Design Improvements and Analysis of Innovative High-Level Waste Pipeline Unplugging Technologies - 12171

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ABSTRACT

Transferring high-level waste (HLW) between storage tanks or to treatment facilities is a common practice performed at the Department of Energy (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 resulting in schedule delays and increased costs. To improve DoE's capabilities in the event of a pipeline plugging incident, FIU has continued to develop two novel unplugging technologies: an asynchronous pulsing system and a peristaltic crawler. 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/depressurization of cavities (inner tubes). The crawler includes a frontal attachment that has a hydraulically powered unplugging tool. In this paper, details of the asynchronous pulsing system's ability to unplug a pipeline on a small-scale testbed and results from the experimental testing of the second generation peristaltic crawler are provided. The paper concludes with future improvements for the third generation crawler and a recommended path forward for the asynchronous pulsing testing.

INTRODUCTION

Transferring 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 resulting in schedule delays and increased costs. In addition, pipeline plugging has been cited as one of the major issues that can result in unplanned outages at DoE sites, causing inconsistent operation [1]. As such, the availability of a pipeline unplugging tool/technology is crucial to ensure smooth operation of the waste transfer. FIU has previously evaluated commercially available pipeline unplugging technologies and found that the methods do not provide a safe, effective, and reliable means to address the scenarios found at the DoE sites [2,3]. To improve DoE's capabilities in the event of a pipeline plugging incident, FIU has developed two novel unplugging technologies: an asynchronous pulsing system and a peristaltic crawler. 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 pulsing the plug from both sides remotely. The peristaltic crawler is a pneumatic/hydraulic operated crawler that propels itself by a sequence of pressurization/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. This paper is organized so that details regarding the design, testbeds utilized and experimental results for each of the technologies are presented in separate sections.

ASYNCHRONOUS PULSING SYSTEM

Method

The asynchronous pulsing system uses a hydraulic pulse generator to create pressure disturbances from both sides of a blockage, asynchronously, to maximize the resulting force on the blockage. A detailed description of the concepts, equipment and validations studies conducted thus far can be found in Reference [3]. The general unplugging procedure for using the asynchronous pulsing system is as follows:

1. Flush the liquid in the pipes and evacuate the air using a vacuum pump on both sides of the blockage, if possible.
2. Fill the pipeline from both ends with water, to a specified pressure.
3. Start asynchronous pulsing by creating positive pressure waves at both ends of the pipeline by adjusting the frequency and phase shift between two pulse generators.

The test pipeline loop used to validate the method contains two identical pipeline sections with a plug between them (**Error! Reference source not found.**). This test loop allows for control of the individual pipeline section pulse characteristics to determine how each pulse influences the total plug dynamic loading. As shown in Figure 1, the experimental test loop was assembled using four straight sections and two 90° elbows. The pipes used for the loop are 7.62 cm (3 in) diameter schedule-10 carbon-steel pipes. Each side of the symmetric loop has a 2.74 m (9 ft) and an 2.44 m (8 ft) pipe with an elbow between them. A blockage was placed at the center of the loop to emulate a plug in the pipeline. The heart of the asynchronous pulsing system are two hydraulic piston pumps that are powered by the pulse generation unit which

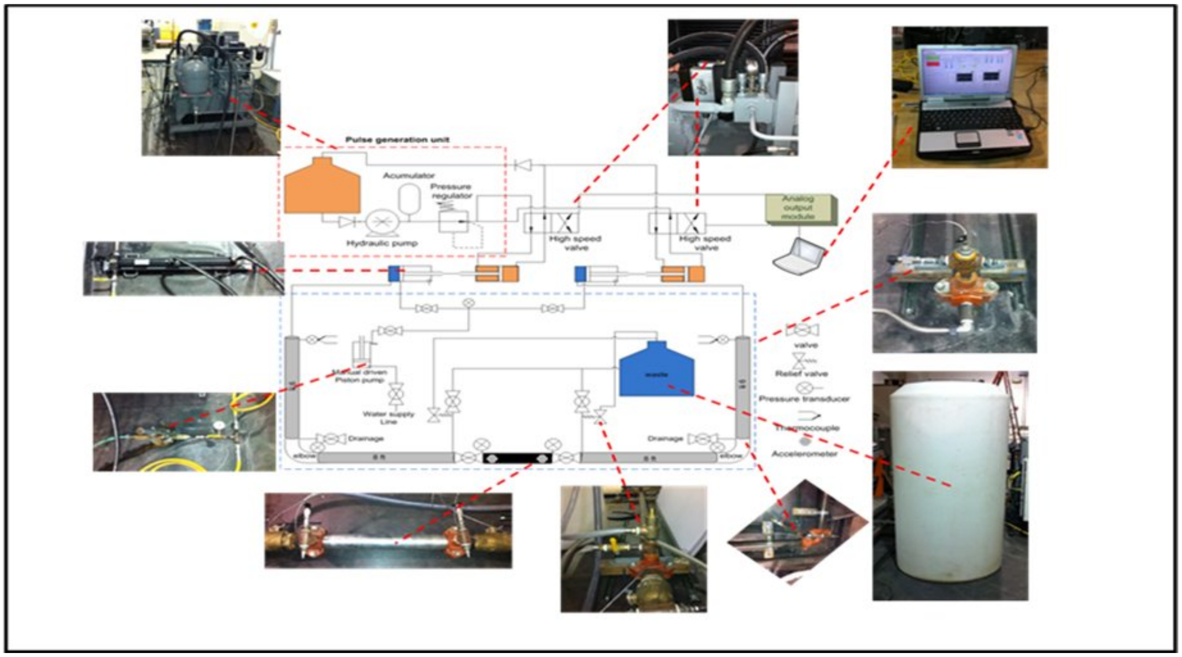


Fig 1. Experimental test loop.

is comprised of a hydraulic power unit and two electronically controlled high-speed valves. The pipeline is instrumented with accelerometers, pressure transducers and thermocouples located at strategic locations to capture the changes of the induced disturbances inside the pipeline.

The experiments included the placement of 0.61 m (2 ft) plugs within the test pipeline loop and using the system to unplug the pipeline. The plugs were made by mixing potassium magnesium sulfate (K-mag) and water at a ratio of 90% K-mag to 10% water by weight.

Hydraulic pressurization tests

Hydraulic pressurization tests were conducted on three randomly selected plug samples to ensure that the plugs would not fail by simply applying low static pressures and to verify the plugs were manufactured consistently. Each of the three plugs tested failed at approximately 2.1 x10^6 N/m^2 (300 psi), above the maximum pressures applied. It should be noted that although the plugs were not completely removed, they were considered unplugged if flow was passed through the blockage.

Asynchronous pulsing trials

Prior to initiating the asynchronous pulsing unplugging trials, several parametric tests were conducted on the system to determine the system's response to various input parameters. A solid aluminum cylinder was placed within the pipeline to emulate a plug and the system was run under various pipeline static pressures, oil hydraulic pressure and pulse frequencies. After analyzing the data from the parametric tests, a test matrix was developed for the unplugging trials. However, it was determined that under certain conditions, the system was capable of generating pressures that exceeded a preset limit of 2.1 x 10^6 N/m^2 (300 psi) in the pipeline. Additionally, the plugs also altered the response of the system, requiring further changes to the original test matrix.

Asynchronous pulsing unplugging trials were conducted using K-mag plugs with pulse frequencies of 1, 2 and 4 Hz and static pressures within the pipeline of 4.1 x 10^5 N/m^2 and 1.4 x 10^6 N/m^2 (60 and 200 psi). These experiments were done with the pipeline 100% filled with water and then repeated with the pipeline filled with 87.5% with water. The pipeline was considered unplugged when the pressures equalized on both sides of the plug.

Typical pressures at each plug faces using a static pressure of 4.1 x 10^5 N/m^2 and a pulse frequency of 1 Hz are shown in Fig 2. The maximum pressure differential was approximately 1.1 x 10^6 N/m^2 (160 psi) on the plug. During this trial, the system was run for over 20 minutes and was unable to unplug the pipeline.

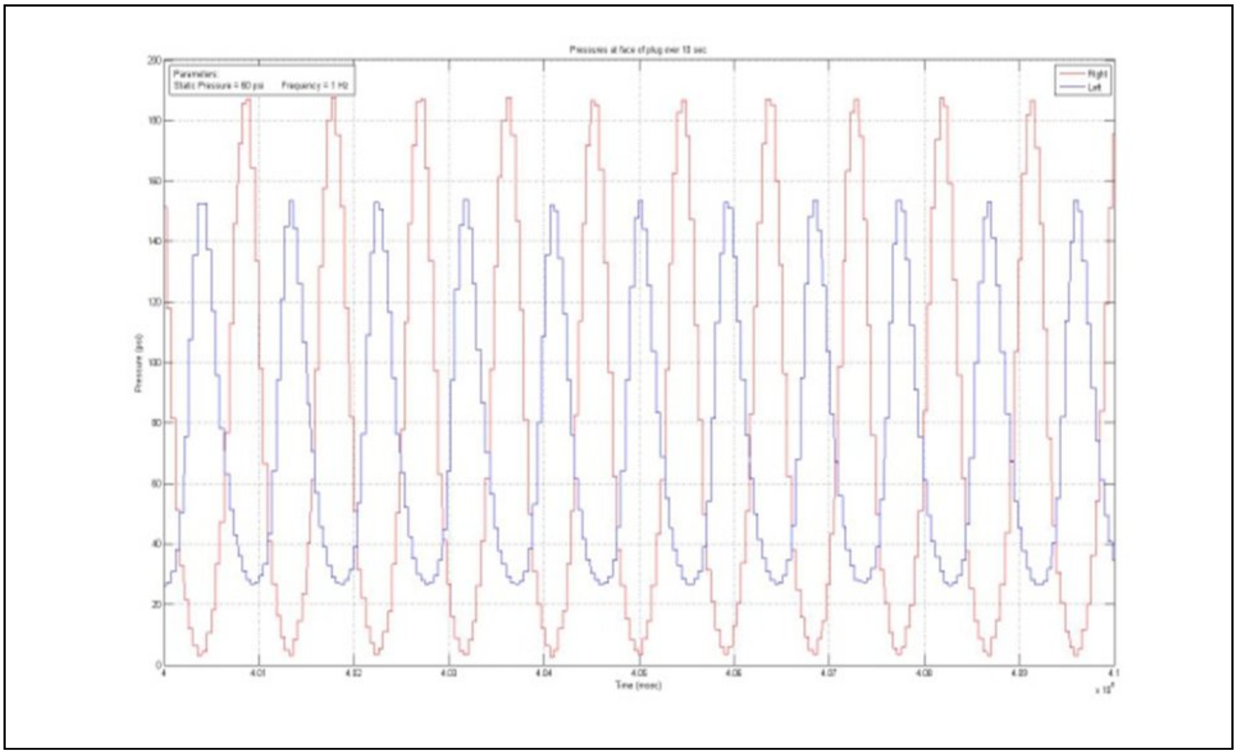


Fig 2. Pressure pulse profile with a 4.1 x 10^5 N/m^2 (60 psi) static pressure and a frequency of 1Hz.

Fig 3 shows the extended time history of the pressure profiles from a trial at a static pressure of 4.1 x 10^5 N/m^2 (60 psi) and a pulse frequency of 2 Hz. During this test, the system was unplugged in less than 7 minutes. The point at which flow broke through the plug is easily located in the figure. It is interesting to note that the

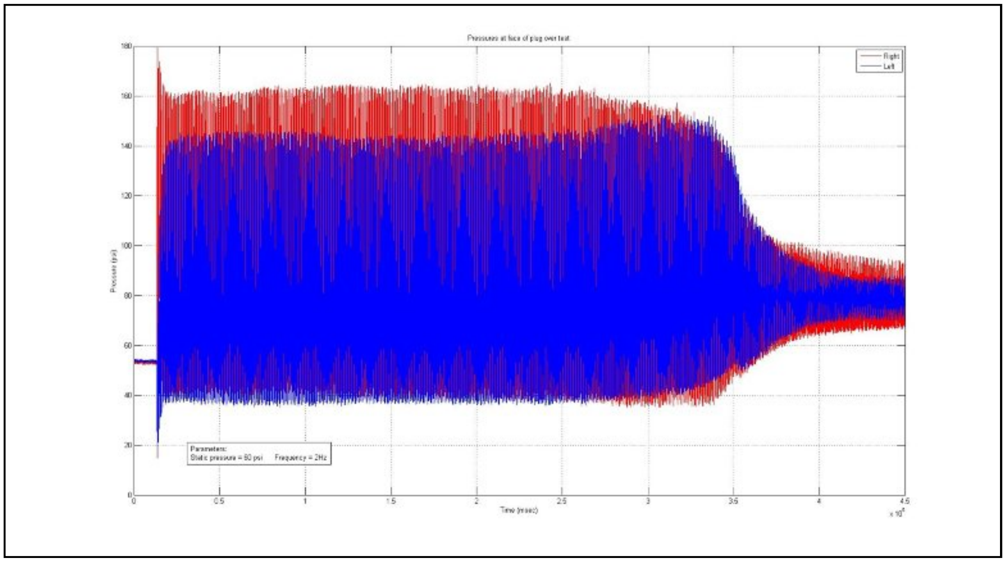


Fig 3. Extended time history of plug face pressures showing unplugging event with a static pressure of 4.1 x 10^5 N/m^2 (60 psi) and a frequency of 2Hz.

differential pressure was approximately 8.3 x 10^5 N/m^2 (120 psi). This differential is less than the 1Hz test, suggesting that resonation may have played a role in the unplugging. This was the only pressure-frequency combination in which the pipeline was unplugged. This experiment was repeated two more times with similar results.

For the 1.4 x 10^6 N/m^2 (200 psi) trials with a pulse frequency of 2 Hz, a significant difference in pressure magnitude on each side of the plug face was observed. This difference is likely due to the variation in the water absorbed at each of the plug faces. During this trial the system was run for over 16 minutes and was unable to unplug the pipeline. During one trial, the static pressure dropped from the initial value of 1.4 x 10^6 N/m^2 (200 psi) to approximately 9.7 x 10^5 N/m^2 (140 psi) before the system was started. This pressure drop was likely due to the plug absorbing the water. This phenomenon was observed in all trials but was most prevalent in the high static pressure tests. Another issue observed during the trial was the drifting of the pressures. This is believed to be due to the combination of both water loss due to absorption into the plug and the drifting of the water pump's pistons. Since the piston's position is controlled by hydraulic oil pressure, under high static pressures, the piston will drift as a result of the inherent lag in the oil pressure control valve.

Results from the trial with a static pressure of 1.4 x 10^6 N/m^2 (200 psi) and a pulse frequency of 4 Hz yielded similar results. During this test, the system was run for over 8 minutes and was unable to unplug the pipeline. As in the previous trial, the static pressure dropped before the system was started. Drifting of the face pressures was also observed.

In the trials with 87.5% water in the pipeline, the pipeline was filled with water and all the air was purged out. The pressure in the fully flooded line was then vented to equalize the pressure to atmospheric pressure. 12.5% of the calculated volume of the pipeline was then pumped out using a peristaltic pump with a vent open which allows air to replace the water that was being removed. All the vents were closed and the pipeline was pressurized to the desired static pressure by adding additional water. No other modifications were done to the system.

For the 2 Hz test with the pipeline filled with 87.5% of water, the pump could only generate a pressure rise up to 6.9 x 10^4 N/m^2 (10 psi). This was due to a low water to pipeline-volume ratio and a piston pump system. Additionally, significant piston drift was observed. Similar results were obtained for the 4 Hz test with the pipeline filled with 87.5% of water. The pump was able to generate a 2.4 x 10^5 N/m^2 (35 psi) increase on the left side which was a greater pressure rise than the 2 Hz test. However there was a significant amount of piston drift as well. None of the trials for the pipeline filled with 87.5% water resulted in an unplugging.

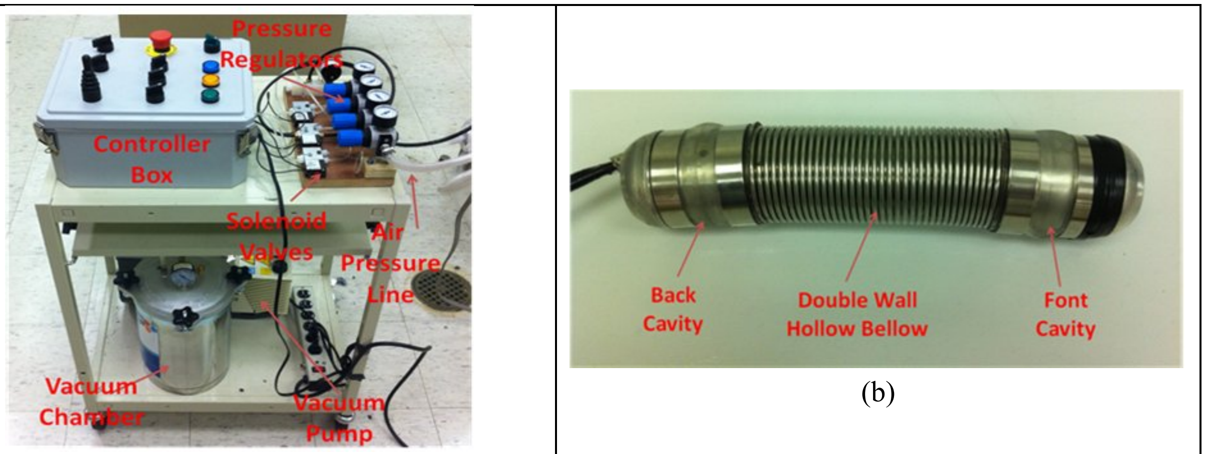
Discussions and conclusions – Asynchronous pulsing system

After analyzing the data of all the test runs, several observations were made. The first is that some of the results from the initial parametric tests conducted on the aluminum plug were unable to be repeated in trials with the K-mag plugs. This was likely due to the reduction of the water volume in the system from the plug absorbing the water as well as the dissolution of the plug which resulted in a reduction of the water to pipeline-volume ratio. A second observation from the 87.5% water tests was that a piston type pump system with a fixed water volume is very sensitive to the water to 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 with replenishment of any lost water. In future work, different plug materials will be analyzed to determine how they affect the system performance. In addition different pump designs will be considered that are less affected by the water to pipeline-volume ratio. Finally, for the fully flooded system, the lower static pressures and a frequency of 2 Hz were optimal operational parameters for the system. This suggests that the removal of the plug is dependent on the resonation of the system. Future work will also include the investigation of operation parameters on resonation with various types of blockage material.

PERISTALTIC CRAWLER

The use of a peristaltic movement mechanism to propel a device inside a pipeline has been previously used in inspection devices. One example is the system presented by Shishido in the patent, “Pipe-Inspecting Apparatus Having a Self Propelled Unit” [4]. Another similar device with this propelling system was invented by Zollinger [5] which was designed to pull tethers behind underground boring devices. The novelty of using peristaltic motion to successfully propel a device inside HLW lines creates the possibility of using the crawler as a vessel to carry unplugging technologies. By reducing the distance between the unplugging tool and the location where the plug formed, the success rate for removing the plug is greatly increased.

The peristaltic crawler consists of two components: the crawler unit and control station. The controls, shown in Fig 4 (a), include a regulator, electronics, and pneumatic system which controls pressure and airflow into the unit. The crawler’s motion is derived from the sequential inflation/deflation of three independent cavities (Fig 4 (b)). When pressurized, the back and front cavity anchor the unit to the pipeline. The double wall hollow bellow controls the longitudinal expansion and contraction of the unit. The bellow consists of two concentric hydro-formed bellows which are welded together.



(a)

(b)

Fig 4.(a) Control station, (b) crawler unit.

Improvements to the crawler unit and control station (second generation)

Based on the results in performance and durability observed in the first generation Peristaltic Crawler [2], a second generation unit was developed. The materials and design were improved to ensure that any issues that compromised the structural integrity of the crawler were eliminated. The bellow material was changed from a reinforced based rubber to stainless steel. This allows for a much higher pressure inside the bellows without rupture of the walls and ultimately increases the pulling force capability of the crawler. Additionally, the attachments of the flanges to the bellows were changed so that they are securely attached using bolts and a high temperature gasket. The flexible membranes forming the front and back cavity were also changed to a flexible PVC material and secured to the flanges using high compression clamps to prevent any leaks at those areas.

The controller of the unit was improved to make the forward and backward navigation of the crawler automated. This was achieved by connecting the solenoid valves to a programmable logic controller (PLC). The PLC was connected to a series of feedback indictors which allow the user to follow the sequence of inflation/deflation of the cavities and bellow. In addition, an individual pressure regulator was implemented to control the pressure supplied to each of the cavities of the crawler which allowed for optimization of the pressures reached. In addition, a vacuum chamber was added to the system that sped up cycle time of the crawler by shortening the time required for the contraction of the bellow.

Experimental Testing (second generation peristaltic crawler)

To optimize the cycle time of the system, the crawler was placed in a clear PVC pipe and pressurized to various limits to determine the best combination of operational pressure, and deflection of the unit with no load. The optimal pressure for the front and back cavities was found to be 6.2×10^5 N/m^2 (90 psi). The optimal pressure for the bellow was found to be 1.4×10^5 N/m^2 (20 psi). The pressures could be increased, but with the current design, the cycle time would be comprised. The inflation/deflation sequencing of the unit was controlled using a PLC. Several sets of operation parameters were tested to find a sequence that allowed full inflation and deflation of the cavities in a minimal time. Using the aforementioned pressures, the optimal cycle time was found to be 16 seconds.

The speed of the crawler was measured using an 203 cm (80 in) long stretch of a 7.62 cm (3 in) diameter clear PVC pipe. Tests were conducted in a dry and fully flooded pipe (water) with essentially no load on the crawler. The minimum time recorded for the dry test was 12 minutes 51 seconds. The minimum time recorded for the flooded test was 13 minutes and 22 seconds. The approximate speed of the crawler in a straight pipe is 0.15 m/ min (0.5 ft/min).

The crawler's ability to negotiate through elbows was tested in a testbed consisting of two straight 7.62 cm (3 in) pipes and one 90° elbow. It was found that the crawler could not turn in a Victaulic elbow (10.8 cm (4.25 in) in radius) but was able to turn in a PVC elbow having a radius of 14 cm (5.5 in). The time recorded for the crawler to clear the elbow was 7 minutes and 34 seconds.

Pull force tests were conducted to establish the ability of the bellow to expand under load. The pull force tests were conducted using a spring scale connected to a frame holding a clear PCV pipe. Two trials of tests were conducted, each with a different spring scale. By using scales with different spring constants it was established that the extension of the bellow has a significant impact on the pulling force. The spring constant of the scales used were 2276 N/m (13 lbs/in) and 11,732 N/m (67 lbs/in). The maximum test pressure was limited by the available air supply which was 6.2 x 10^5 N/m^2 (90 psi). The pulling force recorded at this pressure was 490 N (110 lbs) with 2.53 cm (1.64 in) extension of the bellow. The results indicate that a linear relationship exists between supply pressure and pulling force. However, the extension of the bellow also plays a role in determining the pull force (as the bellow extends the maximum pulling force decreases). This means that as the load increases on the crawler, the stroke and ultimately the speed of the crawler decreases.

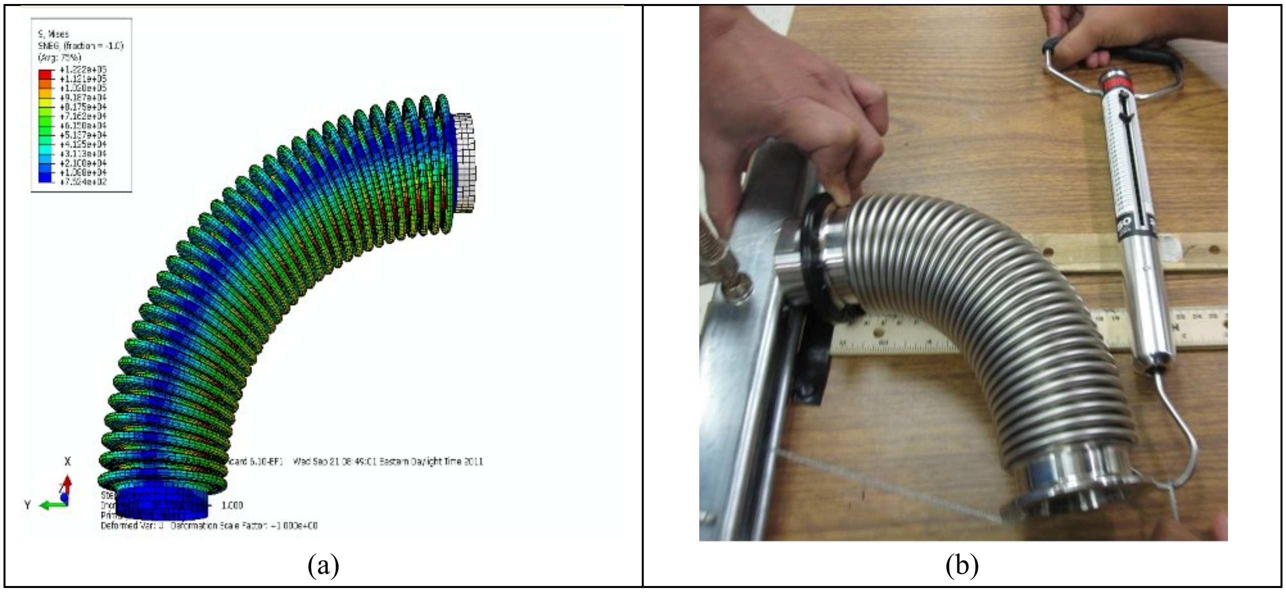
Unplugging tests were performed using two types of nozzles: a rotating nozzle having orifices oriented at 45° and a stationary nozzle having a 15° angle. Tests with the rotating nozzle were conducted on a 60% by weight bentonite plug. The nozzle eroded only 6.35 cm (2.5 in) from the face of the plug. The 15° nozzle was successful in clearing/removing a 0.91 m (3 ft) long bentonite plug in 56 min. This corresponds to an erosion rate of 0.98 m/hr (3.2 ft/hr).

The 15° nozzle was subsequently tested using a sodium aluminum silicate plug. A small 10.2 cm (4 in) long plug was fabricated inside a 7.62 cm (3 in) steel pipe which was coupled to a PVC pipe. Prior to testing, the crawler was positioned 5.1 cm (2 in) from the face of the plug. The time required for unplugging was 6 minutes, resulting in an erosion rate of 1.07 m/hr (3.5 ft/hr).

Improvements to the crawler unit and control station

The experimental testing of the second generation crawler showed that by changing the outer and inner bellows from rubber reinforced to stainless steel hydro-formed bellows increased the time cycle considerably. This is due to the axial spring rate of the bellow (stiffness). Also, the outside diameter of the crawler did not allow it to turn thru a 7.62 cm (3 in) diameter Victaulic elbow. Improvements to generate third generation crawler include reducing the crawler outside diameter, decreasing its axial stiffness, implementation of on-board electronics for visual feedback, and evaluating placement of the pneumatic control valves on the crawler.

The crawler consists of two bellows, one inner bellow nested into an outer bellow. Hydro-formed bellows have shown to perform acceptably when pressurized internally to possible pressures. However, their spring rate increases considerably with a decrease in diameter. The second generation outer bellow has a spring rate of 333 N/m (1.9 lb/in) and the inner bellow has a spring rate of 2802 N/m (16 lb/in) for a total assembly spring rate of 3100 N/m (17.7 lb/in). Because the inner bellow is not subjected to positive radial internal pressures, it allows for the third generation crawler to use an edge welded bellow in the place of the internal bellow. Edge welded bellows have a negligible axial spring rate in compression which allows for the reduction of the diameter of the outer bellow with acceptable assembly spring rate. Finite element analysis (FEA) was performed to numerically predict the response of a smaller diameter hydro-formed bellow. Fig 5(a) shows stress results for the analysis performed on the outer bellow. Fig 5(b) shows experimental measurements taken to validate the analysis. The FEA showed that reducing the outside diameter of the bellow from 9.99 cm (2.75 in) to 5.13 cm (2.02 in) will provide an acceptable increase on the spring rate of the outer bellow (1680 N/m).



(a)

(b)

Fig 5. (a) FEA of bellow, (b) experimental response of bellow.

Using the optimal dimensions provided from the FEA, the design of the bellow assembly was completed. The assembly was designed to have all parts of the crawler welded together, thus minimizing the possibility of leaks. The third generation crawler assembly was also optimized to allow space for additional feedback and control systems (possible on-board pneumatic valve controls). The crawler can house a camera that allows for inspection of the pipeline conditions during unplugging operations. A potential camera being considered has an outer diameter of 2.22 cm (0.875 in) and can be used for lengths up to 305 m (1000 ft). It can provide clear images in a radioactive environment up to 200 rad/hour.

Discussions and conclusions – peristaltic crawler

Tests were conducted to understand the capability of the second generation peristaltic crawler including; unplugging ability, crawler speed, pull strength, and ability to negotiate thru a 90° elbow. Although the crawler successfully navigated thru a PVC elbow with a larger turning radius, it could not pass thru the small Victaulic 7.62 cm (3 in) elbow. This is primarily due to the flexural stiffness of the bellow. Bellow manufacturers do supply data regarding the flexural properties; however, there is data available regarding the linear stiffness. Data from the manufacturer of the hydro-formed bellows shows that the linear stiffness of the bellow dramatically increases as the diameter of the bellow decreases. The outer bellow used has a stiffness of 333 N/m (1.9 lb/in) and the inner bellow's stiffness is 1226 N/m (7 lb/in). The high stiffness of the inner bellow likely prohibited the bellow assembly to turn or flex enough to make it thru the 90° elbow. This high spring rate also affects the speed of the crawler since it requires higher vacuum to achieve the bellow's contraction.

An additional factor that affects the speed of the crawler is the diameter of the air line connected to the bellow. Tests demonstrated that using a 0.16 cm (0.0625 in) diameter 7.62 m (25 ft) long line allowed for full contraction of the bellow in approximately 2.5 minutes. Tests with a 0.42 cm (0.17 in) diameter line allowed for contraction of the bellow in 8 seconds. Further investigation is required to determine the effect of minor loses on the crawler speed.

As expected, the crawler's speed did not significantly vary over an 203 cm (80 in) stretch of pipe when the pipe was flooded or dry. This would likely change using longer testbeds, when the tether weight and drag become more significant. Pull force tests demonstrated that the extension of the bellow affects the available pulling force of the crawler. The maximum pulling force obtained using 6.2 x 10^5 N/m^2 (90 psi) was 489 N (110 lb) at a displacement of 4.12 cm (1.64 in). Additional testing would be required for the complete characterization of the response of the bellow to various pressures.

The unplugging operations showed that the rotating nozzle did not provide enough water pressure to erode a bentonite plug. The cause of the loss in water pressure is attributed to using a rotating nozzle having a small diameter (0.16 cm). Further tests using a rotating nozzle having the same diameter as the stationary nozzle (1.27 cm) will be conducted to determine the effect that the nozzle diameter has in unplugging ability. The 15° nozzle proved effective in unplugging a sodium aluminum silicate with an erosion rate of approximately 1.07 m/hr (3.5 ft/hr). It should also be noted that the eroded material from this plug did not constrict flow thru the crawler.

The improvements in the bellows for the third generation crawler aim to reduce the cycle time of the unit as well as its ability to turn thru a 90° elbow. In addition, the assembly of the unit by welding minimizes the potential for leaks. The addition of electronics for visual feedback enables the user to determine the conditions inside the pipeline to select the optimal unplugging procedure.

Experimental unplugging operations will be performed by using a longer pipeline to determine the crawler's ability to operate at larger distances. Effects such as pressure losses due to increased tether length will be studied as well as the evaluation of mounting the pneumatic control valves on the crawler to even further decrease the cycle time.

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