UTSR Peer Review Workshop III

18-20 October 2005

Turbine Surface Degradation with Service and Its Effects on Performance

– 2-D/3-D CFD Simulations of Rough Surfaces–

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BYU

Objectives

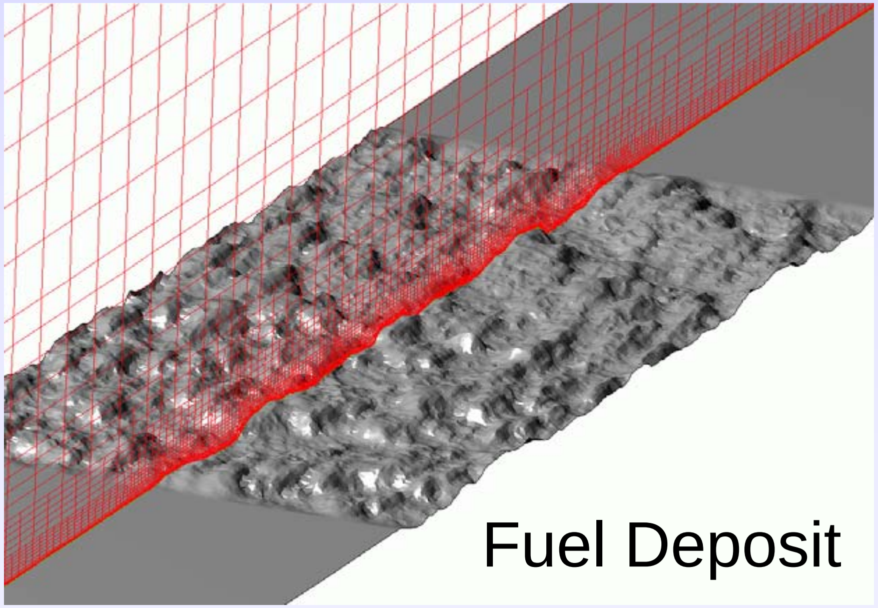
- Perform detailed CFD simulations to generate understanding of flow and heat transfer phenomena over rough surfaces.
- Use understanding generated to develop engineering models to predict heat transfer and friction on rough surfaces.

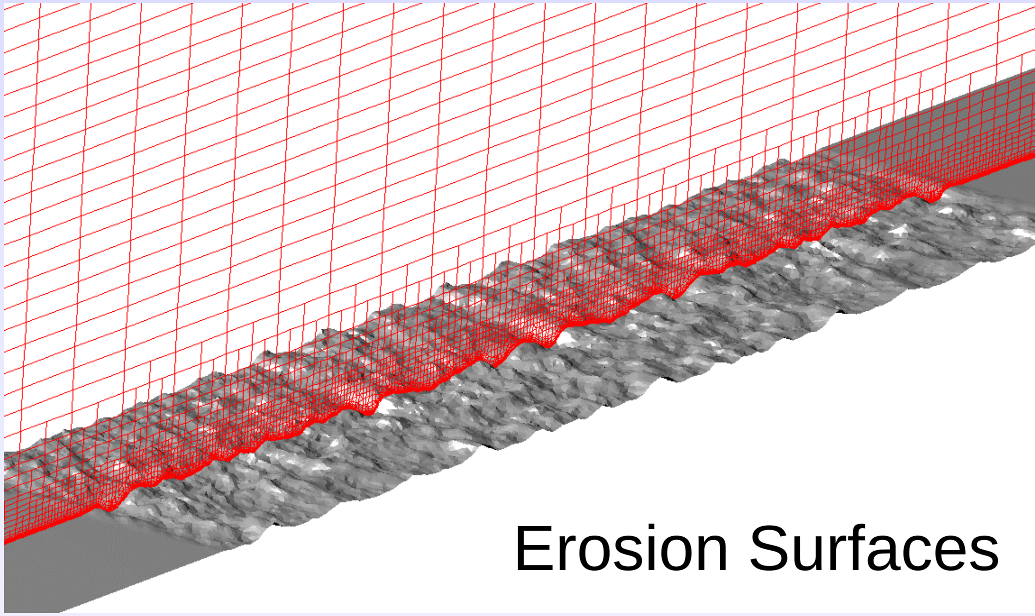
Accomplishments

- Performed 2-D and 3-D CFD simulations.
- Generated a preliminary engineering model.

3-D CFD: Z.J. Wang

- 1/6 -1/3 of the span **(from Jeffrey Bons' experiment)** selected for the computational domain;
- 2 mm, 1 mm and 0.5 mm resolutions for coarse, medium and fine grids at the roughness panels;
- Minimum distance in the wall normal direction about 0.025 mm for a y+ around 1





Flow Solver:
In-House FV Code for Arbitrary Elements

- Second-order accurate Godunov-type finite volume method using linear least squares reconstruction for arbitrary grids;
- Backward Euler or backward difference formula for 1st or 2nd order time integration;
- Efficient block lower-upper symmetric Gauss-Seidel (BLU-SGS) implicit equation solver;
- RANS S-A turbulence model (DES dropped because the grid still too coarse).

Results for Fuel Deposit Roughness (#4)

	0.36 M cells 2 mm	1.26 M cells 1 mm	4.00 M cells 0.5 mm	Experiment
c_f	0.0128	0.00970	0.00873	0.00937
St	0.00260	0.00268	0.00275	0.00308

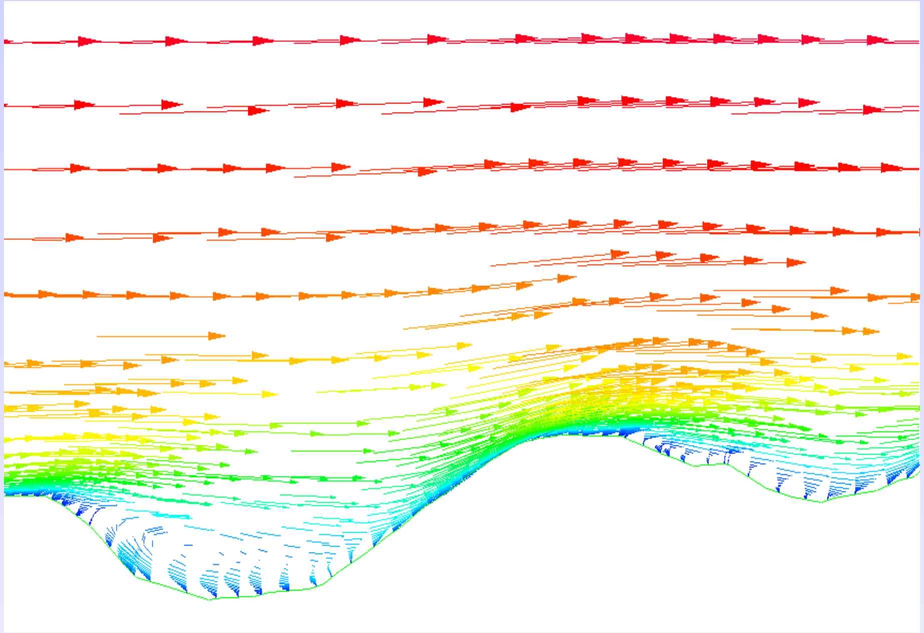
- Coarse grid too coarse
- 3.5-7% and 11-13% difference in c_f and St between computation and experiment.

Results for Erosion Roughness (#6)

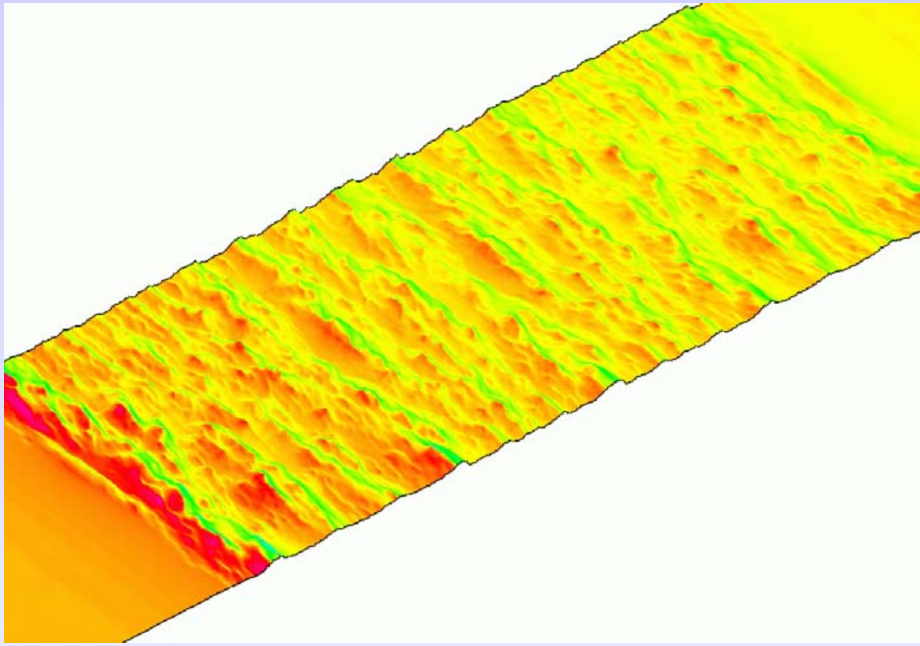
	0.87 M cells 1.0 mm	1.60 M cells 0.5 mm	Experiment
c_f	0.0113	0.0100	0.0103
St	0.0268	0.00304	0.00308

- 3.0% and 1.2% difference in c_f and St between computation and experiment.

Flow Field Characteristics

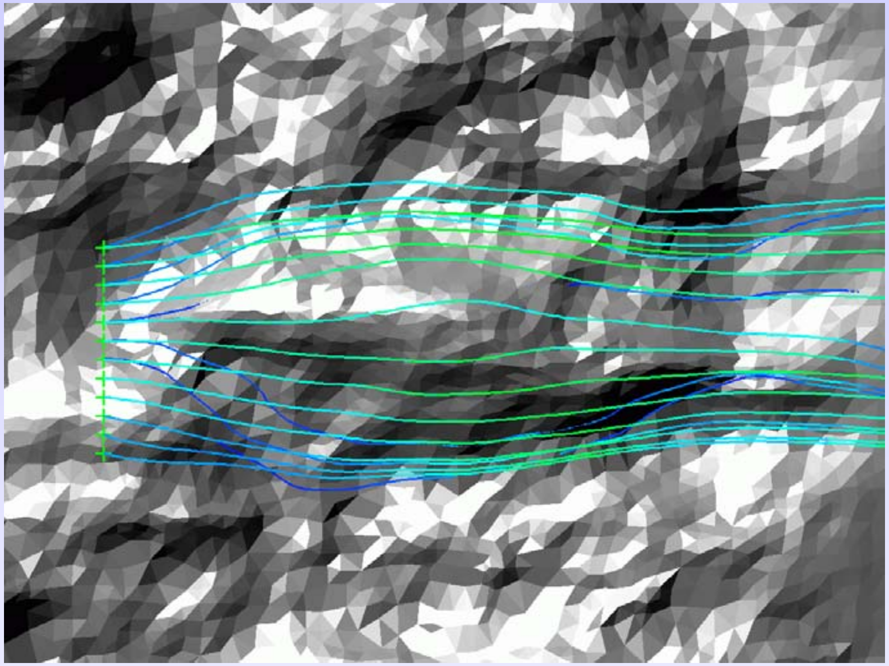


Velocity Vector Plot

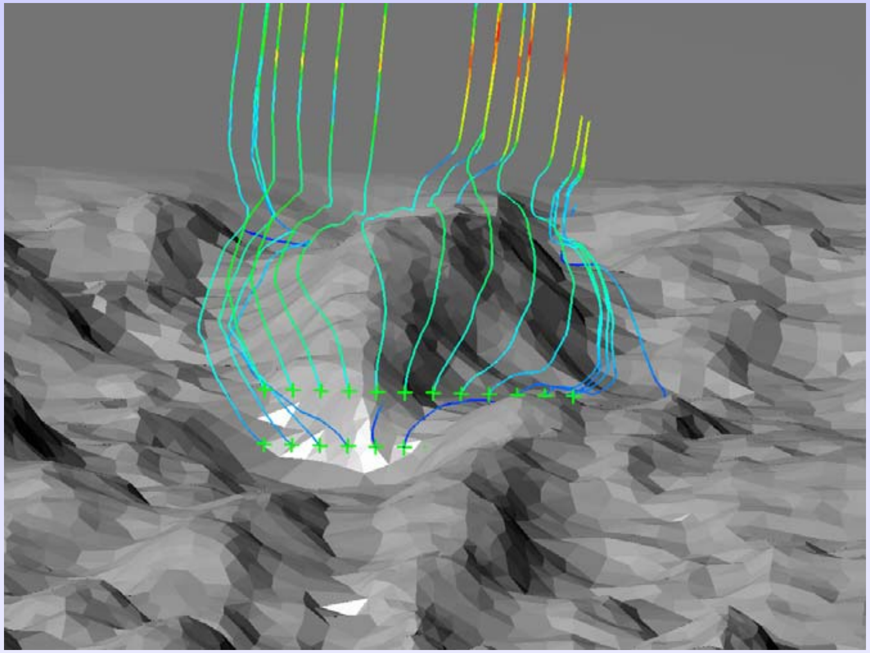


Pressure Distribution

Streamlines Near a Roughness Element



Top View



Front View

Conclusions from 3-D CFD Study

- Viscous adaptive Cartesian grid method can very efficiently and easily grid the detailed geometry of rough surfaces and the flow induced by the surfaces without user interference;
- For real rough surfaces, S-A model predicted c_f within 2-7% of experimental data, 1-11% difference in St;
- Finer grids are needed to demonstrate grid independent solutions.

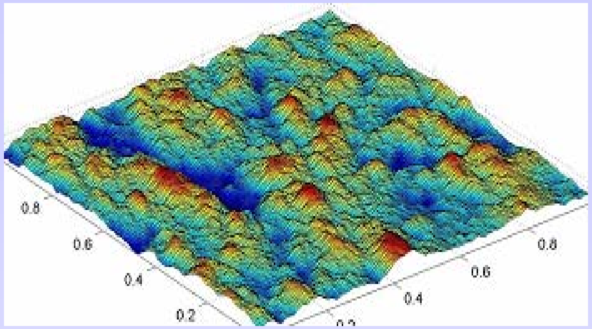
2-D CFD: Shih & Yoon

Objectives

- Since 3-D roughness is expensive to compute, want to explore usefulness of 2-D simulations, where grids can be extremely fine to resolve all features of the roughness and the flow that they induce.

- Develop engineering correlations based on the detailed CFD data.

Roughness Parameters



y_{mean} : average value of magnitude of roughness

$$y_{mean} = \frac{1}{N}\sum_{i=1}^{N}\left|y_{surface\_i}\right|$$

R_a : arithmetic mean of magnitude of roughness

$$R_a = \frac{1}{N}\sum_{i=1}^{N}\left|y_i\right| \quad \left(y_i = y_{surface\_i} - y_{mean}\right)$$

R_q : Root Mean Square (rms)

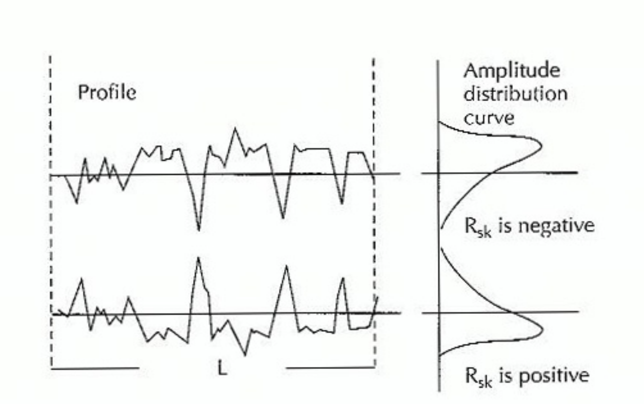
$$R_q = \sqrt{\frac{1}{N}\sum_{i=1}^{N} y_i^2}$$

R_{sk} : Skewness

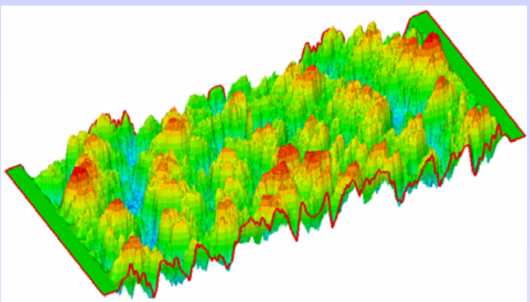
$$R_{sk} = \left\{\frac{1}{N}\sum_{i=1}^{N} y_i^3\right\}\frac{1}{R_q^3}$$

K_u : Kurtosis

$$K_u = \left\{\frac{1}{N}\sum_{i=1}^{N} y_i^4\right\}\frac{1}{R_q^4}$$



One 2-D Slice of a 3-D Rough Surface

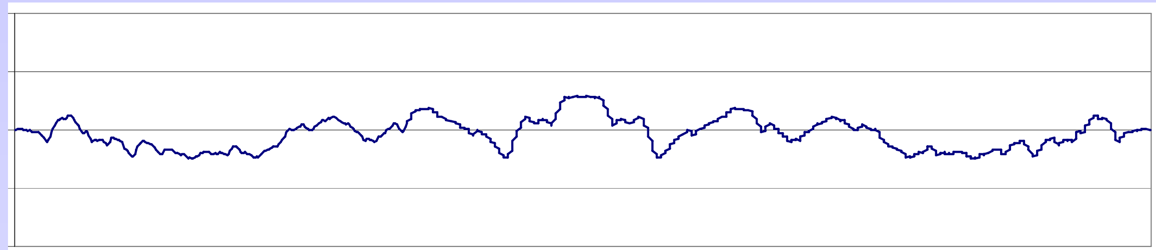


R_a : 1.09585

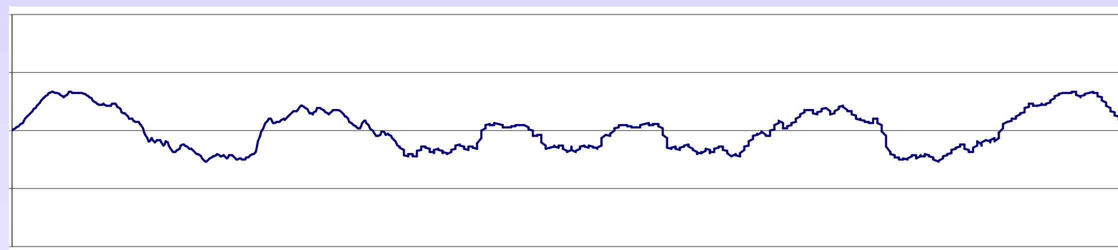
R_q : 1.31822

R_{sk} : 0.111085

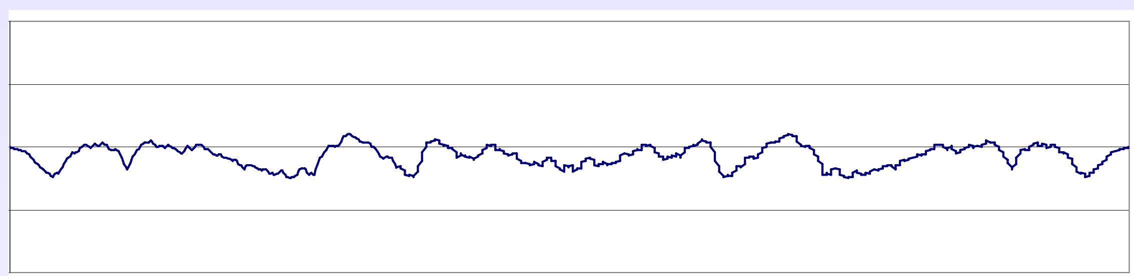
K_u : 2.25267



Similar to 3D, R_a : 1.0984, R_q : 1.3128, R_{sk} : 0.2840, k_u : 2.4155

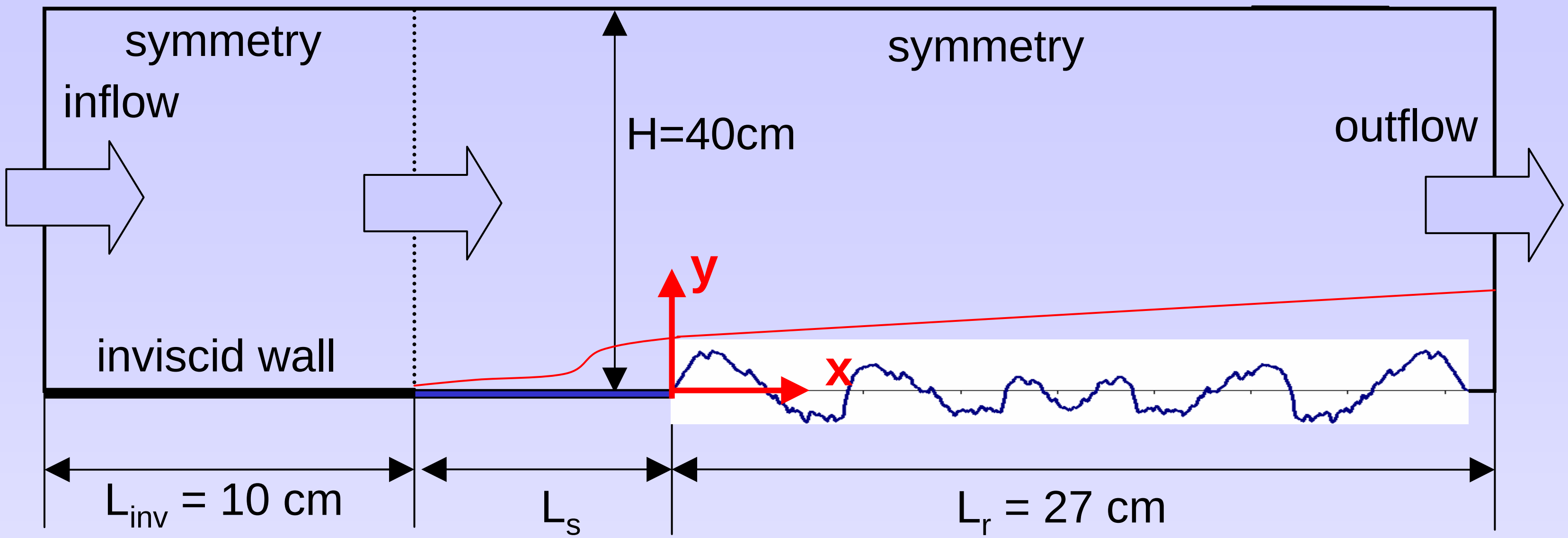


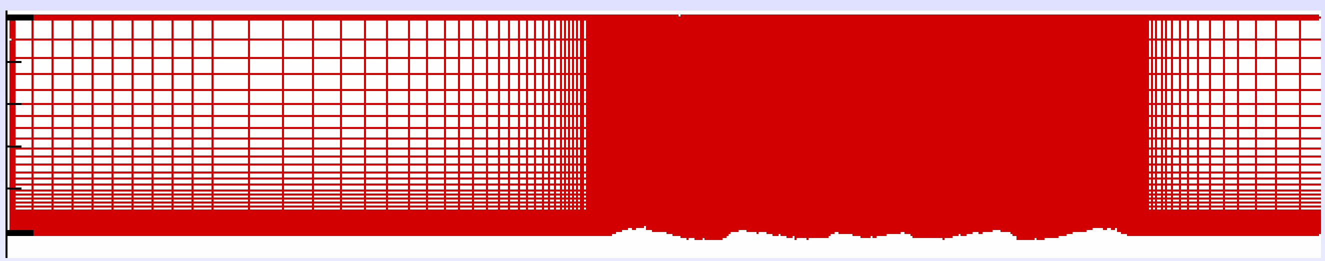
R_a : 1.4828, R_q : 1.7102 (highest), R_{sk} : 0.2507, k_u : 1.8954



R_a : 0.7344, R_q : 0.860 (lowest) , R_{sk} : -0.245, k_u : 2.0103

One 2-D Slice of a 3-D Rough Surface

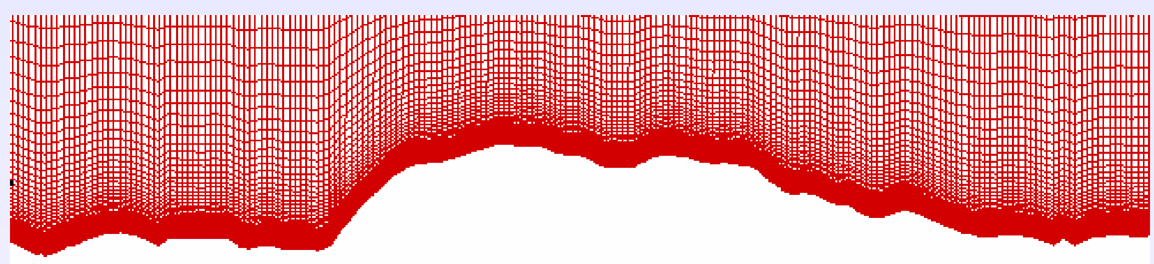




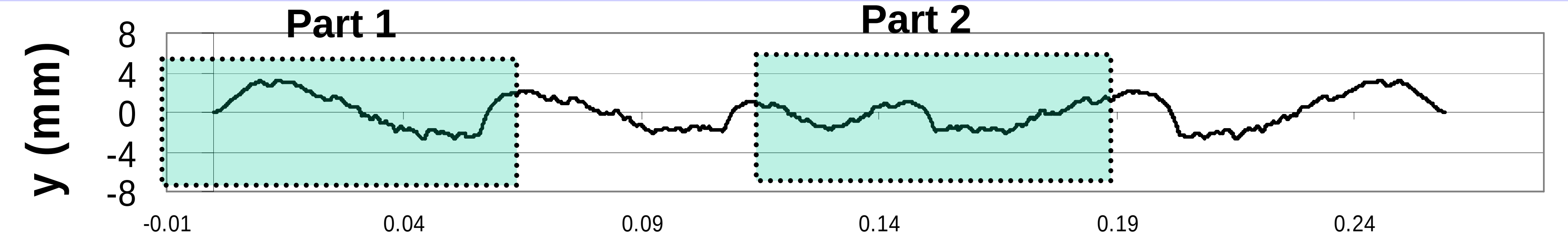
S-A turbulence model

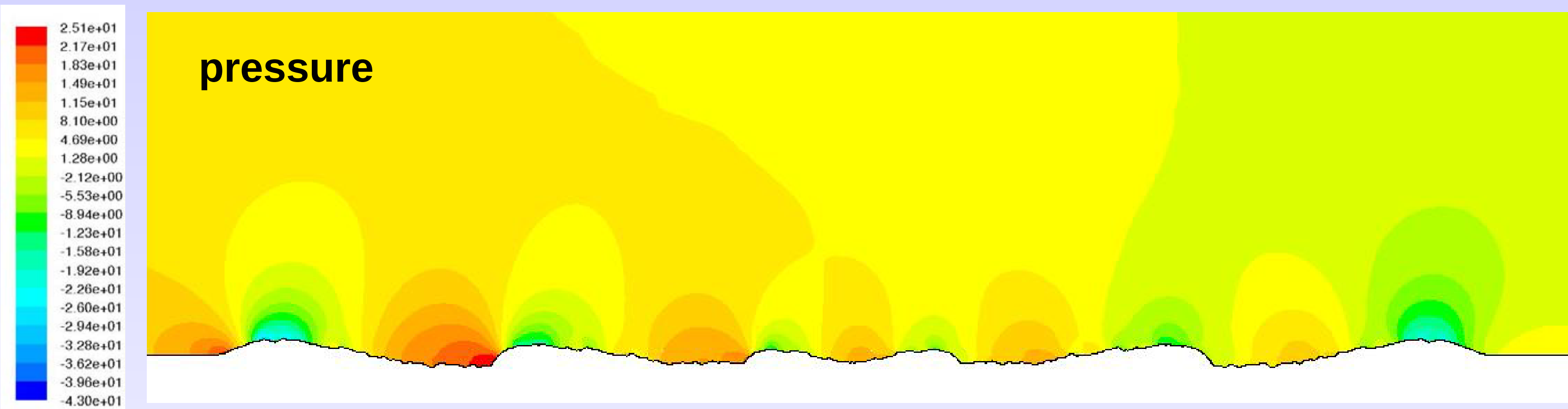
2nd-order differencing

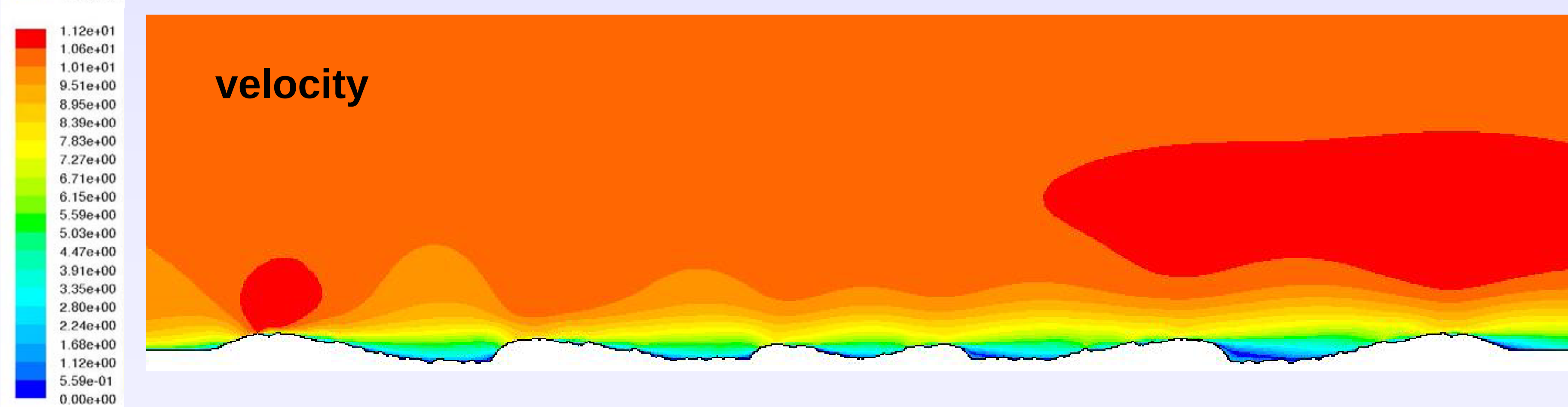
Fluent 6.2



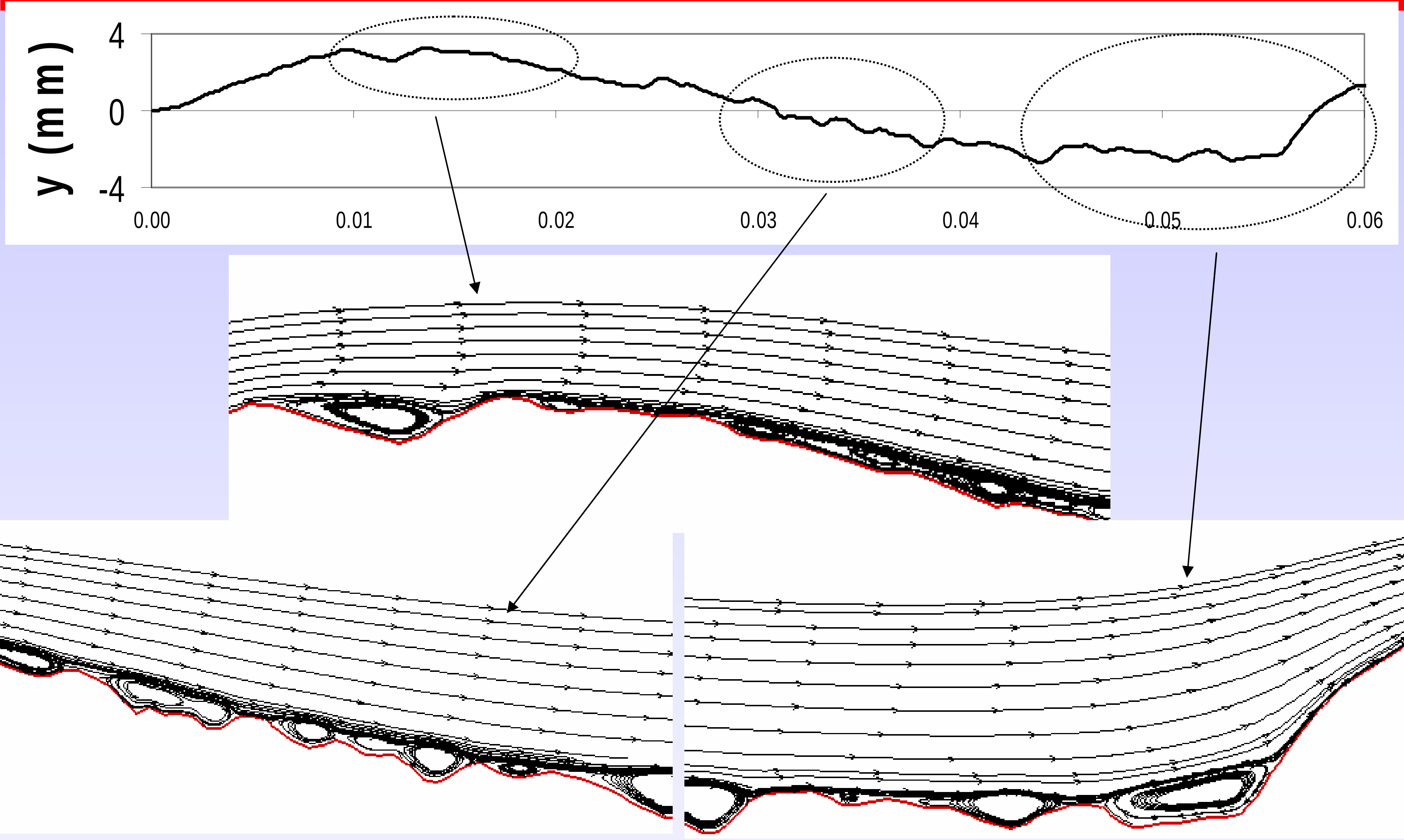
Velocity and Pressure Contour



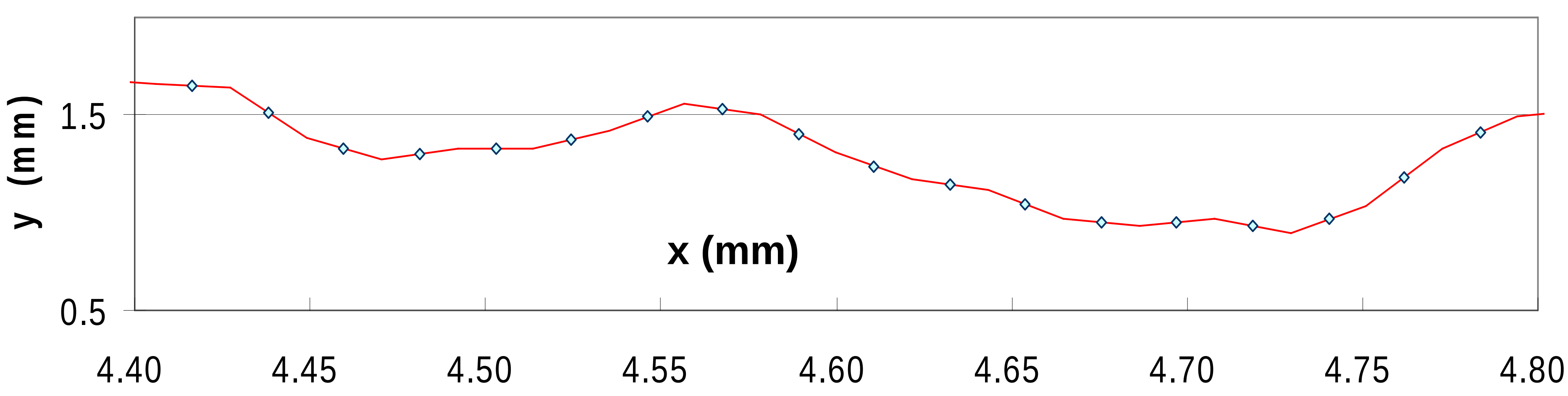


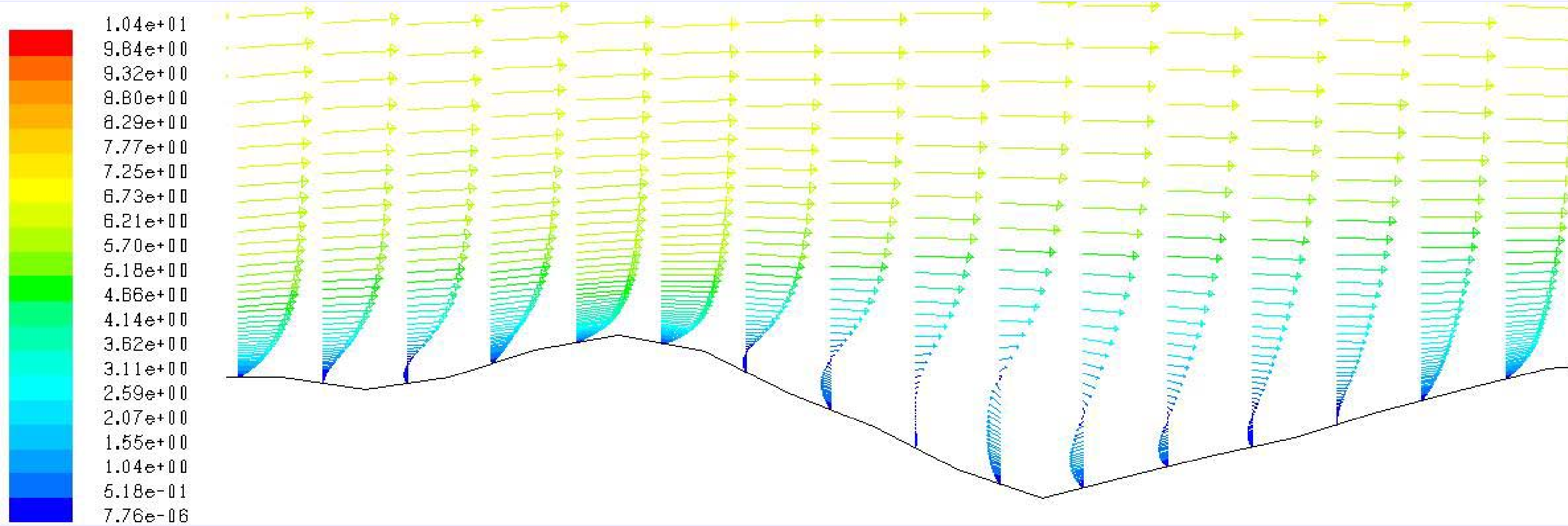


Part 1: Streamlines

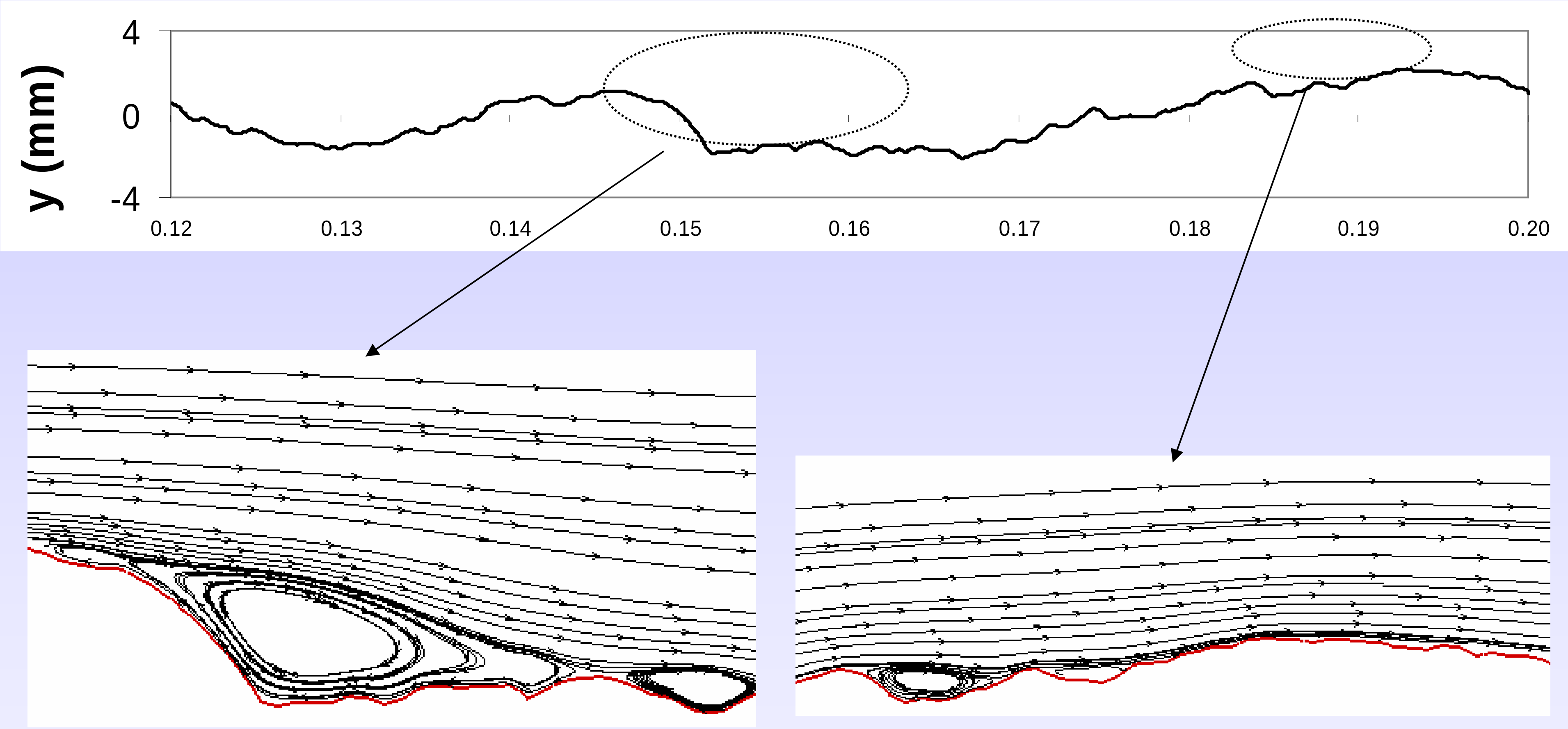


Part 1: Velocity Vectors





Part 2: Streamlines



Models for Rough Surfaces

- Prandtl/ Nikuradse

$$\frac{u}{u_\tau} = \frac{1}{\kappa}\ln\frac{u_\tau y}{\nu} + C - \left\{\frac{1}{\kappa}\ln\frac{u_\tau k}{\nu} + D\right\}$$

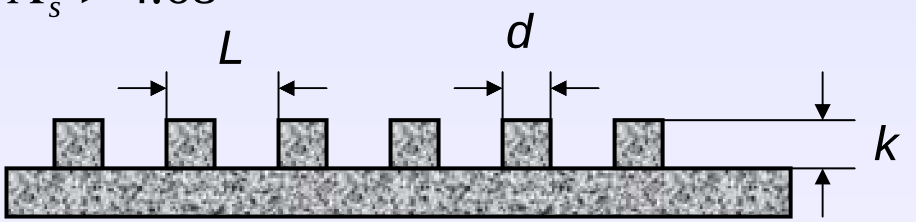
$$C_f = \left[2.87 + 1.58\log\left(\frac{x}{k_s}\right)\right]^{-2.5}$$

D = f(geometry, …)

- Variations by Bettermann (1966), Dvorak (1969), Dirling (1973), Simpson (1973), Sigal and Danberg (1990), ….

$$D = \begin{cases} 12.25\log\Lambda_s - 17.35 & 1 \le \Lambda_s \le 4.68 \\ -2.85\log\Lambda_s + 5.95 & \Lambda_s > 4.68 \end{cases}$$

$$\Lambda_s = \frac{L}{d}$$

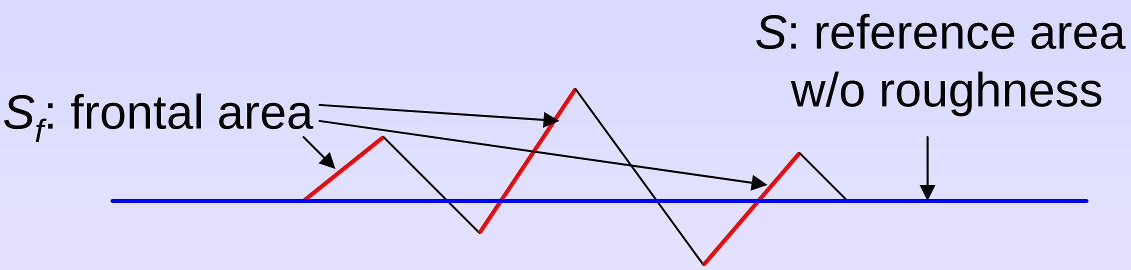


A New Model for C_f

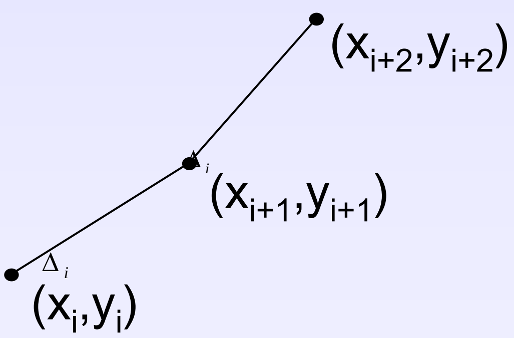
$$C_f = \left(4.2 + 2.7\log\left(\frac{x}{k_s}\right)\right)^{-2.5} + 0.005\left(\Delta_i + \left|\Delta_i\right|\right)$$

$$\frac{k_s}{R_a} = \log\left(-1.5\log\left(\Lambda_s\right) + 0.5\right)$$

$$\Lambda_s = \frac{A_f}{S}\left(\frac{A_f}{A_s}\right)^{-1.5}$$

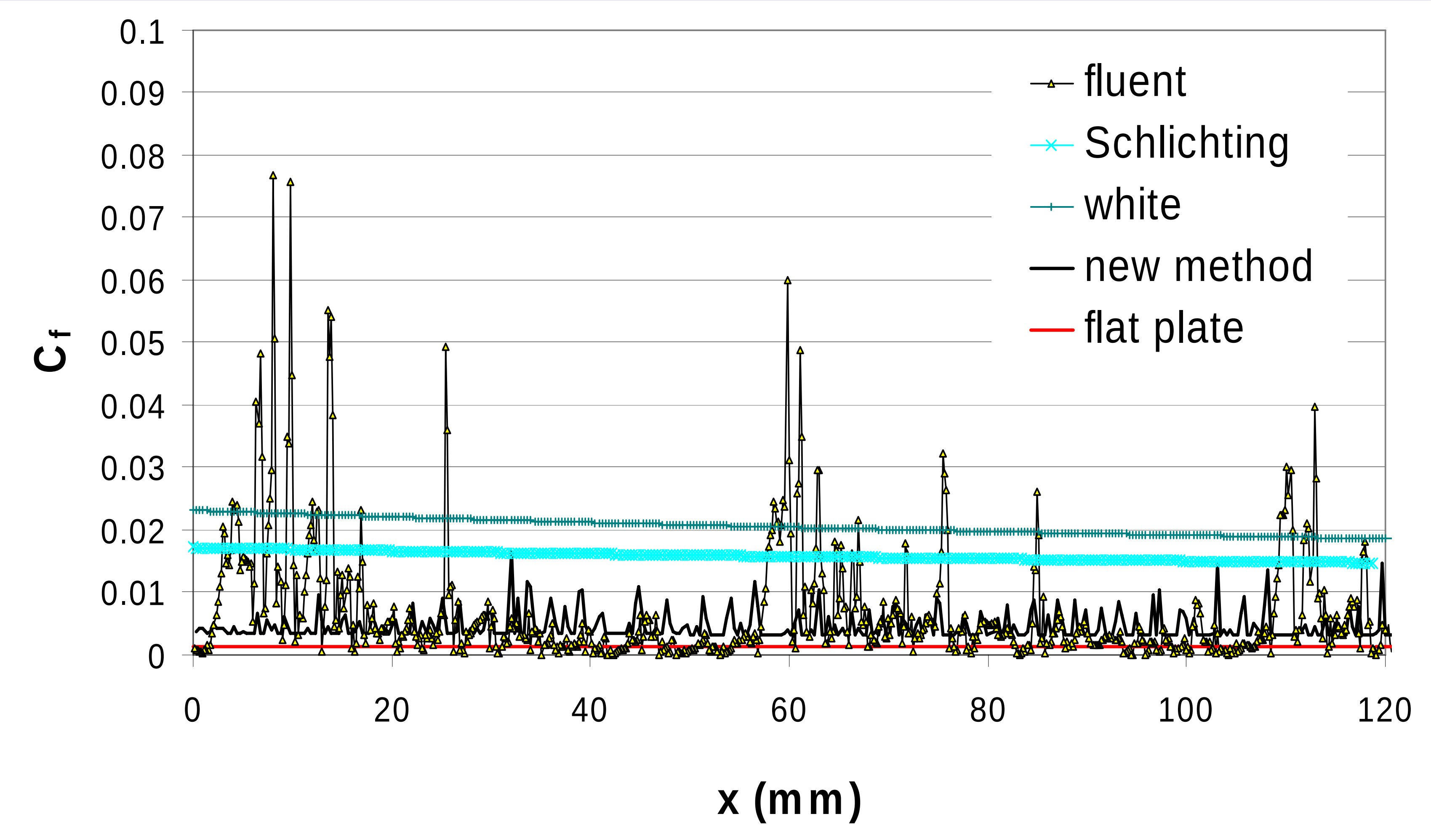


$$\Delta i = \frac{y_{i+1} - y_i}{x_{i+1} - x_i}$$



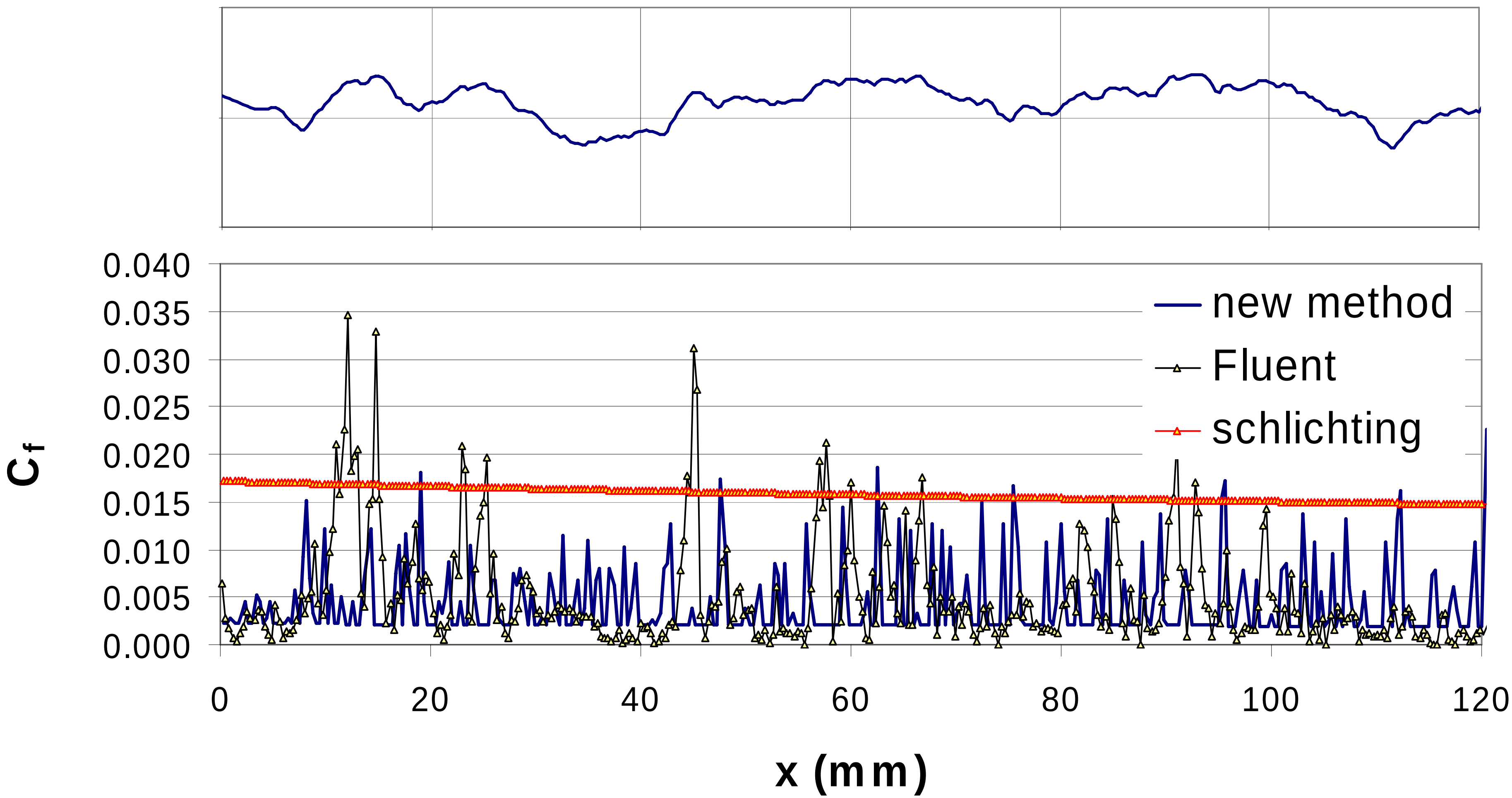
Positive slope increases friction.
Negative slopes contain recirculating regions.

Prediction by New Method



	FLUENT	Schlichting	New Method
$C_{f\_average}$	0.00472036	0.01476	0.0043987

Prediction by New Method for Another Surface



	FLUENT	Schlichting	New Method
$C_{f\_average}$	0.004401	0.015741	0.004401

Summary of 2-D Studies

- Generated CFD simulations of 2-D slices of surface roughness.
- Developed a new model to predict C_f.
- Preliminary results show promise.
- Will apply to 3-D roughness geometry data and evaluate usefulness.