Main Issues of Successful Microstructures
Example: Heat Exchangers

Microstructure devices are excellent tools for laboratory research in many application fields with specific advantages.

MANUFACTURING

For lab-scale-type devices, single microchannel systems, either manufactured from silicon by semiconductor technologies or made from metals by mechanical micromachining, or wet chemical etching are mainly used for flow characterization, heat transfer, and experimental investigation of chemical reactions.

This led to a variety of microstructure devices suitable for several applications, namely heat exchange, evaporation, mixing, generation of emulsions, and running chemical reactions in the lab-scale range.

To achieve higher mass fluxes, parallelization of single microchannel devices, scaling up of the microchannel dimensions, or generation of internally parallelized multichannel systems, (equaling-up) are commonly used.

PROCESS PARAMETER RESTRICTION

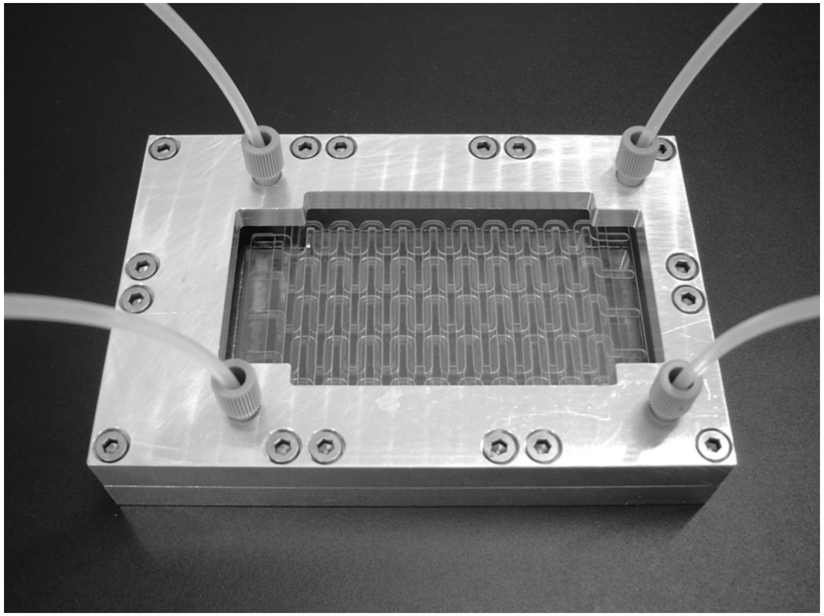
Material Choice –

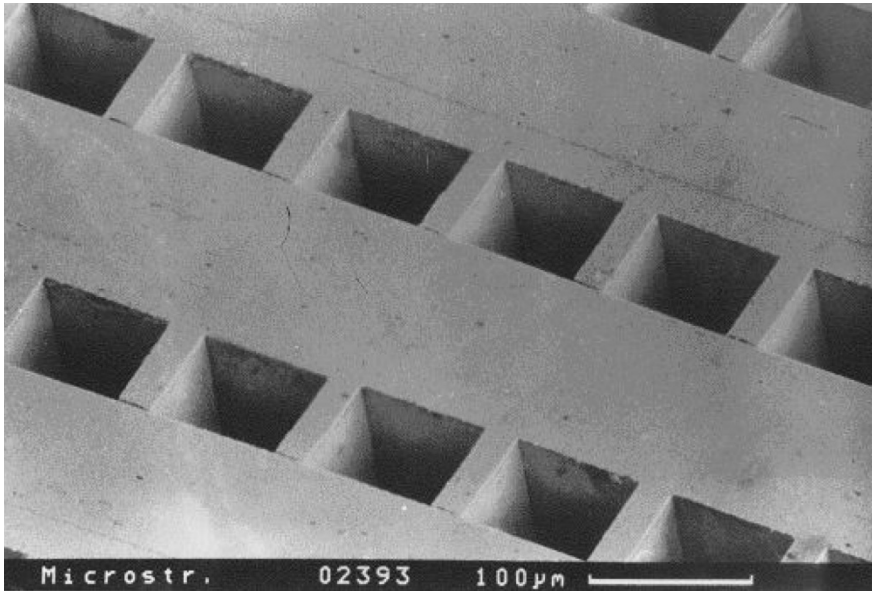
Temperature resistance, corrosion resistance, and thermal properties. Thermal Stress / Corrosion?

Fluid Dynamics Restrictions

Laminar/turbulent, fouling, cleaning - use surface coatings, ultrasound?

Microstructured Devices



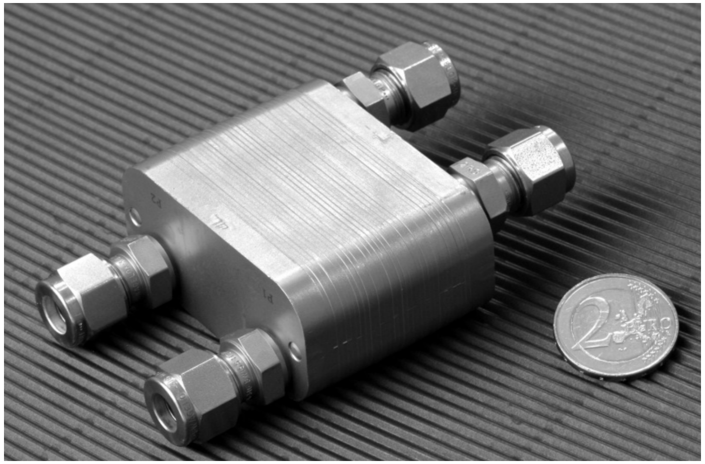


Temperature-controlled residence time module. This glass microstructure device is used to adjust the residence time of a chemical reaction mixture to obtain good performance

Crossflow-arrangement of mechanically machined microchannel foils. The foils are made of stainless steel and connected by diffusion bonding to form a stable stack.

Microstructured Heat Exchangers

Microstructured heat exchangers deliver high transfer rates, but they also have drawbacks, application limits, during design and operation.



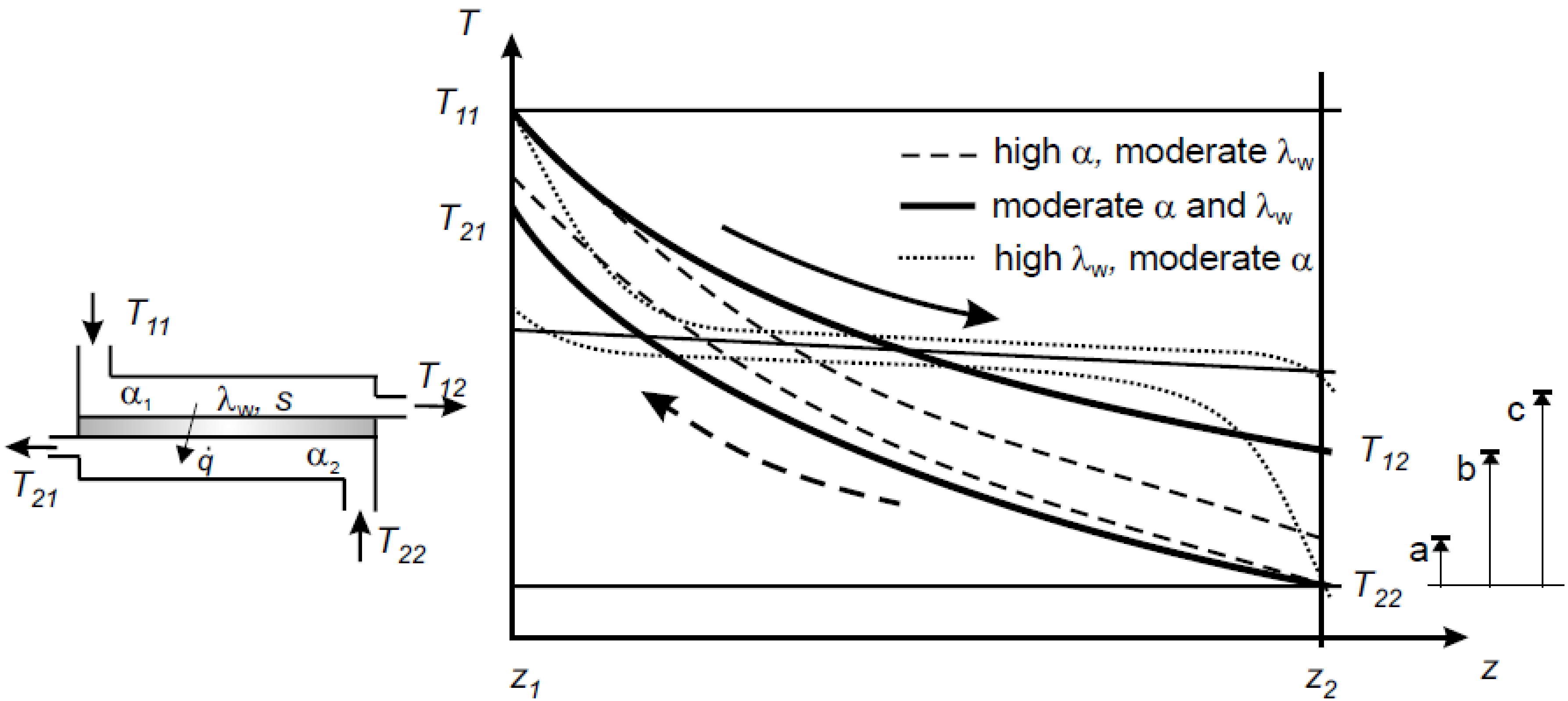
Stainless steel counterflow microstructured heat exchanger

1. Wall heat conductivity
2. Pressure loss, manifold design
3. Corrosion, fouling, and catalyst deactivation

1. Wall heat conductivity

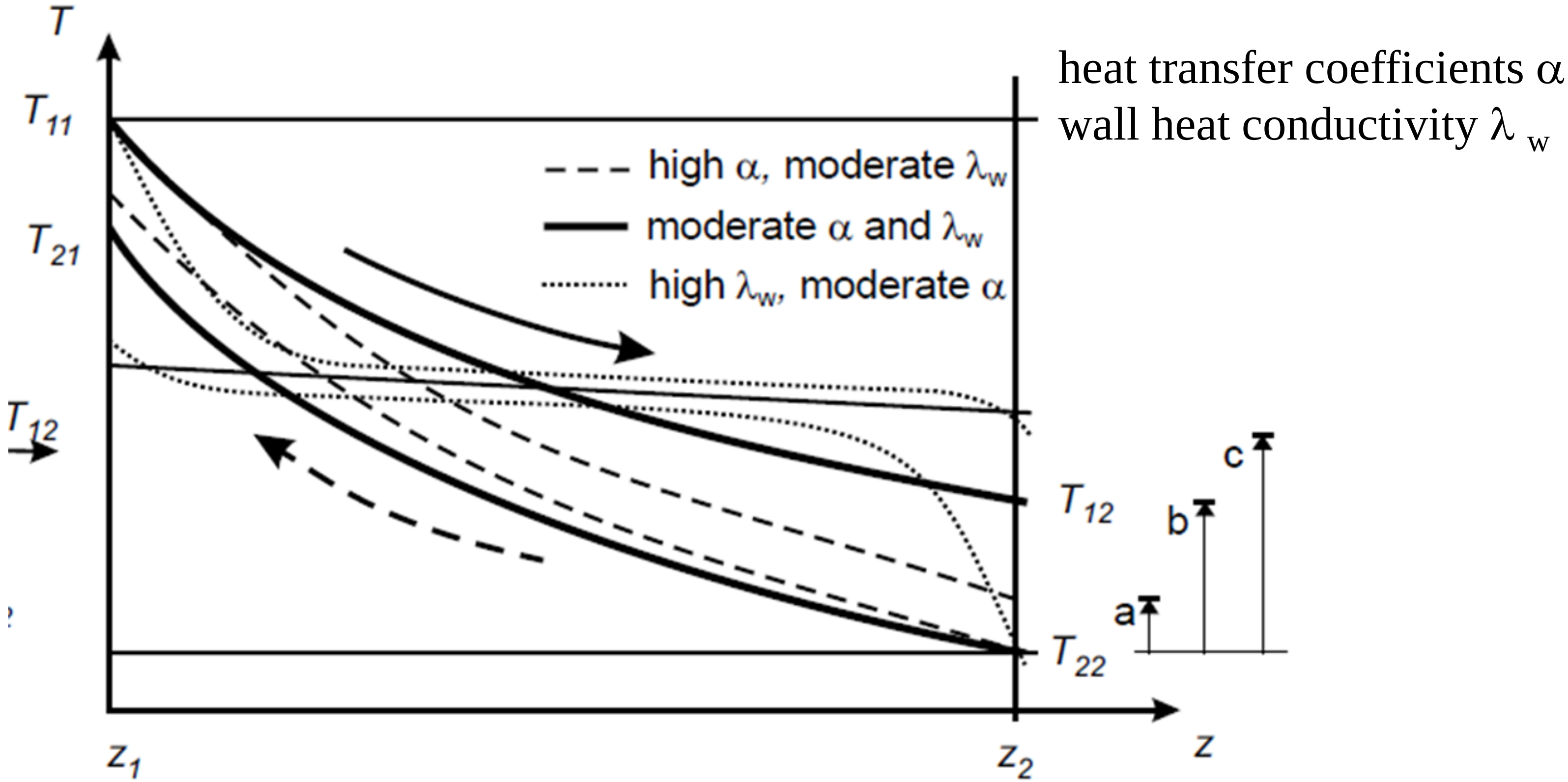
The ratio of wall thickness to channel diameter is relatively high in microchannel devices, hence, a considerable amount of heat is transferred through the wall parallel to the flow direction, which lowers the driving temperature difference and decreases the amount of the transferred heat.

The amount of parasitic heat flux has to be considered for highly conductive wall materials like copper, alumina or silicon, and for a low heat capacity flow of the transfer media, such as gases or low flow velocities.



Heat transfer coefficient - α, wall heat conductivity - $\lambda_{w.}$

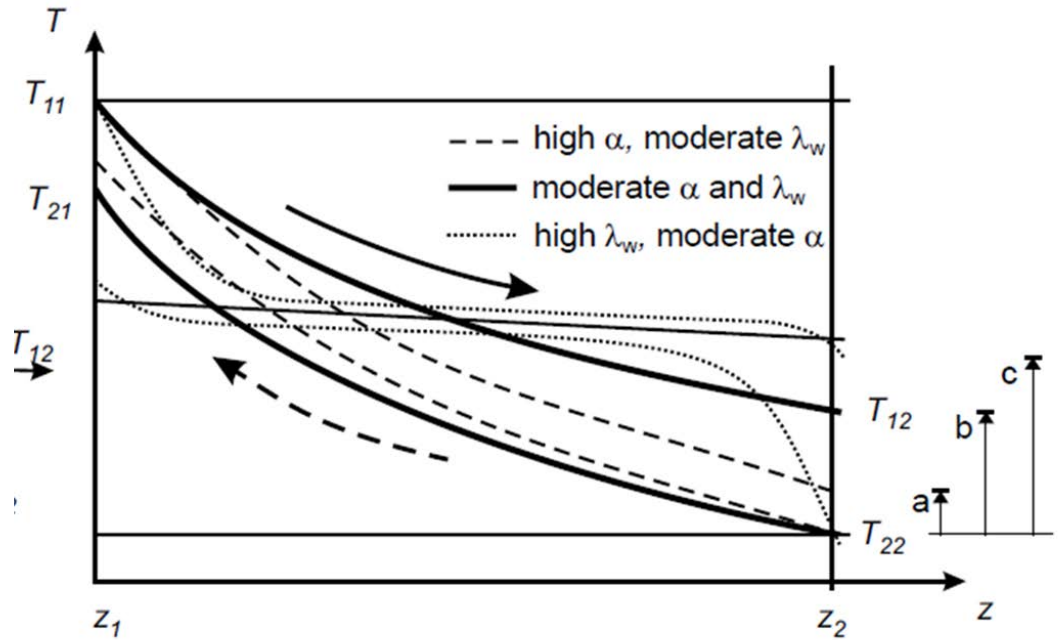
Temperature profile along a counter-flow heat exchanger with different heat transfer coefficients α and wall heat conductivity $\lambda_{w.}$ The fine-dotted line displays the temperature profile in a microstructured heat exchanger with high heat conductivity in the wall and low overall heat transfer coefficient. The temperature difference at the end of the heat exchanger corresponds to the heat exchanger efficiency



Three cases

• moderate axial wall heat conductivity with high convective heat transfer (case a),
• moderate axial wall heat conductivity with moderate convective heat transfer (case b), and
• high axial wall heat conductivity with moderate or even high convective heat transfer (case c).

heat transfer coefficients α
wall heat conductivity λ_w



The first case a) exhibits the best heat exchanger efficiency displayed as the temperature difference at the entrance or outlet of the heat exchanger.

The last case, with high axial heat transfer, in the middle of the device, only a marginal amount of heat is transferred. The temperatures of both fluids are almost identical in the middle of the device with little temperature change.

The area in the middle of the heat exchanger provides inefficient heat transfer and diminishes the device performance.

3. Corrosion, fouling, and catalyst deactivation

Surface roughness may play a dominant role in microchannels.

If the surface elements reach far into the channel, the hydraulic diameter is constricted, which increases the pressure loss and leads to an earlier transition to turbulent flow.

To include the surface roughness ε, a constricted hydraulic diameter d_{cf} is defined with the narrowest gap width instead of the mean inner distance d_t of the channel walls.

$$d_{cf} = d_t - 2\varepsilon$$

The corrected hydraulic diameter explains quite well the observed phenomena in rough microstructured channels

Corrosion becomes relevant in microchannels where the surface roughness influences the flow behavior and the transport characteristics. A corrosion layer of 100 µm is tolerable in conventional systems, but may be fatal for microchannels.

Particle generation and processing are major steps in many applications. Particles may attach to the wall, decrease the cross section, and influence the pressure loss and flow velocity. The particles sticking to the wall may attract more particles and lead to fouling and blocking of the channels.

Heterogeneous catalysis with high exothermic or endothermic character are suitable, but catalyst deactivation or poisoning can be critical for long-term operation

2. Pressure loss

For high flow rates, small channels induce a high pressure loss due to the high surface-to-volume ratio.

Hence, low viscosity fluids are preferred for application in microchannels due to a tolerable pressure loss.

The pressure loss in a channel – from Bernoulli equation:

$$\Delta p_{12} = p_1 - p_2 + \frac{\rho}{2}\left(w_1^2 - w_2^2\right) + g\,(y_1 - y_2)$$

In microchannels, the gravitation force is negligible compared to friction forces

$$\Delta p_{12} = p_{tot,1} - p_{tot,2} \quad with \quad p_{tot} = p + \frac{\rho}{2} w^2$$

The pressure loss is calculated for a complex channel arrangement as:

$$\Delta p = \left(\lambda \frac{l}{d_h} + \zeta \right) \frac{\rho}{2} \, \overline{w}_{ref}^{\,2}$$

$\overline{w}_{ref}$ is the constant reference velocity, λ is the channel friction factor.

The pressure loss consists of portions from straight channels described by λ *(l/d_h)* and portions from bends, curves, connections, and other internals described by ζ.

$$\Delta p = \left(\lambda \frac{l}{d_h} + \zeta \right) \frac{\rho}{2} \overline{w}_{ref}^{2}$$

The pressure loss coefficient ζ is primarily defined for turbulent flow in devices and can be found in textbooks

In general, the flow below Re = 10 can be regarded as straight laminar flow where no vortices appear and the pressure loss coefficient ζ can be neglected.

For high Re numbers, especially for $Re > Re_{crit}$, the laminar contribution can be neglected.

In the transition regimes, $10 < Re < Re_{crit}$, a square fit of laminar and turbulent values can serve as a first estimation for the pressure loss.

$$\Delta p = \left(\lambda \frac{l}{d_h} + \zeta \right) \frac{\rho}{2} \overline{w}_{ref}^{2}$$

hydraulic diameter $d_h = 4A/lp$

For laminar flow in long straight channels the channel friction factor λ is inversely proportional to the Re number in the channel

$$\lambda = \frac{C_f}{\mathrm{Re}} = \frac{C_f \, \eta}{\rho \, d_h \, \overline{w}}$$

The channel friction factor λ is inversely proportional to the channel diameter d_h; <u>smaller channel increases the friction factor</u>.

$$\Delta p = \left(\lambda \frac{l}{d_h} + \zeta \right) \frac{\rho}{2} \, \overline{w}_{ref}^{\,2}$$

The pressure loss in a channel can be calculated from

$$\Delta p = \left(C_f \, \nu \frac{l}{d_h} + \zeta \, d_h \, \overline{w} \right) \frac{\rho}{2} \frac{\overline{w}}{d_h} = C_f \, \frac{\eta \, l}{2 d_h^2} \overline{w} + \zeta \, \frac{\rho}{2} \overline{w}^2$$

In long straight channels, the pressure loss Δp depends mainly on the first term, hence

the pressure loss varies

- almost linearly with the velocity, channel length, and viscosity,

- inversely proportional to the square of the hydraulic diameter d_h.

In curved channels with internals, the hydraulic diameter influences the pressure loss only marginally, but convective effects determine the pressure loss coefficient ζ.

The pressure loss can also be described as

$$\Lambda p = \left(C_f \frac{l}{d_h} + \zeta \,\mathrm{Re} \right) \frac{\rho v^2}{2} \frac{\mathrm{Re}}{d_h^2}$$

The pressure loss depends on Re number with a linear and a quadratic part.

With decreasing device length dimensions, the pressure loss is nearly proportional to the square of the Re number.

The volume flow rate V through N nearly rectangular, parallel channels -

$$V \propto N\left(d_h^2\,\overline{w}\right)$$

The final form of pressure drop for a system of N channels:

$$\Lambda p = \left(C_f\,\eta\,l + \zeta\,\frac{V}{N}\right)\frac{\rho}{2}\frac{V}{N\,d_h^4}$$

This equation only accounts for **parallel channels with a single flow manifold.**

$$\Lambda p = \left(C_f \, \eta \, l + \zeta \, \frac{V}{N} \right) \frac{\rho}{2} \frac{V}{N \, d_h^4}$$

The pressure loss consists of two parts,

1. the laminar part (C_f) varies linearly on the volume flow rate.

2. The convective part of internals (ζ) depends on the square of the volume flow rate.

The hydraulic diameter plays a crucial role with the inverse dependency of the fourth power.

Decreasing the channel diameter and the resulting higher pressure loss can be balanced by either increasing the channel number or decreasing the channel length or volume flow rate.

$$\Lambda p = \left(C_f \, \eta \, l + \zeta \frac{V}{N} \right) \frac{\rho}{2} \frac{V}{N \, d_h^4}$$

The pressure drop increases linearly with velocity and viscosity is less important in short, curved channels with many internals.

Within short microchannels, not only is the pressure loss low, but also precipitation or polymerization of various chemicals are possible due to proper mixing of the immiscible reactants**.**

However,

For gas-flow microreactors with long, straight channels, the pressure loss is approx. 2.5 times lower than in fixed bed reactors for the same mass transfer conditions

The key parameters of the production device, including channel height h or wall thickness s, are equal to the laboratory equipment,

however,

the geometry of the active surface or the fabrication techniques may differ, for example, the microchannels have the same cross section or only the same height, but differ in length.

Application Examples - Recent Experiments on heat Sinks

Requirement of extremely high heat removal rates

- phase change heat transfer
- minimum temperature difference

This is particularly true in flow boiling applications, where only modest increases in device temperature will allow the removal of very large heat fluxes.

In the design of applications, such as microchannel two-phase flow heat sinks and micro thermal pumps, the liquid/vapor two-phase flow pattern is critical.

http://www.rpi.edu/tphtl/research/lvfp/lvfp.html

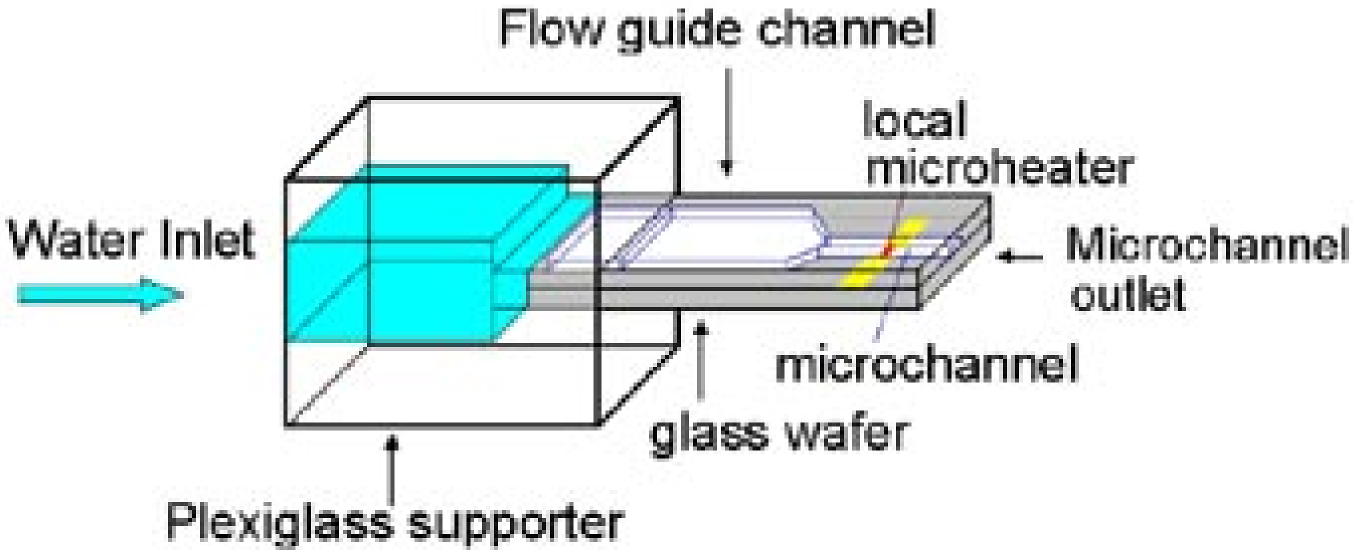
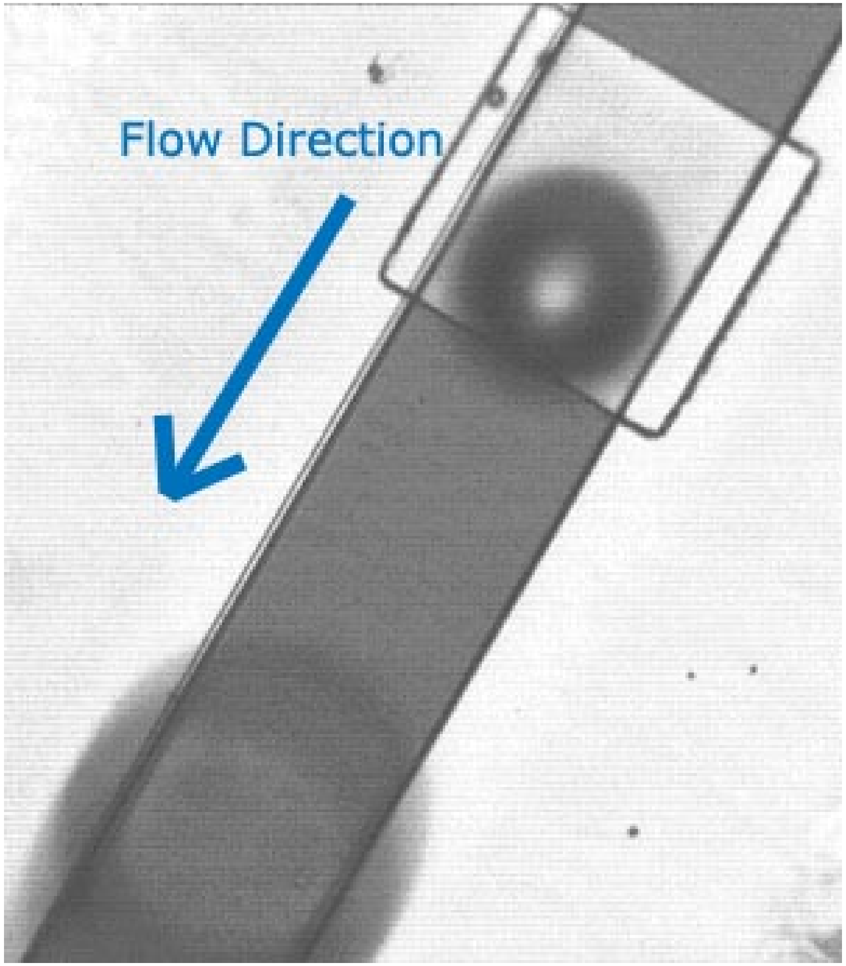


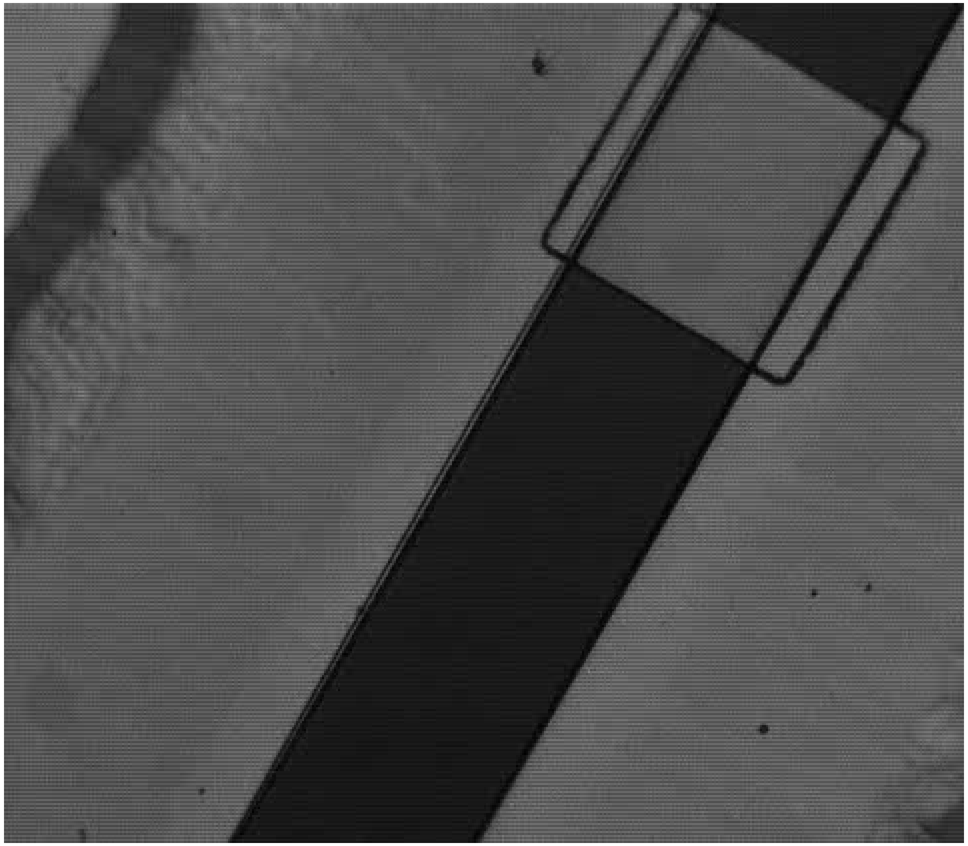
Fig.1 - Configuration of the experimental specimen and test section

- Microscale platinum heater fabricated on a Pyrex glass wafer
- Shallow trapezoidal microchannel with hydraulic diameter D_h = 56μm
- Use high-speed digital CCD video camera and microscope,
- Study the two-phase flow patterns,

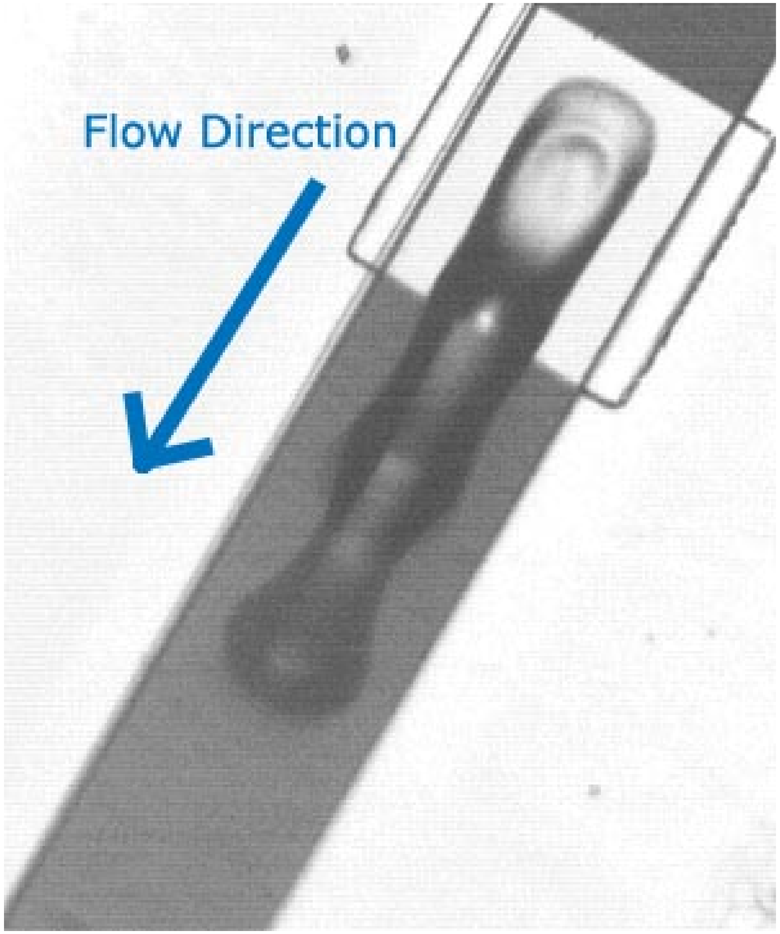
Impact of the size of the microchannel and the mass flow rate on the boiling incipience and two-phase flow patterns are analyzed.



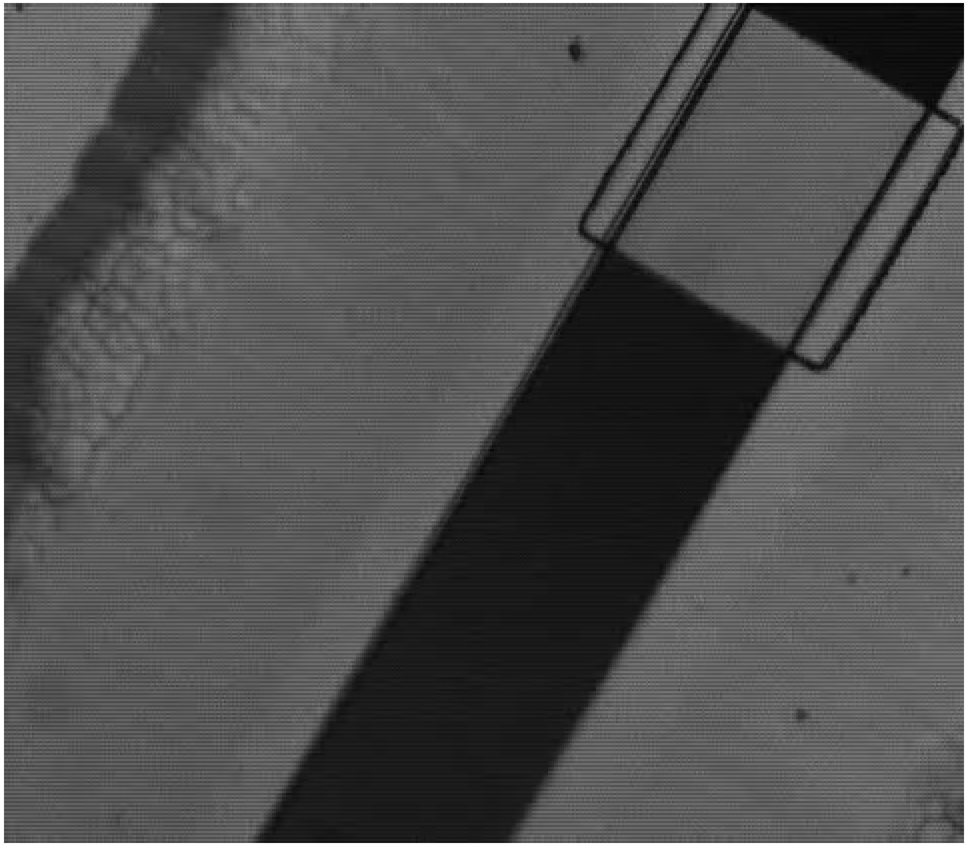
Bubbly flow in the microchannel under small flow rates and low power



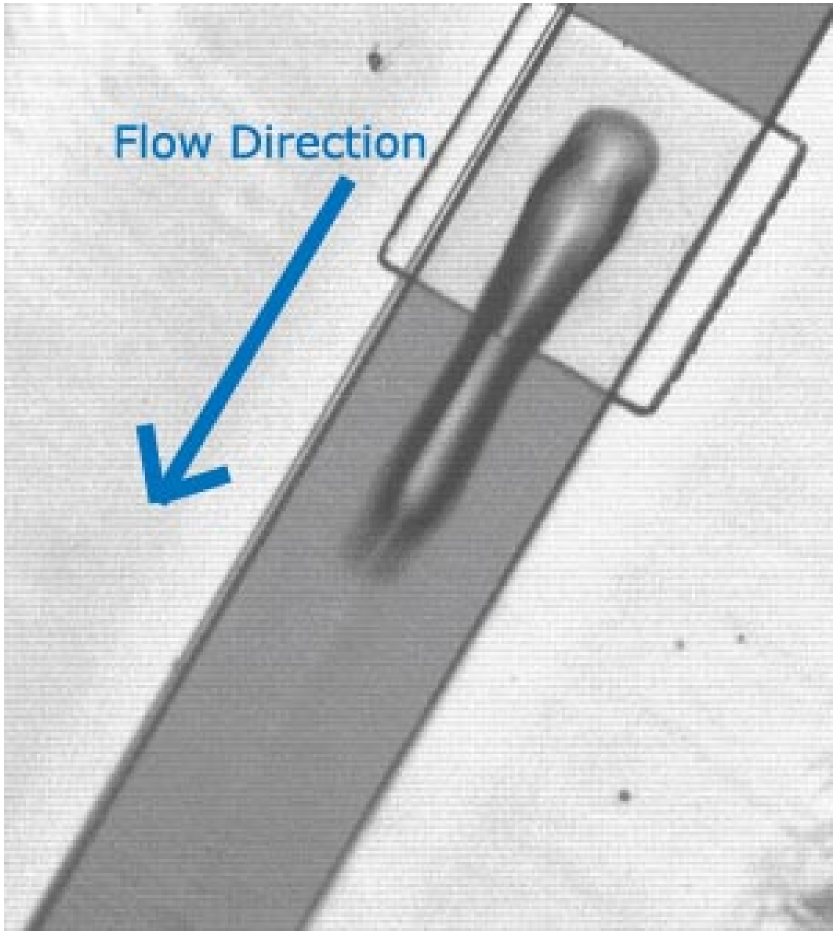
Bubbly Flow



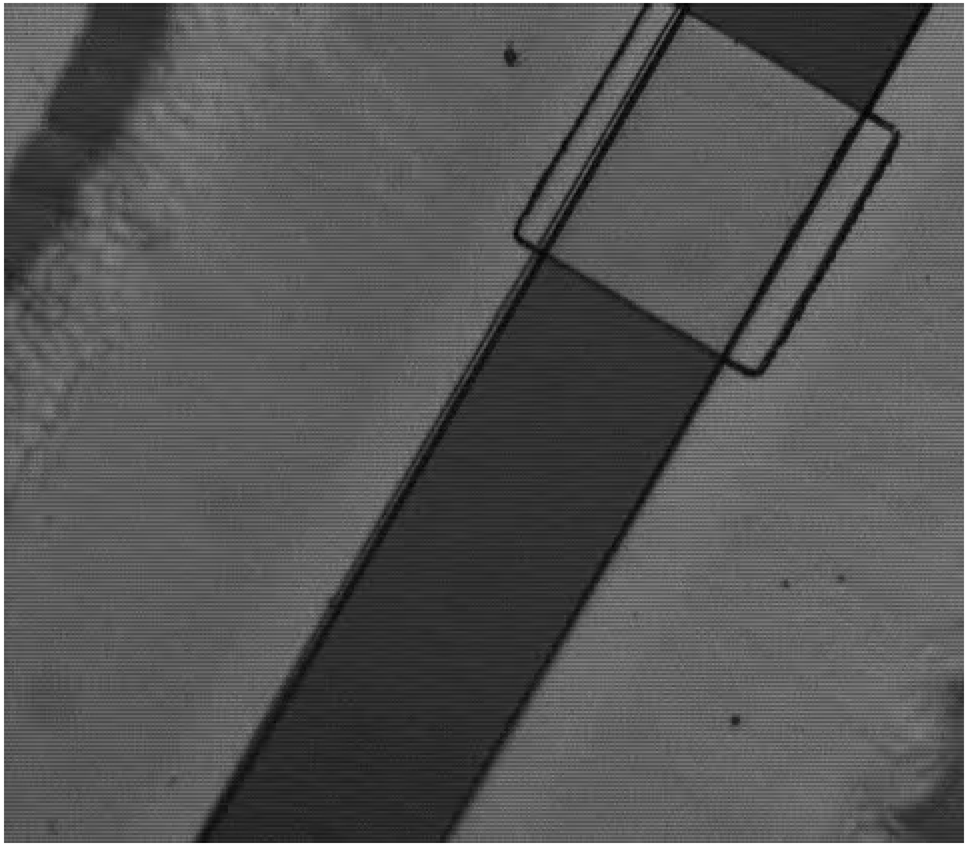
Wavy flow in the microchannel under moderate mass flow rate and moderate power



Wavy Flow



Annular Flow in the microchannel under large flow rates and high power



Annular Flow

A better understanding of the fundamental phenomena occurring in these types of flows

Effects of surface geometry/modifications/properties/heat flux

Microchannel devices present many ***opportunities***

however,

their *disadvantages and special requirements* must be taken into consideration for successful application.