Ice-Pigging – A Step Forward in Commissioning Cleanliness

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Synopsis

Ice-Pigging is a process by which high Ice-Fraction Ice-Slurry is pumped through potentially topologically complex pipe systems to clean them of debris. This paper proposes replacing conventional Water-Flushing with Ice-Pigging for the cleaning of Naval Platform pipe systems pre-commissioning due to the benefits of improved effectiveness and reduced overall flushing time. To demonstrate these benefits a modified Hershel-Bulkley model is developed for Ice-Pigging alongside a Water-Flushing model to simulate the Wall Shear Stresses exerted by each method at a range of velocities and Ice-Fractions. Simulation results demonstrated that Ice-Pigging exerts several factors greater Wall Shear Stresses than Water-Flushing, with the difference increasing as the Ice-Fraction is increased. It was found that the advantages of Ice-Pigging were most prevalent at low flow velocities, where the Yield Stress of the Non-Newtonian Ice-Slurry provided large Wall Shear Stresses, whereas the water not yet in turbulent flow exerted negligible stresses. Thus, for complex pipe paths where it may be difficult to demonstrate high-velocity flow, Water-Flushing would exhibit poor performance, but Ice-Pigging would not be adversely affected. The outcomes support that Ice-Pigging would require significantly less time than Water-Flushing to clean systems to the required specification pre-commissioning, and it would likely remove a greater quantity of debris and particulates, resulting in a more effective overall flush. These advantages provide evidence that implementation of this technology would benefit the timely construction of high-quality Naval Platforms.

Keywords: Flushing, Ice-Pigging, Non-Newtonian Flow, Hershel-Bulkley

1. Introduction

This paper will review Ice-Pigging, a common flushing method used in the food and sewage industry within the UK, as a potential tool for production of Naval Platforms against conventional methods to demonstrate the improvements to the Build and In-service programmes that could be achieved through its implementation. Producing and maintaining a Naval Platform requires years of complex initiatives with lengthy lead times and rigorous planning. Any advancement on existing processes that can decrease required time and assist in the creation of an improved product should be pursued. Due to its potential to drastically reduce the time required to clean systems and its ability to more effectively remove contamination, Ice-Pigging is being considered to replace Water-Flushing methods where practical. Simulations will provide numerical argument for the improved performance of Ice-Pigging and the logistical and practical considerations of introducing the technology will be discussed. Figure 1 depicts a commonly used Ice-Pigging machine, and Figure 2 displays Ice-Pigging in use.

***Figure 1** – A SUEZ AQL 500 Ice-Pigging Machine that generates Ice-Slurry and pushes it through pipelines for cleaning and product-recovery.*

***Figure 2** – Ice-Slurry being pumped into a mains water pipeline from an Ice-Slurry transport and storage vehicle.*

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1.1. Background

Prior to commissioning, initial operation, and the return of vessels into fleet time, systems on Naval Platforms must first be proven to have attained a high level of cleanliness. Failure to meet cleanliness requirements can lead to: valve damage from loose debris, poor flow characteristics, high water conductivity, and surface contamination. Flushing is a commonly used method to clean pipe systems via pumping through fluid at high pressures to dislodge and remove debris. Whilst the primary application of flushing is during pre-commissioning, it can be utilised for the maintenance of In-Service systems to remove particulate contamination that has built up over time, or to remove light surface contamination (Quarini, 2002).

Flushing a system generally requires a significant length of time. Ice-Pigging is considered to generate greater shear stresses than currently used Water-Flushing methods (Quarini, 2015). As such it should be capable of cleaning systems to their required specifications in a shorter time frame. The time saved could be better applied in a platform's program to reduce the overall build time or lower the risk of delays through adding float.

1.2. Scope

This paper will develop mathematical models for the flow of Ice-Slurry and Water-Flushing for application in simulations to determine the expected incurred Wall Shear Stresses. Results obtained will be compared to similar experimental studies to validate the data produced. The simulation results will provide a succinct description of the effect of modifying key parameters in a flush, such as flow velocity and Ice-Fraction. Comparisons will be made between results from the two flushing techniques to determine which is more effective for dislodging and removing debris, and an argument will be presented for the application of the more effective method for the construction of future naval platforms.

1.3. Structure

Section 2 will provide an overview of the basics of flushing, Ice-Pigging, and the Rheology of Ice-Slurry. Section 3 will develop the mathematical models to be applied in simulations, giving the reasoning for following a specific theoretical path. Section 4 will detail the conditions of the simulations, provide the results generated, and explain occurring trends. Section 5 will consist of discussions regarding the uptake of the technology within shipbuilding. Finally, Section 6 will provide conclusions.

2. Preliminaries

2.1. Water-Flushing

To effectively dislodge and remove debris from a system, sufficient shear forces must be generated on the pipe walls. For Water-Flushing techniques this means that the flow velocity must be high enough to ensure turbulent flow. Demonstrating high flow velocities can be challenging in topologically complex systems, such as heat exchangers, thus the time required to ensure a compliant flush must be increased.

A generic Water-Flushing procedure would involve creating a closed loop between two valves of a pipe system, referred to as a flush path, and pumping water through at sufficient velocities to mobilise debris. To collect the debris a filter can be applied in the path, or the fluid can be removed with the debris suspended.

2.2. Ice-Pigging

Pushing a piston-like object through a pipe to clean the walls and remove debris is known as 'pigging'. Conventional pigs are solid objects and introducing them to a pipeline carries a number of risks and requirements. Crucially, solid pigs may get stuck or may damage the pipe system. Additionally, they require the pipeline to be mostly straight and thus cannot navigate systems with complex topologies (Quarini, 2015). Therefore, conventional pigs are not well suited for application on Naval Platforms.

Ice-Pigging involves propelling a pig of thick Ice-Slurry, called an Ice-Pig, through a pipeline at modest speeds (Quarini, 2015) to dislodge, mobilise, and remove loose materials (Quarini, 2002) (Quarini, 2010). The Ice-Slurry is generated by freezing water into a homogenous mixture of small ice crystals and cold water (Quarini, 2015). The ratio of Ice-Crystals to water in the mixture is known as the Ice-Fraction. Adjusting the Ice-Fraction will modify the characteristics of the Ice-Slurry flow, namely as Ice-Fraction increases incurred shear stress increases (Shire G.S.F., 2008). It has been found that due to their unique rheological properties, Ice-Slurries flow as a viscous liquid but provide mechanical properties that generate large shear forces (Quarini, 2015). A generic Ice-Pigging setup is shown in Figure 3.

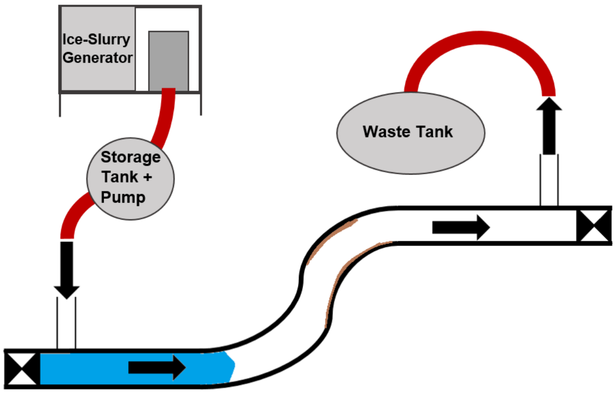

***Figure 3** – An Ice-Pigging setup through a simple flush-path. Generated Ice-Slurry is stored before being pumped through the flush-path, a waste tank must be used to collect used Ice-Slurry due to the additive being potentially harmful.*

Ice-Pigs exhibit properties of both a solid and a fluid, allowing them to fill the topology of a pipe and provide hydrodynamic sealing, tending to 'knit' together and form a solid plug where possible, whilst also retaining the ability to navigate tight bends and small apertures like a liquid (Quarini, 2015). They are capable of being injected into small orifices and expanding to fill pipes that can be up to 200 times larger in area (Ainslie, 2009). The desirable slurry-like characteristics of the Ice-Pig are maintained using a freezing point depressant additive, which prevents the small ice-crystals from welding together and forming blockages by lowering the freezing temperature of the mixture (Quarini, 2002) (Shire, 2005). There are several choices of additive, each having different effects on the Ice-Slurry's rheology (Théo Frazao, 2019). The additive must be chosen on a case-by-case basis, considering factors such as desired Ice-Fraction, desired viscosity, and the chemical requirements of the pipelines being flushed.

Ice-Pigging has found application for cleaning pipelines in a number of fields, such as Water Supply, Sewage, the Oil Industry, and the Food Industry. As such the technology is already well established and requires little to no investment or modification to make it suitable for use in Naval Construction. A generic Ice-Pigging procedure would involve an initial charge of the flush path with water to check the route and to pressure test, followed by introduction of the Ice-Slurry through the path, and finishing with a final flush with demineralised water to return the path to pre-flushing chemical conditions.

2.3. Rheological Properties of Ice-Slurry

The rheological properties of Ice-Slurry can vary drastically due to the variation of Ice-Fraction, Ice-Crystal size, additive choice, and mass concentration of additive. Resulting in a wide range of possible viscosities and fluid characteristics.

It is well-established that Ice-Slurries behave as Non-Newtonian fluids (Quarini, 2015) (Théo Frazao, 2019) (Boumaza, n.d.) (Mellari, 2012), and thus the viscosity will change in accordance with the shear forces being applied. However, the specifics of how its viscosity is affected largely depends on the additive utilised and the Ice-Fraction of the slurry. For the majority of additives, such as Ethanol, Sodium Chloride, and Propylene-glycol the Ice-Slurry will behave as a pseudoplastic (Shear thinning) (Théo Frazao, 2019); these fluids will decrease in viscosity as the shear rate increases, allowing them to be easily pumped once an initial yield stress has been overcome.

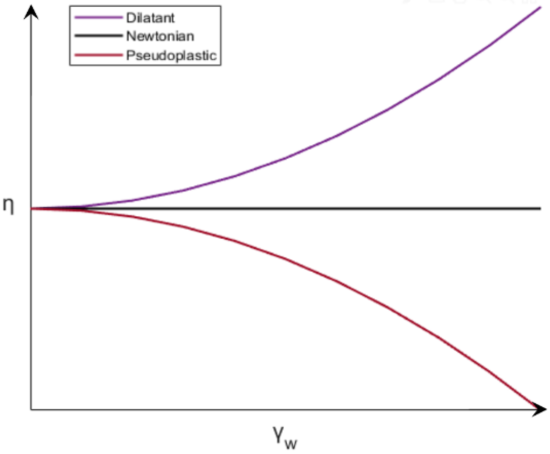

***Figure 4** – Relationship of viscosity (η) against Shear Rate (γ_w) for a Non-Newtonian fluid*

For the purposes of Ice-Pigging, shear thinning (pseudoplastic) flow characteristics, where viscosity decreases with increasing shear rate, are desirable and the additive should be chosen as such. Shear thickening (Dilatant) fluids, where viscosity increases with increasing shear rate, would require significant pressures to effectively pump and would increase the risk of short-term blockages. It should be noted that to achieve desirable piston or pig-like characteristics, it has been found that the Ice-Fraction must be greater than 40% (Quarini, 2015).

Ice-Slurries can consist of Ice-Particles of various shapes and sizes, with the main dependencies being additive choice and concentration, Ice-Fraction, and storage time after generation. The size of the Ice-Particles can range between 100µm - 600 µm (Trabelsi, 2017). It can be expected that as Ice-Fraction or storage time is increased, the Ice-Particle size will increase, resulting in an increase to the viscosity of the Ice-Slurry.

3. Theory and Modelling

This section proposes models derived to calculate the Wall Shear Stresses exerted by Water-Flushing and Ice-Pigging through simulation, with the aim of demonstrating which is more effective for cleaning pipelines.

3.1. Water-Flush Model

The flush shall be conducted in a single pass. The fluid is to be moving at a constant velocity through a horizontal pipe, with the effect of gravity being assumed negligible, so that the balance of forces consist wholly of pressure and viscous effects (Najmi, 2016). The force balance can be written as (1) and simplified to (2):

$$p_1 \pi r^2 - (p_1 - \Delta p)\pi r^2 - 2\pi r l \tau = 0 \tag{1}$$

$$\frac{\Delta p}{l} = \frac{2\tau}{r} \tag{2}$$

Where: p_1 is inlet pressure (Pa), Δp is change in pressure across the flush path (Pa), r is the pipe's inner radius (m), l is the pipe length (m), and τ is shear stress (Pa).

Wall Shear Stress (τ_w) (Pa) occurs when $r = D/2$, where D is the pipes inner diameter (m), and thus (2) can be re-written as (3) (Najmi, 2016), which is true for laminar, transition, and turbulent flow (Christopher A. Bennett, 2016) (Najmi, 2016).

$$\Delta p = \frac{4 l \tau_w}{D} \tag{3}$$

As the flow is fully developed, steady, and incompressible it can be modelled using the Darcy-Weisbach Equation (4). Which when substituted into (3) provides an expression for Wall Shear Stress (τ_w) (Christopher A. Bennett, 2016) (Wilkes, 2005):

$$\Delta p = \lambda \left(\frac{l}{D}\right)\left(\frac{\rho v^2}{2}\right) \tag{4}$$

$$\tau_w = \frac{D}{4l}\lambda \left(\frac{l}{D}\right)\left(\frac{\rho v^2}{2}\right) = \frac{\lambda \rho v^2}{8} \tag{5}$$

Where: λ is the Darcy friction factor, ρ is fluid density (kg/m^3), and v is the velocity of the fluid (m/s).

The Darcy friction factor depends on the flow type and the roughness of the pipe material. The Haaland expression (G. Papaevangelou, 2010) solves for the Darcy friction factor by providing an approximation to the explicit Colebrook equation. The claimed accuracy is within ±2% if the Reynolds number is greater than 3000 (Kiijarvi, 2011), which the flow will achieve at almost all flushing velocities. To produce a consequential force on the pipe walls the fluid velocity must be fast enough for turbulent flow, thus laminar flow equations will be ignored when calculating Wall Shear Stresses induced through Water-Flushing.

$$\frac{1}{\sqrt{\lambda}} = -1.8 \cdot log\left(\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right) \tag{6}$$

$$Re = \frac{\rho D v}{\mu} \tag{7}$$

Where: Re is the Reynolds number for the flow, ε is the roughness of the pipe (m), and μ is the dynamic viscosity of the fluid (Pa·S).

3.2. Ice-Pigging Model

There exist many potential models for describing the flow of Ice-Slurry. The commonly applied Bingham model (Papanastasiou, 1987) (Egolf, 2005) (Hansen, 2001) is characterised by the Yield Stress for flow to overcome and the dynamic viscosity of the fluid. It has been found to be less accurate than other models due to an under-estimation of the pressure drop, particularly at high Ice-Fractions (Ashley C.S. Monteiro, 2010). The Casson fluid model is quantitatively similar to the Bingham model, and with modification closely follows the trends in rheological data for all Ice-Fractions (Ashley C.S. Monteiro, 2010). The Power Law model (Sasaki, 1993) (Lakhdar, 1998) (Guilpart, 1999) (Mellari, 2012) is effective due to its simplicity, however notably the Yield Stress is not included in calculation. The model is separated into laminar and turbulent flow functions, researchers have found the differing dependencies of the model to be unclear (Ashley C.S. Monteiro, 2010). The accuracy of the Power Law model has been found to suffer at exceptionally low or high Shear Rates (Ashley C.S. Monteiro, 2010). The Herschel-Bulkley model (F. Illa´n, 2008) (Mika, 2012) utilises the basis of the Power Law with the addition of the yield stress parameter and the novel inclusion of the diameter of the Ice-Particle within calculations (Ashley C.S. Monteiro, 2010); it being the only model described that takes the Ice-Particle size into account. The importance of the inclusion of Ice-Particle size is reinforced by its accurate prediction of flow trends compared to the other models (Ashley C.S. Monteiro, 2010) (Kamyar, 2019).

A modified Herschel-Bulkley model based on the work in (F. Illa´n, 2008), and adjusted for application using the work in (Mika, 2012), has been chosen for modelling the flow of Ice-Slurry. The generation of model coefficients in (F. Illa´n, 2008) was optimised for use at lower Ice-Fractions, and thus will not provide reliable results over a large range. Thus, functions developed in (Trabelsi, 2017), proven to be accurate for modelling Ice-Slurries with Ice-Fractions ranging from 5% up to 80%, were utilised instead. It is widely accepted that roughness coefficients (ε) are not required due to the thin layer of water that accumulates at the pipe walls, providing a lubricating effect.

The definition of the Wall Shear Stress (τ_w) and the Shear Rate (γ_w) using the Herschel-Bulkley model is given in (F. Illa´n, 2008) as:

$$\tau_w = \tau_y + K\gamma_w^P \tag{8}$$

$$\gamma_w = \frac{8v}{D}\left(\frac{3P+1}{4P}\right) \tag{9}$$

It is found in (Trabelsi, 2017) that the Yield Stress (τ_y) has a minimal effect on the experiments conducted, however in (F. Illa´n, 2008) and (Mika, 2012) the yield stress is found to be the main component of the Wall Shear Stress for low Shear Rate flows. The approach taken in (F. Illa´n, 2008) and (Mika, 2012) is chosen as the including the yield stress as a major component of the force is more consistent with the majority of studies. The author’s hypothesis is that little yield stress is experienced for (Trabelsi, 2017) due to the use of a vane for experiments, which due to its small size may cause different flow characteristics. The Yield Stress (τ_y), is correlated to the Ice-Fraction (φ) and Ice Particle-Pipe Diameter ratio, and the Consistency Coefficient (K) and the Flow Index (P) are correlated to the Ice-Fraction (φ). They are given in (F. Illa´n, 2008), however due to a lack of consistency with experimental results over a range of variables, the Yield Stress (τ_y) is modified for generalised application with an Ice-Particle (d) size of 0.125mm in (Mika, 2012):

$$\tau_y = \left(\frac{d + 1.14 \cdot 10^{-3}}{19.59 \cdot 10^{-3}}\right)\left(\frac{d}{D}\right)^{-0.19} \cdot 10^{5\varphi} \tag{10}$$

Functions for the Consistency Coefficient (K) and the Flow Index (P) that are designed to vary with changes in the Ice-Fraction are provided in (Trabelsi, 2017) for an additive concentration of 14% Propylene-glycol:

$$P = 0.2706\varphi + 0.6429 \tag{11}$$

$$K = 0.1742\varphi + 1.282 \tag{12}$$

Since the Hershel-Bulkley model has been found to fail at medium Shear Rate values, a modified model proposed in (F. Illa´n, 2008) which separates the analysis into a low Shear Rate laminar flow region, and a high Shear Rate turbulent flow region is used instead. The low Shear Rate model is given in (13), it is notable that in this region flow is dominated by the yield stress (F. Illa´n, 2008):

$$\tau_w = \tau_y + K^{1/P}\gamma_w^P \tag{13}$$

The high shear rate model is given in (14), in this region the Yield Stress can be neglected (Trabelsi, 2017) (F. Illa´n, 2008):

$$\tau_w = K\gamma_w^P \tag{14}$$

The critical boundary value of the shear rate, at which the flow characteristics transition from low shear rate laminar to high shear rate turbulent, is determined in (Mika, 2012) as:

$$\gamma_{crit} = 2464.3 - 129.77D^{-1} + 2.46D^{-2} - 0.0146D^{-3} - 11.96\varphi^{-1} + 0.349\varphi^{-2} \tag{15}$$

$$\begin{aligned} \gamma_w \leq \gamma_{crit} &\rightarrow \tau_w = \tau_y + K^{\frac{1}{P}}\gamma_w^P \\ \gamma_w > \gamma_{crit} &\rightarrow \tau_w = K\gamma_w^P \end{aligned} \tag{16}$$

4. Simulation Results

This section will detail the setup for the simulations conducted, provide the results produced, and then explain the trends can be seen to occur.

4.1. Water-Flushing Simulation Setup

The chosen constants for the Water-Flushing simulations are provided in Table 1. Pipe Diameter (D) was required to be small to ensure the Ice-Pigging simulations were of similar design to the work the model was based on (Trabelsi, 2017) (F. Illa´n, 2008) (Mika, 2012); the small Pipe Diameter reflects flushing performance in the tubes of heat exchangers or pneumatic lines. The Pipe Roughness (ε) coefficient was chosen to simulate high quality commercial steel that has not been smoothed for reduced drag. Equations 5 – 7 were directly evaluated using the Matlab software for velocities ranging from 0 – 5m/s with a step of 0.01m/s to output the exerted Wall Shear Stress (τ_w).

4.2. Ice-Pigging Simulation Setup

Equations 9 – 16 were directly evaluated using the Matlab software for the same velocity range as Water-Flushing, with the simulation repeated for different Ice-Fractions ranging from 10% - 80%. The chosen constants for the Ice-Pigging simulations are provided in Table 1. The Ice-Particle size was kept as a constant value of 0.125mm to ensure consistency with the empirical equations derived in (Mika, 2012), in reality as Ice-Fraction is increased Ice-Particle size would also increase, resulting in a slight viscosity increase. However, as the Ice-Fraction varies significantly this does not reflect real world conditions as the Ice-Particle size would likely increase with the Ice-Fraction.

Table 1 *– Constants for Simulations*

Variable	Value
Pipe Diameter (D)	0.025m
Fluid Density (ρ)	998Kg/m^3
Dynamic Viscosity (μ)	0.001Pa·S
Pipe Roughness (ε)	0.045mm
Ice-Particle Diameter (d)	0.125mm

4.3. Results

Figure 3 presents the Wall Shear Stresses exerted from Water-Flushing and Ice-Pigging, at Ice-Fractions ranging from 10% to 80%, against the flow velocity. It can be seen for low flow velocities (≤1m/s) that the yield stresses incurred by Ice-Pigging dominate the flow, causing several factors greater Wall Shear Stresses than Water-Flushing. As the flow velocity is increased the Wall Shear Stresses exerted by Ice-Pigging increase linearly. The stresses exerted by Water-Flushing increase more drastically due to the increasing prevalence of turbulent effects. Overall it can be surmised that Ice-Pigging exerts several factors greater Wall Shear Stresses than Water-Flushing, with the difference being most significant at low flow velocities with high Ice-Fractions.

Figure 4 presents the Wall Shear Stress plotted against the Shear Rate. The trend of the Ice-Pigging results agree well with those provided in (F. Illa´n, 2008) and (Mika, 2012). As water is a Newtonian fluid, shear rates produced through Water-Flushing are several magnitudes lesser than for Ice-Pigging, as such they are not comparable and were omitted. It is notable that as the Ice-Fraction is increased the increase in Yield Stress is exponential, causing high Wall Shear Stresses in high Ice-Fraction slurries with low Shear Rates. This further enforces that for Ice-Pigging, significantly high Ice-Fraction (≥70%) slurries are desirable. A line fitting algorithm was utilised for both plots in Figures 5 and 6 as the sudden switch between the low and high shear rate models induced non-representative results.

Figure 7 presents the ratio of Wall Shear Stresses exerted by Ice-Pigging and Water-Flushing at a flow velocity of 1m/s, against a range of Ice-Fractions. As expected, the ratio increases with the Ice-Fraction in a fairly linear fashion. Lower Ice-Fractions exhibit a far greater ratio than would be expected for a fluid mostly comprised of water. This could be attributed to the presence of the Propylene-glycol additive, or model inaccuracies. These results serve to emphasise again that Ice-Pigging should be conducted with as high an Ice-Fraction as is practical.

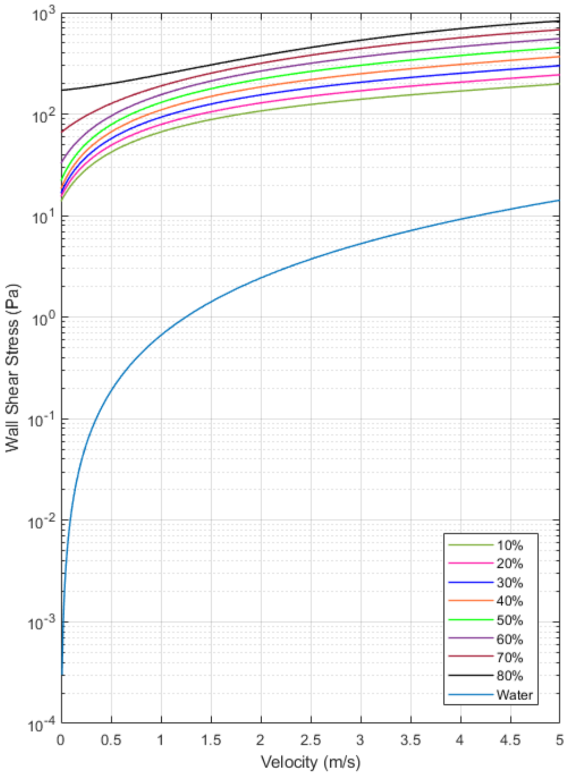

Figure 5 – *Wall Shear Stress (Pa) exerted by Ice-Pigging at a range Ice-Fractions with 14% Propylene-glycol and Water Flushing plotted against the flow velocity (m/s).*

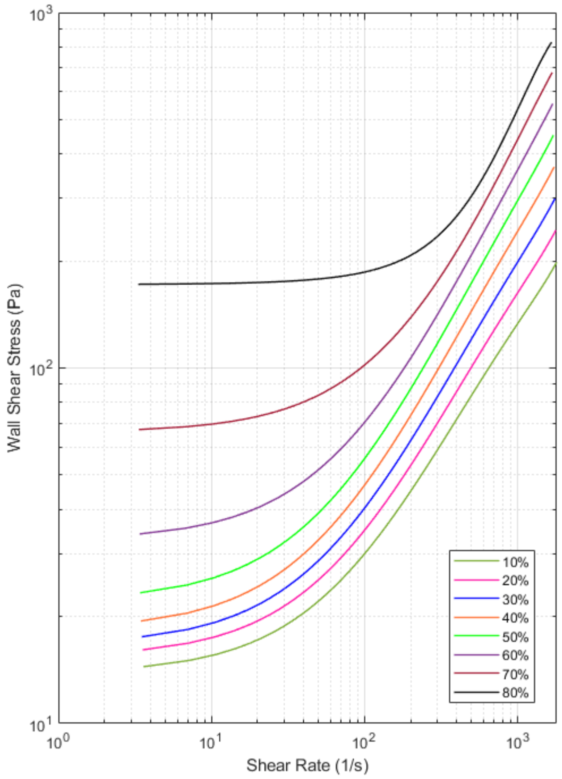

Figure 6 – *The Wall Shear Stress (Pa) exerted by Ice-Pigging at a range of Ice-Fractions with 14% Propylene-glycol plotted against the respective Shear Rate (s^{-1}) of the flows.*

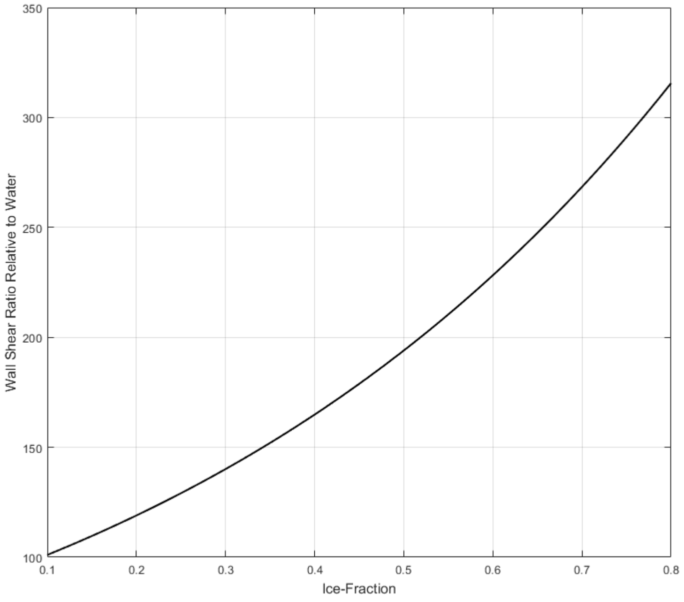

Figure 7– *The ratio of the Wall Shear Stress exerted by Ice-Pigging with Ice-Fractions ranging from 10% to 80% with 14% Propylene-glycol compared to Water Flushing, with both flows at a velocity of 1m/s.*

5. Discussions

5.1. Key Findings

Simulations have clearly established that Ice-Pigging is significantly more effective than Water-Flushing at standard flow velocities, less than or equal to 5m/s, for removing debris and achieving a high level of cleanliness. Mainly due to the greater Wall Shear Stresses it exerts across all flow velocities. This outcome was expected and agrees with the literature reviewed. As the effectiveness of the clean is much greater the required flushing time for each flush path can be reduced, whilst still removing a larger volume of debris and particulates. Thus, using Ice-Pigging, systems can be cleaned to a higher specification in a fraction of the time required by Water-Flushing.

Results demonstrate that it is beneficial to use as high an Ice-Fraction as practical, due to the substantial increase in Wall Shear Stresses that are accrued; this being particularly evident when the flow velocity is low. When choosing an Ice-Fraction for flushing it will be necessary to consider the topology of the system, as Ice-Fractions of 80%+ may cause Ice-Particle agglomeration in tight bends or small apertures, resulting in system blockages. Additionally, the capability for the Ice-Slurry generator must also be considered.

5.2. Limitations

Most of the mathematical work completed in this paper has been based on studies focused on Ice-Slurries for refrigeration. Refrigeration focused studies typically investigate Ice-Slurries with low Ice-Fractions, with the notable exception of (Trabelsi, 2017). In contrast, Ice-Pigging is conducted at high Ice-Fractions. Thus, the models utilised for this paper have not been widely experimentally validated or optimised for work involving high Ice-Fraction Ice-Slurry flow. However, the results whereby the effectiveness and speed of Ice-Pigging for cleaning pipelines is found to be much improved over Water-Flushing align closely with manufacturer claims.

Only one additive, Propylene-glycol, has been investigated in this work. Changes in additive can cause drastic alterations to the rheology and subsequent performance of an Ice-Slurry. Thus, to completely understand the application of Ice-Pigging for use in platforms where a range of additives will be required, work must be conducted to investigate the performance of a wide range of additives applied to high Ice-Fraction Ice-Slurry.

5.3. Application for Naval Systems

Delivering Naval Platforms to a high standard of quality in a timely fashion requires shipbuilders to adopt technologies wherever sufficient advantages are demonstrated. Time saved through the application of Ice-Pigging could assist in improving build times overall. An initiative to move towards an overall clean build, as is seen in some sectors, could negate the requirement to flush altogether. However, the realities of the work conducted at a shipyard mean that in the authors opinion some form of cleanliness control will always be required, especially in cleanliness critical systems such as those on Nuclear Submarines. Thus, advancements in the method by which this cleanliness is achieved should not be ignored if there exists an aim to improve the quality and deliverance of Naval Platforms.

5.3.1. Benefits of Adoption

In practise Ice-Pigging has been found to clean a flush path to specification in 1/20th of the time required by Water-Flushing, providing valuable time and resources to be applied elsewhere in the build. Additionally, Ice-Pigging requires significantly less effluent than Water-Flushing, reducing both costs and waste; these reductions are particularly useful with systems that require a specific and potentially hazardous chemical makeup for their additives to properly flush. Industrial applications have found Ice-Pigging to remove much greater volumes of debris from flush-paths than Water-Flushing.

5.3.2. Difficulties and Considerations

The capability to position the Ice-Slurry supply in close enough proximity to the flush path to allow for a good connection must be ensured for effective Ice-Pigging. As the Ice-Slurry generators can weigh several tons, this can present a major difficulty. To offset this, specialised delivery units can be utilised to move Ice-Slurry, but not only are these still large and heavy, use of them will limit the volume of effluent available for use. As space and lifting equipment use is limited in a shipbuilding area, getting access to systems is one of the most significant difficulties when utilising Ice-Pigging.

Some systems require a specific pH or chemical makeup when in use, and the additive used as a freezing point depressant would be likely to alter this. It should be common practise to conduct an additional Water-Flush following Ice-Pigging to ensure the removal of all additives.

Systems with a temperature sensitive material composition may be adversely affected by the sudden drop in temperatures induced by injection of an Ice-Slurry into flush paths. To prevent potential breakdown of mechanical properties the materials used in a system should all be considered and investigated before Ice-Pigging is applied.

Ice-Pigging requires more energy than Water-Flushing due to the requirement to constantly chill and agitate the slurry before insertion into the flush path. Additionally, pumps efficiencies are lower due to the greater viscosity and Non-Newtonian properties of the Ice-Slurry, further increasing energy requirements over Water-Flushing. However, this is a minor issue and energy costs are unlikely to be a main consideration for those considering implementation.

Whilst there are a number of considerations to be made before Ice-Pigging can be implemented, most issues can be overcome through effective planning and the design of robust processes. The overall benefits of adoption outweigh the difficulties and enhance the cleaning and commissioning of Naval Systems.

6. Conclusion

This paper has presented a modified Hershel-Bulkley model to simulate Wall Shear Stresses at different flow velocities exerted by Ice-Pigging at a range of Ice-Fractions and compare them to those exerted by Water-Flushing. As anticipated, it was found that Ice-Pigging produces several factors greater Wall Shear Stresses, with the difference being most significant at low flow velocities with a high Ice-Fraction. This provides strong evidence that Ice-Pigging is a more effective tool for cleaning pipe systems than Water-Flushing. Thus, application of Ice-Pigging would reduce Naval Platform commissioning time and improve cleanliness standards of constructed pipe systems.

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