mixing and heat exchange.

Reactions with slower side-reactions or unstable intermediates show higher selectivity and higher yield in microstructured devices.

Reactions with high energy demand or release are suitable for micro devices.

The heat transfer in a straight channel with laminar flow is described by a constant Nusselt number Nu,

$$Nu = \frac{h\,d_h}{k} = 3.65$$

for constant wall temperature.

With smaller channel diameter d_h, the heat transfer coefficient ***h*** increases.

Additionally, convective effects in bent channels can increase the Nusselt number for better performance but also increase the pressure loss

The fluid temperature T in the channel quickly approximates the wall temperature according to the following equation

$$T(x) \propto e^{-x/l_h}$$

with the characteristic length of

$$l_h = \frac{\dot{m} c_p}{3.65 \pi k}$$

Combining the channel distance and the mean residence time

with the mean velocity $$x = \overline{w} t$$

Solve the wall temperature relation for the time-dependent temperature change to obtain the fluid temperature

$$T(t) \propto e^{-t/t_h}$$

The characteristic time, t_h is defined as

$$t_h = \frac{\rho\, c_p\, d_h^2}{3.65\, \pi\, k}$$

With decreasing channel diameter, the fluid temperature exponentially approaches the wall temperature.

Efficient heat transfer is also important for high exothermic chemical reactions to transport the heat away from the reaction zone and to avoid hot spots.

The high surface-to-volume ratio is also responsible for the fast heat transfer in microchannels.

Additionally, a high surface-to-volume ratio is beneficial for surface reactions such as heterogeneous catalysis, emulsification or transport-limited processes

With unsteady heat transfer, the characteristic time t for heating or cooling of a body is proportional to the temperature difference and the ratio of the heat capacity mc_p to the heat transfer ***h*** *A* within the environment.

$$t = \frac{m c_p}{h A} = \frac{\rho c_p V}{h A} = \frac{\rho c_p}{h a_V} \propto \frac{\rho c_p}{h} \cdot d_h$$

h is the heat transfer coefficient, A the surface area

With a smaller length scale d_h, the surface-to-volume ratio a_V increases and this characteristic relaxation time t becomes shorter.