Investigation into ILI Tool Velocity and Tool Speed Control Options in a 6-inch and 30-inch Hydrogen Pipeline

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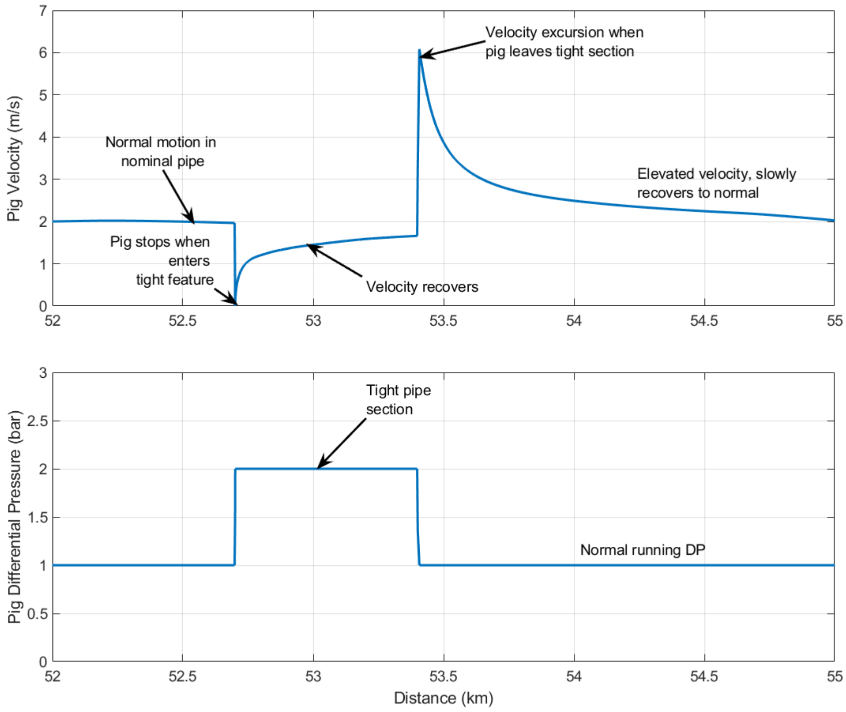
1 ABSTRACT

In a collaborative project, Pipeline Research Limited and the Hydrogen Working Group of the Pipeline Operators Forum investigated In-Line Inspection (ILI) tool velocities for exemplary 6-inch and 30-inch hydrogen transmission pipelines under various conditions. The investigation focused on studying tool dynamics in a hydrogen environment by modelling ILI parameters, operating conditions and pipeline design. Options to control tool speed excursions are investigated to limit the velocity to less than maximum allowable. This maximum is taken as a typical threshold from a safety perspective but also for effective inspection and data collection. The requirements for the tool, control of pressure, inlet and outlet flow and special arrangements such as bypass are studied for both pipelines to allow successful and safe inspection. This investigation sets out opportunities and functional requirements for improving tool velocity control in hydrogen pipelines. Meeting these requirements may pose a challenge to operators and inspection companies in terms of practicality and limitations of current technology.

2 INTRODUCTION

In-Line Inspection (ILI) in gas pipelines can result in unstable velocity due to changes in friction or differential pressure between the tool and the pipe wall. As the tool enters a tight section of pipe (for example thick-walled pipe), then it slows down. As the tool differential pressure builds up to overcome this resistance the velocity recovers. Once the tool leaves the tight section, acceleration occurs as pressure energy is dissipated. Such extremes in velocity from stalling to excessive speed can affect inspection data quality and pose a safety risk.

Figure 1: Anatomy of a typical velocity excursion at a thick wall pipe feature



High product density helps to dampen velocity excursions. In liquid, such a problem is not observed to any considerable extent. In natural gas, at high pressure, the resulting velocity is tolerable in most cases. High pressure is sufficient to render the velocity excursions low in magnitude and comparatively short in duration. As the pressure reduces, the density drops and ability to control tool speed is compromised. A 20 bar operating pressure results in just 17 to 25 kg/m^3 density which offers little dampening or control. As demonstrated below, the problem is exacerbated in hydrogen.

The energy transition from natural gas to hydrogen, using the existing pipeline infrastructure, results in many technical challenges. Inspection or ILI for pipeline integrity management relies on high quality data meeting existing technology requirements. A major question is can existing technologies and ILI tool designs be transferred to a pressurised hydrogen environment with hydrogen pipeline operating conditions. In this paper different aspects of hydrogen ILI tool dynamics are considered.

The Pipeline Operators Forum (POF), through its H2WG (Hydrogen Working Group) is studying various aspects related to in-line inspection of hydrogen transport pipelines. The ability to inspect such lines in a safe and efficient manner is one such aspect that requires study (see API 1163). Pipeline Research Limited has developed a tool dynamics model known as PIGLAB (coded in MATLAB) used to investigate the velocity of tools in gas pipelines under various conditions, pipeline configurations and tool designs. The collaborative work undertaken in this study aims to investigate how tools might be controlled more effectively in hydrogen and provide guidance for operators.

This paper provides a snapshot of the work being undertaken and the various investigations that are ongoing. Control methods and the results are presented to give a flavour of the problem and highlight possible solutions.

3 OVERVIEW OF MODEL AND INPUT DATA

The PIGLAB model works by considering the gas continuity and momentum equations upstream and downstream of the tool. This allows pressure and gas velocity to be determined along the line. It is a fully transient model and what is unique about the method used is its treatment of a moving object (the tool) through a static grid (the pipeline).

The resulting model can handle many different variables: -

- The pipeline in terms of diameter and change in diameter, features, elevation profile;
- The tool or multiple tools in terms of mass, bypass, friction or differential pressure;
- The operation in terms of pressure, temperature and flow control;
- The gas in terms of molecular weight, mole percentages and compressibility.

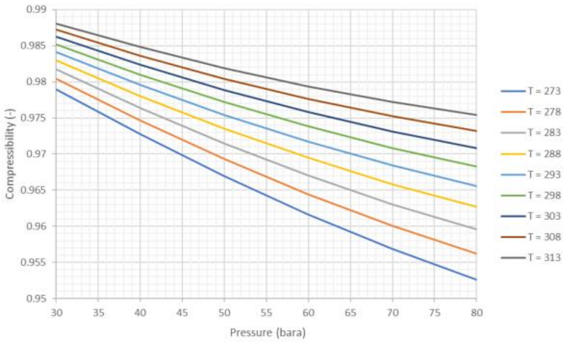
Through discussion with the POF H2WG, it was decided to focus on two candidate pipelines for transport of hydrogen or blend of hydrogen and natural gas. This allows aspects such as elevation profile, diameter and so on to be fixed and provide a starting point. It is recognised that every pipeline has its unique set of circumstances but other more focused analysis could be included later once an initial view is taken.

Diatomic hydrogen – the smallest molecule – has a very low molecular mass of 2.01 g/mol, whereas natural gas can have a molecular mass in the region of 16 to 19 g/mol. This means that the density of hydrogen at 100 bar is just 8.2 kg/m^3 compared to 90 to 120 kg/m^3 for natural gas and therefore even at high pressure, hydrogen can result in severe tool motion instabilities. One advantage that hydrogen may have over natural gas is its high speed of sound. The speed of sound governs how corrective pressure changes are transmitted up and down the pipeline.

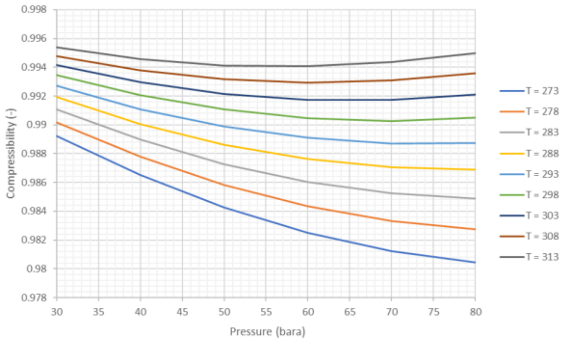
The molecular mass and compressibility of hydrogen and natural gas mixtures is used in this model based on molar percent of constituents. Compressibility and the calculation method is shown: -

Table 1: Calculation and examples of compressibility for mixture of natural gas and hydrogen

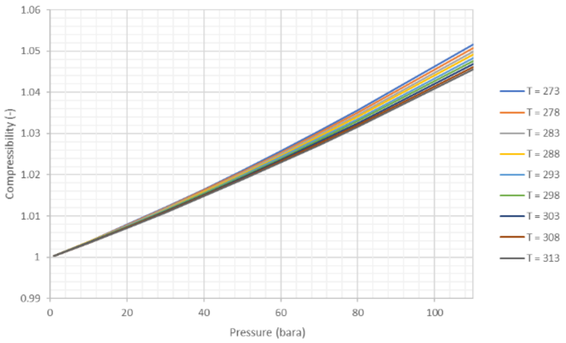
0% hydrogen: -



20% hydrogen: -



100% hydrogen: -



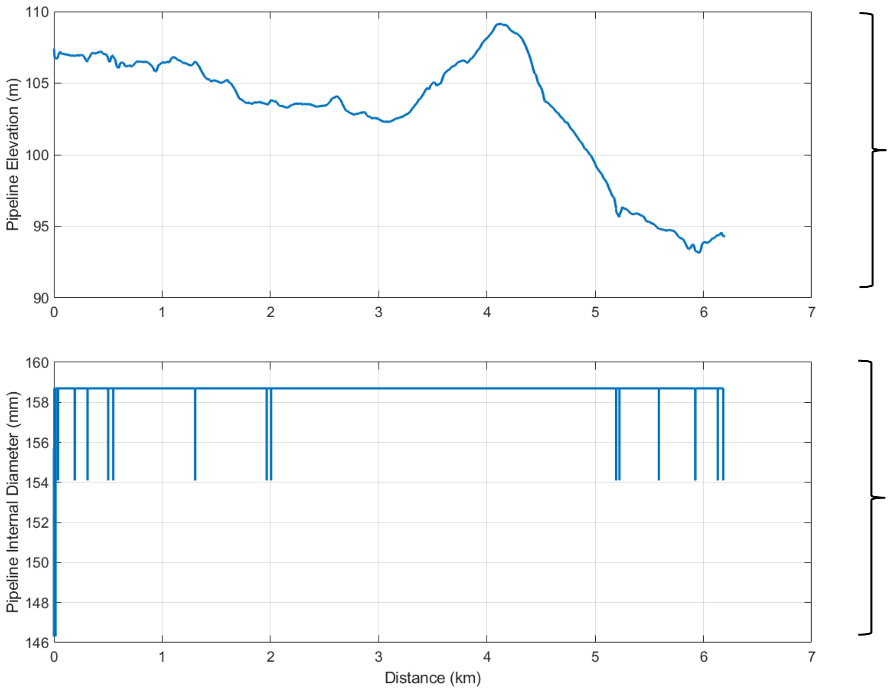
Calculation of compressibility, *z*: -

$$
\begin{aligned}
z \quad = \quad & \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^2} + \frac{A_4}{T_r^5}\right)\rho_r + \left(A_6 + \frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^2 \\
& - A_9\left(\frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^5 \\
& + A_{10}(1 + A_{11}\rho_r^2)\,\frac{\rho_r^2}{T_r^3}\,e^{A_{11}\rho_r^2} + 1
\end{aligned}
$$

$A_1 = 0.3262$;
$A_2 = -1.07$;
$A_3 = -0.5339$;
$A_4 = 0.01569$;
$A_5 = -0.05165$;
$A_6 = 0.5475$;
$A_7 = -0.7361$;
$A_8 = 0.1884$;
$A_9 = 0.1056$;
$A_{10} = 0.6134$;
$A_{11} = 0.721$.

The first line considered is a 6.2 km, 6-inch line operating at high pressure (90 bar) but with low flow (typical flow velocity in the region of 0.25 m/s): -

Figure 2: 6-inch pipeline elevation profile (top) and pictorial bore map (bottom)

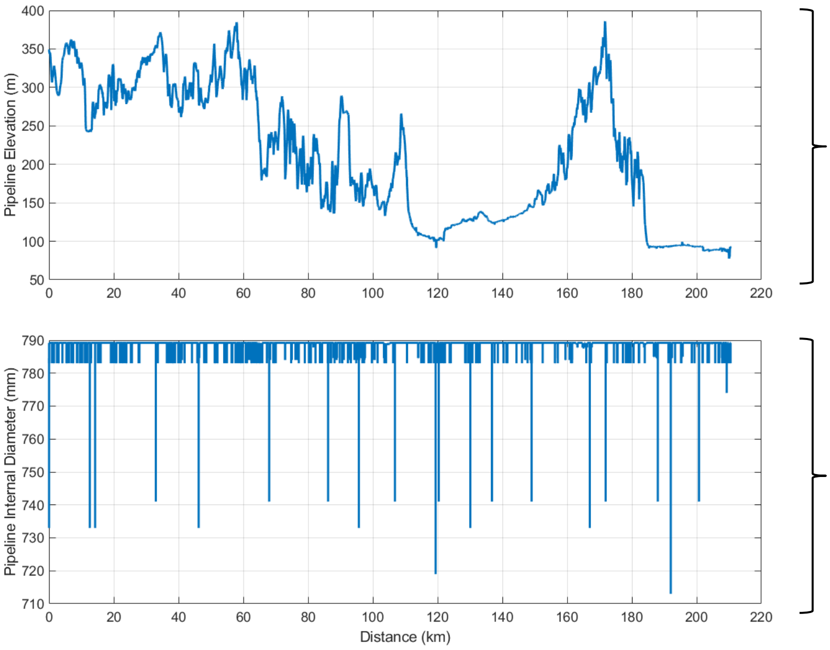


Small change in elevation, ~16 m.

Changes in wall thickness and internal diameter affecting tool DP.

The second line considered is a 210 km, 30-inch line operating at a lower pressure (50 bar) but at circa 1 m/s flow velocity.

Figure 3: 30-inch pipeline elevation and bore map



Hilly terrain.

Changes in wall thickness affecting tool DP at valves, river crossings and bends.

The analysis performed focuses on inspection tools and the following data is used: -

Table 2: Typical ILI tool data

DESCRIPTION	6-INCH DATA	30-INCH DATA
ILI tool mass, *M*	120 kg	2100 kg
Tool DP over ID range	1.5 bar to 2.1 bar	0.25 bar to 0.5 bar
DP in bends	3.6 bar	1.18 bar

4 POSSIBLE SOLUTIONS

Analysis of a complex tool run using a dynamic model allows investigations into aspects that may be too difficult or expensive to trial in the field. This exercise can point to parameters that either help the situation, have no effect or are detrimental to tool velocity stability. For the 30-inch and 6-inch cases, an initial base case was set out for each line. These were based initially on 100% hydrocarbon gas and with 79.8 bara pressure, 0.205 sm^3/sec flow for the 6-inch and 50 bara pressure, 29 sm^3/sec flow for the 30-inch. No bypass was considered and inlet flow / outlet pressure control is utilised.

From this starting point, the percentage hydrogen content (in terms of molar percent) was increased. To control the tool velocity with increasing hydrogen several parameters were investigated: -

1. Effect of line pressure;
2. Inlet and outlet with flow and pressure control;
3. Fixed and active tool bypass control;
4. Variations in tool mass;
5. Using liquid batches with the tool to increase mass and provide hydraulic friction;
6. Reducing tool Differential Pressure (DP) or friction;

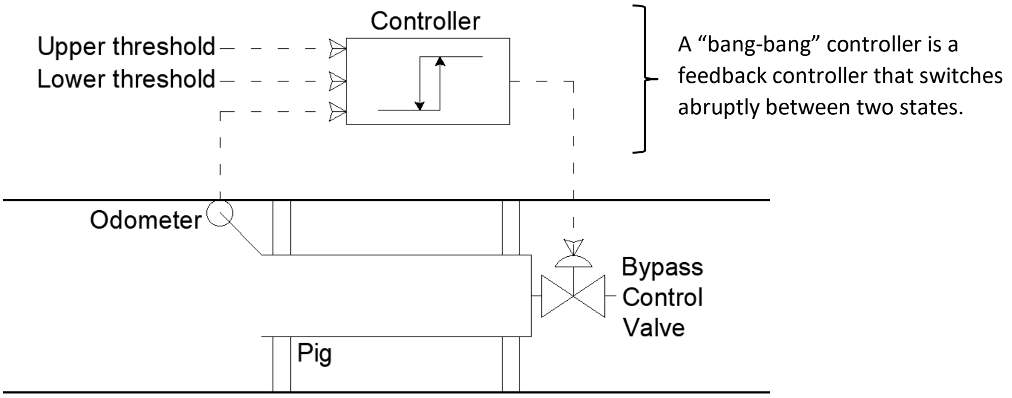
7. Using nitrogen upstream and / or downstream of the tool (with and without batching tools).

Active bypass control was investigated based on an on-off or “bang-bang” system: -

- If the tool velocity increases above an upper threshold, then the control valve opens;
- If the tool velocity is below a lower threshold, then the control valve closes;
- If the tool velocity is between the two thresholds, then the valve remains as it is.

The basic feedback loop is shown below: -

Figure 4: Overview of On-Off or “Bang-Bang” controller for tool velocity control

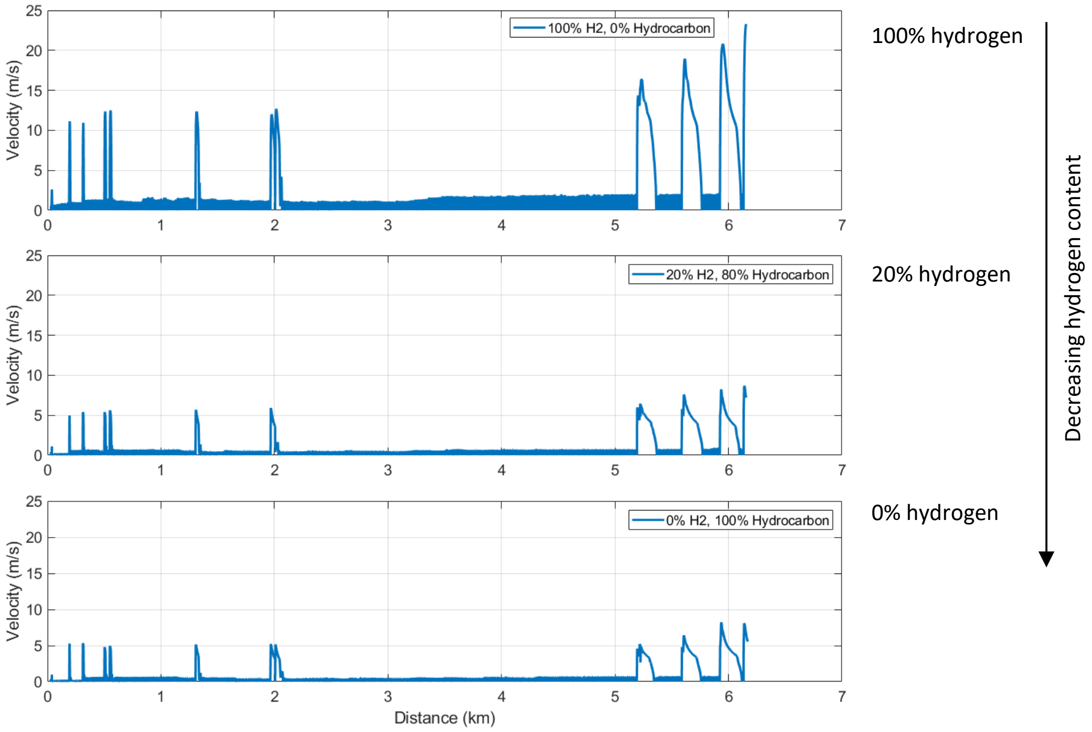


A “bang-bang” controller is a feedback controller that switches abruptly between two states.

5 ANALYSIS

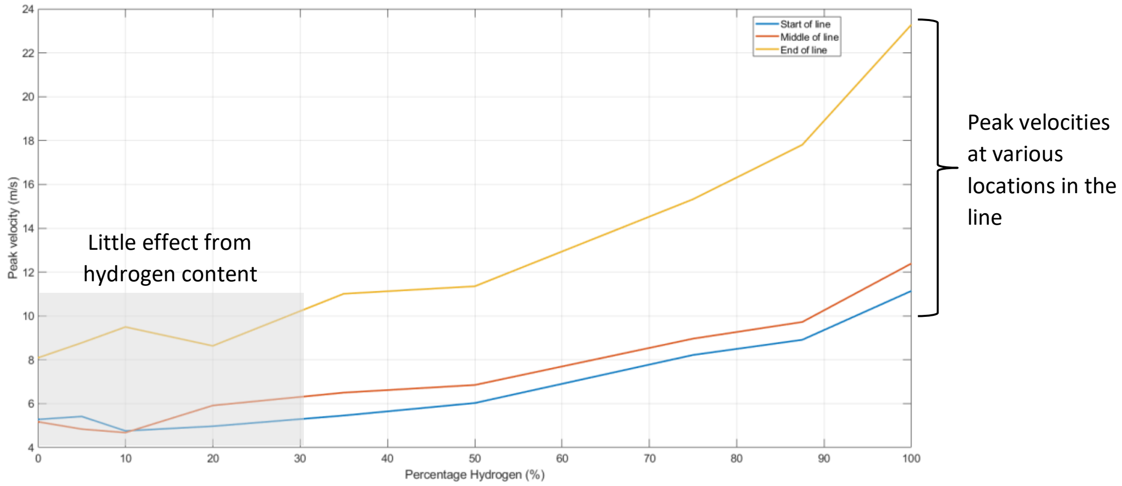
The initial analysis examined the effect on tool velocity of increasing hydrogen content in the 6-inch line. The output is shown here: -

Figure 5: Effect of 100%, 20% and 0% hydrogen content on peak velocity



Peak velocity is plotted against percentage hydrogen and with up to 30% hydrogen, there is little or no effect on peak velocity and no action to control the tool velocity is necessary. This was also evident with the 30-inch line and this is an important conclusion of the work performed: -

Figure 6: Summary of the effect of percentage hydrogen on peak velocities along the 6-inch line

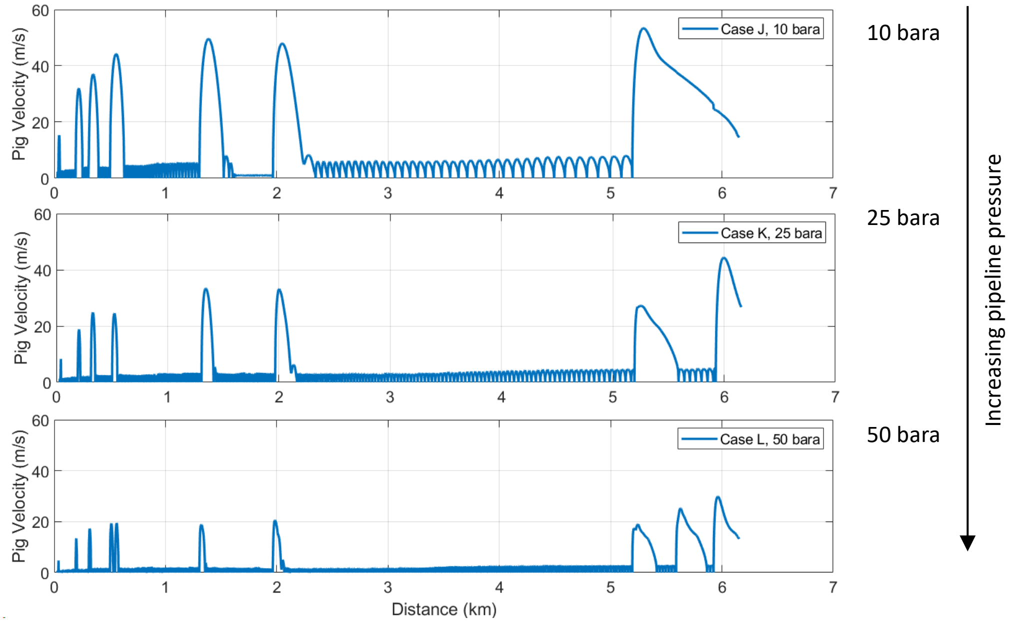


Little effect from hydrogen content

Peak velocities at various locations in the line

Pressure. Attention then focused on controlling tool velocity in 100% hydrogen as a worst case. Increasing line pressure was the obvious initial starting point. As expected, the higher the pressure, the better the tool control. However, it is not always possible to maximise pressure.

Figure 7: Effect of increasing pipeline pressure showing better control at elevated pressures



10 bara

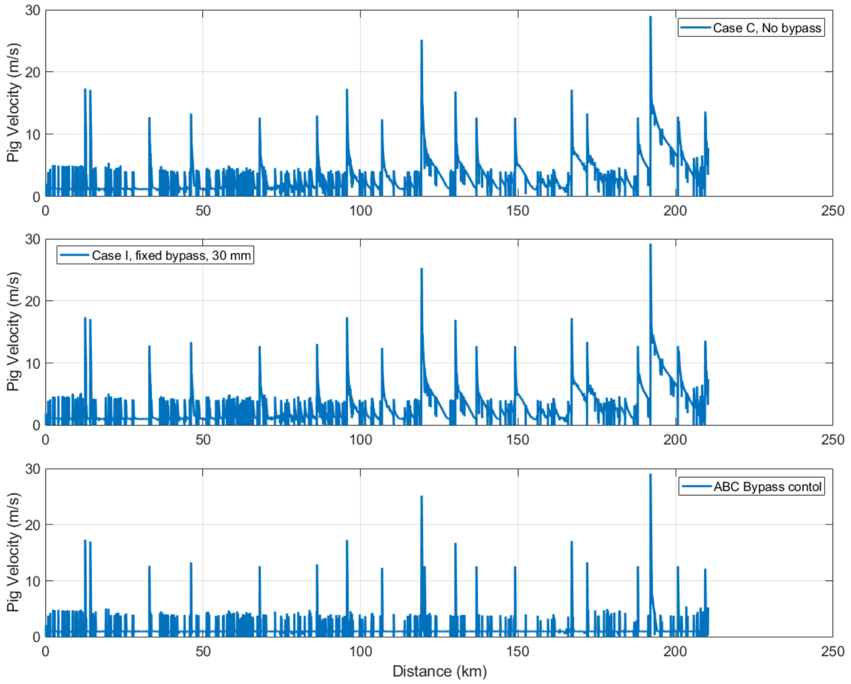
25 bara

50 bara

Increasing pipeline pressure

Bypass. Fixed bypass did not provide much improvement. Bypass size is restricted in hydrogen since the gas density is low and can easily lead to stalling of the tool. The use of Active Bypass Control using an On-Off (or “Bang-Bang”) control system proved useful in the 30-inch line. In the 6-inch line the effect was less pronounced and probably impractical given the difficulty of engineering such a system in a small diameter tool. The output for the 30-inch case with no bypass, fixed bypass and with the actual on-off control is shown below.

Figure 8: Tool velocity profile with no bypass (top), fixed bypass and "Bang-bang" control (bottom). The peak velocity remains high but the duration of the velocity excursions is reduced with bypass control



No bypass

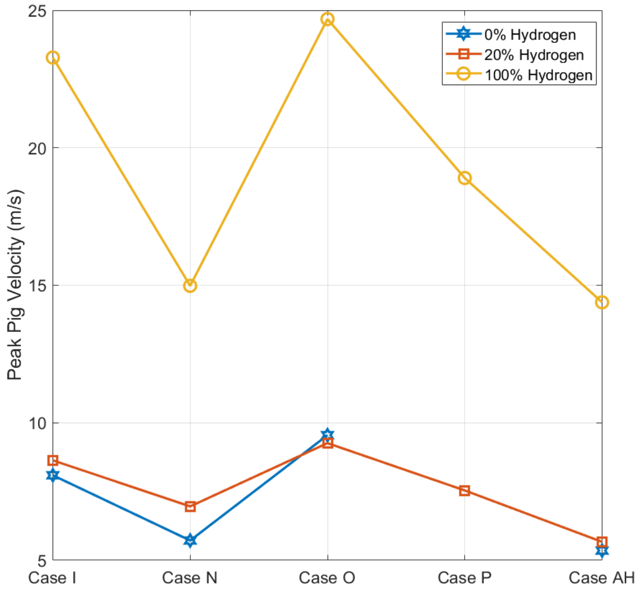
30 mm fixed
bypass

Active bypass
control.

Flow or pressure control. The method of control at the inlet and outlet of the pipeline also proved important for tool stability. Five methods were investigated: -

1. Fixed flow control at the inlet and fixed pressure control at the outlet;
2. Fixed flow control at inlet and outlet;
3. Fixed pressure control at inlet and fixed flow control at the outlet;
4. Flow control at the inlet and alternating between pressure and flow control at the outlet;
5. Flow control at inlet and fixed pressure control at outlet but with an orifice plate upstream of the flow controller (1 bar pressure drop at normal flow).

Figure 9: Peak tool velocity against control method



Flow and pressure control:

Case I, Flow in / pressure out;

Case N, Flow in / flow out;

Case O, Pressure in / flow out;

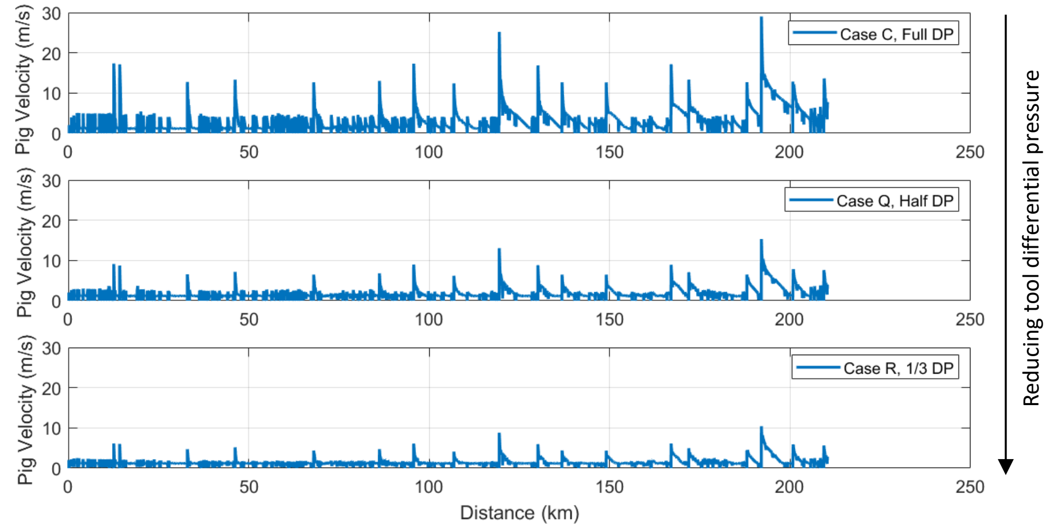
Case P, Flow in / alternating flow and pressure out;

Case AH, Flow in / pressure out with orifice plate

Control of inlet and outlet flow is the best way of helping the velocity of the tool. Pressure control keeps pressure downstream of the tool constant but does not stop high gas velocity and hence high tool velocity.

Tool Differential Pressure. The design of the tool also influences stability. Velocity excursions result from changes in tool differential pressure from feature to feature. Pressure energy is changed to kinetic energy and if the tool DP is reduced, steadier motion would result. In an idealised case where a tool runs at almost constant zero differential pressure, then there is less stored energy and few changes to cause acceleration. Any efforts that can be made to reduce the tool differential pressure and the change in differential pressure between features and pipe spools (the “delta delta P”) will aid stability. This is evident from the following plot showing how peak velocity reduces with reducing tool DP: -

Figure 10: Summary of effect of reducing tool DP



Batching. Finally, inclusion of batches of denser fluids upstream and downstream of the tool are considered: -

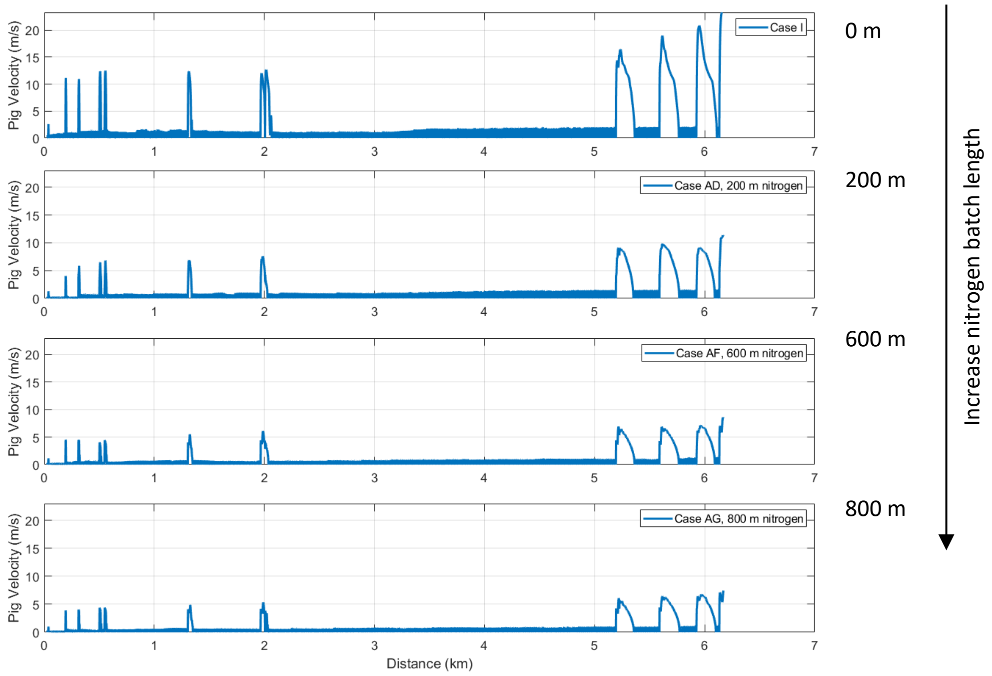
1. Batching a liquid either side of the inspection tool with batching tools;
2. Batching a denser phase gas such as nitrogen either side of the tool with batching tools;
3. Using a denser phase gas such as nitrogen upstream and downstream, without batching tools.

The first approach provides good dampening as the liquid hydraulic losses and the addition of mass to the system provide a reduction in acceleration and a braking system for the tool train. High velocity with a liquid batch causes a back pressure and hence acts to slow the system down, especially for small diameters. On the downside, it means stopping production while the tools and liquid (diesel or MEG for example) are loaded into the line. There is also the problem with having residual liquid remaining and disposal at the receipt end.

Use of nitrogen for example with batching tools also means shutting down production of hydrogen while the batches are established. The denser phase gas does aid velocity control but another problem is observed – there are now at least three tools in the line and every feature results in three velocity excursions rather than one. The velocity of each tool affects the velocity of the others – if one tool stops, then they all stop while pressure builds up.

Using nitrogen without batching tools means that hydrogen can still be produced but mixed with the new gas used to increase density. Based on the earlier conclusion that if the hydrogen molar percent is less than 30%, then there will be sufficient density to aid tool control. Some mixing of the hydrogen into the batches is expected but evidence from pre-commissioning tool runs shows that it is acceptable. More work is necessary to confirm this but the effect on tool velocity is shown in the figure below: -

Figure 11: Reduction in velocity as nitrogen is injected upstream and downstream of the tool



6 FINAL OUTPUT

Based on the analysis performed, to control tool velocity and make the tool run stable with high hydrogen content (greater than 30% on a molar basis), then the following aspects appear to help: -

1. Inlet and outlet flow control (or outlet pressure control with orifice plate);
2. Reducing tool DP as low as possible;
3. Batching the ILI tool in nitrogen (with no batching tools).

For the 6-inch and 30-inch cases, the comparison between no corrective action and implementing these three solutions in combination is shown in the velocity profiles below. The output shows a marked improvement in tool behaviour, velocity and stability. Flow control allows the boundary velocities to be fixed. Reducing the tool DP means that there is less energy available for velocity excursions. In this instance, the tool DP was reduced to a third of the original value for all spools. Finally, provision of an 800 m nitrogen slug upstream and downstream of the tool provides higher density while the hydrogen upstream and downstream of this has a high speed of sound which can transmit pressure signals rapidly along the line. The combination of these leads to much improved speed control.

Figure 12: Worst case 6-inch velocity in blue with corrective action plotted in red

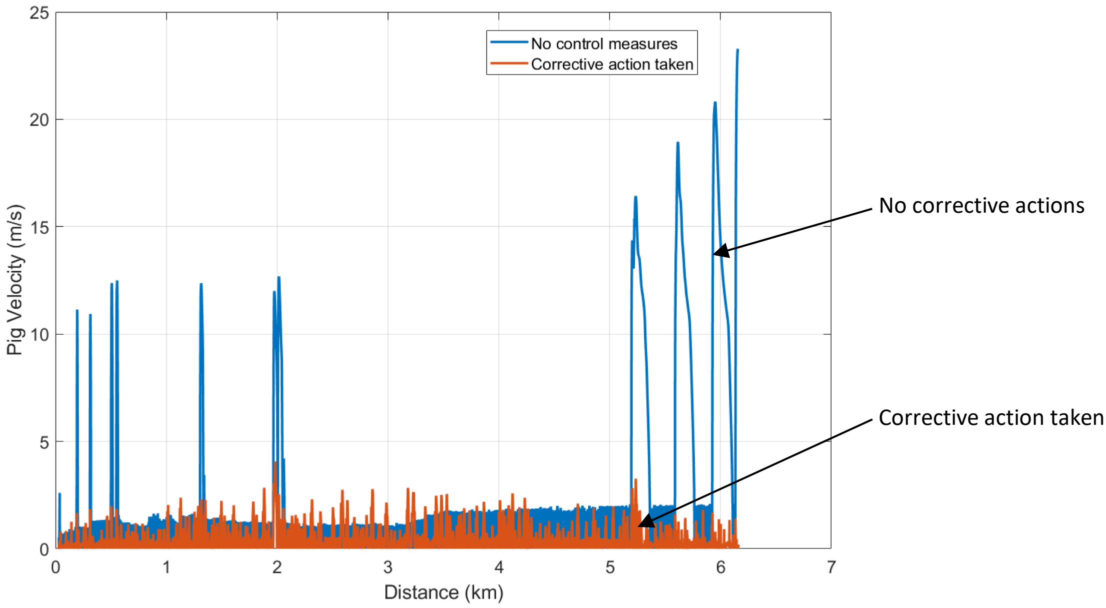
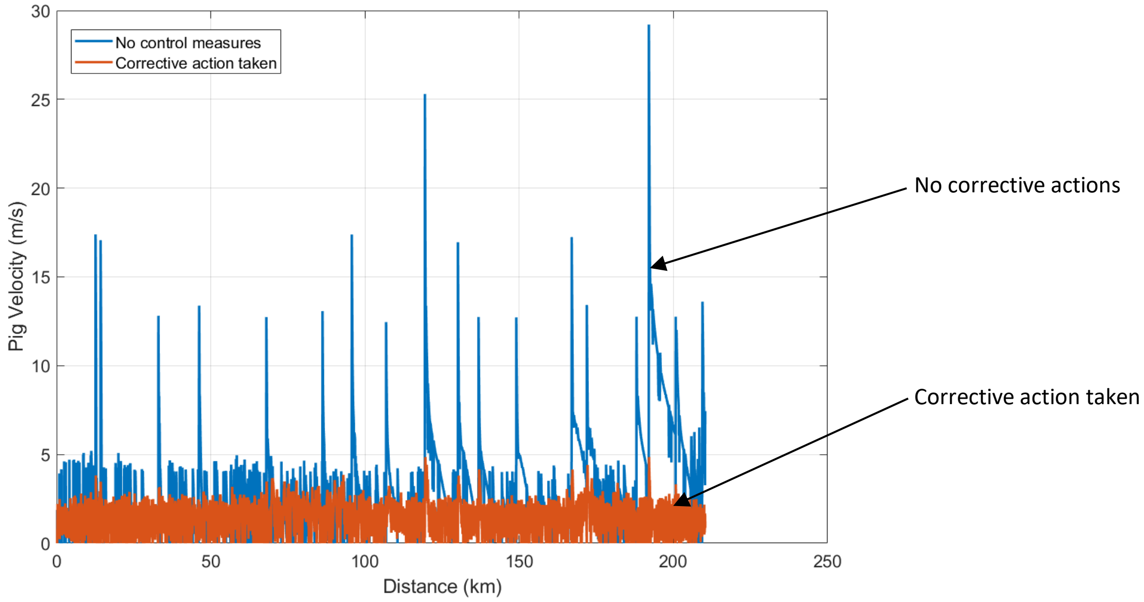


Figure 13: Worst case 30-inch velocity in blue with corrective action plotted in red



Flow control at both ends of the pipeline may require improved instrumentation and control systems. The ability to reduce the tool differential pressure is a challenge to the tool and ILI vendors. There may be a limit to how much this can be achieved. Use of wheels, reduced contact between magnets and sensors on the pipe wall with judicious selection of seals and drive cups can help. Batching nitrogen either side of the tools (or just downstream) relies on the ability to keep this nitrogen intact and to limit mixing with the hydrogen. This research demonstrates that so long as there is less than 30% hydrogen in the mix, then the system should work reasonably well.

Active bypass control could also aid with the 30-inch case but this was not included in these final runs. Sources and sinks of gas along the route and major changes in diameter (dual and multi-diameter tools) will provide further challenges to the tool control but fine tuning the solutions outlined above in combination with special arrangements for ILI runs could provide a starting point for this challenging problem.

7 SUMMARY

The following conclusions are made based on the analysis performed: -

- If the molar percentage of hydrogen is less than 30% in a denser gas, then there is limited effect on the tool velocity peaks and appears no worse than with 100% of the dense gas;
- Active Bypass Control is a useful method of controlling the duration of velocity excursions (peak velocity remains high) in larger bore pipelines assuming it is reliable;
- Optimising the design of tools to reduce the tool differential pressure (DP) and the differential pressure change between features ("delta delta P") is a good step to aiding velocity control;
- Provision of flow control at the inlet and outlet of the line aids velocity stability;
- Batching nitrogen upstream (and downstream) of the tool will aid stability given denser gas immediately adjacent to the tool while maintaining the high velocity of sound associated with hydrogen to transmit pressure signals efficiently along the line. The ability to maintain a batch without batching tools requires confirmation;
- The combination of these techniques appears to provide effective control at this stage.

The study performed in this phase of the POF investigation is largely theoretical to establish what does and does not help the problem. Real world effects such as large diameter changes, inlet and outlet flows along the pipeline, mixing of dense gas and hydrogen and so on also need to be considered. It is likely that this will be on a pipeline-by-pipeline basis but the model does allow such effects to be taken into consideration. In addition, it is planned to provide an overall guideline in terms of line pressure, flow velocity, hydrogen content, line diameter and percentage diameter change for example to let the operator know when such corrective measures are necessary.

The authors would like to thank the Pipeline Operators Forum for their advice and permission to produce this paper. It is hoped that this will provoke discussion and further investigations to aid inspection of hydrogen pipelines.