PIPELINE PIG MOTION AND BEHAVIOUR IN PURE HYDROGEN AND HYDROCARBON / HYDROGEN MIXTURES

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A study has been performed to examine how an inline inspection (ILI) tool would behave in a pipeline with pure hydrogen and with a mixture of hydrocarbon gas and hydrogen (25%, 50%, 75% and 100% hydrogen). The study examines two general effects - pig velocity excursions due to low gas density and possible leakage past the tool. Certain aspects of the pig design are also included such as mass and frictional resistance. To illustrate the various responses, a case study based on a 16-inch, 116 km landline is presented. It is currently being considered to use this line for hydrogen transport and the requirement was to assess the pig behaviour. As well as velocity, an outline pig verification program is presented with a discussion on how the tests should be performed for piggability and leakage assessment.

INTRODUCTION

Hydrogen is likely to be one part of a greener future in combination with other green technologies and existing fossil fuels at least in the near term. Burning hydrogen only produces water vapour and this is an important step in emission reductions. Since hydrogen does not exist in a natural state, how the hydrogen is produced will determine its green credentials – if formed from water or electrolysis, then when using renewable energy, this is close to zero "carbon intensity" whereas if formed from hydrocarbons, it is less than that of the natural gas but certainly not zero [1].

Transportation of hydrogen efficiently using existing gas infrastructure is an attractive prospect either as 100% hydrogen or in a mix with natural gas. Such pipelines will still require inspection and servicing and as a result pigging will be required. At atmospheric pressure, hydrogen is very light and even at high pressure, the density is much less than that of natural gas. Since pig motion in gas pipelines rely on pressure (or more specifically density) to dampen the motion and keep speed under control, then pig motion in hydrogen lines is likely to be less controlled. Barker provides a good example in his paper of high peak velocities during inspection of hydrogen lines with an MFL tool (Magnetic Flux Leakage) [2].

A study has been undertaken and the initial results are published in this paper. Several aspects of pigging in hydrogen have been examined but only velocity and leakage are covered in this paper. Wear and material selection are not presented at this stage. Firstly, a description of the pig motion model (PIGLAB) is provided.

PIG MOTION MODEL

To determine the gas behaviour upstream and downstream of the pig or indeed with no pig in the system, it is necessary to solve a couple of Partial Differential Equations (PDEs), namely the continuity and momentum equations. These equations couple pressure and gas velocity and allow their variation with distance and time to be calculated.

Solving for pressure, p and gas velocity u in space (x) and time (t) enables the behaviour of the gas upstream and downstream of the pig to be determined. Inlet and outlet boundary conditions set the incoming flow rates and pressures for the line but can also change with time. This upstream and downstream pressure around the pig can be determined.

An overview of the pipeline in question is as shown below. The elevation profile of the line against distance and the pig differential pressure against distance are inputs in the form of a data file: -

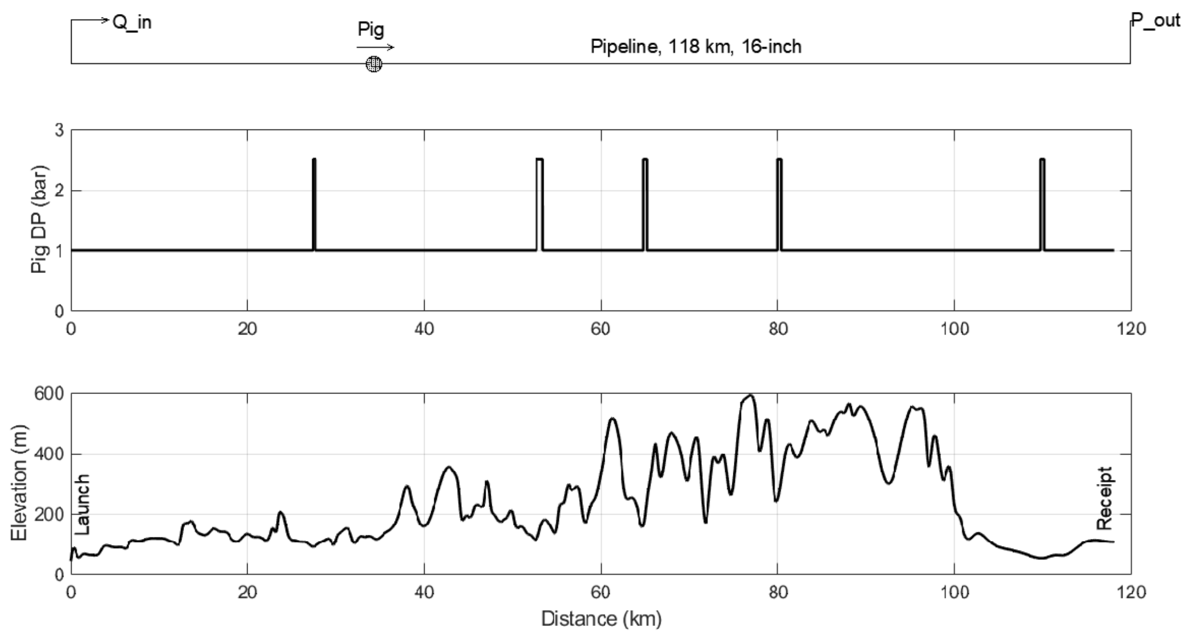

Figure 1 – Model used for dynamic pigging. The line is 16-inch and is 118 km in length. An inlet flow is provided and the outlet pressure is controlled. The middle graph shows the pig differential pressure along the pipeline (an input file). The nominal pig Differential Pressure (DP) is 1 bar but with 2.5 bar at river and road crossings due to thicker walled pipe. The pipeline elevation profile is shown on the lower graph.

CASES

It is assumed that an ideal mixture of the hydrogen and hydrocarbon gas occurs and that the specific gravity and molecular weight are based on a combination of the gas properties [3]. This is a realistic starting point. The base case input for the pipeline is as follows: -

- 100% Hydrogen;
- 50 bar outlet pressure;
- 500 kg pig mass;
- Inlet velocity is 2 m/s and for the sake of this study, the flow is adjusted such that this is the maintained for all cases considered to facilitate comparison.

The following cases are then examined using the model: -

<u>Effect of hydrocarbon content</u>

A. BASE CASE: 100% hydrogen, 50 bara outlet pressure, inlet flow of 1 Sm^3/sec with 500 kg pig mass;
B. 75% hydrogen, 25% hydrocarbon gas;
C. 50% hydrogen, 50% hydrocarbon gas;
D. 25% hydrogen, 75% hydrocarbon gas;
E. 100% hydrocarbon gas.

<u>Effect of pipeline pressure</u>

F. Reduce outlet pressure from base case to 25 bara;
G. Increase outlet pressure to 100 bara;
H. Increase outlet pressure to 150 bara.

Effect of pig mass

I. Increase pig mass to 1000 kg;
J. Increase pig mass to 2000 kg.

Use of Speed Control

K. Speed control with speed set to 2.5 m/s peak;
L. Fixed bypass with 2 x 20 mm bypass ports.

The base case output and sensitivities are presented below.

OUTPUT

Initially, the model is run to achieve a steady state as an agreed starting point for the analysis. Although transient events are allowed during the pig passage, for comparison's sake in this analysis, the only transience introduced was the passage of the pig.

Steady State

The graph shows the steady state velocity and pressure profile along the pipeline route with no pig running in the line. The pipeline elevation profile shows some hilly regions in the latter half of the line but the height is low overall.

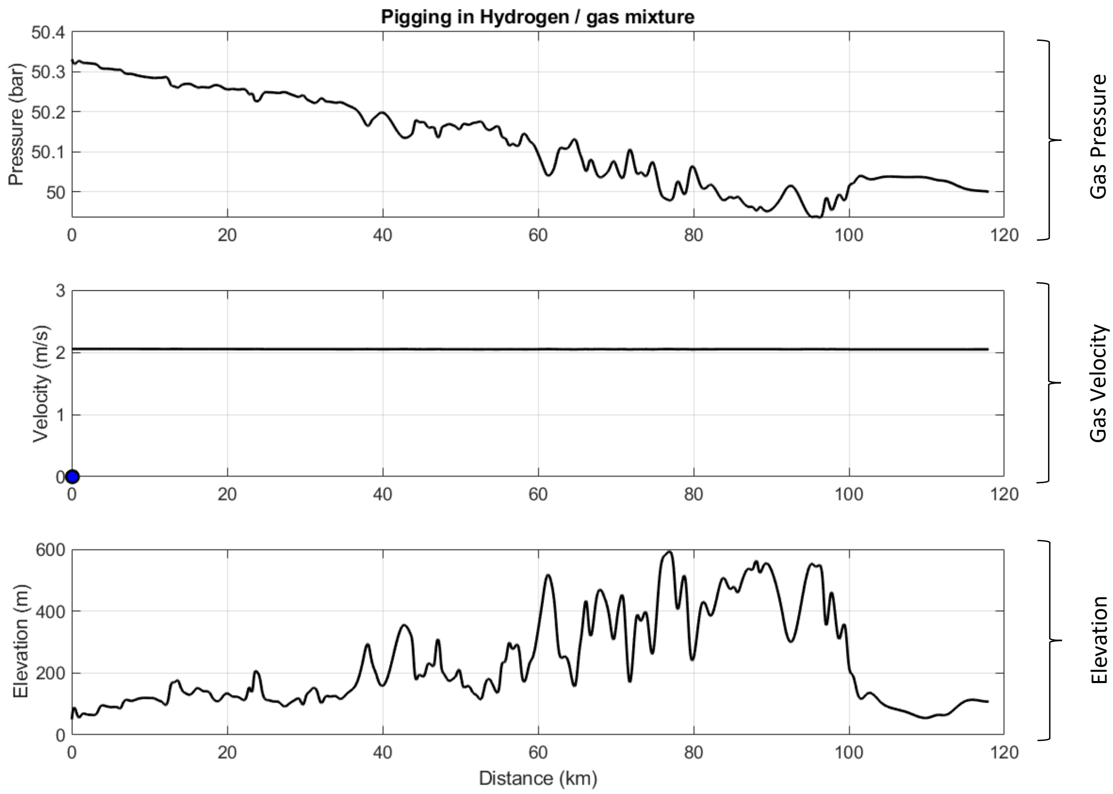

Figure 2 – Steady state output with pressure (top), gas velocity (middle) and pipeline elevation profile (bottom).

Note that this profile is with 100% hydrogen.

Base case output

Initially, the pig is run with 100% hydrogen and at 50 bara outlet pressure to give a velocity profile to compare other analyses against. The output is shown below: -

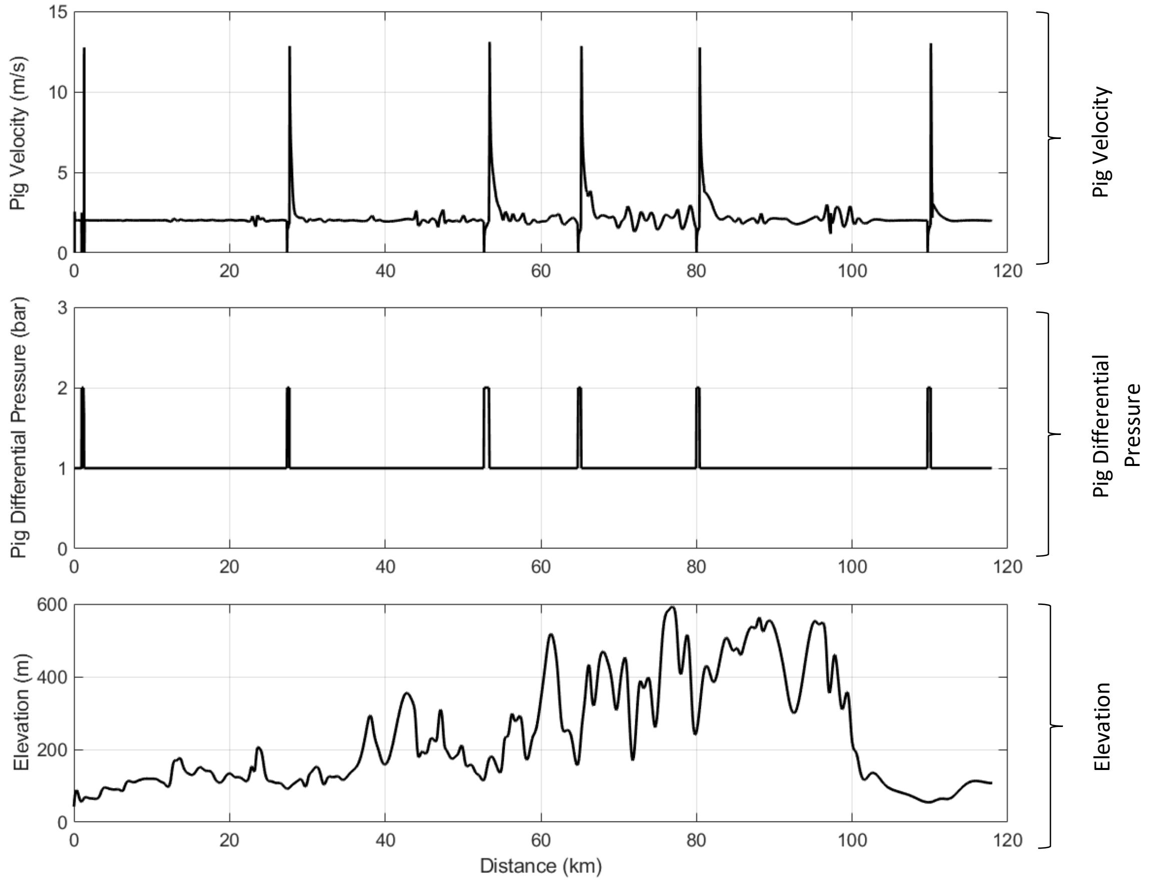

Figure 3 – PIGLAB output for the base case 500 kg pig run in 50 bars pure hydrogen. The top graph shows the pig velocity profile along the route. The middle graph shows the pig differential pressure with peaks at the river and road crossings. The lower graph is the line elevation profile.

In general, the pig velocity remains at circa 2 m/s for most of the run. This is due to the steady differential pressure. In the real world, small changes in friction could be expected between one spool and the next or at the welds – this could also be included in the model but is omitted at this time for clarity.

As the pig enters the tight location (thicker walled pipe) at the road and river crossings, then the pig stalls (for example at Kilometre Point, KP 53) since additional pressure is required to build up. When sufficient pressure is available, the pig moves and once clear of the thick-walled pipe, this additional pressure energy must be dispelled. This is in the form of an acceleration or a velocity excursion. The peak velocity recorded was 13.2 m/s (43.3 ft/sec). For an inspection pig this can mean loss of data and possible damage (to the pig or pipeline).

The velocity excursion is marked by a rapid increase in velocity to a peak and then a slower decline back to nominal flow velocity. The peak velocity is a function of line pressure or density – the higher the density, then the lower the peak velocity as it acts as a dampener. The elevation profile has a small impact on the pig velocity but some fluctuations are noted which tie up with steeper inclination, for example from KP 96 to 100.

Effect of Hydrogen and Hydrocarbon Content

The base case is with 100% hydrogen. A further four cases were examined with reducing hydrogen content and increasing hydrocarbon gas content (mainly Methane). All other aspects were kept the same and the flow rate was altered slightly to maintain a nominal 2 m/s flow speed.

The output is shown below: -

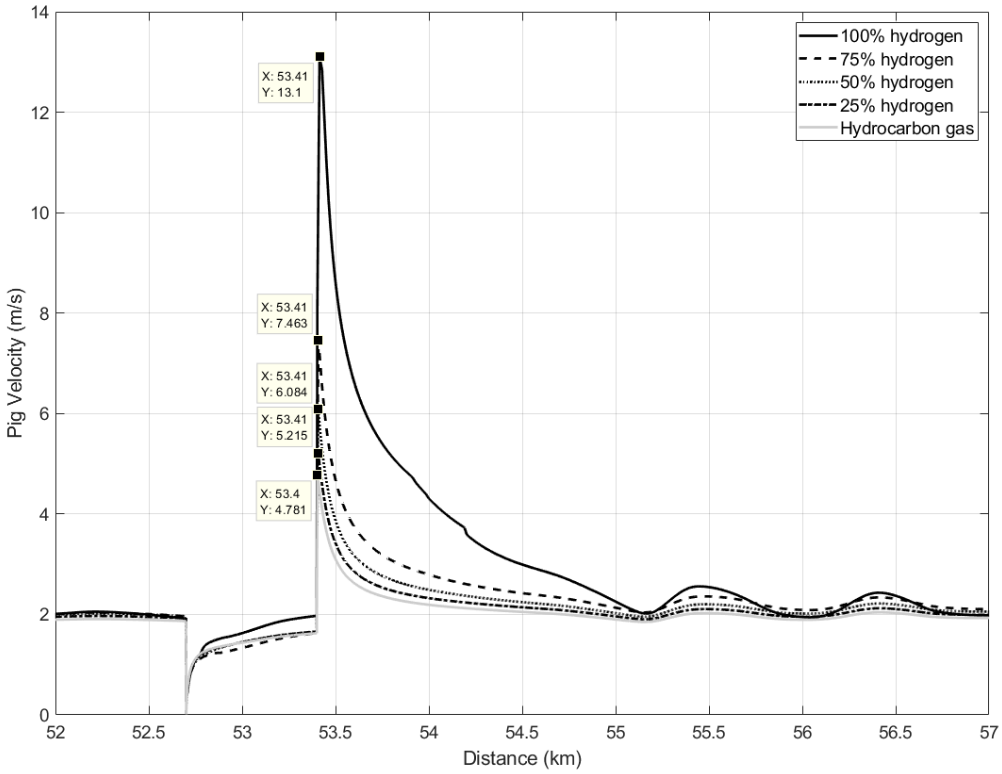

Figure 4 – Reduction in peak velocity (labelled) at KP 53 as the line is run with increasing hydrocarbon gas content. The hydrogen content results in a less dense gas and less control on the pig speed.

Hydrogen has a low molecular weight and low density. For example, at 50 bara and 10 degrees C, the density of 100% hydrogen is 4 kg/m^3. In comparison, the density of hydrocarbon gas at the same conditions is circa 45 kg/m^3. Since the density of the gas acts as a damper to the pig motion, then the dampening is lower with hydrogen and higher velocities are achieved as can be seen in the graph.

The peak velocity in this case is over 13 m/s against a peak with 100% hydrocarbons of 5.6 m/s. If the maximum permitted velocity for the inspection technique is 4 m/s for instance, then the hydrogen case will exceed this for 0.7 km in the output shown compared to 25 m for the hydrocarbon case in Figure 5. For this reason, other steps may be required to get a full and complete inspection of the pipeline to ensure safety.

Effect of pipeline pressure

In general, the higher the pipeline pressure, then the more controlled the pig motion. The analysis is repeated with 100% hydrogen but with 25 bara, 50 bara, 100 bara and 150 bara line pressure: -

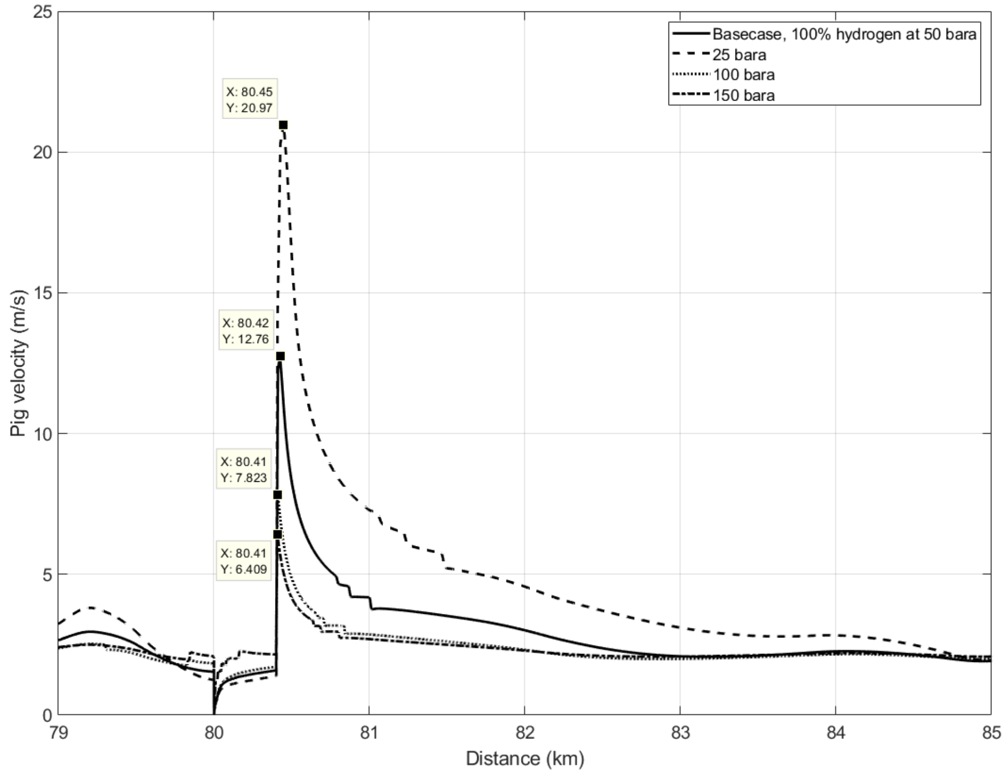

Figure 5 – Due to low pressure, the velocity excursions at 25 bara are extreme – up to 21 m/s. Pressure helps to control this with 150 bara reducing the peak to 6.5 m/s. The data is shown at KP 80 this time.

It may be necessary to stipulate a higher minimum operating pressure for pigging with hydrogen. Increasing pressure reduces the peak velocity. Indications are that there will eventually be limited returns with a peak of 7.8 m/s at 100 bara and 6.4 m/s at 150 bara for example. The lower pressure does give cause for concern. It has also been observed that elevation slope has more effect on velocity at low pressure whereas it is negligible at high pressure.

Effect of pig mass

A further sensitivity has been performed using the pig mass. The base case is with a pig mass of 500 kg (a relatively light inspection tool for instance). Two further runs with 1000 kg and 2000 kg have been examined: -

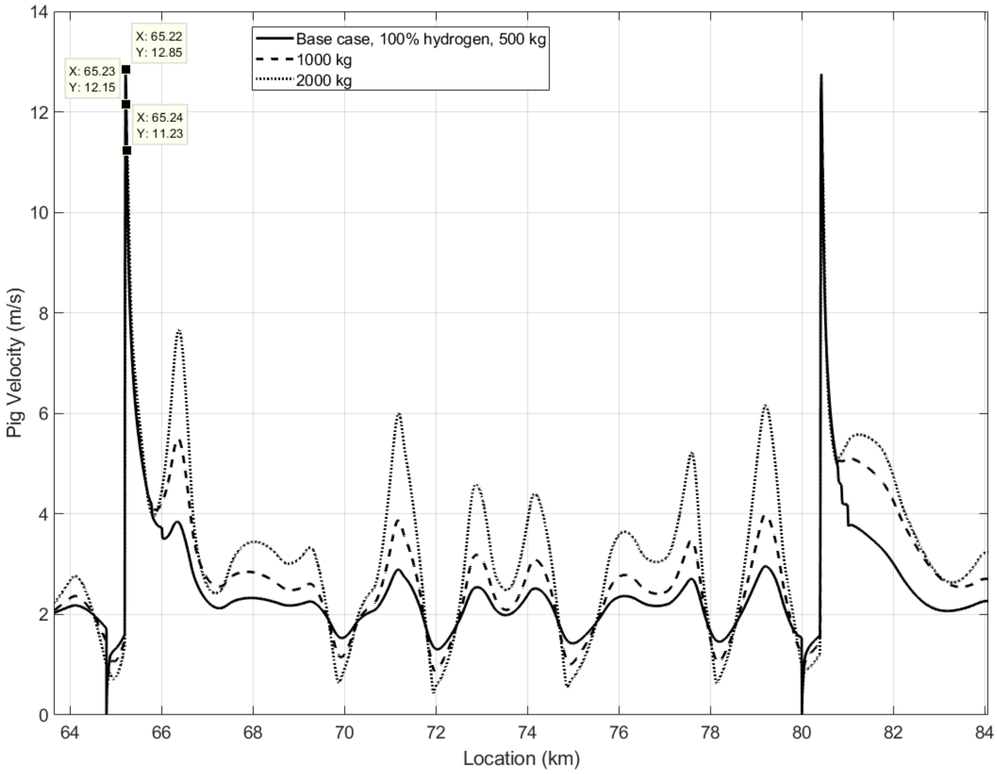

Figure 6 – Heavier pigs take longer to reach a peak velocity. In this time, the line pressure adjusts and adds dampening making the peak velocity lower than for lighter pigs. The elevation profile of the line makes the heavier pig motion more erratic.

Use of bypass
Since the hydrogen is less dense, there is a possibility of higher leakage or that more gas will pass through than expected with bypass pigging. This presents a possible risk of stalling but also presents an opportunity for speed control. Speed control valves could provide a reasonably efficient way of controlling the speed of the pig even with modest pig differentials. Note that *leakage* is defined as undesired flow of fluid past the pig whereas *bypass* is a desirable or deliberate flow of fluids through the pig. This needs to be weighed against the risk of stalling due to excess flow through the pig: -

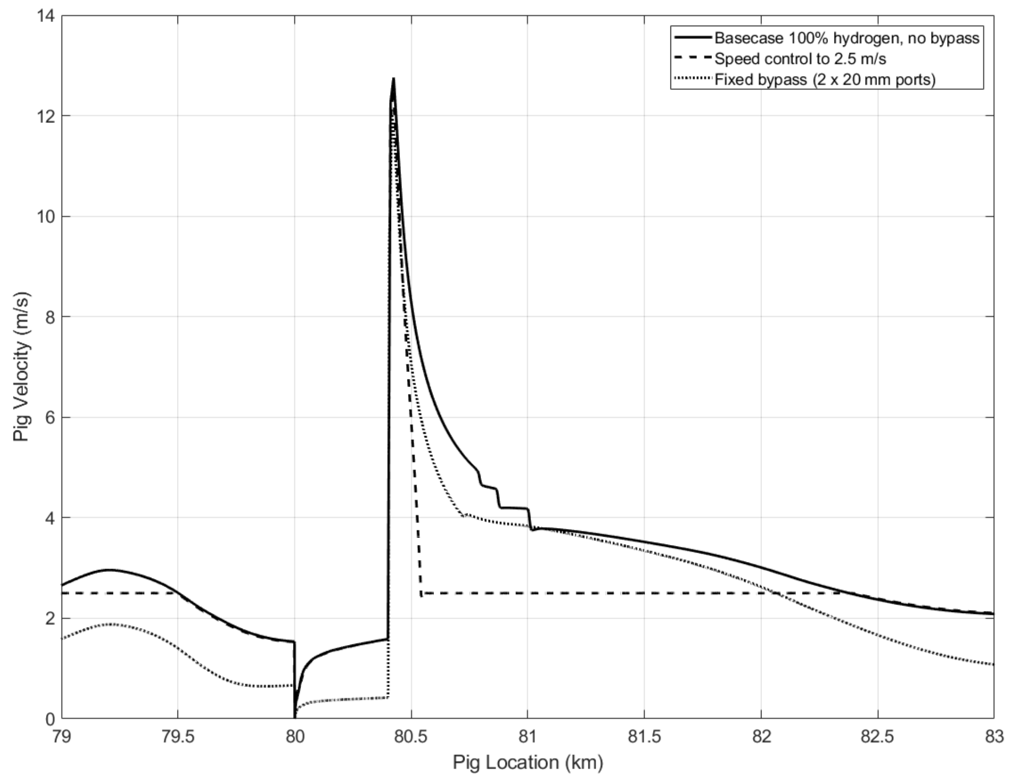

Figure 7 – Modest fixed bypass can result in a large percentage bypass by flow. Pigs need to seal well for use in hydrogen – to guard against leakage and stalling. The ability to control the pig velocity may be possible with active bypass control (using a control valve and feedback loop).

It is not possible to remove the velocity excursion completely as the acceleration takes the pig to high velocity before any control system has a chance to react. Nevertheless, the length of time that the pig is above undesirable velocity is reduced using active bypass.

The risk is excessive bypass due to the low density of hydrogen. For a modest fixed bypass, the steady state bypass by flow percentage is 50%. This makes the bypass in the road crossing very high (circa 80% by flow with a subsequent risk of stalling). An equivalent case with 100% hydrocarbon gas would only result in 15% bypass by flow. Care must be taken with leakage and bypass when working in hydrogen and the next section of this paper suggests how this might be tested.

LEAKAGE PAST THE PIG

Since hydrogen has a low density, it is possible for it to leak past small gaps and openings. This is especially true for the pig seals – given the differential pressure across the pig then any small leakage path or weakness in the sealing system can lead to a potential loss of drive. To avoid problems when pigging, it is required to test the pigs to ensure that the leakage paths are not excessive. Since pig testing is normally performed using water, then there is a mismatch given the high density of water compared to low pressure hydrogen. Although testing with gas is possible, it is seen as difficult and expensive and it is not easy to get meaningful results as the test is performed in a closed loop.

To overcome this issue during tests, it is recommended to do the following: -

- Leakage with water drive during testing will become more of an issue at low velocity. A scaling factor can be used to determine the correct velocity with water to mimic the conditions in the actual pipeline. The following is suggested: -

  $$V_{water,test} = V_{hydrogen,pipeline} \sqrt{\frac{\rho_{gas}}{\rho_{water}}}$$

  Where: -

$V_{water,test}$	=	Equivalent test velocity using water drive;
$V_{hydrogen,pipeline}$	=	Expected flow velocity in the hydrogen pipeline;
ρ_{gas}	=	Density of hydrogen in the pipeline;
ρ_{water}	=	Density of water.

  The following graph provides an example: -

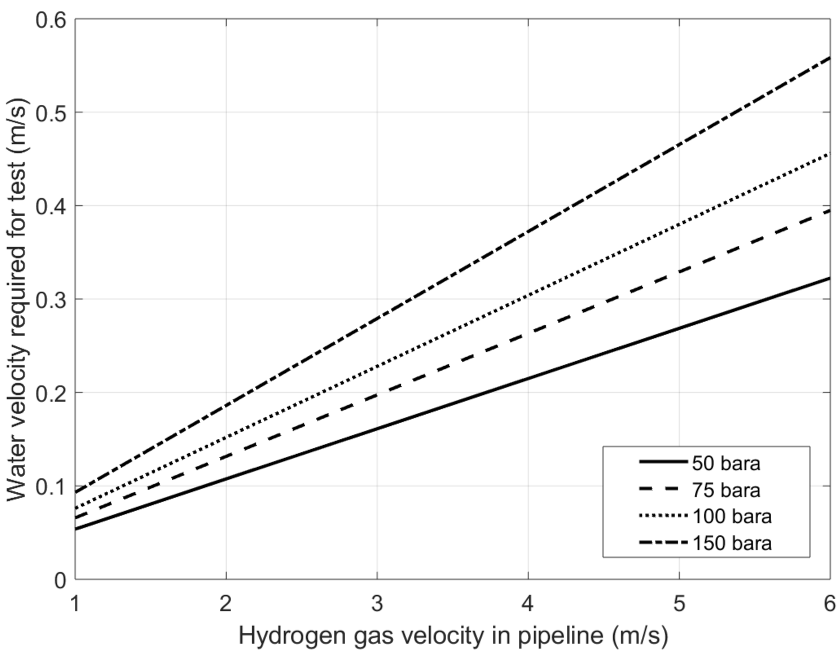

Figure 8 – Curve for equivalent water velocity for test against actual expected pigging velocity in the pipeline. For instance, if the pig is expected to move at 3 m/s in a 100-bara hydrogen line, then the tests should be performed at 0.3 m/s or less.

- Any leakage paths through the pig body during the tests can be eliminated using silicone sealant and capping off bolts once the final pig configuration is determined;

- Testing should be performed open ended to get a clear view of the front of the pig and assess visually any leakage. The aim should be for no visual leakage (with bypass blocked to assess any leakage). Open ended tests require that any air is vented from the pig launcher prior to commencing the tests. If this is done, then the pig should be under control and can be assessed by photographs, visually and using a video camera.

Figure 9 – Still from video of open-ended test showing pig negotiating a bend and leakage through the pig body and bolts. This leakage would be difficult to measure using a flow meter and pig signallers due to errors.

Wear of sealing discs and components may be a root cause of leakage which may not be apparent until the pig is run in the line. Since the hydrogen is expected to be dry and not provide any lubrication for the seals, then this is another aspect that needs to be considered.

SUMMARY

Initial output from a review of pigging in hydrogen pipelines shows that pig motion can be more difficult to control because of the low gas density. Minimum operating pressures may have to be higher or use of tools with lower pig DP and changes in DP (a "lighter touch") would be advantageous.

The consequence of increasing hydrogen content produces peak velocity excursions up to three time that of a 100% hydrocarbon line equivalent. This can damage to the tool or the pipeline. An assessment of velocity must be included in any risk evaluation. Higher pressures can aid the situation but may not be possible. Bypass has the potential for reducing tool speed as the lighter hydrogen gas can pass through the pig efficiently. This makes speed control a possibility even on low friction tools.

This indicates another problem that needs to be considered carefully. Low density means that gas can leak past the tool and cause the pig to stall in the line. Any bypass through the pig must be carefully engineered and other possible leakage paths eliminated. Testing at low velocity and open ended with water is an effective method to understand the problem and make the pig work as required. Other factors such as wear and material selection required to be understood but are not included in this paper.

[1] Injecting hydrogen into the gas network, a literature search, UK Health and Safety Executive, RR1047, 2015;

[2] HyDeploy: The UK's First Hydrogen Blending Deployment Project, Journal of Clean Energy, Vol 3 Issue 2, June 2019;
[3] In-line Inspection Tool Design and Assessment of Hydrogen Pipelines, Tod Barker, TD Williamson, PPSA Seminar 2020;
[4] Thermodynamic and transport properties of hydrogen containing streams, Aliakbar Hassanpouryouzband, Edris Joonaki, Katriona Edlmann, Niklas Heinemann, Jinhai Yang, Nature.com