Polish Academy of Sciences
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TURBULENT FLOW INVESTIGATIONS

in

MICRO-CHANNEL

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http://fluid.ippt.gov.pl/

Introduction

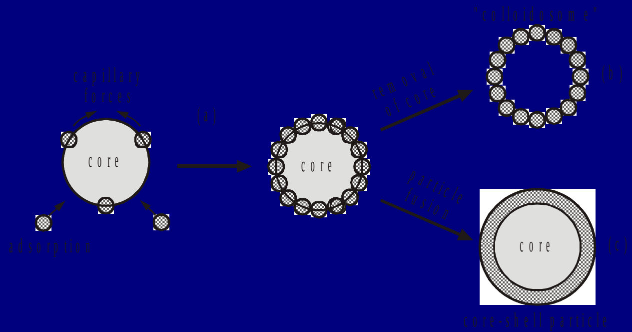
Micro and nano-droplets or bubbles - tool for:

- chemistry: massive chemical tests in micro-reactors
- medicine: drugs delivery (lungs, brain etc)
- biotechnology
- biology: cell response
- optics
- material science: matrix for new material fabrication

Controlled production of uniform droplets:

- drop on demand devices
- micro-fluidic devices
- shear/turbulent drops break-up in micro-channel

massive production



QUESTION TO ANSWER

Production of droplets emulsion in high Re flow in micro-channel

- **Does droplet size correlate with a simple shear-flow based Taylor theory?**

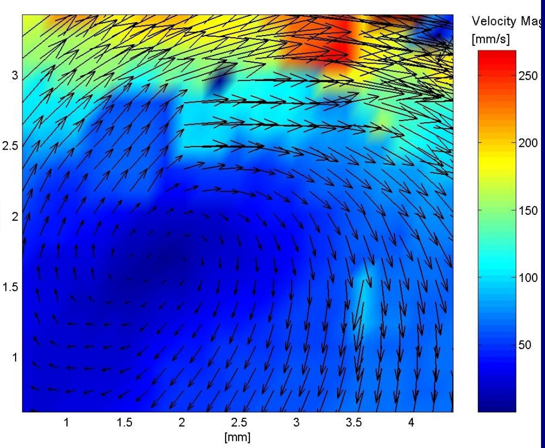
or

- **turbulent break-up like in large scale industrial mixers takes place ?**

Primary aim of the experiment

Emulsification by turbulent flow in micro-channel:

- **Velocity field analysis by micro-PIV technique**
- **Flow structure**
- **Turbulence structure**
- **Shear stress field**
- **Drops break-up - flow field relation**

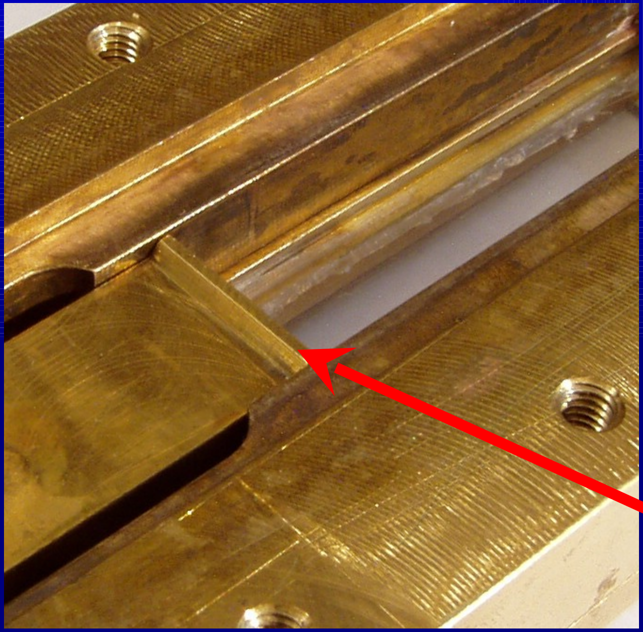


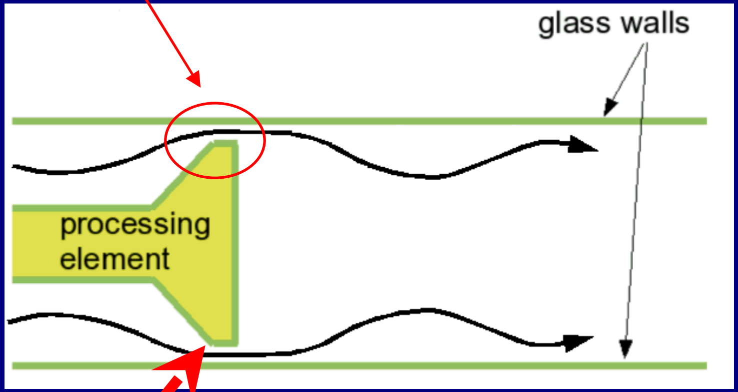
- **Validation of droplets break-up models**
- **Optimisation of the drops size and shape**
- **Optimisation of the emulsifier geometry**

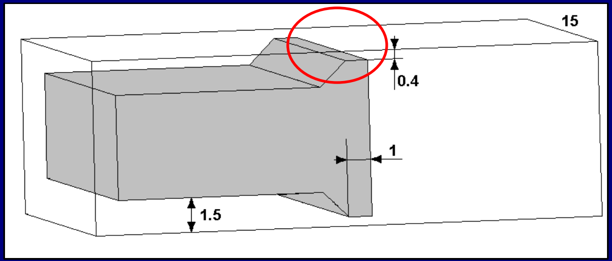
Production of droplets emulsion in turbulent flow

Emulsifier with optical access for flow investigation

micro-channel







High speed imaging and velocity measurements

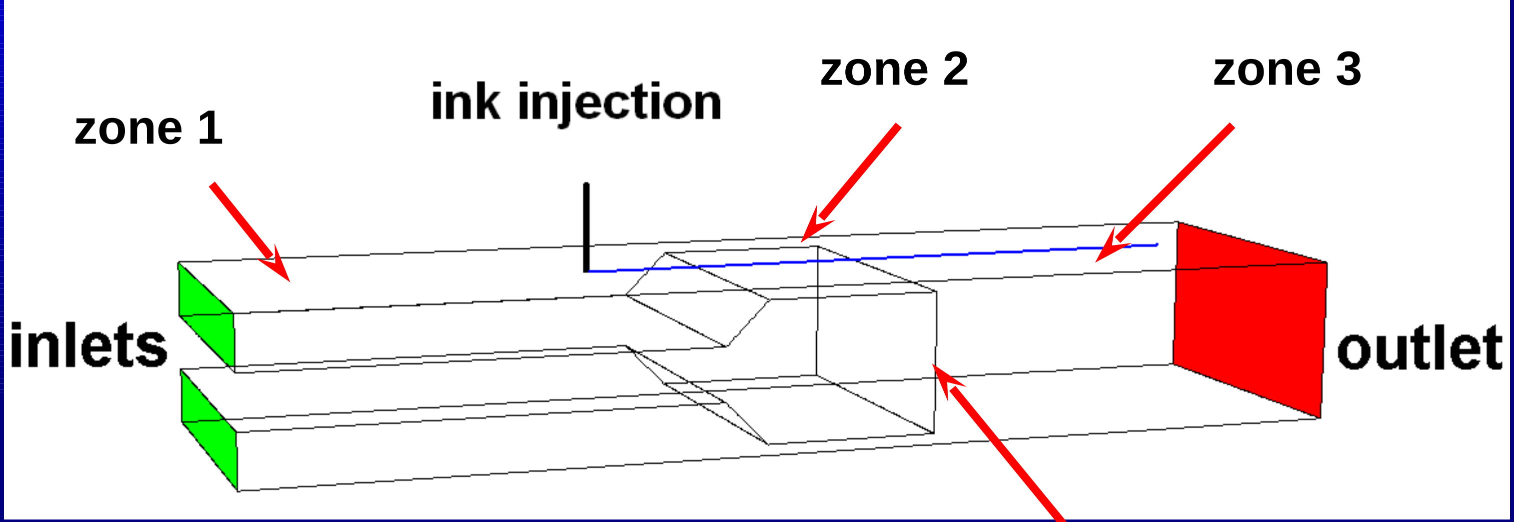
gap: 0.4mm x 1mm x 15mm, flow rate: up to 0.204 dm^3/s, Characteristic Reynolds Number Re=8000

OUR QUESTIONS TO ANSWER

Production of droplets emulsion in turbulent flow

- Is the flow turbulent, what is the critical Re number for our 1mm long micro-channel?

EXPERIMENTAL INVESTIGATION



Processing element

zone 1: 1.5 x 35 x 15 mm

zone 2: 0.4 x 1 x 15 mm

zone 3: 7.5 x 70 x 15 mm

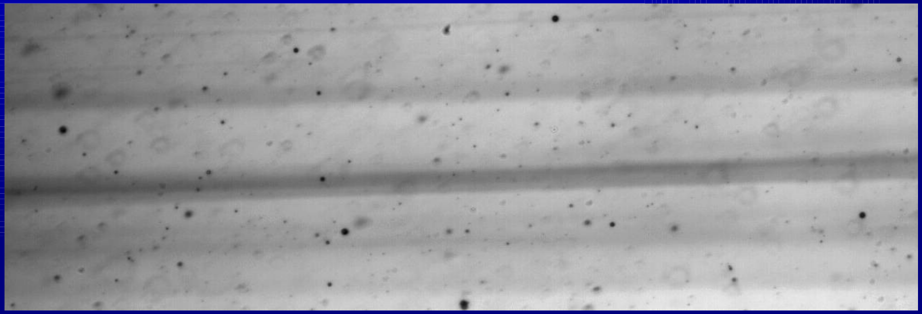
Q=0.204 => Re=8000

EXPERIMENTAL RESULTS

Appearance of the flow instability

processing element

flow direction



Laminar flow

$v = \sim 0.1\ m/s$

$Re = \sim 40$

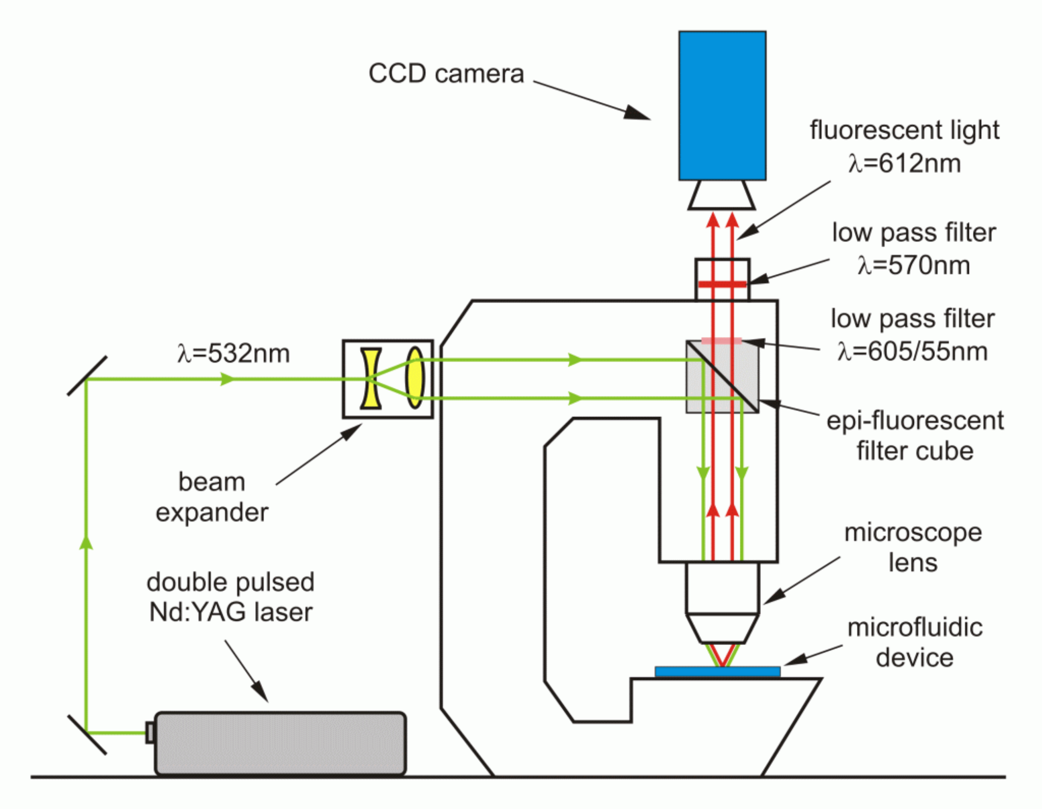
Transition flow

$v = \sim 0.4\ m/s$

$Re = \sim 160$

Micro-PIV

EXPERIMENTAL SETUP

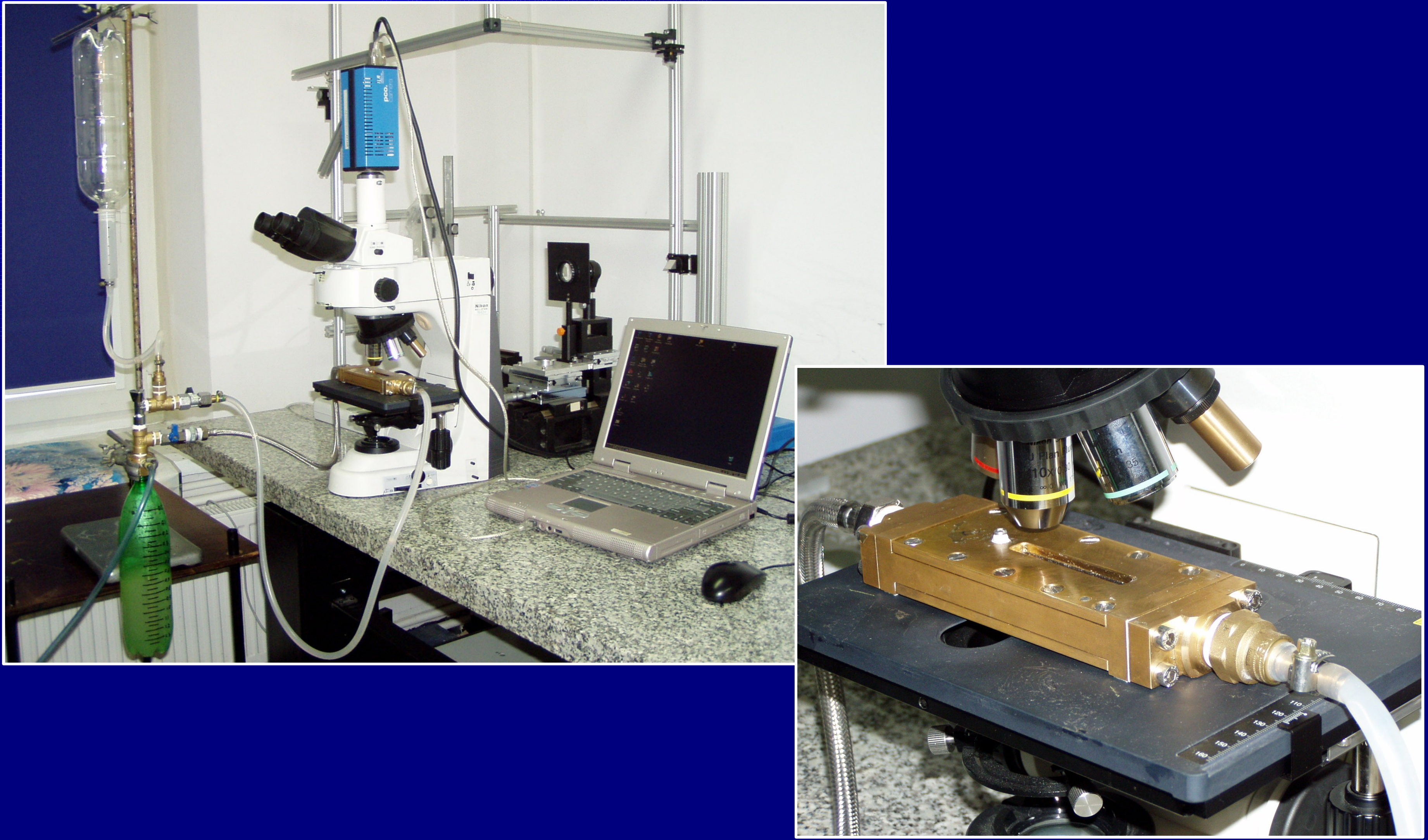


Schematic set-up for micro-PIV

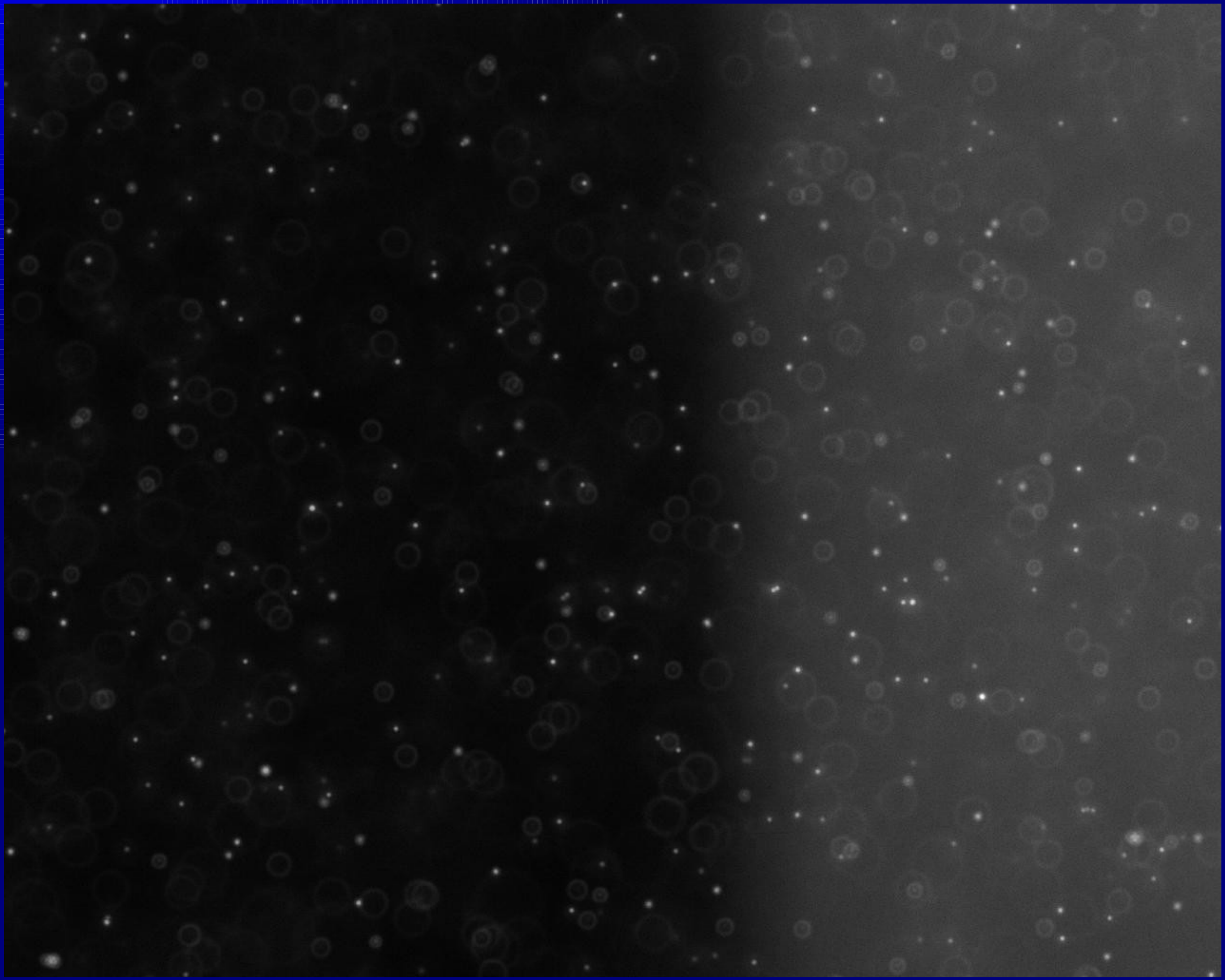
Fluorescent particles (2μm) under microscope

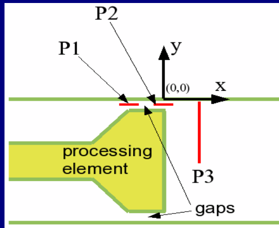
- **PIV Camera – *PCO SensiCam* (resolution 1280x1024)**
- **High Speed CMOS Camera – *PCO 1200.hs* (up to 40720 fps)**
- **Double Pulse Laser Nd-YAG - *SoloPIV NewWave* (30mJ per pulse)**
- **Laser CW Ar 5W**

EXPERIMENTAL SETUP



DOUBLE SHOT OF TRACERS





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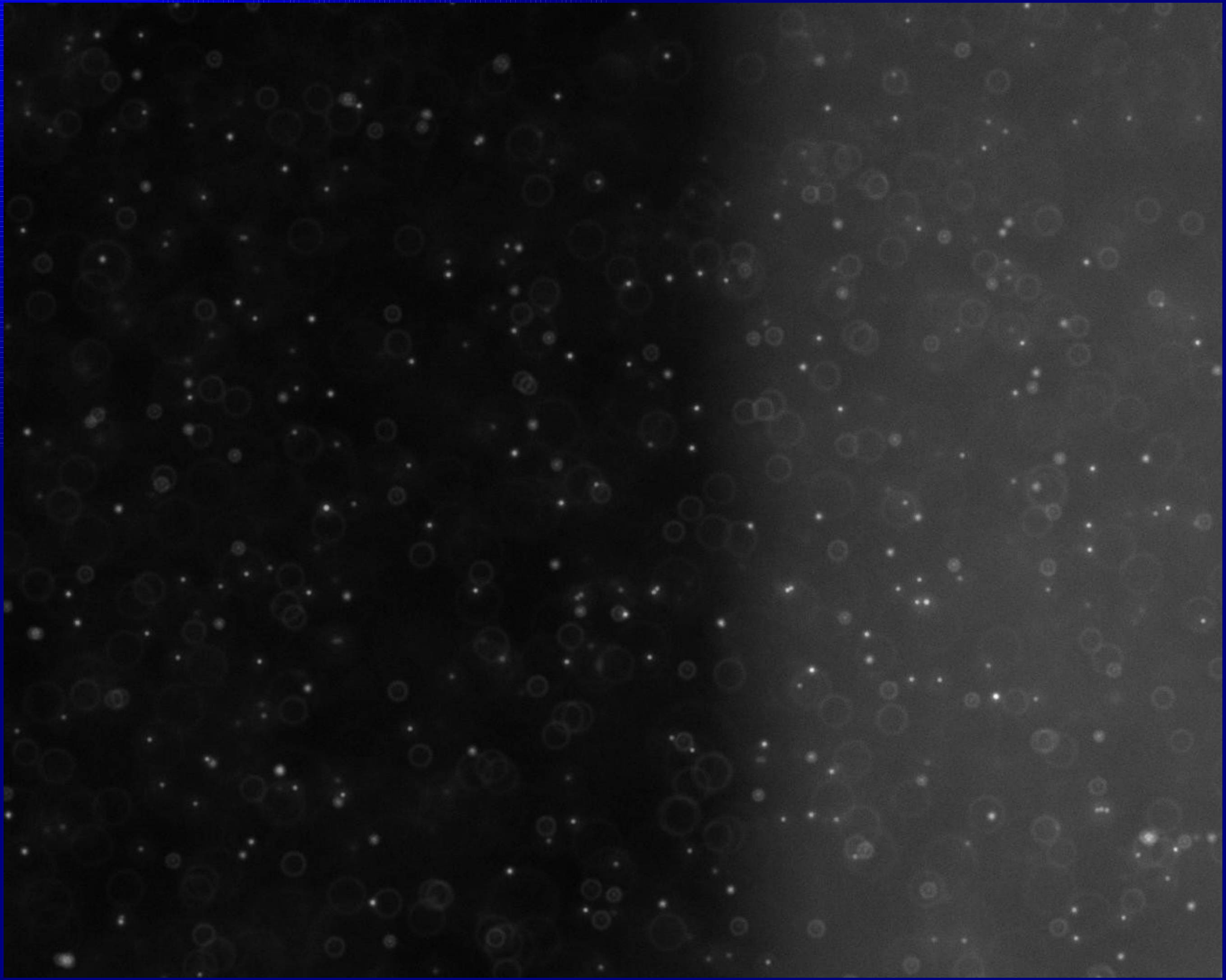
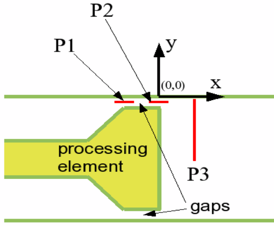
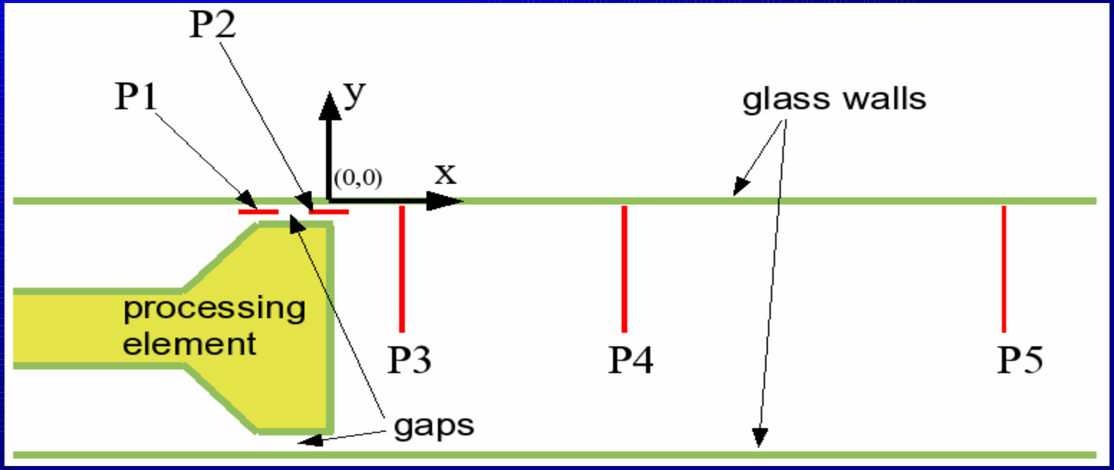




Micro-PIV RESULTS



Schematic view of the emulsifier with coordinates system and positions of selected profiles

Profile	X [mm]	Y [mm]	Z [mm]
P1	-1.45 ÷ -0.7	-0.2	0
P2	-0.35 ÷ 0.35	-0.2	0
P3	1	0 ÷ -3.75	0
P4	3	0 ÷ -3.75	0
P5	8	0 ÷ -3.75	0

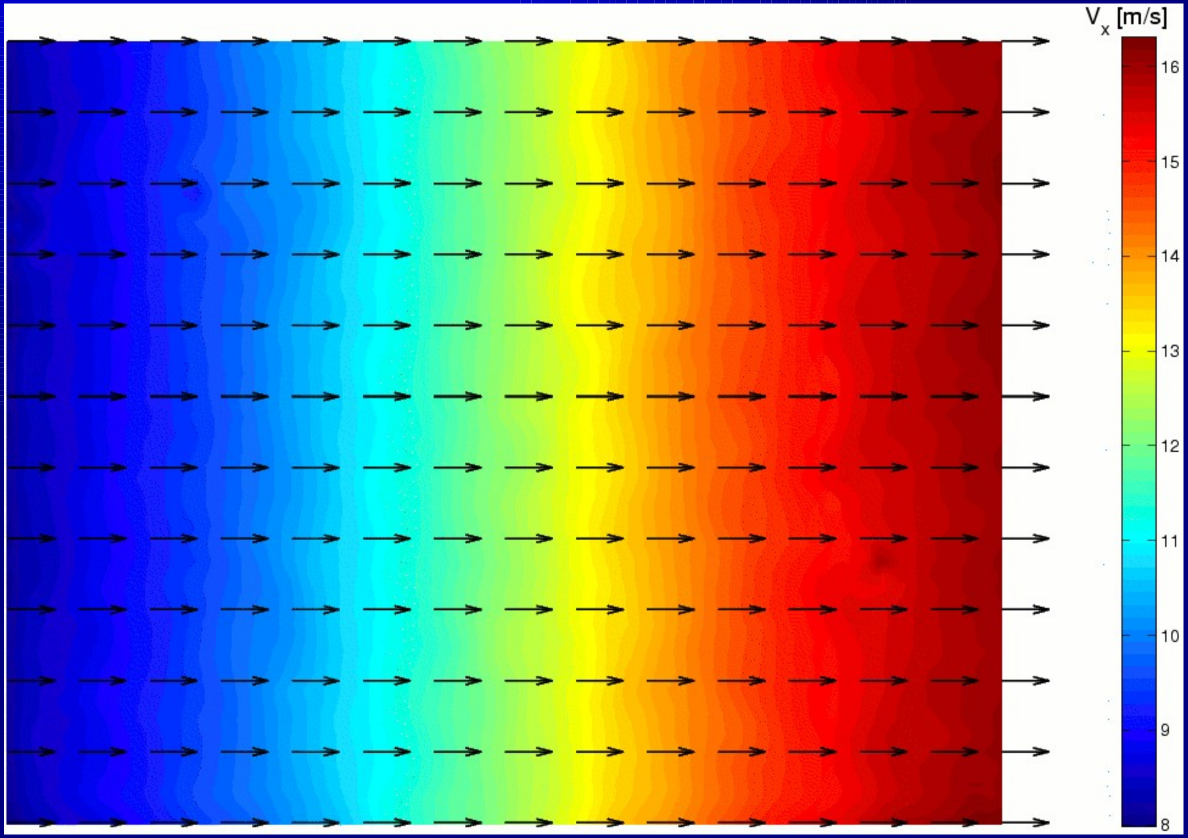
Used tracers: fluorescent particles, 2μm in diameter

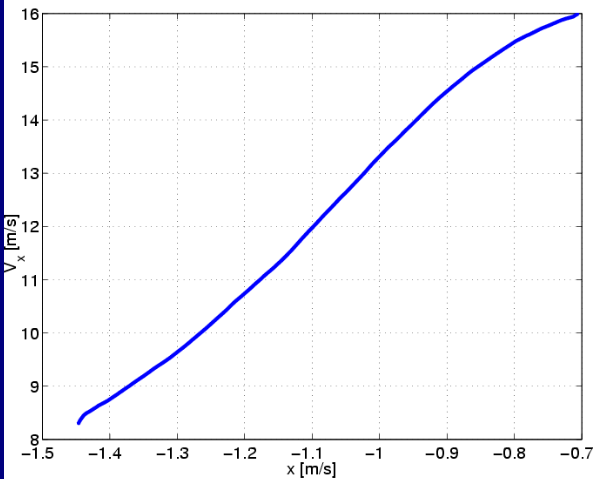
Microscope lens: 10x/NA0.3/WD17.30mm

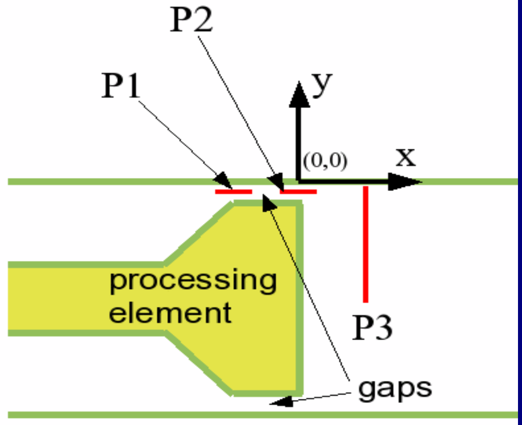
Images width corresponds to 0.7mm

Micro-PIV RESULTS

Average velocity field





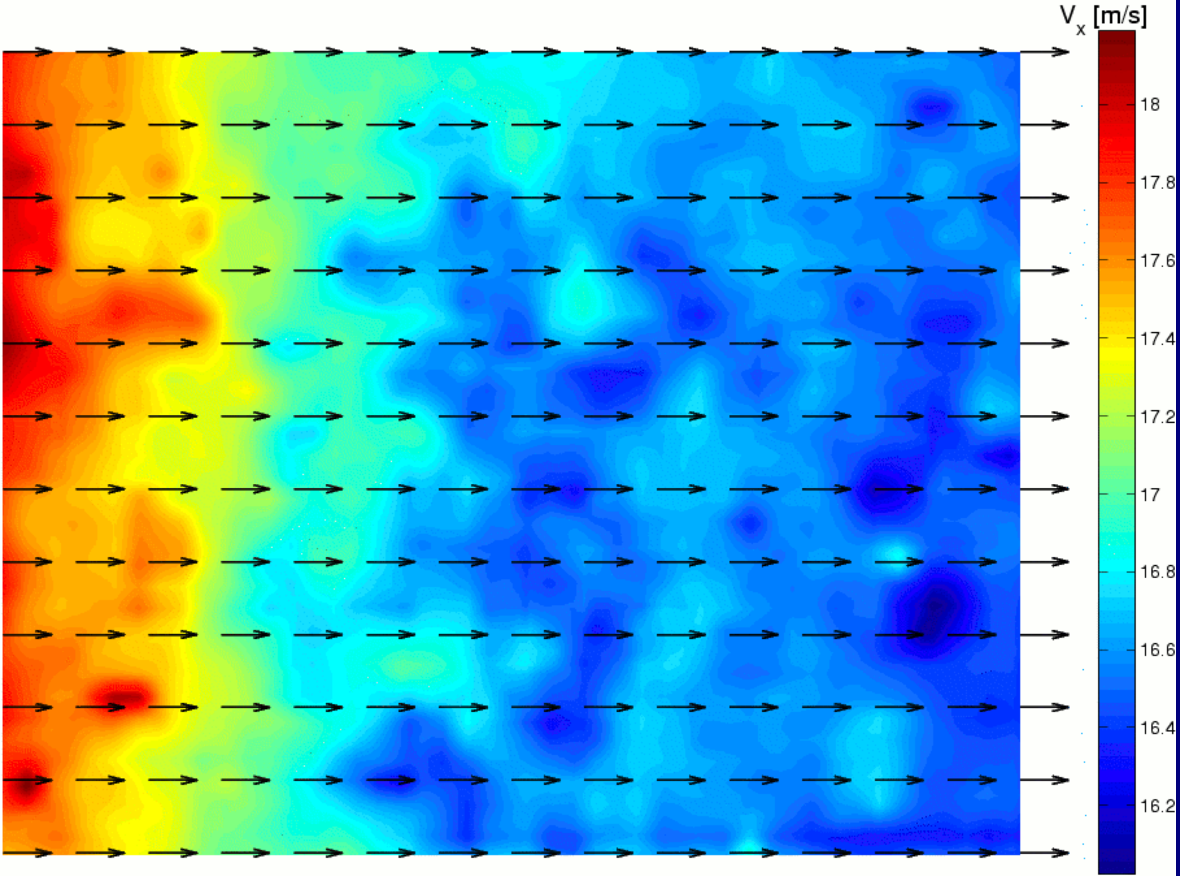


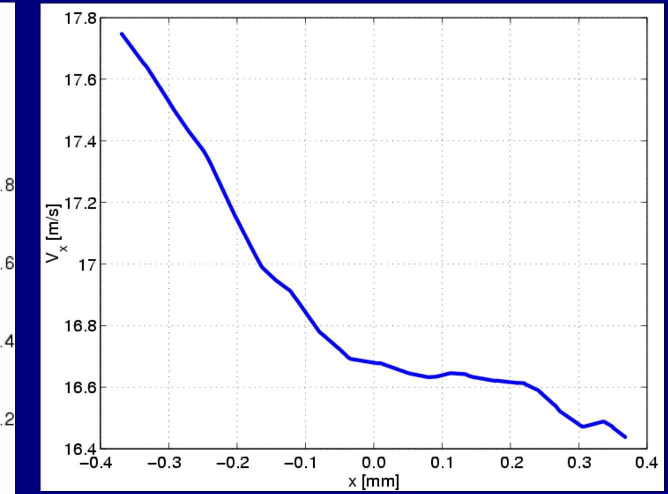
Position P1

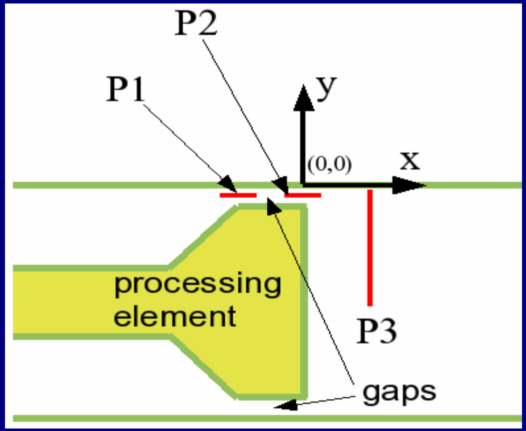
flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

Average velocity field





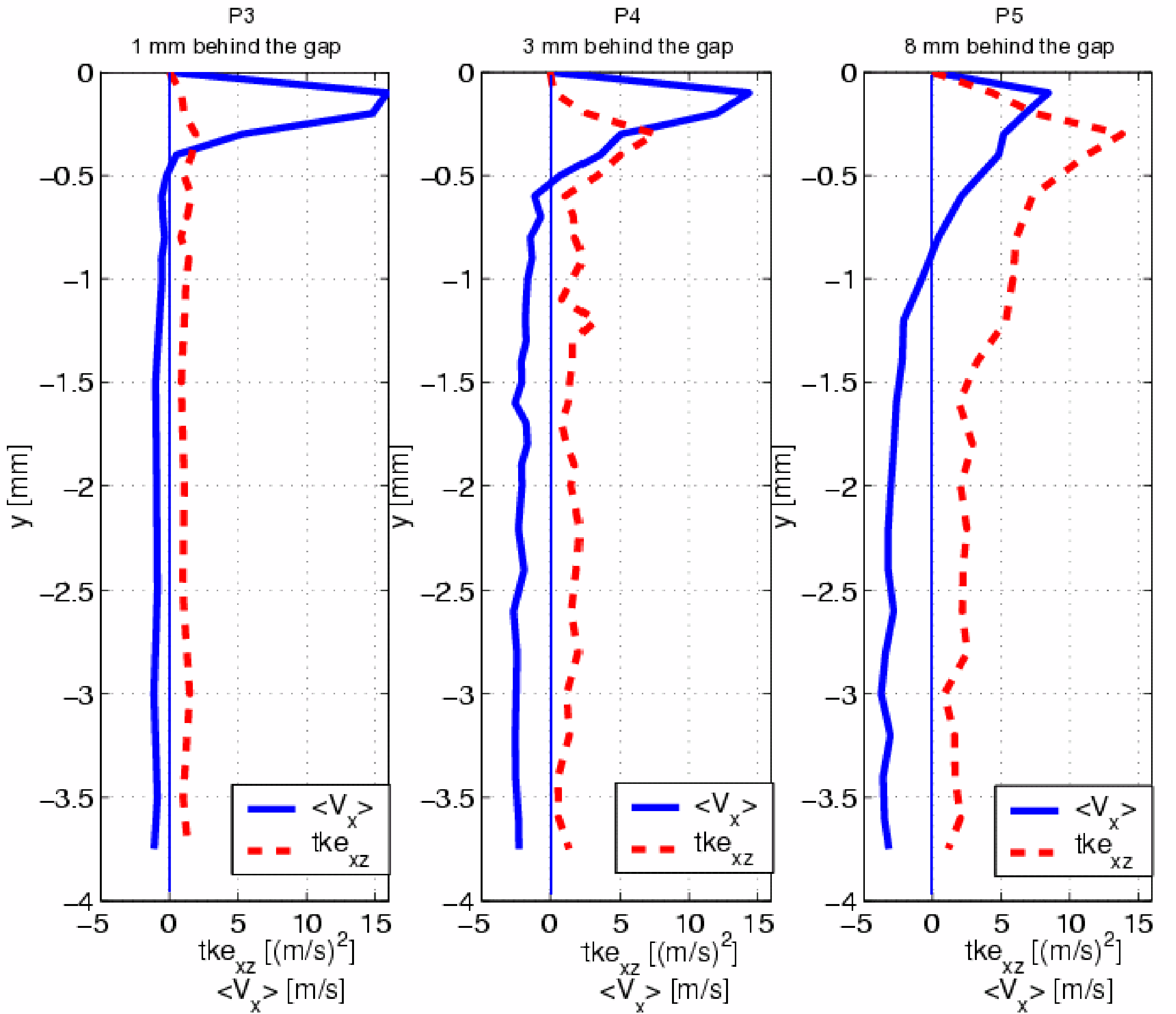


Position P2

flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

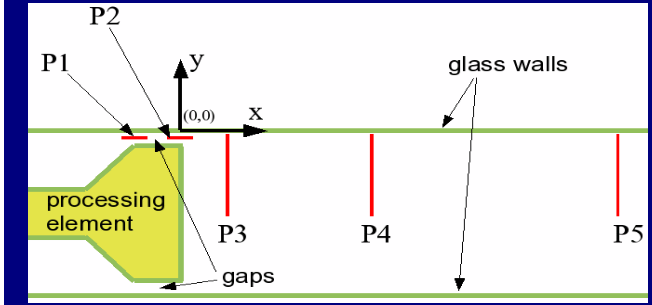
P3, P4 and P5 profiles of the X-Velocity and mean turbulent kinetic energy (xz)

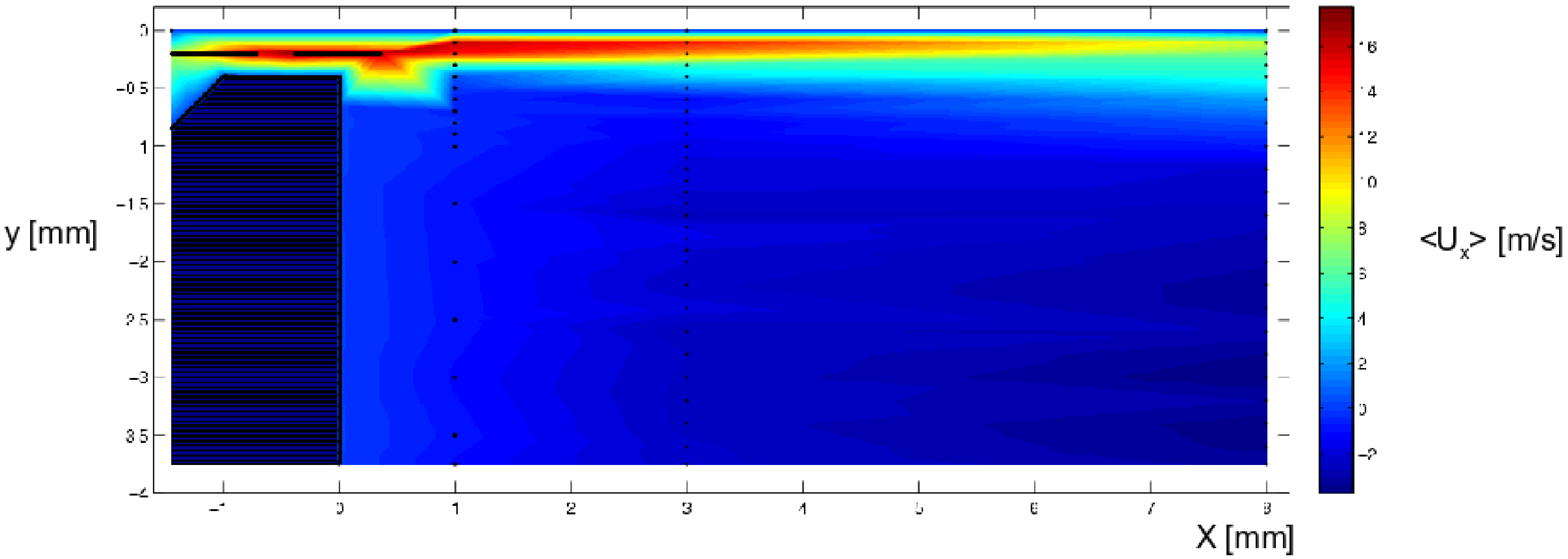


$$V_x=<V_x>+V'_x$$

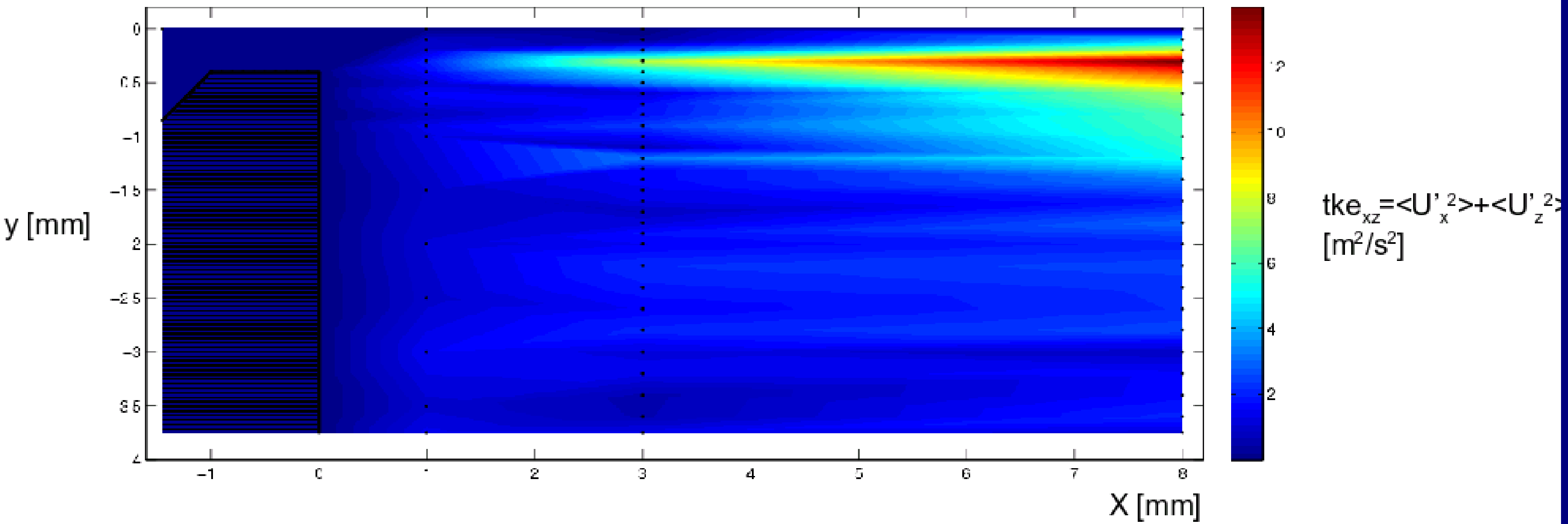
$$V_z=<V_z>+V'_z$$

$$tke_{xz}=<V'^2_x>+<V'^2_z>$$





y [mm]
X [mm]
<U_x> [m/s]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-1
0
1
2
3
4
5
6
7
8
16
14
12
10
8
6
4
2
0
-2



y [mm]
X [mm]
tke_xz=<U'_x^2>+<U'_z^2>
[m^2/s^2]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-1
0
1
2
3
4
5
6
7
8
12
10
8
6
4
2

Numerical simulation

NUMERICAL SIMULATION

Two simulations was done using Fluent 6.2 package:

- Direct Numerical Simulation (DNS) – to evaluate flow fluctuations:

    3D, unsteady, incompressible model

    time step: 10^{-7} s

- k-ε turbulence model – to reproduce flow structure and turbulence characteristics

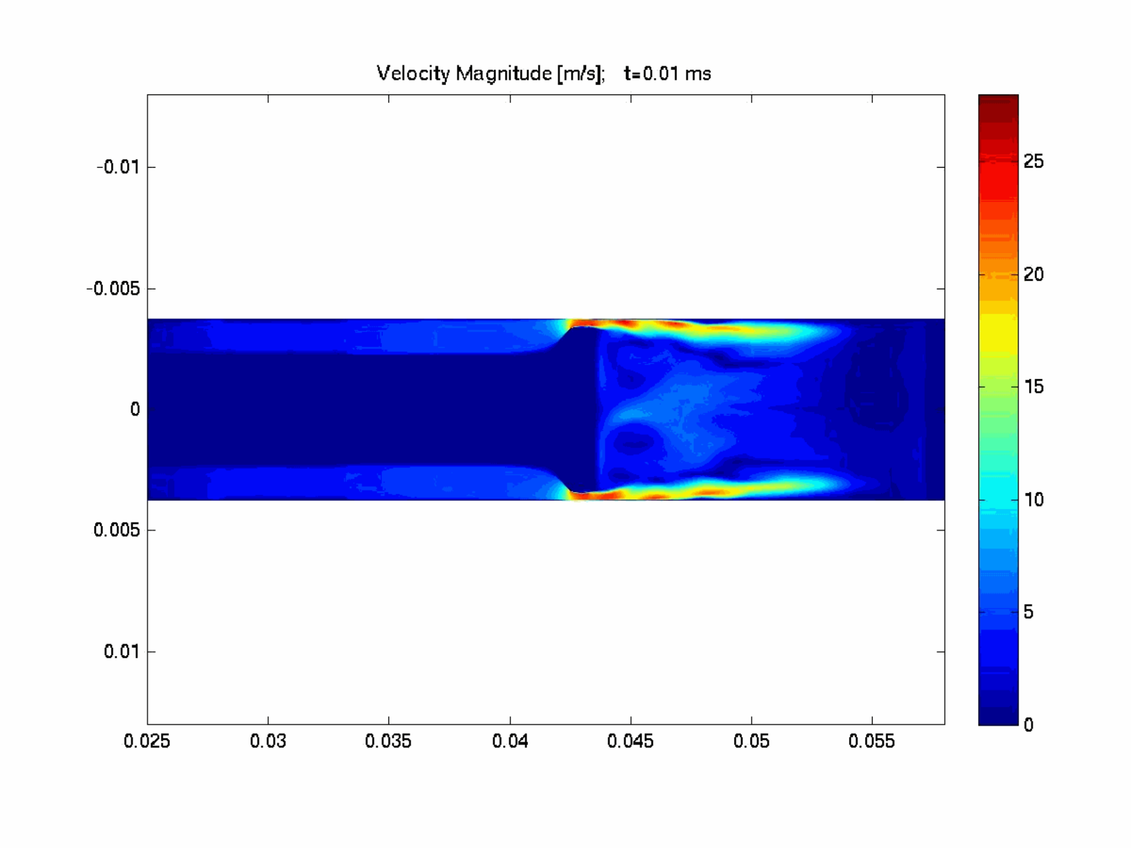
    3D, steady, incompressible model

    dynamic grid adaptation based on velocity magnitude gradient

NUMERICAL SIMULATION

Direct Numerical Simulation results

Contours of velocity magnitude



Laminar – unsteady flow

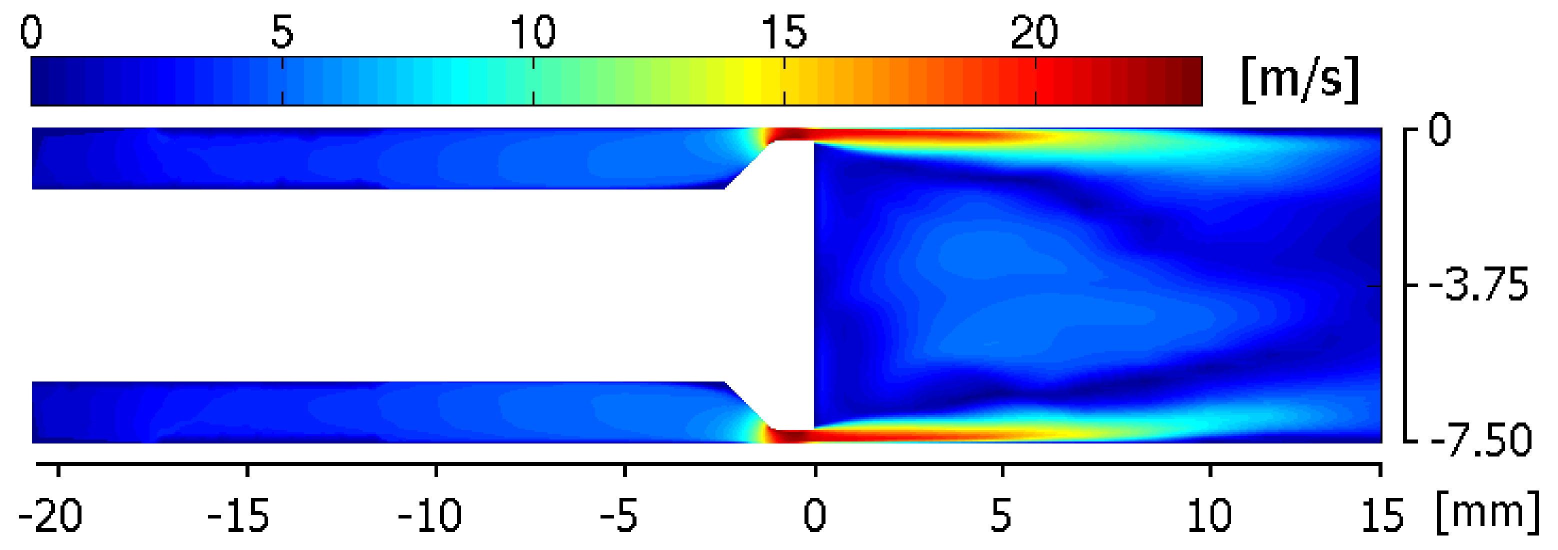
$Q_2 = 0.204\ \mathrm{dm^3/s}$

time step $\Delta t = 1 \cdot 10^{-7}$ s

NUMERICAL SIMULATION

Direct Numerical Simulation results

Contours of averaged velocity magnitude



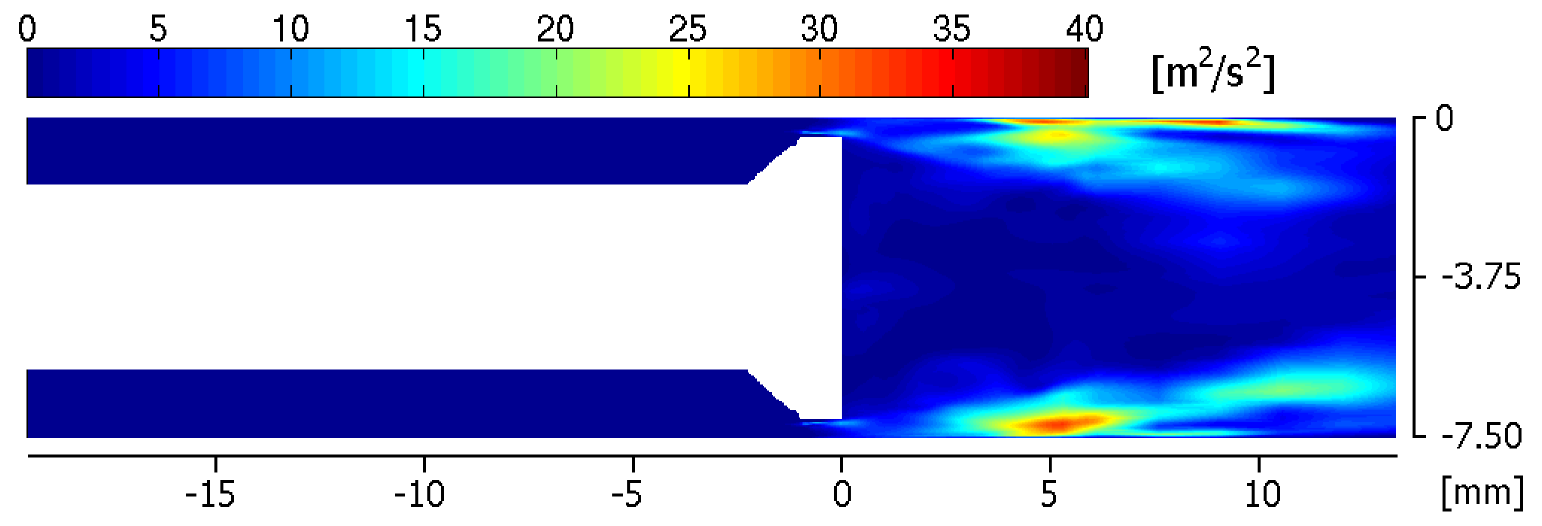
Laminar – unsteady flow, $Q_2 = 0.204\ \mathrm{dm^3/s}$

time step $\Delta t = 1 \cdot 10^{-7}$ s

NUMERICAL SIMULATION

Direct Numerical Simulation results

Contours of mean square value of the velocity fluctuations



$$tke_{xz} \text{¿} = \text{¿}\, V_x \text{¿} + \text{¿}\, V_z \text{¿}\; 2\; 2$$

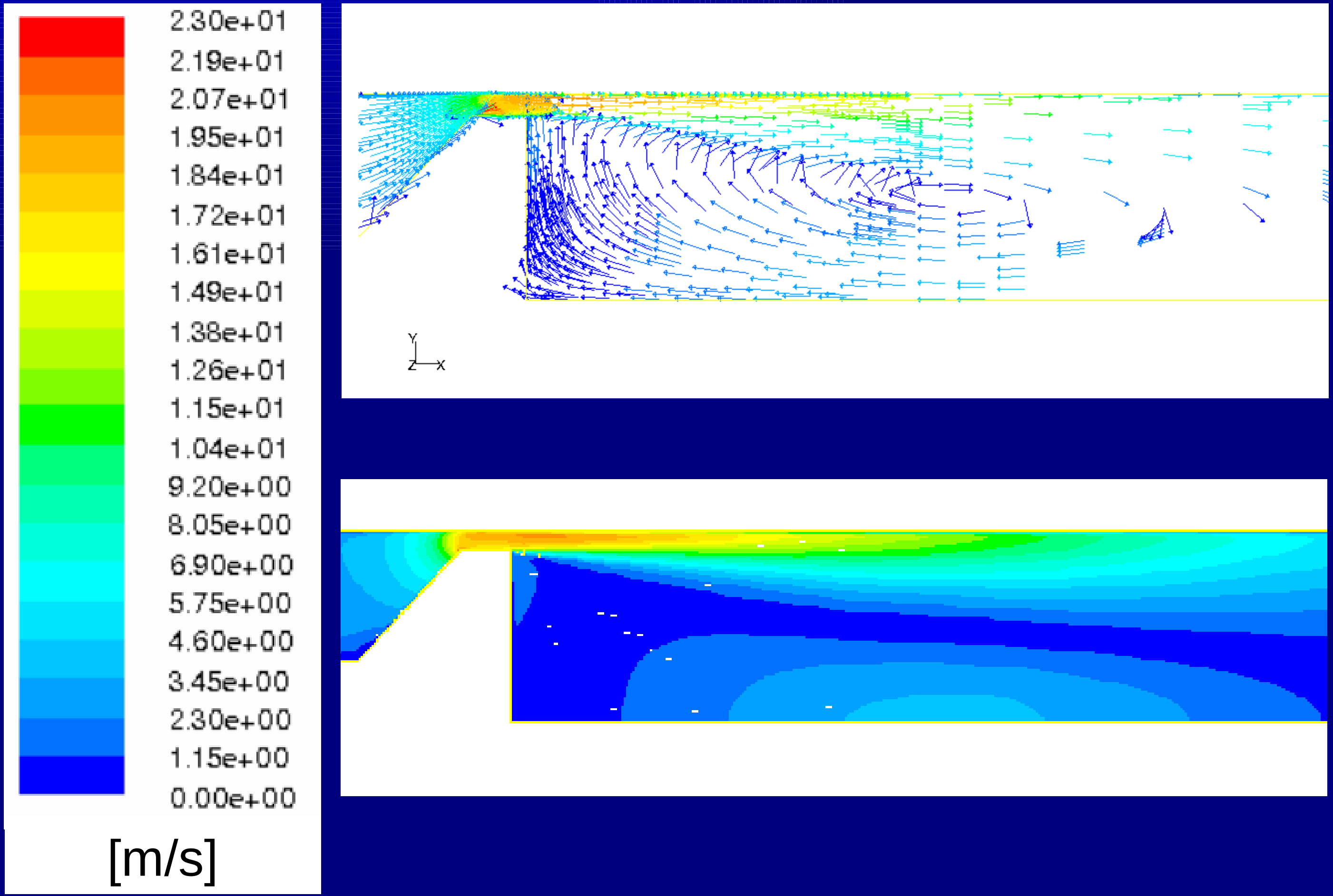
Laminar – unsteady flow, $Q_2 = 0.204\ dm^3/s$

time step $\Delta t = 1 \cdot 10^{-7}$ s

NUMERICAL SIMULATION

Velocity contours and vectors in the vicinity of the processing element

k-ε model + Enhanced Wall Treatment, $Q_2 = 0.204\ dm^3/s$

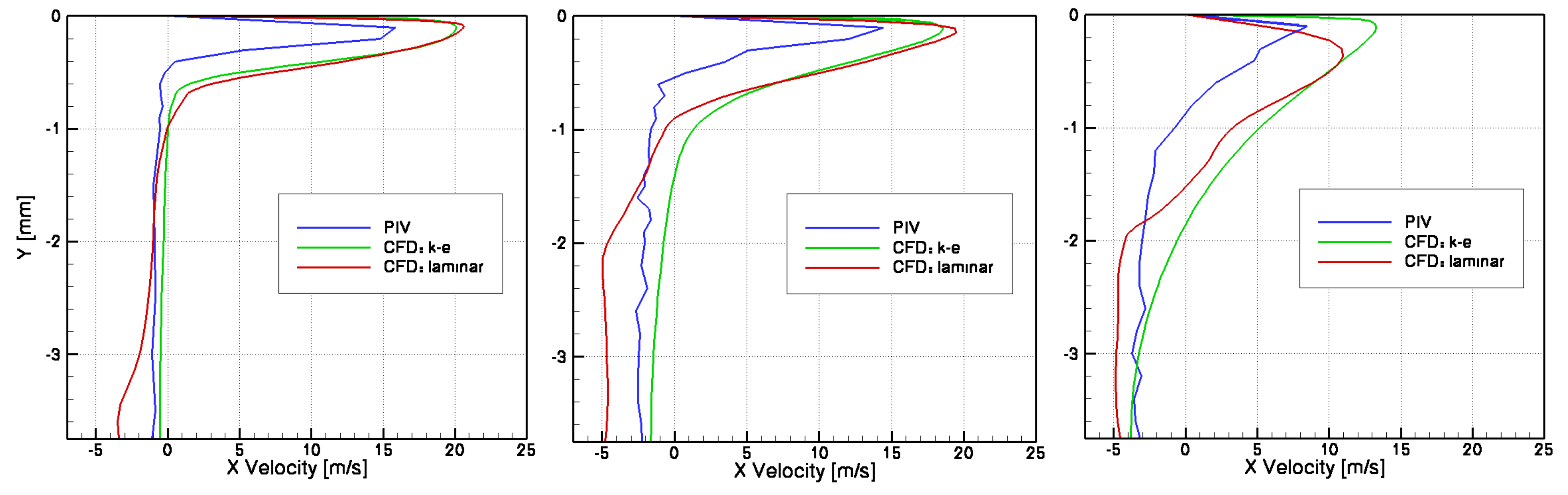


Velocity vectors

Velocity contours

NUMERICAL vs. EXPERIMENTAL RESULTS

Comparison of the numerical and experimental x-velocity profiles:



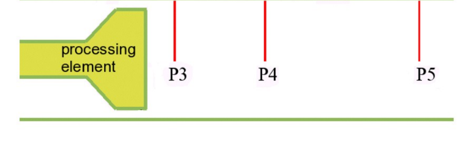
1mm (P3) **3mm (P4)** **8mm (P5)**

behind processing element

<u>CFD:</u> k–ε turbulence model

DNS

$Q = 0.204\ dm^3/s$



TAYLOR ESTIMATION OF DROPS SIZE

for laminar flows and small differences of the fluids viscosity

$$a=\frac{2\quad\left(\mu_d+\mu\right)}{G\quad\left(\frac{19}{4}\mu_d+4\quad\right)}$$

Droplet radius a , where:

μ – medium viscosity

μ_d – drops viscosity

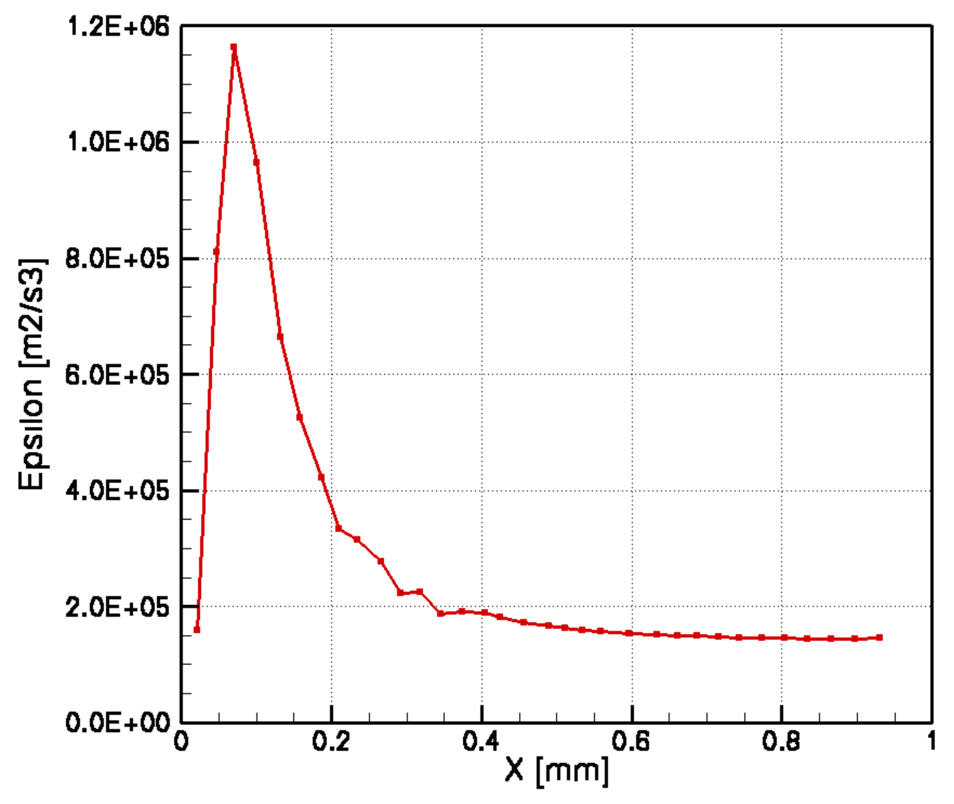
σ – interfacial tension

G – velocity gradient

NUMERICAL SIMULATION

Horizontal profile (P01) of the averaged Turbulent Dissipation Rate *Epsilon* through the gap

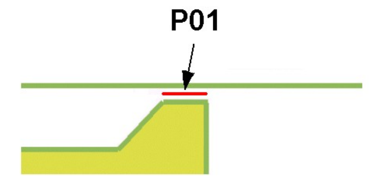
k-ε model + Enhanced Wall Treatment, Q_2 = 0.204 dm³/s



Epsilon averaged over whole gap:

$$\epsilon_{avg} = 3.453 \cdot 10^5 \, m^2/s^3$$

k-ε model + Enhanced Wall Treatment, Q_2 = 0.204 dm³/s



THEORETICAL ESTIMATION OF DROPS SIZE

Kolmogorov-Hinze theory

for turbulent flows and small differences of the fluids viscosity

$$d = 0.749 \frac{\sigma^{3/5}}{\rho_c^{3/5} \cdot \epsilon^{2/5}}$$

Davis theory

for turbulent flows and significant differences of the fluids viscosity

$$d = \frac{K}{\rho_c^{3/5} \cdot \epsilon^{2/5}} \left(\sigma + \frac{\mu_d \sqrt{2} \left(\epsilon \cdot d_{\max} \right)^{1/3}}{4} \right)^{3/5}$$

Where: **d – drops diameter, σ – interfacial tension**

ρ_c – medium density, μ_d – drops viscosity,

ε - turbulent dissipation rate, K – constant (K=0.748)

DROPS SIZE ESTIMATION

Results of the oil drops diameter estimation

Assuming: **$\sigma = 5.5 \cdot 10^{-3}$ *N/m*, ρ_c = 998 kg/m³ (water)**

$\mu_c = 10^{-3}$ *Pa s* (water), $\mu_d = 50 \cdot 10^{-3}$ *Pa s* (S500 oil),

μ_d *= 500 ·10-3 Pa s* (S500oil),

	Hinze model both oils [μm]	Davis model oil S50 [μm]	Davis model oil S500 [μm]
max. epsilon value in gap $\varepsilon_{max} = 1.160 \cdot 10^{6}\ m^2/s^3$	1.97	6.46	32.77
avg. epsilon value in gap $\varepsilon_{avg} = 3.599 \cdot 10^{5}\ m^2/s^3$	3.14	8.95	44.01

Taylor laminar shear flow break-up model: *$d = 6.9\ \mu m$*

<u>Experiment</u>: mean oil-drops size: d= 10.1 μm for S50 oil
d= 20.7 μm for S500 oil

CONCLUSIONS

1. Velocity measurements indicate almost uniform velocity flow field in the gap region. It means that turbulence is still not fully developed and only <u>strong shear gradients may be responsible for the droplet break-up</u> there.

3. Visualization of droplets break-up in the homogenizer indicate that the process takes place few millimetres behind processing element.

5. Direct Numerical Simulation confirms that intensity of turbulence is relatively low in the gap and that the droplets break-up process may depend not only on the turbulent dissipation energy but mainly on the shear gradients.