Design Optimization of Innovative High-Level Waste Pipeline Unplugging Technologies – 13341

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ABSTRACT

Florida International University (FIU) is currently working on the development and optimization of two innovative pipeline unplugging methods: the asynchronous pulsing system (APS) and the peristaltic crawler system (PCS). Experiments were conducted on the APS to determine how air in the pipeline influences the system's performance as well as determine the effectiveness of air mitigation techniques in a pipeline. The results obtained during the experimental phase of the project, including data from pipeline pressure pulse tests along with air bubble compression tests are presented. Single-cycle pulse amplification caused by a fast-acting cylinder piston pump in 21.8, 30.5, and 43.6 m pipelines were evaluated. Experiments were conducted on fully flooded pipelines as well as pipelines that contained various amounts of air to evaluate the system's performance when air is present in the pipeline. Also presented are details of the improvements implemented to the third generation crawler system (PCS). The improvements include the re-design of the rims of the unit to accommodate a camera system that provides visual feedback of the conditions inside the pipeline. Visual feedback allows the crawler to be used as a pipeline unplugging and inspection tool. Tests conducted previously demonstrated a significant reduction of the crawler speed with increasing length of tether. Current improvements include the positioning of a pneumatic valve manifold system that is located in close proximity to the crawler, rendering tether length independent of crawler speed. Additional improvements to increase the crawler's speed were also investigated and presented. Descriptions of the testbeds, which were designed to emulate possible scenarios present on the Department of Energy (DOE) pipelines, are presented. Finally, conclusions and recommendations for the systems are provided.

INTRODUCTION

Transferring high-level waste (HLW) between storage tanks or to treatment facilities is a common practice performed at the DOE sites. Changes in the chemical and/or physical properties of the HLW slurry during the transfer process may lead to the formation of blockages inside the pipelines [1]. Current commercially available pipeline unplugging technologies do not provide a safe, cost-effective and reliable means to address the current problems [1]. Florida International University (FIU) has continued to develop two novel unplugging technologies that have the potential to efficiently remediate cross-site line and transfer line plugging incidents: an asynchronous pulsing system and a peristaltic crawler system [2]. The asynchronous pulsing system uses a hydraulic pulse generator to create pressure disturbances at two opposite inlet locations of the pipeline to dislodge blockages by attacking the plug from both sides remotely. The peristaltic crawler is a pneumatic/hydraulic operated crawler that propels itself by a sequence of pressurization and depressurization of cavities (inner tubes). The changes in pressure result in the translation of the vessel by peristaltic movements. The crawler includes a frontal attachment that has a hydraulically powered unplugging tool.

ASYNCHRONOUS PULSING SYSTEM

System Description

The APS uses a hydraulic pulse generator to create pressure disturbances that dislodge blockages within the pipeline. The APS utilizes two hydraulically-driven piston pumps that are driven by a hydraulic power unit and two electronically controlled high-speed valves (Figure 1). The valves are actuated electrically, and are driven by a controller that utilizes pressure transducer data, as well as position feedback from a piston position transducer (LPT) to determine the valve throttle position. The system is designed to be attached to a pipeline on both sides of a blockage. This allows for pressure pulses to be applied to both sides of the blockage, where one side's pulse is π radians out-of phase with the other. This dynamic loading provides greater stress on the plug, thereby causing the plug to either breakdown or dislodge.

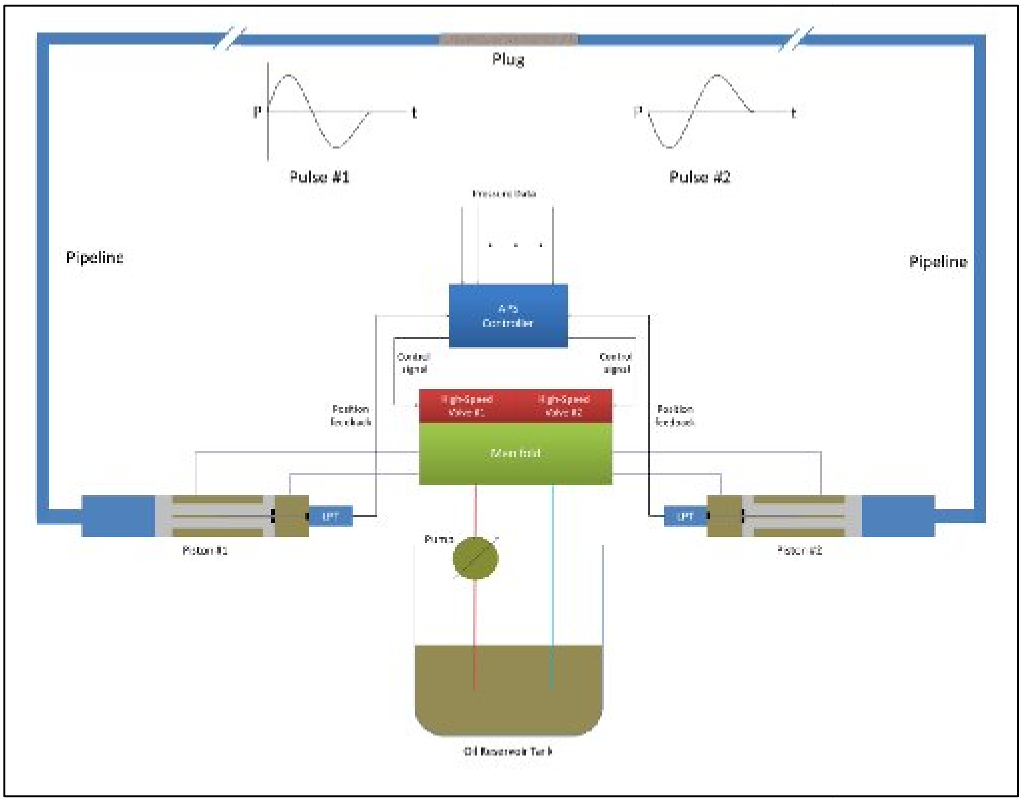

Figure 1. APS Schematic with major components labeled.

Experimental Design

During the previous unplugging phase of experiments [3], excessive pipeline deflection was observed in the test loop. This is believed to be due to the type of connectors used to connect the various components of the pipeline. Therefore, the pipeline loop was redesigned using 7.6 cm (3 in) SCH-40 threaded pipes. Threaded pipe was utilized to minimize pipeline deflection that would affect the pressure pulse propagation. The focus of this phase of experiments was to develop a systematic process that could be used to better estimate system performance at various lengths and configurations. In addition, this phase of experiments focused on quantifying the effect air in the pipeline on the pulse magnitude and propagation characteristics. For these experiments, only one piston water pump was attached to one end of the 7.6 cm (3 in) SCH-40 threaded pipeline and is used to create the pressure waves in the system. The experiments for this phase were conducted on three pipelines loops of 21.8, 30.5, and 43.6 m in total length. The loops were identified as loop 1, loop 2 and loop 3, respectively. The two larger loops contained an elbow in order to determine if the losses around the elbow were significant. Six pressure transducers located throughout the pipeline measured the pressure pulse as it propagated through the loops. Loop 1 consisted of a 20-meter straight section connected to a 1.8-meter straight section via a sweeping 90° elbow. Loop 2 consisted of a 20-meter straight section connected to 3.70-meter and 6.9-meter straight sections via two sweeping 90° elbows. Loop 3 consisted of two 20-meter straight sections connected to a 3.7-meter straight section via two sweeping 90° elbows.

Pressure Pulse Tests

The asynchronous pulsing system's ability to generate a specific pulse profile and unplug K-mag plugs was validated during prior work [3]. While conducting the unplugging tests, the asynchronous pulsing system's performance was found to degrade when air was present within the pipeline. Experiments were conducted on fully flooded loops with and without air present in the pipeline. Air quantities equal to one-half and the full displacement of the pump were introduced into the pipeline. Each loop was initially filled and pressurized with water and all the air was purged from it with the pump's piston in the retracted (back) position. If air was required in the loop for the experiment, a vent valve was opened and the loop was depressurized. The pump piston was then driven forward either a half stroke or full stroke with the vent valve still open to eject water equal to half or full displacement of the pump from the pipeline. With the vent valve still in the open position, the piston was then retracted either half way or all the way to its back position. This allowed a quantity of air to enter the pipeline equal to the either half or full displacement of the pump. The pump's half and full displacements are 64.35 cm^3 and 127.1 cm^3, respectively. **Error! Reference source not found.** shows the air percentage in each test loop for the half and full displacements. The vent valve was then closed and the pump was driven forward at a rate fast enough to produce a 500 millisecond pulse in the pipeline. The pressure pulses for the scenarios were evaluated by comparing the inlet pressure transducer and the endpoint pressure transducer profiles.

Table I. Loop Volumes and Air Percentage

Loop #	Total loop volume (m^3)	Air percentage of total volume (V_a/V_t) @ ½ stroke	Air percentage of total volume (V_a/V_t) @ full stroke
L1	0.1098	0.059%	0.116%
L2	0.1460	0.041%	0.087%
L3	0.2099	0.030%	0.066%

Air Bubble Compression Tests

In order to determine if the effects of air entrained in the loop could be mitigated, each loop was filled with a preset amount of air following the same procedure utilized during the pressure pulse tests. This air/water mixture volume was then compressed using the piston, to determine the static pressure rise for a certain volumetric compression. When the piston had completed a full stroke, the static pressure in the loop was measured. The piston would then be retracted, and the loop would be pressurized to the full stroke static pressure through the addition of water. This approach allowed air/water compression testing to occur up to the maximum allowable loop pressure of 4137 kPa. The purpose of these tests was to determine the static pressure at which the air entrained was compressed sufficiently so that the loop would act like a fully flooded loop during pulsing. The static pressure data was collected at all points during the compression.

Test Results

Table II shows the experimental data collected for 500 millisecond pressure pulse tests in all three loops with and without air. The injection of air impacted the magnitude and profile of the pulse, while the pulse front time was maintained the same for all three loop lengths. The pressure peaks suffered from significant reduction in magnitude with the injection of air into the loop. This effect depends on the percentage of air in comparison to the overall volume of the pipeline loop. The pressure amplification values quantify the waterhammer effect experienced by the endpoint of the pipeline, which is caused by the pulse. The pressure amplification found in all the fully flooded tests began to disappear as more air was injected.

Table II. Test results for no air, half stroke and full stroke of air on three loops.

Loop #	Maximum Pressure (kPa)			Pressure Amplification (kPa)			Front Time (ms)		
	No Air	Half Stroke	Full Stroke	No Air	Half Stroke	Full Stroke	No Air	Half Stroke	Full Stroke
L1	1310.0	248.2	110.3	68.9	0.0	-41.4	550	550	550
L2	1447.9	399.9	137.9	68.9	48.3	-20.7	650	65	65
L3	1379.0	517.1	199.9	68.9	55.2	-103.4	680	680	680

One other aspect influenced by the presence of air in the pipeline was the profile of the pressure pulse. The multiple relfections that occur in the pipeline after a single pulse causes oscillations in pressure as the overall pressure offset is increasing. The dampening effect of the air entrained in the loop absorbs some of the pulse energy; this decreases and delays the oscillations seen at the endpoint transducer. Figure 2 shows the effects of air on the pressure profile for Loop 1. The degradation with a small amount of air is significant, as the piston travel must initially be used to compress the air.

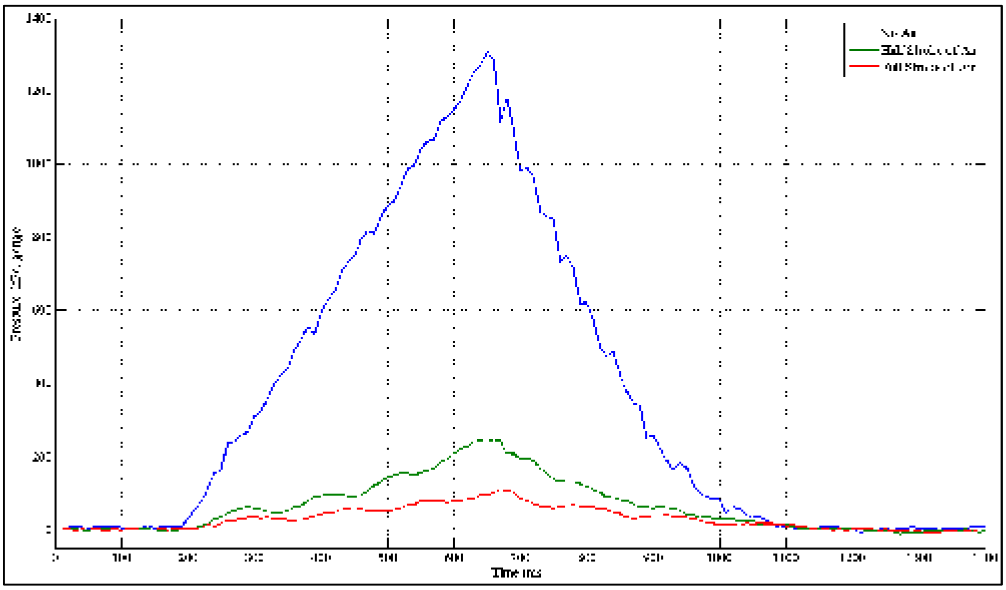

Figure 2. Loop 1 plug pressure readings at the endpoint transducer.

For the air bubble compression tests, Figure 3 shows the results of these tests that were performed with no air within the loops. The constant pressure rise for increasing compression was the expected result. This is due to the additional "compressible space" for a larger volume of water; the slope slightly decreases as the volume increases. This accounts for the general decrease in pulse magnitude as the pipeline length increases.

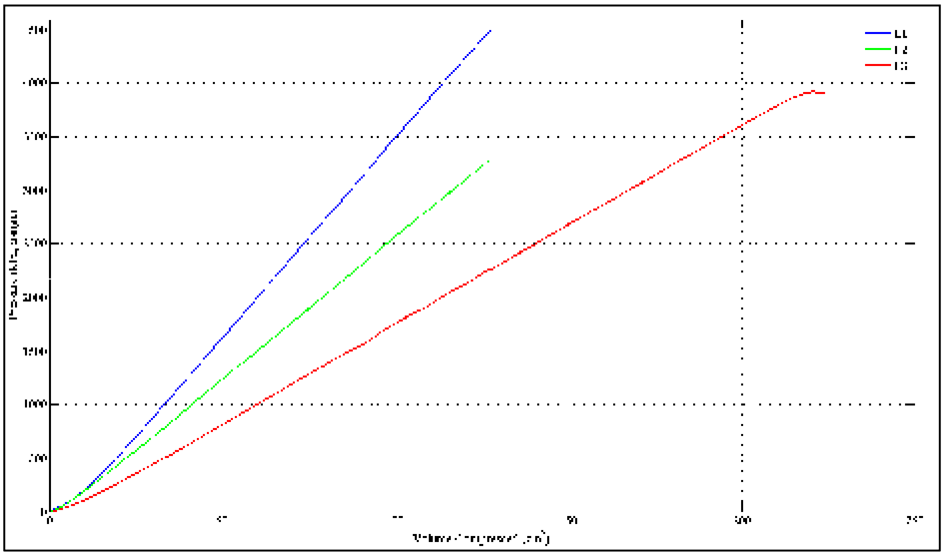

Figure 3. Compression tests of with No Air in the loops.

With the addition of a half-stroke of air (Figure 4), the initial compression must overcome the void presented by the air before the constant pressure per volume relationship becomes evident. Again, the increasing pipe length causes a decrease in the slope of that pressure per volume relationship. This behavior is also present in a full-stroke of air; additional tests being performed with larger volumes of air show similar behavior, with changing transition points.

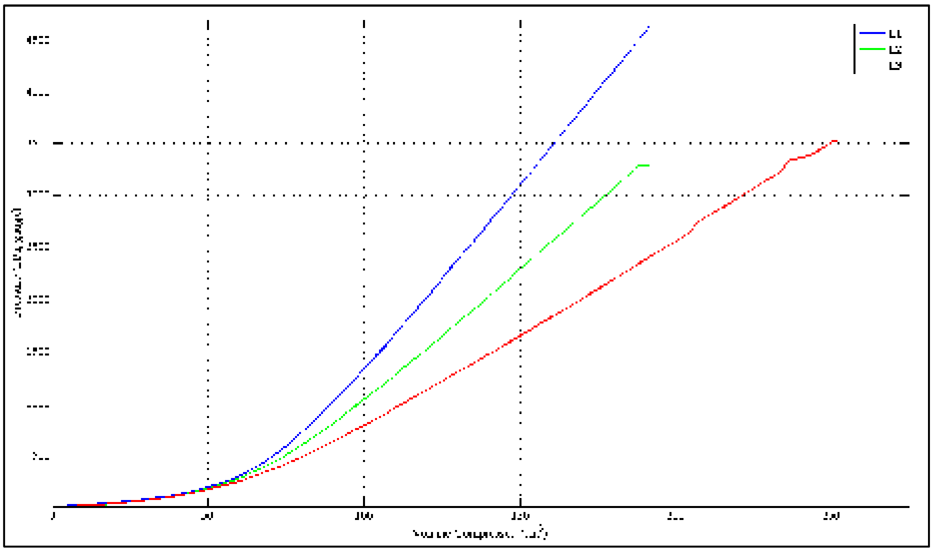

Figure 4. Compression tests for Half-stroke of Air in the loops.

The test results indicated that the effects of an air bubble entrained in the system on a transient pulse can be effectively mitigated by increasing the static pressure of the water above atmospheric pressure. As is visible in the figures, the effect of air being present in the pipeline caused very limited pressurization of the loop as the air is compressed. When that bubble is compressed to a certain density, the system begins to respond to a volume reduction in a similar manner to a no-air system. This behavior can be exploited to ensure larger pressure changes (i.e. more force loading) at the plug face. The observed relationship can now be used to determine minimum static pressure required so that the air/water mixture can act as a water-only system. The pre-pressurized value should be the minimum at which the compressibility of the system resembles the compressibility of water. These relationships will now be used to establish how much air can remain in longer pipe loops, and what will be the minimum static pressure required to cause significant dynamic loading of the plug during pulsing.

PERISTALTIC CRAWLER SYSTEM

General Description

The peristaltic crawler system (PCS) consists of a crawler unit, a control station, and a 152.4 m. long tether assembly. The control station includes the controller box, pneumatic regulators, a vacuum pump and vacuum chamber. Encased in the controller box is a programmable logic controller (PLC) which is programmed to operate the pneumatic valves in a sequence that pressurizes/depressurizes the crawler's cavities to generate the motion of the unit [4]. The crawler consists of a double walled bellow assembly (an outer hydrofomed bellow and an edge welded inner bellow) and a front and back rim which flexible sleeves are clamped to, forming the front and back cavities. Attached to the front rim is a nose cap designed to hold the unplugging tools and the camera. Figure 5(a) shows a rendering of the crawler unit and Figure 5(b) shows an exploded view of the assembly.

Figure 5. (a) Rendering of crawler, (b) exploded view of crawler assembly.

Design Improvements

The improvements to the PCS included the implementation of an electrically powered reel with rotating manifold/connectors containing pneumatic, hydraulic and electrical lines. The rotating manifold consists of four 6.4 mm FNPT ports and 6 electrical conductors. The current reel holds the 152.4 m tether assembly and is designed to hold up to a 304.8 m of tether. Additionally, a visual feedback systems was implemented to provide images of the conditions inside the pipeline. Several commercially available systems were evaluated based on their compatibility with the crawler requirements. The criteria for selection required that the visual feedback system should not hamper the navigational capabilities of the unit, must be small enough to be contained within the crawler, must be able to operate at a minimum distance of 304.8 m from the inlet point and must be able to operate in a HLW environment. The visual system selected was the INUKTUN Mini-Cristal Cam®. This system uses a camera that is 22.2 mm in diameter and connects to a display station using a fiber optic cable. It has an operational range of 304.8 m and can function in HLW environments up to 300 rad/hour. Figure 6 shows a close-up of the camera and the display station.

Figure 6. (a) Camera, (b) display station.

The front assembly of the unit was re-designed to accommodate both the unplugging tool and the camera. The front assembly consists of a hollow rim and a nose cap that positions the camera and a high pressure hydraulic nozzle with enough clearance to fit inside the crawler. The high pressure nozzle selected is manufactured by Arthur Products (model AP0125RNH-01). The design process included the computer design and rapid prototyping of the front assembly to test for fit, form and function. The crawler assembly was then manufactured using 316-stainless steel. Figure 7(a) shows the front of the unit prior to assembly and Figure 7(b) shows the assembled crawler.

Figure 7. (a) Front assembly of the crawler, (b) 3rd generation crawler.

The pneumatic valves that control the cavities of the unit were relocated from the controller box to a trailing capsule placed approximately 1 ft from the rear of the unit. This change allows the pneumatic lines of the tether assembly to remain at a constant pressure, making the cycle time independent of tether length. The capsule encases 3 12-volt DC pneumatic valves connected to the tether assembly. The use of the new pneumatic valves required changes to the electric configuration of the controller since it previously operated 110 Volt AC pneumatic valves. Figure 8(a) shows the reel and tether assembly and Figure 8(b) shows the assembled capsule manufactured using ABS (acrylonitrile butadiene styrene).

Figure 8. (a) Reel and tether assembly, (b) capsule manufactured from ABS.

Experimental Testing

The improvements implemented in the 3rd generation PCS were experimentally tested using a bench scale testbed consisting of two 0.9 m long clear PVC straight sections connected with a 90° elbow and a 0.9 m long carbon steel section.

Crawler Speed Test

For the speed tests, the PLC that controls the pneumatic valves was programmed for a total cycle time of 16 s/cycle and the tether length was 152.4 m. A total of four speed tests were conducted. Three tests were conducted with a rubber sleeve of various thickness clamped over the crawler bellow to aid in decreasing the cycle time. Testing without a sleeve yielded the slowest speed of 1.1 m/hr and the 3.18 mm thick sleeve yielded the fastest speed recorded of 5.8 m/hr. Figure 9 shows the results from the crawler speed tests in a straight pipeline section using different sleeve configurations. An additional speed test of the crawler with the valves at the control box is also provided in the figure.

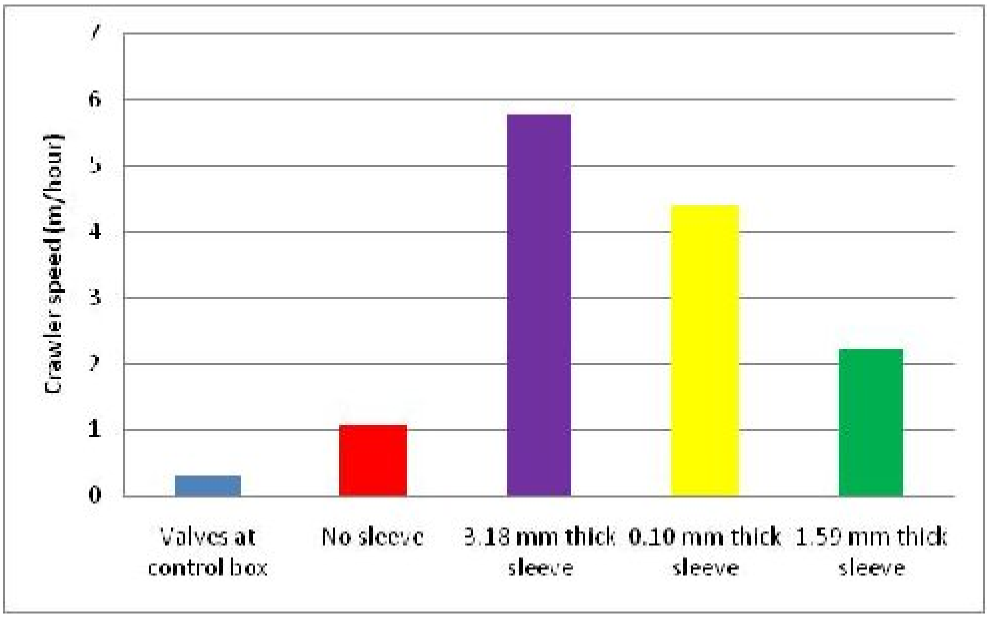

Figure 9. Speed of crawler using different sleeve configurations.

Maneuverability Test

Results from the previous experimental testing showed that the crawler has the ability to navigate through a 90° Victaulic elbow (107.95 mm radius). The time recorded for the crawler to clear the elbow was 11 minutes and 23 seconds. For this phase of testing, the maneuverability was tested with the crawler having the various rubber sleeve installed. The tests performed showed that the addition of the sleeve prevents the crawler from clearing a 107.95 mm radius elbow. However, the crawler was able to clear a standard 141.22 mm 90° Victaulic elbow with a 1.01 mm thick sleeve. The time recorded to clear the elbow was 12 minutes.

Pipeline Inspection Capability

The PCS inspection capabilities were tested using PVC and carbon steel pipe sections. The visual system proved to fit inside the front of the unit without affecting the pneumatic line that controls the flexible cavity located at the front flange. Additionally, the fiber-optic line did not adversely affect the radial stiffness of the unit. Figure 10(a) shows an image of the crawler from inside the PVC pipeline after clearing an elbow and Figure 10(b) shows a screen capture of the display station when the crawler is moving within the 0.9 m carbon steel pipe section.

Figure 10. (a) Crawler navigating an elbow, (b) screen capture of carbon steel pipe section.

DISCUSSIONS AND CONCLUSIONS

After analyzing the data from asynchronous pulsing system test runs, several observations were made. Firstly, a piston type pump system with a fixed water volume is very sensitive to the water/pipeline-volume ratio. This is because the piston pumps have a fixed discharge volume per stroke and are limited to the pressure they can produce when air is present in the pipeline. Secondly, when air is present in the pipeline, pressure propagation and amplification is degraded. Static compression experiments demonstrated that by simply increasing the static pressure of the loop above atmospheric pressure, air entrainment issues will be mitigated.

Tests were conducted that validate the improvements to the 3rd generation peristaltic crawler. The results include its navigational speed, capability to negotiate through a 90° elbow, and pipeline inspection capability. The tests verified the functionally of all the pneumatic systems required to perform an unplugging operation on a 152.4 m pipeline. The relocation of the pneumatic valves from the control box to the rear of the crawler significantly increased the crawler’s navigational speed and made the cycle time independent of tether length. The use of a sleeve to aid in the contraction of the crawler proved to be an effective method to increase the speed of the crawler, however, it increased the radial stiffness of the unit. The increase of the radial stiffness decreases the crawler’s ability to negotiate through an elbow. Further investigation of sleeve configurations can provide an optimal sleeve thickness that will maximize crawler speed without significantly increasing the radial stiffness. The visual feedback system provided clear images that can be used for inspecting pipeline conditions. Further evaluation of the camera’s ability to assist during pipeline unplugging operations will be conducted.

Even though both the asynchronous pulsing and the peristaltic crawler systems have proven to be viable options for unplugging plugged pipelines at the DOE, work will continue on the optimization of both systems. The next phase of work on the APS will include utilization of a vacuum pump to evacuate any air within the pipeline. This is anticipated to reduce the amount that the initial static pressure needs to be elevated to. In addition, alternate pressure sources will be evaluated that are capable of producing equivalent performance as the piston pumps but are not affected by any air in the pipeline. Future efforts of the PCS will focus on integrating all systems onto a single platform. This will require the design and manufacturing of a skid that can accommodate the pneumatic, hydraulic, electrical, and video system of the PCS. Additionally, optimal sleeve thicknesses for the PCS will be investigated that provide adequate radial stiffness and while maximizing the navigational speed.

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