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Investigation and development of an innovative pigging technique for the water supply industry.

Abstract

Water supply companies monitor the state of their pipe networks and ensure that the pipes are clean and free of inert loose deposits by flushing and pigging. Flushing involves forcing high speed water through the pipes so as to carry away particulates, pigging consists of forcing an object (the pig) through the pipe so as to push or wipe away the loose material. Both systems have drawbacks; the first tends to use very large volumes of water, and it may be impossible to get the required velocities in large diameter pipes. The second requires purpose built launch and receive stations and may run the risk of damaging the pipe walls. This paper presents an innovative alternative to water flushing or conventional pigging for the potable water supply industry. This alternative uses a phase change material (ice-water slurry), which can be introduced into and removed from existing pipe networks with minimal alterations. The underlying concept is that when an ice slurry is propelled through pipes at modest speeds, the wall shear is two to four orders of magnitude higher than that which would have been achieved had water (only) been travelling in the pipe at the same speed. Thus, even with relatively low speeds, the 'ice pig' is able to achieve efficient cleaning and removal of loose materials. This technology has the advantage that the ice pig changes its shape to fit the containing topology, hence it is able to navigate bends, contraction/expansions and partly open vales, whilst cleaning the containment walls and transporting particulates. Lastly, the ice pig is guaranteed never to get stuck, as it will simply melt away, if left for sufficient time.

The paper presents laboratory experimental data, qualitatively demonstrating the capability of the technique and quantitative data enabling engineers to scale and size the ice pig for full scale trials. Finally, preliminary work from full scale trails on live water trunk mains is briefly presented and discussed.

Introduction

There have been a number of reviews and assessments of perceived and actual water quality in the UK; for example, the Scottish Executive have recently commissioned an independent investigation to explore public awareness and views of drinking water quality in Scotland [1]. This revealed that the drinking water quality showed a high level of compliance, with 99.56% of tests on consumers' taps meeting the required standard. However, despite the high level of compliance with drinking water quality standards, complaints about water quality continue to be reported. The largest proportion of complaints related to discoloured water (56%), followed by chlorine taste or odour (16%) and particles in the water (10%). The Scottish survey also considered 24 water companies in England & Wales for which consumer contact data was available, issues relating to water appearance represented the greatest cause of contact for 22 of these companies.

The Drinking Water Inspectorate, DWI, stipulates exact requirements for drinking water quality in England and Wales [2]. For example it specifies maximum allowable levels of different compounds in drinking water as well as identifying the clarity of the water. The opposite of clarity is known as turbidity, which is a measure of the cloudiness of a liquid and is usually quantified in nephelometric turbidity units, NTUs. Water containing greater than 5 NTUs appears cloudy to the naked eye, and thus the DWI has set the maximum allowable NTU level at the consumer's tap at 4. It has also set a much tighter limit for the NTU of the water leaving the water utility's treatment works at NTU = 1 or less. The NTU levels in the water tend to fluctuate between the treatment works and the customer taps as flow rates within the supply pipes change to meet the varying customer loads.

Water supply companies work hard to ensure customer complaints are minimised and preferably eliminated. Given that water discolouration appears to be the biggest single complaint, the water utilities have developed a hierarchy of methods to reduce water discolouration problems [3, 4 and 5]; the first is to prevent particles from entering the water supply network, the second is to prevent suspended particles from settling and the last is to remove the sediments from the mains. This paper focuses on the last approach. There are a number of methods of cleaning supply pipes in an attempt to ensure that the NTU levels are kept within the statutory limits. One of the common procedures is known as 'flushing' to remove loose deposits from their supply pipe networks. This involves forcing large volumes of water through the pipes at sufficiently high velocity to mobilise the sediment and carry away the loose deposits. Flushing can be wasteful in water and ineffective for large diameter pipes, where it is difficult to achieve the required velocity. An alternative to flushing is to adopt some form of pigging technique. This consists of propelling or pulling an object, which is almost the same size as the internal diameter of the pipe, through the pipe to physically push or wipe away the loose material. This poses its own challenges (required launch and recovery stations, potential damage to the inner surface of the pipe and problems associated with changing dimensions of the pipes).

A drinking water supply company, Bristol Water, BW, has begun an innovative programme of work to investigate the potential use of ice pigs as an alternative to water flushing and conventional pigging. The ice pig consists of an engineered ice slurry (typically 50 to 90% ice fraction). The pig has an interesting rheological property of 'holding' itself together, under adverse conditions of imposed shear. The work to date has demonstrated that it is possible to introduce the ice slurry from a small diameter duct into a much larger one, to form a continuous and topologically 'perfect' pig that has the ability to cleanse the pipe.

This paper presents the laboratory-based work demonstrating the potential of this technology and the first preliminary 'in-field' trials. The results are very encouraging.

The potential advantages of this technology are considerable and include the guarantee that the pig never gets stuck (it eventually melts!), reduced water consumption (typically orders of magnitude less than for water flushing) and suitability for any topology, with minimal introduction/removal costs

Underlying physics and previous work

The transport of particulates within a continuous carrier fluid has fascinated many, including Einstein [6] for many years. The original work was aligned to deducing how the effective viscosity of the slurry varied with particulate loading. The original work, such as that of Einstein, focused on very low particulate loading. If the particle loading is sufficiently low, such that there is no appreciable interaction between the particles, then the effective, μ_{eff}, viscosity of the slurry is related to the viscosity of the carrier fluid, μ:

$$\frac{\mu_{eff}}{\mu} = 1 + 2.5\phi$$

where ϕ is the particle fraction of the neutrally buoyant particles. The low particulate solids work was extended to higher solid fraction. For most particulate matter, there is a maximum packing density, giving an upper limit of ϕ, ϕ_m, which will be less than unity. One of the best-known and widely used correlations is that due to Thomas [7],

$$\frac{\mu_{eff}}{\mu} = 1 + 2.5\phi + 10.05\phi^2 + 0.00273e^{16.6\phi}$$

More recent work by Ismail [8] suggests

$$\frac{\mu_{eff}}{\mu} = \left(1 - \phi - 1.18\phi^2\right)^{-2.5}$$

The important point to note is that the effective viscosity increases rapidly with particulate fraction; for example, the last correlation suggests that the effective viscosity goes to infinity as ϕ approaches 0.5897. This suggests that slurries may be able to provide a way of increasing mechanical scouring at the wall, without having to increase the flow rate which may prove beneficial in either cleaning or pigging operations. Ismail's correlation is particularly pertinent, in that it not only suggests that it is possible to get enhanced cleaning at relatively low velocities, it also implies that it is possible to get the slurry to bind and lock up if ϕ is too large. Much of the earlier work on the transport of particulates in fluids was limited to passive particles in which there is no mass transfer between the fluid and particles. As can be envisaged, the flow of a melting/freezing slurry is much more complex.

Although there are lots of examples of ice-water slurries in nature, until recently there have not been much documented academic or commercial interest in the topic. This started to change with the ever-increasing demands for on-tap cooling, energy efficiency and the desire to reduce energy peak demands resulting from air conditioning systems. It is now recognised that ice slurries may be an environmentally sound way of storing cold in a manner which is easy to access. This consists of generating ice slurries using off-peak electrical power, storing the slurry until it is required and pumping it to required locations. Provided the slurry is not too 'thick', say less than 20 to 25% ice fraction, it is easily pumped using conventional equipment. Research activities in ice slurry work have increased rapidly over the past fifteen years to provide the engineering design knowledge to service this ‘cold storage’ industry. Much of the work has focused on relatively low ice fractions. There are quite a lot of relatively recent data available in the literature regarding pressure loss characteristics of low ice fraction slurries (most of this work being driven by the desire to use ice slurries to replace secondary refrigerants). Much of the data suggests that the pressure vs flow rate for these low ice fraction slurries is similar to those expected for pure water. However, there seems to be no universal agreement on the quantitative data. Many workers suggest that there is a minor increase in pressure loss as the ice fraction increases, although Knodel [9] reports that the pressure loss actually decreases slightly with increase in ice fraction. Knodel suggested that this paradoxical behaviour resulted from a complex re-laminerisation process, with the ice crystals effectively reducing stochastic turbulent activity. Bellas [10] reported that the hydrodynamic pressure losses in a plate exchanger increased with ice fraction, however this increase was very minor for ice fractions below 5%, and was only around 15% greater than that expected for pure water when the ice fraction was as high as 20%.

The apparent lack of comprehensive agreement is probably an indication of the extraordinarily complex and multi-dimensional nature of the systems that are being studied. Ice fraction alone is not sufficient to define these systems, the absolute size of the ice crystals is also important, as is the relative size of the ice crystal to the characteristic dimensions of the ducts. It is difficult (if not impossible) to deduce what the exact operating conditions were for the various data reported in the literature, and hence it is difficult to draw meaningful comparisons. Given this confusion, it may be reasonable, as a starting approximation, to assume that the pressure loss characteristics for low ice fraction slurries is similar to those of pure water, for both simple ducts as well as complex heat exchanger topologies

There is also some confusion on exactly what happens to heat transfer as the ice fraction is increased. Even for geometry as simple as a straight pipe, some workers, for example Knodel et al [9], have found that the heat transfer coefficient decreases as the ice fraction is increased from zero to about 4 to 10%. The reduction in coefficient is of the order of 12 % from that which would have been expected if the flow had consisted of carrier fluid only. The coefficient then stabilises and does not decrease further with further increase of ice fraction. Other workers, for example Christensen and Kauffeld [11], found that for a nominally similar geometry, the heat transfer coefficient increased slightly with increasing ice fraction. Both sets of workers offer very reasonable explanations for their findings; Knodel suggests that there is a reduction in heat transfer coefficient as a result of re-laminerisation which allows the thermal boundary layers next to the walls to thicken and hence reduce the heat transfer rate. Christensen and Kauffeld point out that their increase in heat transfer coefficient is due to the melting of ice adjacent to the heat transferring wall and hence a decrease in the temperature gradients in the boundary layer. They further suggest that there is very little increase in heat transfer coefficient for ice fractions between zero and 5%. A significant doubling of the heat transfer coefficient then follows this as the ice fraction is increased from 5 to 25%. These apparent discrepancies are discussed by Egolf [12]. He concludes by noting that ice slurry research is still in an early stage, with some experimental data being deduced from ‘difficult’ to assure boundary conditions. Bellas [10] found that the cooling duty within a plate heat exchanger increased by 30 or so % with ice fractions between 5 and 20% over that of chilled water.

It is important to note that although there is a connection between heat transfer coefficients and heat transfer capacity, they are not the same. It is self evident that an ice slurry has more cooling capacity than chilled water (with a freezing point depressant) at the same temperature. The unique and very desirable characteristic of an ice-water slurry is its ability to absorb large quantities of heat without incurring any appreciable increase in temperature.

Until ice slurries began to be viewed as potential ‘pigging’ devices, the literature had focused on:

- The increase in apparent viscosity of a fluid transporting particulates,
- The increased pressure loss or pumping power required to push a particulate slurry through equipment,
- The thermal and hydrodynamic characteristics of low ice fraction slurries, to provide alternative secondary refrigerants.

As a result of this documented work the following observations can be drawn:

1. Slurries with very low particulate loading seem to have thermal and hydraulic properties similar to the pure carrier fluid.
2. Increasing the particulate loading increases the effective viscosity of the slurry.
3. The effective viscosity increases very rapidly as a critical particle loading is approached. Beyond a critical particle fraction, the slurry ‘locks up’ and displays solid like characteristics.
4. Increasing the ice fraction in an ice-water slurry appears to have little effect on its effective viscosity or heat transfer characteristics, provided the ice fraction is below say 15 to 20%. However, its ability to cool is almost linearly related to the ice fraction.

Ice pigging; drivers and underpinning physics

The passive particulate slurry work reported in the literature suggests that it might be possible to increase the shear on the walls of a pipe by introducing particulates into the fluid. This increased shear can be achieved without increasing the flow speed of the slurry. Increasing wall shear corresponds to increasing the propensity to remove and clean material from the surface of the wall. Although introducing particulate slurries into equipment may not be appropriate, it appears to offer a potential way of cleaning/scouring.

The ‘slurry cleaning’ method becomes more attractive, if, it could provide cleaning while:

- requiring minimum quantities of slurry,
- holding itself together (i.e. did not become diluted in the carrier fluid)
- being inexpensive to make and was environmentally acceptable,
- being easily removed,

Recent work [13 to 25] with high ice fraction slurries has indicated that these can behave as effective ‘pigs’, with all of the above desirable attributes.

Ice Pigging in the Potable Water Supply Industry

There are two major sources of fine inorganic particulates in drink water received at the customer’s tap, one is from the original water source and its processing before being introduced into the distribution network and the other is from the pipe-work and associated fittings and infrastructure. Typically drinking water is sourced from springs, rivers or wells, it is filtered in sand filter beds to remove relatively large particulates and then chlorinated to reduce biological activity to desired levels before being introduced into the potable network. The sources and processing routes do not necessarily remove very fine particulate from the water. Once it is in the distribution network the particulates are transported by the water flow, there is a tendency for these particles to settle under gravitational effects on the bottom of larger pipes with low flow velocities. The pipes themselves can be sources of particulates; for example iron pipes rust and rust particles break off exposing more metal which in turn rusts, thus providing a continuous supply of fine iron oxide deposits. The flow of water within cement pipes erodes the pipe wall and transports the eroded inert particles to low velocity regions where they have a propensity to deposit under gravity forces. The existence of inert particulates in the water supply pipes is not a problem, provided they remain deposited as sediments. The problem arises if as a result of transient flow surges or other phenomena the sediment is disturbed and taken into the main flow and eventually delivered to the customer's tap. The water supply companies are required by the regulator to ensure that the water in their pipes is of a given clarity standard. The companies want to minimise customer complaints and ensure that the water delivered to the customer is within and if possible better than the minimum legal requirement. There are a number of water industry standard ways of removing sediments from pipes. The simplest is water flushing. As the name suggests this consists of allowing a fast flow of water (necessarily higher than the usual flow rate) through a given section of pipe and dumping the outlet water to drain. This waste water should carry off the sediments and leave a clean pipe. Water flushing can work very well for relatively small diameter pipes where it is fairly easy to achieve high flow velocities without wasting excessive quantities of water. It is difficult to achieve good results for larger diameter pipes where it is hard or impossible to achieve reasonable flow velocities, simply because the volume flow rates required are not available. When it is difficult to achieve the desired flow velocities with water flushing, it may be possible to isolate a given length of pipe and blow high velocity air through it. In order to increase the shear on the walls, it is common to allow small quantities of water to be propelled through the pipe by the high-speed air. This process is known as air scouring. An alternative to either water flushing or air scouring is a process known as swabbing. This consists of dragging appropriate materials (usually rags tied to ropes) through the pipe. Swabbing requires access at both ends of the length of pipe being cleaned. For larger pipes the water industry uses foam pigs, these are piston-like soft foam objects which are introduced into the pipe at an appropriate 'launch station' the foam pig is then pushed through by water behind it. As it moves through the pipe it displaces the sediment and cleans the pipe walls. Foam pigs also require a 'receive station'. The launch and receive stations are significant engineering additions, being many times the size of the pipe diameter.

In practice water flushing tends to be very wasteful in water, and in some cases not very successful even in relatively small diameter pipes. Swabbing can prove expensive if special engineering modifications have to be introduced to allow access to the pipe for insertion of ropes/cables and rags. Air scouring can be damaging to the internal pipe wall, as well as being noisy, messy and time consuming. Retrofitting foam pigging facilities is very expensive. Enabling costs associated with the introduction of engineering modifications such as the provision of valves, hydrants, and launch/receive stations can be very high, and in some cases prohibitively so. Further, the cost of providing alternative water supplies during the down-time associated with cleaning of the pipe section makes the operation very unattractive, and in some cases it is simply not possible/not practical to even attempt to do so.

The driver for the ice pigging work in the water supply industry is establish whether the technology can replace the use of water flushing, swabbing, air scouring and foam pigging whilst providing reduced enabling costs, reducing or eliminating down-time and reducing man-time costs in a safe, risk–free manner.

Initial Laboratory Work

The initial laboratory work [13] established that an ice slurry consisting of small ice crystals within a water based carrier fluid could be kept stable with desirable flow properties for many hours. It was found that carrier fluids containing freezing point depressants retarded the aging process of the ice slurry. Several freezing point depressants were tried. Common salt (NaCl) was found to be very acceptable, as it is inexpensive and readily available in high purity. Hence most of the work was undertaken using brine as the base fluid.

The simple 'cafetiere' method of estimating the ice fraction was adopted [16 and 21]. This consisted of placing a given volume of ice slurry in the beaker and then pressing down on the filter-plunger to push the ice crystals to the bottom, forming a compact cylindrical block. The plunder is then removed from the beaker and the estimated cafetiere ice fraction, ϕ_c, is computed as the ratio of the ice block volume to the original ice slurry volume. It is clear that, the true, calorimetric ice fraction, ϕ, is less than the apparent cafetiere value, i.e. $\phi < \phi_c$. Nonetheless, the measurements of ϕ_c are repeatable and provide a reliable indication of the properties of the slurry.

The preliminary experimental work suggested that when ϕ_c is less than 30 to 40%, the slurry does not exhibit appreciable pigging capabilities, however, when ϕ_c was 70 to 80% or higher, it is still possible to pump the slurry and the slurry has very desirable rehological attributes. The most interesting and perhaps the most valuable for this particular application is its propensity to flow like a plug wherever it is possible to do so. Thus simple pipe flow at low velocity, which would have been in the laminar regime, had the fluid been pure water, becomes plug flow, with slip boundary conditions at the wall. The ice slurry appears to be able to hold together in regions of low shear and behave as though it were a solid, it is however able to exhibit fluid-like properties as the shear is increased . Thus is becomes possible to pump the slurry from a small diameter deliver pipe into a larger diameter pipe, where it forms a respectable plug, ready for a pigging operation [21].

The initial work investigated the ability of the ice pig to remove 'easy and soluble fouling' from the inside of pipe walls. For example, the pig was use to remove jam and ketchup from the walls of a glass pipe. This proved remarkably successful. The initial trials suggested one unit volume of ice slurry was able to achieve similar cleaning as 10 or more volumes of water [8]. More recent work suggests that this factor is probably closer to 100 for ice slurries with ice fractions, $\phi_c > 60\%$. Very recent work undertaken to for the Nuclear Decommissioning Agency suggested that for some sediments, water flushing (at achievable flowrates) is simply unable to dislodge deposits, whilst, the ice pig is able to clear out the duct using relatively small volumes [21].

Supporting Experimental Work in the Laboratory

A simple series of experiments using a two-metre length of 1-inch glass pipe containing loose sand was undertaken to investigate the potential of ice pigging technology for the potable water supply industry. In the first experiments, water was pumped through the pipe and the flow velocity found at which the sand started to be displaced and eventually removed. In the second experiments, ice slurries of different ice fraction replaced water and the same procedure was followed. In the second series of experiments, water was initially pumped through the pipe with sand deposits, ice slurry forming the pig was then introduced and this was then followed by more mains water; the water acted as the propellant, pushing the ice pig through the pipe, as far as possible the flow speed was kept constant. These experiments clearly demonstrated that for relatively low flow rates, the water simply had no effect on the sand, the ice pig 'absorbed' the sand (without bulldozing it), leaving a clean clear pipe for the propelling water, as seen in Figure 1a,b and c. Figure 1a shows the sand at the bottom of the tube. The sand does not move when water is pumped through it at speed up to 20 cm/s. When the ice pig is introduced, it is able to transport the sand away at very low speeds typical 1 to 2 cm/s (Figure 1b), leaving a clear pipe with no sand deposits, Figure 1c.



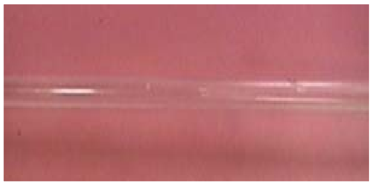

Figure 1a	Figure 1b	Figure1c
Sand in the pipe,	Ice pig transports the sand,	Leaving clean pipe.

The experimental programme was extended to investigate 90 degree bends and vertical pipes. Figure 2 shows sand being lifted from the bend of a vertical pipe by the slow moving ice pig.

Figure 2, 90-degree bend joining a horizontal and vertical pipe. The sand was originally at the bend at the bottom of the vertical pipe. The figure show the sand as it is being transported up the vertical section.

The preliminary results were encouraging; ice slurries with $\phi_c > 60$ or so percent were able to remove loose sand (builders sand), at very low flow speeds of typically 5 mm/s, an impossible task with water at similar flow speeds. The preliminary work established the fact that ice pigging could indeed remove and transport loose fine material in pipelines at much lower flow velocities than could be achieved with water.

The next stage of the exploratory experimental work was to demonstrate that the ice pig could be introduced into a pipe in a simple, elegant and inexpensive manner. Once introduced it should form a viable pig able to do its 'cleaning' tasks, and finally should be easily removed from the pipe with minimal extra equipment or enabling work. To this end, a simple experimental rig was set up to investigate what happens when ice is delivered through a small diameter pipe into the larger main. A 75mm diameter borosilicate glass pipe was used to represent the main but instead of the hydrant, ice was delivered through a 22mm pipe (ID ~18mm). This set-up represents a 16:1 increase in cross sectional area for the ice to negotiate. This is equivalent to delivering ice into a 12inch main through a 3inch standpipe. Figure 3 and 4 show a photograph of part of the rig and a schematic of the test section

Figure 3 75 mm diameter pipe with a T feed from an 18mm diameter delivery pipe.

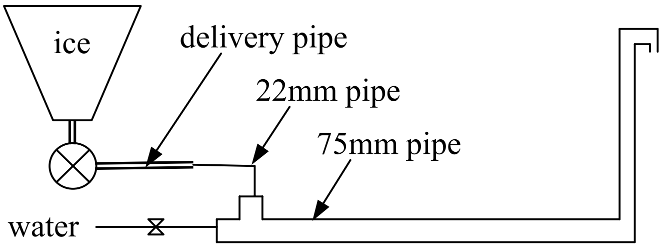

Figure 4. Schematic of experimental rig.

Some sand was placed in the glass section representing the main, which was then filled with water. Ice was then pumped through the 22 mm pipe (18mm id) and via the T into the glass 'main' to form a pig, which was then pushed through using water entering from the other arm of the T-piece.
The rig demonstrated the feasibility of entering a mains pipe from a small diameter pipe and the ability to form a viable pig in the larger duct, as seen on Figure 5

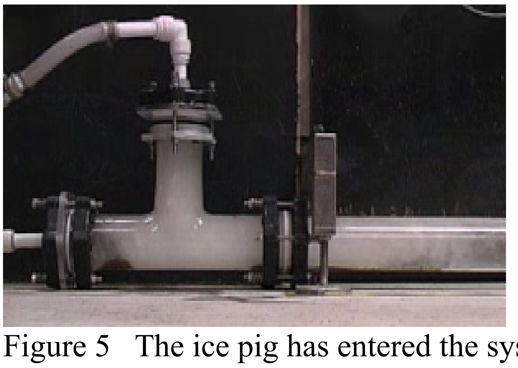

Figure 5 The ice pig has entered the system from the small 22mm pipe at the top of the T and has formed a viable pig in the horizontal 75 mm internal diameter pipe.

A limited series of laboratory based experiments were undertaken with short (1 metre length) 4 inch diameter iron pipe that had been removed from a live main. The pipes had been in the ground for about 25 years and were heavily corroded. A portion of such a pipe is shown on Figure 6.

Figure 6 Cut out iron pipe from a 4 inch trunk main. Note the corrosion and rough internal surface.

Approximately 40 litres of thick ice was pumped through each test piece. The ice fraction was above 60%. The ice pig was observed to remove large quantities of debris from within each pipe, even though the lengths of pipe had been stored in water in the intervening period between being removed from the ground to the point where they were used in the experiment. Further, ice pigging appeared not to have damaged any of the passive rust layers on the pipe's inner surface.

Initial trials with in-the-ground pipes

The very first in-the-ground trials were undertaken on a site owned by Bristol Water, using a 65m length of 4 inch iron pipe buried approximately 1 m below the ground. To gain visual access, a 1 metre length was removed and replaced by length of borated glass tube of the same diameter. This glass viewing section was approximately 40m from the hydrant inlet to the pipe. The complete pipe was flushed with mains water until all flows appeared clear. Figure 7a

Figure 7a Clear water in the pipe

Figure 7b Ice pig in the pipe.

The mains flow was valved off and approximately 80 to 100 litres of ice slurry (ϕ_c = 60%) was introduced via the hydrant. The hydrant was then valved off and mains water was used to push the ice pig through the pipe. As the ice pig removed significant loose material, which had been left by the water flushing. Figure 7b shows the ice pig as it passes the viewing window. The red/brown colouration is a result of fine sands, rust and other particulate matter. The virgin ice pig is pure white.

The first in-the-ground test was followed by a more demanding trial on a live160m long, 3 inch diameter iron pipe [21]. Although the ancillary equipment including pumps, ice maker, storage and delivery facility were undersized for the trial, the results were very encouraging.

Two hydrants (one at the inlet and the other at the outlet of the 160 m length) and associated valves enabled the ice pig to be inserted, and effluent removed, in a manner similar to to initial in-the-ground trial. The 160 m length of pipe was flushed with fresh water until the water from the outlet was clear, the water supply was cut off and the ice slurry pumped into the pipe. As the ice was pushed into the pipe, the effluent water at the outlet hydrant ran clear. Insertion of ice slurry was then stopped and the valve upstream of the insertion point was opened exposing the ice pig in the pipe to mains pressure. The valve opening was controlled to produce a flow speed of approximately 0.3 to 0.4 m/s in the pipe. The effluent from the outlet riser was visually monitored and discharged into the bowser.

The effluent initially ran clear, but as the ice pig got to the outlet and began to be discharged, the colour changed to a dark rich non-translucent brown colour, as seen on Figure 8a. After the ice pig had been discharged, the colour changed (relatively quickly, within a 100 to 200 litre volume flow), from the brown colour to lighter brown and eventually to translucent clear water (Figure 8b).

Figure 8a Pig removing debris

Figure 8b Clear water, 5mins after the ice pig

There was no evidence of the ice pig causing any damage to the passive rust layers on the inner pipe wall; once the ice pig had been through the water ran clear and there was no evidence of 'bleeding'.

Initial trials of full scale ice pigging technology in the water supply industry

The laboratory and initial in-the-ground experimental work indicated that the technology could provide benefit in certain pipe cleaning applications. However, the technology had not been proven, and there were a number of detailed questions including how much ice is required, what are the maximum length and diameters that can be cleaned, how long can the ice slurry be stored for, does the pipe material have an effect on the effectiveness of the technology. It became clear that these questions could only be answered by full-scale trials. Hence a very large refrigeration/ice maker was purchased and a purpose specific delivery unit was designed and constructed to undertake specific trials. The delivery unit is a 10 tonne stirred horizontal tank mounted on an articulated lorry. The lorry has its own diesel generator set, delivery pump and geared stirrer. Ice slurry is made using the stationary icemaker. The icemaker is located in a large store into which the lorry is garaged whilst the delivery tank is filled with ice slurry. Once sufficient ice slurry has been loaded into the delivery tank, it is driven to the required location for ice pigging operations. Figure 9 shows the ice pig lorry at its delivery location, ready to undertake an ice pigging operation.

Figure 9 The ice-pig delivery lorry ready to undertake a live trial

The procedure consists of inserting the ice pig into the water supply pipe via a hydrant, using mains pressure to propel the pig through the pipe and out of the system via another downstream hydrant. This may require some enabling work to be undertaken on the pipe, if appropriate hydrants are not available. The specific procedure involves valving off from mains supply pressure the length of pipe to be cleaned, by shutting off valves A and C on Figure 10. Hydrant valves B and D are then opened, and the ice pig delivery tank attached to hydrant B. The self contained pump on the delivery unit forces the ice pig into the hydrant and typically fills many tens of diameter length of pipe with good quality, high ice fraction ice slurry. The displaced water from the pipe runs to waste from hydrant D. The valve on hydrant B is then closed and the delivery tank removed. Valve A is opened, this allows mains water to push the ice pig through the pipe, the waste leaves at hydrant D. As the ice pig reaches hydrant D, a waste tanker is connected to the hydrant to catch most of the ice pig and the associated sand deposits. The water following the ice pig rapidly turns clear, and can again be allowed to run to waste, with no need to tanker it away. Once the clarity of the exiting water has reached the desired levels, this happens very quickly, typically within 1/10th to 1/5th of the water inventory within the length of pipe that has been pigged, hydrant D is valved off and valve C opened, returning a cleaned pipeline to the mains infrastructure.

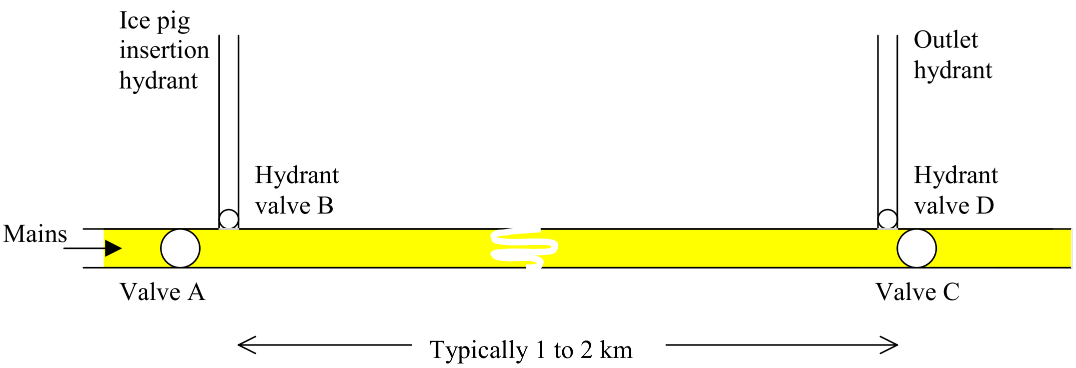

Figure 10 Schematic of the ice pigging proceedure

Diagnostic instrumentation is used at both the inlet and outlet hydrants. Typically, pressure, flow rate, temperature and conductivity (to detect salt concentration) are monitored. Samples are also taken from the outlet hydrants as the pigging operation proceeds, these samples are then analysed to obtain particulate removal rates (see Figure 11). Depending on the diameter and the length of pipe pigged as well as its state, fine sands, ferric and manganese compounds weighing 5 to 18 kg are removed, form what are 'live' potable water supply pipes.

Figure 11
Samples taken during the ice pigging operations. First bottle (top left hand side) taken when first signs of ice pig were noted, colour becomes progressively darker, until the ice pig has passed and water quickly goes clear (bottom right hand side)

To date (September 2008), 20 real trials have been undertaken, 18 of these have been carried out on 'live' mains pipes. The longest distance successfully pigged has been a 2 km long 10 inch diameter Asbestos Cement (AC) pipe. Iron pipes have also been successfully pigged (lengths varying from 60 to 1600m with diameters varying from 3 to 10 inches.

Conclusions

Fine particles in drinking water distribution systems are the main cause for water discolouration and resultant customer complaints. Water companies have developed remedial procedures to manage particle accumulation and transportation within their pipe networks in an attempt to reduce customer complaints; the current industry standard procedures include uni-directional water flushing, air scouring and swapping or pigging. None of these are ideal. Some result in excessive waste of water, others cause undesirable erosion of the pipe wall materials and some require expensive infrastructural enabling works [4].

An innovative alternative consisting of thick pumpable ice slurries acting as pigs has been explored in this paper. The generic concept of ice pigging has been demonstrated within a laboratory environment to provide benefit to the water supply industry by offering a gentile, rapid and potentially cost effective way of removing loose inorganic fouling from water supply pipes. The work has been taken to the next stage by demonstrating the potential of the technology in in-the-ground pipes and more recently in live mains. The results to date are very encouraging; sufficiently so for a major water utility company, BW, to invest resources to initiating the commercialisation of the technology.

Specifically, the technology offers a way of cleaning pipes of given dimensions (to date the technology has been proven on pipes up to 12 inch diameter and of lengths up to 2 km), in a fast and economic manner; requiring little or no enabling work to be undertaken on the existing pipe distribution system. The technique is safe and can be guaranteed of never getting any inserted objects stuck in the system. All experience to date suggests that it will reduce water waste and down-time when compared with existing methodologies.

Given the potential benefits ice pigging can bring to the potable water supply industry, it is likely that the technology will become more widely adopted. The rate of adoption will be accelerated by environmental concerns associated with sustainability, water usage, down time and supply interruptions. It is also likely that the technology will find uses in the effluent treatment components of the water utility business.

The immediate next steps in the enabling this technology to be of practical use to the water industry in reducing water discolouration challenges are:

1. The development of real, in-depth understanding of the complex rheology of ice slurries and the manner the slurries behave when exposed to water utility pipe cleaning demands. For example, it has been found that for stiff ice slurries it is possible to observe pressure losses across orifice plates which are *lower* than those which would have occurred if water at the same volume flow rate was flowing [24].
2. The development and validation of predictive tools which can estimate the viable range for the ice pig for prescribed boundary conditions [25]

Nonetheless, the technology is beginning to provide benefit to other industries including food processing [20], pharmaceutical manufacture, chemical production and the surface coatings industries. Activities as diverse as nuclear waste disposal and hydrocarbon recovery [19] are also beginning to explore the potential of the technology for their specific and idiosyncratic needs. It is likely that generic developments and improvements in the use of the technology in one specific application area will benefit others, as the technology is an underlying one proving benefit and environmental advantages to all user industries, without threatening their commercial or competitive advantages [22].

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