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## The frictional resistance induced by bacterial based biofouling within drainage pipelines

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*Running Head:* The frictional resistance induced by bacterial biofouling

# The frictional resistance induced by bacterial based biofouling within drainage pipelines

## ABSTRACT

The aim of this study was to improve the current scientific understanding of bacterial based biofouling within drainage pipelines. To this effect, biofilms were incubated with synthetic wastewater on a high density polyethylene pipe, within a purpose built pipeline facility for 20 days at three steady-state flow regimes. The results presented within this study, with regards to the influence of flow hydrodynamics on biofilm frictional development over time have gone beyond that previously documented. The study has confirmed that the presence of a biofilm can cause a significant increase in frictional resistance. The impact of biofouling on frictional resistance was further compounded by the fact that traditional frictional relationships and their derivatives are not applicable to biofouled surfaces in their current forms. In particular, the von Kármán constant, which is an integral aspect of the Colebrook-White equation, was found to be non-universal and dependent on Reynolds Number for biofouled pipes.

*Keywords:* Biofilm; bacterial based biofouling; drainage pipelines; equivalent roughness; non-universal von Kármán constant; pipe flow.

## 1 Introduction

Population growth, urbanisation and climate change will undoubtedly put increasing pressure on pipeline infrastructure over the next century (Astarai-Imani et al., 2012; Mikovits et al., 2014, Kharin et al., 2013). It is widely acknowledged that the magnitude and intensity of precipitation in extreme events will increase as a direct result of climate change (Interagency Climate Change Adaptation Task Force, 2011; IPCC, 2012; Kharin et al., 2013). The increased runoff and storm water discharge will increase the likelihood of surcharge and flooding, particularly in highly populated urban areas. Global population growth will further exacerbate the impacts of climate change on combined sewer systems, especially in urbanised areas where it is forecast that the majority of the growth will be absorbed (United Nations, 2012). The effective management of Drainage Networks (DNs) is therefore of paramount importance to the water industry, and it represents one of their greatest challenges from both operational and public health standpoints. This challenge is exacerbated by the environmental complexities of DNs; which are characterised by highly diverse and variable flow rates, temperatures and their contents. Fouling mechanisms, such as bacterial based biofouling, contribute to, and are governed by these inherent complexities. Bacterial based biofouling refers to the natural, albeit sometimes undesirable process through which a complex microbiological slime layer – known as a biofilm – forms upon a surface. Biofilms within pipelines are generally classified on the macro-scale as either low-form gelatinous or

filamentous; and their presence can cause a significant increase in boundary shear stresses and surface roughness (Picologlou, 1980; Lambert et al., 2008; 2009; Barton et al., 2008).

The magnitude of the change in surface roughness caused by biofouling is a function of the physical nature of the biofilm (Schwartz et al., 2003; Barton, 2006; Andrewartha et al., 2008). Moreover, due to its viscoelastic nature and in particular, through a vibrating and oscillating action; a biofilm has the ability to remove significant amounts of energy from a flow field (Barton, 2006; Andrewartha et al., 2008; 2010; Walker et al., 2013). As a result, a biofilm's effective roughness can be significantly higher than that predicted based upon traditional wall similarity hypothesis, i.e. using the classical Nikuradse-type equivalent sandgrain roughness,  $k_s$  as defined within the Colebrook-White (C-W) equation;

$$\frac{1}{\sqrt{\lambda}} = -2.00 \log \left( \frac{k_s}{3.7D} + \frac{2.51}{R\sqrt{\lambda}} \right) \quad (1)$$

where  $\lambda$  is the Darcy-Weisbach friction factor;

$$\lambda = \frac{2gDS_f}{\bar{U}^2} \quad (2)$$

where  $g$  is the acceleration due to gravity (i.e.  $9.81 \text{ m/s}^2$ ),  $\bar{U}$  is the average freestream velocity,  $D$  is the internal pipe diameter and  $S_f$  is the friction slope or Pressure Gradient ( $=dH_f/dL$ ; where  $H_f$  is hydraulic headloss ( $=\Delta P/\rho g$ ; where  $\Delta P$  is pressure drop,  $\rho$  is the specific density of the fluid) and  $L$  is streamwise length.

Solving Eq. (1) for  $k_s$  yields:

$$k_s = 3.7D \left( 10^{\frac{-1}{2\sqrt{\lambda}}} - \frac{2.51}{R\sqrt{\lambda}} \right) \quad (3)$$

The mechanisms by which a biofilm interacts with a fluid along with its physical morphology are governed by the conditions under which it is grown (Stoodley et al., 1998a; 1998b). There is compelling evidence to suggest that flow hydrodynamics and nutrient availability are the two most influential factors governing biofilm development within pipelines (Cloete et al., 2003; Lauchlan et al., 2005; Tsvetanova, 2006). However, within DN's where it is likely that sufficient nutrients would be available, flow hydrodynamics will be the primary controlling factor due to its potential to remove existing biofilms and/or counteract further growth. Nevertheless, an inherent link exists between flow hydrodynamics and nutrient availability on biofilm development, owing to their combined influence on mass transfer and diffusion. The mass transfer and diffusion potential of a system is predominantly controlled by the level of turbulence in the flow, which is conventionally estimated by the dimensionless parameter, Reynolds Number,  $R$  ( $=\rho\bar{U}D/\mu$ ; where,  $\mu$  is the dynamic viscosity of the fluid).

The prevailing conditions within a typical DN mean the presence of a biofilm is realistically unavoidable, and as a consequence the accurate evaluation of a biofouled surface is imperative for efficient pipeline design and effective control strategies. However, this is not possible through the application of conventional design approaches which utilise traditional frictional relationships and roughness scales. In particular, the C-W equation (Eq. (1)) and  $k_s$  have been deemed inadequate for biofouled surfaces in their current forms (Schultz, 2000; Barton et al., 2004; Barton, 2006; Lambert et al., 2009; Perkins et al., 2013; 2014). It has been widely suggested that complex surface dynamics of a biofilm cannot be adequately defined by a single one-dimensional parameter, such as  $k_s$  (Picloglou 1980; Schultz and Swain 1999; Barton 2005; Lambert et al. 2008; 2009; Andrewartha 2010). However, as such a parameter (or series of parameters) has yet to be successfully formulated the Nikuradse equivalent sandgrain height was used herein to define  $k_s$ .

Lambert et al. (2009) used experimental observations on freshwater biofilms to obtain a modified C-W equation (Eq. (4)), which aimed at addressing the inadequacy of Eq. (1). Lambert et al. (2009) found that for biofouled pipes the von Kármán constant,  $\kappa$ , which is an integral part of the Eq. (1) (Matthew, 1990) was non-universal, dependant on  $R$ , and lower than the conventional value (i.e.  $\kappa = 0.42$ ).

$$\frac{1}{\sqrt{\lambda}} = -\frac{1}{\sqrt{8.08\kappa}} \ln \left( \frac{k_s}{0.85D} + \frac{2.51}{R\sqrt{\lambda}} \right) \quad (4)$$

Solving Eq. (4) for  $k_s$  yields:

$$k_s = 0.85D \left( e^{\frac{-1\sqrt{8.08\kappa}}{\sqrt{\lambda}}} - \frac{2.51}{R\sqrt{\lambda}} \right) \quad (5)$$

Similar observations were reported by Perkins et al. (2013; 2014) for biofilms incubated within a hydropower system. However, these studies assessed a very specific set of environmental conditions, and in the case of Lambert et al. (2009); a very limited range of flow conditions (at low  $R$ ). Furthermore, the environmental conditions within a hydropower or freshwater system are inherently different to those found within a DN, and this would be reflected in the respective system's biofilm. This ultimately affects the broader application of the reported observations, particularly with respect to DNs. Nevertheless, the existence of a non-universal Log-Law is not a new concept, as there is debate within the classical theory as to whether the  $\kappa$  is truly independent of  $R$  (Zanoun et al., 2003; Wei et al., 2005; Nagib and Chauhan, 2008). The highly dynamic nature of a biofouled surface will undoubtedly add an additional layer of complexity to the debate. The implication of a non-universal  $\kappa$  on roughness and flow rate determination (using Eq. (1)) could be considerable. This would be reflected in pipeline design through pipe sizing issues; and this could have financial and environmental ramifications especially if the pipe is oversized (Cowle et al., 2014; Cowle,

2015). From a purely academic standpoint, the impact of a non-universal  $\kappa$  would also be detrimental to wall similarity techniques, and in particular, in terms of their ability to effectively establish the local roughness for biofouled surfaces. This is because, these techniques, which are commonly used to determine parameters such as the wall shear velocity,  $u^*$  by fitting experimental data to the law of the wall (Eq. (6)) are reliant on the existence of a universal Log-Law.

$$\frac{u}{u^*} = \frac{1}{\kappa} \ln \left( \frac{yu^*}{v} \right) + 5.60 - \Delta U^+ \quad (6)$$

where  $u$  is the local freestream velocity,  $y$  is the distance from the wall (invert side),  $v$  is the kinematic viscosity of the fluid and  $\Delta U^+$  is the roughness function.

As a result, the frictional data derived from wall similarity techniques are highly sensitive to  $\kappa$  (Wei et al., 2005). The current prevailing understanding of biofilm-flow interactions is predominantly based upon observations established from wall similarity techniques, and thus a universal Log-Law (Barton, 2006; Barton et al., 2007; 2010; Andrewartha et al., 2008; 2011; Andrewartha, 2010, Walker et al., 2013). The potential non-universality of  $\kappa$  will bring the conclusions of these studies into question.

Ultimately, the inadequacies in current design practices and hydraulic theory are a reflection of the current state of scientific understanding on biofouling within DN's (Cowle et al., 2014). The increasing awareness and emphasis on sustainability within the water industry with respect to both the capacity and efficiency of existing networks and future installations means that it is now more important than ever to change the perception of biofouling and address the inadequacies in current pipe design approaches.

The aim of this study was to evaluate the impact of biofouling on the surface roughness of a drainage pipe within a controlled laboratory environment; for the purpose of providing a platform through which the inadequacies in current pipe design approaches could be addressed. The specific objectives of the study were to comprehensively determine the impact of biofouling on surface roughness and mean-velocity; investigate the impact of flow shear on biofilm development; and examine whether  $\kappa$  is non-universal for biofouled pipes.

## 2 Material and Methods

### 2.1 Experimental facility

The experiments reported herein were conducted within a purpose built pilot scale pipeline facility, located in the Hydraulics Laboratory, at Cardiff University School of Engineering. The facility, which was outlined in detail by Cowle (2015), was designed and developed as an open loop, recirculating system for the specific purpose of studying biofilm-flow interaction

within DN<sub>s</sub>, over a wide range of flow conditions. It was mostly fabricated from high density polyethylene (HDPE) and consisted of a storage tank (350 l), working part and recirculation part. The fluid within the pipeline was recirculated by a 2.25 kW single phase centrifugal water pump (*Clarke* CPE30A1). The pump is capable of operating within the range of  $0.3 \text{ m/s} < \bar{U} < 1.3 \text{ m/s}$  (or  $3.0 \times 10^4 < R < 1.30 \times 10^5$ , based on a fluid temperature of 20°C). The fluid temperature within the system was maintained by an external cooling unit (*D&D*, DC-750) and was measured using two universal temperature probes (model: *LabJack* EI-1034). The probes had a typical accuracy at room temperature of  $\pm 0.22 \text{ }^\circ\text{C}$  and were calibrated under non-flow and flow conditions using a mercury thermometer (which had an accuracy of  $\pm 0.10^\circ\text{C}$ ). Temperature control is essential in both biofilm and boundary layer investigations; for the purpose of environmental and *R* control. The fluid temperature within the facility was maintained at  $21.5 \pm 0.9^\circ\text{C}$ , which is representative of the temperature found within European DN<sub>s</sub> during the summer (i.e. 18-22°C) (*Cipolla and Maglionico*, 2014).

*[Insert Fig. 1]*

The working part of the facility was 9.5 m in length and consisted of a test pipe (8.5 m) and visualisation pipe (1.0 m). The test pipe comprised of four individual solid wall high density polyethylene (S-HDPE) pipe segments. The discrete pipe segments were carefully aligned and connected by flexible pipe coupling in such a manner to ensure a smooth transition between the segments. Nevertheless, it was inevitable that the joints would cause some disruption to the velocity fields in the system.

An S-HDPE pipe was selected due to its ubiquitous presence within the water management industry; particularly within the UK, and especially within modern projects (*Lauchlan et al.*, 2005; *Nielsen et al.*, 2005). The inner diameter of the test pipe was measured at 8 axial locations at 6 different positions along the length of the pipeline, and it was found to be  $102.08 \pm 0.44 \text{ mm}$ .

*[Insert Fig. 2]*

As illustrated in Fig. 2, the test pipe composed of a run-in section and test section. The run-in section was 3.35 m (or 34 *D*) long and corresponded to the region of  $0.00 \text{ m} < x < 3.35 \text{ m}$ . Using the criteria outlined by *Zagarola and Smits* (1998), the length of the run-in section was deemed sufficient for fully developed mean flow to be obtained within the test section. The test section was 5.0 m in length and was located between  $3.35 \text{ m} < x < 8.35 \text{ m}$ .

A hydrodynamic evaluation of the test pipe under non-fouled conditions over the range of  $3.15 \times 10^4 < R < 1.23 \times 10^5$  indicated that it had a *k<sub>s</sub>* value of 0.01 mm. A surface is

considered hydraulically smooth if the roughness Reynolds Number,  $k_s^+ (=k_s\nu/u^*)$  is less than or equal to five (Nikuradse, 1933). The maximum value of  $k_s^+$ , which coincides with the maximum  $R$  investigated (i.e.  $R = 1.23 \times 10^5$ ) was found to be 0.51 and as a result, the test was considered to be hydraulically smooth.

## 2.2 Measurements and instrumentation

### *Volumetric flow rate*

The volumetric flow rate,  $Q$  within the facility was recorded using a “time of flight” ultrasonic flowmeter (Nixon CU100). The meter had a reading accuracy of  $\pm 1.5\%$  and was located within the recirculation part of the system. The flow rate recorded by the ultrasonic flowmeter was verified against values of  $Q$  established from local mean-velocity data using a Pitot probe and conservation of mass principles. The diameter of the Pitot probe,  $d_p$  ( $=1.0$  mm) used to measure the mean-velocity data limited the spatial resolution near the wall to approximately 0.5 mm. As a result, a near wall correction was required, especially for high  $R$  (Zagarola, 1996). The values of  $Q$  determined from the flowmeter and Pitot probe were found to have a strong correlation, with a coefficient of determination,  $R^2$  of at least 0.92 being attained.

### *Pressure Gradient*

As the flow within the test section was fully developed, the frictional resistance of the pipe can be accurately determined from the system’s Pressure Gradient (PG) by application of simple equilibrium considerations. The test section’s PG was measured using a series of static wall tappings located at various circumferential and longitudinal positions as shown in Fig. 2. In order to minimise the impact of the wall tappings on the external flow field, the tappings were designed in accordance with the recommendations outlined by McKeon and Smits (2002). The key size characteristics of the wall tappings were  $d_h = 0.75$  mm,  $d_h/D = 7.35 \times 10^{-3}$ ,  $l_h = 7.0$  mm,  $l_h/d_h = 9.3$ ,  $d_c = 2.5$  mm and  $d_c/d_h = 3.33$ ; where  $d_h$  is the wall tappings’ diameter,  $l_h$  is the wall tappings’ length and  $d_c$  is the diameter of the connection to pressure gauge. Four wall tappings linked in a pressure ring arrangement were located at five streamwise locations (i.e.  $P_1, P_2, P_3, P_4, P_5$ , as shown in Fig. 2) along the test section. The pressure ring arrangement allowed a circumferential average pressure to be determined at each location, which reduced potential errors caused by uneven and unstable flow distributions (Barton, 2006). During a typical PG traverse, the time-averaged static pressure at each of the five streamwise locations was recorded at least 4 times and an average value determined. The wall tapping correction criteria outlined by McKeon and Smits (2002) was applied to all static pressure measurements recorded within the study.



### *Local velocity measurements*

A Pitot probe, which was located at  $P_5$  (i.e.  $x = 8.35$  m) was used to obtain all time-averaged velocity profile traverses within the test pipe. The probe's aperture, which was square ended and 1.0 mm in diameter was located in the same plane as the wall tapings at  $P_5$ . However, the main body of the probe was offset from the plane by 30.0 mm in a downstream direction; and this minimised any potential flow disruptions caused by the probe. A watertight gland allowed the probe to freely traverse 93% of the pipe's vertical plane. The distance along the pipe's vertical centreline relative to the wall (invert side) was accurately determined using a digital height gauge (*Rapid* AK9636D), which had an accuracy of  $\pm 0.01$  mm. A typical velocity traverse consisted of at least 45 logarithmically spaced wall-normal positions. Several corrections were applied to all pressure measurements recorded by the Pitot probe and static wall tapping to account for the effects of viscosity, velocity gradient, the presence of the wall and turbulence (McKeon and Smits, 2002; McKeon et al., 2003).

The wall similarity technique outlined by Perry and Li (1990) – referred to herein as the PL Method – was used to determine the local frictional conditions at  $P_5$  for the purpose of evaluating the mean-velocity data. The PL Method, which has been used to evaluate biofouled surfaces (Andrewartha, 2010, Walker et al., 2013) is known to consistently produce highly accurate values of local  $u^*$  (Walker, 2014). The von Kármán Constant applied during the analysis was 0.42. The Nikuradse's roughness function,  $B$ , which assumes different values depending on the flow regime was determined using the procedure outlined by Ligami and Moffat (1986) (for fully rough flow  $B = 8.48$ ). To establish  $u^*$  using the PL Method the exact location of the wall must be known, however, this was difficult to achieve given the position of the probe within the test pipe. Consequently, a wall origin correction,  $\varepsilon$  was applied. An adaptation of the method proposed by Perry and Joubert (1963) was integrated into the PL method in order to solve for  $\varepsilon$  and  $u^*$  simultaneously using an iterative approach.

### *Pressure transducers and data acquisition*

All pressure measurements were obtained using three high accuracy pressure transducers (*Omega* PXM409-070HG10V), designated 1 to 3, which had a full scale accuracy (including effects of linearity, hysteresis and repeatability) of  $\pm 0.08\%$  (or  $\pm 0.57$  mmH<sub>2</sub>O (at 20°C)). The pressure transducers were regularly calibrated to within  $\pm 0.5$  mm using individual wall mounted water manometers. Transducers 1 and 2 were used to record the pressure measurements required for each of the PG and velocity profile traverses. Transducer 3 always recorded the static pressure at location  $P_I$  during each of the respective traverses; and this was done for the purpose of removing any temporal variations observed during testing.

For each measurement interval within each of the PG and velocity profile traverses, the pressure, temperature and flow rate were simultaneously recorded by their respective devices and streamed to a desktop PC at a frequency of 100 Hz using a multifunction 24-bit datalogger (*LabJack* U6-Pro). Appropriate sampling times were derived for each of the variables using a cumulative time-averaged approach. For each discrete measurement, a setting time of 30 s and an acquisition time of 24 s was used to ensure transients had settled and accurate time averaged pressure measurements could be attained.

### 2.3 Operating Conditions

Biofilms were incubated within the facility under full bore and steady state conditions with synthetic wastewater and with three separate flow regime assays, including the  $R = 5.98 \times 10^4$  (or  $\bar{U} = 0.60$  m/s) assay,  $R = 7.82 \times 10^4$  (or  $\bar{U} = 0.75$  m/s) assay and  $R = 1.00 \times 10^4$  (or  $\bar{U} = 1.00$  m/s) assay. The flow conditions within the respective assays are common within DN's within the UK, particularly in pumping/force mains which typically operate full bore and between the range of  $0.6 \text{ m/s} < \bar{U} < 1.0 \text{ m/s}$  (Lauchlan et al., 2005). The maximum recorded variation in  $R$  was  $\pm 3\%$ , which indicates that the flow conditions within the respective assays were reasonably homogenous. The shear stress,  $\tau_w$  acting on the biofilm was  $\tau_w = 1.42 \text{ N/m}^2$  for the  $R = 5.98 \times 10^4$  assay,  $\tau_w = 2.15 \text{ N/m}^2$  for the  $R = 7.82 \times 10^4$  assay and  $\tau_w = 2.95 \text{ N/m}^2$  for the  $R = 1.00 \times 10^4$  assay. These values are based upon the initial conditions (i.e. without fouling) and the principle that the primary force acting on the biofilm was the shear force generated by the flow (Stoodley et al., 2002). The internal hydraulic retention time within the facility during the three flow assays was at least 73 s, and therefore, the systems were considered to be well-mixed (Teodósio et al., 2010).

The synthetic wastewater was prepared according to the specification outlined by the Organisation for Economic Cooperation and Development (OCED, 1984) for the purpose of providing nutrient conditions that were representative of those found within typical DN's in Europe (i.e. COD = 541 mg/l, TN = 48 mg/l and TP = 8 mg/l, as outlined by Pons et al. (2004)). The wastewater had the following composition: 320 mg/l of Peptone, 220 mg/l of meat extract (540 mg/l as Chemical Oxygen Demand (COD)), 30 mg/l of Urea ( $\text{CH}_4\text{N}_2\text{O}$ ) (50 mg/l as Total Nitrogen, (TN)), 12 mg/l of di-potassium hydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ) (10 mg/l as Total Phosphorus (TP)), 7 mg/l of sodium chloride, 4 mg/l of Calcium Chloride Dihydrate ( $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ ) and 2 mg/l of Magnesium Sulfate Heptahydrate ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ). The pH, Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC) of the prepared wastewater was  $7.95 \pm 0.15$ , 244 mg/l and 201 mg/l, respectively. The physico-chemical properties of the wastewater within the three flow assays are presented within Table 1. The three flow assays were run for 20 d (480 h) which, based upon the nutrient conditions was

deemed sufficient for the biofilms to reach a state of equilibrium, at least in terms of their frictional resistance (Picologlou et al., 1980; Lambert et al., 2008; 2009; Andrewartha, 2010).

Prior to any experimental work, the whole facility was disinfected using a concentrated chlorine solution. Sodium thiosulfate was used to neutralise any residual chlorine within the facility post disinfection.

*[Insert Table 1]*

## 2.4 Experimental Uncertainty

The uncertainties associated with the frictional parameters measured and calculated within the current study are given in Table 2. The uncertainties listed in Table 2 were determined from repeatability test and represent a 95% confidence interval. The repeatability tests were undertaken under non-fouled conditions over the range of  $3.15 \times 10^4 < R < 1.23 \times 10^5$  (at increments of  $R \approx 1.00 \times 10^4$ ). Each  $R$  increment included a PG and velocity profile traverse and was repeated at least three times.

*[Insert Table 2]*

The uncertainties listed in Table 2 for the non-fouled pipe represent the worst case conditions for the facility. This is as a result of the smoothness of the non-fouled pipe and the  $R$  assessed. Higher Reynolds Numbers, in excess of  $R = 1.30 \times 10^5$ , which would have improved the experimental uncertainties listed in Table 2 could not be achieved using the facility in its current arrangement. A test section of greater overall length would have improved the experimental uncertainties, however, this could not be achieved due to laboratory restrictions, which limits the facility's total length.

## 3 Results and Discussion

### 3.1 General description of the fouled pipes

The biofilms incubated with wastewater within the current study displayed a predominantly low-form gelatinous structure. Filamentous type development was observed but very rarely, with filaments seldom exceeding 10 mm. The fouled pipes showed various amounts of microbial material with very different morphologies, depending on the conditioning. Typically, the biofilm incubated at high shear (i.e. in the  $R = 1.00 \times 10^5$  assay) had a seemingly more uniform coverage than the biofilm incubated at low shear (i.e. in the  $R = 5.98 \times 10^4$  assay), which had a more isolated structure. Molecular analysis of the biofilms showed that

they were diverse arrays of microbial cells, embedded within an extracellular polymer matrix of which carbohydrates dominated. Polymerase Chain Reaction-Denaturing Gradient Gel Electrophoresis (PCR-DGGE) indicated that the biofilms were dominated by *Bacteria* and in particular, members of the phyla *Alphaproteobacteria*, *Betaproteobacteria*, *Actinobacteria*, *Bacteroidetes* and *Firmicutes*. These species are commonly found within DNs, and as a result, the biofilms were considered representative and accurate to those found within real systems, at least on terms of bacterial dominance (Santo Domingo et al., 2011).

### 3.2 Impact on frictional resistance and mean-velocity

A complete set of PG and mean-velocity traverses were taken at least 3 times a day during each of the biofilm incubations, with the exception of the  $R = 7.82 \times 10^4$  assay where only PG data was collected. A total of 60 PG and mean-velocity (if applicable) profiles were taken during the incubation phase of three flow assays.

The influence of biofilm development on the frictional resistance over time is depicted in Fig. 3 in the form of  $\lambda$ . The values of  $\lambda$  presented in Fig.3 for the three flow assays were determined from system's PG using Eq. (2) where  $S_f$  was derived from a linear fit on profiles of static pressure (and therefore represent the space-averaged conditions over the whole) test section. The static pressure profiles recorded within this study for all the fouled pipes, at all flow rates and time intervals were always a linear function.

[Insert Fig. 3]

The increases in frictional resistance, as indicated by the increases in  $\lambda$  caused by the biofilms were significant, particularly with respect to the initial non-fouled conditions. This is consistent with the findings outlined previously within the literature (Lambert et al., 2008; 2009; Barton, 2006; Barton et al., 2008). The observed increases in frictional resistance would have potentially resulted in a reduction in  $Q$  of between 15-22%, had the pressure drop been held constant within each of the respective flow assays. It is evident from Fig. 3 that  $\lambda$  begins to depart from the non-fouled value after just 25 h of incubation. The biofilms reached a state of equilibrium, in terms of their frictional development after approximately 180 h (see Fig. 3). A summary of the frictional conditions recorded after the biofilms had reached a state of equilibrium is presented within Table 3, where  $c_f$  is the skin friction coefficient. The values of  $k_s$  presented within Table 3 where determined using the traditional C-W equation (i.e. Eq. (3)) and therefore should be viewed with caution, as discussed in Section 1.

[Insert Table 3]

It is evident from Table 3 and Fig. 3 that the highest values of  $\lambda$  were measured within the  $R = 5.98 \times 10^4$  assays, where  $\lambda$  plateaued at 0.034. The lowest values of  $\lambda$  were measured within the  $R = 1.00 \times 10^5$  assay where  $\lambda$  plateaued at 0.026. The  $R = 7.82 \times 10^4$  assay represented the intermediate. Single factor analysis of variances (ANOVAs) conducted on the three flow assay datasets indicated that the differences in  $\lambda$  between the respective assays were statistically significant, within the experimental uncertainty. The significance level of all ANOVAs was set at  $\alpha = 0.05$ .

Dimensionless mean-velocity profiles are presented in Fig. 4 for the range of  $0 \leq (y+\varepsilon) \leq R$ . Figure 4 illustrates that the presence of the biofilms caused a gradual shift in the velocity profiles associated with increasing surface roughness. This was also observed by Walker et al. (2013) for biofilms incubated within a hydropower channel for between 2-52 weeks, at  $\bar{U} \approx 1.0$  m/s. Once the biofilms had reached a state of equilibrium, the respective profiles appeared to collapse well onto a single curve (see Fig. 4c). Varying degrees of roughness are evident with Fig. 4. Typically, the biofilm cultivated within the  $R = 5.98 \times 10^4$  assay had the greatest influence on roughness, as exhibited by the greatest shift away from the non-fouled data. The mean-velocity data is presented in velocity defect form in Fig. 5. It is evident from Fig. 5 that the non-fouled and fouled data collapsed well onto one curve in the outer region of the boundary layer. This suggests that the presence of a biofilm did not affect the mean-flow structure in the outer region and therefore it provides support for Townsend's wall similarity hypothesis, which has also been observed within the literature for freshwater and marine biofilms (Schultz, 2000; Barton, 2006; Andrewartha, 2010; Walker et al., 2013).

*[Insert Fig. 4]*

*[Insert Fig. 5]*

It is evident that the frictional resistance induced by a biofilm is a function of the biofilm's conditioning. In particular, the lower the conditioning  $R$  the greater the frictional resistance imposed by the biofilm. This was to be expected, as the overall thickness of a biofilm is heavily dependent upon the shear conditions in which it is incubated; and that typically, the higher the conditioning shear the thinner the biofilm (Barton, 2006; Celmer et al., 2008; Lambert et al., 2008; 2009). As biofilm thickness defines to some extent the physical and effective roughness of a biofouled surface, the thinner the biofilm, the lower frictional resistance (Barton, 2006; Lambert et al., 2008; 2009; Andrewartha, 2010). Naturally, the opposite is true of thicker biofilms.

Furthermore, the mass transfer and drag limitation potentials associated with lower  $R$  would typically foster a more isolated and irregularly distributed biofilm (Stoodley et al., 1998a). Such a roughness distribution would induce a higher overall frictional resistance than that imposed by a uniformly distributed biofilm (Stoodley et al., 2002; Andrewartha, 2010). This could further explain the relatively high nature of the frictional data recorded within the  $R = 5.98 \times 10^4$  assay. Alternatively, the increased mass transfer and diffusion potentials associated with higher  $R$  would have induced a more uniformly distributed biofilm (Liu and Tay, 2001; Stoodley et al., 2002; Celmer et al., 2008). The increased uniformity coupled with the limits imposed on maximum thickness by the inherently high drag could explain the low values of  $\lambda$  recorded within the  $R = 1.00 \times 10^5$  assay.

The irregularity of the biofilm's space-averaged roughness distribution was evaluated by examining parts of the test section discreetly (i.e.  $P_1-P_5$ ,  $P_1-P_4$ ,  $P_1-P_3$  etc.). Figure 6 illustrates the standard deviation in  $\lambda$  for the  $R = 5.98 \times 10^4$  and  $R = 1.00 \times 10^5$  assays. The average standard deviation in  $\lambda$  determined under non-fouled conditions of  $1.25 \times 10^3$  is also presented in Fig. 6 for reference purposes. It is evident from Fig. 6 that the variation in space-averaged conditions along the test section after the biofilms had reached a state of equilibrium, was far greater within the  $R = 5.98 \times 10^4$  assay than within the  $R = 1.00 \times 10^5$  assay. This was supported by single factor ANOVAs conducted on the respective flow assays (where  $\alpha = 0.05$ ) which indicated that the differences in the values of  $\lambda$  recorded along the test section within the  $R = 5.98 \times 10^4$  assay were statistically significant, whereas, the ANOVAs performed on the  $R = 1.00 \times 10^5$  assay data showed that the differences in values of  $\lambda$  were statistically insignificant. The observed variation in the space-averaged values of  $\lambda$  supports the assumption that biofilm's overall coverage within the  $R = 5.98 \times 10^4$  assay was more irregular and thus less uniform (over the length of the system) than the respective coverage within the  $R = 1.00 \times 10^5$  assay.

[Insert Fig. 6]

The observed heterogeneity of the biofilms roughness serves to highlight the problem of characterizing a biofilm's effective roughness using a single scale, i.e.  $k_s$ .

### 3.3 Influence of Reynolds Number on mature biofilm development

Once the biofilms incubated within the  $R = 5.98 \times 10^4$  and  $R = 1.00 \times 10^5$  assays had reached a state of equilibrium in terms of their frictional resistance they were then subjected to varying flow regimes (over the range of  $3.05 \times 10^4 < R < 1.23 \times 10^5$ ). A total of 10  $R$  increments were assessed within this phase of testing, which will be referred to as the mature testing phase herein. A complete set of PG and mean-velocity traverses were recorded for each of the

fouled pipes at each  $R$  increment. A total of 62 PG and mean-velocity profiles were recorded during the mature testing phase; and this took place after approximately 480-500 h of incubation and took approximately 12-15 h to complete. An unforeseen complication which led to the death of the biofilm incubated within the  $R = 7.82 \times 10^4$  assay prior to the 500 h mark precluded it from this phase of testing.

The influence of  $R$  on  $\lambda$  is illustrated in Fig. 7. The relationships between  $R$  and  $\lambda$  depicted within Fig. 7 for the respective fouled pipes are evidently different to that expected based on standard convention (i.e. Eq. (1)). In particular, it is evident from Fig. 7 that  $\lambda$  increases with increasing  $R$ . For the  $R = 5.98 \times 10^4$  assay, the  $\lambda$  rises to a maximum of  $3.34 \times 10^{-3}$  at  $R = 9.02 \times 10^4$ . Whereas, the value of  $\lambda$  for the  $R = 1.00 \times 10^5$  assay increases to a maximum of  $2.74 \times 10^{-3}$  at  $R = 9.61 \times 10^4$ . Consequently, the current study is in agreement with the general consensus that the biofilm roughness does not follow the traditional C-W relationship (Schultz and Swain 1999; Schultz 2000; Barton 2006; Barton et al. 2008; Lambert et al. 2008; 2009; Perkins et al. 2013; 2014).

*[Insert Fig. 7]*

The magnitude at which  $\lambda$  increases with  $R$  is seemingly a function of the biofilm's overall effective roughness (and thus roughness distribution). In particular, the greater the roughness the greater the increase in  $\lambda$ . Lambert et al. (2009) reported a similar phenomenon for biofouling albeit for smaller diameters pipes (i.e.  $D = 25$ -50 mm).

Once the local maximum was reached,  $\lambda$  begins to decrease with increasing  $R$ . In the case of the  $R = 5.98 \times 10^5$  assay, this decrease was significant; whereas the equivalent decrease in the  $R = 1.00 \times 10^5$  assay was far more gradual. Similar trends have been reported within the literature (Barton et al. 2008; Lambert et al. 2008; 2009; Perkins et al. 2013; 2014). For instance, Perkin et al. (2014) found that the  $\lambda$  of a biofilm incubated within a hydropower pipeline increased gradually with increasing  $R$  between  $9.32 \times 10^4 < R < 1.57 \times 10^5$  to a maximum of 0.033, before decreasing significantly with increasing  $R$  between  $1.57 \times 10^4 < R < 2.66 \times 10^5$ . The biofilm assessed by Perkin et al. (2014) was conditioned at  $\bar{U} = 1.30$  m/s. The apparent reduction in  $\lambda$  with  $R$  after the local maximum was reached could be explained by a reduction in biofilm thickness caused by the biofilm compressing itself under loading (Percival 1999; Douterelo et al. 2013; Perkins et al. 2014) or by it being sheared from the surface (Schultz and Swain 1999; Barton 2006; Barton et al. 2008; Lambert et al. 2008; 2009; Andrewartha 2010; Douterelo et al. 2013). The usual reduction in  $\lambda$  with  $R$  could also explain the evident trend (Perkin et al. 2014).

To indirectly determine whether the increase in flow shear could actively remove the biofilm from the surface, the concentration of TOC with the bulk water was measured at each

R. Bulk water samples were taken directly from the storage tank and stored at  $-20^{\circ}\text{C}$  before being analysed. Due to the relatively short time it took to complete each of the mature testing phases (i.e.  $< 15$  h) any changes in water chemistry during this phase of testing would have likely been caused by biofilm detachment. The concentrations of TOC recorded within the bulk water for the  $R = 5.98 \times 10^5$  and  $R = 1.00 \times 10^5$  assays is presented in Fig. 8. It is evident from Fig. 8, that the concentration of TOC increased significantly within the  $R = 5.98 \times 10^4$  assay as flow shear increased. In particular, a significant increase in TOC was evident when  $R$  exceeded  $6.54 \times 10^4$ . The equivalent increase was less extreme in the  $R = 1.00 \times 10^5$  assay, although an increase was evident when  $R$  exceeded  $9.60 \times 10^4$ . The observed increase in organic content within each assays' bulk water suggests that biofilm detachment was likely to have occurred. However, based on the magnitude of the respective increases, the degree of detachment will have varied between the assays. For instance, the concentration of TOC within the bulk water of the  $R = 5.98 \times 10^4$  assay following the increase in flow shear was  $62.5 \text{ mg/l}$ , whereas, the equivalent concentration within the bulk water of the  $R = 1.00 \times 10^5$  assay was  $10.9 \text{ mg/l}$ . Therefore, it could be suggested that greater biofilm detachment was likely to have occurred within the  $R = 5.98 \times 10^4$  assay than within the  $R = 1.00 \times 10^5$  assay. The presumed detachment point for the  $R = 1.00 \times 10^5$  assay's biofilm, as suggested by the increase in bulk water organic content is the same point at which a reduction in  $\lambda$  was first recorded (see Fig. 7).

*[Insert Fig. 8]*

The gradual reduction in  $\lambda$  combined with the relatively low increase in TOC with  $R$ , observed within the  $R = 1.00 \times 10^5$  assay could potentially suggest that the respective biofilm was merely thinned or compressed by the increase in flow shear. Alternatively, the considerable changes in  $\lambda$  and TOC observed within  $R = 5.98 \times 10^4$  assay would suggest that large scale detachment occurred within the respective assay. However, as  $\lambda$  did not approach the non-fouled curve post shear, it was unlikely that the biofilm was completely removed. The point at which  $\lambda$  began to decrease with  $R$  within the  $R = 5.98 \times 10^4$  assay did not coincide with the detachment point implied by the changes in bulk water chemistry (i.e.  $R > 6.54 \times 10^4$ ). In fact,  $\lambda$  continued to increase beyond the presumed detachment point, which suggests that biofilm detachment did not occur. However, it is possible that the initial detachment which gave rise to the increases in bulk water organic content had a negligible effect on the biofilm's frictional capacity. Conversely, it is equally possible that the initial biofilm detachment could have given rise to a more heterogeneous roughness distribution, which could have directly contributed to, or been the reason for the observed  $\lambda$  relationship.



### 3.4 Determining $\kappa$ for biofouled surfaces

In order to establish whether  $\kappa$  had a dependence on  $R$  for a biofouled surface, the PG and mean-velocity data recorded during the mature testing phase was evaluated using the linear regression approach outlined by Lambert et al. (2009). In this approach a linear regression line of best fit was fitted to the Log-Law region of  $U^+$  against  $\ln((y+\varepsilon)/k_s)$  plot. The inverse of the slope of this regression line was equal to  $\kappa$  (i.e.  $\kappa = 1/[d(U^+)/d(\ln((y+\varepsilon)u^*/\nu))]$ ). The location of the Log-Law region within the boundary layer was determined experimentally using the method outlined by Saleh (2005) and was found to be unaffected by the presence of a biofilm. The location of the Log-Law region was taken as  $50 < yu^*/\nu < 0.18r^+$ , which is also where standard convention states it should be (George, 2007).

Wall similarity techniques, such as the PL Method are typically used to determine local frictional conditions at a particularly streamwise location from mean-velocity data. However, such techniques are inherently dependent on a universal Log-Law in which  $\kappa$  is a known constant and typically equal to 0.42. As  $\kappa$  is the unknown in this instance, wall similarity techniques cannot be applied. Consequently, with no other means of determining the local frictional data, the global data determined from the system's PG was used. In particular, the frictional data determined between  $P_3$  and  $P_5$  was used. It should be noted that although the global values of  $u^*$  are unaffected by  $\kappa$ , the global values of  $k_s$  required re-calculation using Eq. (5). This was an iterative process and it required 3-4 iterations for a suitable convergence to be obtained.

Though, the applied global data represents the frictional conditions within the same section at which the mean-velocity data was recorded, it still may not be a true reflection of the local conditions at  $P_5$  (i.e. where the mean-velocity data was recorded). This is because a biofilm's roughness distribution is typically heterogenous, as highlighted by the biofilm incubated within the  $R = 5.98 \times 10^4$  assay. Furthermore, although the biofilm incubated within the  $R = 1.00 \times 10^5$  assay displayed a seemingly uniform roughness distribution, it is still highly unlikely it was truly homogeneous over the system. Any error in the frictional data used to determine  $\kappa$  would naturally result in errors in established values  $\kappa$  (Wei et al. 2005) As a consequence, the results presented herein should be viewed with caution.

The relationship between  $\kappa$  and  $R$  is presented in Fig. 9, which illustrates the combined data measured within the two fouled pipes. The two fouled pipe's datasets were combined as it was not possible to distinguish between them. It is evident from Fig. 9 that  $\kappa$  has a dependency on  $R$ , and in particular, a trend of increasing  $\kappa$  with increasing  $R$  can be observed. The elastic nature of a biofilm may have contributed to these trends. The lowest value of  $\kappa$  was measured for  $R = 2.50 \times 10^5$  and was equal to 0.32. The reduction in  $\kappa$  from the conventional value lessened as  $R$  increased. This could have been a result of the assumed

detachment of the biofilm and the smoothening of the pipe's surface under loading. This is supported by the fact that the value of  $\kappa$  approaches the canonical value as  $R$  increases.

*[Insert Fig. 9]*

The relationships of  $\kappa$  with  $R$  were found to be linear functions ( $R^2 > 0.95$ ), as given by:

$$\kappa = 9.443 \times 10^{-7}R + 0.302 \quad (7)$$

The trend observed within the current study for  $\kappa$  is consistent with the findings outlined by Perkins (2014) and Lambert et al. (2009). However, the values of  $\kappa$  found within the current study were generally higher than the equivalent values reported by Perkins (2014), who assessed the impact of biofouling on  $\kappa$  within a pipe of similar diameter to that used within the current study (i.e.  $D = 101.6\text{mm}$ ). Nevertheless, the biofilms observed by Perkins (2014) had a significant filamentous component. Visually, the filaments pictured by Perkins (2014) were considerably more abundant than those observed within the current study. Filamentous type development is known to induce a considerable amount of drag on a system, and in some extreme cases, it can alter the mean flow structure in the outer region of the boundary layer (Barton et al., 2006; Andrewartha, 2010). However, as a result of inherently dark conditions within a pipe, it was unlikely that the filaments observed by Perkins et al. (2014) would have been as long as those reported in the extreme cases, which typically relate to biofilms incubated within open channels. Nevertheless, the interactions between the filaments and the fluid may have contributed to the lower values of  $\kappa$  observed by Perkins et al. (2014). Consequently, the degree and type of biofouling may have had a greater influence on  $\kappa$  than was first thought, based on the observations reported within this study.

The observed non-universality of  $\kappa$  means that as expected the values of  $k_s$  values derived using Eq. (3) and presented in Table 3 are unrepresentative of the actual conditions. The equilibrium state values of  $k_s$  as derived from Eq. (5) (where  $\kappa$  is defined by Eq. 7) for the  $R = 5.98 \times 10^4$  and  $R = 1.00 \times 10^5$  assays were 0.11mm and 0.08mm, respectively. Therefore, on average, the traditionally derived  $k_s$  values overestimated the actual conditions by 49% for the  $R = 5.98 \times 10^4$  assay and 85% for the  $R = 1.00 \times 10^5$  assay. However, although the magnitude of the  $k_s$  values changed, the influence of conditioning shear on biofilm induced  $k_s$  remained the same. Figure 10 presents the experimentally determined post incubation values of  $\lambda$  recorded within the  $R = 5.98 \times 10^4$  and  $R = 1.00 \times 10^5$  assays, along with the theoretically determined values derived from Eq. (5) and (7). It is evident from Fig. 10 that prior to the local maximums being reached the modified C-W curves established using Eq.(5) and (7) are in good agreement with the experimentally determined values of  $\lambda$ . In particular, it was found

that the maximum discrepancy between the measured and predicted values was  $\pm 7.21\%$ . The average discrepancy between the respective friction factors was  $\pm 2.82\%$ . These discrepancies are within the experimental uncertainty in  $\lambda$  presented in Table 2.

*[Insert Fig. 10]*

The suggestion that wall similarity applies to biofouled pipes can also be questioned due to the observed non-universality of  $\kappa$ . This is because the velocity defect plots presented in Fig. 5, which support wall similarity for biofouled pipes were scaled by values of  $u^*$  derived from the PL Method. Velocity defect plots, which have been scaled by values of  $u^*$  determined directly from the system's PG are presented within Fig. 11 for the  $R = 5.98 \times 10^4$  and  $R = 1.00 \times 10^5$  assay. The observed collapses of the non-fouled and fouled profiles suggest that wall similarity is valid for biofouled surfaces, irrespective of the non-universality of the Log-Law constants.

*[Insert Fig. 11]*

## **4 Conclusions and Recommendations**

### *4.1 Conclusions*

Biofouling in drainage networks is realistically unavoidable. Consequently, the frictional properties of a biofilm, which are characterised by their highly dynamic and case-specific nature, should represent the “true” underlying surface roughness of all pipelines in service. However, such understanding is currently not recognised within conventional design practices; and this which is to the detriment of efficient and sustainable operation, given that:

- a biofilm's inherent ability to induce an effective roughness which is well in excess of what its physical structure would traditionally suggest;
- the traditional frictional relationships fail to adequately account for the true nature of a biofouled surface in their current manifestation.

The current study has for the first time comprehensively evaluated the impact of biofouling on frictional resistance of a high density polyethylene drainage pipe. The results presented within this study, with regards to the influence of flow hydrodynamics on biofilm frictional development over time have gone beyond that previously documented within the literature.

An initial increase in roughness caused by biofilm development was observed after just 25 h of incubation and it continued to increase until a statistically steady state was achieved. The time at which the biofilms reached a state of equilibrium was found to be independent of the conditioning shear and equal to 180 h. The magnitude of a biofilm's frictional resistance was evidently a function of the shear conditions under which the biofilm was incubated. Most notably, it was found that the lower the conditioning shear the higher the frictional resistance imparted by the biofilm. The biofilm's impact on frictional resistance was further compounded by its influence over the von Kármán constant. In particular, the current study has provided conclusive evidence that the von Kármán constant for biofouled surfaces are non-universal, dependent on Reynolds Number, and lower than the conventionally accepted values. As a consequence of the non-universality of the von Kármán constant, the traditional Colebrook-White equation is not applicable to biofouled pipes. The Friction Factor for a biofouled surface was shown to increase with increasing Reynolds Number, until a critical threshold was reached. After which friction factor decreased with increasing Reynolds Number. This decrease was partly attributed to the biofilm becoming detached under loading. Changes in bulk water chemistry, and in particular organic content supported this assumption.

The modified Colebrook-White equation (i.e. Eq. (3)) can be applied to drainage networks, provided the von Kármán constant is defined by Eq. (7). Furthermore, it was found that, although wall similarity is valid and applicable to biofouled surfaces, it is reliant on either the von Kármán constant or shear velocity being known, without which the results are likely to be unrepresentative of the actual conditions.

#### *4.2 Recommendations for further research*

The incubation conditions used within the current study were purposely designed to be representative of those found within natural sewer systems, albeit for those operating at full bore. The resultant biofilms incubated and evaluated within this study can therefore be considered equivalent to those found within real systems. However, wastewater systems with the exception of rising mains are rarely operated at full bore, and drainage networks as a whole are generally unsteady in nature. Consequently, although the study has provided much needed data on the topic of biofouling within DNs, further research is still required in order for biofouling to be truly incorporated within pipeline design practices. Such research should ideally expand on the fundamental ideas and concepts outlined within this study. In particular, it is recommended that biofilm development over time is evaluated for a greater range of conditions including a broader range of flow regimes, nutrient levels, operating depths and temperatures. Similarly, given the highly variable nature of real systems it seems prudent to incorporate and evaluate typical daily and seasonal variations in operational and environmental conditions within future studies.

This study has however provided the platform and equipment needed for this to be achieved

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