Rheology for Rapid Screening of Drag-Reducing Marine Coatings

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Drag due to biofouling on ships

- **Biofouling** - the accumulation of marine organisms on the hulls of ships - increases hydrodynamic **drag** according to the type of fouling growth
- Estimates of the likely increase in **total resistance** caused by fouling:

• SLIME	Bacteria / diatoms / silt	≤18%
• WEED	Green / brown /red macroalgae	} ≤30%
• SOFT animals	Sea-squirts / sponges	
• HARD animals	Barnacles / tubeworms / mussels	≤ 75%

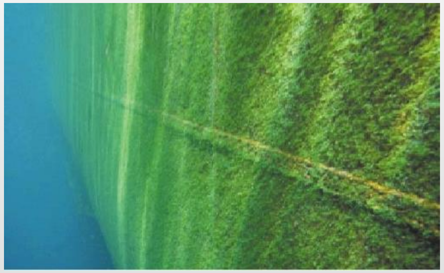

Image credits (l-r)

International Paint
International Paint
Micanti

Schultz, M. P., et al. *Biofouling*, Vol. 27, No. 1, (2011), 87–98

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Ways of estimating drag

- Schultz also compared 3 standard experimental ways of measuring the hydrodynamic drag due to surface roughness:
- Towed plate
  - **115 m** long towing tank
- Velocity profile method
  - Flat plate in a **1.8 m** long closed circuit water tunnel
- Rotating disc
  - Circular tank, **0.33 m** in diameter
  - Can achieve higher Reynolds Numbers

Schultz, M. P., Myers, A., *Experiments in Fluids*, Vol. 35, (2003), 372–379

Flow caused by a rotating disc

Flow around a rotating disc is complex.

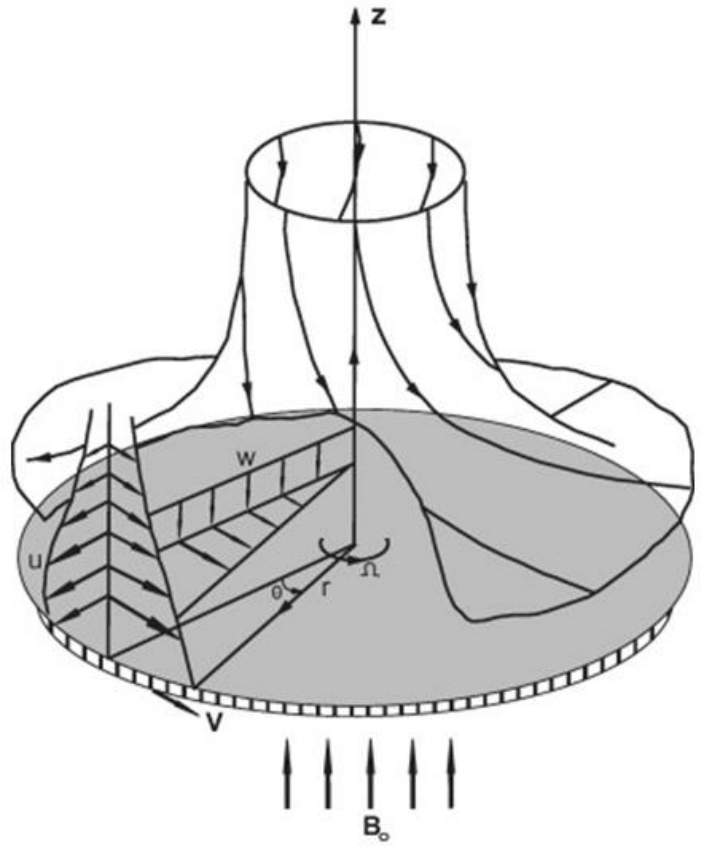
Flow varies across the surface of the disc – there are tangential and radial flows.

Boundary effect causes radial flow due to centrifugal force.

Radial outflow causes the disc to act like a pump.

Edge effects are significant.

If the fluid reservoir is not infinite, flow depends on the geometry of the container.



Sahoo, B., *Communications in Nonlinear Science and Numerical Simulation*, 14, 7, (2009), 2982-2998

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On the flow due to a rotating disc

- **Analyses**
  - <u>von Karman</u>, T., *Z. für Angew. Math. und Mech.*, 1, **1921**, 233-252
    - Momentum-integral solution
  - <u>Cochran</u>, W. G., *Mathematical Proceedings of the Cambridge Philosophical Society*, 30, **1934**, 365-375
    - Power series solution
  - <u>Benton</u>, E. R., *J. Fluid Mech.*, 24, 4, **1966**, 781-800
    - Steady state solution

<u>Note</u>: Each author pointed out errors in the previous works

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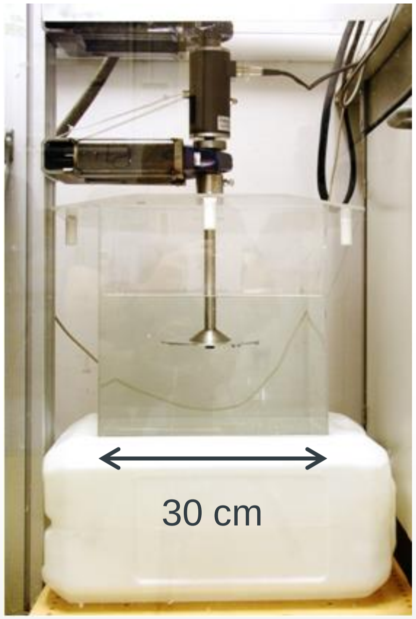
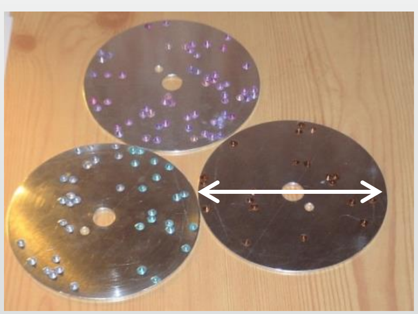
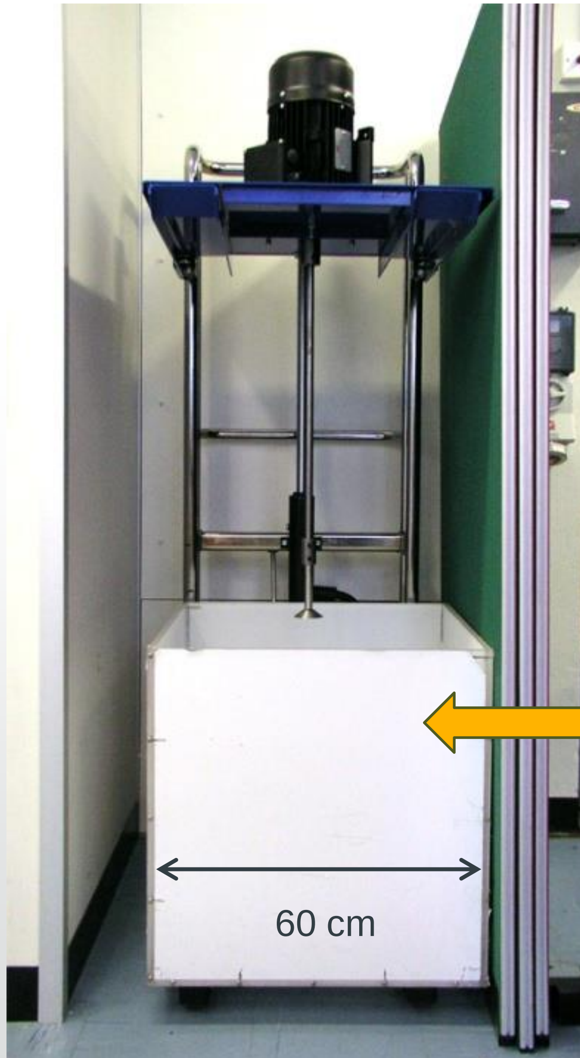
Prototype rotating discs





14 cm



Discs exposed to fouling in the sea

28 cm

***Bearings** are critical*

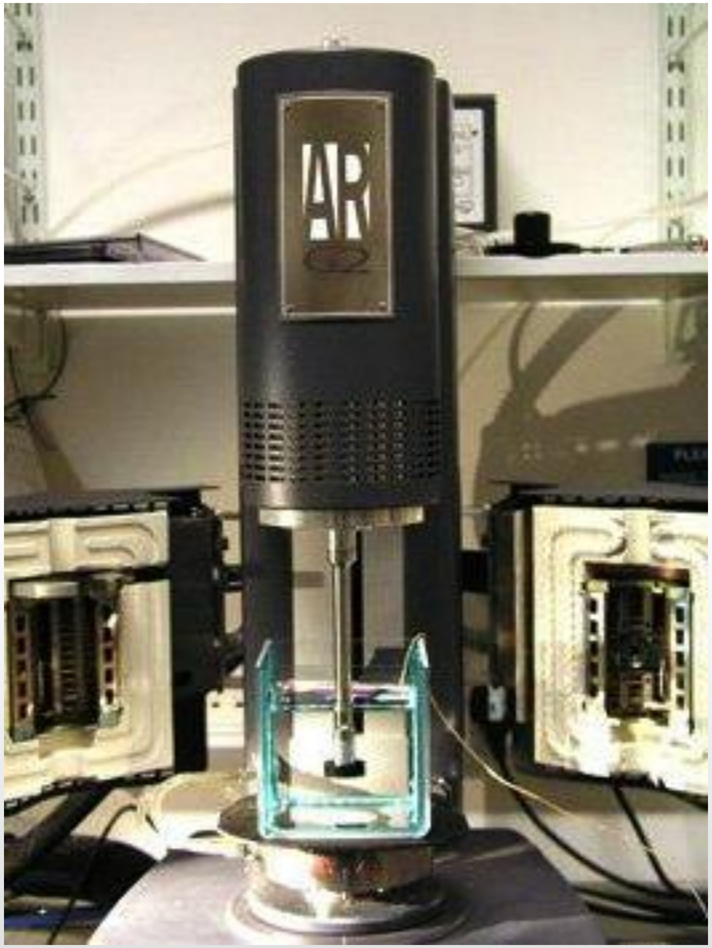
<u>Large disc rotor</u>

28 cm diameter discs

60 cm x 60 cm x 60 cm water tank

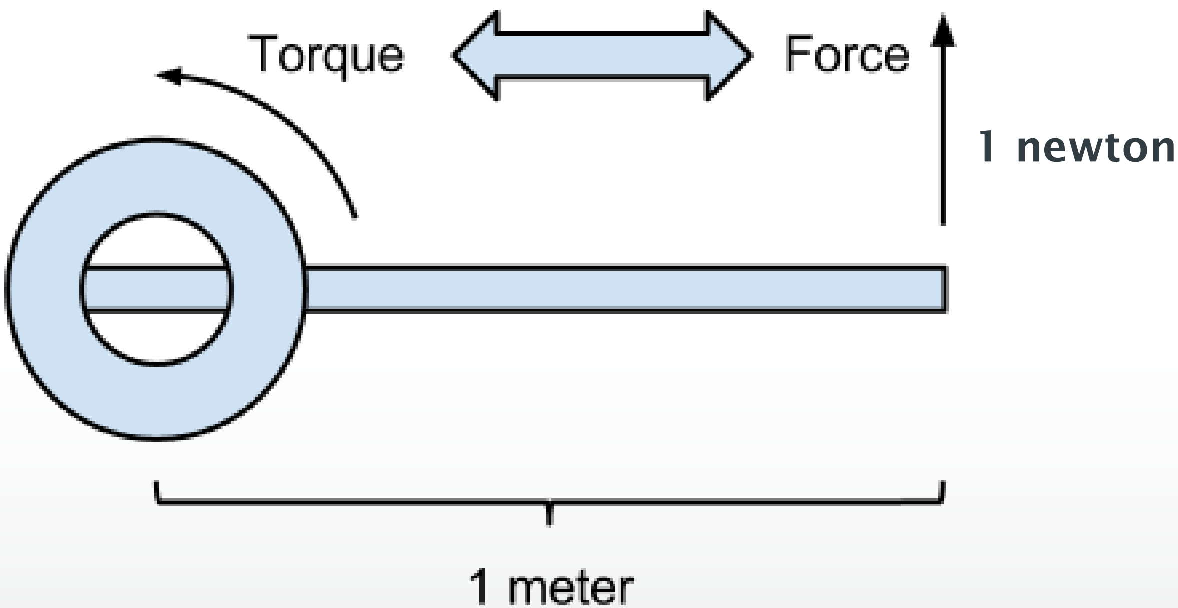
Torque measurement using a Rheometer

- A sensitive rheometer (AR-G2, TA Instruments) owned by NPL was adapted for measuring the hydrodynamic torque (drag) on small sample discs (25 mm and 40 mm diameter)
- Has an induction motor with magnetic bearing
- Sensitivity: Can measure torque of 0.01 µN.m with an error of 1 nN.m



- A 10 cm ***square*** water tank gave best flow
- Discs with known sandpaper roughness were prepared and evaluated
- Discs coated with antifouling materials and exposed in the sea at NOCS were tested

Torque



Torque = Force x Distance
= newton x metre (N.m)

$1N = 1kg.m.s^{-2}$

In earth gravity 1N is the force on ca. **100g**

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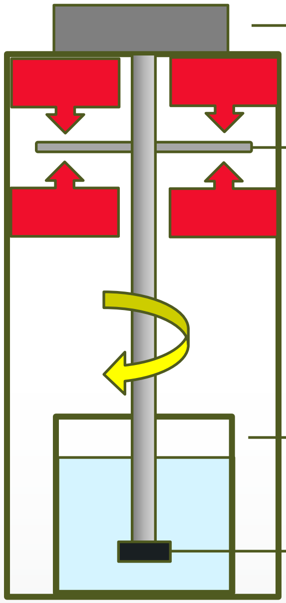
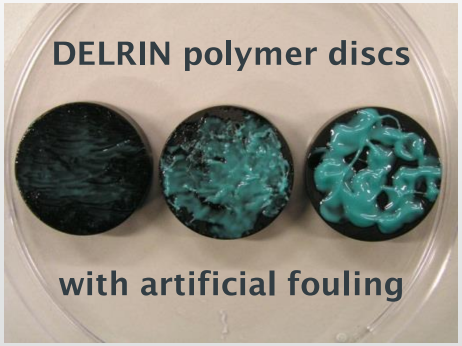
Schematic of rheometer

- <u>Conditions</u>
- **AR-G2** rheometer (TA Instruments)
- Reservoir: 100 mm x 100 mm x 100 mm
- Water depth = 80 mm (800 mL)
- Distance of disc from bottom = 10 mm
- Rotational speed 1 000 – 3 000 rpm



Material of Disc	Diameter mm	Thickness mm
Plastic	25	6
Aluminium	40	3



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Flow caused by the rotating disc

Flow around a rotating disc is complex

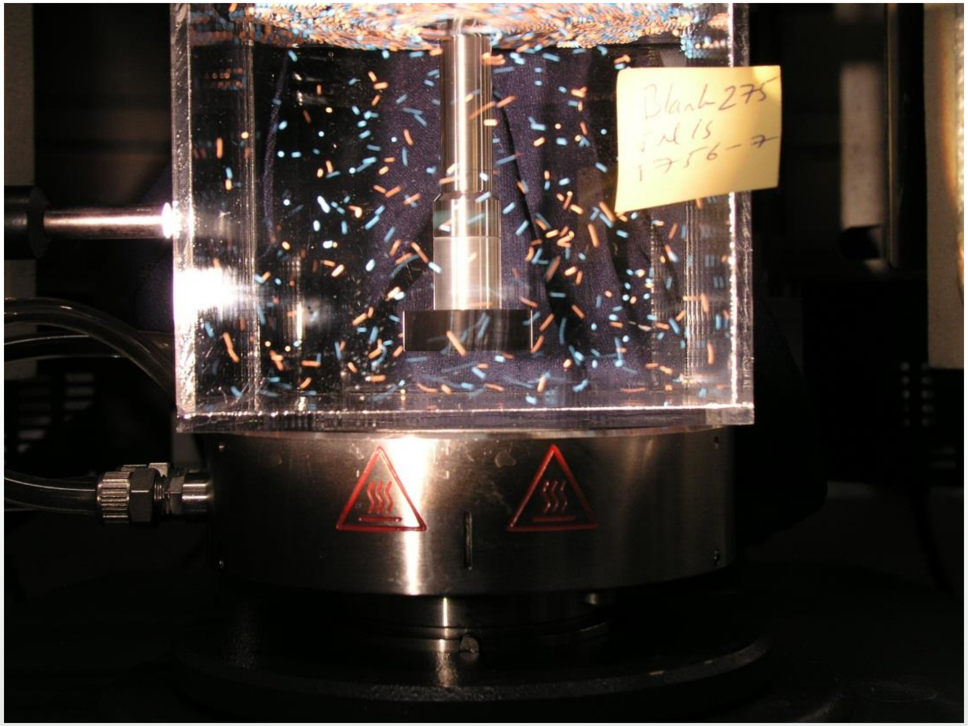
Flow varies across the surface of the disc – there are tangential and radial flows

Boundary effect causes radial flow due to centrifugal force

Radial outflow causes the disc to act like a pump

Edge effects are significant

If the fluid reservoir is not infinite, flow depends on the geometry of the container



BLANK plastic disc at 275 $rad.s^{-1}$ (2626 rpm)

Sahoo, B., Communications in Nonlinear Science and Numerical Simulation, 14, 7, (2009), 2982-2998

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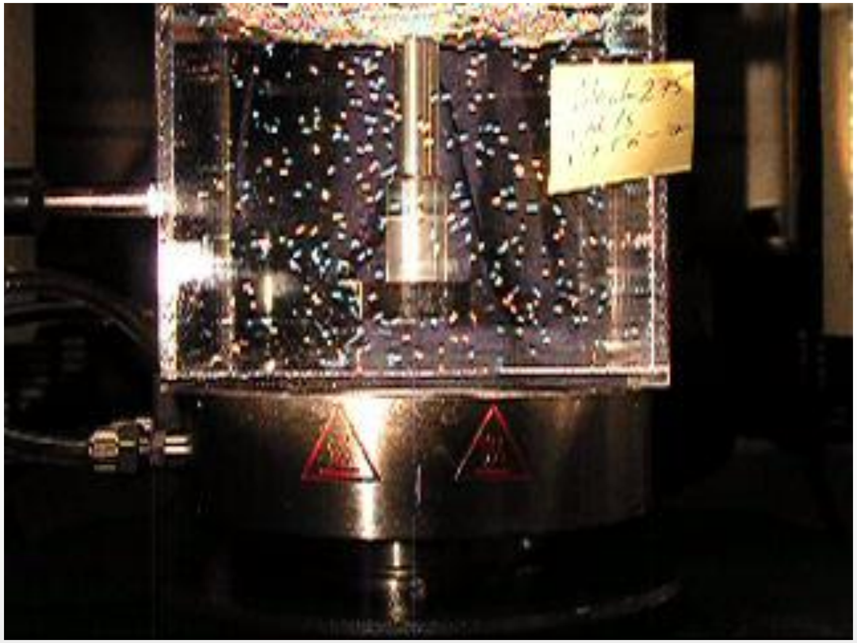

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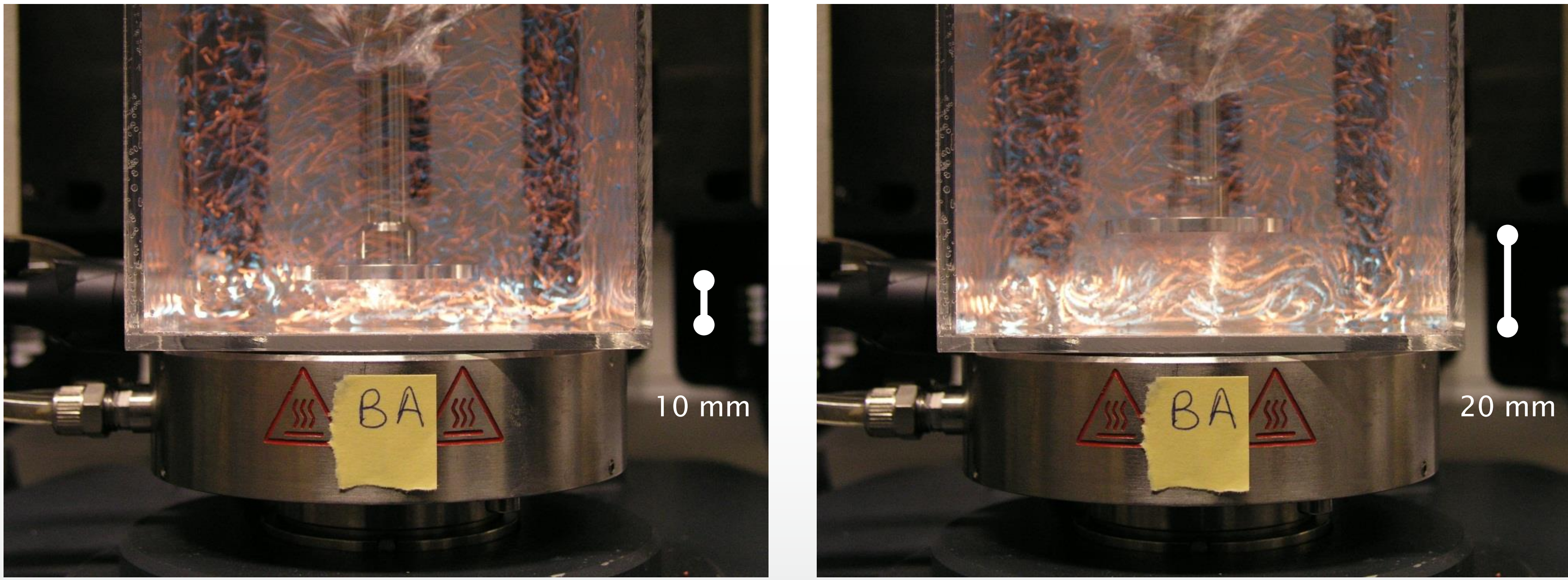
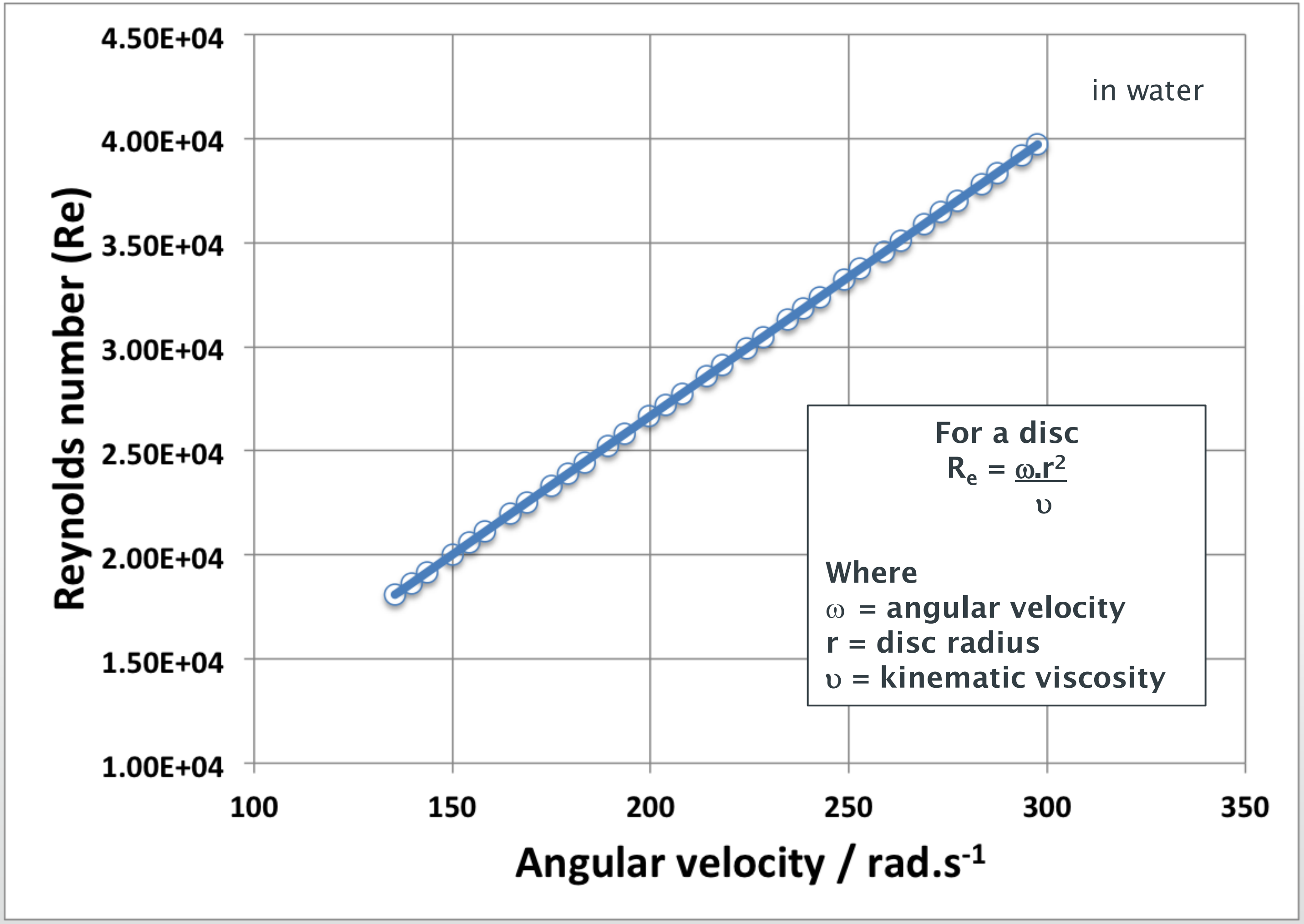
Rotating disc with pseudo-barnacles



ALUMINIUM disc with pseudo-barnacles, at 2 different gap sizes (height from bottom)
45 mm diameter @ 275 rad.s^{-1} (2626 rpm) *Camera shutter speed = 1/30 s*

Reynolds Number for disc 25mm diameter



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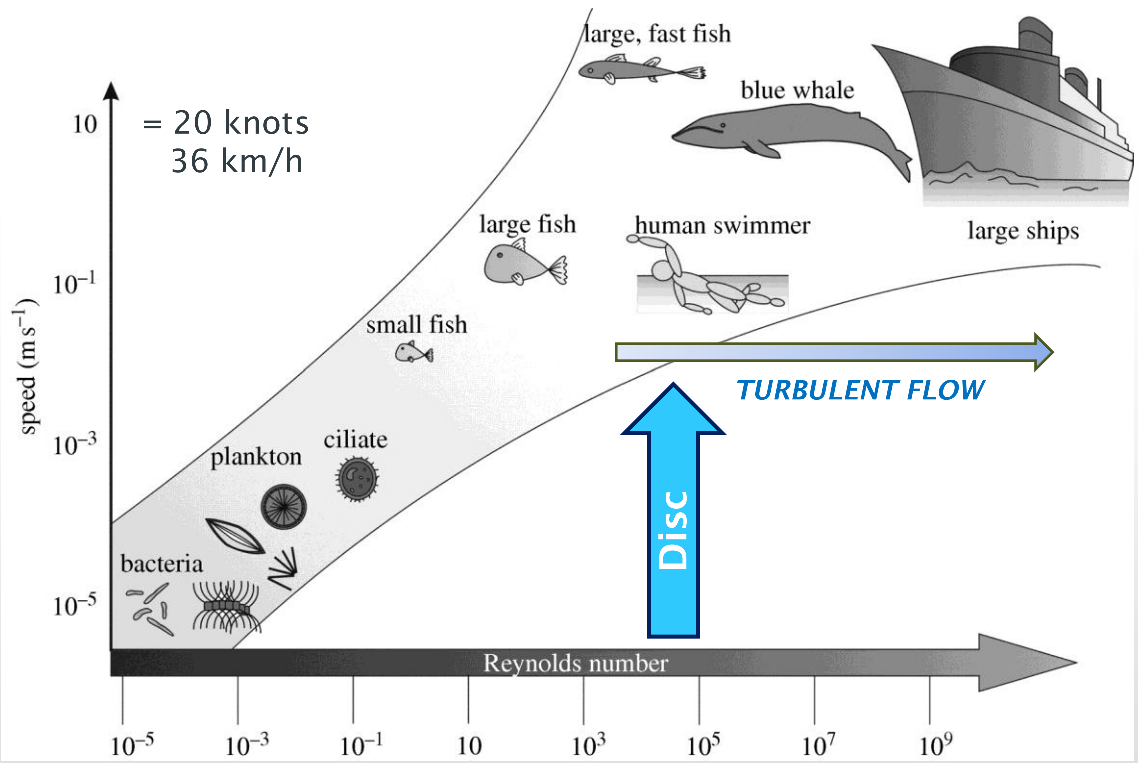
Reynolds Number

- Reynolds number (R_e) = $\frac{\text{Inertial forces}}{\text{Viscous forces}}$ (*dimensionless*)



In general

$$R_e = \frac{av}{\upsilon}$$

Where:

a = dimension
v = velocity
υ = kinematic viscosity

Salta, M., at al., Phil. *Trans. R. Soc. A,* 368, 1929 (2010), 4729-4754

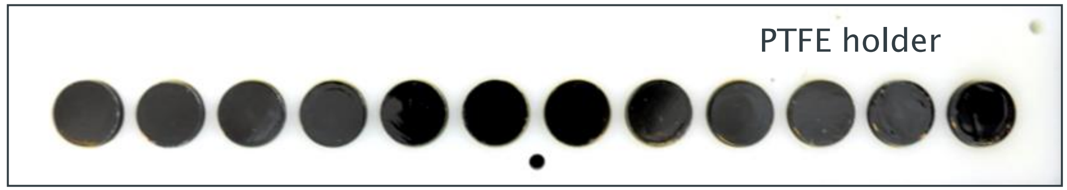
Experimental matrix

- 4 DELRIN* discs were coated with each of the materials below and exposed to fouling in the sea at the National Oceanography Centre, Southampton (NOCS)
  - REF coating
  - Coating (E)
  - Coating (F)

- The discs were removed after 10 days and kept cold in artificial seawater (ASW) until tested

- **DELRIN is an ACETAL resin (polyoxymethylene or POM) with low water absorption*

Exposing discs at NOCS

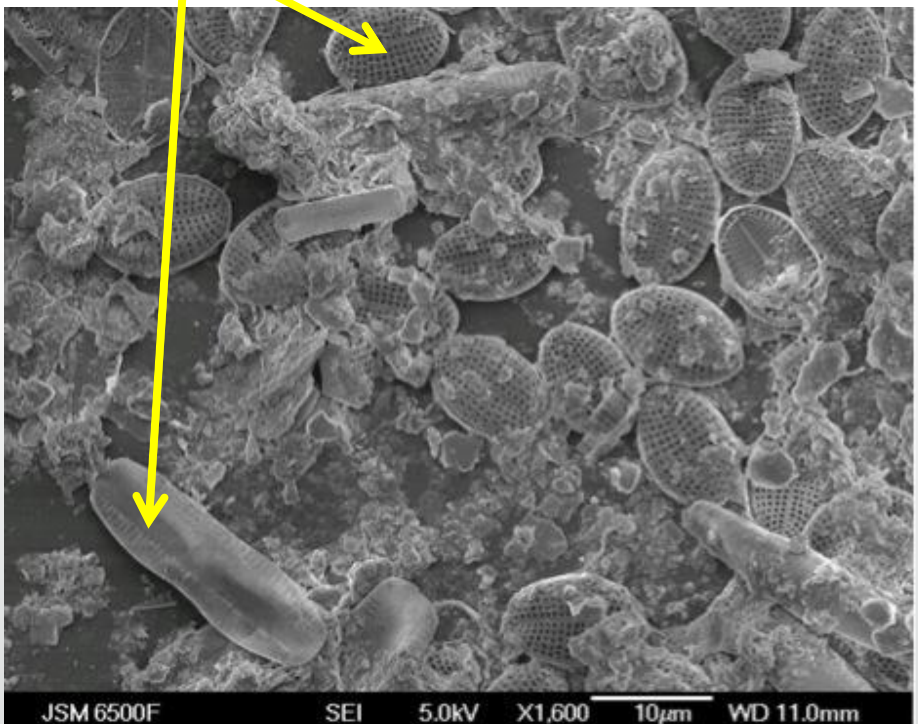


Exposed for 10 days in summer

SEM Images

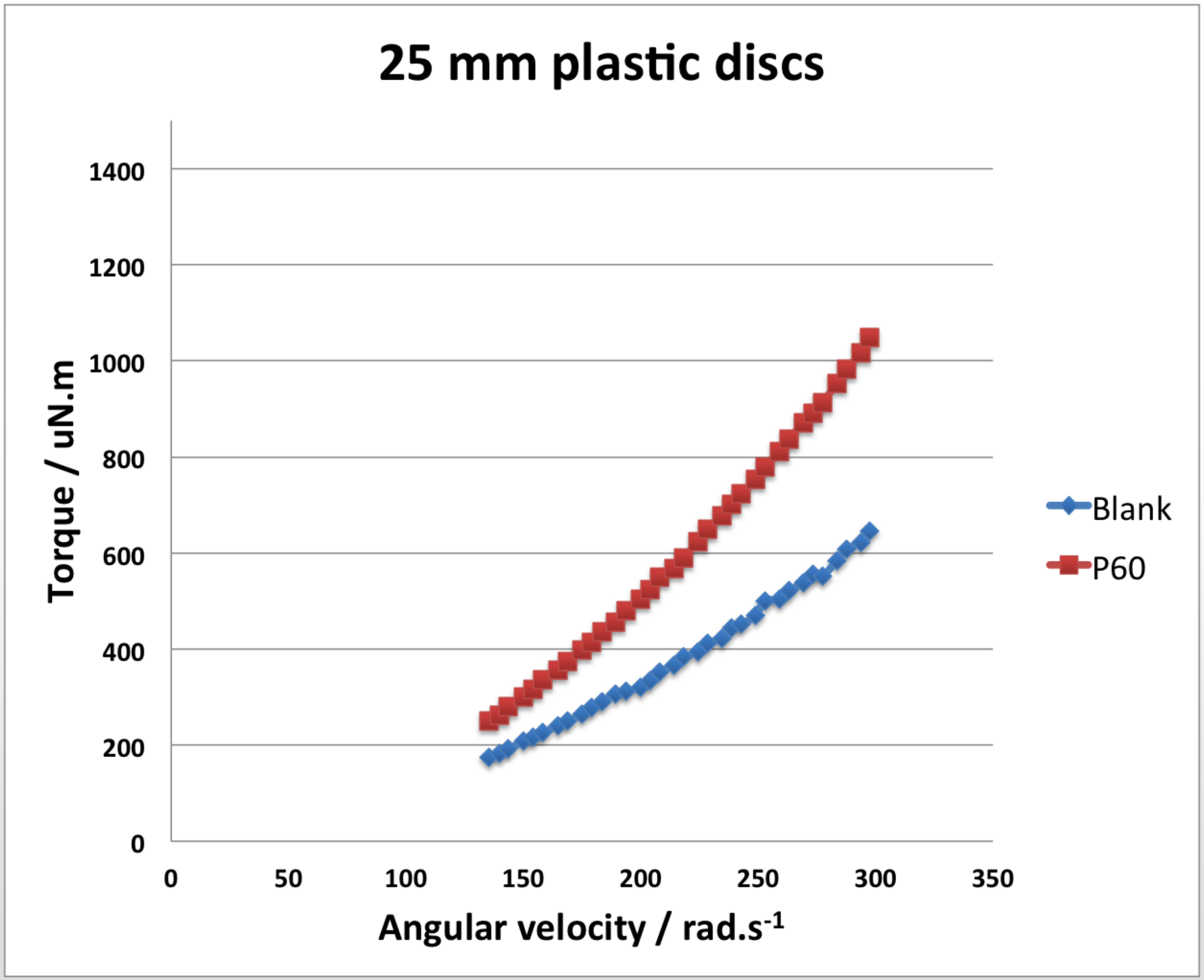
2 fouled discs, each with coating (F)

DIATOMS



BACTERIA and DIATOMS

Raw data for smooth and rough discs



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Coefficient of Momentum (C_m)

$C_m = (2M)/(\rho R^5(\Phi\omega)^2)$ (Schultz 2003)

Where M is torque, ρ is density of the fluid, and Φ is an empirical "swirl factor" for the testing tank

Due to water flowing tangentially around with the disc

Swirl factor = $(1/\sqrt{Cm})_{\infty}/(1/\sqrt{Cm})_{en}$

Measured at the same $Re_R(Cm)^{1/2}$

Their measured value of Φ was 0.854

Plot

TORQUE (M)

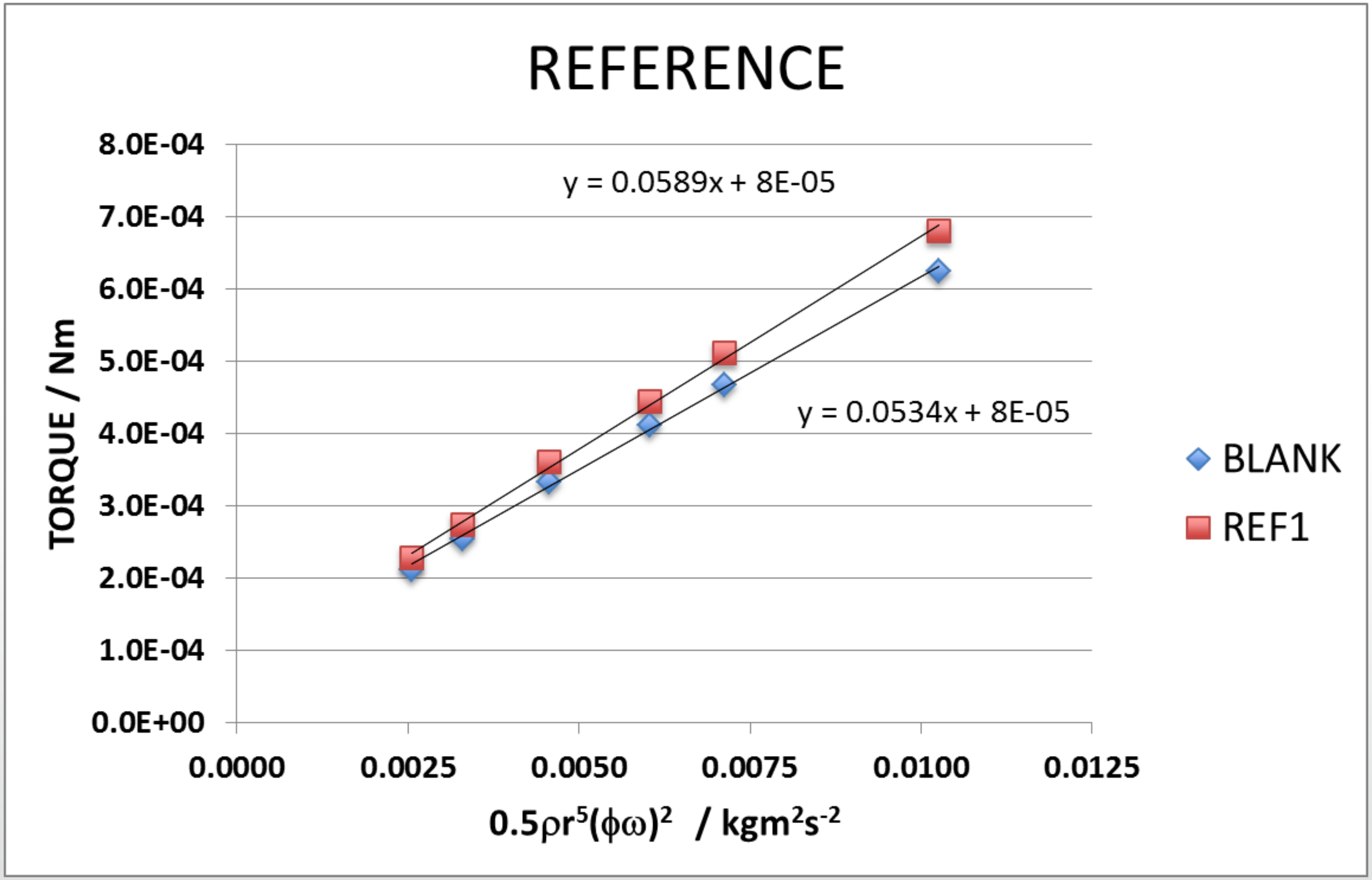
against

$\frac{1}{2}(\rho R^5(\Phi\omega)^2)$

SLOPE = C_m

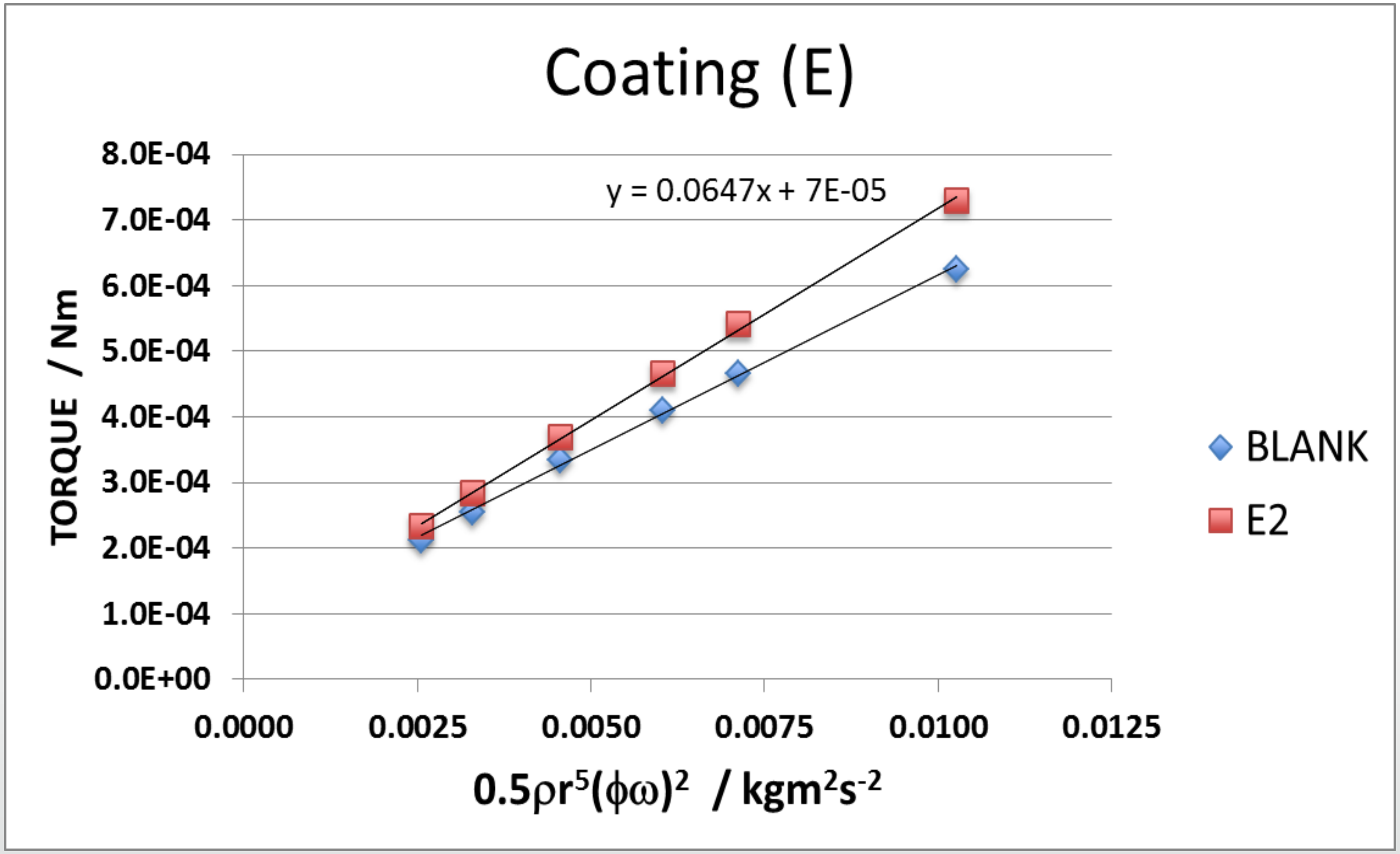
Schultz, M. P., Myers, A., *Experiments in Fluids*, Vol. 35, (2003), 372–379

C_m for Reference coating



Cm for REF1 = 0.0589 Cm for REF2 = 0.0602 **mean Cm = 0.0596**

C_m for Coating (E)

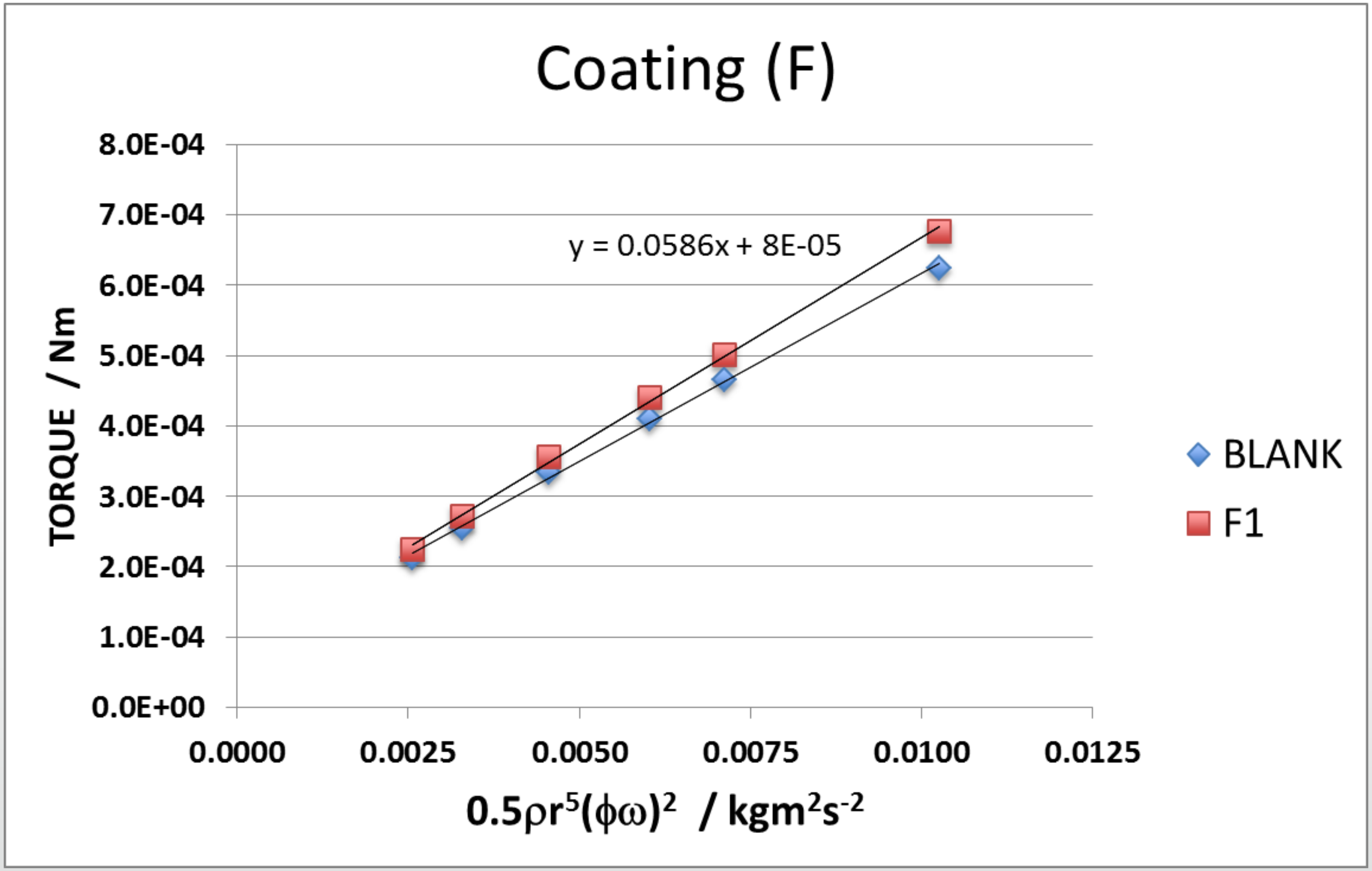


Cm for (E)1 = 0.0612

Cm for (E)2 = 0.0647

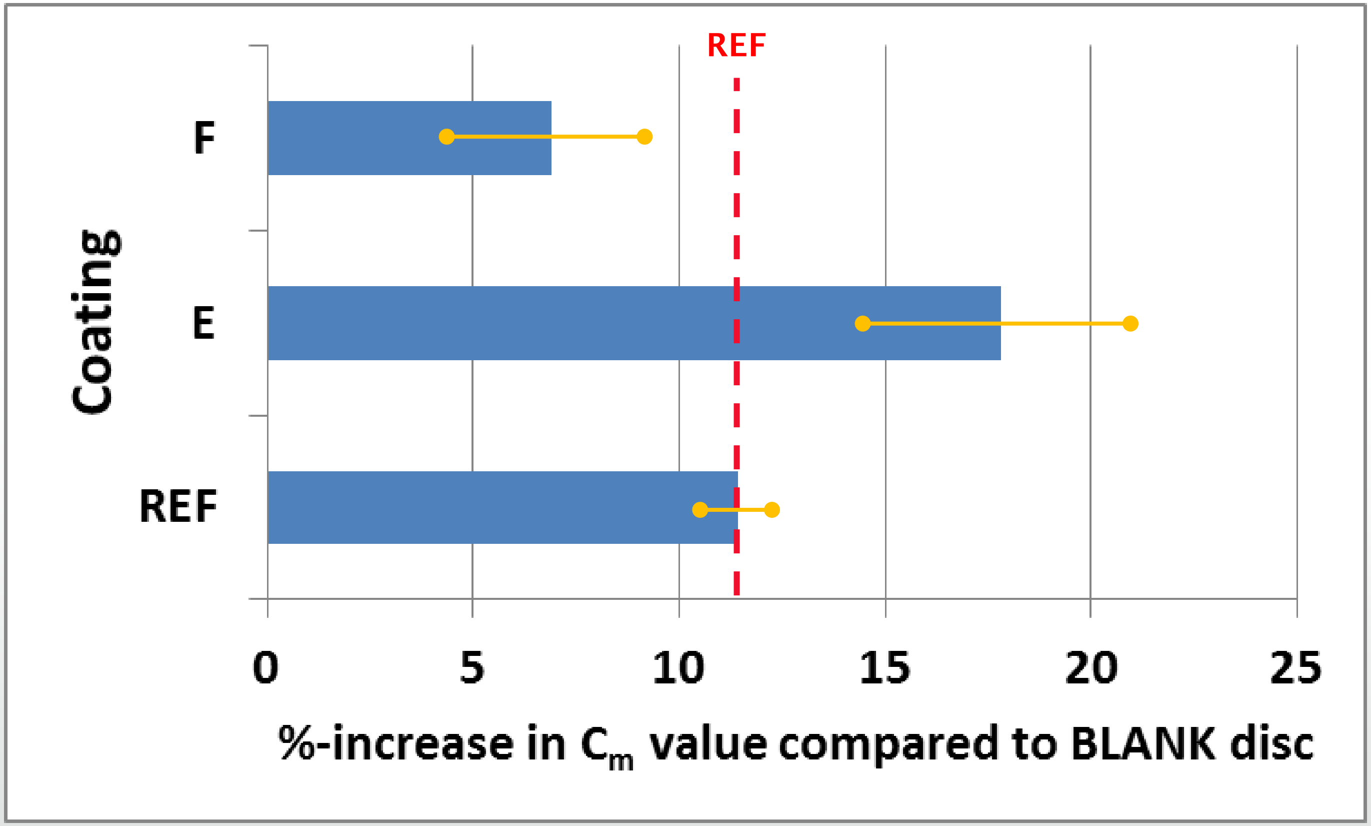
mean Cm = 0.0630

C_m for coating (F)



Cm for (E)1 = 0.0586   Cm for (E)2 = 0.0557   **mean Cm = 0.0571**

C_m increase - compared to unfouled disc



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Conclusion

- A sensitive rheometer has been used to measure the torque on small discs, both fouled and unfouled, rotating in water
- Drag due to slime fouling accumulated after 10 days exposure in the sea could be detected using this method
- In calibrated systems using identical discs, the coefficient of momentum provides a measure of drag increase due to the slime coverage
- The method is simple and rapid

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Extra slides

http://www.soton.ac.uk/ncats/

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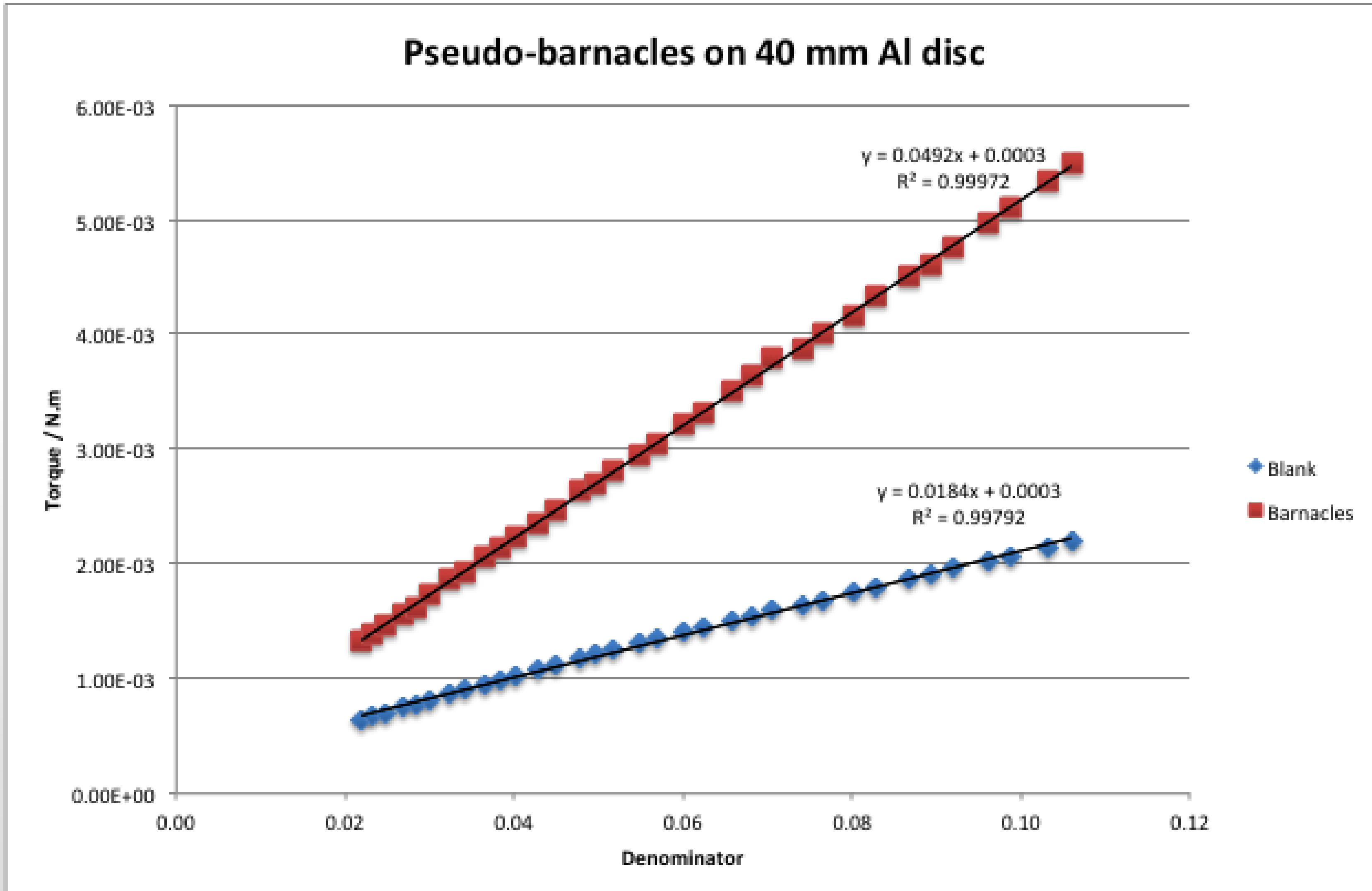
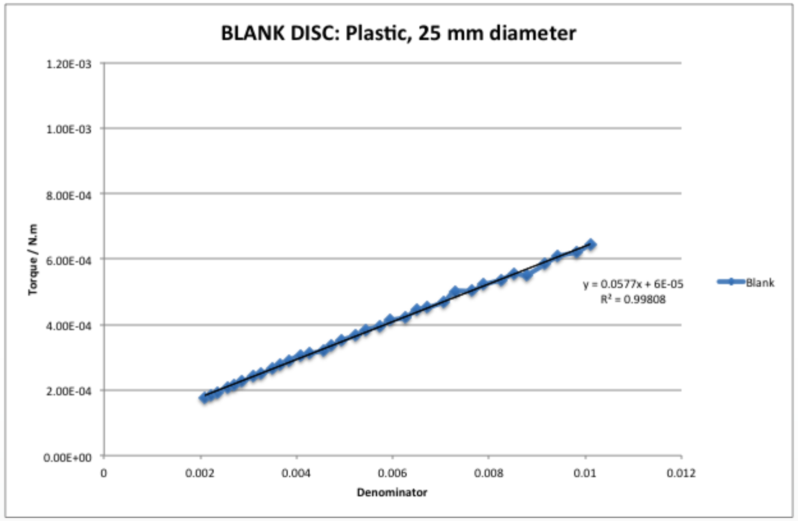
nCATS

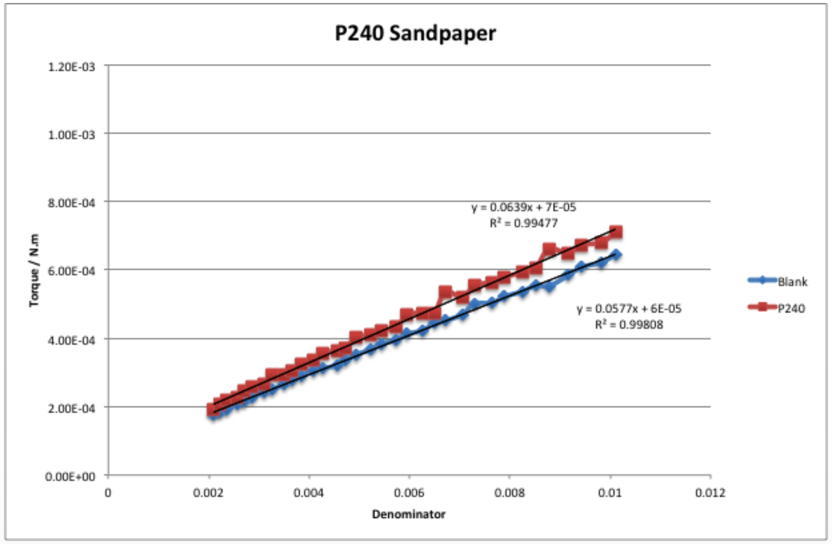
- The moment of inertia for a uniform circular disc is:
- $I = ½ MR^2$ where M is the Mass and R is the Radius
- The rotational kinetic energy of a rigid body is:
- $K = ½ I\omega^2$ where ω is angular velocity ($rad.s^{-1}$)
- Torque = b.ω where b is the coefficient of rotational friction (Alam 2011)
- Rotational form of Newton's 2nd Law:
- $T_f = -I\, d\omega/dt$ (Mungan 2012)

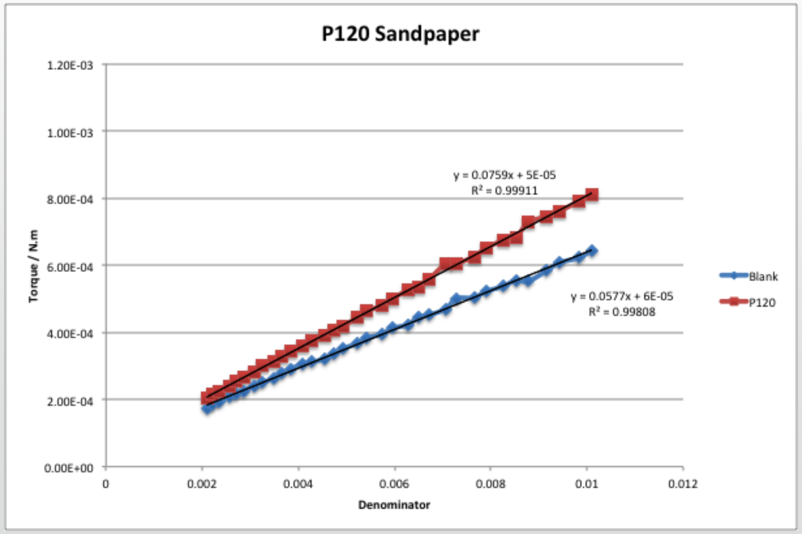
C_m of roughened 40 mm aluminium disc

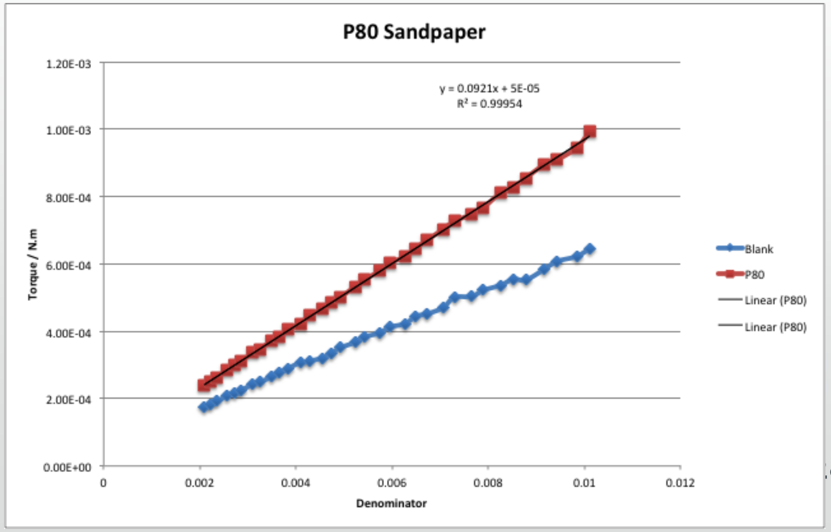


Deriving C_m for Sandpaper Grades









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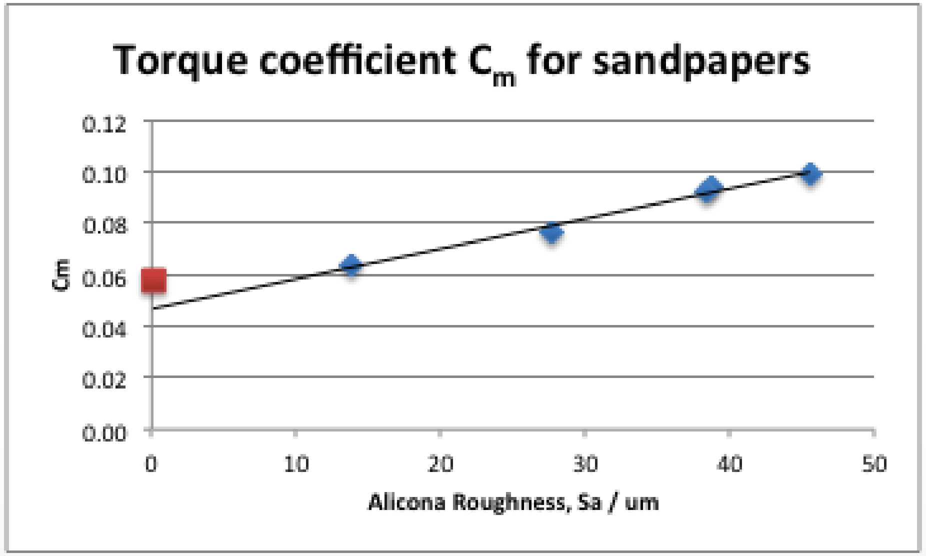
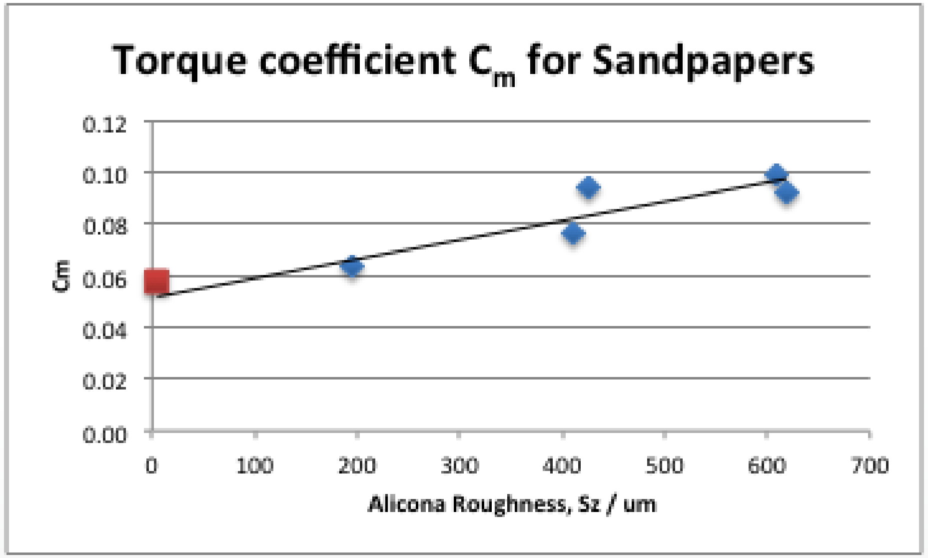
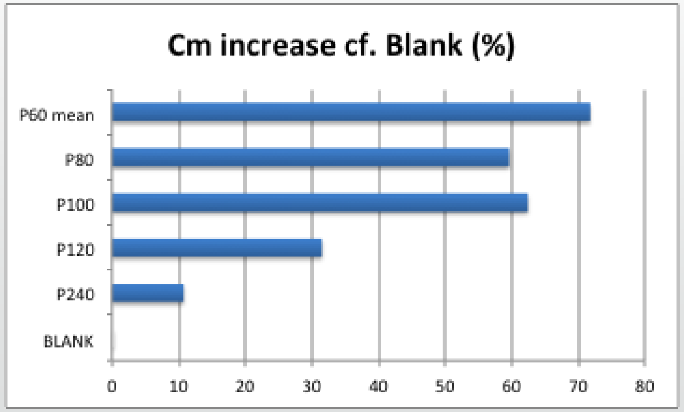
C_m as a function of surface roughness





Roughness	Sa (μm)	Sz (μm)
Al blank	0.099	5.29
P240	13.80	195.30
P120	27.70	409.90
P100	38.70	424.30
P80	38.40	618.60
P60	45.50	607.57



<u>Note</u>: Roughness and C_m values for P100 and P80 sandpapers were similar