Estimating the impact of new-generation antifoulings on ship performance

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Abstract

Due to the phase-out of TBT-SPCs imposed by the IMO, new-generation antifoulings are set to replace 80% of the existing antifouling market. Two types of coatings are claimed to offer satisfactory performance over 5 years: Tin-free SPCs and Foul Release coatings, which were both commercially introduced in the mid 1990s. This paper describes how the performance of these coatings is evaluated and monitored. The findings show that the antifouling performance is on a par with TBT-SPCs with regards to macrofouling, but that there are concerns that Foul Release systems are covered by slime films. A review of the literature on the effect of slime films on ship resistance shows that it is relatively obscure and possibly underestimated.

A research project carried out at the University of Newcastle-upon-Tyne has demonstrated that newly applied Foul Release coatings exhibit between 2 and 20% less drag than Tin-free SPCs. This has been related to the respective differences in roughness characteristics. Slime films may jeopardise the drag benefits of Foul Release coatings and the collection of in-service data is required. The inclusion of roughness measurements in coating performance is recommended.

1. Introduction

For years the most widely applied marine antifoulings have been Tributyl-Tin Self-Polishing Co-Polymers (TBT-SPC). They can keep a ship free of fouling for 5 years by means of a steady release of the TBT toxin. A chemical reaction occurs at the surface-seawater interface (known as the "leached layer") and forms a water-soluble product that is able to dissolve away, resulting in the surface "polishing" with time. However, due to environmental side effects related with TBT, the International Maritime Organisation (IMO) has decided in October 2001 to prohibit the application of TBT-SPCs from 2003 and hence completely phase out their use by 2008.[1]

There are currently two alternatives on the market that can also offer 5 years of satisfactory antifouling performance. The first alternative, Tin-free SPC, uses the same chemical principle but instead of TBT gradually leaches copper-based toxins which are complemented by so-called 'booster biocides' since copper toxins alone do not have a sufficiently broad antifouling spectrum. Some of these booster biocides have come under increasing environmental scrutiny, but others, such as zinc pyrithione, degrade rapidly in seawater and have therefore much less impact on the marine environment.[2-3] Unlike the cheaper Controlled Depletion Polymers (CDPs), the release of the toxins continues when the ship is stationary and most prone to foul, as illustrated in Figure 1. Assessments made during dry-docking have shown that the antifouling performance of Tin-free SPCs is equivalent to TBT-SPCs over a five year period.[4]

The second alternative, Foul(ing) Release coatings, acts as a physical rather than a chemical defence against fouling.[5] Instead of killing marine organisms that have attached to the hull, they try to prevent the attachment of the organisms altogether by virtue of their surface properties. Most of the Foul Release coatings currently on the market are silicone elastomers based on polydimethylsiloxane (PDMS). PDMS has an extremely flexible backbone, which allows the polymer chain to readily adapt to the lowest surface energy configuration. The surface energy represents the capability of the surface to interact spontaneously with other materials. Brady and Singer[6] found experimentally that the relative adhesion of fouling organisms on a material is directly proportional to $\sqrt{E\gamma_c}$, whereby E is the elastic modulus of the material, and γ_c its surface energy. This parameter for silicone materials is at least an order of magnitude smaller than for other materials. Eventually, fouling organisms will attach to the surface, but it has been shown that algal and animal organisms attach less strongly on PDMS than on other materials and that the strength of attachment of macrofouling is inversely proportional to the thickness of the coating[7-8]. This explains why these macrofouling organisms (e.g. weeds, barnacles,…) will release from the surface under the influence of relatively small hydrodynamic shear forces. The speed at which these organisms release has been measured by Kovach and Swain[9], who towed a plate, which was coated with a Foul Release system and covered by fouling, and observed that the organisms started to release at speeds above 12 knots. These tests have shown that, with the current Foul Release technology, speeds in excess of 15 knots will prevent most types of fouling from settling on the surface. Foul Release systems are therefore particularly suited for ships which spend a short time in port and travel at sufficiently high speeds.

When Foul Release coatings were commercially introduced in the mid 1990s and first applied on a high-speed catamaran ferry to replace a CDP, the recorded fuel consumption was lower at the same service speed, implying lower drag characteristics.[10] A research project was therefore undertaken at the University of Newcastle-upon-Tyne with the objective of collecting data on the drag, boundary-layer and roughness characteristics of Foul Release and Tin-free SPC coatings, and to compare them systematically.[11] A summary of the findings of this research project is presented in the following section of the paper.

Dry-docking assessments have indicated that a microbial slime layer is present on ship hulls coated with Foul Release systems. The effect of slime on drag and an estimation of the possible repercussions on ship performance of hulls coated with Foul Release coatings is reviewed in Section 3 of this paper. The paper is concluded in Section 4 with some recommendations for dry-dock assessments.

2. Drag, boundary-layer and roughness characteristics of Tin-free SPC and Foul Release coatings

This section summarises the findings of a research project carried out at the University of Newcastle-upon-Tyne to systematically compare the drag, boundary-layer and roughness characteristics of Tin-free SPC and Foul Release coatings. The coatings used in this study were a PDMS (*Intersleek)* and a copper-pigmented acrylic polymer that contains zinc pyrithione as booster biocide (*Intersmooth Ecoloflex)*.

Drag measurements have been carried out in towing tank experiments with two friction planes of different size, which showed that the Foul Release system exhibits less drag than the

Tin-free SPC system. The difference in frictional resistance varied between ca. 2 and 23%, depending on the quality of application.[12] Rotor experiments were also carried out to measure the difference in torque between coated and uncoated cylinders. In addition to both coatings applied by spraying, a Foul Release surface applied by rollering was included because there were indications that this type of application might affect the drag characteristics. The measurements indicated an average 3.6% difference in local frictional resistance coefficient between the sprayed Foul Release and the sprayed Tin-free SPC, but the difference between the rollered Foul Release and the sprayed Tin-free SPC was only 2.2%.[13]

The friction of a surface in fluid flow is caused by the viscous effects and turbulence production in the boundary layer close to the surface. A study of the boundary-layer characteristics of the coatings was therefore carried out in two different water tunnels using four-beam two-component Laser Doppler Velocimetry (LDV) and the coatings were applied on 1m long test sections that were fitted in a 2.1m long flat plate set-up, as shown in Figure 2. The intersection of the laser beams is characterised by an optical interference fringe pattern in the "probe volume" which allows accurate determination of the velocity in the streamwise and wall-normal direction. The probe volume diameter was 276μm for the (blue) wall-normal channel and 291μm for the (green) streamwise channel. The velocity measurements were conducted over 20s or until 4096 validated samples were collected, whichever came first. A traverse mechanism allows the probe to be positioned to within ±12.5μm and moves the probe away from the wall so that a boundary-layer velocity profile is measured. Velocity profiles were measured at five different streamwise locations and at five different free-stream velocities.

Figure 3 shows the boundary-layer velocity profiles at 1.607m from the leading edge for a free-stream velocity U_e = 5m/s. The distance from the surface, $y+\varepsilon$, and the streamwise velocity component U have been scaled by the viscous length scale ν/U_τ and the friction velocity U_τ respectively. An outer-layer wall similarity method and the Reynolds stress method were used to determine the friction velocity and both methods showed good agreement with each other.[11] The measurments showed that the friction velocity for Foul Release surfaces is significantly lower than for Tin-free SPC surfaces. This indicates that at the same streamwise Reynolds number the ratio of the inner layer to the outer layer is smaller for Foul Release surfaces. The inner layer is that part of the boundary layer where major turbulence (and hence drag) production occurs. By definition the friction velocity is equal to:

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}} = \sqrt{\frac{c_f}{2}} U_e \tag{1}$$

whereby τ_w is the wall shear stress, ρ is the density of the fluid, c_f is the local frictional resistance coefficient and U_e is the free-stream velocity. Consequently, the downward shift in the log-law region (where the velocity increases linearly with the logarithm of the distance from the wall) of the velocity profiles shown in Figure 3 is a direct indication of the difference in local frictional resistance between a rough and the uncoated smooth reference surface. This parameter ΔU^+ is known as the velocity loss or roughness function.

Statistical analysis of the obtained values of the roughness function by means of multiple pairwise comparison using Tukey's test indicated that the roughness function for Foul Release surfaces is significantly lower than for Tin-free SPC surfaces at a 95% confidence level. These findings are consistent with the drag characteristics measured in the water tunnel and rotor experiments, as shown in the overview in Table 1.

In addition to the difference in frictional resistance and the roughness function, Table 1 shows the average roughness of each of the surfaces. This parameter was measured with the BMT Hull Roughness Analyser, which is the stylus instrument that is most frequently used in dockyards and which has a cut-off length of 50mm and a sampling interval of 1.25mm. It is clear from the rotor experiments and the large plate towing tank experiments that this single amplitude parameter does not correlate with the measured drag increase for Foul Release surfaces.

A detailed non-contact roughness analysis was carried out with an optical measurement system fitted with a 3mW laser. Measurements were taken on sample plates coated alongside the surfaces tested in the towing tank and water tunnel experiments and representative of their surface characteristics, and on slabs, cut from the cylinders used in the rotor experiments. A moving average 'boxcar method' was applied to filter long-wavelength curvature. The upper bandwidth limit or cut-off length was set at 2.5 and 5mm, whereas the lower bandwidth limit or sampling interval was set at 50µm. Typical roughness profile for each type of coating are shown in Figure 4.

The detailed roughness analysis revealed that when the profiles are filtered, the amplitude parameters of the sprayed Foul Release surfaces are in general lower than those of the rollered Foul Release surfaces and the SPC surfaces. However, the rollered Foul Release surfaces display a roughness height distribution which is considerably more leptokurtic (i.e. exhibits a larger number of sharp roughness peaks) than the sprayed Foul Release surfaces.

The greater number of high peaks on the rollered Foul Release surfaces is expected to engender higher drag than sprayed Foul Release surfaces.

The main difference between the Foul Release and the Tin-free SPC systems lies in the texture characteristics, as shown in Figure 5 and Figure 6 for two typical roughness measurements of a Foul Release and a Tin-free SPC coating applied by spraying. Whereas the Tin-free SPC surface displays a spiky ‘closed texture’, the wavy ‘open’ texture of the Foul Release surface is characterised by a smaller proportion of short-wavelength roughness. This is particularly evident in texture parameters such as the mean absolute slope and the Fractal Dimension. There is relatively little data available in the literature on the influence of texture of irregular surfaces on drag, but Grigson[14] has mentioned that open textures have a beneficial effect on drag.

It is thought that the rheology of the paint (which is dependent on the viscosity and significantly different for Foul Release and Tin-free SPC coatings) has a direct effect on its texture, whereas amplitudes depend significantly on the application quality. Correlation of the texture parameters with the amplitude parameters, however, shows that the two are inter-related so that bad application can be expected to have a knock-on effect on the texture parameters.

A correlation analysis between the roughness and drag characteristics was carried out and reasonably good correlation was achieved if a “characteristic roughness measure” is used which takes both the amplitude and the texture of the surface into account. At present, the procedure adopted by the International Towing Tank Committee to correlate roughness with drag only accounts for a single roughness amplitude parameter.[15] This procedure will not work for Foul Release surfaces, unless a texture parameter is included in the roughness characterisation. Even then, full-scale data should be gathered in order to adjust and validate the prediction of added drag from measured roughness characteristics. It is also recommended that more roughness profiles will be collected from dry-dockings since this study has only analysed newly applied coatings. This is only useful if a relatively simple modification of the BMT Hull Roughness Analyser is carried out to record the entire profiles digitally, rather than only the average extreme amplitude.

The effect of slime on ship performance

In the previous section, it was shown how newly applied Foul Release surfaces exhibit drag benefits over surfaces coated Tin-free SPC. These differences in drag may seem relatively small but would nevertheless offer significant fuel savings, were it not for the fact that Foul Release surfaces quickly become fouled with slime films. The effect of this slime fouling on ship performance has not been thoroughly investigated, but ship operators who have compared fuel consumption of Foul Release applications with TBT-SPC report that little differences can be seen.[4] It would therefore appear that slime fouling annihilates drag benefits of newly applied Foul Release coatings but does not increase drag beyond that. This section reviews the literature on the effects of slime fouling on drag and addresses the repercussions on ship performance of hulls coated with Foul Release surfaces.

Fouling starts from the moment the ship is immersed in seawater. The hull rapidly accumulates dissolved organic matter and molecules such as polysaccharides, proteins and protein fragments.[16] This conditioning process is regarded as the first stage of fouling, which begins within seconds, stabilises within hours, and sets the scene for later fouling stages. When a conditioning film has been formed, bacteria and unicellular organisms such as diatoms then sense the surface and settle on it, forming a microbial film.[17] This slime film involves the secretion of muco-polysaccharides, and generally eases the way for macrofouling settlement (i.e. weeds, barnacles, …).[18]

The genesis of fouling almost invariably occurs when the ship is at rest, most commonly in port. Ports differ considerably in their tendency to cause fouling and it is commonly known that the problem of fouling is more severe in tropical waters. The nature of the fouling community depends on the species of animal and plant life present in the water, the salinity and temperature of the water, the degree of illumination of the hull surface, the season when berthing takes place and the time spent in port. Considerable differences in the nature and intensity of fouling on a Foul Release surface were measured by Swain et al.[19] at seven different marine sites.

While the consequences of macrofouling are well known because it has a catastrophic effect on resistance, much less attention has been paid to the effect of slime films. McEntee[20] was probably the first to mention this. A separate section was devoted to the effect of slime fouling in the monumental work on antifouling for the first half of the 20th century, *Marine Fouling and its Prevention*.[21] Towing tank experiments carried out by the US Navy and involving different paints showed that after 1 days' exposure the increase in resistance was very small, but that after 10 days' exposure the resistance was increased more than 10% was measured and attributed to the effects of the slime film. It was observed however, that a significant part of the slime film released and that after 30 days' exposure the biofilm consisted of an upper layer which sloughs off and with a harder slime layer underneath that does not release. It was therefore estimated that the eventual drag increase on ships would be within a few percent of the painted hulls in clean condition, and within this context it is interesting to mention that the formation of slime on the 'Lucy Ashton' after a 40 days' mooring period resulted in a 3.5% increase in total resistance.[22]

Very similar conclusions were reached by Watanabe et al.[23] who carried out an elaborate series of rotor (with cylinders and discs) and towing tank experiments (with a 9m model) to study the effect of slime on resistance. They predicted a 9-10% increase in total full scale resistance. Compared to the towing tank experiments of Todd[24] with painted surfaces, the added drag of a slime film would similar to a painted surface of (now very) poor finish. The rotor experiments showed, however, that a very large quantity (> 90%) of the slime film will be removed at speeds above 8m/s.

Picologlou et al.[25] carried out pipe flow experiments with slime layers of thickness varying between 10 and 1000μm and found that the frictional resistance increased with increasing thickness.

Loeb et al.[26] measured the effect of several different types of microbial slimes on the drag of rotating discs of different materials with different roughness. The results showed that the drag of the discs was increased by 10 to 20%. Based on similarity law characterisation methods, a drag increase of 5 to 8% was predicted at 40 knots for smooth planes.

Lewthwaite et al.[27] developed a technique for determining the local skin friction of a ship's hull under seagoing conditions. Using a small pitot type probe, detailed measurements of the boundary-layer velocity profile and hence the local frictional resistance coefficient were obtained. As the hull became covered with a dense slime film but remained virtually free of weed and shell growth, an increase in skin friction of about 80% was recorded together with a 15% speed loss.

Since it is not easy to experiment with slime films because of detachment problems, a few experiments have been carried out with "artificial slime films". Lewkowicz and Das[28] used nylon tufts to simulate fouling in general and measured the turbulent boundary-layer characteristics in a wind tunnel. El-Labbad[29] applied agar-gel of different concentrations on a friction plane to simulate light and heavy slime films in particular. The towing tests showed that the frictional resistance coefficient was increased by 4-11% and 13-21% respectively.

Bohlander[30] carried out power trials after underwater cleaning of a US navy frigate. A significant change in power consumption, ranging between 8 and 18%, was measured after the removal of a 22-month old mature slime layer and the maximum speed of the test ship, was increased after cleaning by about 1 knot.

More recently, Schultz and Swain[31] investigated the effect of biofilms on the turbulent boundary layer structure by comparing the boundary-layer characteristics of different surfaces with two-component LDV. They found that the frictional resistance coefficient was dependent both on the biofilm thickness and on its morphology. An average increase in the skin friction coefficient for slime films with a mean thickness of 163μm and 347μm before testing was 33% and 68% respectively. By comparison, the average increase for a surface dominated by filamentous green algae (*Enteromorpha* sp.) with a mean thickness of 310μm was 187%.

Slime films are not washed off from Foul Release surfaces because their adhesion strength is much higher than the adhesion strength of other organisms. Several evaluation tests have been carried out recently to measure the adhesion strength of fouling organisms to Foul Release surfaces. Most data is available on the shear adhesion strength of barnacles because this is recognised as a standard method to test the efficacy of Foul Release materials.[32] Swain et al.[19] measured the barnacle adhesion strength of Foul Release surfaces at seven different marine sites and the pooled data showed that the barnacle adhesion strength was on average around 80Pa for the coating used in the experiments in Section 2 (i.e. Intersleek). Even though large variations are possible due to factors such as the nature of the biofilm, the temperature and salinity of the seawater and others, this value can be taken as a critical value to predict the release of barnacles under shear for different vessels.

Walderhaug[33] gives the following approximate formula for the friction velocity:

$$U_\tau = \frac{U_e}{(\ln \mathrm{Re})^{1.2}} \tag{2}$$

so that the wall shear stress can be approximated by:

$$\tau_w = \frac{\rho U_e^{\;2}}{(\ln \mathrm{Re})^{2.4}} \tag{3}$$

whereby U_e is the free-stream velocity, Re the Reynolds number and ρ the density of the fluid. White[34] gives an alternative formula:

$$\tau_w = 0.0135 \nu^{1/7} \rho U_e^{13/7} x^{-1/7} \tag{4}$$

whereby ν is the kinematic viscosity of the fluid and x the streamwise distance from the leading edge. Equation 4 has been used to calculate the wall shear stress at the stern for a 2m long friction plane, a 90m long high speed ferry and a 250m long tanker in seawater at 15°C (for which[35] $\rho = 1025.9\text{kg/m}^3$ and $\nu = 1.18831 \cdot 10^{-6}\text{m}^2/\text{s}$). The wall shear stress against free-stream velocity is shown in Figure 7. Taking the barnacle adhesion strength $\tau_{adh} = 80\text{Pa}$ as the critical shear stress, it can be seen that the release of barnacles is expected at speeds exceeding 7.75m/s for the friction plane, 10.38m/s for the high speed ferry and 11.23m/s for the tanker. These predictions compare well with the towing test results of Kovach and Swain. The use of Equation 3 would make relatively little difference for the tanker and high speed ferry, but would predict the release of barnacles at speeds exceeding 8m/s for the friction plane. The advantage here of Equation 3 is that it can easily be converted to predict the velocity $U_{release}$ above which fouling organisms are expected to release from a ship of length L once the adhesion strength τ_{adh} of those organisms is known:

$$U_{release} = 10.15648 \nu^{-1/13} \rho^{-7/13} L^{1/13} \tau_{adh}^{7/13} \tag{5}$$

Monitoring antifouling performance after the TBT ban

- the need for in-service data
- recommend roughness (and propeller torque) measurements

Suggested input from Colin

- Latest figures on TBT-SPC, Tin-free SPC, CDP and Foul Release market shares
- Are there any roughness measurements after 10/2001? Can we publish a Table genre Table 2-1?
- Review Maxim’s (brief) description of antifouling monitoring and I/P dataplan

- Review Maxim’s description of Foul Release characteristics with regards to slime

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Figures

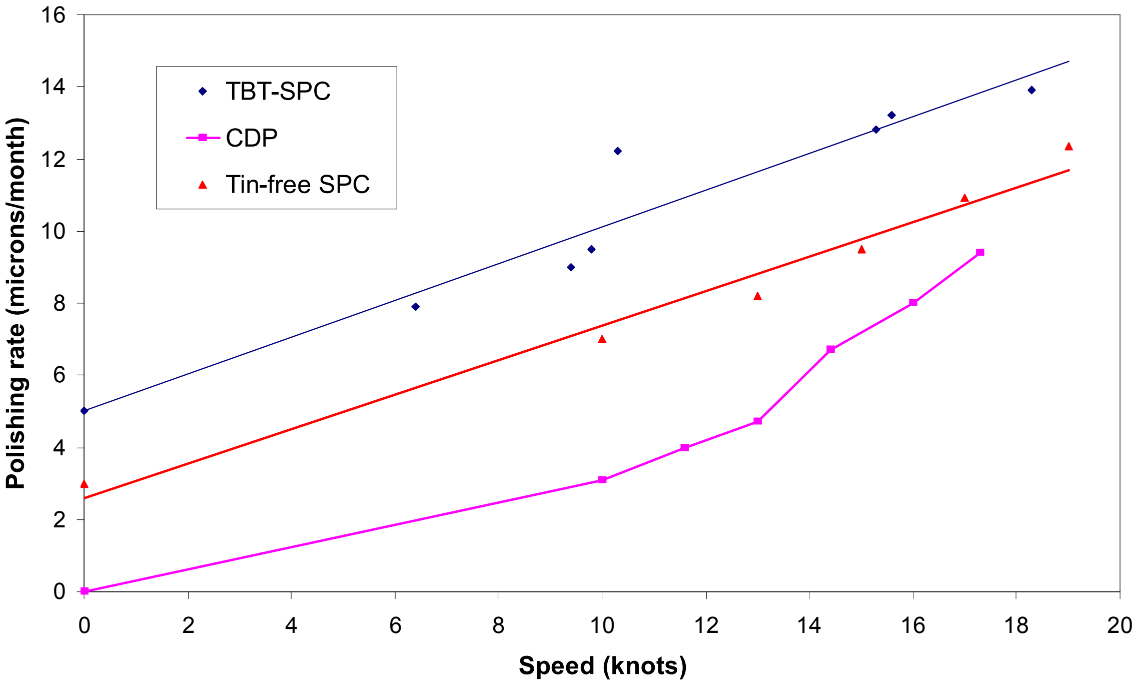

Figure 1. Polishing rates of toxic antifoulings.

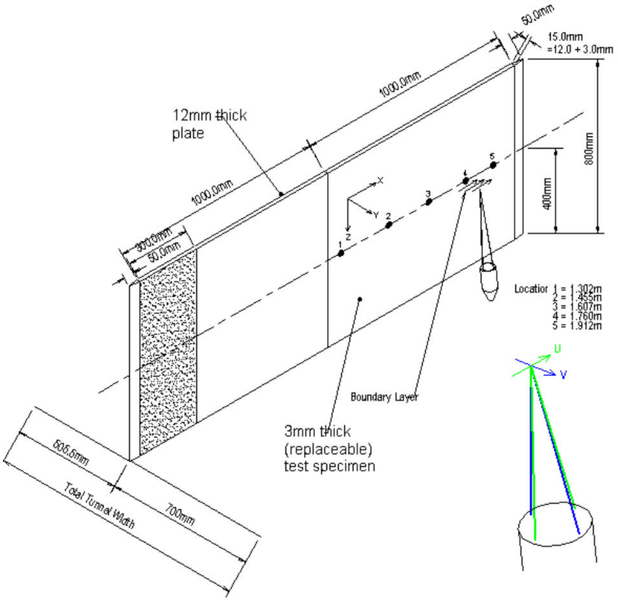

Figure 2. Schematic set-up for the LDV boundary-layer experiments.

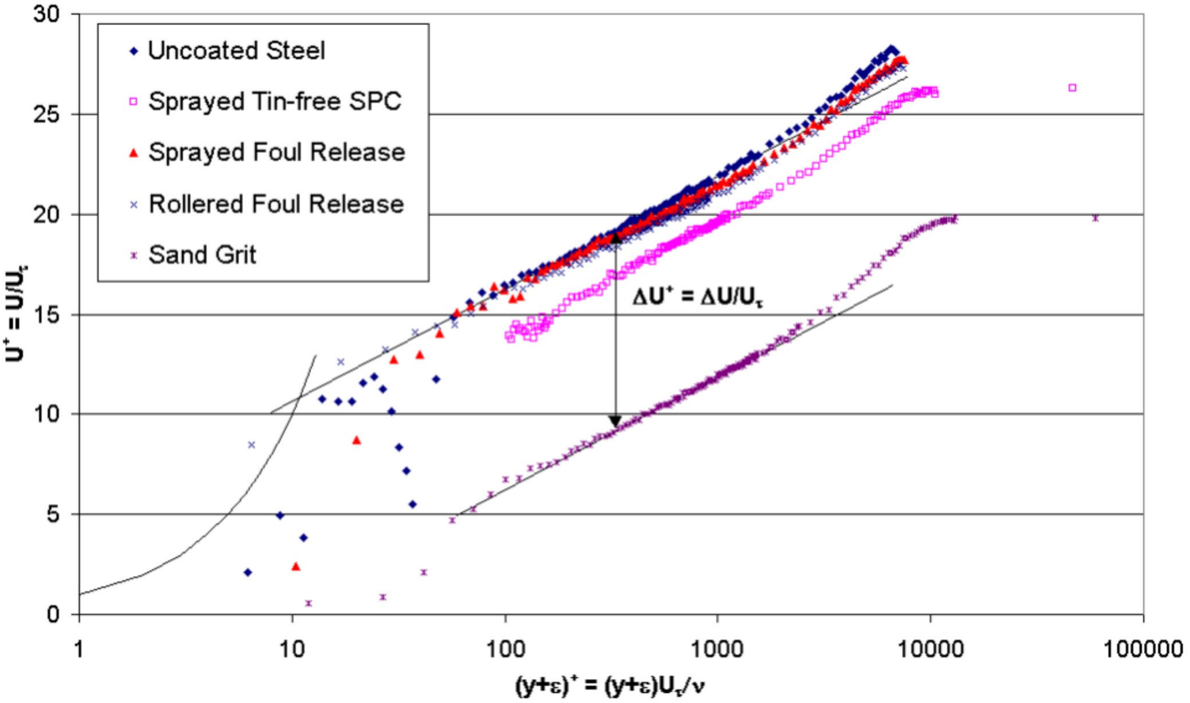

Figure 3. Boundary-layer velocity profiles in inner co-ordinates at U_e = 5m/s and at a streamwise location x = 1.607m from the leading edge. A rollered and a sprayed Foul Release surface were tested to investigate the effect of application method. A surface covered with sand grit was tested in order to have a very rough comparison. The velocity loss function ΔU^+ indicates the difference in frictional resistance between a rough and a smooth surface. (Experimental precision uncertainty over the log-law region: U^+: ±1.72% for the uncoated steel surface, ±1.94% for the rough surfaces; ΔU^+: ±14.74%).

Table 1. Overview of the drag characteristics

Towing tank experiments	**ΔC_F (compared to reference, %)**	**ΔU^+ (on average)**	**Average Roughness (μm)**
2.55m long plate	$2.0\cdot10^6 < Re < 4.2\cdot10^6$		
Sprayed Foul Release	3.9	0.20	44
Sprayed SPC	23.4	2.17	75
6.3m long plate	$2.0\cdot10^7 < Re < 4.0\cdot10^7$		
Sprayed Foul Release	2.1	0.21	62
Sprayed SPC	3.8	0.62	39
Rotor experiments	**Δc_f (compared to reference, %)**	**ΔU^+ (on average)**	**Average Roughness (μm)**
Cylinder	$1.0\cdot10^6 < Re < 2.1\cdot10^6$		
Sprayed Foul Release	4.3	1.00	108
Rollered Foul Release	5.7	1.31	218
Sprayed SPC	8.0	1.80	54
Water tunnel experiments	**Δc_f (compared to reference, %)**	**ΔU^+ (on average)**	**Average Roughness (μm)**
1m long vertical plate (Emerson Cavitation Tunnel)	$8.5\cdot10^3 < Re_{\delta 1} < 3.4\cdot10^4$		
Sprayed Foul Release	10.9	1.25	51
Rollered Foul Release	13.1	1.54	60
Sprayed SPC	16	1.80	69
1m long horizontal plate (CEHIPAR Cavitation Tunnel)	$1.6\cdot10^4 < Re_{\delta 1} < 4.6\cdot10^4$		
Sprayed Foul Release	14.6	1.68	50
Sprayed SPC	22.9	2.71	30

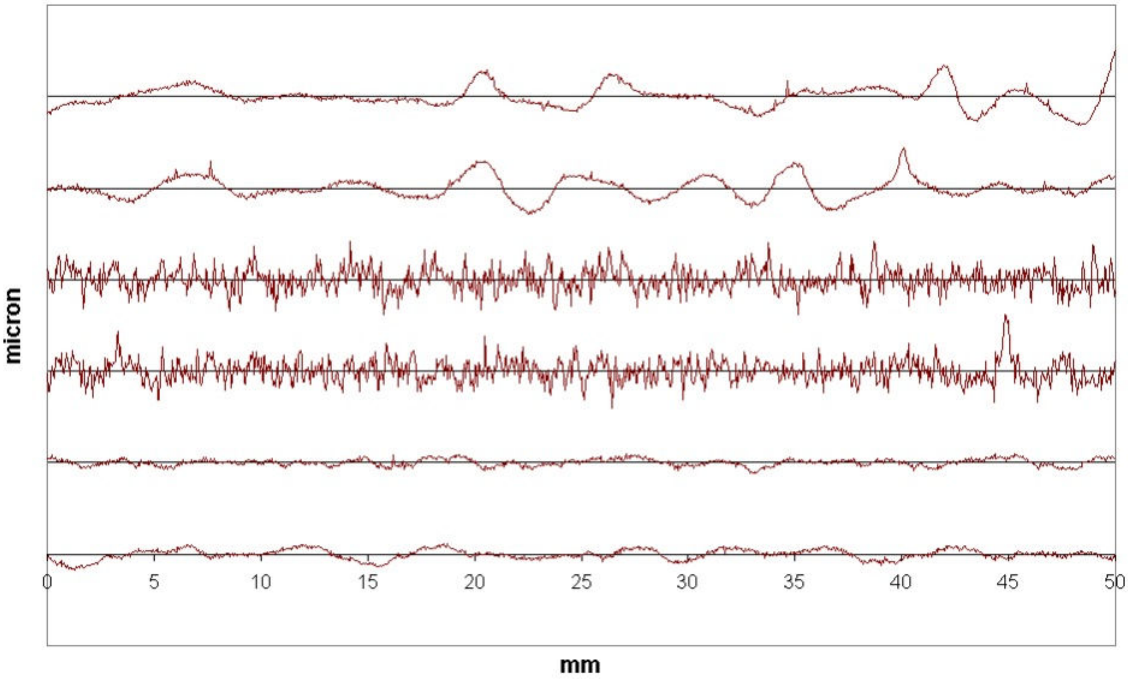

Figure 4. Two typical roughness profiles of (from bottom to top respectively) a Foul Release scheme applied by spraying, a Tin-free SPC scheme applied by spraying and a Foul Release scheme applied by rollering. The horizontal gridlines are separated by 25μm.

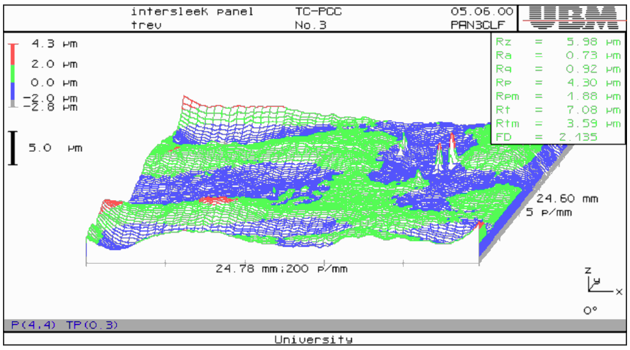

Figure 5. Typical roughness measurement of a sample (sprayed) Foul Release surface.

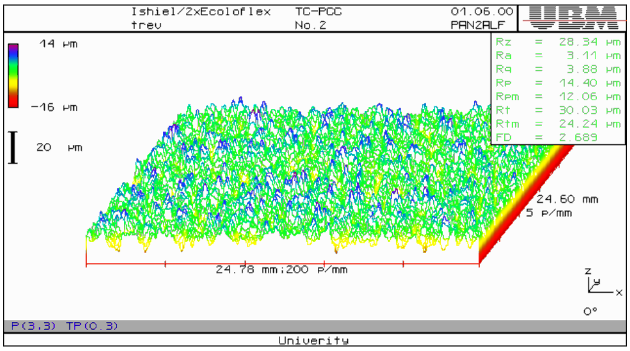

Figure 6. Typical roughness measurement of a sample Tin-free SPC surface.

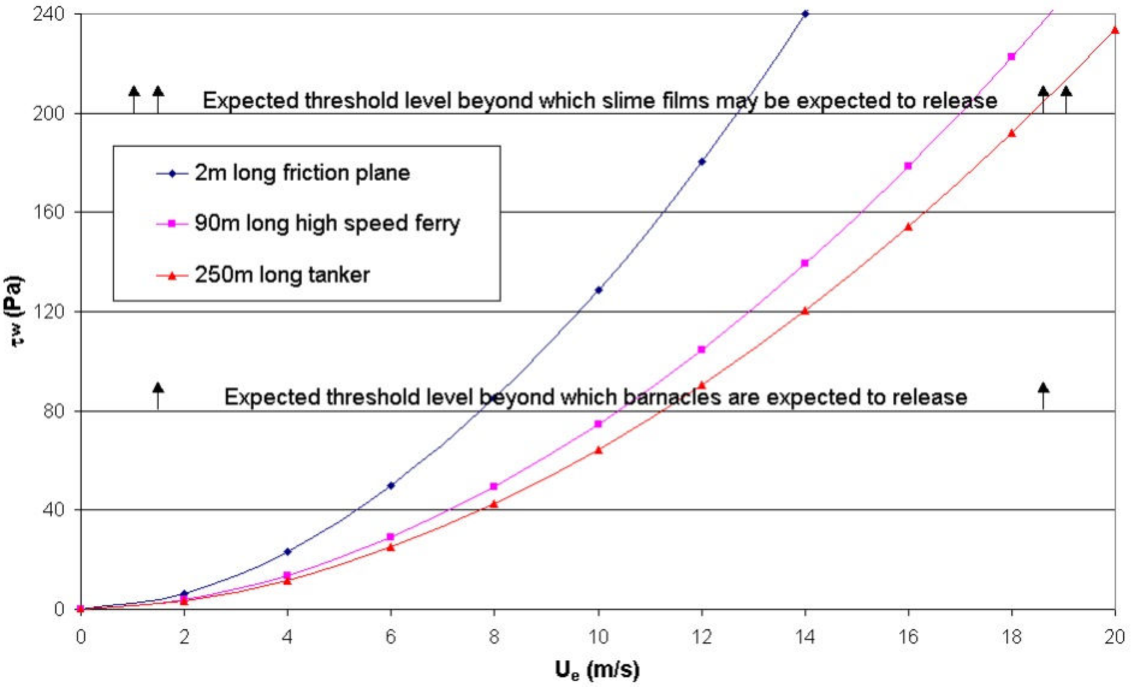

Figure 7. Wall shear stress against free-stream velocity. The expected threshold release levels for barnacles (80Pa) and slime films (200Pa) are indicated.

Comments

Becker, 1993, one barnacle and one polychaete species on seven different substrata. Both species adhere much better on substrata with higher surface tension, colonization pattern of these two speciesis not influenced by surface tension or by colonization of microfouling

Jounal of Colloid and Interface Science, Vol. 104, no 1 devoted to "Initial events on Bioattachment at the solid-liquid interface

Fletcher, M. and Pringle, J.H. (1985), The effect of surface free energy and medium surface tension on bacterial attachment to solid surfaces, *J. Coll. Interf. Sci.*, Vol. 104, pp. 5-14.
→ bacteria attachment does not depend surface tension

Dexter, S.C. (1979), Influence of substratum critical surface tension on bacterial adhesion – in situ studies, *J. Coll. Interf. Sc.*, Vol. 70, pp. 346-354.
Interfactial tension may explain difference between in vitro and in situ. In situ indicates that bacterial adhesion is lowest on 20-25mN/m. Complicated.

Crisp, Nature, 1953, Vol. 171, p. 1109, left out.

Hsieh, Y.-L. and Timm, D.A. (1988), Relationship of substratum wettability measurements and initial *Staphylococcus aureus* adhesion to films and fabrics, *J. Coll. Interf. Sc.*, Vol. 123, pp. 275-286.
→ wettability not dominant factors, adhesion influenced by other properties

Baum C., Meyer, W., Steizer, R., Fleischer, L.-G. and Siebers D. (2002), Average nanorough skin surface of the pilot whale (*Globicephala melas,* Delphinidae): considerations on the self-cleaning abilities based on nanoroughness, *Marine Biology*, pp. 653-657

Gollasch, S. (2002), The importance of ship hull fouling as a vector of species introductions into the North Sea, *Biofouling*, Vol. 18, pp. 105-121.

Matsui, Y., Nagaya, K., Funahashi, G., Goto, Y., Yuasa, A., Yamamoto, H., Ohkawa, K. and Magara, Y. (2002), Effectiveness of antifouling coatings and water flow in controlling attachment of the nuisance mussel *Limnoperna fortunei, Biofouling*, Vol. 18, pp. 137 – 148.

Matsui, Y., Nagaya, K., Yuasa, A., Naruto, H., Yamamoto, H., Ohkawa, K. and Magara, Y. (2001), Attachment strength of *Limnoperna fortunei* on substrates, and their surface properties*, Biofouling*, Vol. 17, pp. 29-39.
→ adhesion strength lower on silicones,
surface roughness (Ra) did not affect the mode of release of the mussel, surface free energy did
findings suggest that a substratum with a low hydrogen bonding surface freee energy is a prerequisite to decrease the detachment energy

Kavanagh, C.J., Schultz, M.P., Swain, G.W., Stein, J., Truby, K. and Wood, C.D. (2001), Variation in adhesion strength of *Balanus eburneus, Crassostrea virginica* and *Hydroides dianthus* to fouling-release coatings, *Biofouling*, Vol. 17, pp. 155-167.
→compares adhesion strength of barnacles, oysters and tubeworms on eight silicone foul-release coatings that contain oil additives. Oil additives reduced barnacle adhesion strength but not oysters and tubeworms:
barnacle adhesion strengths: lowest between 15-35Pa, highest 70-100Pa
study suggests that further investigation is needed into the fracture behaviour of biological adhesives to determine the controlling mechanisms of release. Factors may be chemical and physical properties of biological adhesives, variable geometry of interfacial contact…

Amongst algal colonizers diatom slime adhere tenaciously to silicone elastomers (Callow et al., 1987, Waterman et al., 1997) whilst common macrofouling algae such as *enteromorpha* and *Ectocarpus* do not (Callow et al., 1986)
Low numbers encountered on raft panels was largely the consequence of grazing and predation (Swain et al., 1998). Thus the performance of silicone elastomers as low-foul or foul-release coatings depends on a number of variables, including colonisation, strength of attachment and grazing. The type of curing agent used in the polymerization of silicone elastomers also has an effect on the settlement and adhesion of *enteromorpha* zoospores (Callow and Callow, 1998)

Callow, M.E., Pitchers, R.A. and Milne, A. (1986), The control of fouling by non-biocidal systems. In: *Algal Biofouling*, L. V. Evans and K. D. Hoagland (Ed.), Amsterdam, Elsevier**,** Chapter 10.
Callow, M.E., Pitchers, R.A. and Santos, R. (1987), Non-biocidal antifouling coatings. *Biodeterioration 7*, Elsevier Applied Science, Cambridge, pp. 43-48.
Callow, M.E. and Callow, J.A. (1998), Enhanced adhesion and chemoattraction of zoospores of the fouling alga *Enteromorpha* to some foul-release silicone elastomers. *Biofouling,* Vol. 13, pp. 157-172.
Swain, G.W., Nelson, W.G., Preedeekanit, S. (1998) The influence of biofouling adhesion and biotic disturbance on the development of fouling communities on non-toxic surfaces. *Biofouling*, vol. 12, pp. 257-269.
Waterman, B., Berger, H.-D., Sonnichsen, H., Willemsen, P. (1997), Performance and effectiveness of non-stick coatings in seawater. *Biofouling*, Vol. 11, pp. 101-118.

Stoodley, P., Boyle, J.D., deBeer, D. and Lappin-Scott, H.M. (1999), Evolving perspectives of biofilm structure, *Biofouling*, Vol. 14, pp. 75-90.
Confocal scanning laser microscopy have indicated the existence of cell clusters within the biofilm and its extracellular polysaccharide slime matrix have shifted the conceptual models from homogeneous to heterogeneous
Convective mass transfer can occur within biofilms(much faster than diffusion), the velocity gradient (and wall shear stress) was directly proportional to average bulk velocity

Implications of heterogenous structures is that, unlike planar biofilm where drag will mainly occur from friction, fluid flow will also result in pressure or form drag. The hydrodynamic drag will not only depend on thickness alone, as suggested by Picologlou et al. (1980), but will also depend on the degree of surface coverage of the biofilm and the distribution of cell clusters on the substratum: wake interaction flow regime. It is possible that the detachment of a few cell clusters may change the flow regime and the triggering of sloughing events

Within the biofilm channels exist, whose influence on nutrient and waste product exchange becomes more pronounced at higher flow rates

Stoodley, P., Boyle, J., Cunningham A.B., Dodds, I., Lappin-Scott, H.M. and Lewandowski, Z. (1999), Biofilm structure and influence on biofouling under laminar and turbulent flows. In: Keevil, C.W., Godfree, A., Holt, D., Dow, C.(Eds), *Biofilms in the Aquatic Environment*, The Royal Society of Chemistry, Cambridge, UK, pp. 13-24.

Turley, P.A., Fenn, R.J., Ritter, J.C. (2000), Pyrithiones as antifoulants: environmental chemistry and preliminary risk assessment, *Biofouling*, Vol. 15, pp. 175-182.
Pyrithiones rapidly degrade in water to less toxic compounds

Pasmore, M., Todd, P., Pfiefer, B., Rhodes, M. and Bowman, C.N. (2002), Effect of polymer surface properties on the reversibility of attachment of *Pseudomonas aeruginosa* in the early stages of biofilm development, *Biofouling*, Vol. 18, pp. 65-71.

Verran, J. and Boyd, R.D. (2001), The relationship between substratum surface roughness and microbiological and organic soiling: a review, *Biofouling*, Vol. 17, pp. 59-71.
→ three scales of roughness: macro (ca. 10): influence mechanical properties of the interface; micro (ca. 1 micron) plazque, and nanoroughness (< 1 mcron) hygiene
different measurement techniques exist, Ra alone limited descriptor
in earlier literature surface roughness was included as a factor in enhancing the adhesion of microrganisms, but it might be argued that retention is a more appropriate term in this context

Köhler, J., Hansen, P.D. and Wahl, M. (1999), Colonization patterns at the substratum-water interface: how does surface microtopography influence recruitment patterns of sessile organisms?, *Biofouling*, Vol. 14, pp. 237-248.
→ settlement lowest on smoothest surfaces, but it appears that certain configurations in the micrometer range may have antifouling effect

Verran, J. and Hissett, T. (1999), The effect of substrate surface defects upon retention of, and biofilm formation by, microorganisms from potable water. In: Keevil, C.W., Godfree, A., Holt, D., Dow, C.(Eds), *Biofilms in the Aquatic Environment*, The Royal Society of Chemistry, Cambridge, UK, pp. 25-33.

White, D.C., Kirkegaard, R.D., Palmer, R.J.Jr., Flemming, C.A., Chen, G., Leung, K.T., Phiefer, C.B. and Arrage, A.A. (1999) The biofilm ecology of microbial biofouling, biocide resistance and corrosion. In: Keevil, C.W., Godfree, A., Holt, D., Dow, C.(Eds), *Biofilms in the Aquatic Environment*, The Royal Society of Chemistry, Cambridge, UK, pp. 120-130

(1995), *Water, Science and Technology*, Vol. 32, No. 8.

Thomas, K.V. (2001), The environmental fate and behaviour of antifouling paint booster biocides: a review, *Biofouling*, Vol. 17, pp. 73-86.

Kennedy, F.E., Brown, C.A., Kolodny, J. and Sheldon, B.M. (1999), Fractal analysis of hard disk surface roughness and correlation with static and low-speed friction, *ASME Journal of Tribology*, Vol. 121, pp. 968-974.
→ scale dependent fractal parameters smooth-rough crossover (SRC) and area-scale fractal complexity (Asfc) give more info than Ra and Rq, the start-up friction (stiction) increases as SRC decreases

Walderhaug (1986):
$U_\tau = V/\ln(Re)^{1.2}$

Terlizzi et al. (2000) Biofouling
2 year exposure tests, Adhesion strengths were measured. Brown algae represented border point between early community (dominated by slime, micro- and macro –algae) and late community (bryozoans,spnges, molluscs, polychaetes. Best performing coatings (silicone easy-release without additives) influenced community structure shifting it to earliest stages of colonization and were unsuitable for colonization by late community by virtue of thei surface energy.
Silicones without additives: adhesion strength of Barnacles: between 15-30psi (0.1MPa-0.2MPa), no increase in adhesion strength (lowest 7.2psi-50000Pa)
Water-jet pressure required to remove slime between 60-150psi (0.4MPa-1MPa) (lowest 55, highest 135),
Average ca. 100, no increase in slime adhesion recorded throughout period of immerison

Swain G., Anil, A.C., Baier, R.E., Chia, F.-S., Conte E., Cook, A., Hadfield, M., Haslbeck, E., Holm, E., Kavangh, C., Kohrs, D., Kovach, B., Lee, C., Mazzella, L., Meyer A.E., Qian, P.-Y., Sawant, S.S., Schultz, M., Sigurdsson, J., Smith, C., Soo, L., Terlizzi, A., Wagh, A., Zimmerman, R. and Zupo, V. (2000), Biofouling and barnacle adhesion data for fouling-release coatings subjected to static immersion at seven marine sites, *Biofouling*, Vol. 16, pp. 331-344.
→differences in biofouling and adhesion on three known silicone formulations and an epoxy controil at seven different sites. Releative performance of coatings was similar but significant differences in type and intensity of fouling and in barnacle adhesion strength. Includes Intersleek (IN5), Intergard as primer (epoxy polyamide) two coats of 125micron, IN tiecoat 125, topcoat 150micron dft., critical surface tension 28.2N/m, total surface energy 30.5J/m^2 (other RTV silicones of GE and Dow Corning – designed for other purposes- 23.8 and 20.7). by far Intersleek best performing, lowest fouling coverage, lowest mean adhesion, adhesion strengths will be modified by underlying fouling or coating damage, pooled data from all sites: 80kPa,Hawaii lowest , Singapore highest

White, F.M. (1994) Fluid Mechanics, 3rd Edition, McGraw-Hill, New York, 736pp.
$\tau_W = 0.0135\nu^{1/7}\rho Ue13^{/7}x^{-1/7}$
→ gives roughness limit, used by Berntsson et al (2000)

Title: The adhesion of the barnacle, Balanus improvisus, to poly(dimethylsiloxane) fouling-release

coatings and poly(methyl methacrylate) panels: The effect of barnacle size on strength and failure
mode
Author(s): Mattias Berglin; Ann Larsson; Per R. Jonsson; Paul Gatenholm
Source: Journal of Adhesion Science and Technology Volume: 15 Number: 12 Page: p1485 --
p1502
DOI: 10.1163/156856101753213321
Publisher: VSP
Reference Links: 34

Berntsson et al. (2000) reduction in barnacle recruitment on riblets, trigonometric inclination most significant geometrical parameter (between 20 and 80degress)

Hermanowicz, S.W., Schindler, U. and Wilderer, P. (1995) Fractal structure of biofilms: new tools for investigation of morphology, *Water Science & Technology*, Vol. 32 (8), pp. 99-105.
→ confocal laser scanning microscope, image analysis software:
small scale biomass clusters (< 5 micron) FD close to topological dimension and larger aggregates with FD considerably smaller
Berkeley

Gibbs, J.T. and Bishop, P.L. (1995) a method for describing biofilm surface roughness using geostatistical techniques, *Water Science & Technology*, Vol. 32 (8), pp. 91-98.
Real biofilms compared with agar roughed with sand paper of varying grit size
Length scale very improtant

Lewandowski, Z. and Stoodley, P. (1995), Flow induced vibrations, drag force and pressure drop in conduits covered with biofilm, *Water Science & Technology*, Vol. 32 (8), pp. 19-26.
→ individual microcolonies behave like blunt bodies shedding vortices, vibrating “streamers” correlation roughness, drag should be re-examined in context biofilm viscoelasticity and heterogeneity. Perhaps more appropriate to use Re based on biofilm structure length scale

van Loosdrecht, M.C.M., Eikelboom, E., Gjaltema, A., Mulder, A., Tijhuis, L. and Heijnen, J.J. (1995) Biofilm structures, *Water Science & Technology*, Vol. 32 (8), pp. 35-43.
When shear forces are high a patchy biofilm will develop, whereas at low shear rates the biofilm becomes highly heterogeneous with many pores and protuberances