Numerical modeling of rectangular channel with shallow dumbbell dimples based Code Saturne

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Purpose of the study

design of surface of energy-efficient heat exchange

research tasks

- development of mathematical models
- numerical study of the flow in rectangular channel with dimples
- test simulation
- numerical study are conducted for rectangular channel with dumbbell dimples

The formulation of the problem, grids

Mathematical model:

Navier-Stokes equations
for laminar flow

$$
\begin{cases}
\dfrac{d\rho}{dt} + \mathrm{div}\left(\rho \underline{u}\right) = \Gamma \\
\dfrac{d\left(\rho \underline{u}\right)}{dt} + \underline{\mathrm{div}}\left(\underline{u} \otimes \rho \underline{u}\right) = -\underline{\nabla} P + \underline{\mathrm{div}}\left(\mu\left[\underline{\underline{\nabla}}\underline{u} + \underline{\underline{\nabla}}\underline{u}^{T} - \dfrac{2}{3} tr\left(\underline{\underline{\nabla}}\underline{u}\right)\underline{\underline{Id}}\right]\right) + \rho \underline{g} + \underline{ST}_{\underline{u}} - \underline{\underline{K}}\underline{u} + \Gamma \underline{u}^{in}
\end{cases}
$$

The formulation of the problem, grids

for turbulent flow

$$\begin{cases} \dfrac{d\rho}{dt} + \mathrm{div}\left(\rho \underline{\bar{u}}\right) = \Gamma \\ \rho \dfrac{d\underline{\bar{u}}}{dt} + \underline{\underline{\nabla \bar{u}}} \cdot \left(\rho \underline{\bar{u}}\right) = -\underline{\nabla P} + \underline{\mathrm{div}} \left(\mu \left[\underline{\underline{\nabla \bar{u}}} + \underline{\underline{\nabla \bar{u}}}^{T} - \dfrac{2}{3} tr\left(\underline{\underline{\nabla \bar{u}}}\right) \underline{\underline{Id}} \right] \right) + \rho \underline{g} - \underline{\mathrm{div}}\left(\rho \underline{\underline{R}}\right) + \\ \qquad + \underline{ST}_{\underline{u}} - \underline{\underline{K}}\,\underline{u} + \Gamma\left(\underline{\bar{u}}^{in} - \underline{\bar{u}}\right) \end{cases}$$

$$\underline{u} = \underline{\bar{u}} + \underline{u'}$$

$$\underline{\underline{R}} \equiv \overline{\underline{u'} \otimes \underline{u'}}$$

$$\mu = \mu_l + \mu_T$$

$$\rho \underline{\underline{R}} = \frac{2}{3} \rho k \underline{\underline{1}} - 2 \mu_T \underline{\underline{\bar{S}}}^{D}$$

$$k \equiv \frac{1}{2} tr\left(\underline{\underline{R}}\right)$$

The formulation of the problem, grids

turbulence model

Model SST - a hybrid model

- The wall region using k-ω model
- In the external flow using k-ε model
- The viscosity is limited SST (Shear Stress Transport)

$$\frac{Dk}{Dt} = \nabla \bullet \left(\left(\nu + \sigma_k \nu_T \right) \nabla k \right) + P_k - \beta^* \omega k$$

$$\frac{D\omega}{Dt} = \nabla \bullet \left(\left(\nu + \sigma_\omega \nu_T \right) \nabla \omega \right) + \frac{\gamma}{\nu_T} P_k - \beta \omega^2 + \left(1 - F_1 \right) \frac{2\sigma_{\omega 2}}{\omega} \left(\nabla k \right) \bullet \left(\nabla \omega \right)$$

Switching between k-ε and k-ω models carried out by the function F1

$$F_1 = \tanh\left(\arg_1^4\right), \arg_1 = \min\left[\max\left(\frac{\sqrt{k}}{0.09\omega d}, \frac{500\nu}{d^2 \omega} \right), \frac{4\sigma_{\omega 2} k}{CD_{k\omega} d^2} \right]$$

$$CD_{k\omega} = \max\left(D_{k\omega}, 10^{-20} \right), D_{k\omega} = \frac{2\sigma_{\omega 2}}{\omega} \left(\nabla k \right) \bullet \left(\nabla \omega \right)$$

turbulence model

Cross-diffusion term

$$\phi = F_1\phi_1 + (1 - F_1)\phi_2, \ \phi = \{\sigma_k, \sigma_\omega, \beta\}$$

$$\sigma_{k1} = 0.85, \sigma_{\omega 1} = 0.5, \beta_1 = 0.075,$$

$$\sigma_{k2} = 1.0, \sigma_{\omega 2} = 0.856, \beta_2 = 0.0828$$

limiter of SST

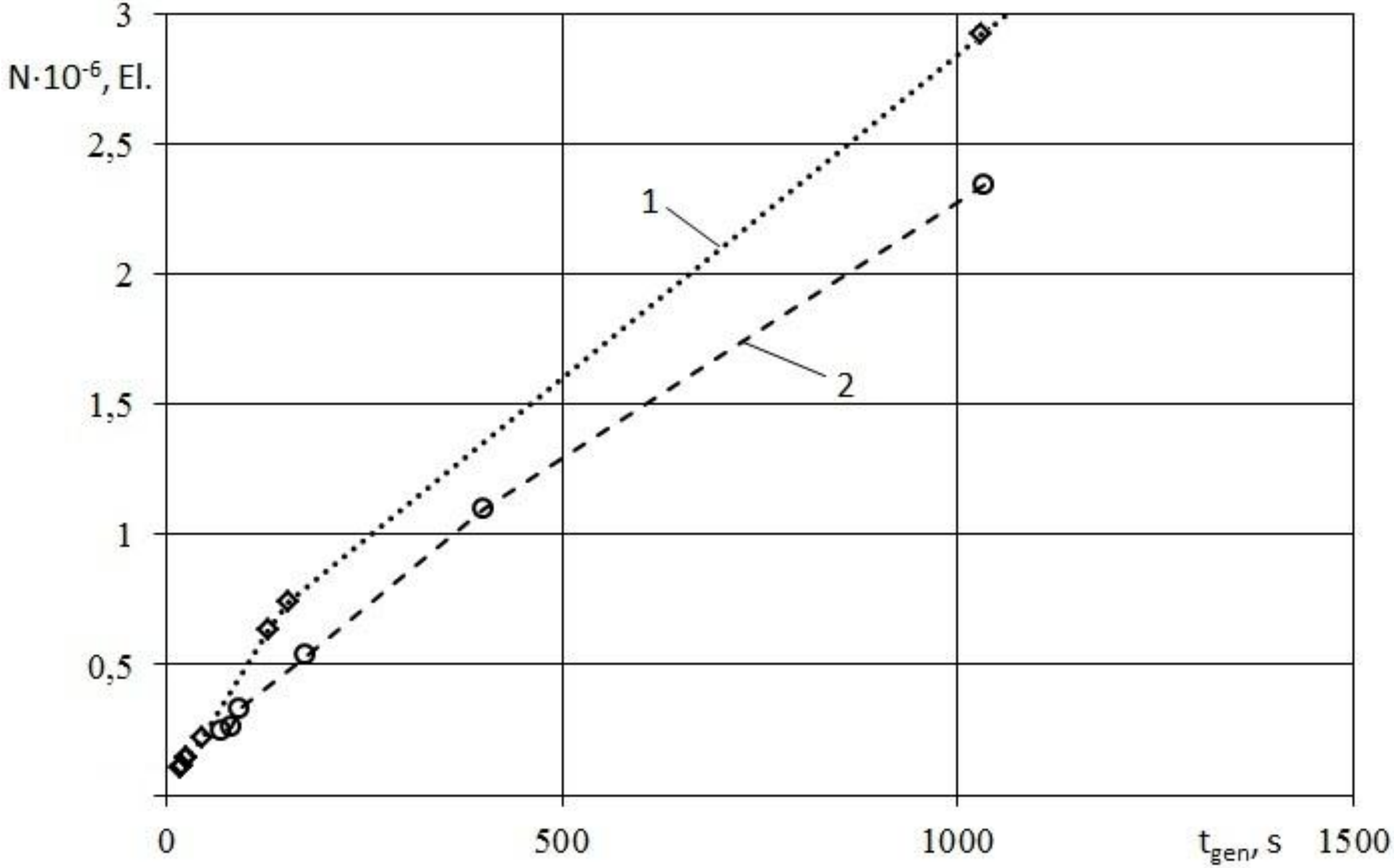
$$\nu_T = \frac{a_1 k}{\max(a_1\omega, \Omega F_2)}, \qquad F_2 = \tanh(\arg_2^2), \arg_2 = \max\left(\frac{2\sqrt{k}}{0.09\omega d}, \frac{500\nu}{d^2\omega}\right)$$

constants of model

$$\beta^* = 0.09, \kappa = 0.41, a_1 = 0.31, \gamma = \beta/\beta^* - \sigma_\omega \kappa^2/\sqrt{\beta^*}$$

The formulation of the problem, grids

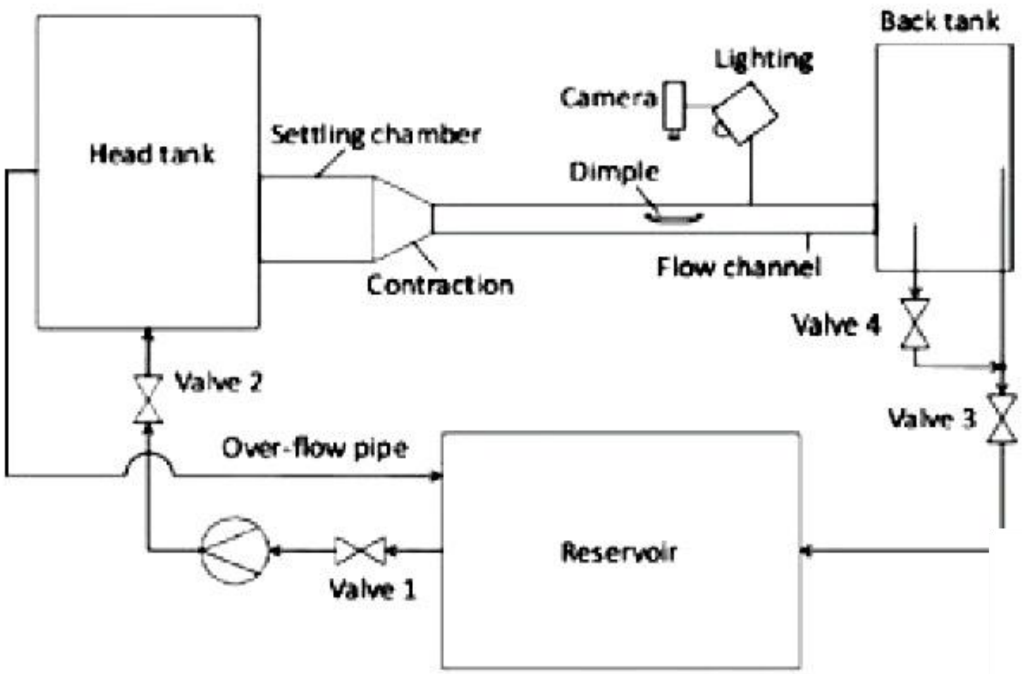
Discretization of study field



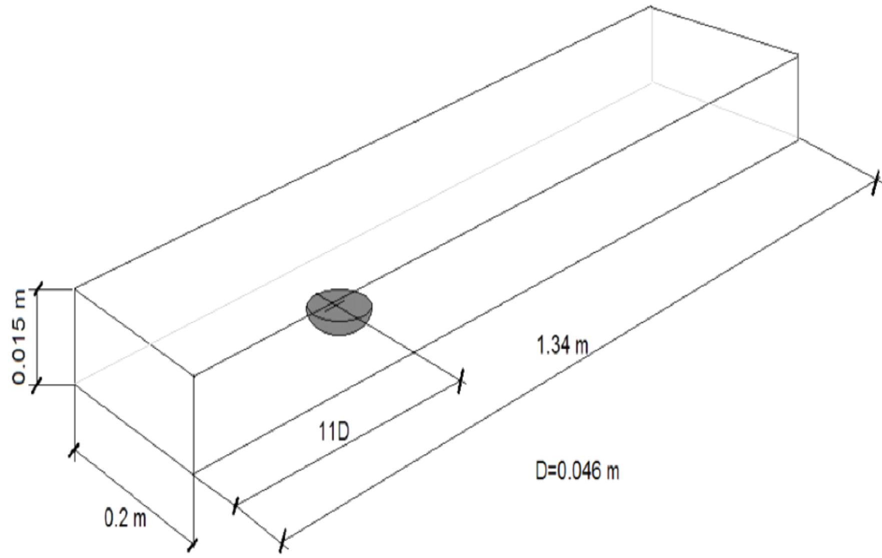
1 - unstructured grid; 2 - structured grid

Check of adequacy

Experimental scheme (Terekhov V.I. et al [12],
V. Voskoboinick et al [13,14]



Study field



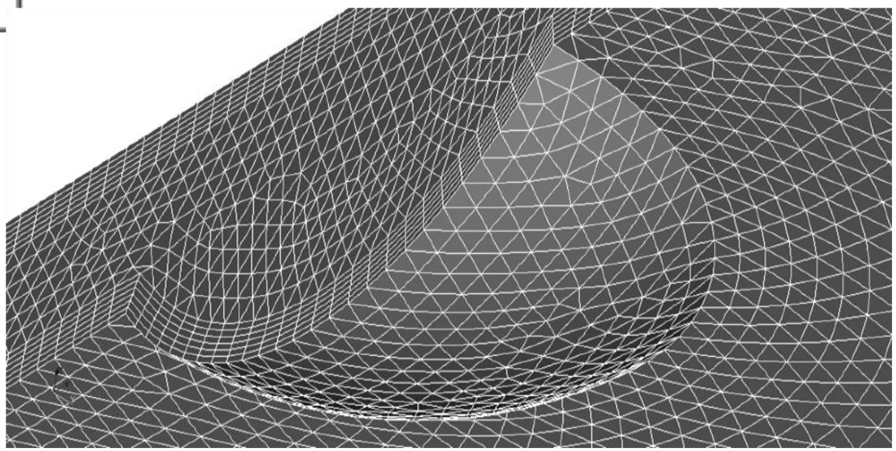
Discretization of study field

3D - Tetrahedron(Netgen)

2D - Netgen 1d-2d, Lmin=0,7mm,

Lmax=2,5 mm

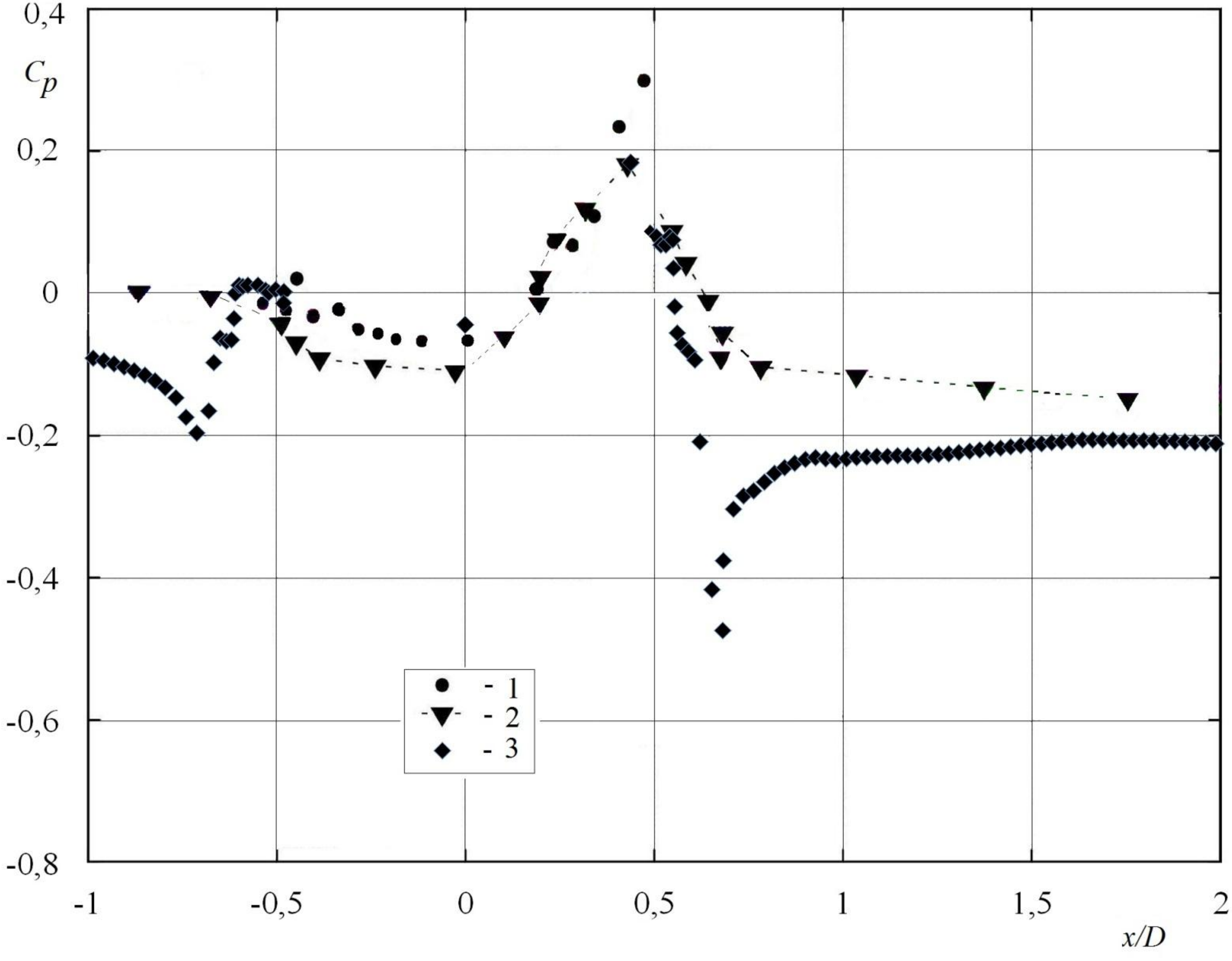
Nel=878977



Check of adequacy

Numerical study

$$C_p = (p_i - p_0)/\left(\rho \bar{u}_S^2 / 2\right)$$

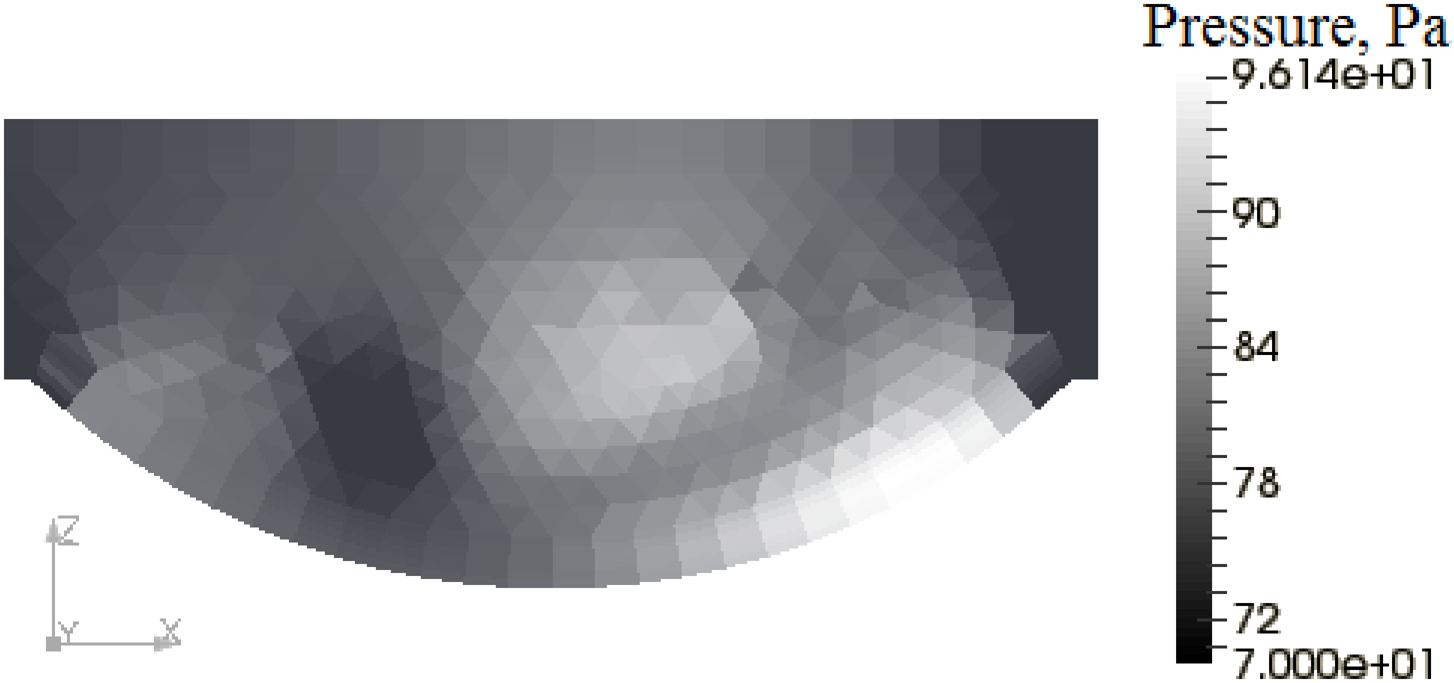


1 – experimental study of Terekhov et. al. [12];
2 – experimental study of Voskoboinic et.al. [13,14];
3 – result of computation

u_0=0.43 m/s
Re= 20000

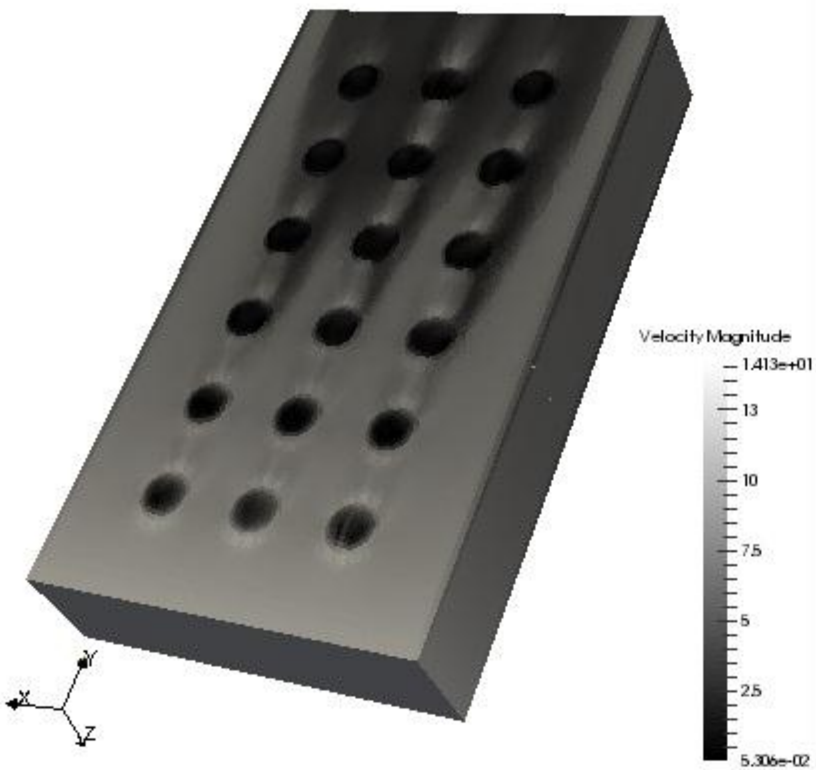
Check of adequacy

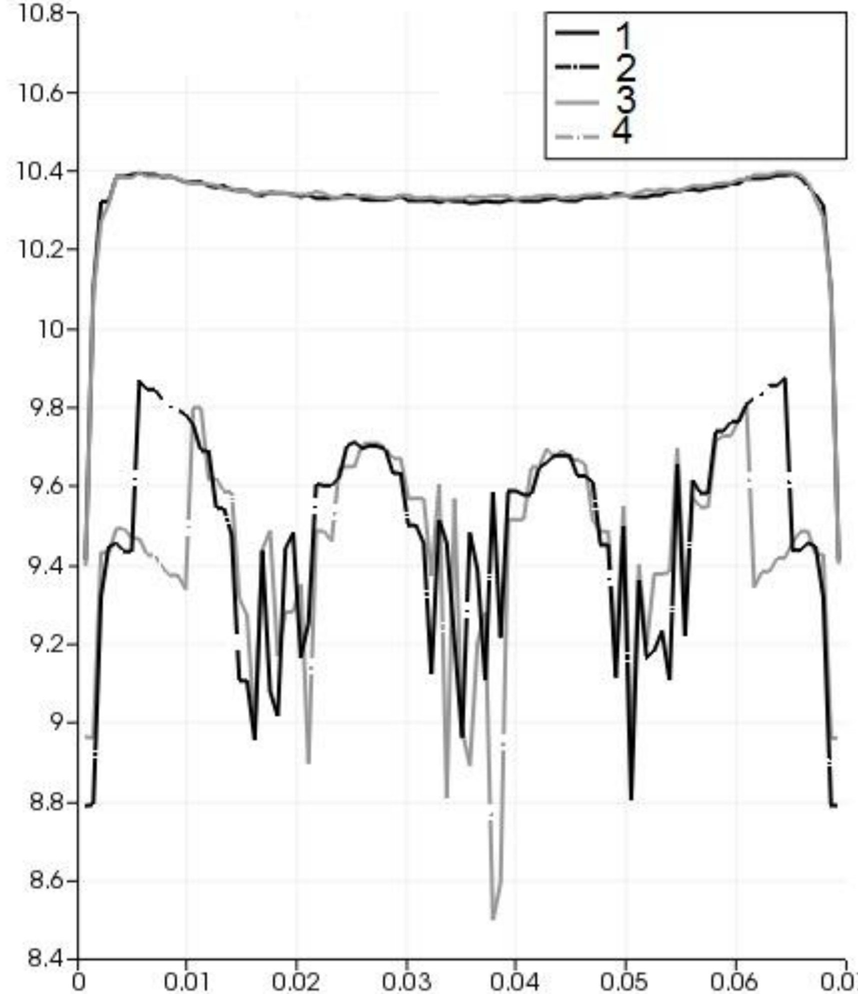
Numerical study



Numerical study

Discretization of study field

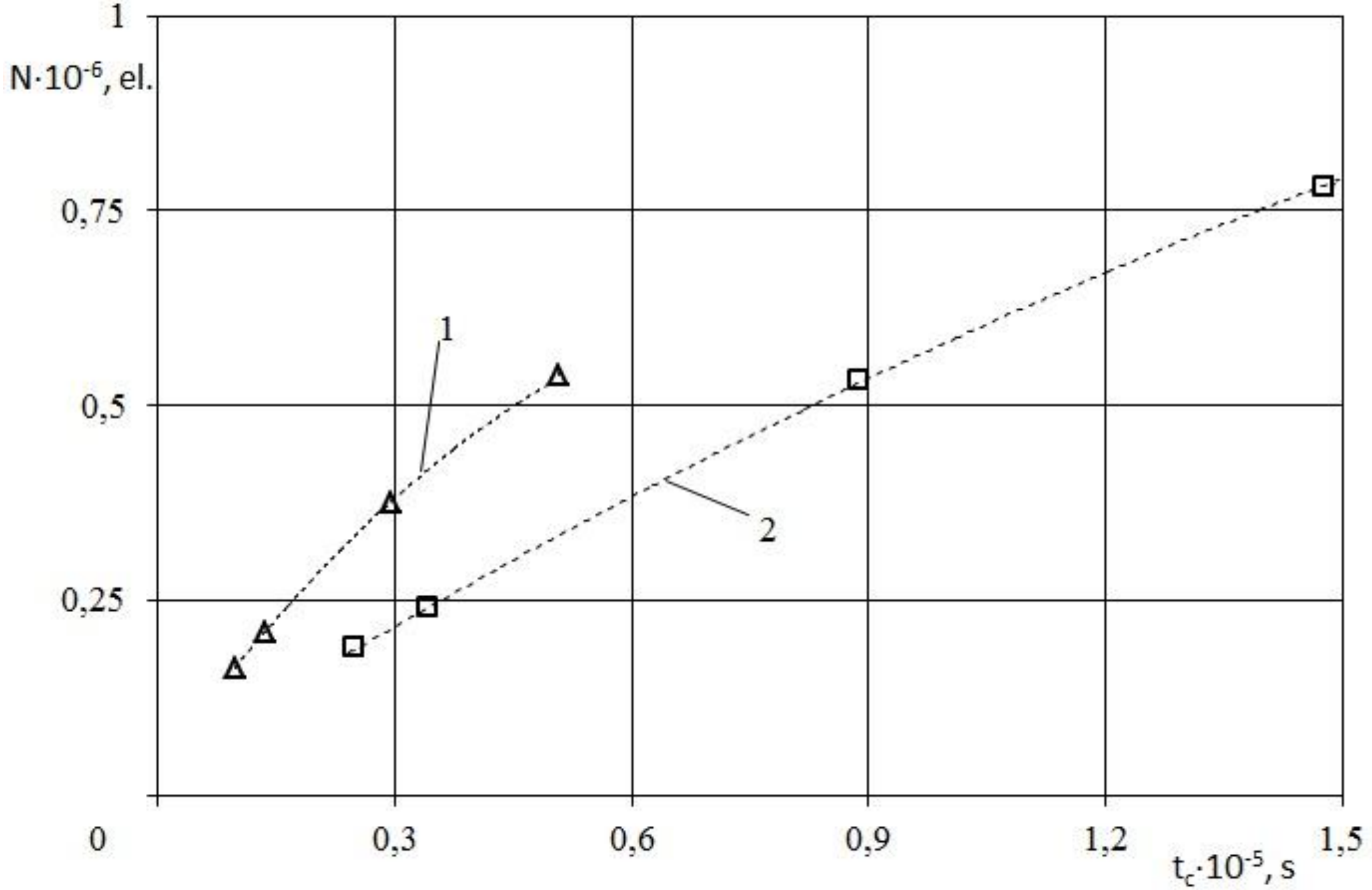




1, 2 – velocity profile on the axis of the channel and near the surface with dimples for N_{el}=766796; 3,4 – for N_{el}=537459

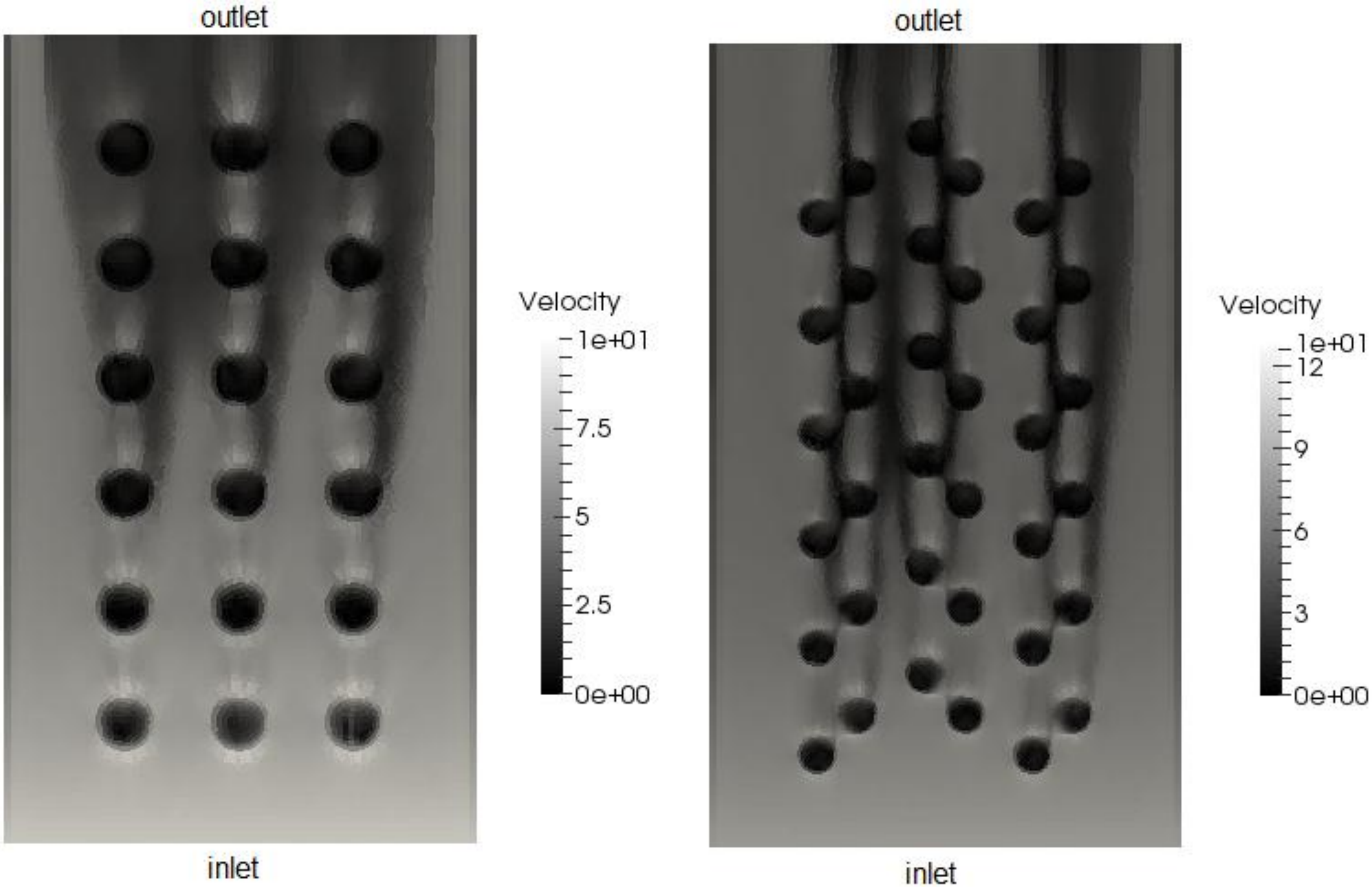
Numerical study

Discretization of study field



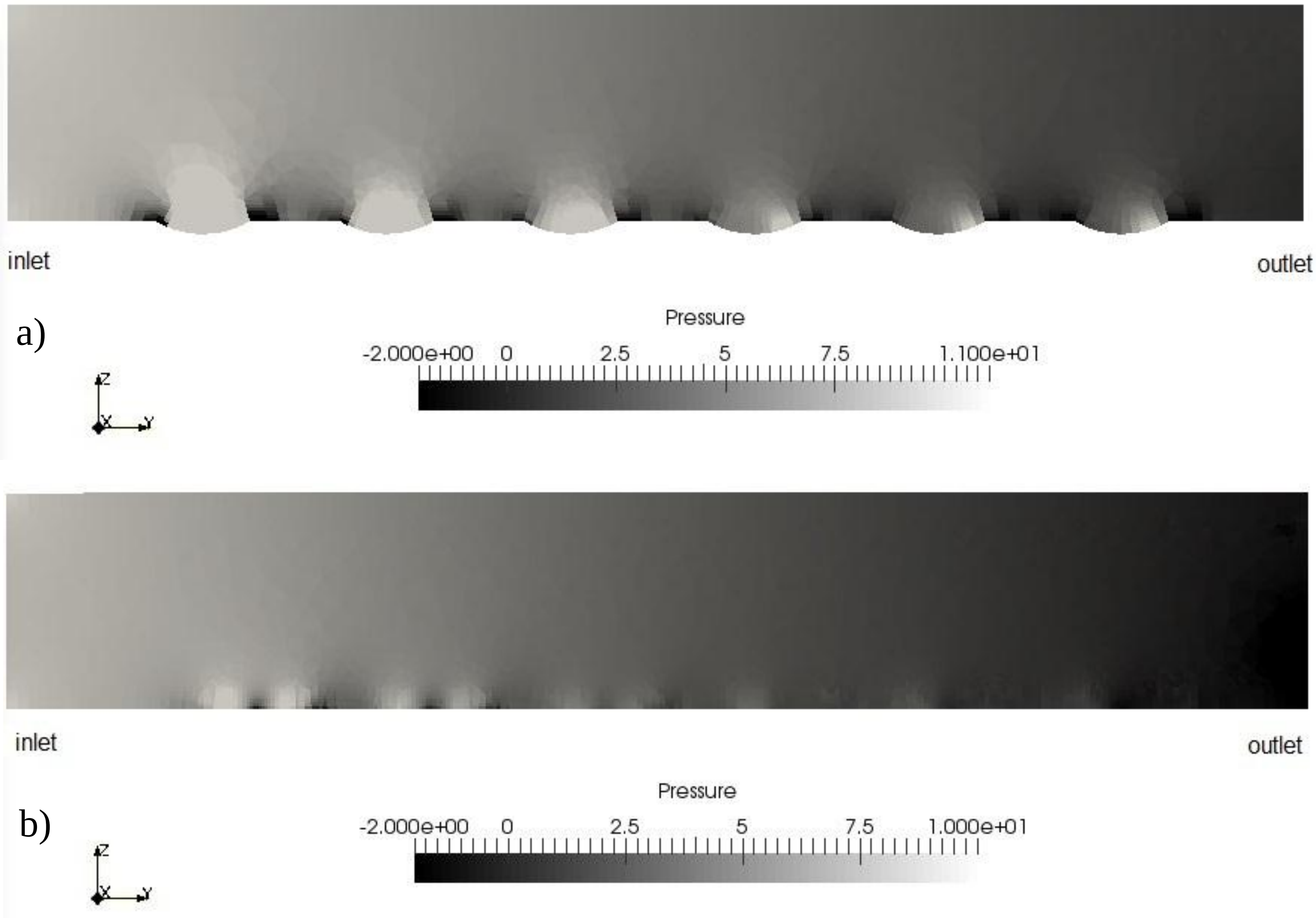
Time of computational: 1 – discretization of the computational domain into triangular elements; 2 – discretization of the computational domain into rectangular elements

Numerical study



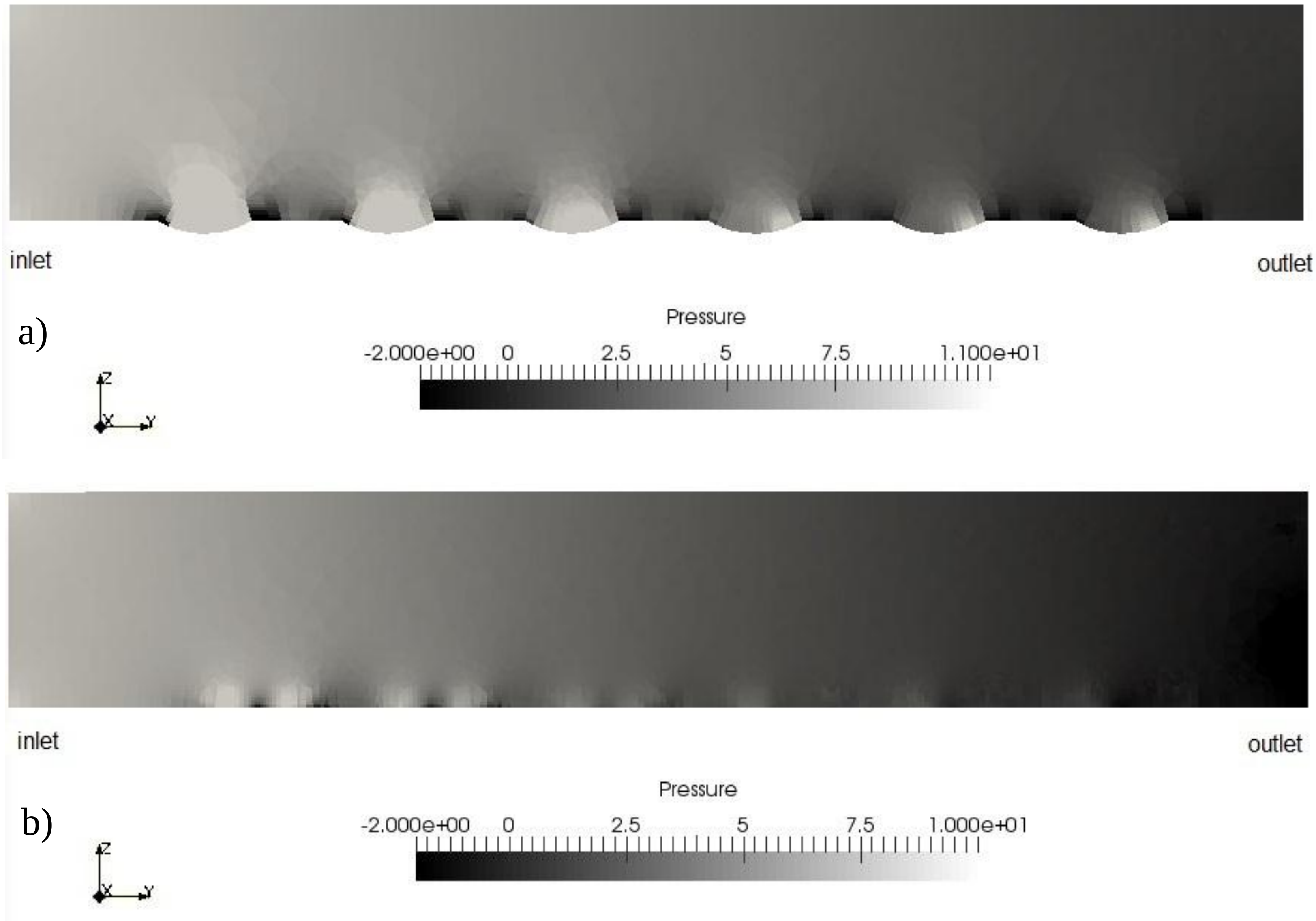
Velocity field: a – spherical dimples; b – dumbbell dimples

Numerical study



Pressure field on the axis: a – spherical dimples, b – dumbbell dimples

Numerical study



Pressure field on the axis: a – spherical dimples, b – dumbbell dimples

Resume

A turbulent flow (Re = 31627) in rectangular channel with shallow dumbbell dimples was modelled with open source Code_Saturne. An ideal gas (p = 1.205 kg/m^3) was considered as working medium. A 3D computation domain was meshed with open source Salome Meca for 0.77 million elements ranged 0.2...1.0 mm. Six viscous layers totalling 2 mm thick were applied to smooth walls. Unsteady flow simulated with k-w SST model utilizing 2nd order discretization schemes (SOLU) for velocity. 2000 iterations were calculated so far with pseudo time step of 0.1 ms. Additionally impact of mesh quality regarding elements size on computation results was shown. Generation time of mixed mesh (quadrangles and triangles on surface) was proved to be greater than of strictly triangular one. Obtained results showed a strong dependence of flow velocity from inclination of dumbbell towards flow axis. Adjacent dumbbell dimples cause partial flow laminarization. Developed model shows aerodynamic advantage up to 10 % of dumbbell dimples over spherical ones of the same depth (h = 1.2 mm) and contact patch area (S = 59.76 mm^2).

Thanks for your attention!