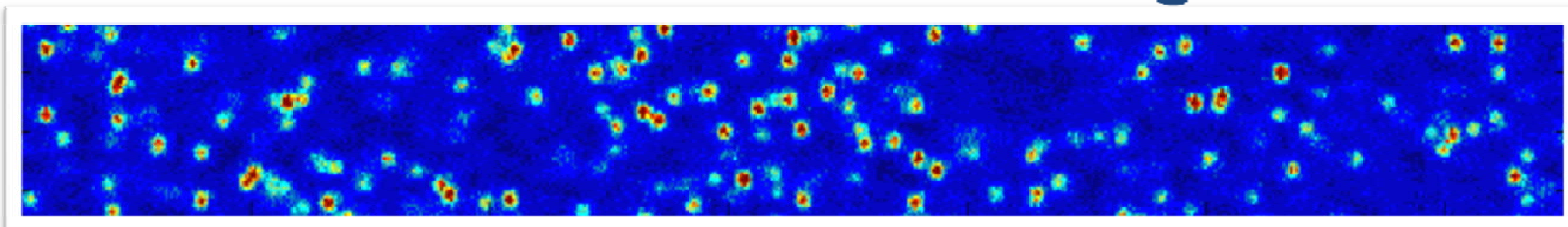
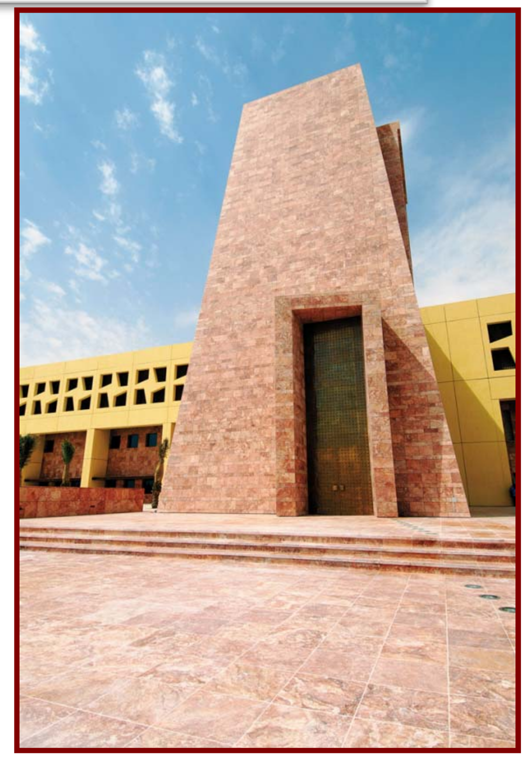
Nano-Particle Image Velocimetry (nPIV);

Data Reduction Challenges





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OUTLINE

- Introduction
  - Nano Particle Image Velocimetry (nPIV)
    - Experimental set up
  - Numerical method
    - Theory & Simulation
- Results
  - Surface forces
    - Particle distribution near the wall
  - Effect of Brownian motion + non uniform illumination
  - Effect out of plane velocity gradient
- Experimental results
- Conclusions

nPIV

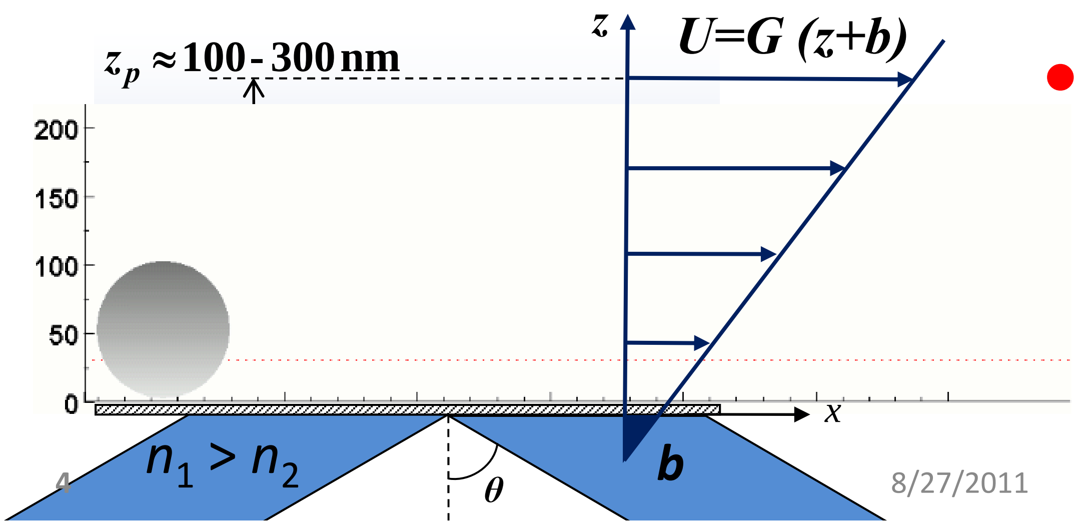
- New diagnostic technique to study near-wall flows at the sub-micron (“nano”) scale
- Measure two components of nearly instantaneous velocity parallel to wall

[Li and Yoda, Exp Fluids , 2008]

- Extension of standard (macroscale) PIV
  - Use evanescent-wave illumination: TIR
  - Seed flow with neutrally buoyant fluorescent particles
  - Record tracer particle images over time
  - Particle velocity ≈ flow velocity

nPIV: IMPLEMENTATION

- Illuminate flow with evanescent wave from TIR of light at solid-fluid interface
- Occurs at angle of incidence $\theta > \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$
- Evanescent wave propagates parallel to wall
- Intensity $\propto$ $\exp\{-z / z_p\}$, $z_p = \frac{\lambda_0}{4\pi n_1}\left[\sin^2\theta - \left(\frac{n_2}{n_1}\right)^2\right]^{-1/2}$



- Brownian motion causes particle drop out/in illumination region

[Sadr et al., Exp. Fluids, 2005]

BROWNIAN MOTION

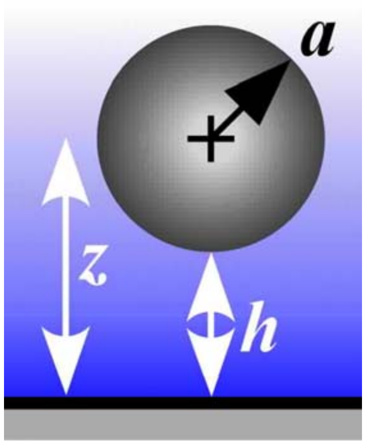
- Random motion of submicron particles in a fluid due to thermal energy

$$D_{B\infty} = \frac{kT}{6\pi\mu a}$$

  - Brownian diffusion hindered by wall
    - Out-of-plane (z) diffusion

[Bevan & Prieve 2000]

(*a*=50nm, T=300 K) $D_{B\perp} = 0.47 D_{B\infty}$ for $h/a = 1$



  - Over Δt = 6.5 ms (f =153 *Hz*)

$$\delta z_{B\perp} = 160 \text{ nm for } h/a = 1$$

- Langevin equation

$$\Delta\vec{x} = \sum_{t=0}^{t=\Delta t}\left\{(\vec{\nabla}\cdot D)\delta t + \chi\delta\vec{r}\right\}$$

  - χ =Normally distributed random numbers ; mean=0 , σ=1

SURFACE FORCESS

- Electrostatic force
  - $F_{el} = f_n(k, T, a, \varepsilon_0, \varepsilon, e, \lambda, \zeta_p, \zeta_w)$

  ε = permibility, e = elementry charge

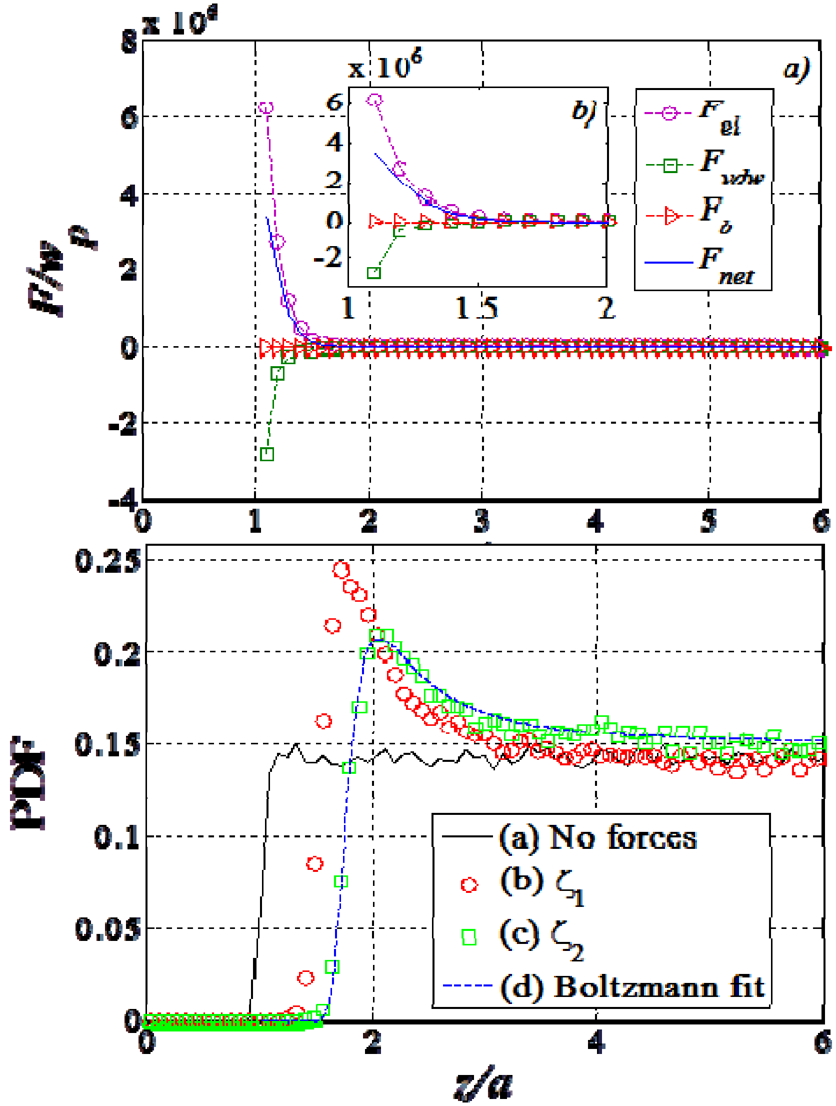
  γ = Debye lengths, ζ= Zeta potential

  [Oberholzer et al., J Chem Phys 1997]

- van der Waals forces
  - $F_{vdw} = f_n(z, a)$
- Buoyancy forces,
  - $F_b = f_n(V, \rho_f, \rho_p)$
- Langevin Equation

Surface effects

$$\Delta\vec{x} = \sum_{t=0}^{t=\Delta t}\left\{\left(\vec{\nabla}\cdot D\right)\delta t + \chi\delta\vec{r} + \frac{D}{kT}F\delta t\right\}$$



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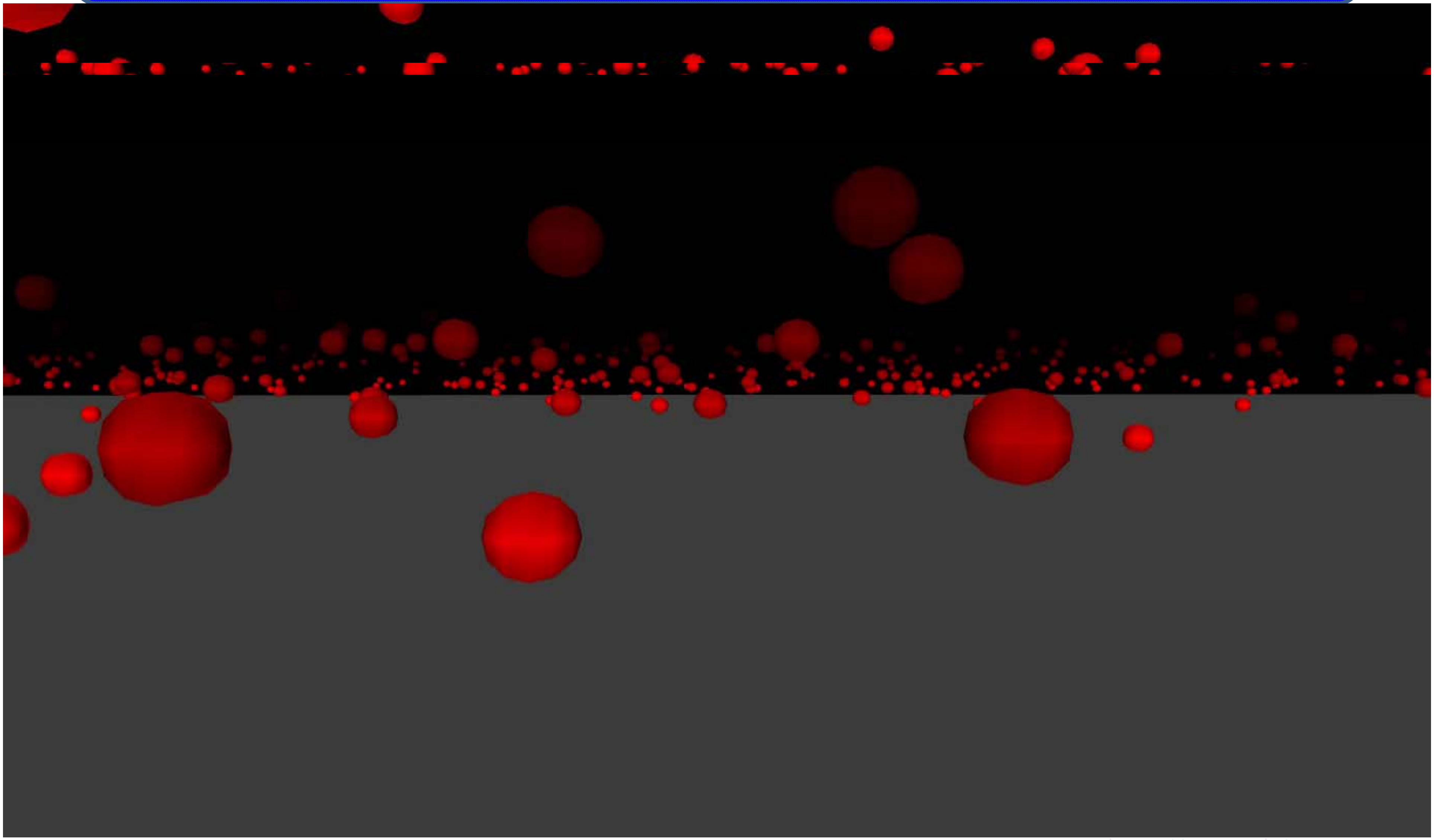
SIMULATION PARAMETERS

- Tracer: size and number density
- Fluid: velocity profile:

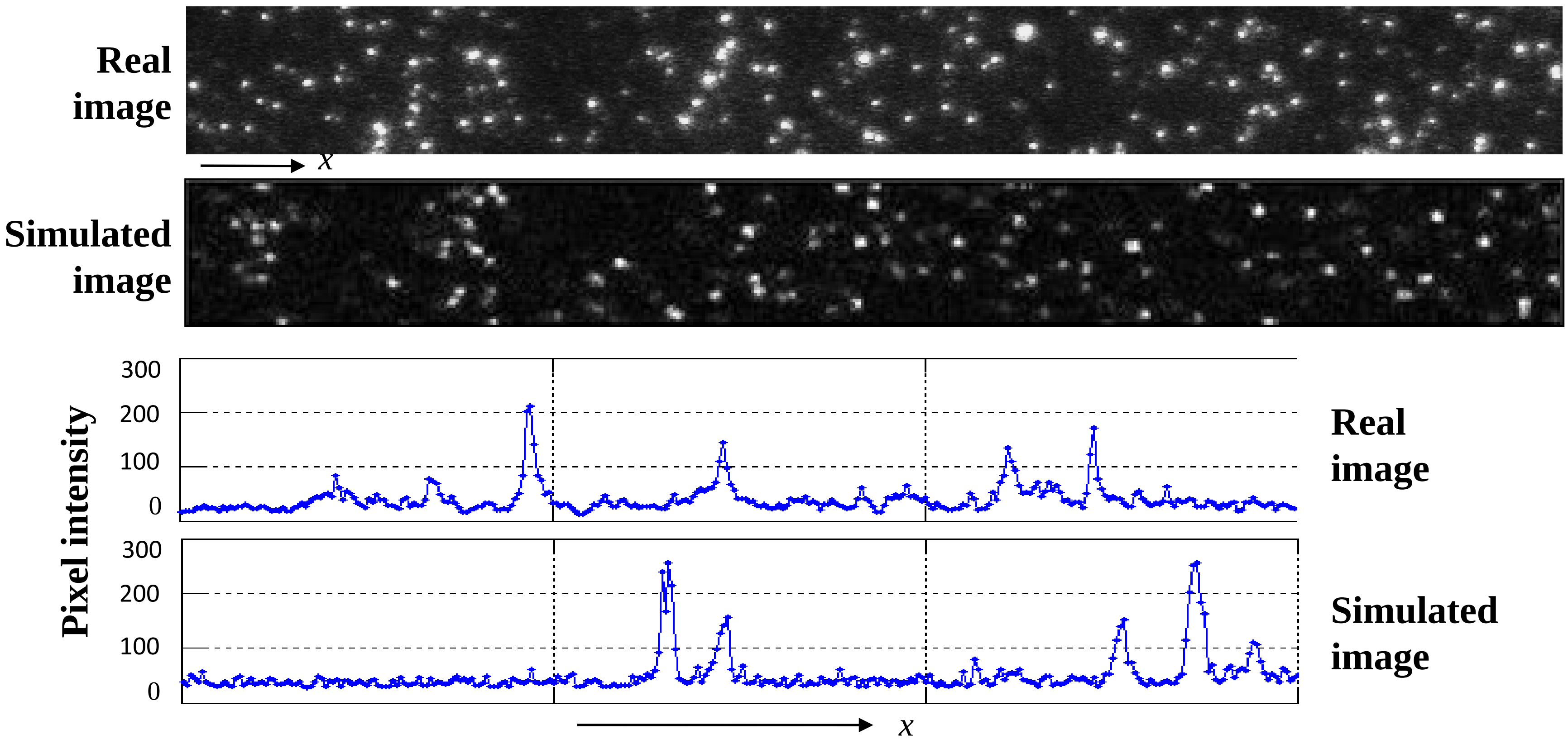
$$U_c = G \cdot \left(\frac{z_v}{2} + a \right)$$

  - Shear vs. uniform
- Hindered Brownian motion
- Surface and Buoyancy forces
- Illumination characteristics:
  - *Uniform, Z_v = 280 nm* *(non real!)*
  - *Linear, Z_v = 280 nm* *(non real!)*
  - *Exponentially decaying, Z_p = 120 nm (real)*
- Camera characteristics: shot and electronic noise

3D VIEW



nPIV IMAGES



- Standard image processing
  - FFT-based cross correlation method to obtain average tracer displacement
    - 2D Gaussian peak-finding algorithm

[Sadr et al., Exp. Fluids, 2005]

[Li et al., Exp. Fluids, 2006]

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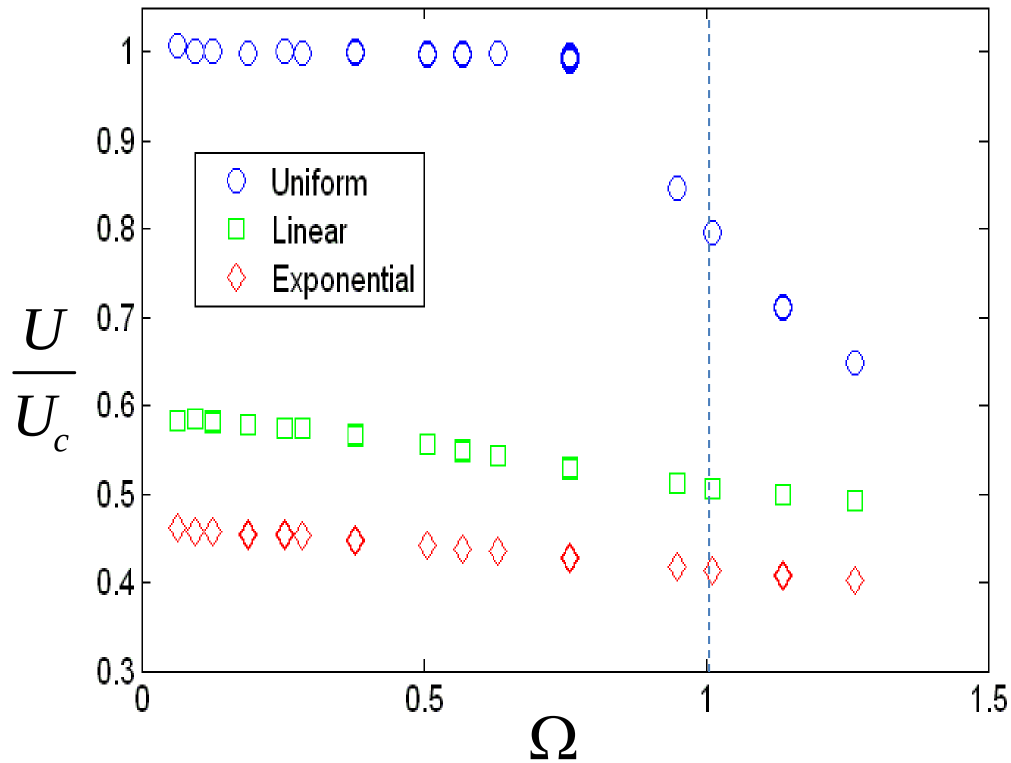
MEASURED MEAN VELOCITY

Shear flow with no Brownian motion

- Light illumination profiles:
  - Uniform, $I = I_0 \text{ for } 0 \le z \le z_v + a$
  - Linear, $I = \frac{I_{noise} - I_0}{z_v}(z-a) + I_0$
  - Exponential, $I = I_0 \exp\left\{\frac{z}{z_p}\right\}$
- Decaying Light illumination affects measured velocity for shear flow
- Strongest effect is for exponentially decaying light

$$\Omega = \frac{\Delta t \cdot U_c}{r_s} \quad r_s \rightarrow\rightarrow \text{ search radius}$$

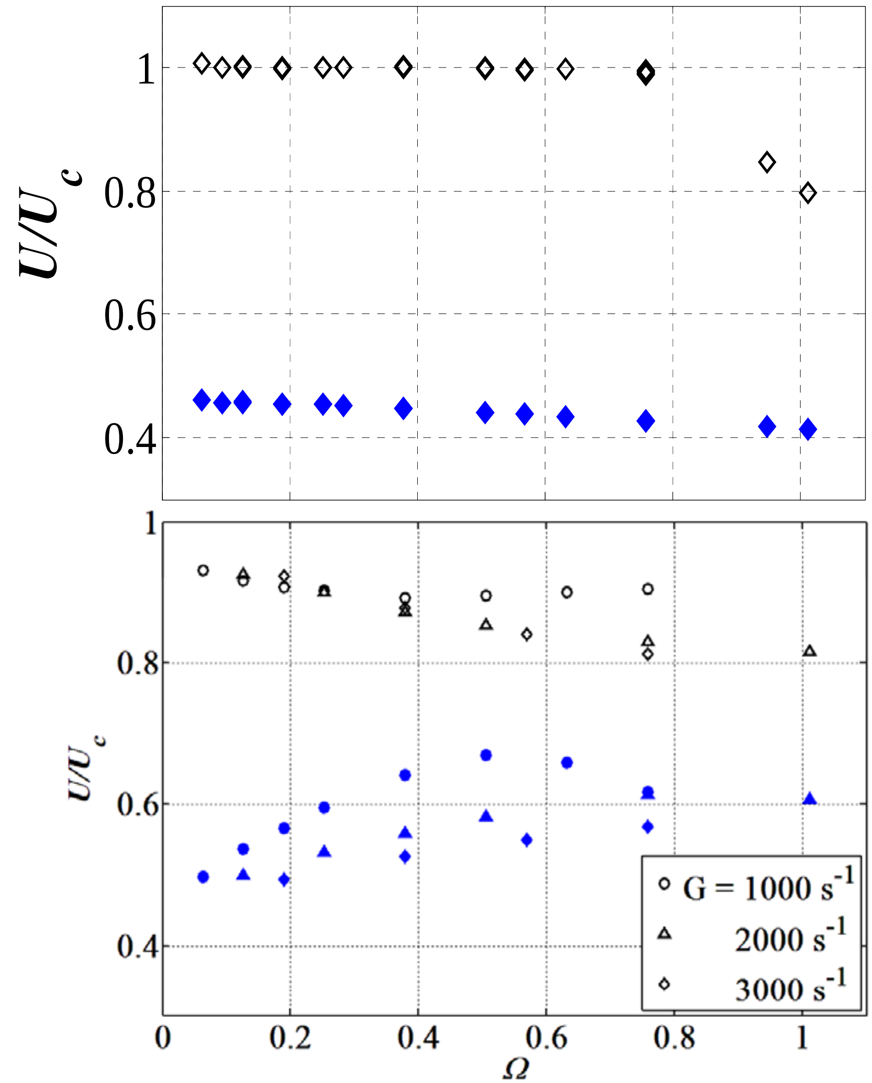


Each line contains all the shear rates study in this work, i.e. *G=1000 to 3000 s⁻¹*

BIAS IN PIV DATA REDUCTION RESULTS

No Surface effects

- Shear flow without Brownian motion
  - Significant effect of illumination
  - Small effect of time delay
  - No affect of shear
- Shear flow with Brownian motion
  - Significant effect for illumination
  - Significant effect for time interval
  - Effect of shear depends on all shear, illumination, and time interval



EFFECT OF CORRECTION FACTORS

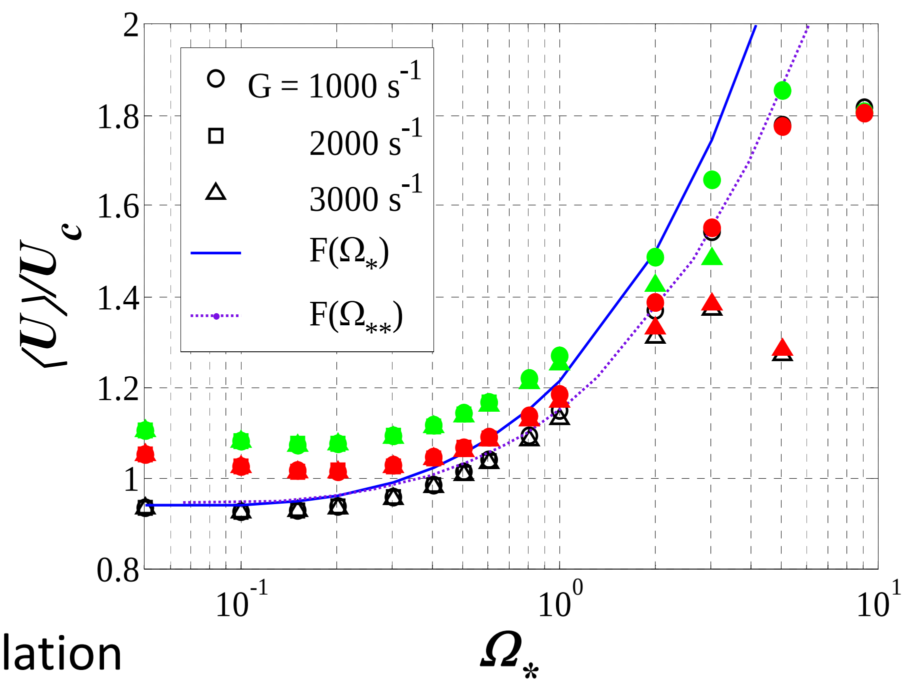
Surface effects

- Correction factors for Brownian motion [Sadr *et al.*, JFM, 2007]

$$F(\Omega_*) = \langle U \rangle / U_C = 0.21 + (1 - 0.21)\exp\left\{-1.72\sqrt{\Omega_*}\right\} + 0.86\sqrt{\Omega_*} \qquad \Omega_* = \frac{D_\infty \Delta t}{(z_v + 0.8a)^2}$$

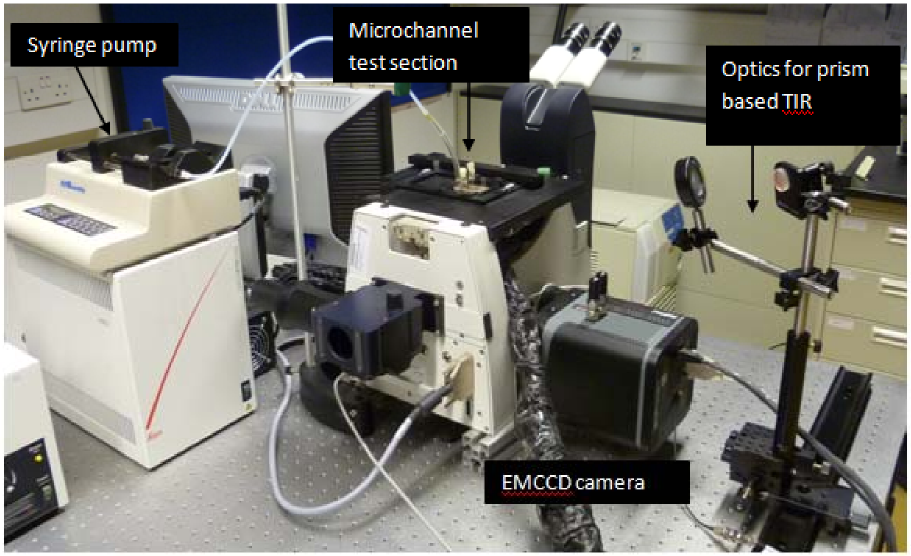
  - Surface effects are not considered
  - Based on particle displacement
    - No illumination affects are present
  - $F(\Omega_{**})$ [Huang et al. , JFM, 2009]
  - Based on particle displacement
    - No illumination affects are present

- Estimated tracer velocity well predicted
  - The bias pattern is well predicted
  - The models fail to correct the correlation based PIV data reduction results



EXPERIMENTAL RESULTS

- **Inverted epi-fluorescent Leica DMI6000 microscope**
  - Adapted for evanescent-wave illumination from Ar^+ laser
  - 40× objective w/adjustable working distance
- Princeton Pro EM 512
  - On-chip gain (no intensifier): quantum effic. ~90% at 500 nm
  - Image size 512×100 pixels
  - Image pair time delay Δt=1.3ms
- Fused silica micro channel
  - H=25 μm, W=53 μm
- Constant flow
  - Syringe pump



G (s^{-1})	z_v (nm)	Dt (ms)	Correction factor	U_{cal} (m/s) Theory	U_{exp} (m/s) Measured	U_{corr}(m/s) Corrected Velocity
2055	240	2.28	1.29	3.62E-4	2.41E-4 →	3.12E-4

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SUMMARY

- nPIV: Near wall velocity measurement at Z <300 nm
- Surface forces are significant at nano scale and cause non uniform tracer distribution near the wall
- Combination of shear and non uniform illumination also affects obtained velocity using correlation methods
- Existing correction for tracer displacement does not correct for PIV data reduction via correlation method
- Our results partially corrects the underestimation of the obtained velocity

ACKNOWLEDGEMENTS

Thank you

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