NORDITA-FLOW Spring School on Turbulent Boundary Layers – 6-9 April 2010

Issues in Experiments - part2

Facilities and wall shear stress measurements

Material prepared
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KTH Mechanics

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HIGH REYNOLDS NUMBER EXPERIMENTS

Topics

- High Reynolds number experiments
- Issues with facilities
- Wall shear stress measurements

Motivations

- High Reynolds number data required for fundamental turbulence research and flows of industrial interest
- Need for data with simultaneously
  - High Reynolds number
  - Resolution of all scales
  - Well converged statistics

Minimum Reynolds number

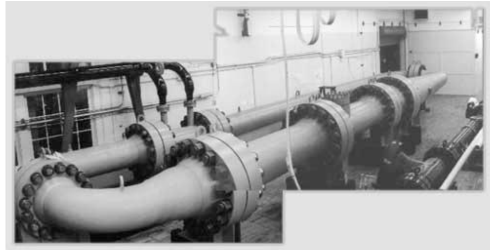
- Overlap region of the log law:
  - Approx: 300 < y+ < 0.15 R+
- 1 decade of y^+ in the Logarithmic region
  - R+ > 20000

$$\frac{u}{u_\tau} = \frac{1}{\kappa} ln(y^+) + B$$

High density experiments

"SuperPipe" in Princeton

- $D \approx 13$ cm
- $L/D = 200$
- High pressure (about 200 atm)
- Extremely large Re range : $Re \approx 5000 - 38 \times 10^6$
- Very small viscous length scales



Zagarola and Smits, 1998

How to get high Re?

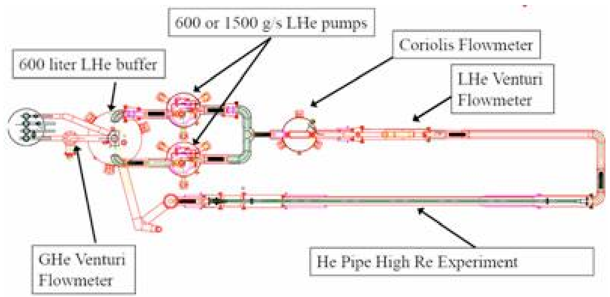
$$\mathrm{Re} = \frac{UL\rho}{\mu}$$

- High velocity (Limited by compressibility)
- Large size (Good resolution)
- High density (Pressurized facility)
- Low viscosity (Cryogenic facility)

Cryogenic experiment

Cryogenic flows at EUTUCHE (CERN)

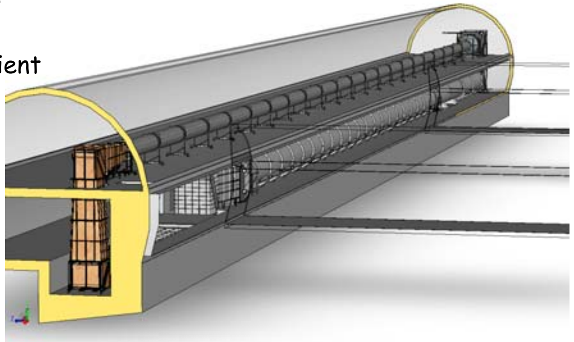
- very High Reynolds (up to $2*10^7$) in axisymmetric jet and pipe geometries (HePipe, R^+ up to 3.10^5),
- Very small viscous length scales



Large experiment

Long Pipe at CICLoPE, University of Bologna (in construction)

- Diameter: 0.9 m
- Length: 120 m
- Maximm R+: 50000
- Viscous length scale: > 12 μm
- Resolution of all scales
- Friction from pressure gradient
- Fully developed flow
  - Mean velocity
  - Higher moments

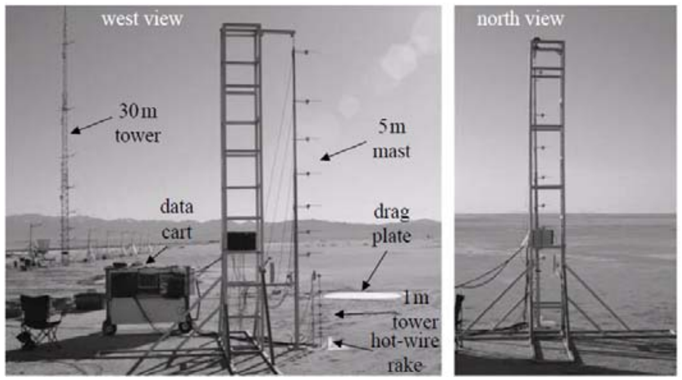


Talamelli et al. 2009

ISSUES WITH FACILITIES

Outdoor experiments

- **SLTEST Facility, UTAH salt flats**
- Very high Reynolds number
- Resolution of all scales
- Large variability due to the nature of the flow



Flow quality

- Flow homogenity
- Flow angularity
- Turbulence intensity
- Noise level
- Temperature stability
- Velocity stability
- Pressure gradient control

Close loop Wind tunnel

- Test section can work at ambient pressure (easy access with sensors)
- High flow quality
- Optimal flow control
- Need of cooling to keep temperature constant

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Flat plate versus wall flow

- Flat plate inside the test section
  - Clean flow developing on the flat plate
  - Easy conditioning of the surface
  - Surface temperature generally equal to flow temperature
  - Blockage under the flat plate
- Flow developing on the wall
  - Easy access trough the wall
  - Lot of space for bulky elements outside of the tunnel
  - Use of the full height of the test section for the flow

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Open loop Wind Tunnel

- Simpler and cheaper than close loop wind tunnel
- Limited control of the flow conditions
- Dust contamnination
- More power required for given speed
- Test section at ambient pressure (Blowing)
- Test section at low pressure (Suction)

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Flow control

- Fan regulation
- Stable flow conditions over long time period for good statistics
  - Velocity control
  - Temperature control
  - Reference velocity and temperature measurements

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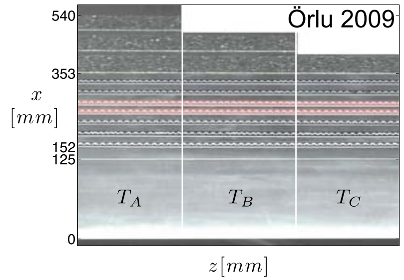
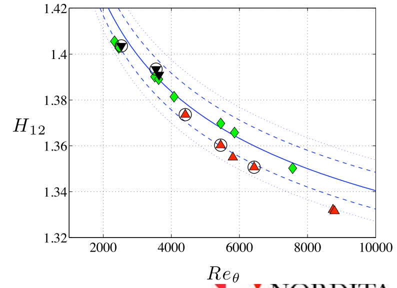
Inlet flow conditions

- Turbulence manipulators
  - Perforated plate
    - Homogenization of the mean velocity
  - Honeycomb
    - Elimination of large eddies, flow angularity
  - Screens and settling chamber
    - Small scale mixing to homogenize the flow
    - Decay of the small eddies

Boundary layer tripping.

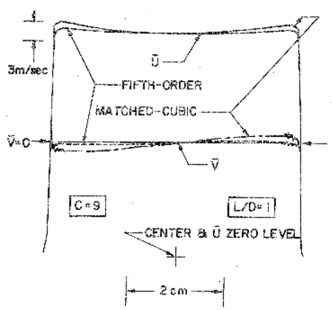
- Fix the transition point and the virtual origin of the turbulent BL
- Ensure span-wise flow homogeneity
- Ensure constant tripping position at different velocities
- The shape factor H is a good indicator of the tripping effect (Chauhan et al. 2009)
- Issue for DNS simulation of boundary layer flows





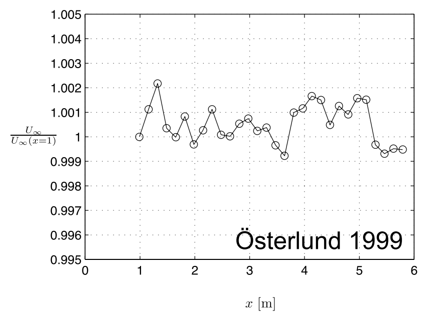
Contraction

- The design has a large impact on the flow quality
  - Flat velocity profile
  - No flow separation for low turbulence level
  - No improvement of the flow quality for contraction ratio greater than 9:1
- Shape
  - Zero curvature at inlet & outlet
  - Gentle curvature after the inlet
    - Concave curvature destabilize the flow
    - Danger of flow separation -> high rms
  - Stronger curvature near the outlet
    - Convex curvature stabilize the flow



Pressure gradient control

- Mobile roof panels (stream-wise and span-wise)
- Constant free-stream velocity
- Zero pressure gradient
- Measurements
  - Pressure taps
  - Velocity traverse



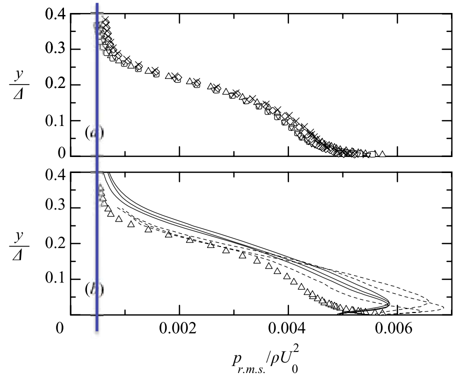
- Target pressure gradient for ZPG experiments O(0.1%)
- A test performed in the NDF at IIT (Nagib et al 2009) showed that a pressure gradient of 4% results in a change of the friction velocity of about 4%.

Blockage

- Asymmetric blockage due to traversing system, support, etc generate circulation around the flat plate
- The circulation increase the angle of attack and can lead to leading edge separation
- Control of the circulation using a flap at the trailing edge of the flat plate

Noise level

- Noise source
  - Fan noise
  - Flow generated noise
- Noise reduction
  - Sound absorbing material
  - Acoustic mufflers
- Requirement for the MTL
  - prms < 0.00015*q
  - (84dB at 60 m/s)
  - 1/10 of the minimum turbulent pressure fluctuation level



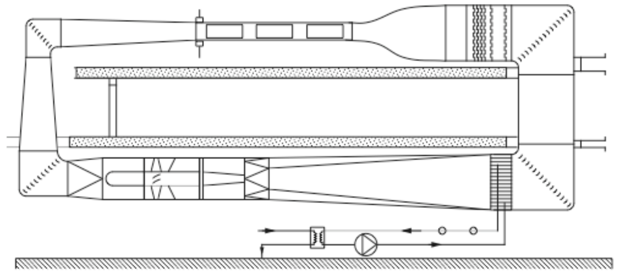
Tsuji et al. 2007

Diffuser

- Long diffuser
  - Prone to large scale separation
  - Separation affect the flow quality in the test section
  - Turbulence generators may have to be installed near the flap to avoid flow separation in the diffuser
  - Detached flow from models can also lead to diffuser separation
- Split diffuser
  - Create little more pressure drop that long diffuser
  - Compact
  - Less sensitive to inlet flow conditions
  - Separation, if any, is localized, hence has less influence on the flow quality

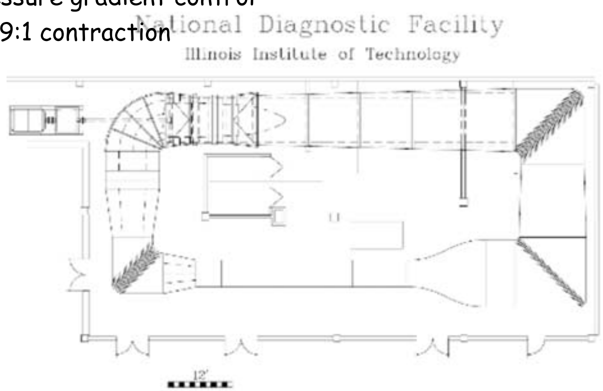
MTL at KTH, Stockholm

- Test section 0.8 x 1.2 x 7 m (H x W x L)
- Maximum velocity: 69 m/s (empty test section)
- Mean flow uniformity < 0.1%
- Turbulence intensity < 0.03%
- Temperature stability < ±0.1°C
- Honeycomb, 5 cleanable screens and 9:1 contraction
- Acoustic level 83 dB at 60 m/s
- Flat plate at mid-height
- Long diffuser



NDF at IIT, Chicago

- Test section 1x1x10 m (H x W x L)
- Maximum velocity: 110 m/s
- Mean flow uniformity < 0.1%
- Turbulence intensity < 0.05%
- Motorized ceiling for pressure gradient control
- Honeycomb, screens and 9:1 contraction
- Flat plate at mid height
- 1:3 Split diffuser



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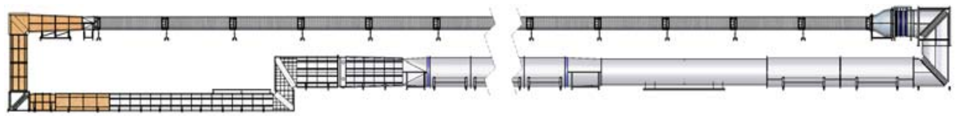
Long pipe at CICLoPE, Bologna

- **Expected characteristics**
- Test section: 0.9x115 m (D x L)
- Maximum velocity: > 65 m/s (R+ > 65'000, Power: 340 kW)
- Viscous length scale 11 μm @ 38 m/s (R+=40'000)
- Resolution of all scales with hot-wires
- Fully developed flow (Mean velocity, higher moments)
- Friction from pressure gradient
- Temperature stability O(±0.1°C)
- Velocity stability O(±0.1%)
- Acoustic level < 87dB (69 m/s)
- Honeycomb, 5 cleanable screens and 4:1 contraction
- Split diffuser



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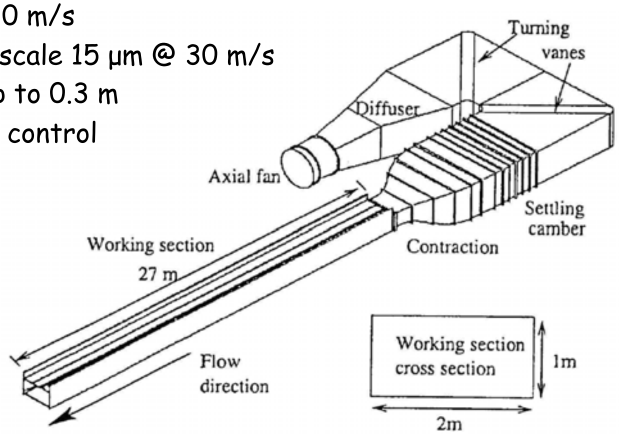
HRNBLWT in Melbourne

- Test section: 1x2x27 m (H x W x L)
- Maximum velocity: > 30 m/s
- Ret: 20'000 @ 30 m/s
- Visocous length scale 15 μm @ 30 m/s
- B.L. thickness up to 0.3 m
- No temperature control
- Wall flow
- No diffuser



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WALL SHEAR STRESS

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Direct techniques

- No hypothesis on the velocity profile

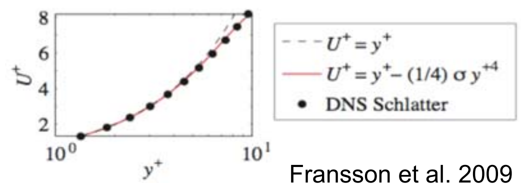
- Pressure drop in fully developed pipe (channel) flow
- Oil film interferometry
- Wall balances
- Momentum technique

Near wall measurements

- Rely on the existence of a linear viscous sub-layer bellow y+ = 5 (3.5)

- Measurement techniques
  - Hot-wires
  - Optical techniques
    - (μ)LDA
    - (μ)PIV

$$U^+ = y^+ - \frac{1}{4}\sigma y^{+4} \ldots$$



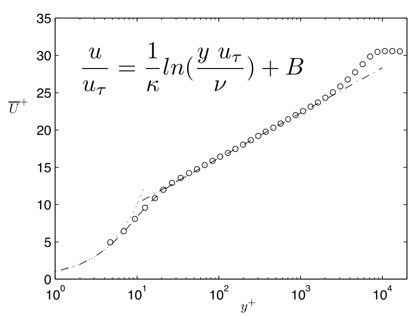
Fransson et al. 2009

- The viscous sub-layer is very thin at high Reynolds number, hence making measurements in this region fairly complicated

Indirect techniques

- Hypothesis on the velocity profile
- Calibration with a reference shear flow

- Preston tube
- Clauser plot, profile fit
- Wall fence
- Wall hot-wire, pulsed wire
- Wall film, MEMS film
- Micro pillar, micro fence
- Liquid crystals
- Etc…

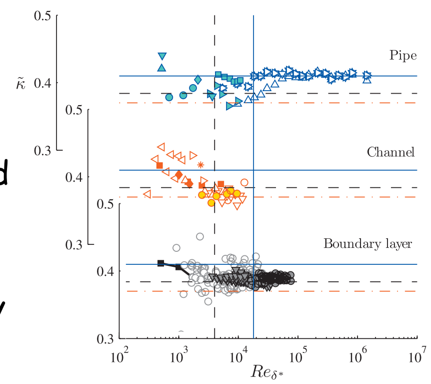


Mean wall shear stress

- Crucial for the scaling in inner variables

- Von Karman "κ" is NOT constant, hence profile based techniques should only be used with great care if at all

- Direct techniques are the only solution as long as one don't have a clear understanding of the behavior of the Karman "κ"

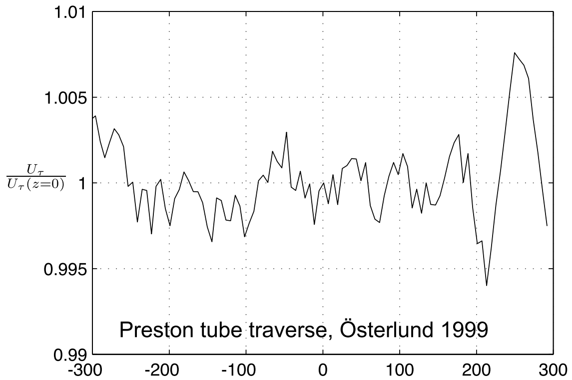


Nagib and Chauhan 2008

- Direct measurement techniques:

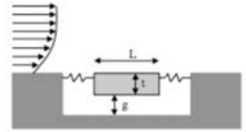
Wall shear stress variability

- Span-wise wall shear stress variation
  Very sensitive to experiment setup
  A proper setup allows very good span-wise homogeneity



Wall balances

- Flush mounted elements
  - Sensitive to alignment, gap size, pressure gradient and vibrations
- Sensing element size
  - Large to be sensitive
  - Small to measure local skin friction
- New development in MEMS balances
  - Favorable scaling of errors at micro scale
- Not commercially available anymore?



Naughton et al. 2000

Momentum integral method

- Does not require fully developed flow
- Difficult to use in practice
- Limited accuracy

$$\frac{\overline{\tau}}{\rho\, U_\infty^2} = \frac{d\theta}{dx} + (H+2)\frac{\theta}{U_\infty}\frac{dU_\infty}{dx}$$

Pressure drop

- Balance between wall friction and pressure drop

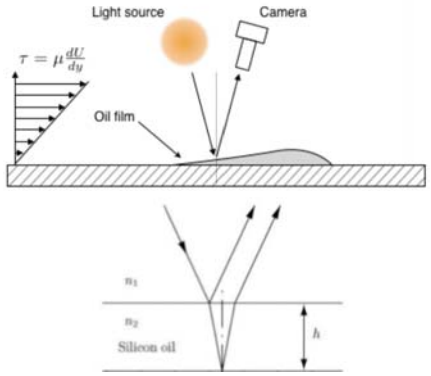
$$\overline{\tau} = \frac{\Delta P}{2}\frac{R}{L}$$

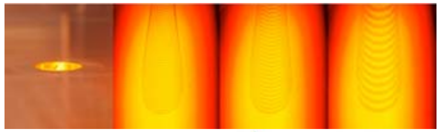
- Only applicable in fully developed flows
- Correction for channel
- Care must be taken with the tap design for the static pressure measurement

Oil film interferometry (OFI)

- Measurement of the thinning rate of an oil film
- Setup
  - Monochromatic light source
  - Digital camera
  - Glass surface
  - Silicone oil
  - Surface temperature sensor

$$\overline{\tau_w}\ k + \overline{\tau_w}\frac{h_0}{\Delta h} = \mu\ u_k \frac{2\sqrt{n^2 - sin^2\alpha}}{\lambda}$$

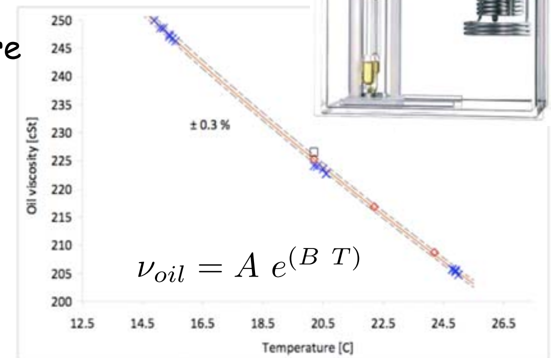




OFI - Oil viscosity calibration

- Thermo-regulated bath
- Capillary viscometer
- Optical barrier or stop watch
- Reference temperature sensor
- Accuracy ≈ 0.3%

$$\frac{1}{\nu}\frac{\partial\nu}{\partial T} \approx 2\%/°C$$



Rüedi et al., 2009

OFI - Measurement procedure

- Independent calibration of the oil viscosity vs. temperature
- Spatial calibration with a target
- Acquisition of the images
- Analysis of the fringe spacing vs time

OFI - Temperature measurements

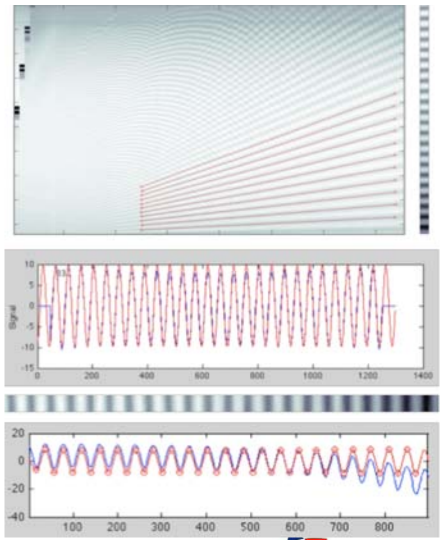
- Evaluation of the surface temperature

$$\frac{\Delta T_{(oil-air)}}{\Delta T_{(oil film)}} \simeq O(10^3)$$

Type	Principle	Accuracy without calibration	Size	Danger
Thermocouple	Junction voltage	1.0-2.2°C	Small	
RTD (PT100)	Resistor	0.03-0.3°C	Large	(Self heating)
Thermistor	Resistor	0.1-0.3°C	Small	Self heating

OFI Analysis method

- XT, Wavelength, Peak distance
- Very good agreement between the methods is obtained when used correctly
- Initial transient due to the formation of the oil film
- The manual selection of the fringes (XT method) is very user-dependent and can lead to a large scatter of the results



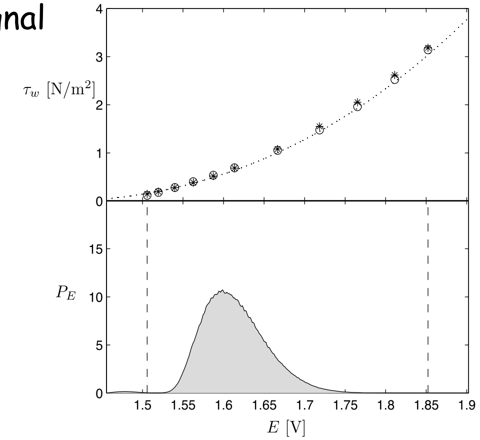
Fluctuating wall shear stress

- Characteristics of the signal
  - Long tail PDF
  - S ≈ 1, F ≈ 4

$$\tau'/\overline{\tau} \approx 0.4$$

- Calibration range

$$0.3 - 3\ \overline{\tau}$$

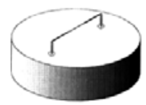


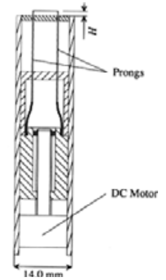
OFI - Time and spatial range

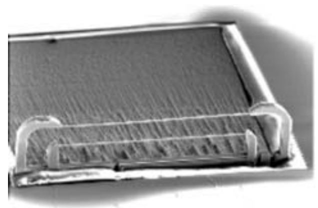
- Transient apparent decrease of the wall shear stress due to the formation of the oil film
- Potential surface tension effect at the edge of the oil film

Wall wire devices

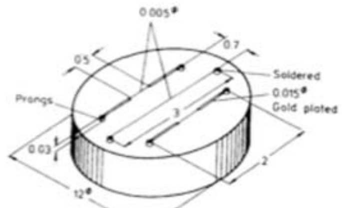
- Calibration in a reference flow
- Measurement of the mean and fluctuations
- Problems:
  - Height of the sensor limit its use
  - Heat transfer at the wall





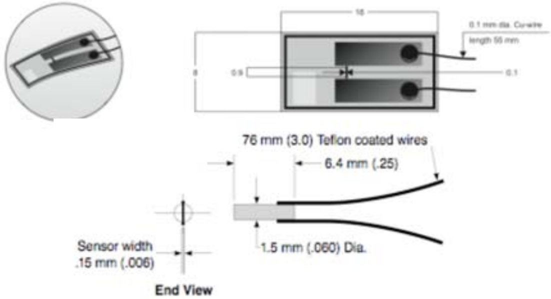


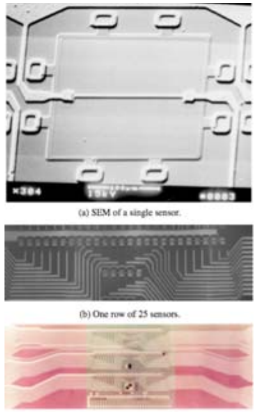
Löfdahl et al. 2003



Wall film devices

- Calibration in a reference flow
- Measurement of the mean and fluctuations
- Problems:
  - Heat transfer trough the surface
  - Surface temperature





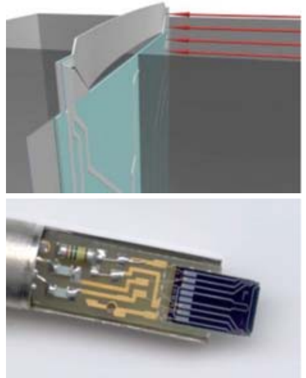
Jiang et al. 1996

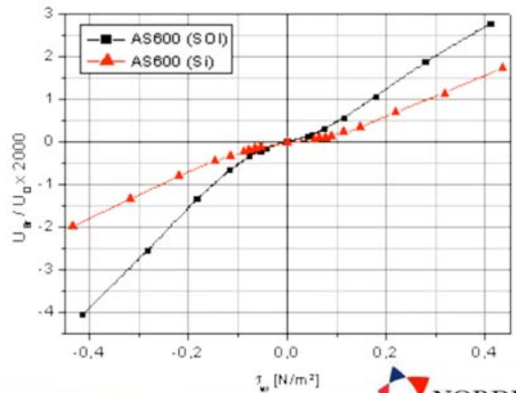
MEMS surface fence

Micro-sensor and actuator technology center TUB, Berlin

Principle: Deformation of an element by the flow

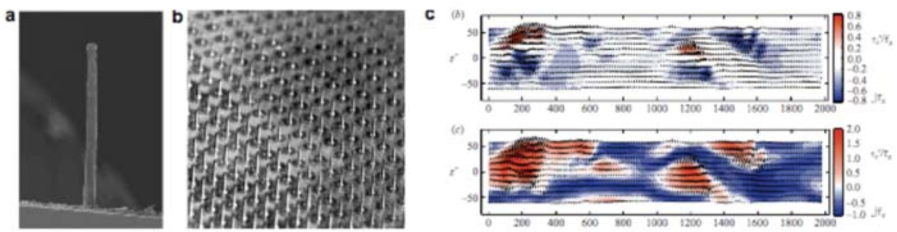
Static calibration in a reference flow





Micro pillar

- Institute of Aerodynamics, RWTH Aachen University
- Principle: Optical measurement of the deformation of pillars by the flow near the wall
- Static calibration in a reference flow
- Dynamic calibration using a magnetic field



Grosse et al. 2009

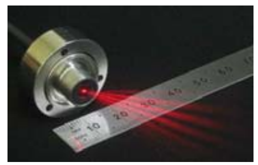
Micro-Optical sensor

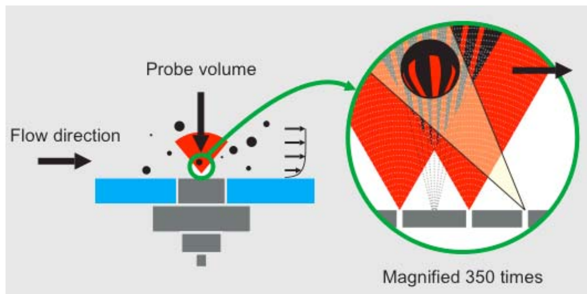
Micro-Optical Sublayer Shear Stress Sensor, MSE

Frequency proportional to the velocity gradient

Commercially available from MSE

Measurement height: 75 μm and 135 μm





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