Onset of flow instability and turbulence development over distributed sinusoidal 2D and 3D roughness

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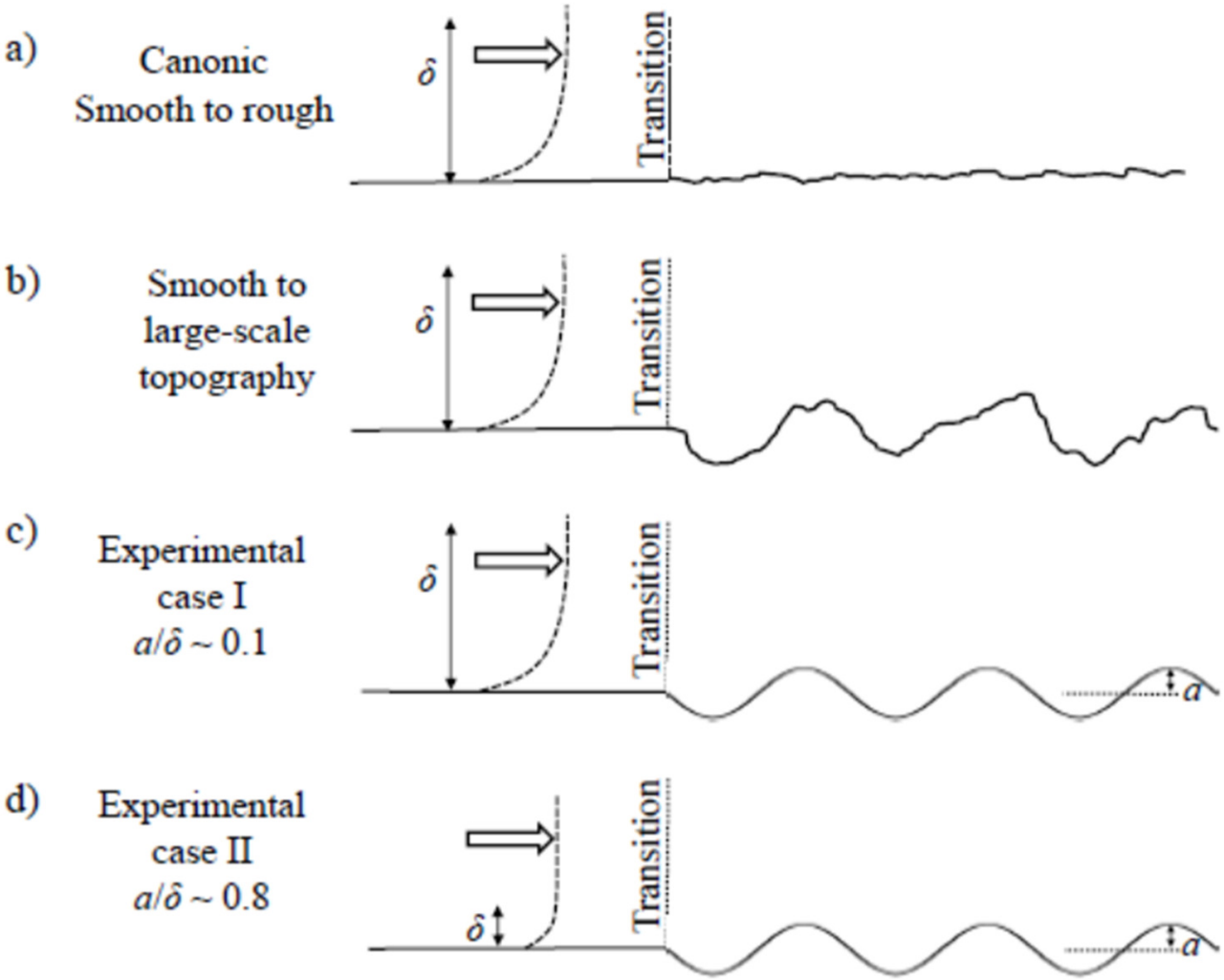
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Problem statement



General

- Geophysical flows are strongly modulated by large-scale topological features of complex terrains.
- These flows exhibit rich, energetic turbulence dynamics across a broad spectrum of scales
- A largely untapped phenomenon of high practical interest is the flow development past a rough-to-geophysical scale transition, and those dominated by large-scale modulations..
- Relevant in Wind Energy applications, scalar transport phenomena, erosion control.

We are examining this problem by performing laboratory experiments in a refractive-index-matching facility



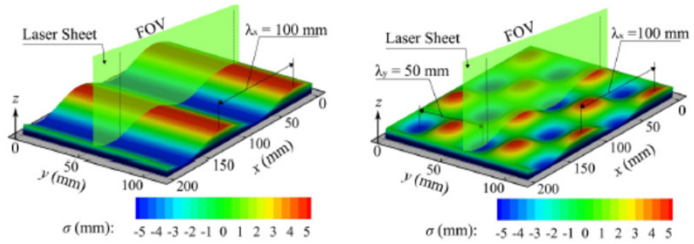
Adapted from www.polartrec.com



Key cases of large-scale topography ➧ 2D/3D waves

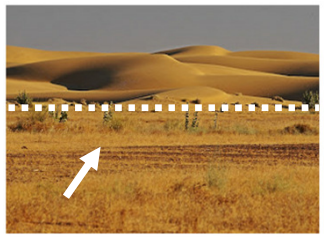
❑ Low-order large-scale topography

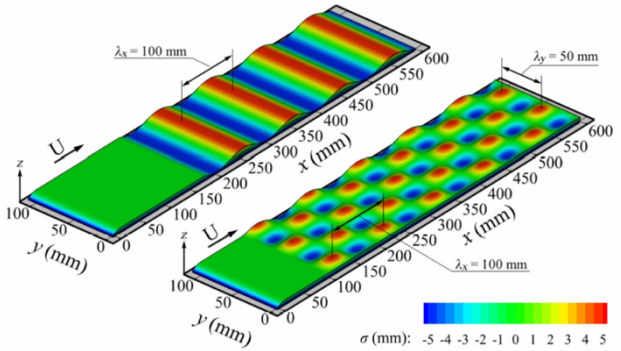




❑ Abrupt topography transition

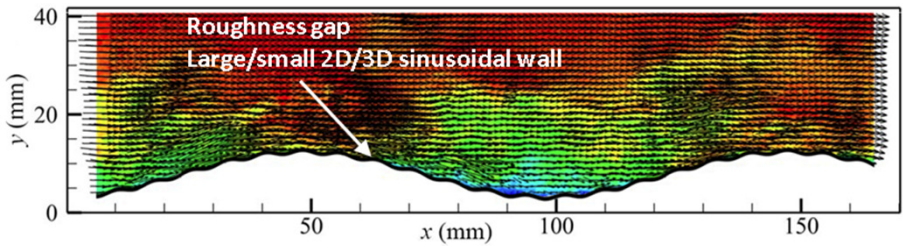






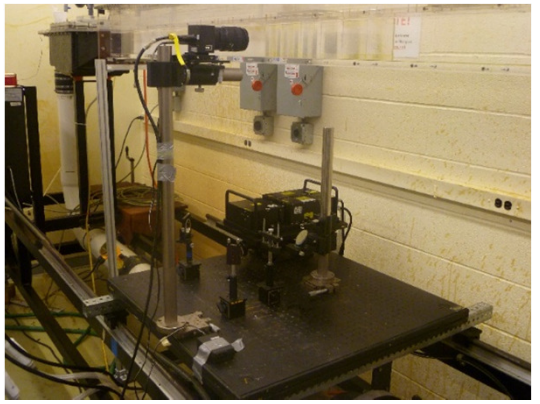
❑ Low-order large-scale topography

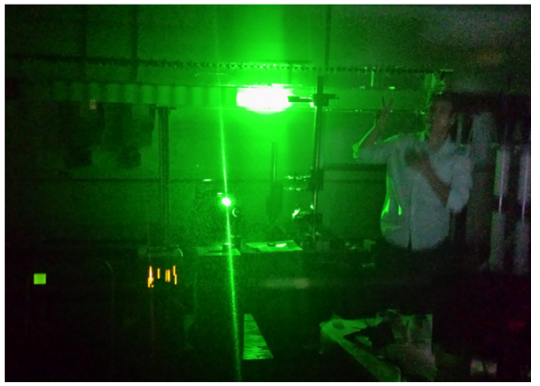




Technical approach

High-resolution PIV in a refractive-index-matching channel



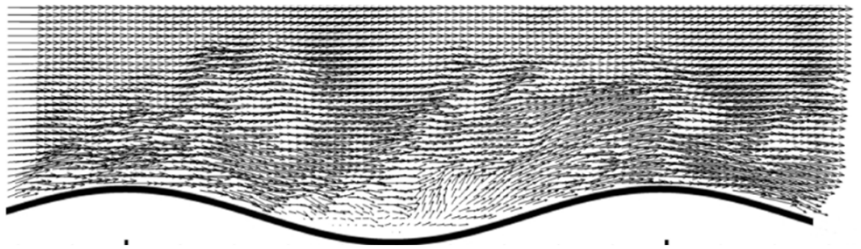


Refractive-index-matching (RIM)

- ❑Small channel 11.2 cm × 11.2 cm × 2.5 m
- ❑Large channel 40 cm × 40 cm × 2.5 m
- ❑NaI solution ~63% by weight
- ❑PMMA RI ~1.495
- ❑Match can be achieved through temperature control

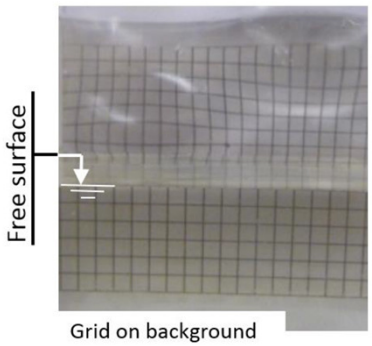
High spatial Resolution PIV

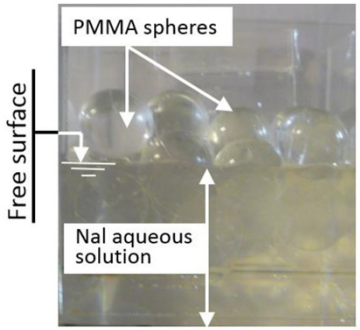
- ❑ 250 mJ/pulse laser
- ❑ 11MP CCD PIV cameras
- ❑ Achieve up to 100 micron vector spacing with a relatively large FOV



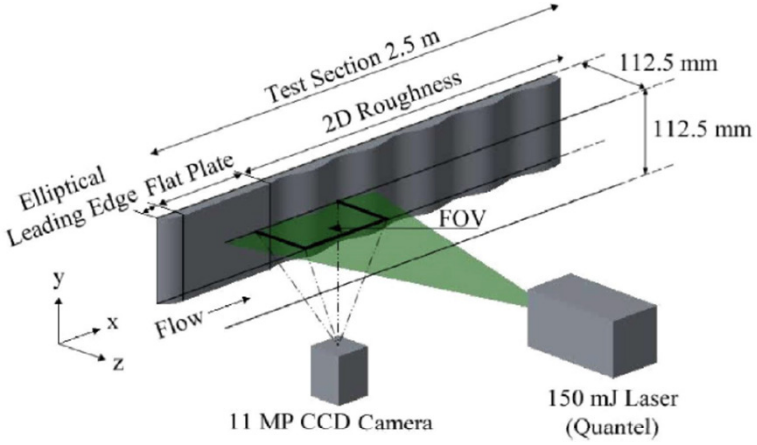
Large refractive-index-matching flume

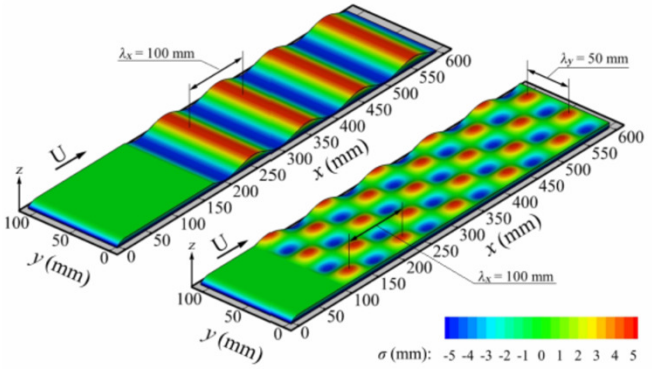






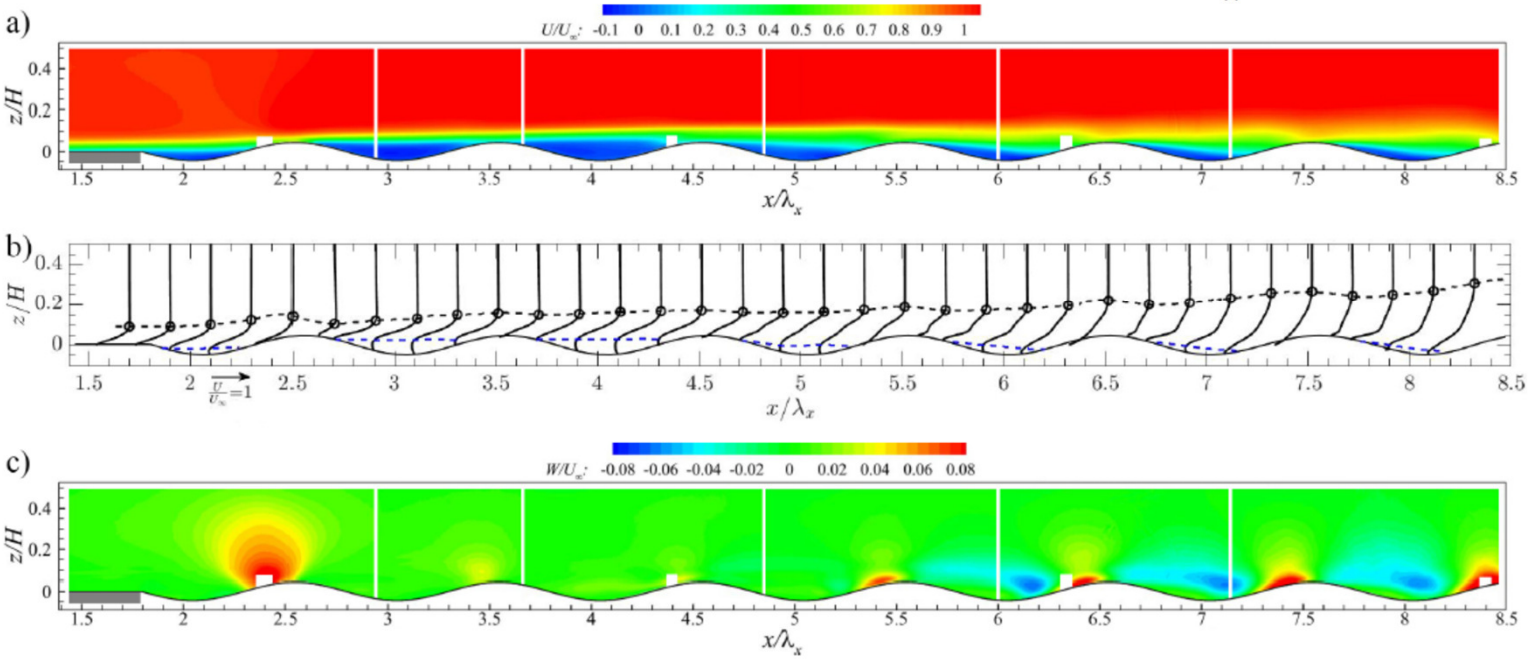
Flow transition to turbulence



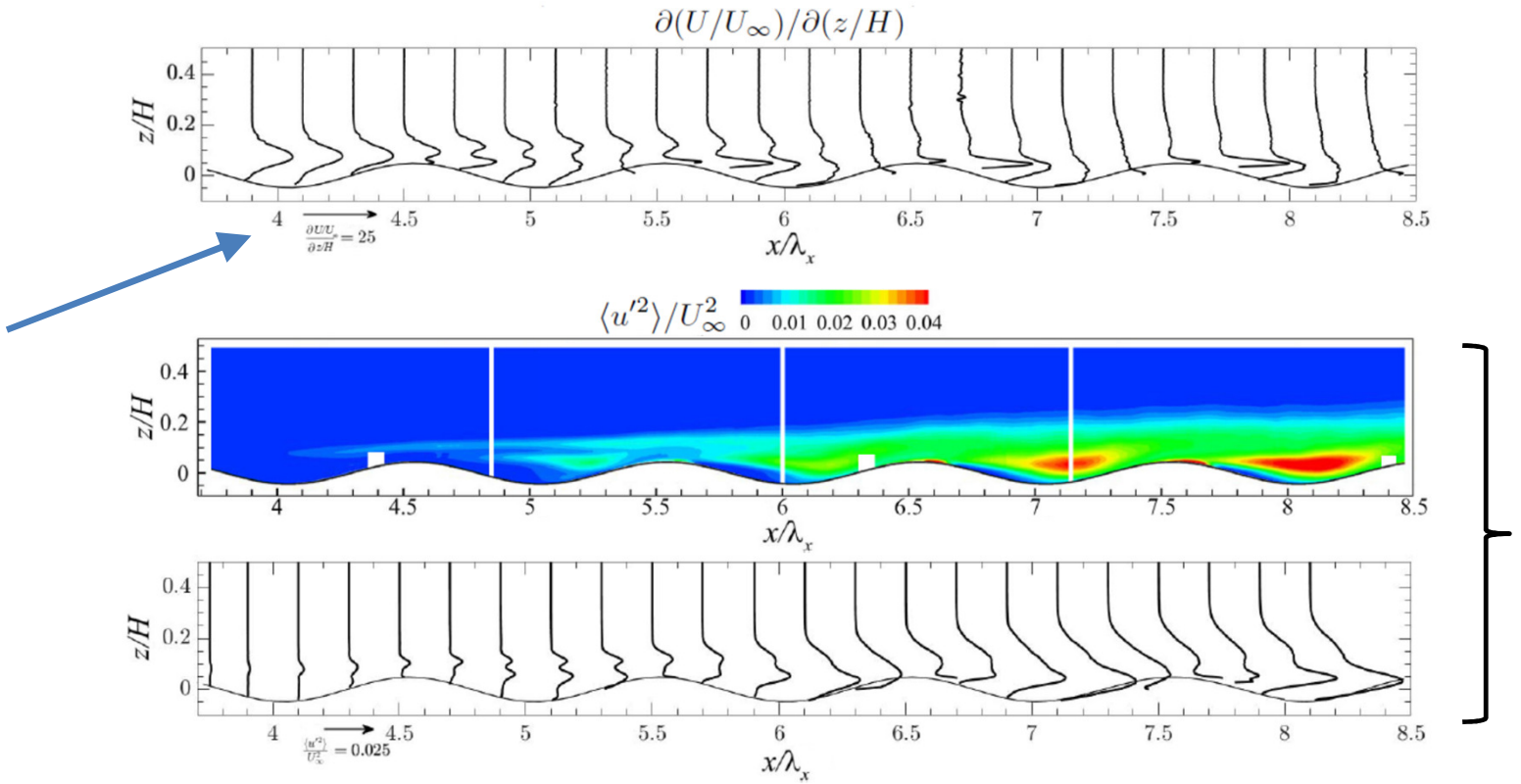


Roughness Reynolds number $Re_k \approx 300$

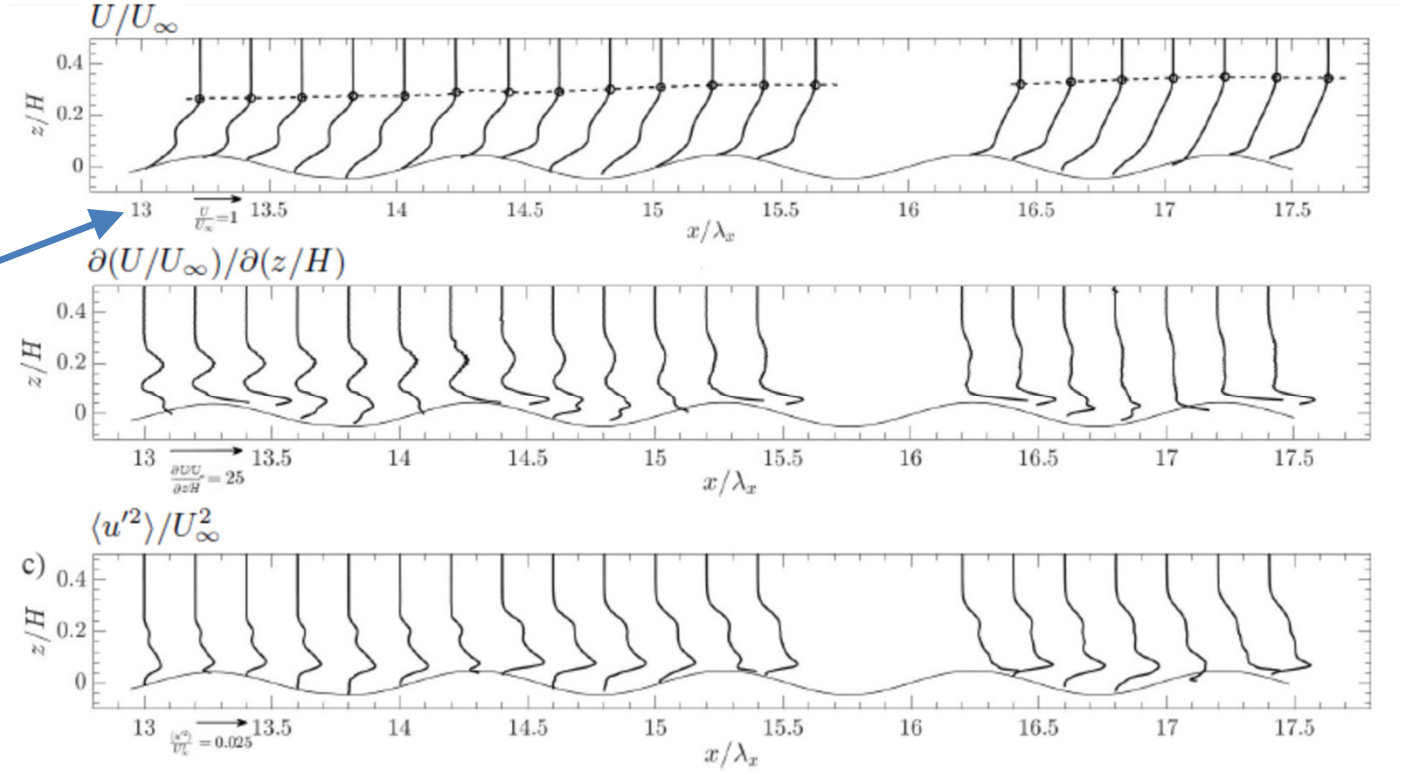
$$Re_h = 4600$$
$$U_\infty = 0.09 \text{ m s}^{-1}$$

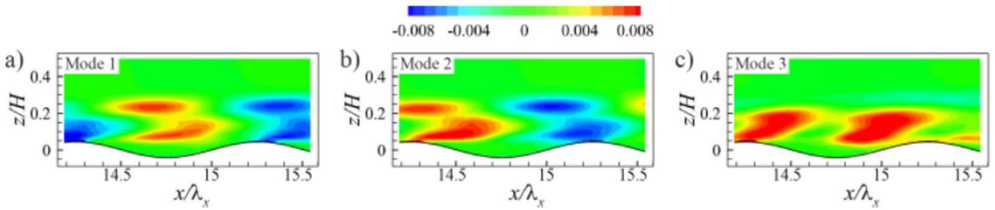


Transition to turbulence over a 2D wavy wall



Transition to turbulence over a 3D wavy wall







Flow over 2D/3D wavy walls in the developed region

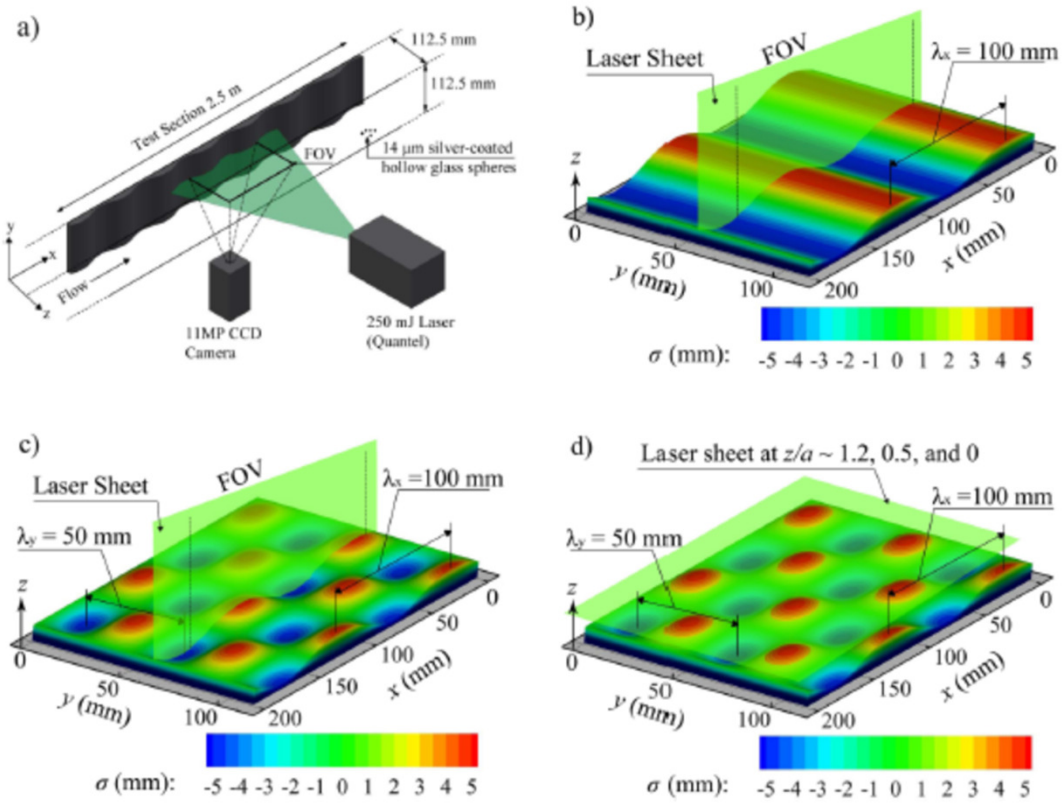
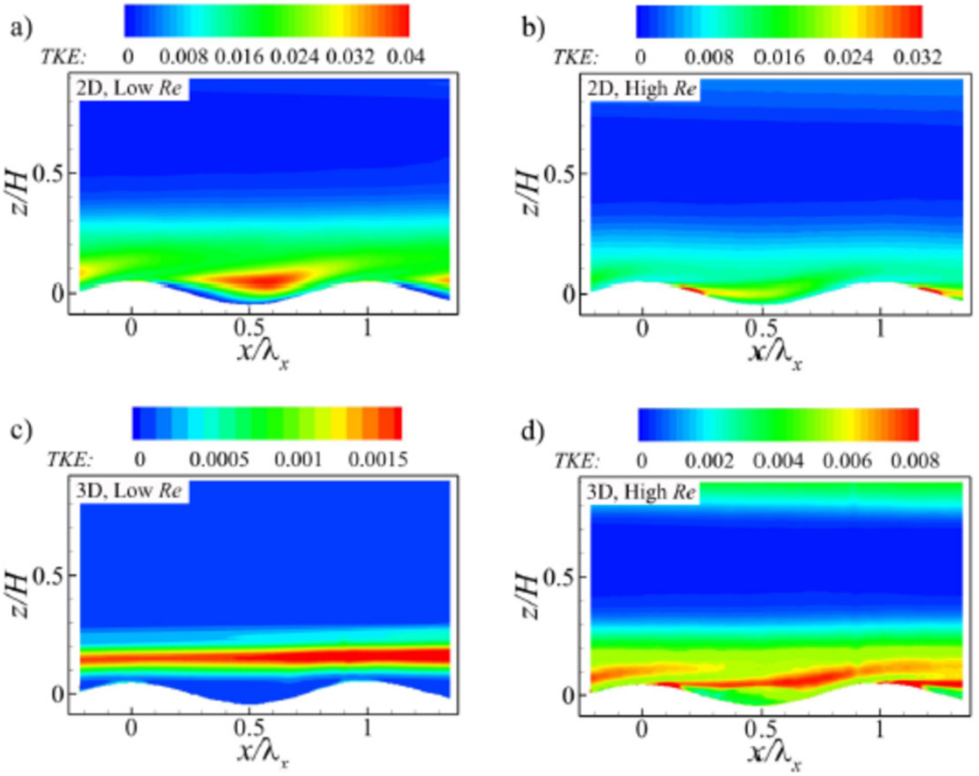


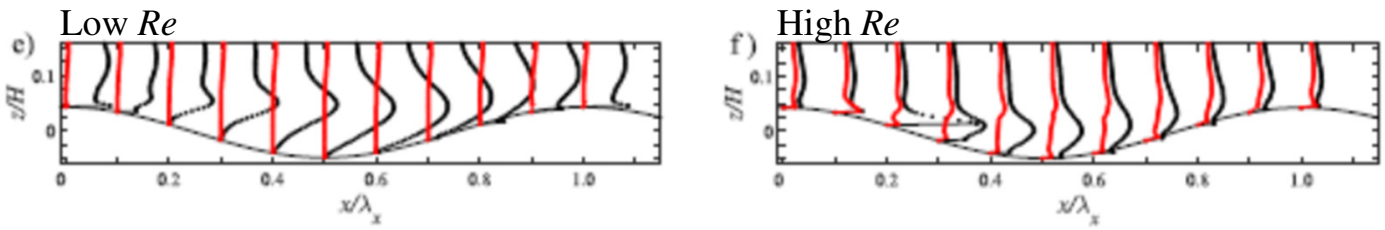
TABLE I. PIV experimental parameters for the low and high *Re*.

Measurement plane	Case	Number of realizations	FOV (mm × mm)	Final interrogation window (pixels)	Vector spacing (μm)
Wall-normal	2D	10 000	160 × 107	16 × 16	350
Wall-normal	3D	10 000	160 × 107	16 × 16	350
Wall-parallel $z/a \simeq 1.2$	3D	5 000	144 × 96	16 × 16	290
Wall-parallel $z/a \simeq 0.5$	3D	2 000	145 × 97	16 × 16	290
Wall-parallel $z/a \simeq 0$	3D	5 000	146 × 98	32 × 32	590

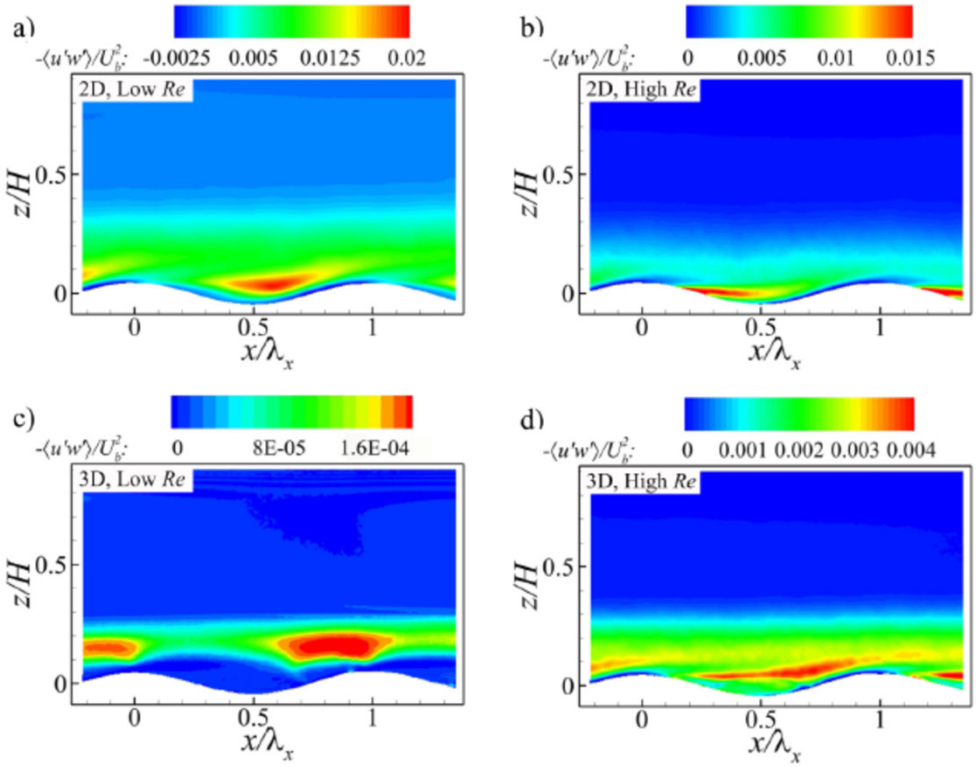
Turbulence Intensity



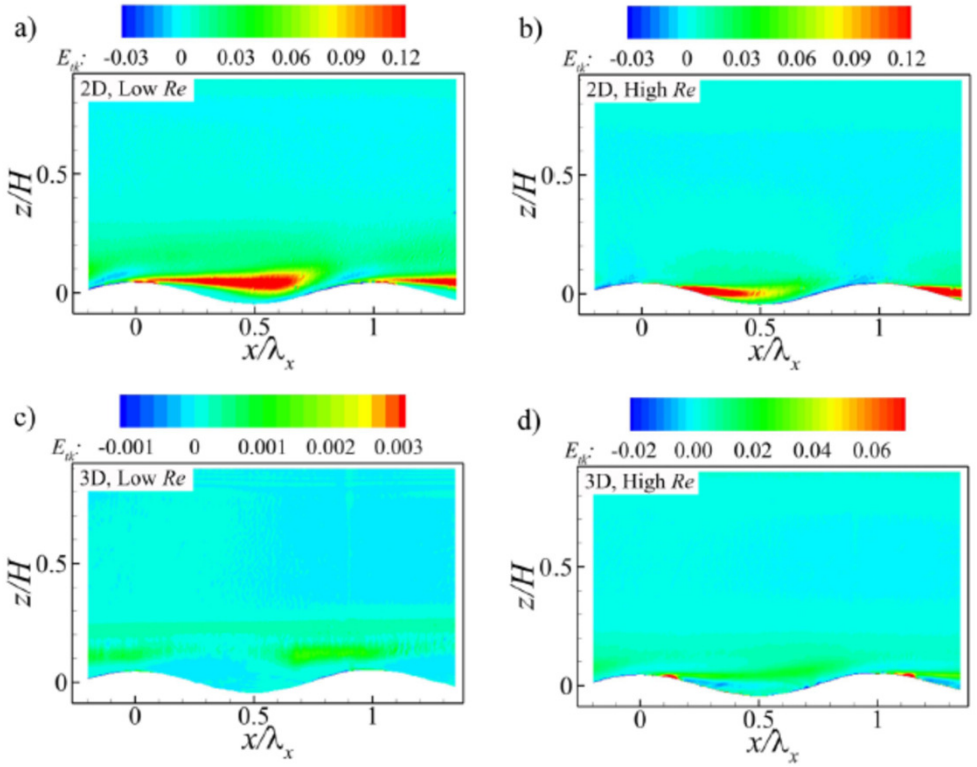
2D
3D



Kinematic shear stress

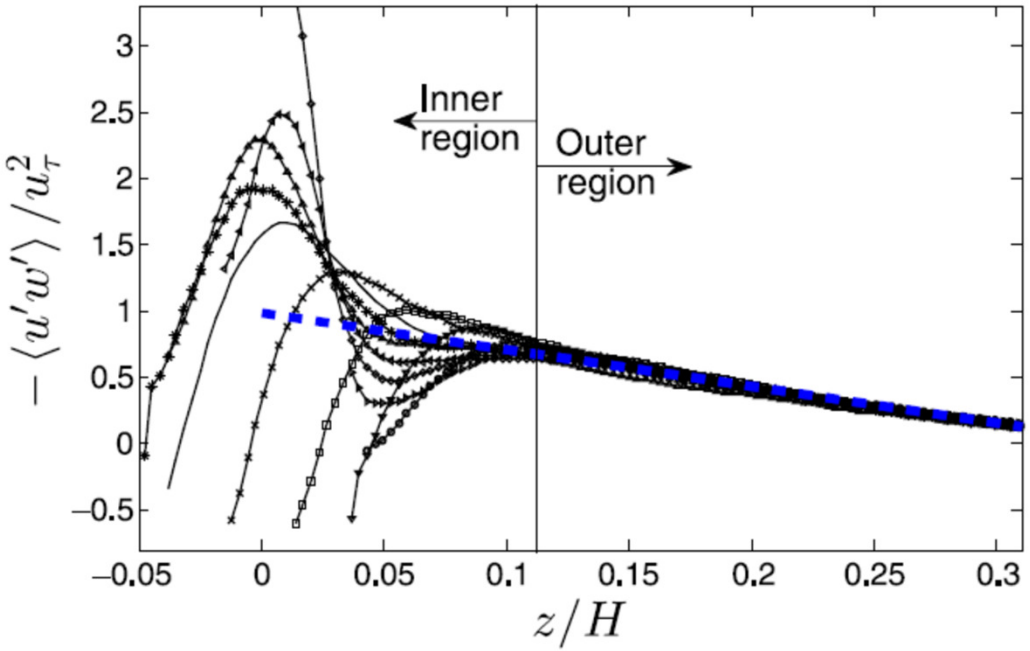


Turbulence Kinetic Energy Production



$$E_{tk} = -\langle u'w' \rangle \frac{\partial U}{\partial z} - \langle u'^2 \rangle \frac{\partial U}{\partial x} - \langle u'w' \rangle \frac{\partial W}{\partial x} - \langle w'^2 \rangle \frac{\partial W}{\partial z}$$

1D profiles of Reynolds Stress

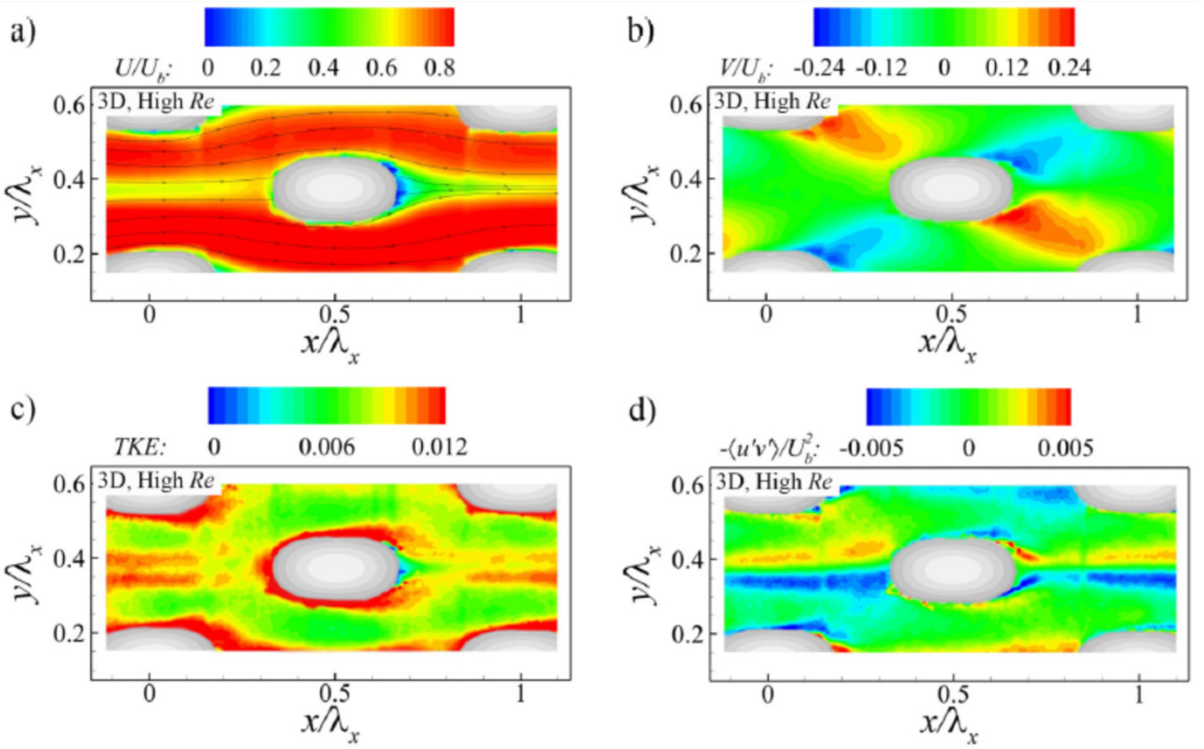


2D wavy wall, High Re.

$$u_\tau^{3D}/u_\tau^{2D} \simeq 0.83$$

$$\tau_w^{3D}/\tau_w^{2D} = (u_\tau^{3D}/u_\tau^{2D})^2 \simeq 0.7$$

Wall-parallel flow in the 3D wavy wall



Remarks

- Location of turbulence
  Rex(2D) = 50,000
  Rex(3D) = 120,000

- Mean wall shear stress:

$$u_\tau^{3D}/u_\tau^{2D} \simeq 0.83$$

$$\tau_w^{3D}/\tau_w^{2D} = (u_\tau^{3D}/u_\tau^{2D})^2 \simeq 0.7$$

