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The influence of bacteria based biofouling on the wall friction and velocity distribution of hydropower pipes

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Abstract

Algae biofouling such as the freshwater diatoms *Gomphonema tarraleahae* and *Tabellaria flucculosa* have been investigated thoroughly in open channel flows. Their presence has been shown to cause a significant increase in the local skin friction coefficient, the overall drag coefficient and can produce reductions in flow capacity of up to 10%.

This present study extends previous work to investigate bacteria based biofouling that forms on the inside walls of pipelines and machinery that are not exposed to sunlight. The effect of biofouling on a 1.5m long internally painted pipe section was investigated. The pipe section was first installed in a hydropower scheme for an extended period to allow the growth of flow conditioned biofilms at an average flow velocity of 1.3 m/s. It was then returned to the laboratory and tested at 15 different flow rates corresponding to a range of Reynolds numbers from $Re_D = 0.9\times10^5 - 3.9\times10^5$. At each flow rate the head loss of the fouled pipe was measured as well as the complete velocity profile at the downstream end of the pipe to ensure the full effect of the biofouling was captured. These results were used to evaluate the pipe friction factor and sand equivalent surface roughness, which could then be compared to values predicted by the Colebrook-White Equation.

Trends in the experimentally determined values of pipe friction factor with varying Reynolds number are significantly different from those predicted by the Colebrook-White Equation. Initially the friction factor increases gradually, before a sharp increase is observed at $Re_D = 1.53\times10^5$. Following this spike, the friction factor decreases rapidly compared to theoretical plots. The friction factor of a 3.5 m clean pipe was also tested simultaneously, which closely matched the expected prediction for a hydraulically smooth pipe flow.

Experimental velocity profiles show significant deviations from the theoretical prediction of flow through a rough pipe with a higher maximum velocity observed in the centre of the pipe but a lower velocity in the near wall region. All experimental values of velocity are lower than those predicted for hydraulically smooth pipe flow.

Introduction

Hydraulic Engineers have faced the challenge of designing reliable, efficient and economical pipe systems for irrigation, drainage and the transport of large volumes of water in Hydropower schemes for centuries. As with many engineering problems research has focused on the development of accurate modeling techniques to predict the carrying capacity and flow characteristics in pipes and channels.

After an extensive experimental program, which tested a wide range of flow rates in pipes that were commonly found in use commercially, Colebrook and White [2] developed the widely accepted and commonly applied Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} - \frac{2.51}{Re_D\sqrt{f}}\right) \qquad (1)$$

The friction factor f of a given new, clean pipe is dependent on the following parameters:

- Distance between joints
- Types of joints
- Deviation from nominal circular cross-section
- Deviation from longitudinal straightness
- Internal surface roughness of the pipe, ε

All but one of these factors, the internal surface texture of the pipe, are fixed and unchanging with time. The internal surface texture or roughness has been shown, in many instances, to vary significantly in time through erosion, surface deposits and the formation of algae and bacterial biofilms. Such changes have led hydraulics engineers to measure pipe flow characteristics that differ significantly from those predicted by empirical equations.

Barton *et al.* [1] investigated the hydraulic performance in pipelines of three Hydro Tasmania hydroelectric schemes. Pre and post cleaning tests were carried out in pipes that contained significant bacteria dominated biofilm growth. The tests showed an improvement in hydraulic efficiency was achieved by the removal of a thin layer of biofouling and that the friction law for conduits with biofouling can show trends significantly different to those predicted using the Colebrook-White type equation. Similar findings were reported by Lambert *et al.* [3], however the trend they observed differed significantly from that seen by Barton *et al.* [1].

Lambert *et al.* [3] conducted an experimental program with 25 mm and 50 mm diameter pipes coated with biofouling grown under laboratory conditions at maximum Reynolds numbers of $Re_D \simeq 5\times10^4$. Lambert *et al.* observed an increase in skin friction factor (f) with Reynolds number (Re_D) before a critical value was reached where a rapid decrease in f was recorded. This was attributed to the biofilm being sheared and washed off the pipe wall at high velocities. Their results also showed that the von Karman constant is much lower that the normal values of 0.4 in fouled pipes and this value varies with Reynolds Number.

Experimental Measurements

An experimental program was carried out in an open circuit pipe rig in the Hydraulics Laboratory of the School of Engineering at the University of Tasmania. The rig was designed using dimensional analysis and similarity methods to study the effect of biofouling in pipe flow.

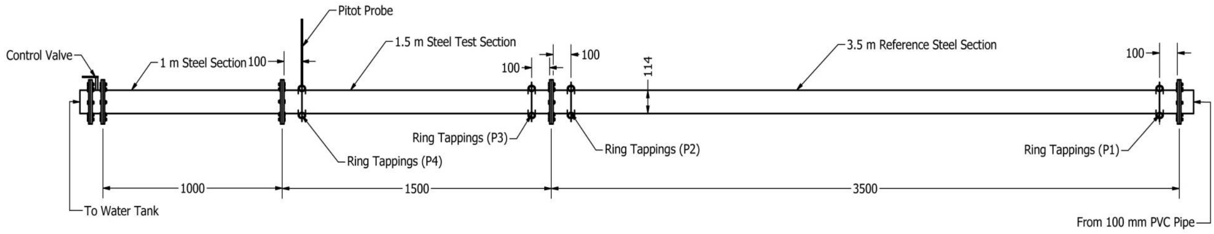

Figure 1: Schematic diagram of the experimental facility

The test rig has an internal pipe diameter of 101.6mm and achieved a Reynolds number range of $Re_D = 9.15 \times 10^4 - 4.0 \times 10^5$. This range places all test cases in between those covered by Lambert *et al.* [3] and Barton *et al.* [1] adding to the current body of research in this area. This range of Reynolds numbers is typical of many industrial flows where as the Reynolds number ranges tested by Lambert *et al.* are too low and by Barton *et al.*, too high, for many practical flow situations.

A series of static pressure ring tappings were placed along the test section and the clean upstream section of the system. These were used for the measurement of static pressure drop along the pipe system. A series of pitot probe traverse locations were also included in the design to investigate the development of the test section's velocity profile under fouled and clean conditions. The measurement locations can be seen in Figure 1.

Water was drawn from a sub floor holding tank through the pipe system by a 22 kW centrifugal water pump before travelling through a contraction, a honey comb flow straightener, a 3 m clean pipe section, the 1.5 m test pipe section, a butterfly valve and finally returning back into the holding tank. The internal surface of the pipes was coated with Interzone 954: a single coat modified epoxy barrier coating manufactured by International Paints.

The flow rate through the system was measured with two independent methods. A Yokogawa US300PM Ultrasonic Flowmeter and a 90^o V-notch weir located in a discharge tank before the holding tank. The US300PM has a reported velocity accuracy of ± 0.01 m/s and the water level of the V-notch weir was measured using an ultrasonic level sensor with a rated accuracy of ± 0.05 mm. The maximum difference between flow rates measured using the US300PM and V-notch methods was less than 2.75%.

Dynamic pressures across the pipe and static pressure drops along the various sections were measured using three Validyne DP15 differential pressure transducers. Each transducer had a different diaphragm to maximise output range and they were calibrated independently.

For each measurement point a settling time of 5 s and a acquisition time of 20 s were used to ensure any transients had settled in the system and high quality time averaged pressure could be measured. The water temperature was also recorded at each measurement point to provide an accurate calculation of density and viscosity.

A Labview program was used to control all data acquisition including the automated stepper motor controlled traverse gear. The flow rate was manually adjusted by controlling the pump speed.

In Field Test Section Fouling

To ensure that an accurate representation of the fouling found inside actual Hydropower pipelines was attained, the test sections were fouled on site using the same feed water as the Hydro penstocks. A continuous open loop pumping system was installed at Tarraleah Power Scheme Pond Number 1 to grow flow conditioned biofilms, which can be seen in Figure 2. A pump was used to transfer water from the pond through the test section pipes with a mean velocity of $U = 1.3$ m/s.

This approach placed unavoidable practical limitations on length of the test section which meant the ideal entrance length could not be placed between the straight flange joint and the first measurement location. However, directly upstream of the flange joint was a long straight length of pipe that ensured fully developed turbulent flow upstream of the flange.

Figure 2: Photograph of flow conditioned biofouling inside the test section before testing

The growth of flow conditioned biofouling is a critical element in the current investigation as the majority of work previously published has been based on lab developed biofouling under controlled conditions. It is hoped that the current technique will provide a better representation of how actual Hydropower pipelines will perform under the influence of biofilms.

Scope of Investigation

The current investigation looks at the velocity profile and pressure drops along the 1.5 m test section under clean and fouled conditions. The pressure drop was also measured along the 3.5m clean section of pipe upstream of the test piece to provide a consistent reference case. Tests were carried out at 15 equally spaced average flow speeds between 1 m/s and 4.5 m/s, which provided a Reynolds number range of $Re_D = 9.15 \times 10^4 - 3.92 \times 10^5$.

Results and Discussion

Influence of Biofouling on Friction Factor

Friction factor is an important characteristic of a pipe flow, which is often plotted against Reynolds number on the Moody diagram. Figure 4 shows friction factor results from the current investigation with a series of previously published experimental results and predicted values of friction factor using the Darcy-Wesibach Major Loss equation where:

$$f = \frac{1.325}{\left[\ln\left(\frac{e}{3.7D} + \frac{5.74}{Re_D^{0.9}}\right)\right]} \tag{2}$$

for $5000 \leq Re_D \leq 10^8$. The experimental values of f were based on static head differential H_f as given by

$$f = H_f \frac{D}{L} \frac{2g}{U^2} \tag{3}$$

Initial observations clearly depict significant differences between values predicted using Equation 2 and the experimental friction factors for the fouled test section, however the clean pipe follows the expected trend well (Figure 3). As Reynolds

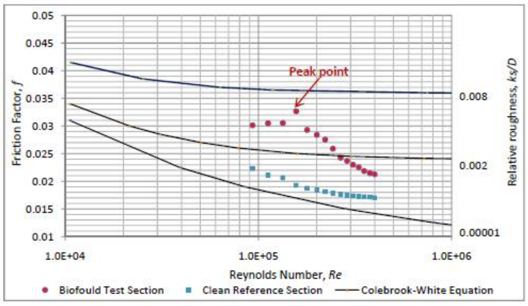

Figure 3: Moody diagram showing experimental and predicted values of friction factor

number is increased from $Re_D = 0.9 \times 10^4 - 1.57 \times 10^5$, the experimentally determined friction factor increases gradually before spiking to a maximum value at $Re_D = 1.57 \times 10^5$. The peak in f is followed by a significant decrease between $Re_D = 1.57 \times 10^5 - 2.66 \times 10^5$. The gradient of decreasing f then begins to relax with a further increase in Re_D and appears to be approaching a trend similar to that predicted theoretically at $Re_D = 4.00 \times 10^5$. Lambert *et al.* [3] observed a very similar trend, but at much lower Reynolds numbers, which are labeled as *Lambert1* and *Lambert2* in Figure 4.

The sudden decrease in friction factor is attributed in the most part to the biofouling shearing away from the surface by the flow of water at a critical velocity, which in this case was $U_{crit} = 1.77$ m/s. It is also possible that the increase in velocity causes the biofouling to flatten against the pipe wall, decreasing the value of ε/D. Similar reasoning was attached to observations made by Lambert *et al.* [3].

Figure 5 shows a photo of the biofouling inside the pipe after testing and clearly displays that the majority of the biofilm has detached from the surface. This apparent self cleaning capacity of bacteria based biofilm in pipes could have a significant influence on cleaning methods for such pipes where there is the capacity to increase the flow velocity significantly compared to that used under normal operating conditions where the biofilms grow.

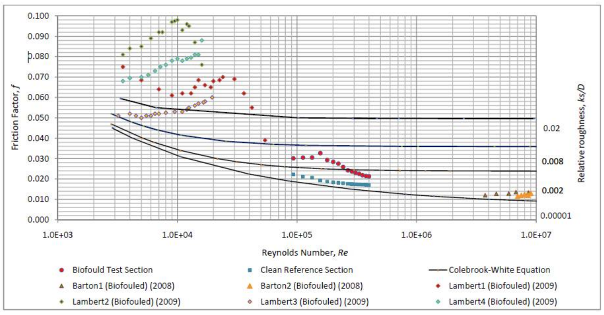

Figure 4: Moody diagram showing experimental predicted values of friction factor for a range of experimental programs

Figure 5: Photograph of flow conditioned biofouling inside the test section after testing

Lambert *et al.* [3] modified the Colebrook-White equation to improve theoretical predictions for pipes with biofilms (Equation 4). This relationship is plotted along with the experimental finding from this investigation and predicted values using the unmodified Colebrook-White Equation (Figure 6). The modified equation predicts the initial increase in friction factor well, however it the predicts a continuous and increasing gradient of friction factor with Reynolds number and diverges from the experimental results close to the critical shearing velocity of $U_{crit} = 1.77$ m/s. This is an expected result as it has no way of accounting for a highly dynamic surface roughness.

$$\frac{1}{\sqrt{f}} = -\frac{1}{\sqrt{8\kappa}} ln\left(\frac{k_s}{0.85D} + \frac{2.51}{Re_D\sqrt{f}}\right) \tag{4}$$

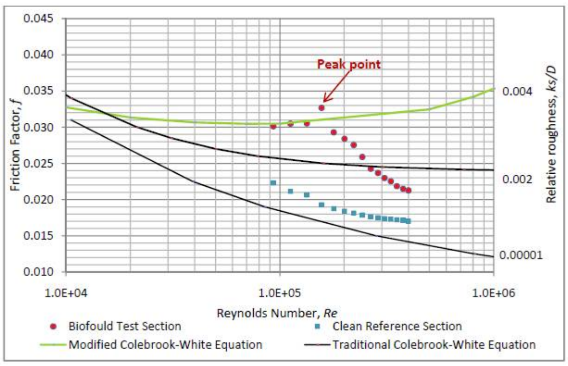

Figure 6: Moody diagram showing experimental, predicted (original and modified) values of friction factor

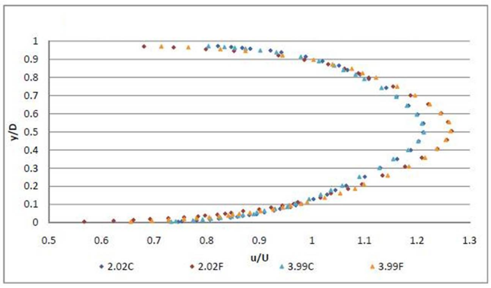

Figure 7: Non-dimensional velocity profiles of the test section with biofouling for clean (C) and fouled (F) pipes

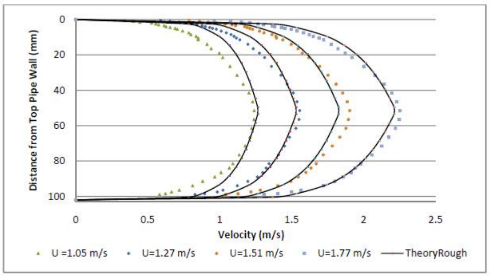

Figure 8: Comparison between measured and theoretical velocity profiles in the fouled test section with $\kappa = 0.4$ and $B = 8.48$

Influence of Biofouling on Pipe Velocity Profiles

Non-dimensional velocity profiles over a range of tested flow rates can be seen in Figure 7 for the fouled and clean test cases. The profiles clearly match up well and show that they are independent of Reynolds number above a flow speed of $U = 2.02$ m/s. A slight Reynolds number dependency was observed at very low flow rates below $U = 1.5$ m/s.

Theoretical velocity profiles of an artificially roughened pipe with a sand equivalent surface roughness, which is calculated using Equation 6, are evaluated using Equation 5 and plotted in Figure 8.

$$\frac{u}{u^*} = \frac{1}{\kappa} ln \frac{y}{k_s} + B \tag{5}$$

$$k_s = 3.7D \left(exp^{-\left(\frac{1.3254}{f}\right)^{0.5}} - \frac{2.51}{Re_D \sqrt{f}} \right) \tag{6}$$

Comparing theoretical and experimental velocity profiles in Figure 8 substantial differences can be identified. In the near wall region, experimental values of velocity are lower then the theoretical predictions, however towards the centre of the pipe the opposite trend is observed and the two profiles cross over. The same trend was also observed at the higher flow rates tested. Initial theoretical predictions used a Von Karman constant of $\kappa = 0.4$ and $B = 8.48$. A linear regression method was implemented to determine new values of κ and B for biofouled pipes. This provided a unique set of constants for each flow rate, which in turn could be used to determine a new modified set of theoretical velocity profiles. These are plotted against the experimental traverse results in Figure 9. It is immediately clear that the modified constants create a far more accurate and now acceptable series of velocity profiles and that a single value of κ and B should not be applied with accuracy to pipes with biofouling. The same trend was also observed at higher flow rates.

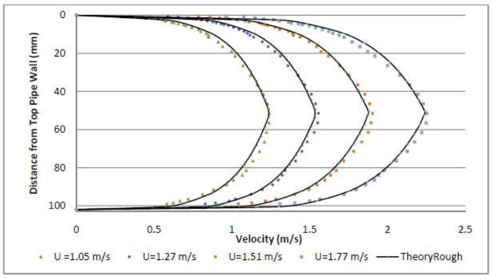

Figure 9: Comparison between measured and modified theoretical velocity profiles in the fouled test section with κ and B varied for each test case

Conclusions

Flow conditioned biofouling has a significant impact on major loss and calculated values of friction factor inside pipelines over a range of Reynolds numbers commonly used in commercial and industrial situations. An increase in friction factor was observed with Reynolds number until a critical flow speed $U_{crit} = 1.77$ m/s was reached where the biofouling sheared away from the surface and was washed off the wall causing a sharp decrease in friction factor.

Empirically-based predictions of the velocity profile across an artificially roughened pipe did not match well with results obtained experimentally in the fouled test section when the Von Karman constant κ and the constant B were set to 0.4 and 8.48 respectively, in Equation 5. These constants were then matched to the conditions at each tested flow rate using a linear regression technique used by Lambert *et al.* [3]. Upon modifying κ and B for each test case the theoretical velocity profiles aligned well with the experimental results.

This highlights the deficiencies of standard flow prediction methods developed empirically using artificially roughened pipes in very controlled environments when applied to pipes with biofouling and adds further support for the need of a modified Colebrook-White equation.

Acknowledgements

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