Polish Academy of Sciences
Institute of Fundamental Technological Research

Turbulencja w mikrokanale i jej wpływ na proces emulsyfikacji

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PRESENTATION OUTLINE

0 Introduction

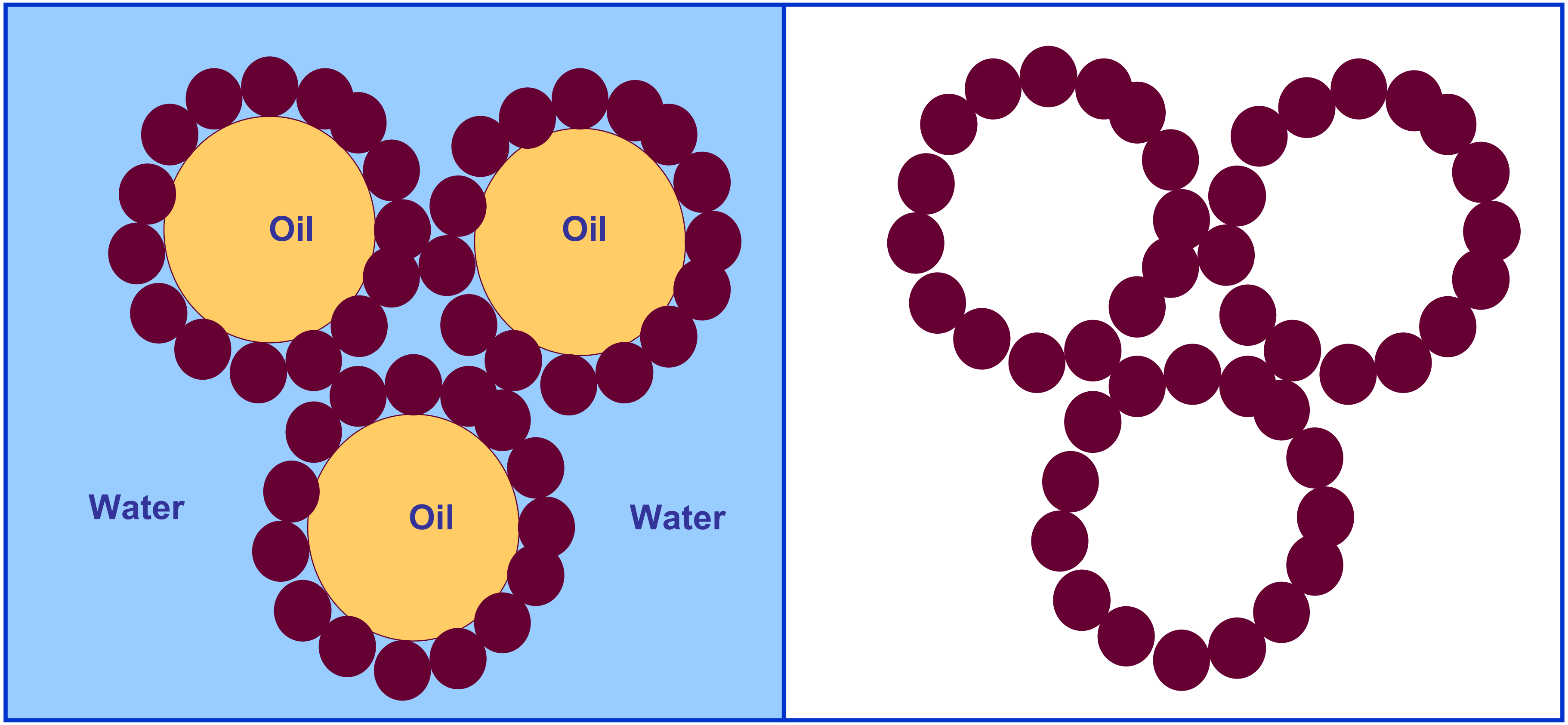
I Flow structure investigation in the vicinity of the processing element by Particle Image Velocimetry

II Visualization of droplets break-up process and emulsion flow in the vicinity of the processing element

III Numerical simulation of the flow through the planar emulsifier

IV Summary and conclusions

Structuring nano-particles at the interface



The emulsion with thin layers of third substance at the surface between oil and water

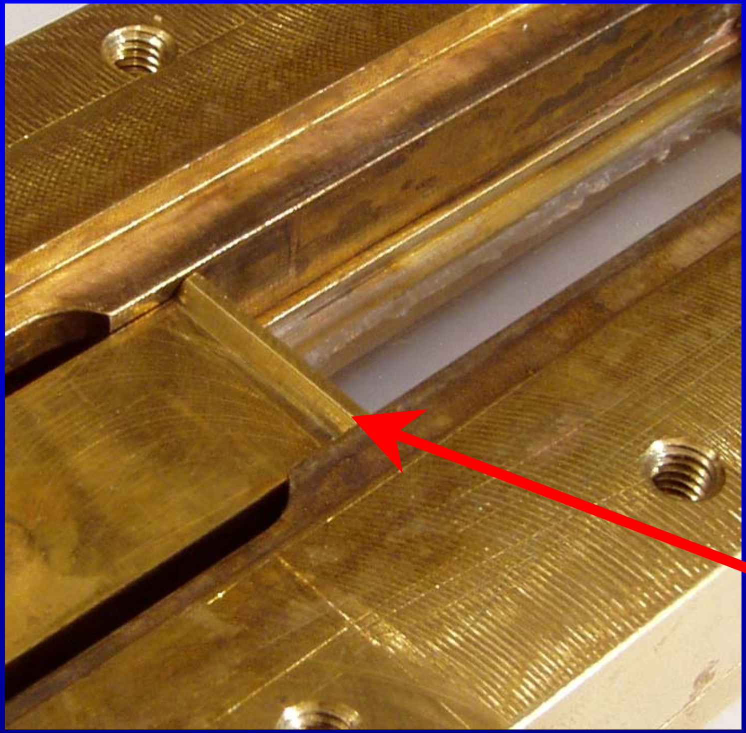
The structure of nanomaterial after removing water and oil

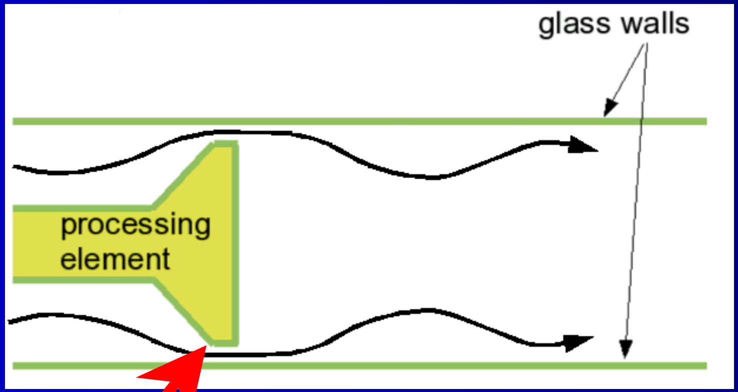
MAIN IDEA

1. Well defined turbulent flow in emulsificator with micro-channel
2. Emulsification of oil in water to obtain uniform in size micro-emulsion in turbulent flow
3. Drop – nano-particle interaction
4. Composite layer formation at the interface
5. Removal of both fluids to achieve new material

Production of droplets emulsion in turbulent flow

Experimental cell with optical access for flow investigation inside emulsifier

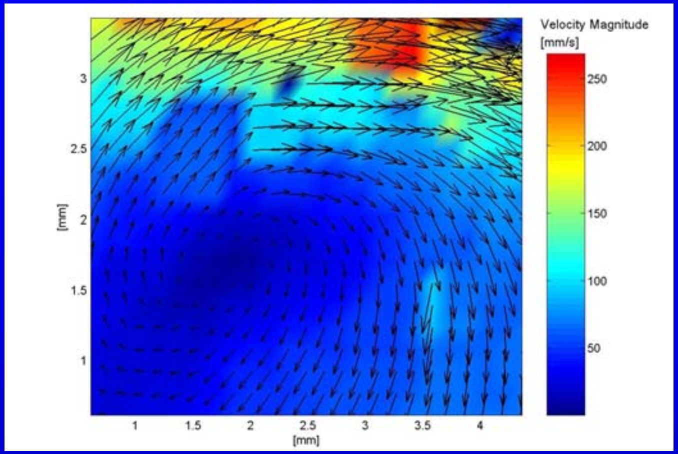




High speed imaging and velocity measurements

gap: 0.4mm x 15mm, flow rate: up to 0.204 dm^3/s

Primary aim of the experiment



- Instantaneous velocity and vorticity by micro-PIV technique
- Flow structure
- Turbulence structure
- Shear stress field
- Drops break-up

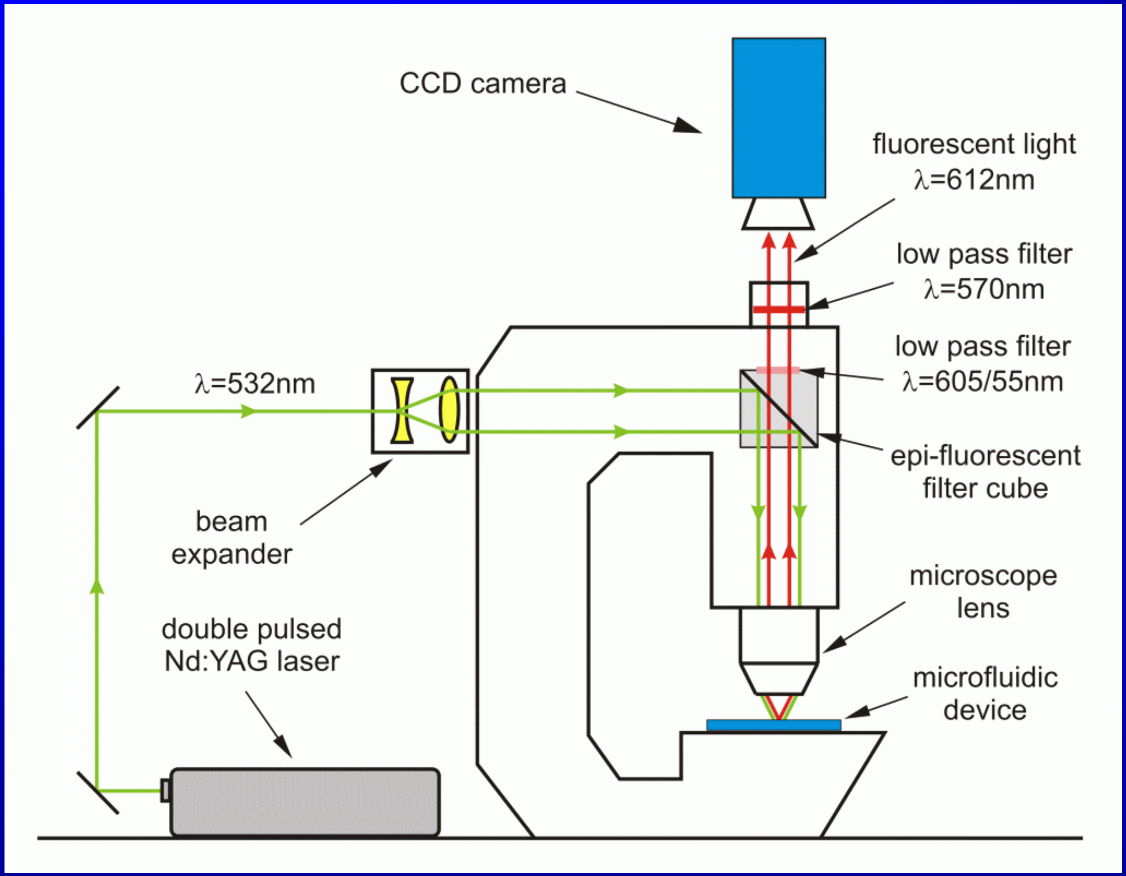
- Validation of the CFD models
- Optimisation of the drops size and shape
- Optimisation of the emulsifier geometry

EXPERIMENTAL METHODS

- **Full Field Measurements of velocity and drops shape:**
- **Epifluorescent microscope – *Nikon ECLIPSE E-50i***
- **PIV Camera – *PCO SensiCam* (resolution 1280x1024)**
- **Double Pulse Laser Nd-YAG - *SoloPIV NewWave* (30mJ per pulse)**
- **High Speed CMOS Camera – *PCO 1200.hs* (up to 40720 fps; 636fps in full resolution 1280x1024)**
- **Laser CW Ar 5W**
- **Fluorescent micro- and nanoparticles (30nm – 7 μm)**

- **Other equipment:**
- **Optical system for forming and redirection of laser light (lenses, mirrors, etc.)**
- **Pressure system (gas cylinder with argon, pressure regulator and conduits, pressure sensor)**
- **Two precision syringe pumps**

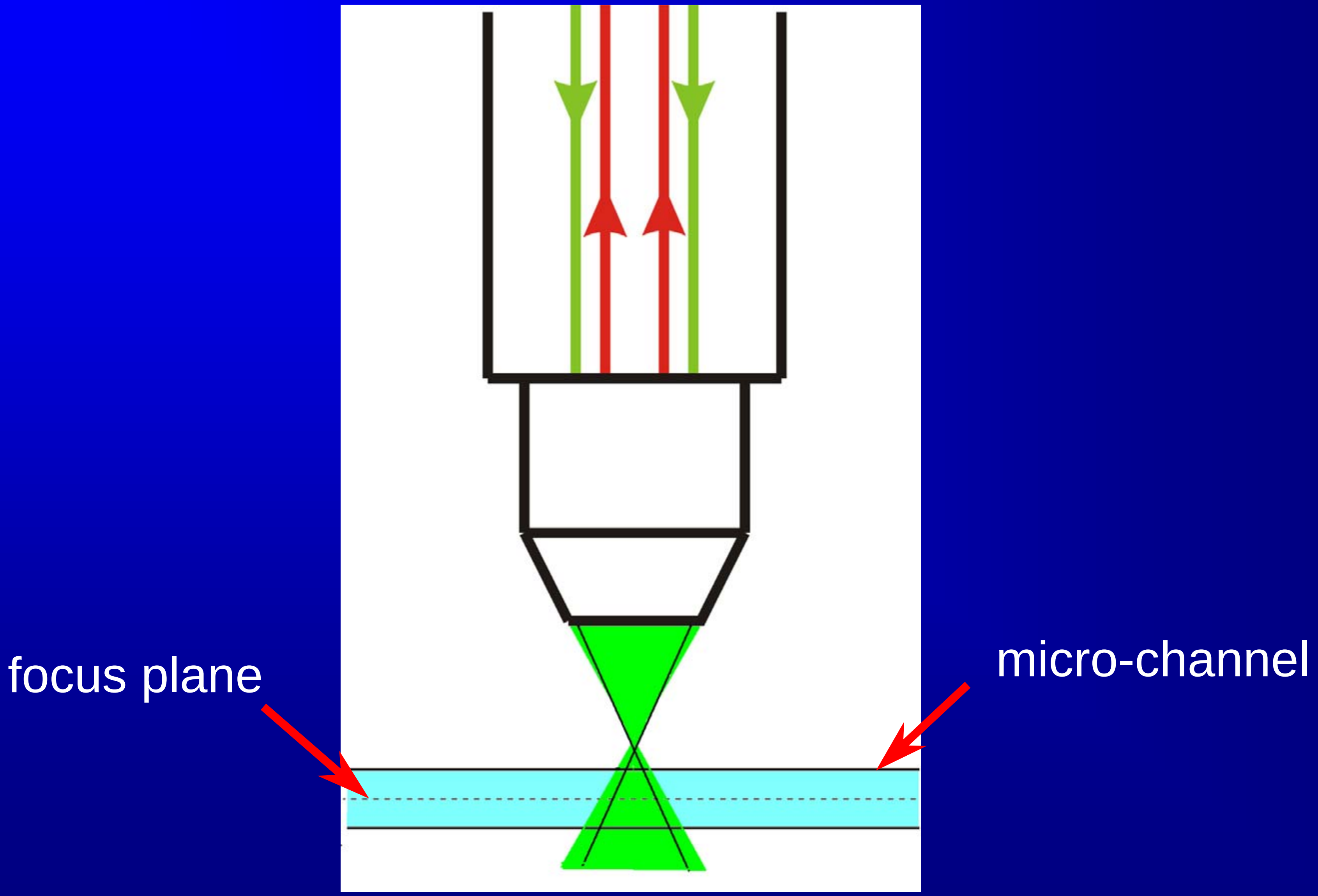
EXPERIMENTAL SETUP



Schematic set-up for microPIV

Fluorescent particles under microscope

EXPERIMENTAL SETUP



EXPERIMENTAL SETUP

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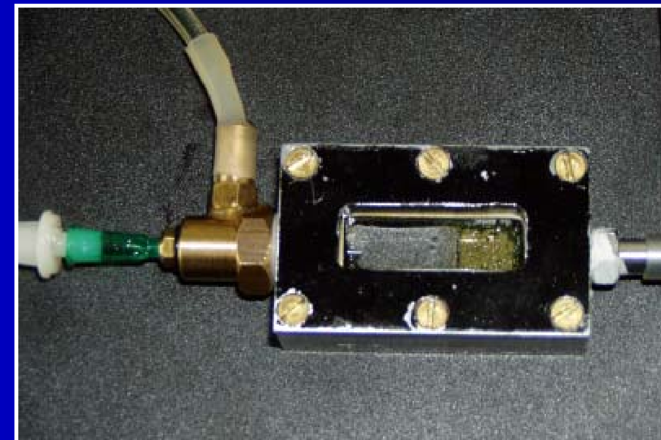
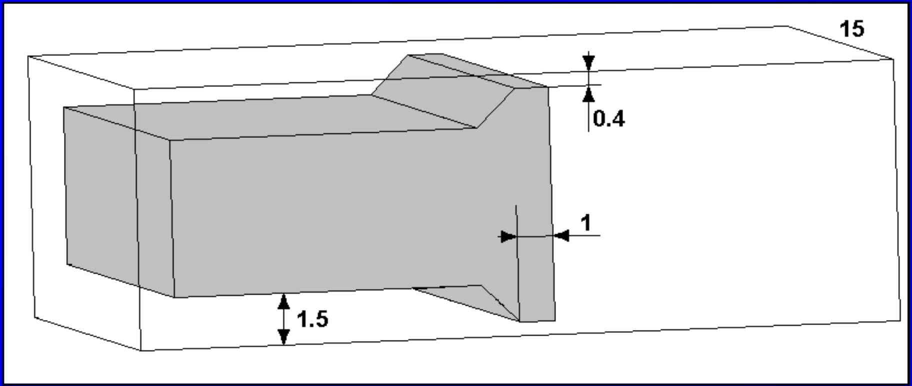
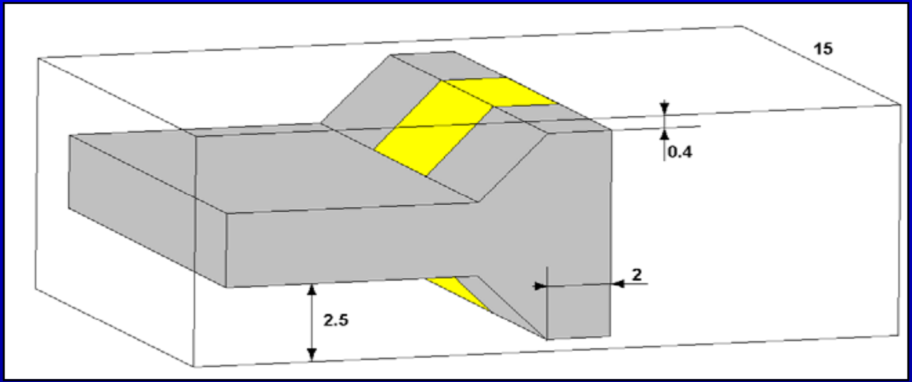


GEOMETRY OF THE MODELS



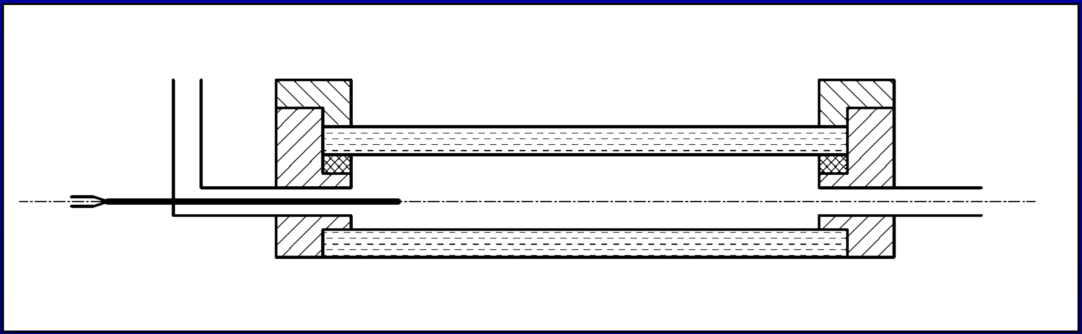
Geometry G1 – non-transparent processing element

size of the gap: 1 x 0.4 x 15 mm



Geometry G2 – transparent processing element

size of the gap: 2 x 0.4 x 15 mm



Geometry G3 for jet breakup observation

channel size: 30 x 8 x 10 mm

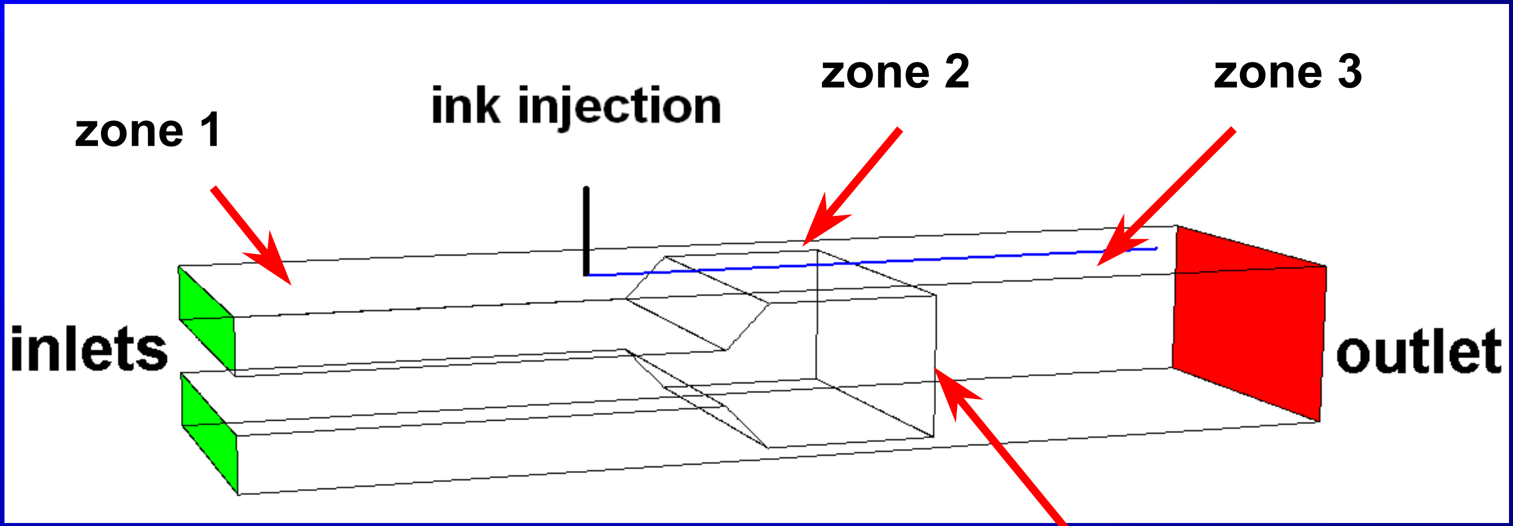
needle diameter: 0.5 mm

OUR QUESTIONS TO ANSWER

Production of droplets emulsion in turbulent flow

- Is flow turbulent, what is the critical Re number?

EXPERIMENTAL INVESTIGATION



zone 1: 2.5 x 15 mm

zone 2: 0.4 x 15 mm

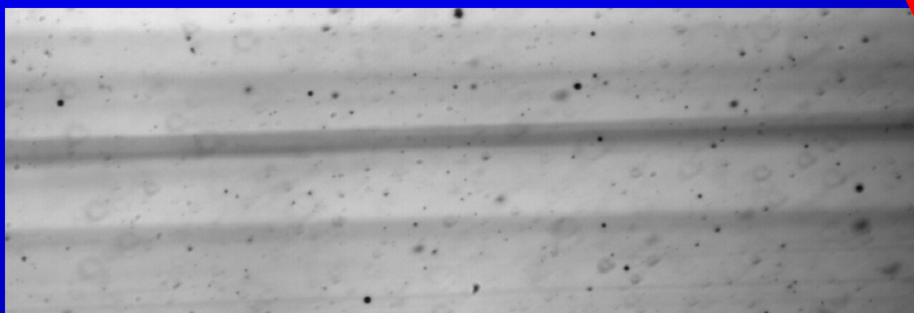
zone 3: 7.5 x 15 mm

Processing element

EXPERIMENTAL RESULTS

Laminar – turbulent transition

flow direction ← processing element ↓



Laminar flow

v* = ~ 0.1 *m/s

***Re* = ~ 250**

Transition flow

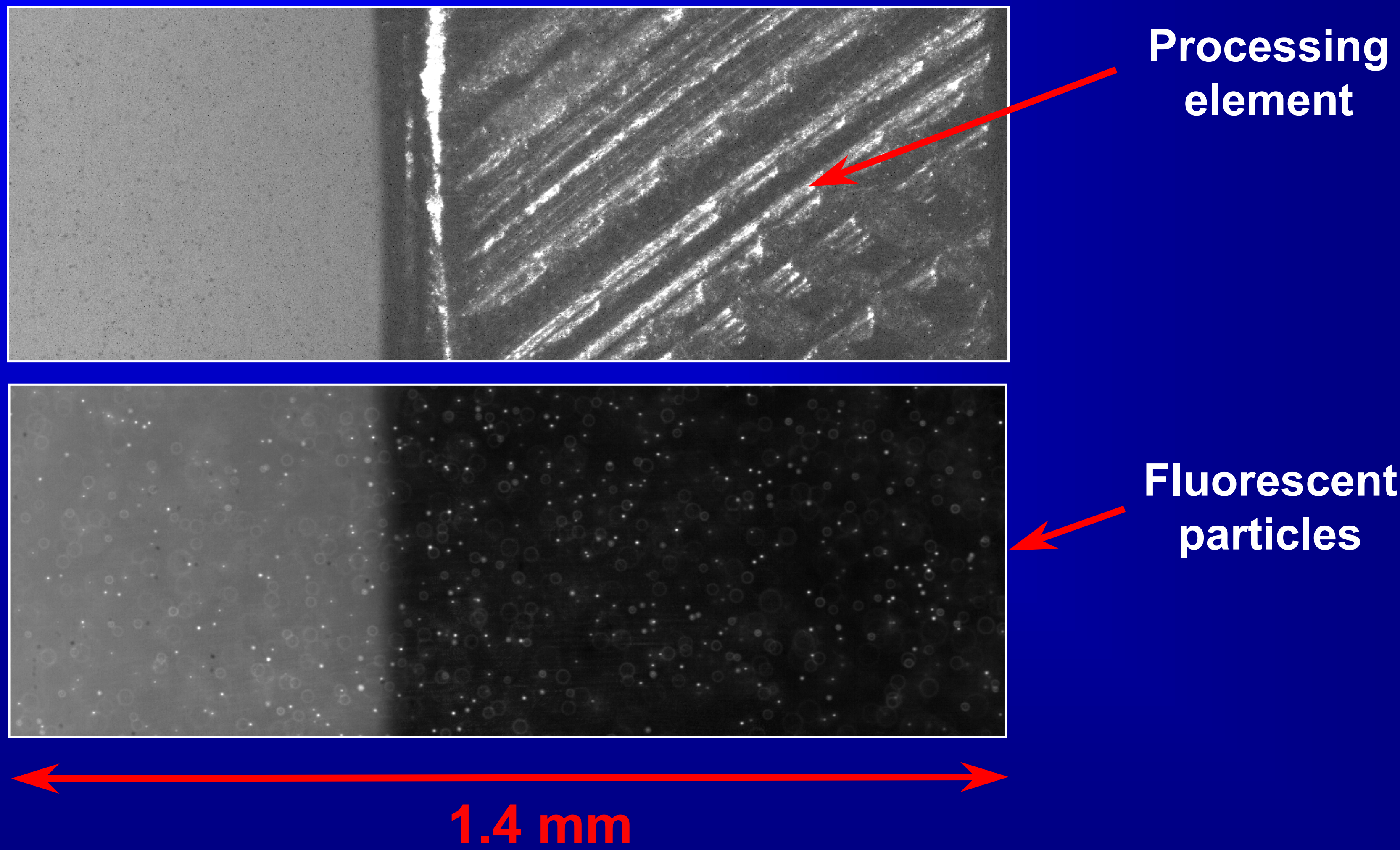
v* = ~ 0.4 *m/s

***Re* = ~ 1000**

Part I

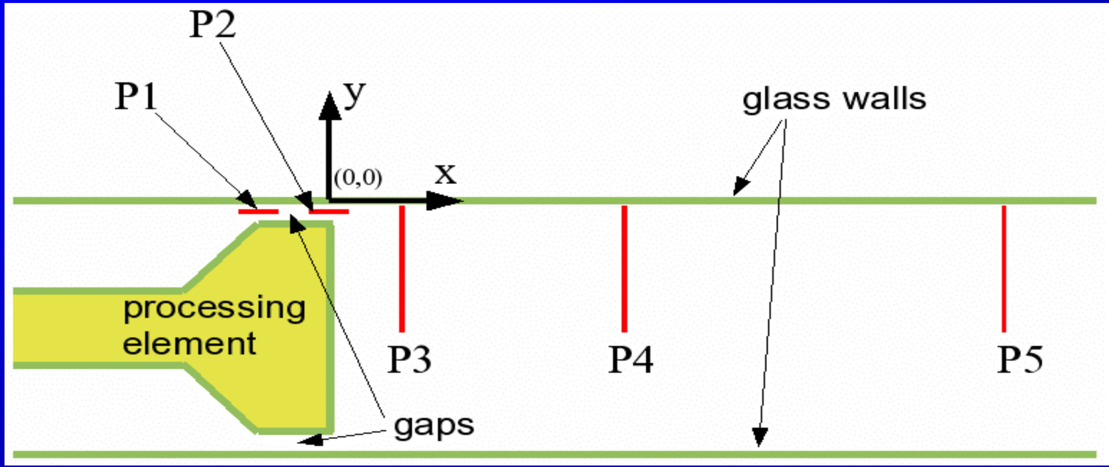
Micro-PIV RESULTS

Micro-PIV RESULTS



Micro-PIV RESULTS

Micro-PIV measurements was done for flow rate $Q_2=0.204 dm^3/s$ using geometry G1 (non-transparent proc.el.)



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

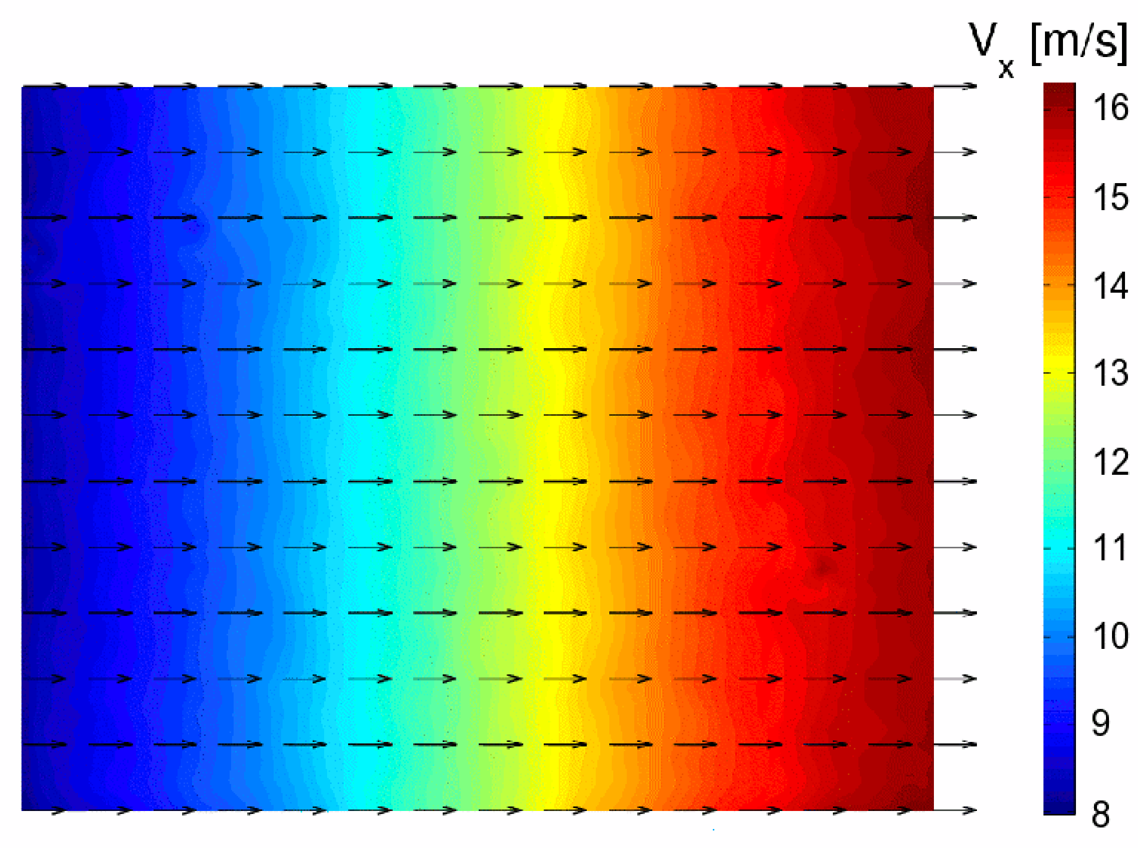
Used tracers: fluorescent particles, 2µm in diameter

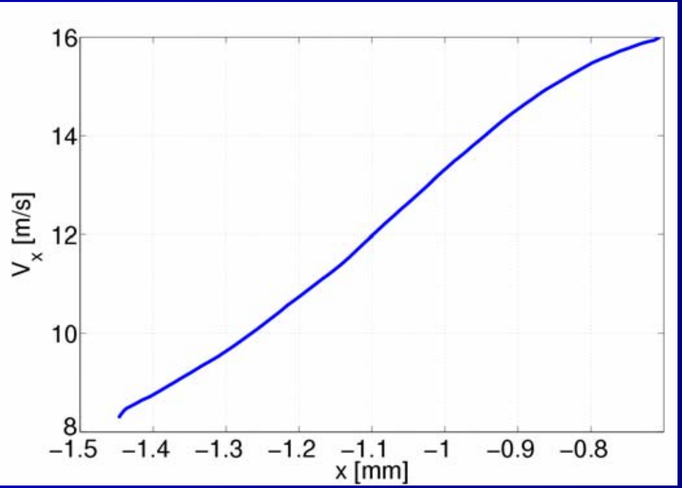
Microscope lens: 10x/NA0.3/WD17.30mm

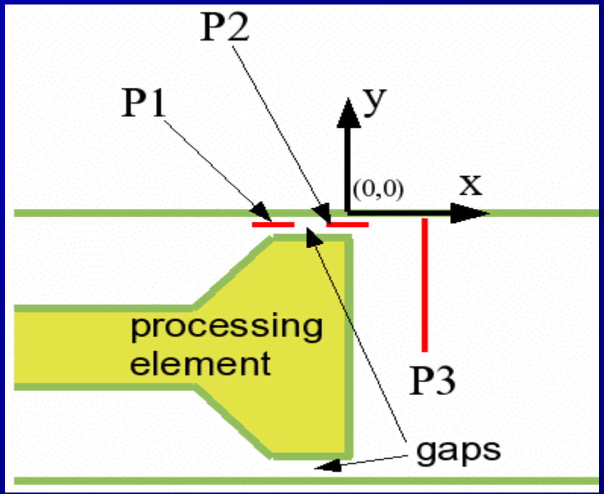
Images width corresponds to 0.7mm

Micro-PIV RESULTS

Velocity field





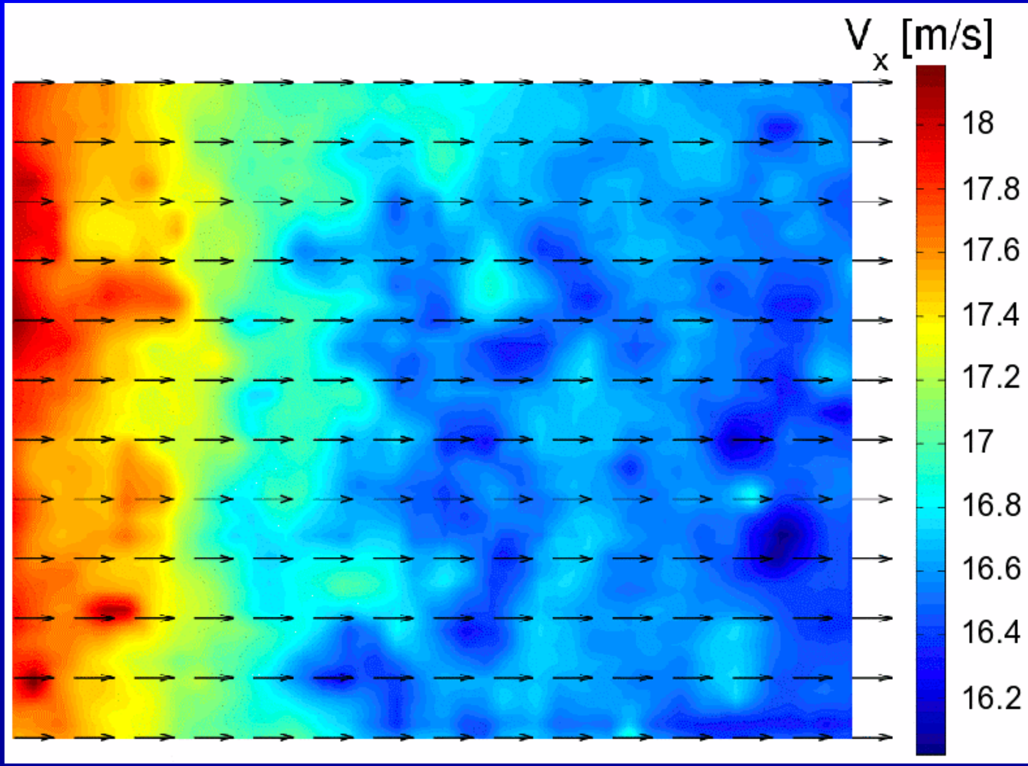


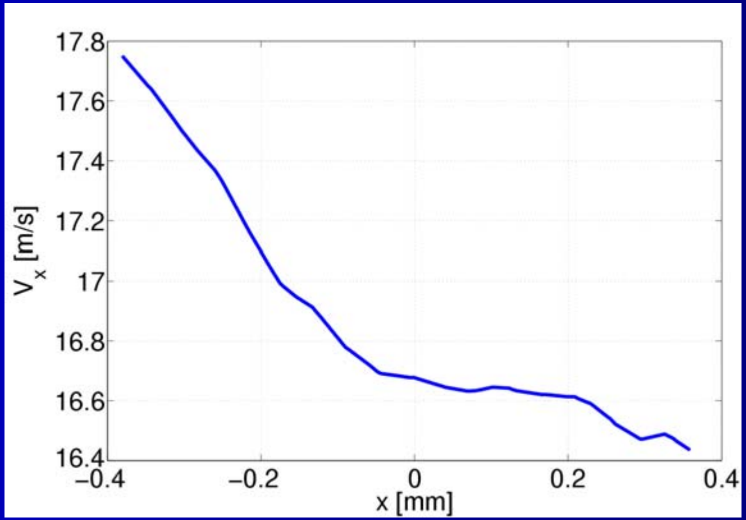
Position P1

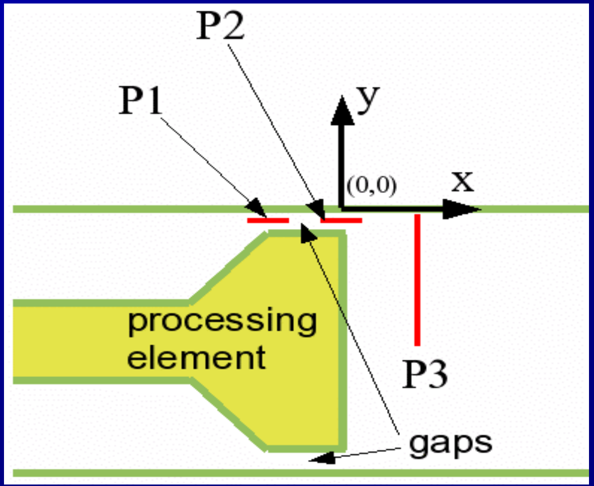
flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

Velocity field





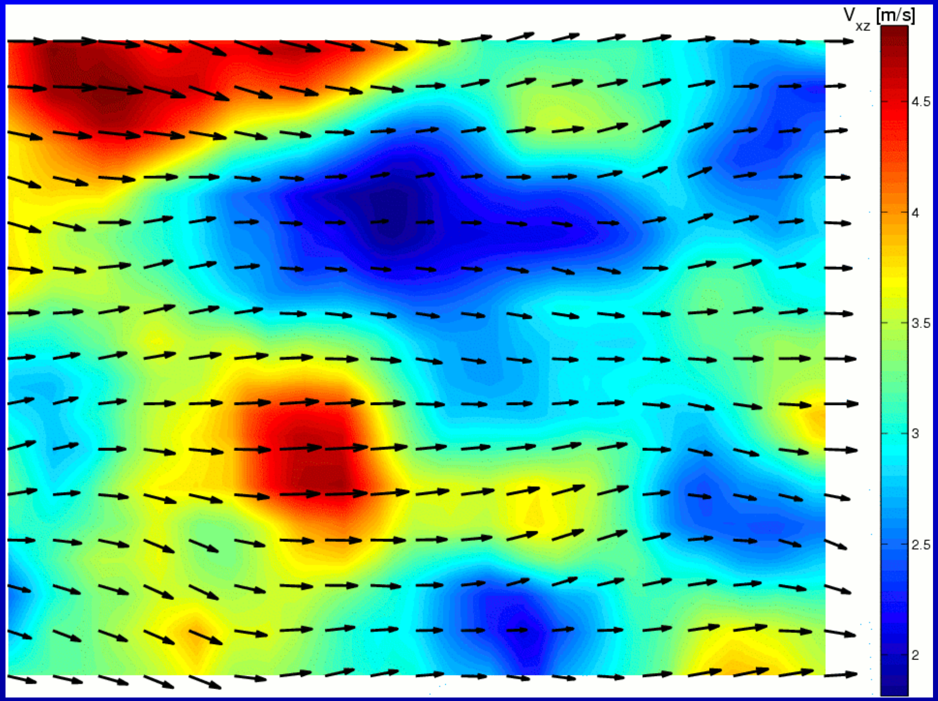


Position P2

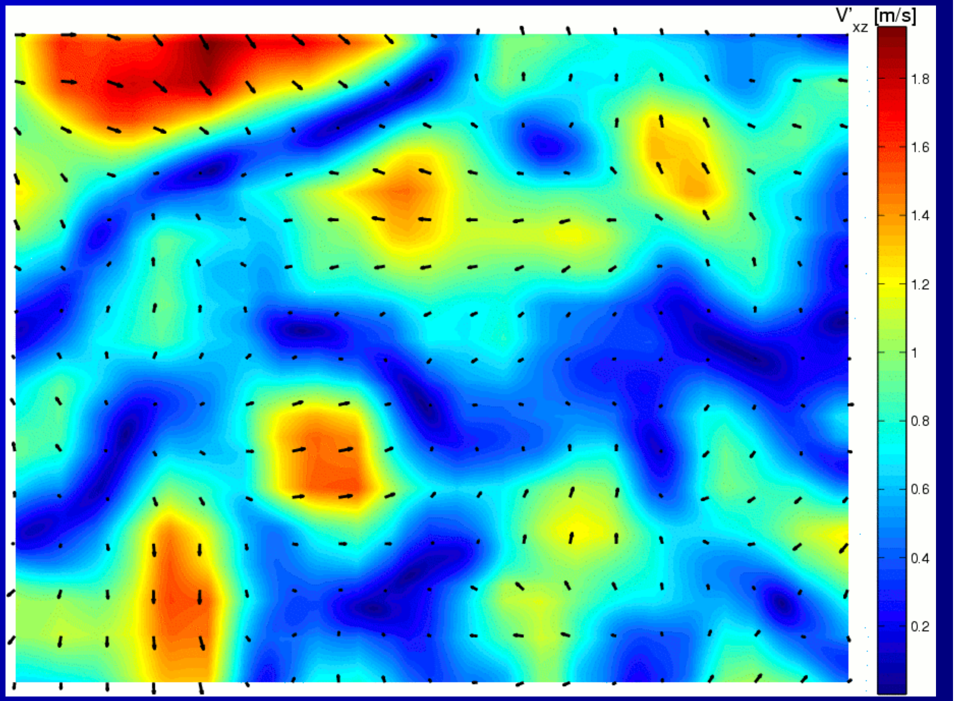
flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

Instantaneous velocity field and fluctuations field



velocity field



fluctuations field

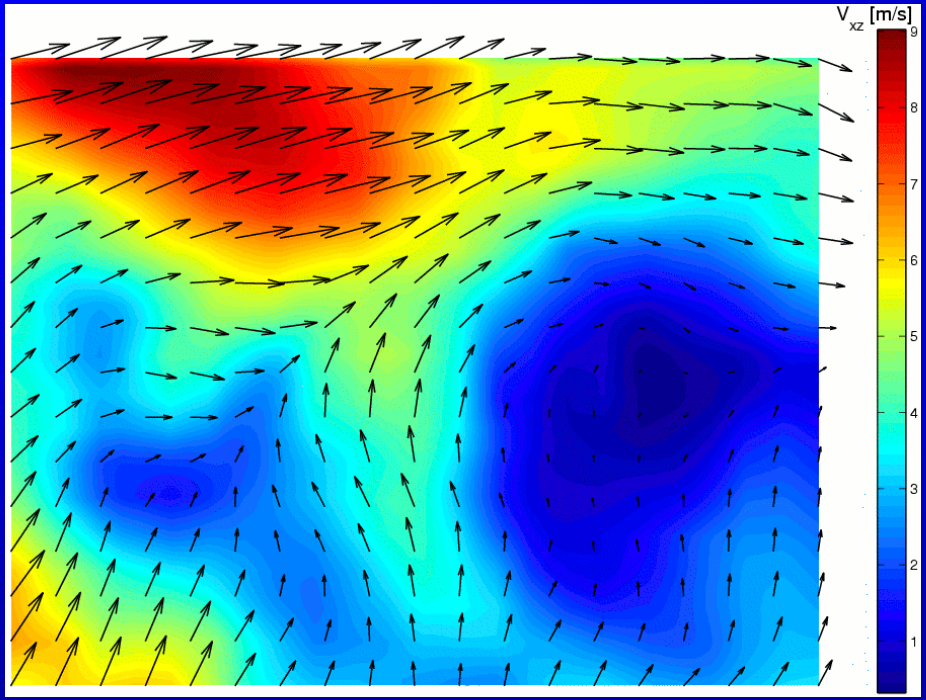
Position:

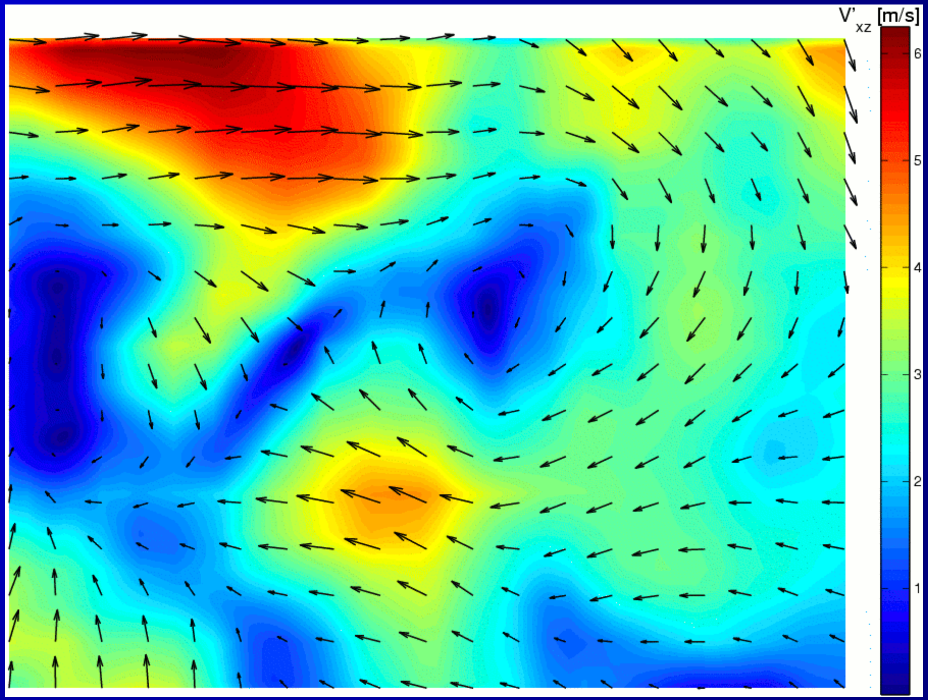
1mm behind processing element, 0.3mm below glass wall

flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

Instantaneous velocity field and fluctuations field





velocity field | **fluctuations field**

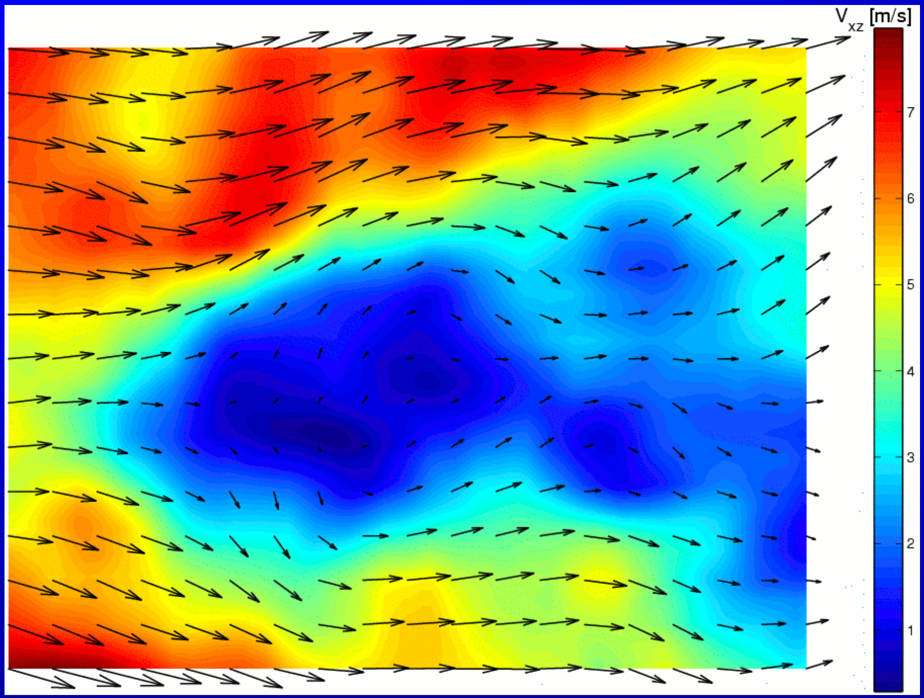
Position:

3mm behind processing element, 0.3mm below glass wall

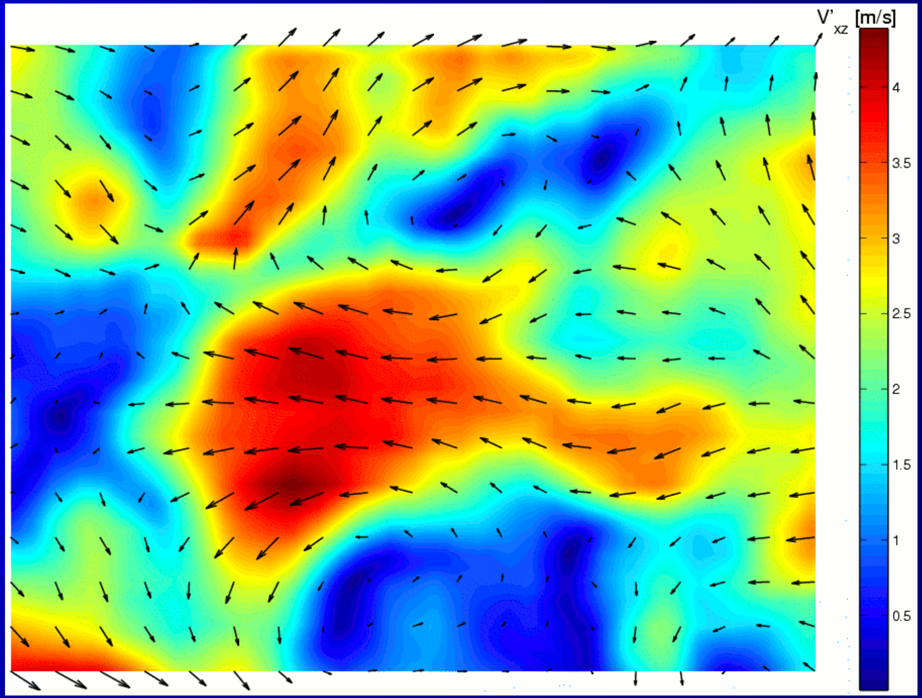
flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

Instantaneous velocity field and fluctuations field



velocity field



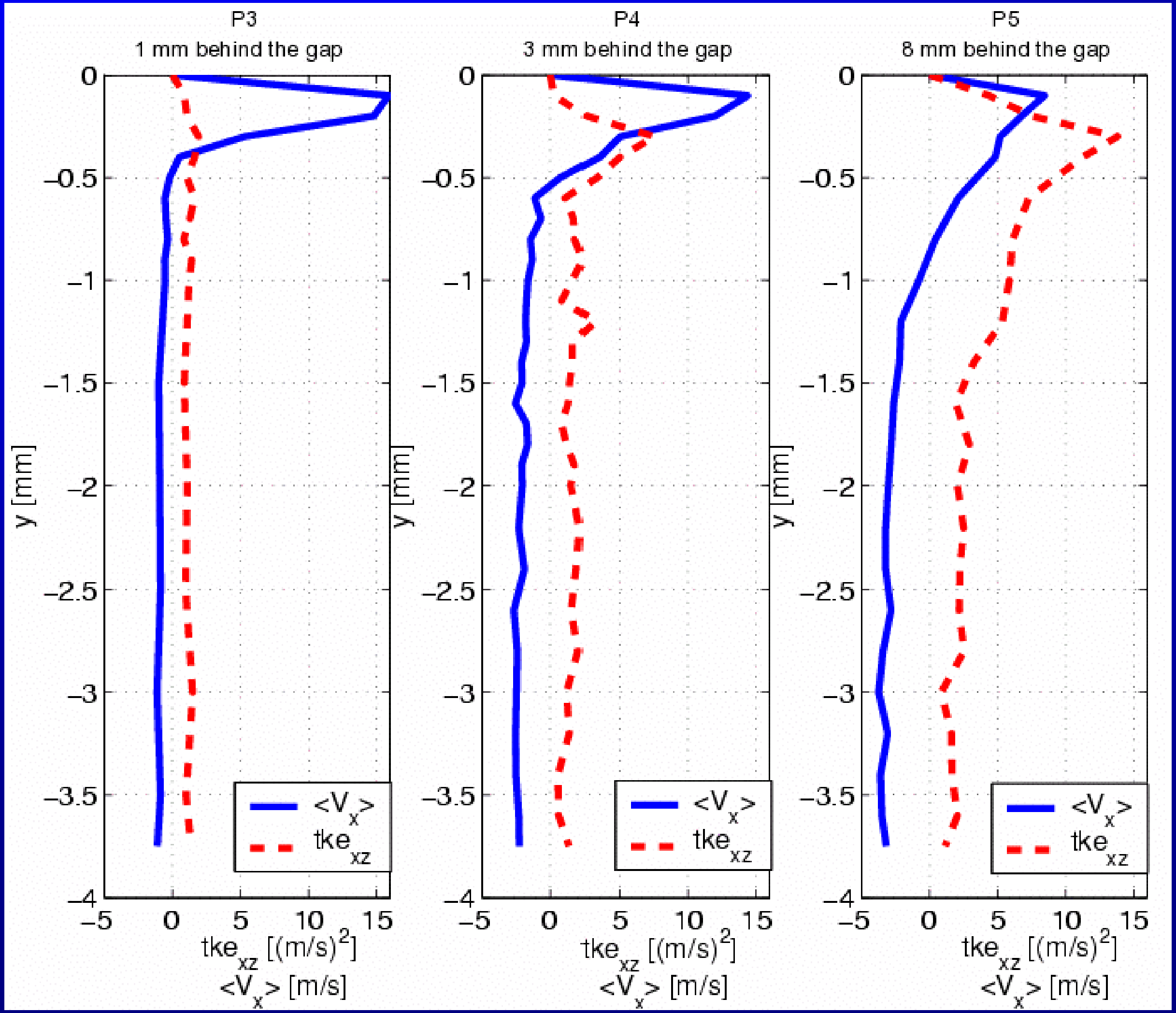
fluctuations field

Position:
8mm behind processing element, 0.3mm below glass wall

flow rate = 0.204 dm^3/s

Micro-PIV RESULTS

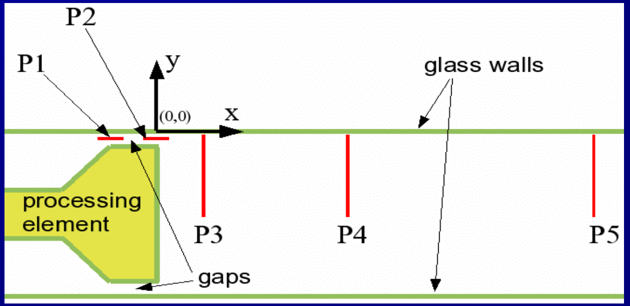
P3, P4 and P5 profiles of the X-Velocity and mean turbulent kinetic energy (xz)



$$V_x = \langle V_x \rangle + V'_x$$

$$V_z = \langle V_z \rangle + V'_z$$

$$tke_{xz} = \langle V'^2_x \rangle + \langle V'^2_z \rangle$$



Part II
Drops break-up visualization
RESULTS

Drops break-up visualization

Used geometry: G2 (emulsifier with transparent element)

Used materials:

1. de-ionized water + 10mM NaCl + S50 silicone oil (0.01)
2. de-ionized water + 10mM NaCl + S50 silicone oil (0.01) + 1%wt SDS
3. de-ionized water + 10mM NaCl + S500 silicone oil (0.01) + 1%wt SDS

Flow rate: $Q_2 = 0.204\ dm^3/s$

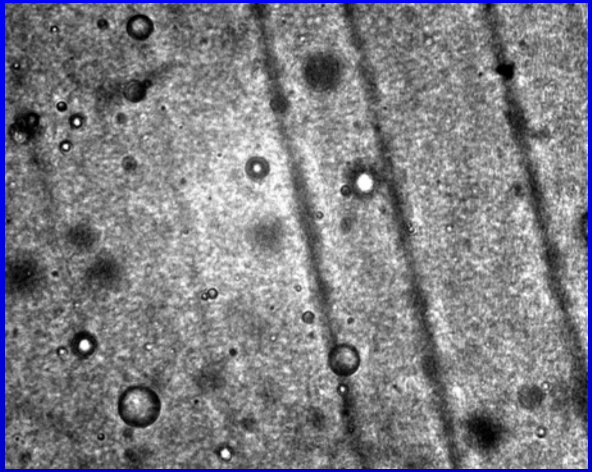
Used microscope lens: 10x/NA0.3/WD17.30mm

images width corresponds to 432μm

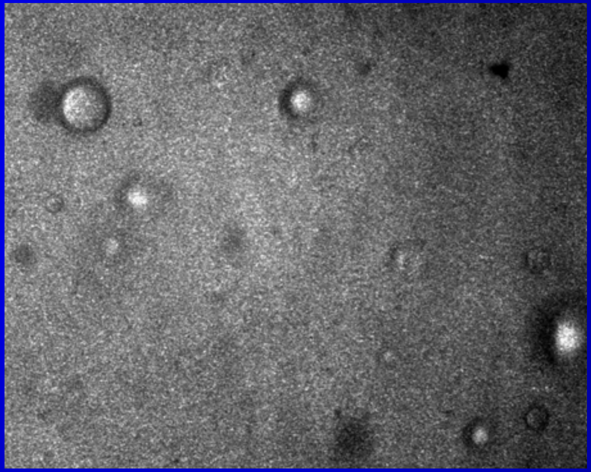
Interval time between images: 1μs or 5 μs

Position	Velocity V_d [m/s]	Comments
water + 10mM NaCl + S50 oil		
Gap	12.1	lack of oil-drops deformations
x = 0; y = - 0.3	10.8	lack of oil-drops deformations
x = 2; y = - 0.4	4.5	oil-drops deformations occurs
x = 5; y = - 0.4	6.7	lack of oil-drops deformations
water + 10mM NaCl + S50 oil + 1%wt SDS		
Gap	12.3	lack of oil-drops deformations
x = 2; y = 0.0	10.3	lack of oil-drops deformations
x = 2; y = - 0.1	10.9	lack of oil-drops deformations
x = 2; y = - 0.2	9.7	oil-drops deformations occurs
x = 2; y = - 0.4	4.7	oil-drops deformations occurs
water + 10mM NaCl + S500 oil + 1%wt SDS		
Gap	12.6	lack of oil-drops deformations
x = 0; y = - 0.2	11.3	lack of oil-drops deformations
x = 2; y = - 0.2	10.5	oil-drops deformations occurs

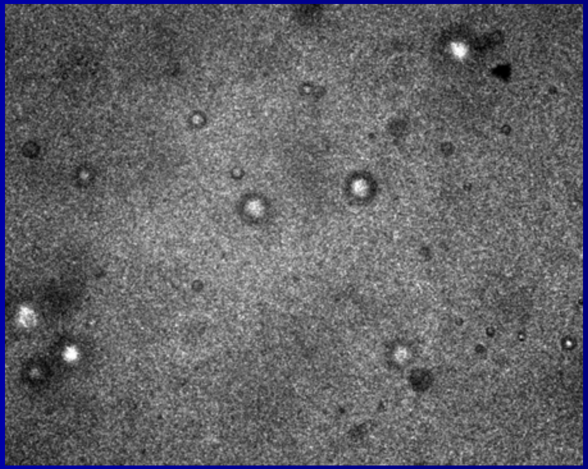
Drops break-up visualization results



drops in the gap
v_d=12.1m/s



drops just behind processing element
v_d=10.8m/s



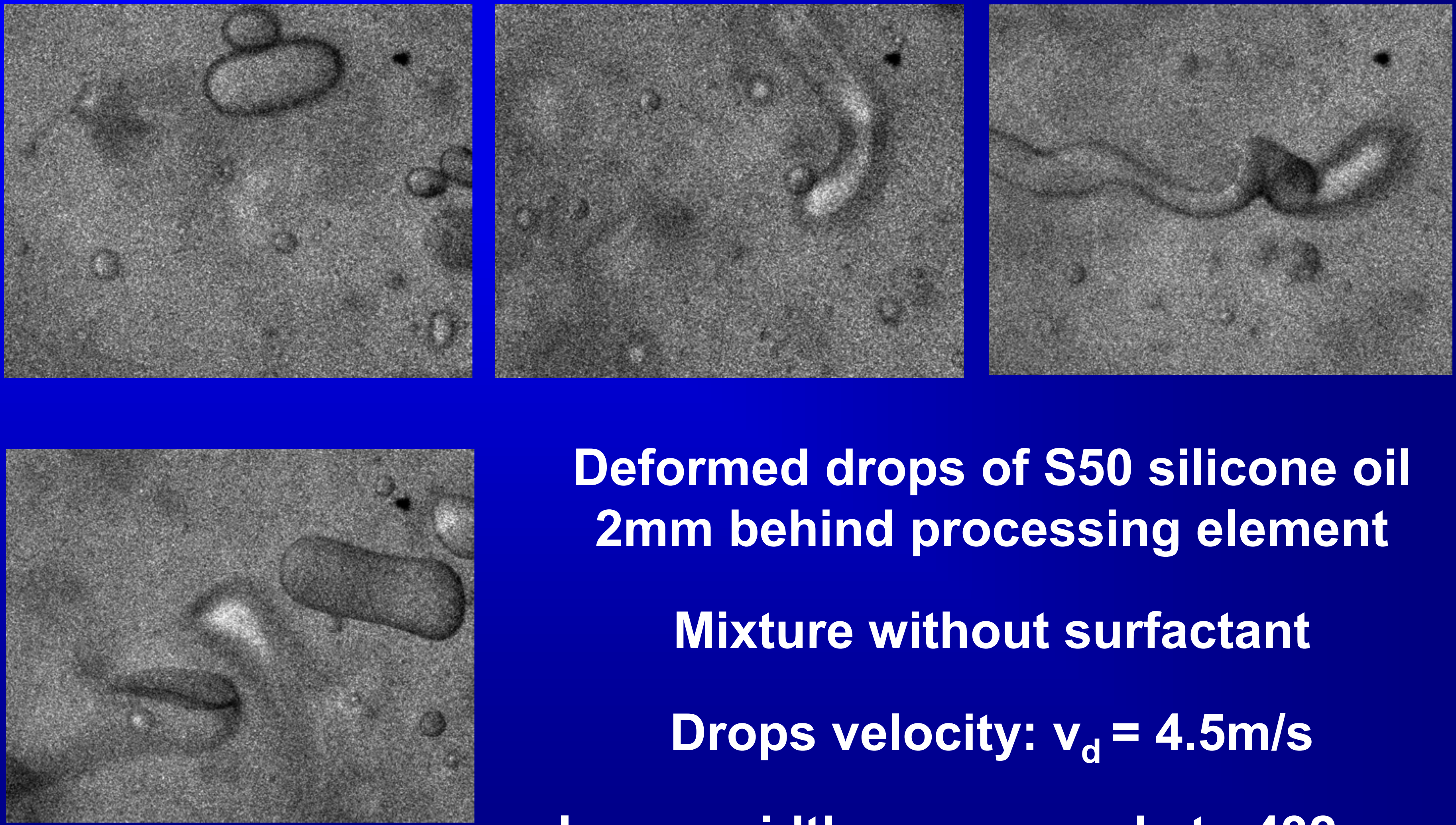
drops 5mm behind processing element
v_d=6.7m/s

Non-deformed drops of S50 silicone oil

Mixture without surfactant

Image width corresponds to 432 µm

Drops break-up visualization results



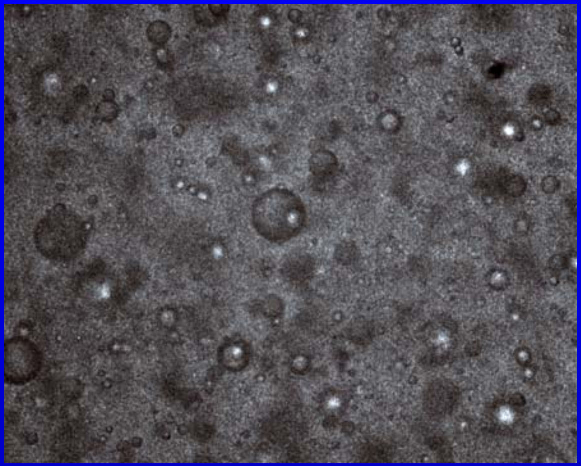
Deformed drops of S50 silicone oil 2mm behind processing element

Mixture without surfactant

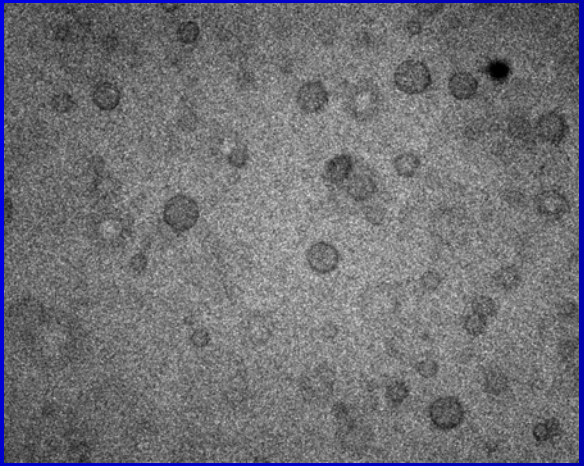
Drops velocity: $v_d = 4.5m/s$

Image width corresponds to 432 µm

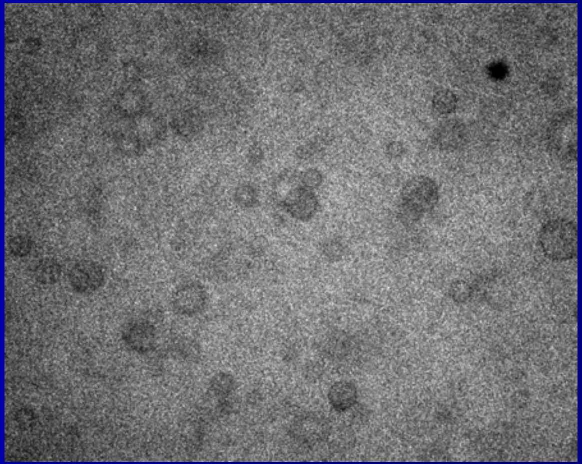
Drops break-up visualization results



drops in the gap
v_d=12.3 m/s



drops 2mm behind processing element just below wall
v_d=10.3 m/s



drops 2mm behind processing element 0.1mm below wall
v_d=10.9 m/s

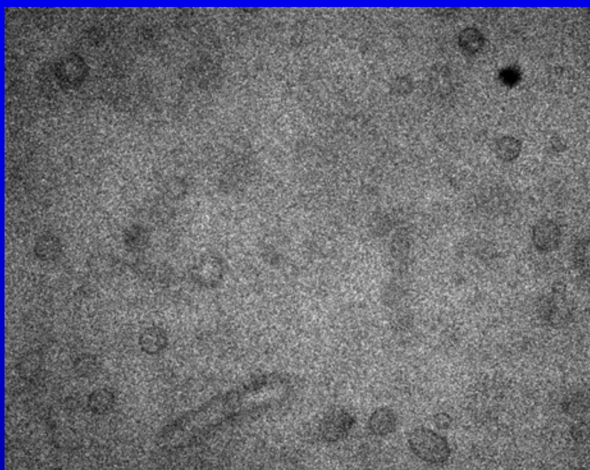
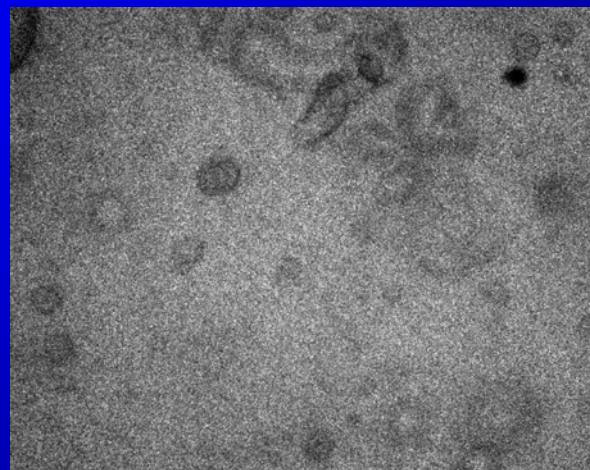
Non-deformed drops of S50 silicone oil

Mixture with 1%wt SDS surfactant

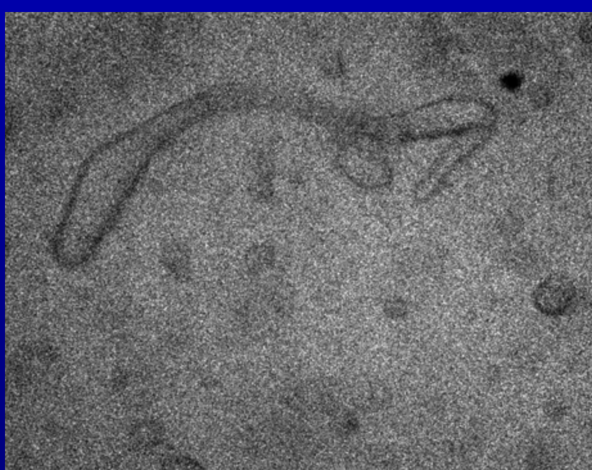
Image width corresponds to 432 μm

Drops break-up visualization results

Deformed drops of S50 silicone oil
Mixture with 1%wt SDS surfactant
Image width corresponds to 432 μm

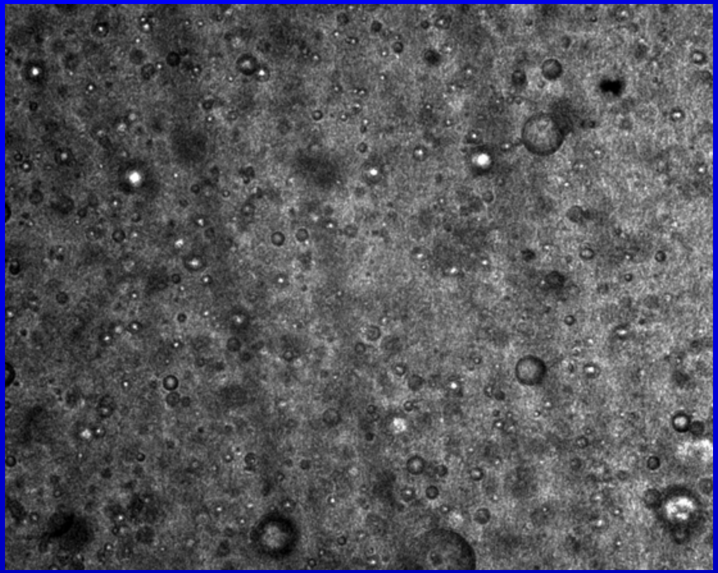



drops 2mm behind processing element and 0.2mm below wall
v_d=9.7 m/s

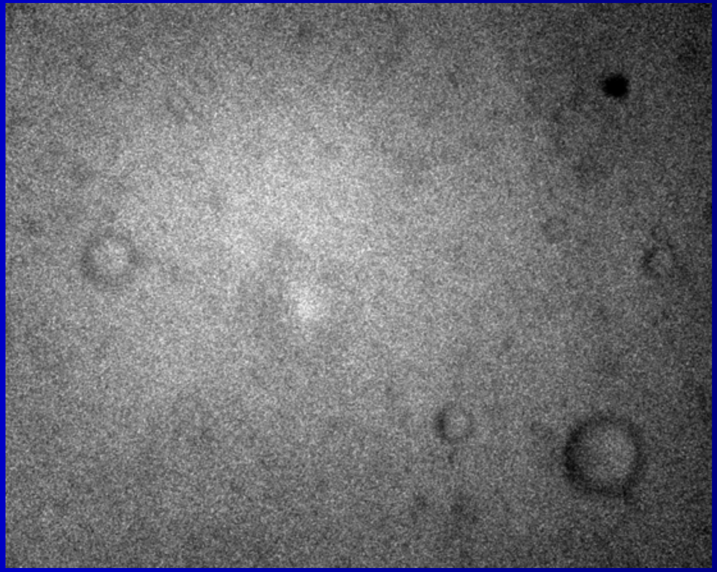



drops 2mm behind processing element and 0.4mm below wall
v_d=4.7 m/s

Drops break-up visualization results



drops in the gap
v_d=12.6 m/s



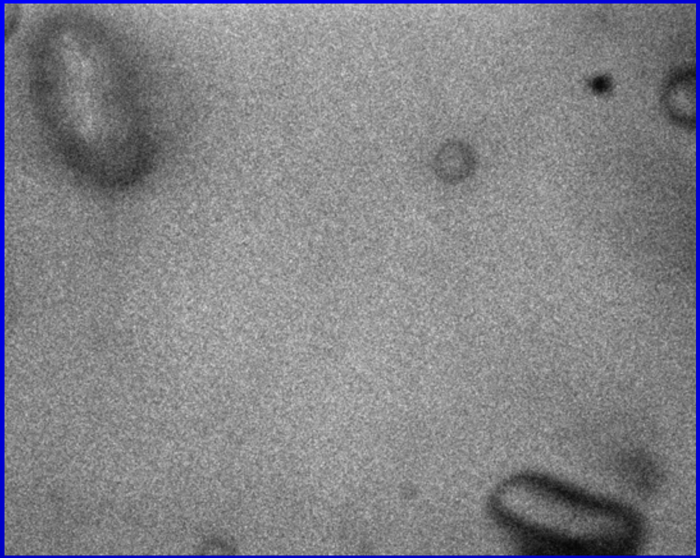
drops just behind
processing element
0.2mm below wall
v_d=11.3 m/s

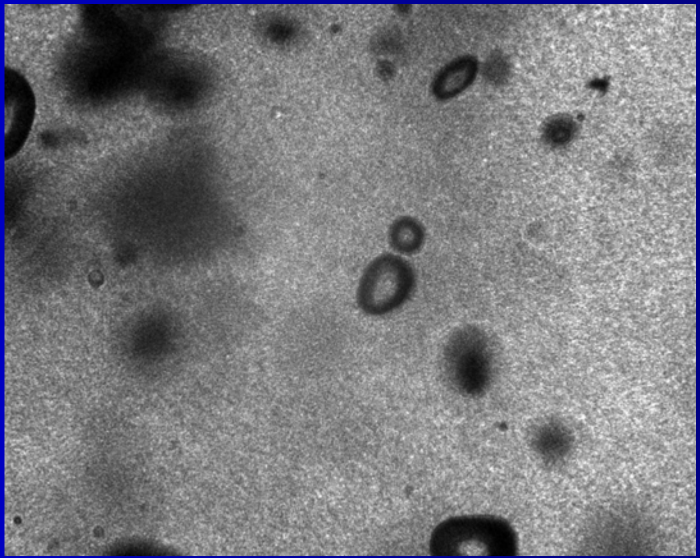
Non-deformed drops of S500 silicone oil

Mixture with 1%wt SDS surfactant

Image width corresponds to 432 µm

Drops break-up visualization results

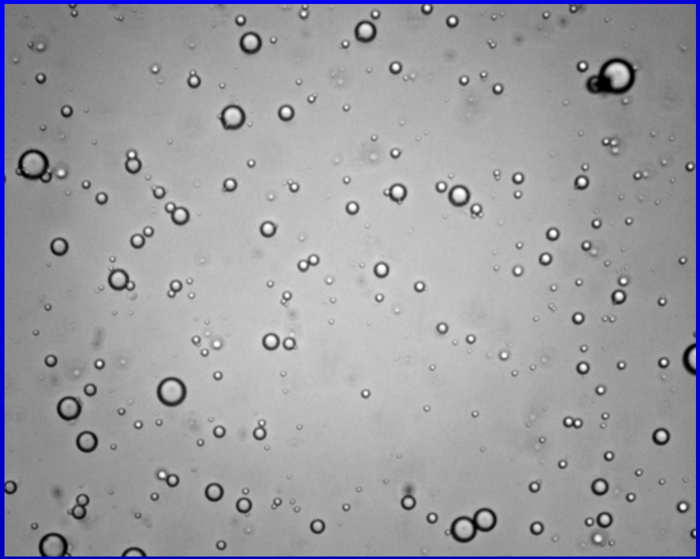




drops 2mm behind processing element
And 0.2mm below wall
v_d=10.5 m/s

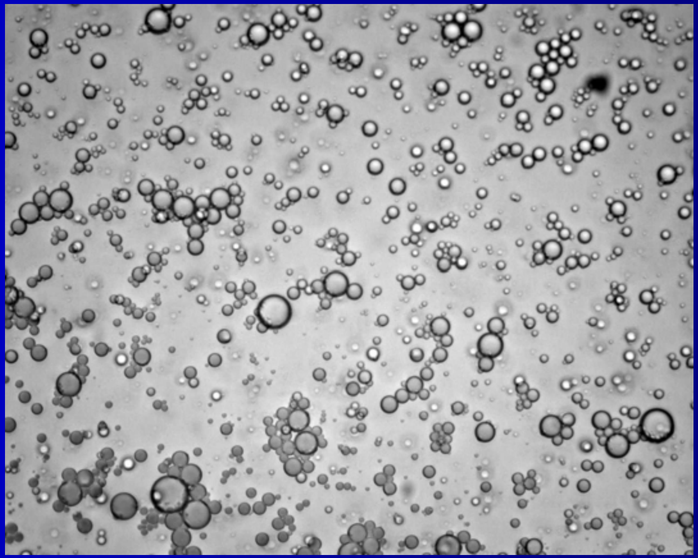
Deformed drops of S500 silicone oil
Mixture with 1%wt SDS surfactant
Image width corresponds to 432 µm

Drops break-up visualization results



S50 silicone oil
+ 1%wt SDS

mean drops size: 10.1 µm



S500 silicone oil
+ 1%wt SDS

mean drops size: 20.7 µm

Motionless emulsion observer under microscope

Image width corresponds to 432 µm

Part III

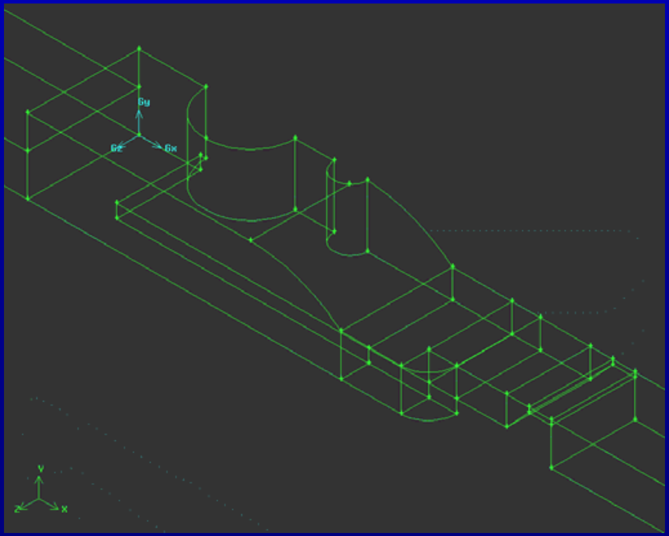
Numerical simulation

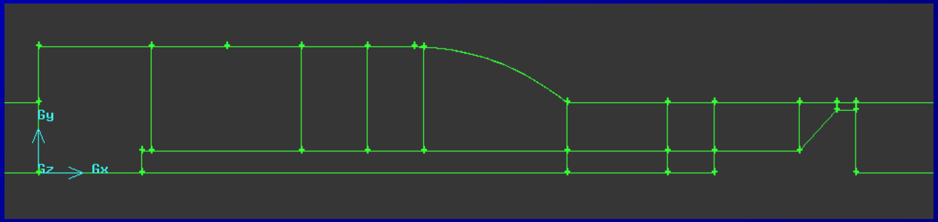
RESULTS

NUMERICAL SIMULATION

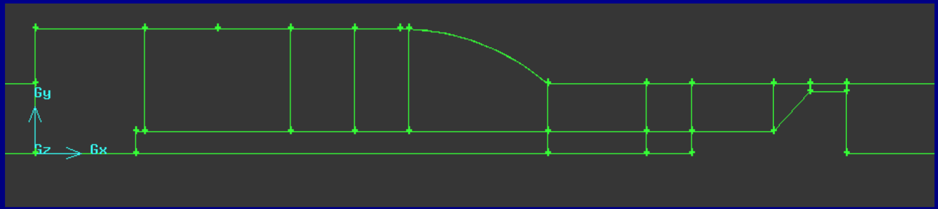
Numerical simulation was done using two geometries:

- G1 – one quarter of the model with non-transparent processing element
- G1v – full 3D geometry of the model with non-transparent processing element
- G2 – one quarter of the model with transparent processing element





G1



G2

NUMERICAL SIMULATION

CFD Modelling Using Fluent 6.2

Numerical simulation was done in following steps:

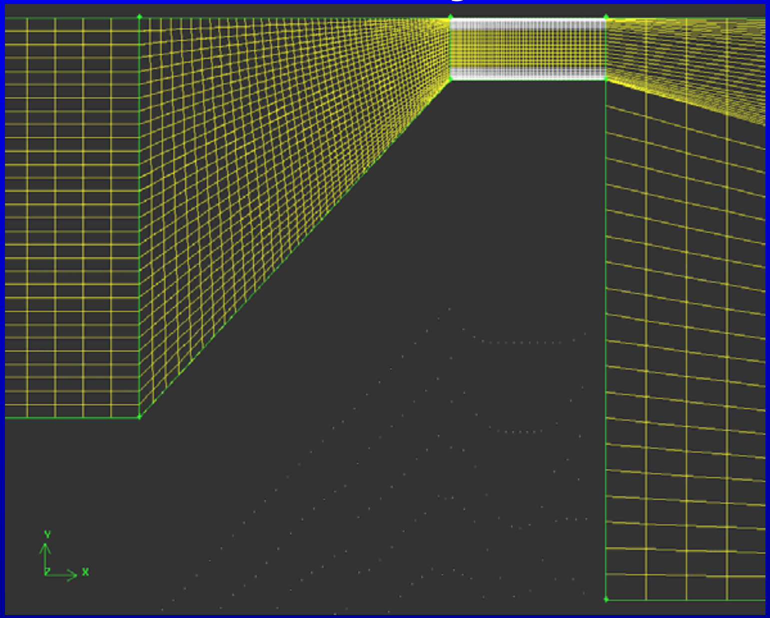
1. 3D unsteady laminar flow
2. 3D steady flow, turbulence model: k-ε with Standard Wall Function
3. 3D steady flow, turbulence model: k-ε with Enhanced Wall Treatment
4. + grid adaptation based on the gradient of velocity magnitude
5. + grid adaptation based on the Y_{plus} value

NUMERICAL SIMULATION

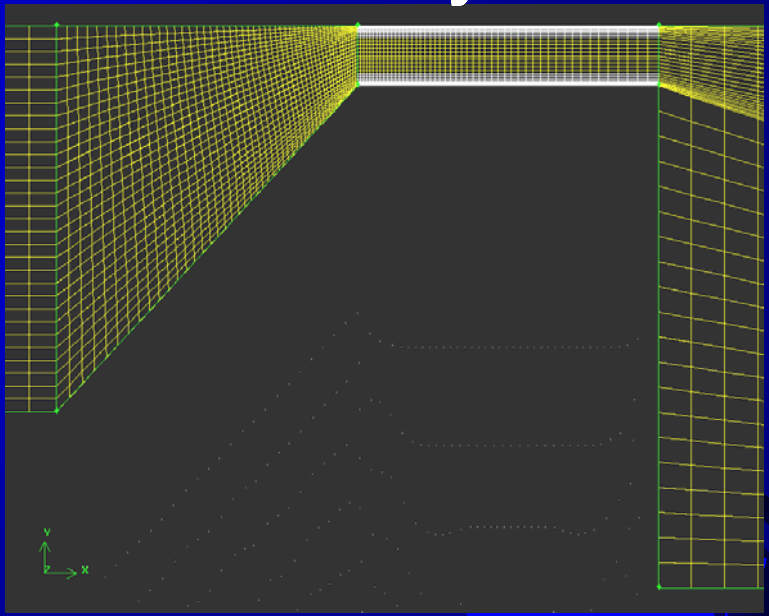
CFD Modelling Using Fluent 6.2

Mesh in the vicinity of the processing element for

Geometry G1



Geometry G2



Generated mesh

Mesh size: 457473 cells, 1189395 faces, 302334 nodes

NUMERICAL SIMULATION

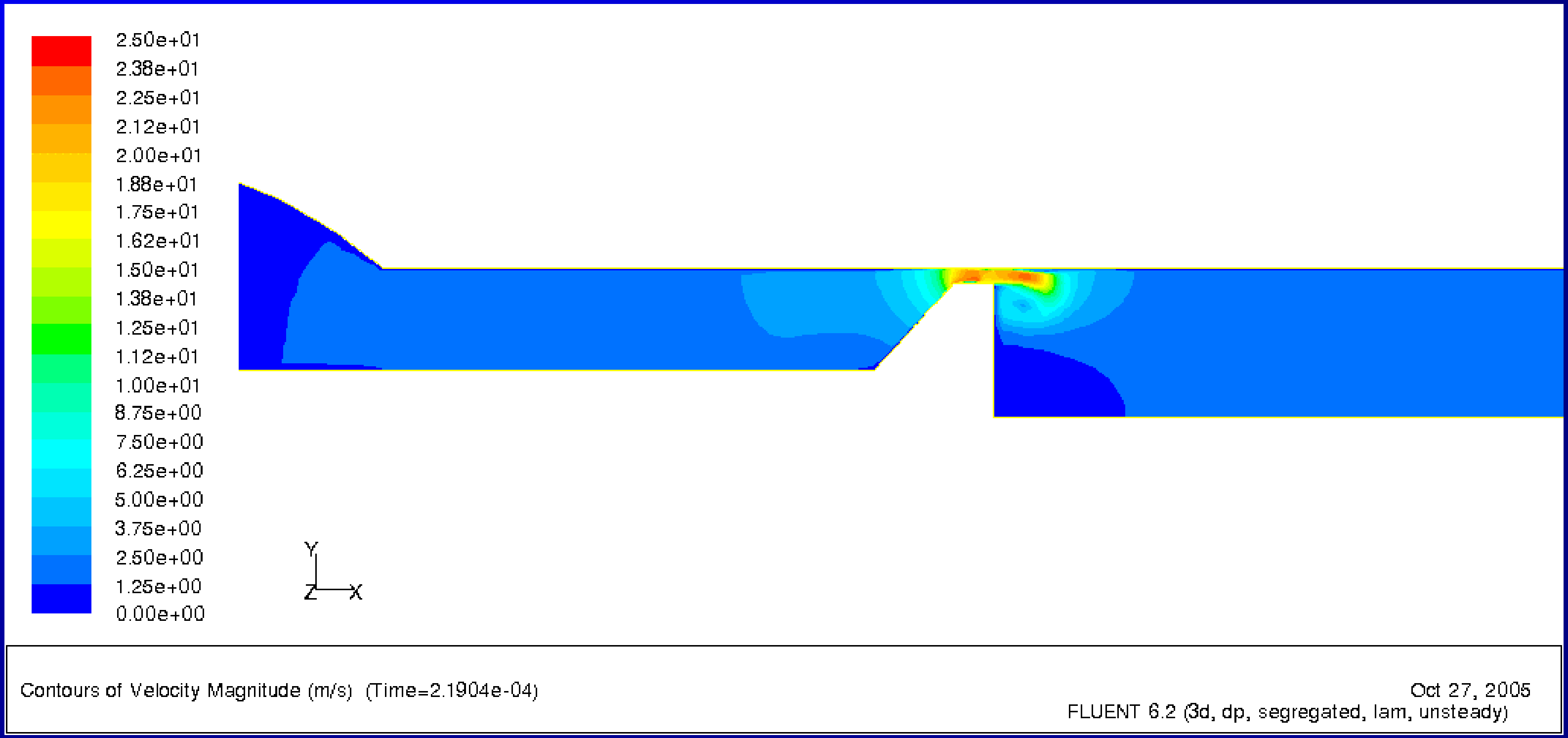
Laminar – unsteady simulations was done using:

Used package and version	Fluent 6.2.16, double precision, segregated
Flow type	three-dimensional, laminar, unsteady, incompressible
Flowed medium	water, constant density ρ= 998.2 *kg/m³* and viscosity μ=0.001003 *kg/ms*
Mass flow-rate	0.204 *kg/s* or 0.051 *kg/s*
Inlet	mass-flow inlet
Outlet	pressure outlet
Discretization Scheme	Pressure: standard Momentum: Second Order Upwind
Time Step Size	1e^{-7} s
Geometry and grid	- one quarter of the model geometry (G1); 457473 cells - whole model geometry (G1v); 1745830 cells

NUMERICAL SIMULATION

Contours of velocity magnitude

Geometry G1 – non-transparent processing element



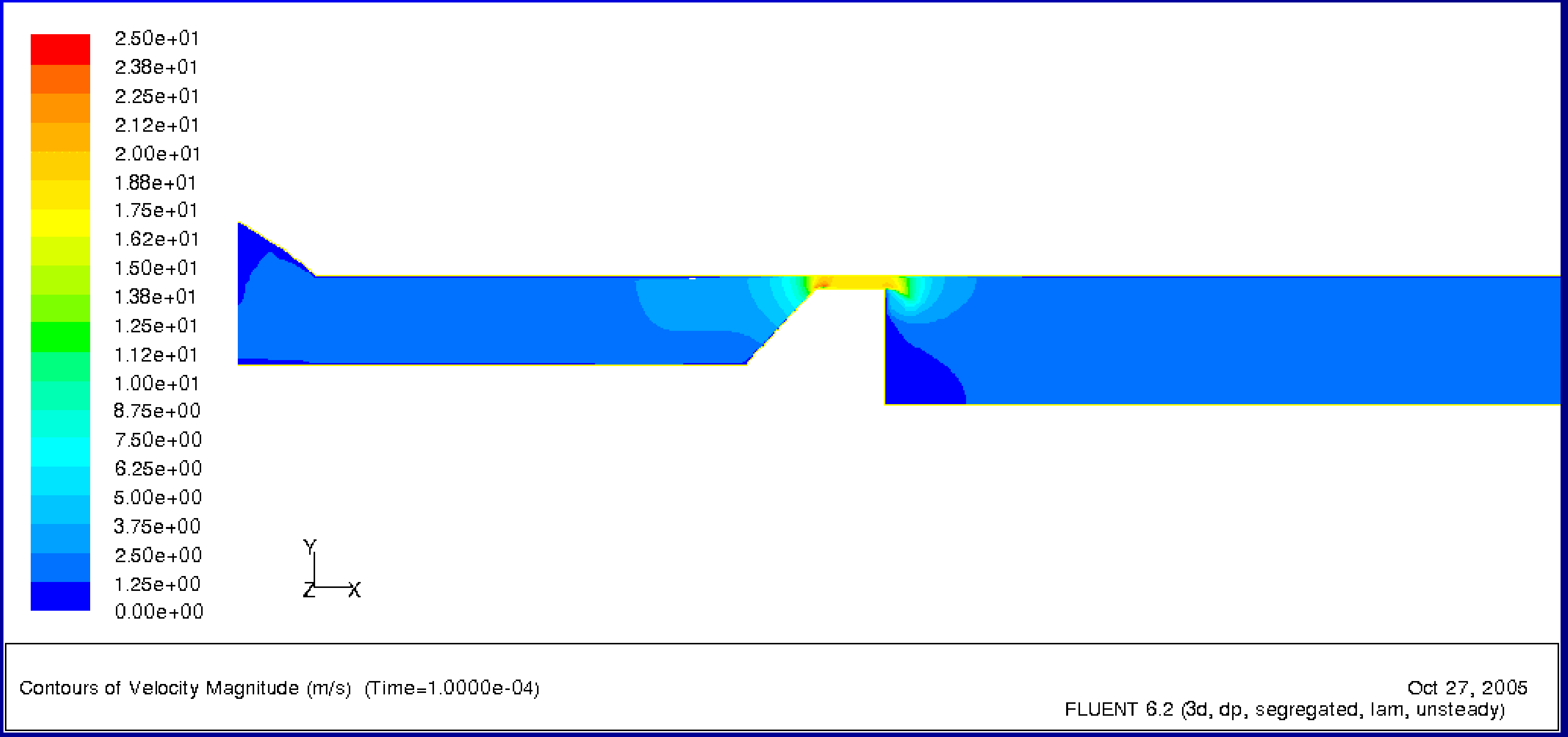
Laminar – unsteady flow, $Q_2 = 0.204\ dm^3/s$

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

NUMERICAL SIMULATION

Contours of velocity magnitude

Geometry G2 – transparent processing element



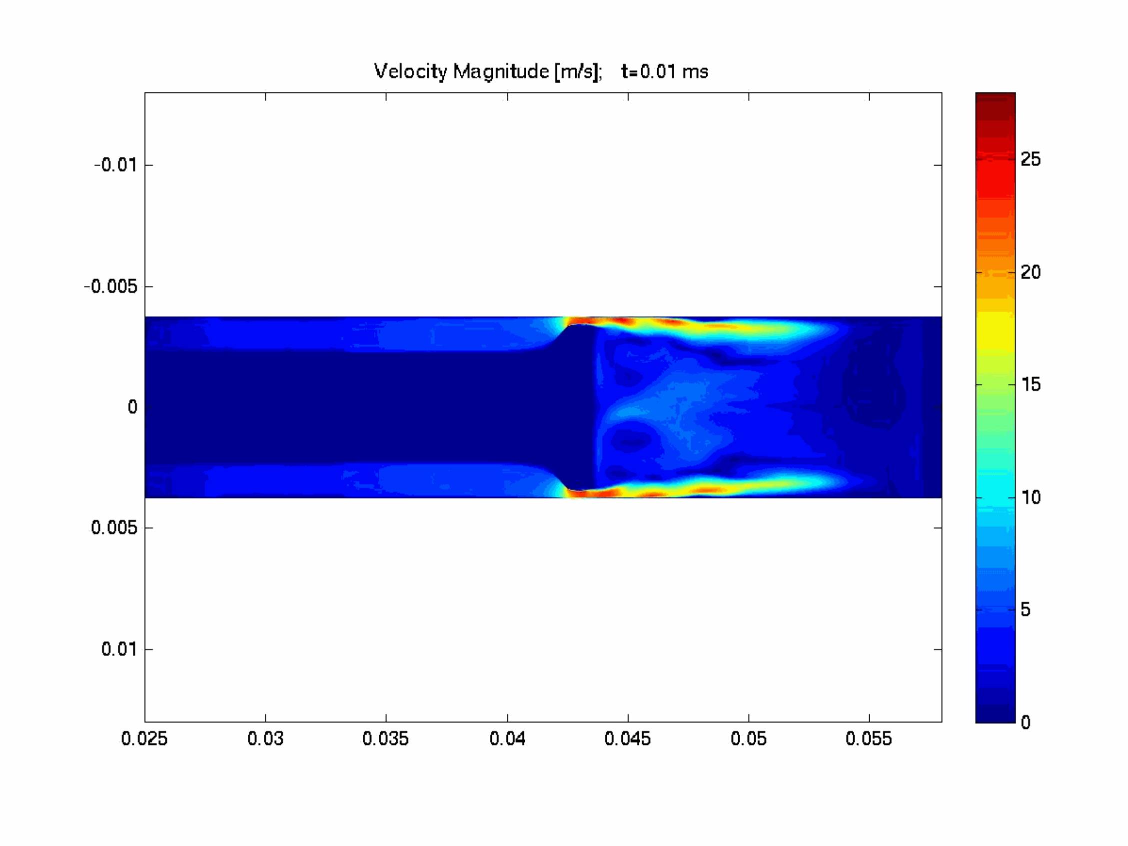
Laminar – unsteady flow, $Q_2 = 0.204\ dm^3/s$

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

NUMERICAL SIMULATION

Contours of averaged velocity magnitude

Geometry G1v – non-transparent processing element



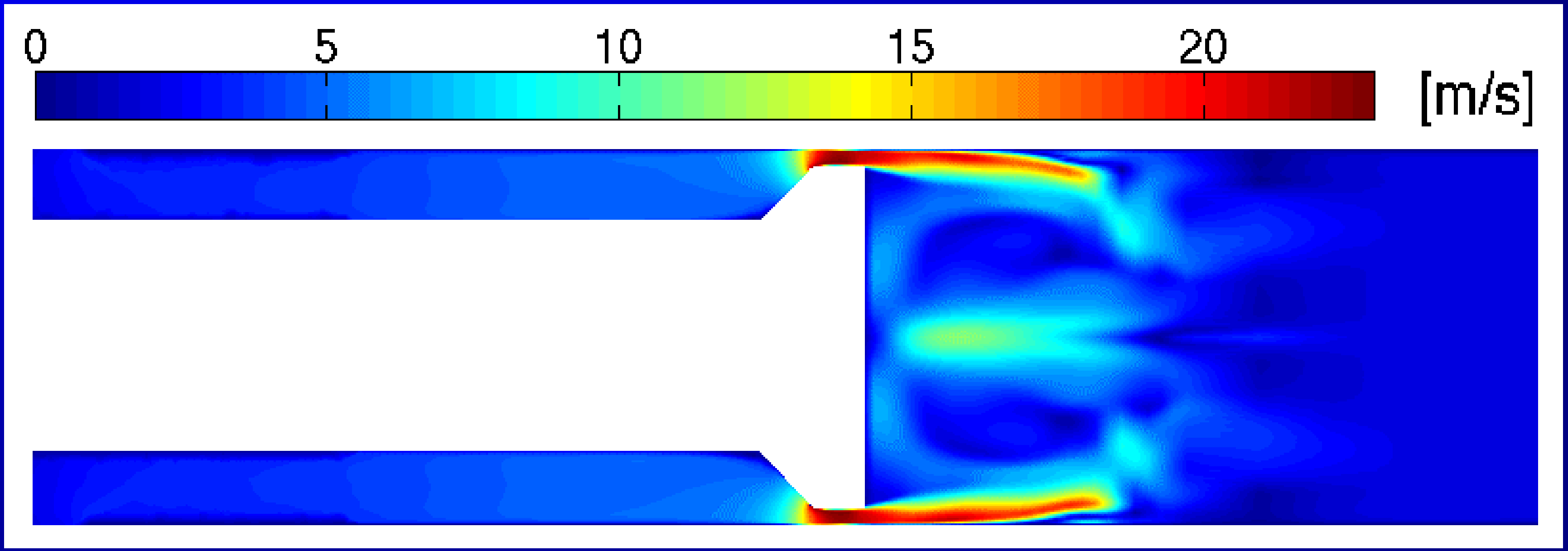
Laminar – unsteady flow, $Q_2 = 0.204\ dm^3/s$

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

NUMERICAL SIMULATION

Contours of averaged velocity magnitude

Geometry G1v – non-transparent processing element



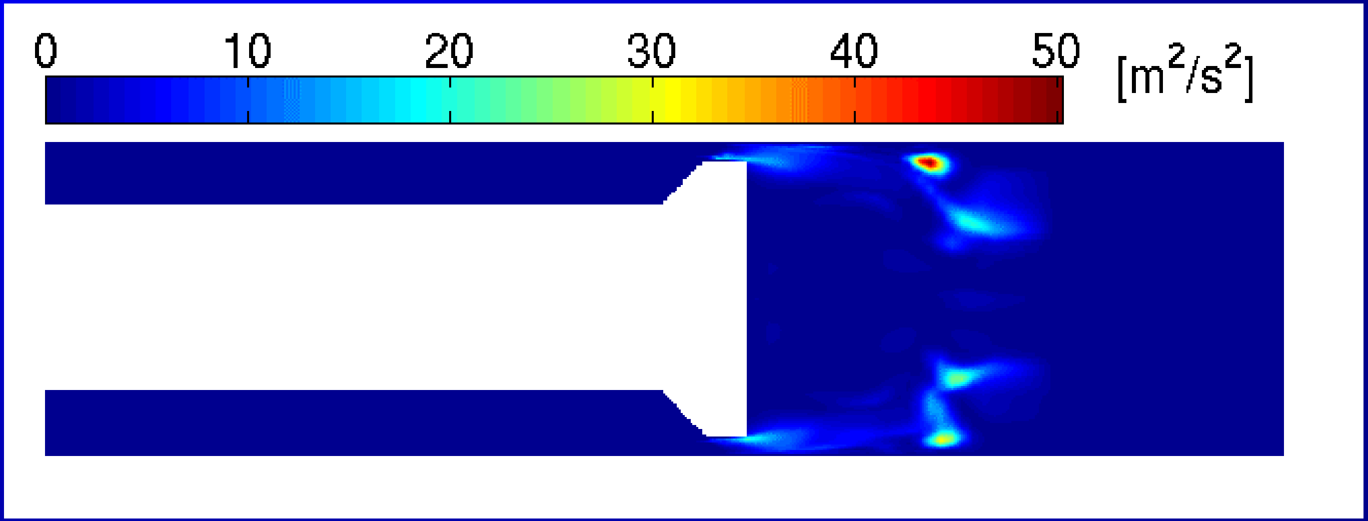
Laminar – unsteady flow, $Q_2 = 0.204\ dm^3/s$

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

NUMERICAL SIMULATION

Contours of mean square value of the velocity fluctuations

Geometry G1v – non-transparent processing element



$$tke_{xz} = \left\langle V_x'^2 \right\rangle + \left\langle V_z'^2 \right\rangle$$

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

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

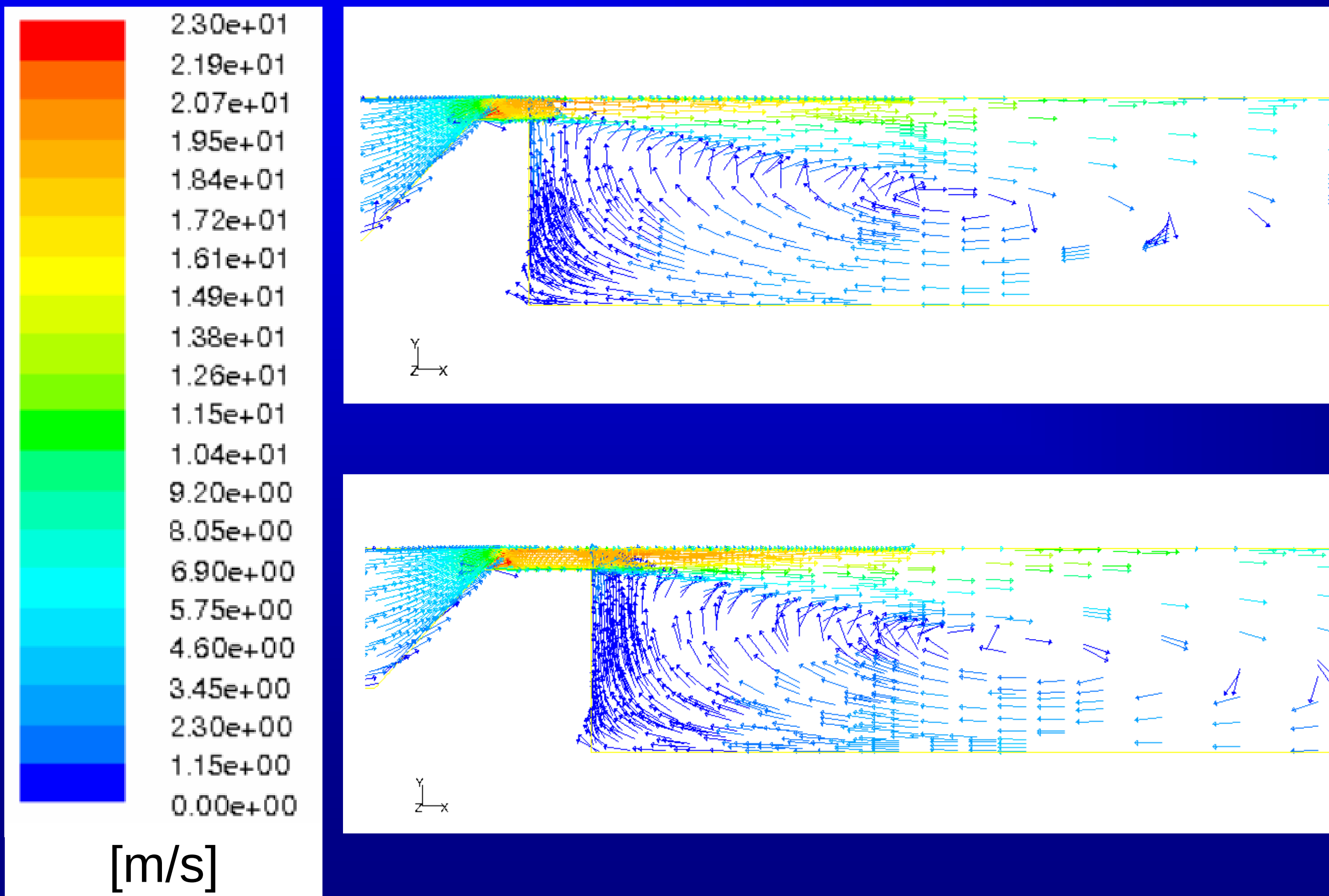
Final simulations was done for geometry G1 and G2 using:

Used package and version	Fluent 6.2.16, double precision, segregated
Flow type	three-dimensional, steady, incompressible
Viscous	standard k – ε turbulence model with Enhanced Wall Treatment
Mass flow-rate	0.051 *kg/s* (one quarter of Q=0.204 *kg/s*)
Inlet	mass-flow inlet turbulence intensity 12.1% hydraulic diameter 0.0109
Outlet	pressure outlet turbulence intensity 12.1% hydraulic diameter 0.0109
Grid Adaptation	dynamic adaptation based on velocity magnitude gradient: refine threshold 0.0001, interval: 20 iterations Y_{plus}: allowed value 1 – 2

NUMERICAL SIMULATION

Velocity vectors in the vicinity of the processing element

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



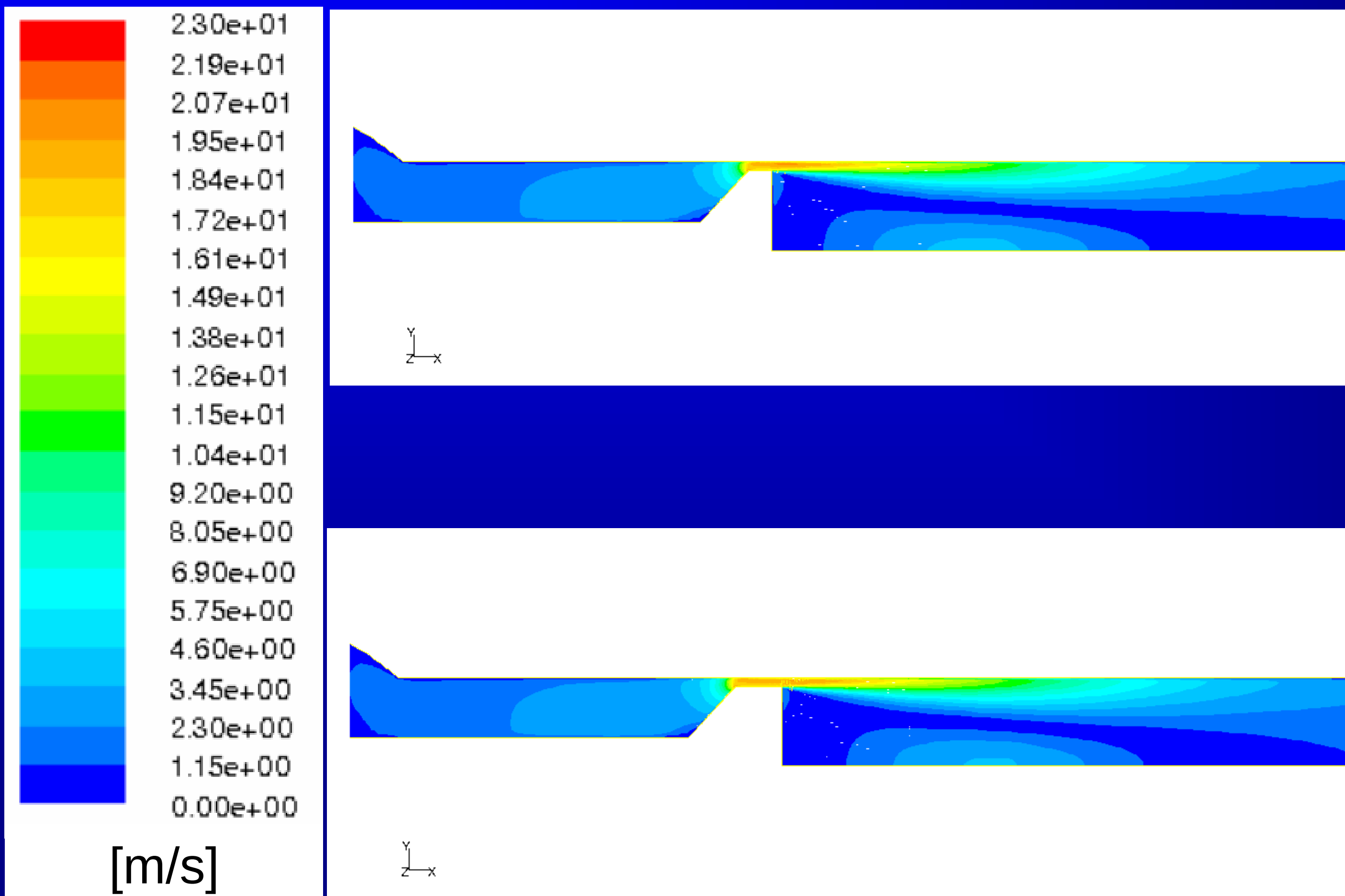
Geometry G1

Geometry G2

NUMERICAL SIMULATION

Contours of velocity magnitude

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



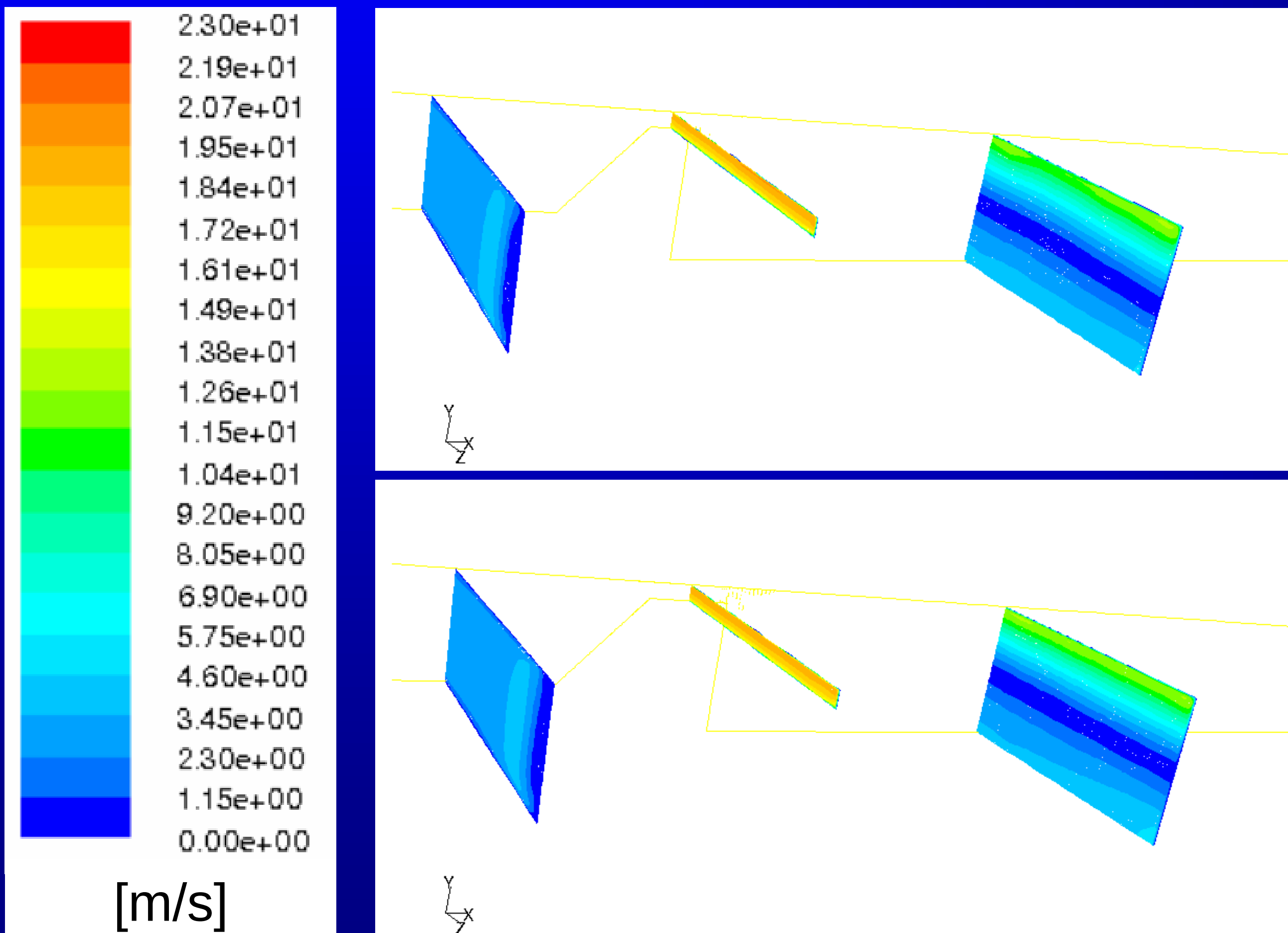
Geometry G1

Geometry G2

NUMERICAL SIMULATION

Contours of velocity magnitude – selected cross-sections

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



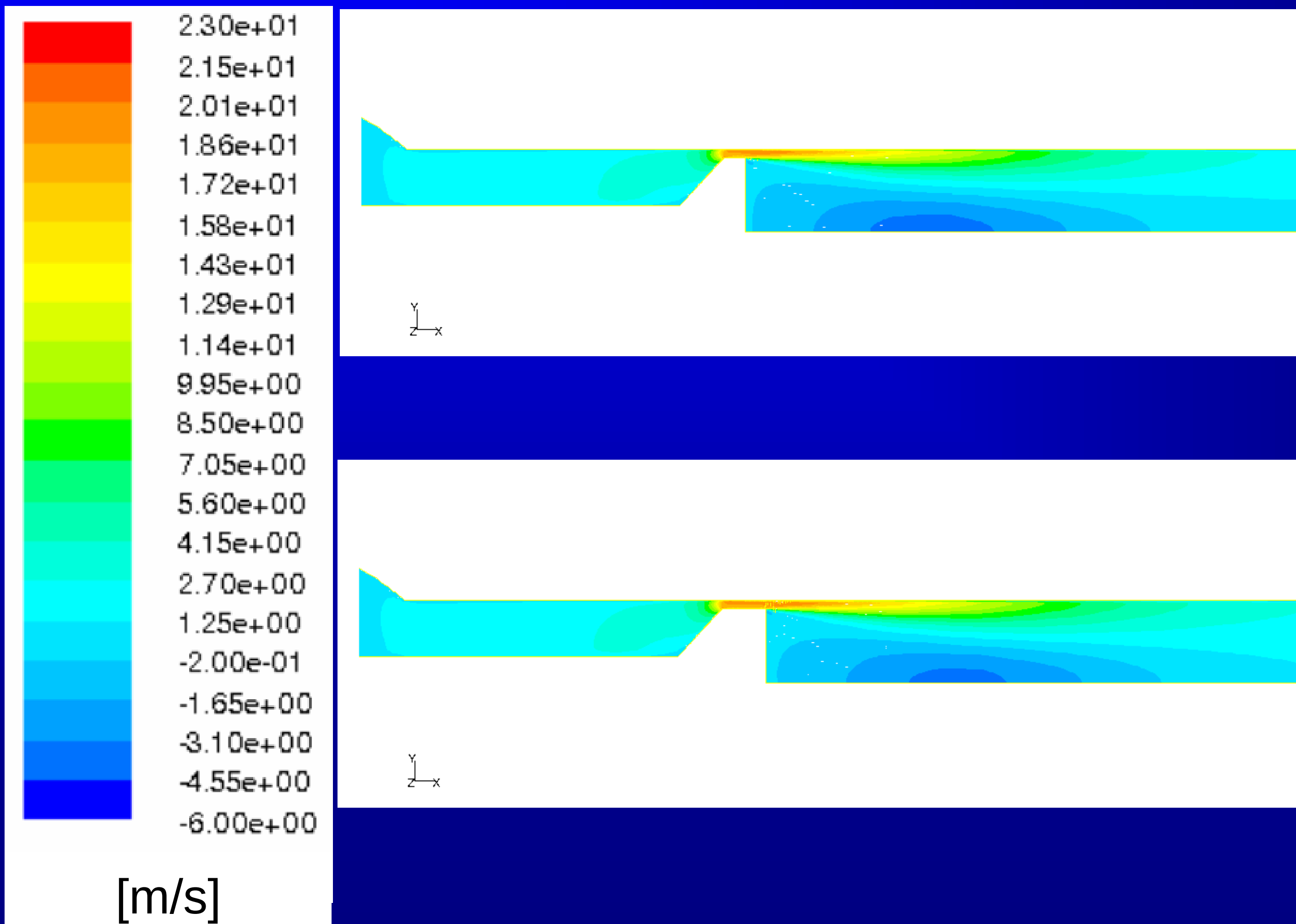
Geometry G1

Geometry G2

NUMERICAL SIMULATION

Contours of velocity x-component

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



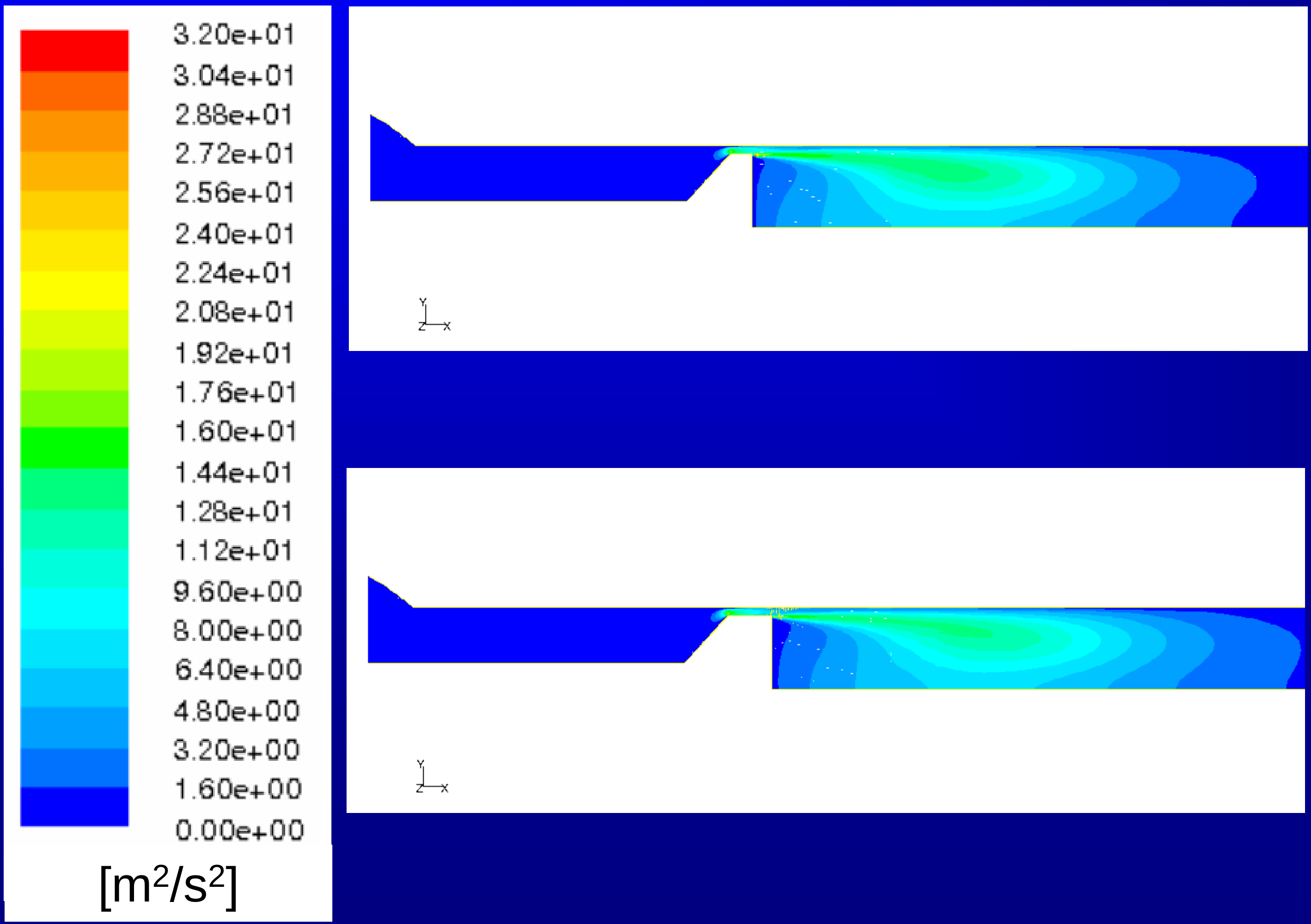
Geometry G1

Geometry G2

NUMERICAL SIMULATION

Contours of turbulent kinetic energy

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



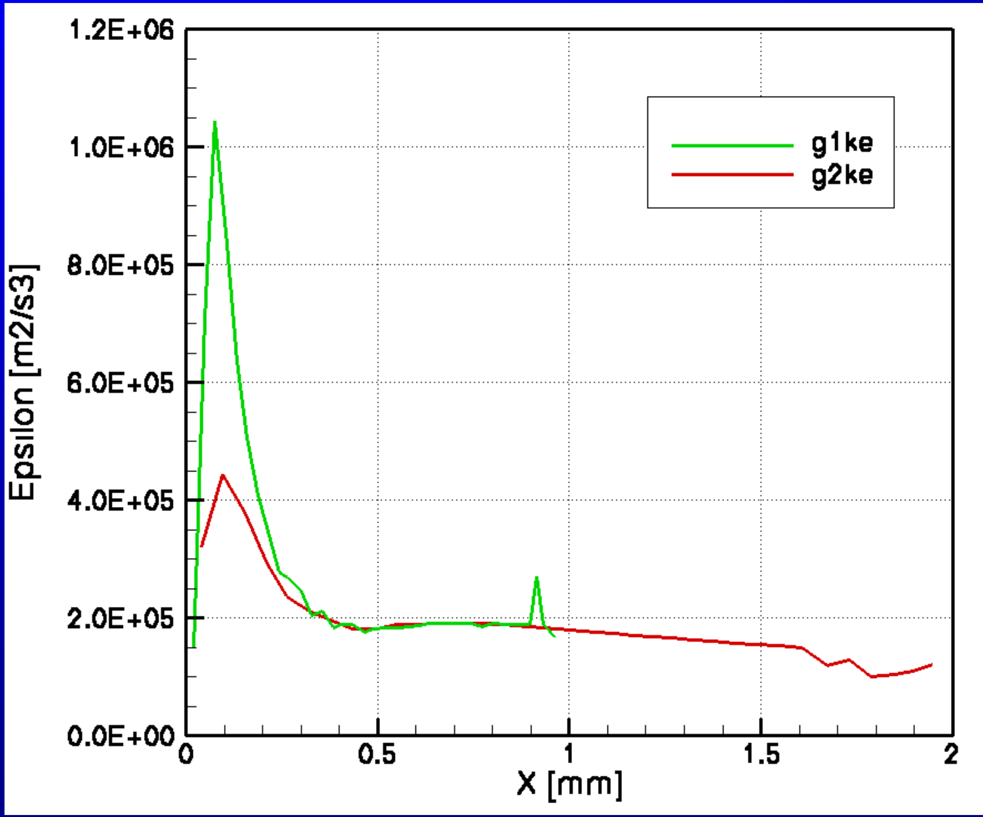
Geometry G1

Geometry G2

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 dm^3/s



g1ke – non-transparent

g2ke – transparent

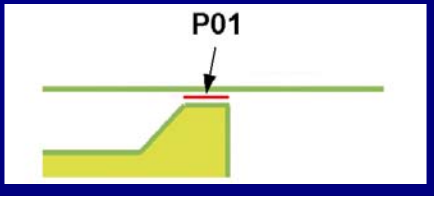
processing element

***Epsilon* averaged over whole gap:**

$$\varepsilon^{avg}_{g1ke} = 3.453 \cdot 10^5 \, m^2 / s^3$$

$$\varepsilon^{avg}_{g2ke} = 2.011 \cdot 10^5 \, m^2 / s^3$$

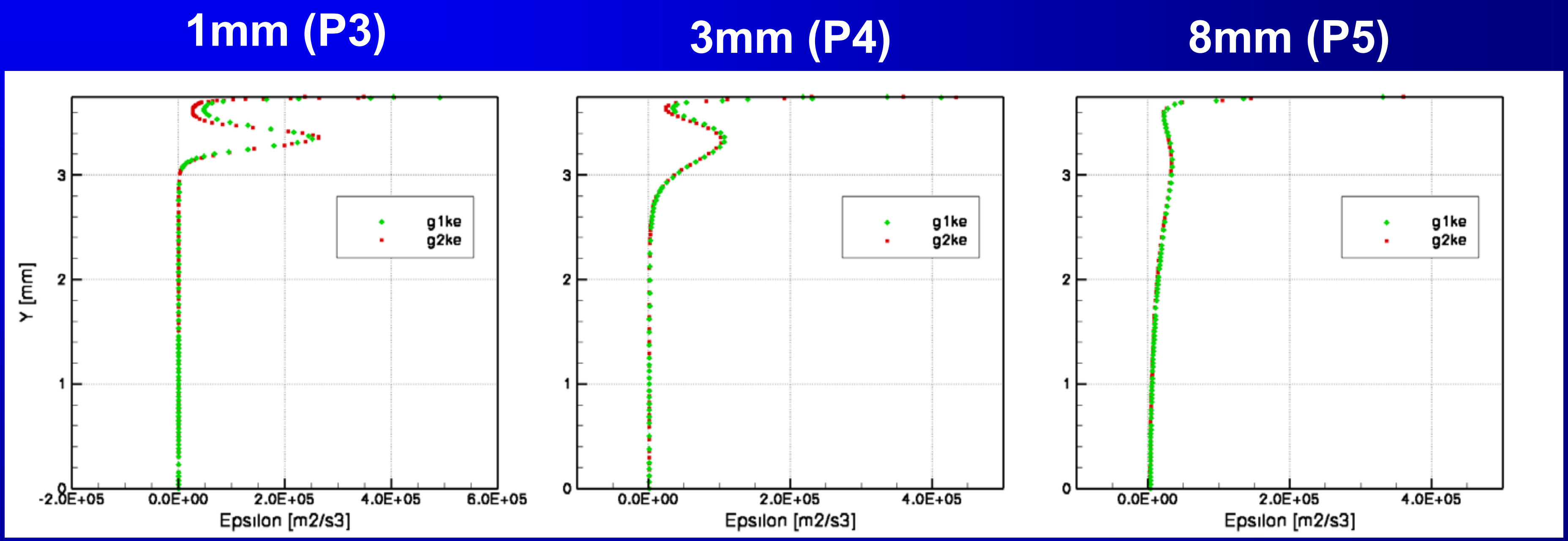
k-ε model + Enhanced Wall Treatment, geometryG1; Q_2 = 0.204 dm^3/s



NUMERICAL SIMULATION

Vertical profiles of Turbulent Dissipation Rate

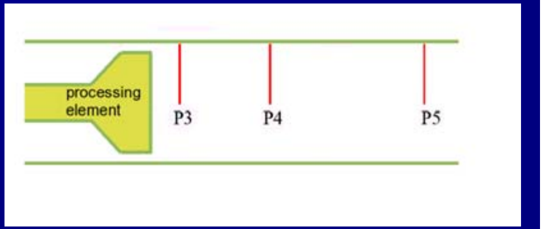
k-ε model + Enhanced Wall Treatment, $Q_2 = 0.204\ dm^3/s$



behind processing element

g1ke – non-transparent processing element

g2ke – transparent processing element

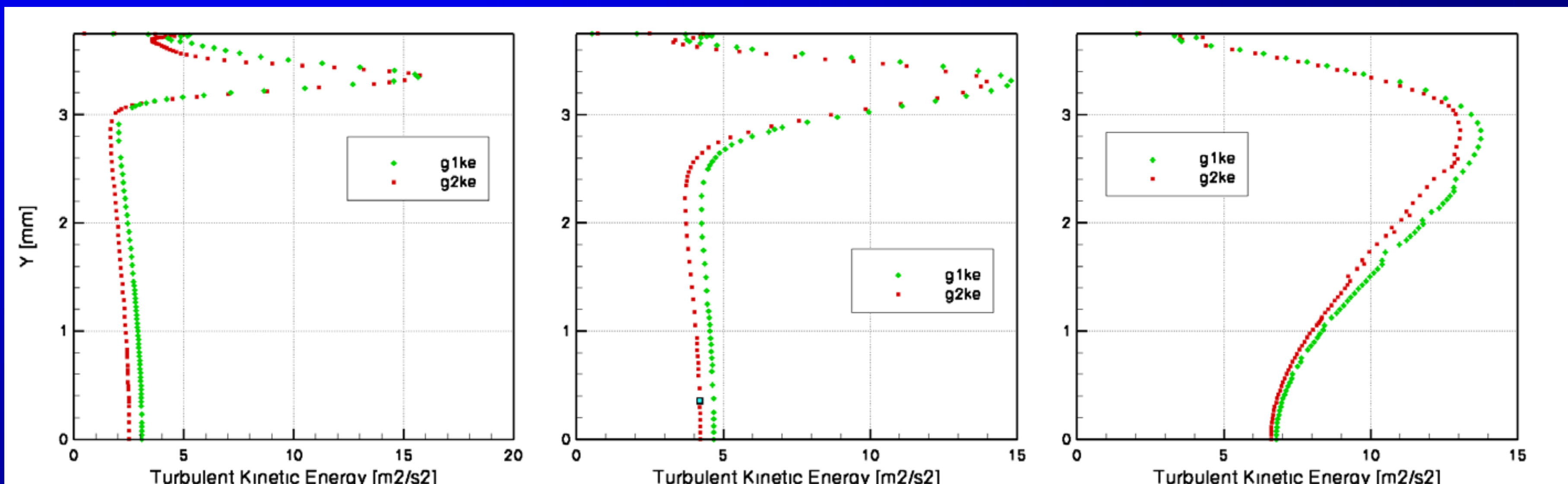


NUMERICAL SIMULATION

Vertical profiles of Turbulent Kinetic Energy

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

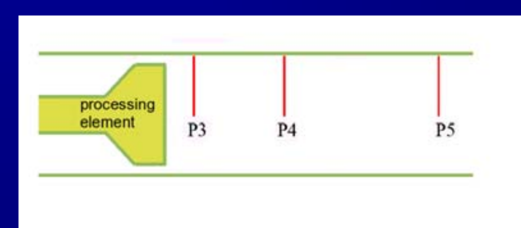
1mm (P3) **3mm (P4)** **8mm (P5)**



behind processing element

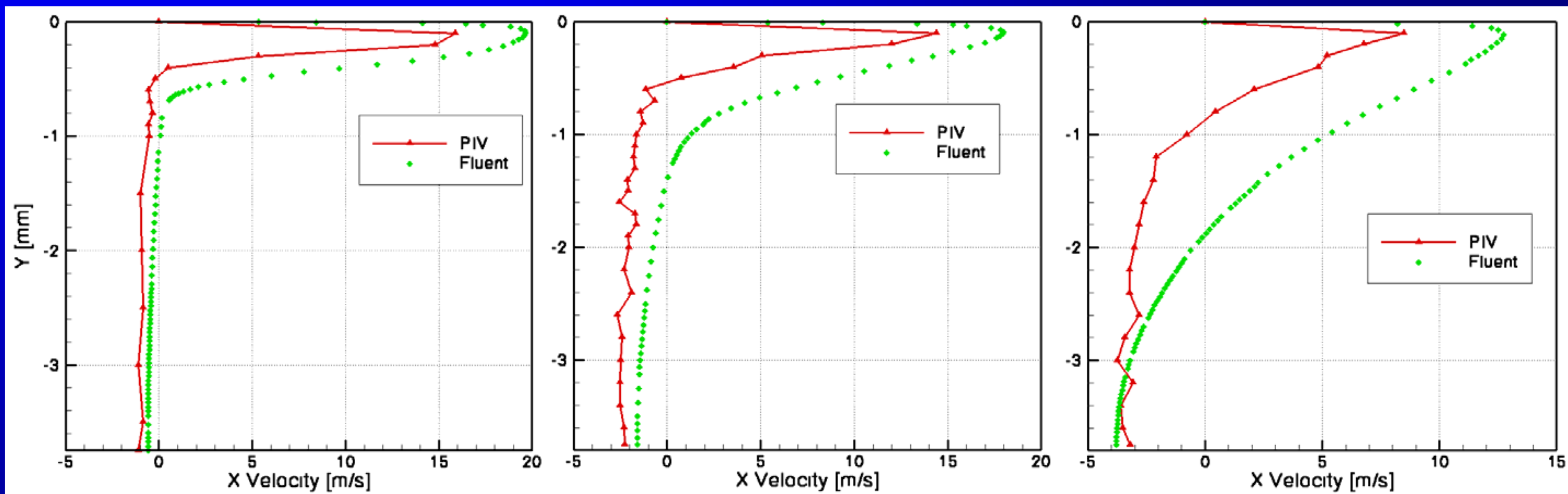
g1ke – non-transparent processing element

g2ke – transparent processing element



NUMERICAL vs. EXPERIMENTAL RESULTS

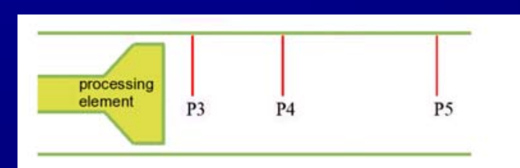
Comparison of the numerical and experimental x-velocity profiles:



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

behind processing element

<u>Fluent:</u> k-ε model + Enhanced Wall Treatment,
Q_2 = 0.204 dm^3/s, geometry G1



THEORETICAL ESTIMATION OF DROPS SIZE

Kolmogorov-Hinze theory

for turbulent flows and small differences of the fluids viscosity

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

Davis theory

for turbulent flows and significant differences of the fluids viscosity

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

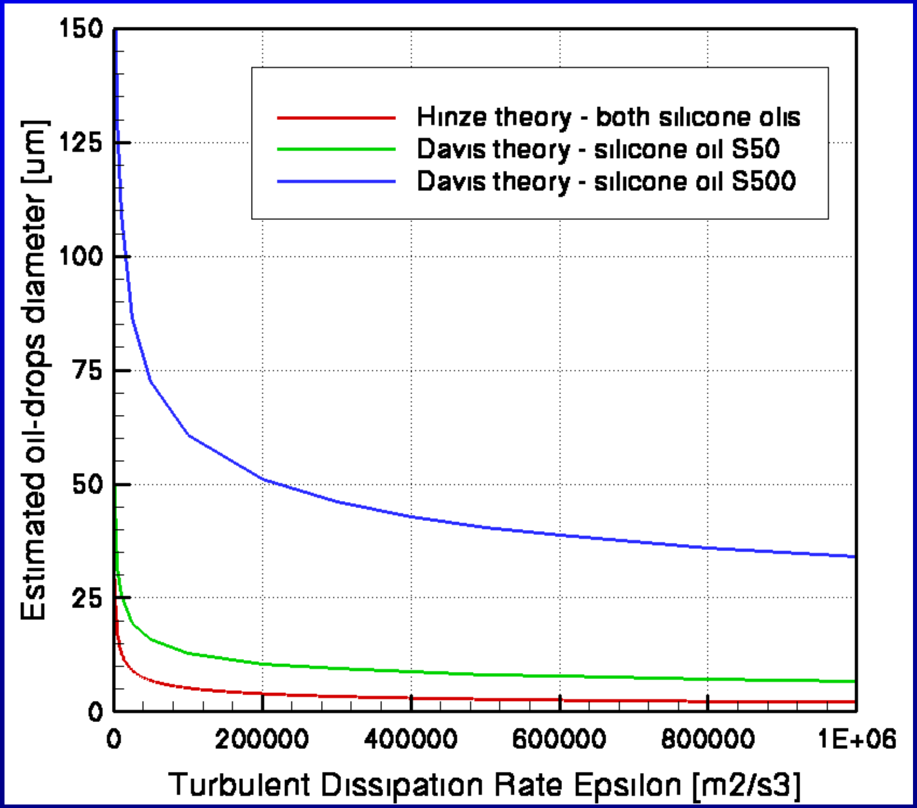
Where: d – drops diameter, σ – interfacial tension

ρ_c – medium density, μ_d – drops viscosity,

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

DROPS SIZE ESTIMATION

Estimated dependence between Turbulent Dissipation Rate *Epsilon* and oil-drops diameter



Estimation for two silicone oils:

S50 oil: $\mu_d^{S50} = 50 mPas$

S500 oil: $\mu_d^{S500} = 500 mPas$

Dispersing medium properties:

ρ_c = 998 kg/m^3

σ=5.5 mN/m

which corresponds to properties of de-ionized water with 1%wt SDS

DROPS SIZE ESTIMATION

Results of the oil drops diameter estimation

	Hinze model both oils [μm]	Davis model oil S50 [μm]	Davis model oil S500 [μm]
max. epsilon value in gap $\varepsilon_{max}=1.160 \cdot 10^6$ m²/s³	1.97	6.46	32.77
avg. epsilon value in gap $\varepsilon_{avg}=3.599 \cdot 10^5$ m²/s³	3.14	8.95	44.01

Experiment: mean oil-drops size: 10.1 µm for S50 oil
20.7 µm for S500 oil

CONCLUSIONS

- Almost uniform velocity flow field in the gap region - turbulence is still not fully developed
- Transition from laminar to turbulent flow regime occurs probably behind the processing element (strong recirculation zone, fluctuations of the velocity, asymmetry of the flow)
- Numerical modelling can be applied for predicting conditions for oil-droplets break-up in a shear flow
- Turbulent-flow drop break-up model (Hinze) appears to work well
- Validation of the numerical models of turbulent flow in micro-channel using μPIV is possible but difficult due to:
  - low particle concentration
  - short measurement time at high flow rates

ACKNOWLEDGMENTS

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