Project report

Transportation of Debris by Hydrogen Flow inside PE Pipelines

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A consolidated summary report by Steer Energy Solutions Ltd

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SGN

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Document control

Version

Version	Status	Date	Author(s)	Summary of Changes

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1. Introduction

1.1. Executive summary

SGN commissioned Steer to provide a short overview of how Hydrogen is likely to transport the current debris found inside pipelines compared to Natural Gas, how this relates to erosional velocity. New pipe systems in which there is negligible construction debris, and which are fed by clean dry hydrogen, such as SGN propose under Methilltoune and H100 will not be exposed to the appreciable effects of debris mobilisation, erosion and deposition.

This work was undertaken over a 3-week period and restricted itself to desk-based analysis of the situation. The theory used has been developed from wind-blown transportation (i.e. sand dunes), river hydraulic research, high-fraction pipeline conveyance, as well as “rules of thumb” developed by the oil and gas industry. There should therefore be a reluctance to accept the findings of this work based on the theoretical work, and Steer would recommend that a number of exploratory experimental tests be carried out in the short term in order to validate the indications from this work.

This work indicates that the “erosiveness” of debris carried by Hydrogen when compared to Natural Gas is affected by two key components:

- The relative gas flow velocity
- The relative mass flow rate of the debris (how much dust can be transported by the gas).

The relative gas flow velocity for Hydrogen is calculated to be up to 3.5 times that for Natural Gas due to the decision to run with equal calorific value and maintaining the same pressure. This therefore increases the likelihood of erosion. It should be noted however that the operating pressure limits of the pipe may prevent this increased velocity being reached and the same calorific delivery being achieved.

This theoretical work would therefore indicate that when moving from natural gas to Hydrogen:

1. The propensity to initiate particle motion and to pick up particles (Shields Parameter, Rizk) would be greater, but that particles would then be more likely to drop out of the flow (settling velocity) before again being picked-up and transported (saltation increases).
2. That particles would more likely to be transported as a suspension (Rouse number), but for very fine debris (circa 50µm diameter) the particle suspension may be appreciably lower (Kalman). This is significant because suspended particles will tend to cause more erosion than if they were transported as bedload.
3. The total mass transport of debris would be around 50% lower (Bagnold).

The particle transportation regime will be significantly different for Hydrogen compared to Natural Gas, primarily due to the higher velocities at which it will be flowing. The analysis suggests, with significant reservations over its reliability, that there will be increased wall collisions as the gas is more likely to cyclically pick up and dropout particles, increasing the likelihood of pipe wall erosion.

1.2. Summary of recommendations

It is recommended that exploratory experimental work is carried out on a small scale to re-assess the theoretical indications reported and to support the simulation of network capacity and effective flow velocities under dynamic conditions. This will provide much needed confidence in subsequent estimates of the risks (or otherwise) of erosion within the gas network in the switch to Hydrogen.

1.3. Project background

SGN have commissioned Steer to provide a short overview of how Hydrogen is likely to transport the current debris found inside gas pipelines. This work will therefore explore the differences between natural gas[1] and Hydrogen in pipeline velocity and how this relates to erosional velocity in PE pipes.

Key will be understanding how and when particles are mobilised and deposited. This will allow assumptions to be made on the erosion potential of Hydrogen. The aim is to carry out calculations for conversion to 100% Hydrogen, delivering the same energy as Natural Gas.

This work was undertaken over a 3-week period and restricted itself to desk-based analysis of the situation with a number of significant assumptions having had to be made. It is noted that current academic exploration of the transportation of particles by low density gas flows is particularly limited, and therefore aeolian (wind blow transportation, such as sand particles) and river mechanics theory is used to support the majority of the work.

This is an area of significant complexity and therefore Steer have restricted itself to presenting the overall understanding of the work, and the likely differences that will be observed when changing from Natural Gas to Hydrogen. This builds upon the basic principles of particulate transportation to provide "rules of thumb". Commentary is made on how this affects erosion of the PE Pipe, and what further work to validate the conclusions.

The deliverables for this Project are a short report, alongside an Excel Calculation Spreadsheet.

1.4. Supplier's background and qualifications

Steer Energy is a technology catalyst company that specialises in solving problems by providing novel products and services across a range of diverse sectors and disciplines.

With a strong level of experience at the coal-face of early stage technology development and delivery, Steer Energy seek and support new ideas and technology providers to offer alternative and valuable solutions to complex problems across a range of specialities.

1.5. Project objectives

To provide a short overview of how Hydrogen is likely to transport the current debris found inside pipelines compared to Natural Gas, and how this relates to erosional velocity.

2. Project team structure

Iain Chirnside has over 15 years' experience working in new technology development within the oil and gas, and utilities industries. He provides a blend of real-world entrepreneurial experience, knowledge and understanding of technology company start-ups as well as a significant experience in developing and commercialising pioneering technologies.

[1] Methane properties used as a substitute where values are not received for Natural Gas.

Iain has a MEng (Civil and Structural) from the University of Aberdeen and an M.Sc (New Venture Creation) from Glasgow Caledonian University. He was been involved with research throughout his career, first as a Research Assistant in the Environmental and Industrial Fluid Mechanics Research Group (University of Aberdeen), then commissioning work in his role at Brinker Technology and now Steer Energy.

Iain was awarded a Royal Society of Edinburgh Enterprise Fellowship in 2001, and was a founding member of the Young Academy of the Royal Society of Edinburgh (2011 – 2016). He is a member of the Energy Innovation Centre's Innovator Impact Panel.

Dr Jon Harris joined Steer Energy in January 2015, having previously worked as a subsea systems engineer at BP, and at Shell in a range of subsea roles (largely production operations) for a total of 10 years.

Jon has been involved in both design and operations, working with multiple service companies to get technology working and to keep it working.

His time in oil and gas included:

- Being responsible for subsea integrity management of hydrocarbon systems.
- Flow assurance for subsea separation production systems, including subsea separator gas-liquid performance.

Work in the UK gas industry has included:

- Project managing the workshop and laboratory testing of the 'Ironclad' corrosion-remediation technique for SGN. This involved co-ordinating the work of international collaborators, multiple UK universities and specialist suppliers/consultants.
- Development (with colleagues and client) of the detailed problem definition for improving the tooling available for operators responding to High Volume Gas Escapes (an ongoing NIA funded series of projects for SGN).

Technical, operational and commercial review (with colleagues) of trends in PE pipe joint failures for WWU and NGN. This resulted in a series of recommendations for further work which the clients continue to pursue before further engineering work.

3 Project delivery

The debris currently present in pipes can be approximated as being at an equilibrium state for the current gas composition fluctuating with, for example, flowrate as customer demand oscillates. This equilibrium is a combination of:

- Debris being generated;
- Debris depositing;
- Debris deposited and not mobilizing;
- Debris deposited and mobilizing;
- Debris collecting in intolerable places and being removed by intervention;
- Debris leaving the system in the gas flow.

The approximate equilibrium will shift with a switch to pure Hydrogen. Therefore, there will be debris behaviour for:

- the switch period as a new equilibrium is established;
- a new equilibrium.

The key aim of this work is to explore how debris is likely to be mobilised and then deposited in Hydrogen, rather than in natural gas.

In the worst case, the presence of particles in a pipeline will cause erosion. This is an ongoing process in gas networks, caused by particles (believed to be mainly dust particles) which are carried by the gas flow hitting the pipe wall. The amount of damage each individual particle makes is dependent on factors such as:

1. Pipeline Properties (microstructure, surface hardness, composition, strength);
2. Particle properties (size, shape, density, hardness, friability, strength);
3. Environmental factors (temperature, gas composition);
4. Impact parameters (particle velocity, impingement angle, collision rate).

The focus on erosion, rather than debris being transported relatively harmlessly through the pipes, means that the mobilisation of debris through bed motion (that is, a “bed” of particles moving together) is less of a concern than the direct impingement of particles carried at high speed in the bulk gas flow onto the pipe wall. Note that, in terms of geometry, the erosion of straight pipe sections is not understood to be a serious problem within the gas industry. Rather, erosion occurs most aggressively in pipe bends, tube constrictions, and other structures that alter the flow field.

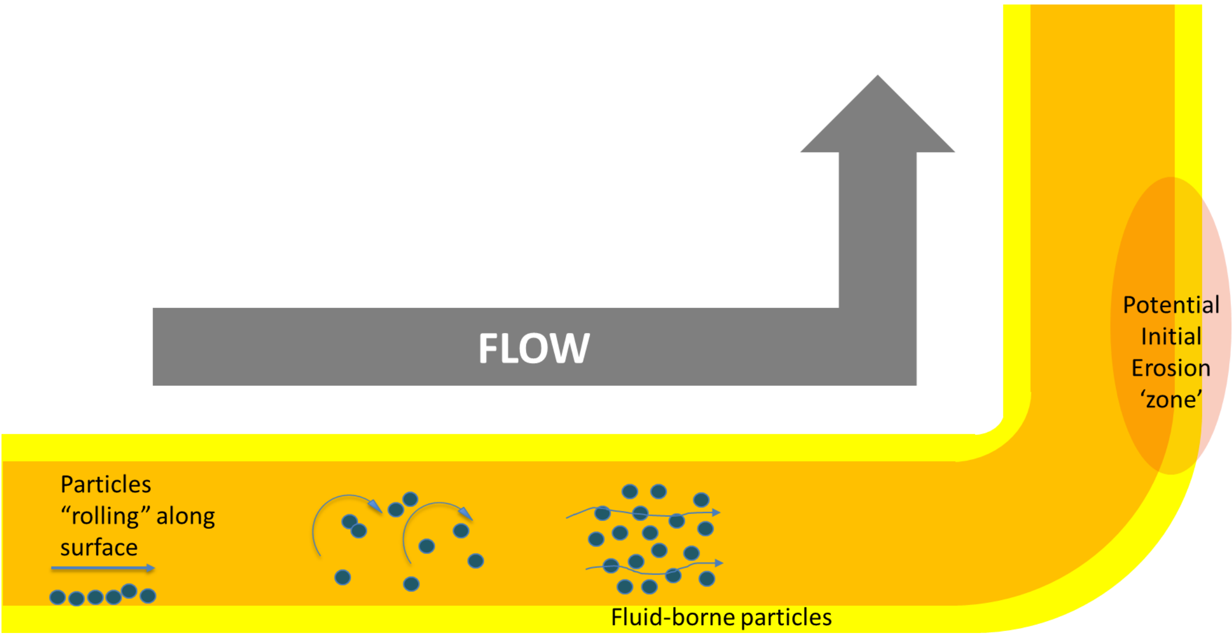


Figure 1: Erosion in pipeline bends

3.1 Pipeline Properties

The assumption has been made, based on the background material provided to Steer by SGN, that any calculations should be carried out for a 315mm PE Pipe. It is understood that GPS (for example) provides this pipe with SDRs of between 11 and 26, equating to an internal diameter of between 257.8mm and 290.8mm.

No distinction between PE80 and PE100 has been made in this work, recognising that no noticeable difference is anticipated. It is also assumed that the durability of current PE pipe has been reviewed for the current operating envelope and deemed "fit for service" with the debris transported by natural gas.

3.2 Particle Properties

The main component of debris is believed to be "Mains dust", a hard containment which is caused by corrosion of the internal walls of cast iron pipelines. This contains various forms of Iron sulphide, iron oxides, and iron carbonates. These components are chemically combined with other contaminants such as salts, sand, liquid hydrocarbons and metal debris. Their composition is understood to be site specific because different pipeline operators report different compositions. Indeed there is wide variability and the composition is not well understood in terms of "its chemical and physical properties, sources, formation mechanisms, prevention or management of its impacts.[2]"

This work will assume, in calculations, that the particles are spherical and have the same density as Iron Oxide (5250 kg/m^3).

Through speaking with SGN, we understand the textural consistency of the "mains dust" to be similar to "grains of sand".

[2] Project Closure Report, "Magnetic Filter Trial", NIA_SGN0070, April 2017

3.3 Environmental factors

The section outlines the physical properties adopted to characterise the fluid flow. Steer were provided with the typical natural gas composition below that SGN receive from St Fergus.

GAS	Mol% Average
Nitrogen	0.7
Carbon Dioxide	1.7
Methane	92.5
Ethane	0.0
Propane	4.99

Figure 2: Typical natural gas composition SGN at St Fergus Offtake

It is possible to use software such as Multiflash™ to calculate specific properties from these compositions. However, it is believed that this would be unlikely to enhance the analysis at this stage given the range of other approximations already needing to be made. Steer have therefore sourced data[3] for calorific value, absolute dynamic viscosity and density for a nominal natural gas as well as hydrogen and methane (Figure 3).

	Calorific Value (CV) MJ/m3			Absolute dynamic viscosity	density
	Upper	Average	Lower	Pa.s	kg/m3
H_2	12.7	11.75	10.8	8.80×10^{-6}	0.0899
CH_4	39.8	37.8	35.8	1.10×10^{-5}	0.717
Natural Gas	43.0	40.25	37.5	1.10×10^{-5}	0.7 - 0.9

Figure 3: Gas Properties

The values above reflect those at standard gas temperature (15°C). It is understood that the temperature inside the pipeline will be closer to 10°C, with some seasonal variation. However, this impact of this is deemed negligible in comparison to the effect of other factors and approximations (e.g. roundness of debris particles, fluctuating operating pressure).

It is assumed that, in the switch from natural gas to hydrogen, the regulated pipe pressures are unchanged but that flowrates are increased to meet the calorific demand from customers. Indeed, as requested by SGN, the hydrogen is expected to supply the **same calorific rate as Natural Gas** (i.e. the efficiency of gas appliances with the two gases presumed identical). If this is the case then, on the basis of the above figures, the flowrate of hydrogen must be around 3.5 times greater than natural gas, i.e.

$$\frac{CV_{Natural\ Gas}}{CV_{Hydrogen}} = \frac{37.5}{10.8} = 3.47 \approx 3.5$$

[3] From www.EngineeringToolbox.com and https://www.nationalgridgas.com/data-and-operations/calorific-value-cv

Steer have been advised[4] that the natural gas network is operated in a pressure constrained manner at which point it is described as operating at 100% capacity (see following figures). This capacity limit is described as being a result of pressure limits.

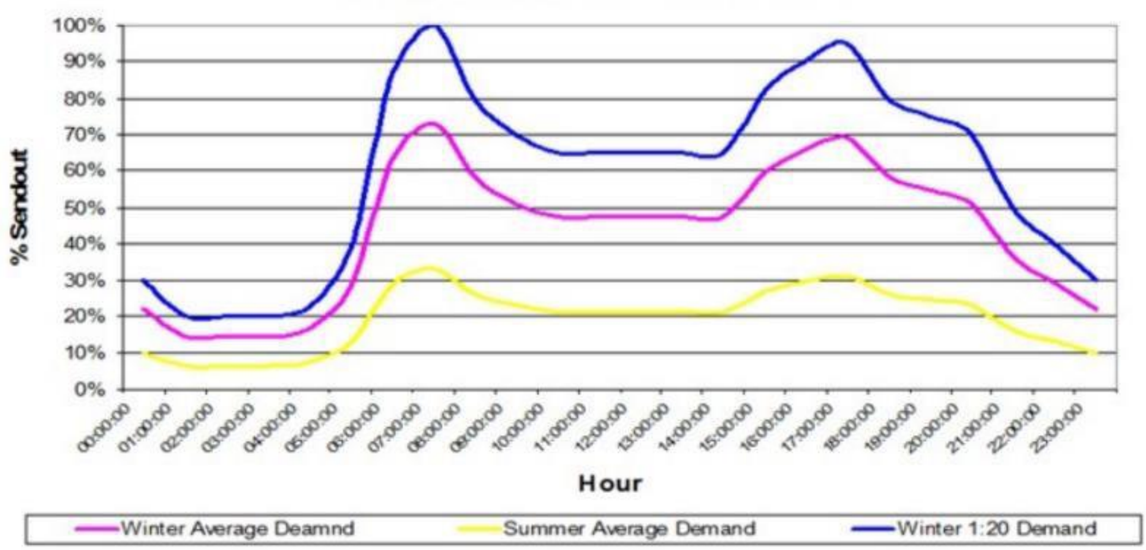


Figure 4: Example Diurnal Demand Profile provided by SGN

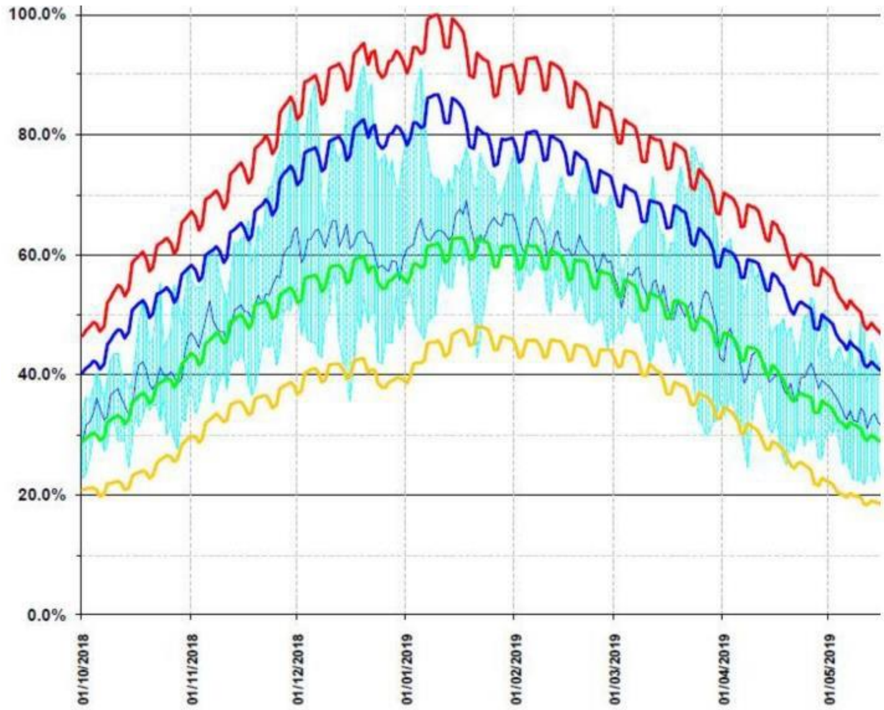


Figure 5: Example seasonal effected daily demand profile provided by SGN

These can be thought of as being two extremes of operating mode that will encounter different pressure limits: Packed line and Depleting Packing.

[4] Email string with Dayna Seay ending Monday, September 9, 4:56 PM

Packed Line

- The pipelines are designed so that when operating in this condition (i.e. when demand has passed its cyclical daily minimum and gas import is still outstripping demand), import does not need to be curtailed.
- In theory the pressure may reach close to maximum operating pressure throughout the line (depending on just how low demand and minimum import rates are).
- During periods of extremely low demand the quantity of energy that could be stored with hydrogen, within a previously natural gas network, would be reduced by a factor of about 3.5.

Depleting Packing

- The pipelines are designed so that when operating in this condition (i.e. when demand is at its peak) the representative gas velocity does not exceed 40m/s.
- In this case the upstream pressure may be as high as maximum operating pressure (or some other limit depending on code) and the downstream pressure at regulator outlet or customer supply pressure.
- In this condition, no higher rate can be delivered by the network without exceeding the pipeline maximum operating pressure (or other limit specified by code).
- The rate at which hydrogen could be delivered through the same network - with the same pressure constraints - will vary across the network (depending for instance on flow regime) and is outwith the scope of this report (see Chapter 1). It can be generally noted however that:
    - Pipes with a nominal diameter of 100mm or greater will be flowing in a turbulent regime at an effective flow speed of 40m/s for both hydrogen and natural gas. These flows may be modelled using the compressible isothermal flow equation.
    - Hydrogen will flow faster because of its slightly lower viscosity and because of its lower density permitting greater acceleration as it expands along the pipe. Flow may be on the order of 2-3 times faster where the pressure drop along the pipe is significant.

3.4 Impact parameters

SGN have already carried out some preliminary calculations on the flow regime as shown in the table below.

Property	Units	Natural Gas	Hydrogen				
		P = 25 mbarg D = 315 mm	P = 25 barg D = 315 mm	Increase flow to match energy	P = 2.401 barg D = 315 mm	P = 25 barg D = 422 mm	P = 75 mbarg D = 315 mm
Actual flow	m³/h	6,148	6,153	20,128	6,153	20,128	19,203
Mass flow	kg/h	5,082	537	1,757	1,757	1,757	1,757
Volume flow	sm³/h	3,600	3,600	20,621	20,621	20,610	20,610
Energy flow	MJ/h	249,443	76,255	249,443	249,443	249,443	249,443
Gas velocity	m/s	22	22	72	22	40	68
			Hydrogen equivalent	Optimised on energy	Optimised on pressure	Optimised on pipe diameter	Increase pressure to 75 mbarg

Figure 6: Original Flow calculations for Hydrogen

These calculations have been amended and these are presented below in Figure 7. This presumed that the above calculations (Figure 6) have been worked out from an initial starting place of 3,600sm^3/h, with an internal diameter of 315mm. Amendments have included:

- Taking account of wall thickness;
- Aligning values and stated units.

These amendments mean that the peak reported hydrogen pipeline velocity is reduced from 72m/s to 50m/s, noting that the velocity for the Natural Gas "set up" case also dropped from 22m/s to 15m/s).

Property	Units	Natural Gas	Hydrogen				
Scenario			Direct swap to hydrogen	Optimised on energy	Optimised on pressure	Optimised on pipe diamter at a 'max' gas velocity	Increase pressure to 75 mbarg
Pressure		25	25	25	2.5	25	75
		mbarg	mbarg	mbarg	barg	mbarg	mbarg
	bara	1.025	1.025	1.025	3.511	1.025	1.075
Diameter Pipe	mm	315	315	315	315	358	315
SDR		26	26	26	26	26	26
ID	mm	291	291	291	291	330	291
Actual Flow	m3/h	3,512	3,512	12,031	3,512	12,031	11,472
Mass Flow	kg/h	2,581	324	1,109	1,109	1,109	1,109
Volume Flow	Sm3/h	3,600	3,600	12,332	12,332	12,332	12,332
Energy Flow	MJ/h	144,900	42,300	144,900	144,900	144,900	144,900
Effective Gas velocity	m/s	15	15	50	15	40	48

(orange)	Entered value
(green)	Value of interest
(yellow)	Kept fixed value

Figure 7: Updated Flow calculations for Hydrogen

3.5 Erosional Velocity Principles

In the oil and gas industry, the effects of erosion from both solid or liquid particles are faced in a wide range of conditions and steps are put in place to minimise its impact. This includes designing facilities to keep the flow velocity below a threshold "Erosion Velocity": this is effectively a velocity limit below which the system is safe to operate without appreciable erosion.

Two widely adopted oil and gas approaches to this are outlined in the rest of this chapter:

- API RP 14E
- DNV PR O501

Note that this chapter focuses on the abrasion process (effectively the mechanical wearing of materials). However, it is noted that erosion can occur due to the removal of 'loose material' from the pipe wall. This may be prevalent in the transition phase from natural gas to hydrogen as debris is moved to its new quasi-equilibrium.

3.6 American Petroleum Institute Recommended Practice 14E

The erosion velocity depends on many factors, but the American Petroleum Institute Recommended Practice 14E (API RP 14E) proposes a pragmatic correlation for Erosional Velocity, V_e, for gas-liquid mixtures as follows:

$$V_e = \frac{c}{\sqrt{\rho m}}$$ [5]

It is recognised that the application of this equation to the current problem is limited as the distribution gas industry does not transport the same liquid levels in their pipelines as the upstream sector. However, if we assume a small water level in natural gas (0.2g water per m^3 gas/liquid volume), then the Erosional Velocity ratio (H_2 / CH_4) would be 1.8. This would mean that the velocity at which Hydrogen is expected to begin causing erosion is nearly twice that Natural Gas. This would be expected, recognising that the ability of Hydrogen to pick up and move particles through the pipeline will be impaired by its lower density and lower viscosity.

However, in order to achieve equal Calorific delivery rates, as has been stated earlier, Hydrogen will be flowing at speeds 3.5 times greater than Natural Gas. This more than offsets the effects of Hydrogen's lower density and viscosity and means such a hydrogen flow would be more erosive than its calorific equivalent of natural gas.

3.7 DNV Recommended Practice O501 (Revision 4.2 – 2007)

The DNV RP O501 (Erosive wear in pipe systems) practice is potentially more instructive than the API guidance for the present problem. It, "provides guidelines for the assessment of erosive wear in piping systems associated with production and transportation of oil and gas and injection of water and gas into the reservoir".

The practice provides guidelines both in the form:

1. Limit states for fluid parameters and material grades which will not result in erosive wear;

[5] c = 100 for continuous service, c = 125 for intermittent service for solid-free fluids and when corrosion is not anticipated, the constant could rise to c = 250. Note that this equation uses densities in lb/ft^3

2. A recommended procedure for calculation of erosive wear in fluids containing sand particles.

A general expression is provided[6] by which to calculate the erosion rate:

$$E_L = \frac{\dot{m}_p K U_p{}^n F(\alpha)}{\rho_t A_t} c_{unit}$$

The equation above can be simplified by using a 'network parameter' (N_{SGN}) for the gas network, assuming no hardware modifications, that incorporates all values that will not change with the change to Hydrogen. This reads:

$$\dot{E}_L = N_{SGN} \dot{m}_p U_p{}^n$$

The suggested values of '*n*' are 2.6 for steel and 3.6 for PE (note that these are not gas dependent). This would suggest that comparative 'erosive-ness' of debris with Hydrogen versus Natural Gas, in the same gas network, will be affected only by:

1. The relative gas flow velocity i.e. a factor of 3.5 (making the assumption that the particle impact velocity is equal to the fluid velocity);
2. The relative mass flowrate of debris that can be sustained by each gas.

The next chapter explores this second point.

[6] Section 8.1, DNV RP O501

3.8 Debris Transportation Principles

The basic principles of particulate transportation in gas pipes are:

- the threshold of motion, effectively when the forces acting on the particle are large enough to begin to roll it along the pipe (**bed creep**)
- fluid threshold where the drag and lift forces are sufficient to lift a given particle off the pipe wall and transport it a distance down the pipe (**Saltation**)
- threshold of **Suspension**, where the drag and lift forces are sufficient to retain the particles in the gas flow off of the pipe surface.

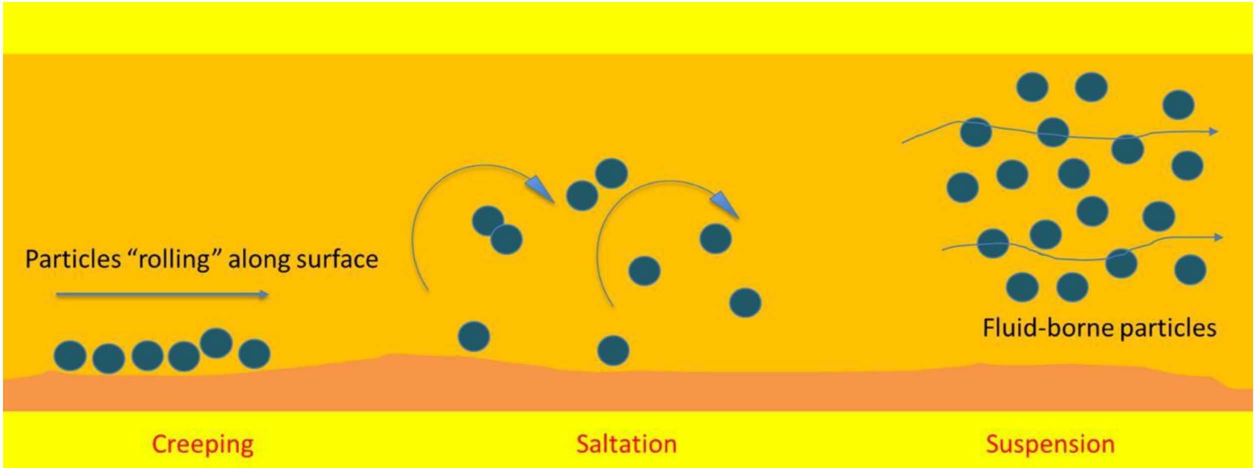


Figure 8: Outline of types of transportation of particles

All three types of transportation can contribute to abrasion of a pipeline. However, it is likely that saltation (particles being picked up and dropped) will cause the largest portion of abrasion due to the higher number of fast particle-pipewall impacts that it will create.

Ideally it would be possible to calculate precisely the ‘load’ that can be carried by creeping, by saltation, and by suspension. However, these are heavily dependent upon the properties of the debris which are not well characterised other than being known to vary widely. Conversely, and rather uniquely, the effect of these different gases is being explored for exactly the same pipe network and, as a first approximation, the debris can be treated as being unchanged.

This allows a number of the key aspects of sediment transport to be looked at in terms of the *difference* between Natural Gas and Hydrogen. This includes exploring:

- the settling velocity;
- the regime the particles are likely to be transported in;
- the initiation of motion of sediment;
- the likelihood of the flow picking up debris;
- the ability of the flow to transport particles by suspension.

This comparison makes no discriminatory assumptions about the nature of the debris particles.

It should also be noted that the ‘bedform’ (i.e. how the particles lying on the walls of the pipe) can be important in transportation rates. For example, the cohesion between the particles combined with the shielding of particles from the flow, as well as the angle of pivot, will directly influence the ‘pick up' of the particles in the flow and affect how it is transported. However, this is a level of complexity greater than is relevant for this work.

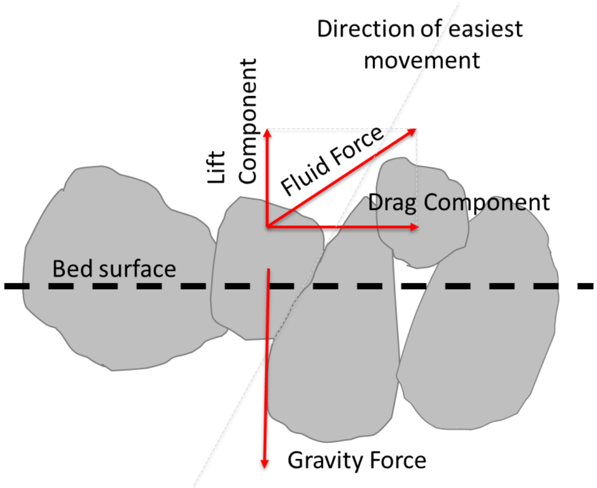


Figure 9: Forces of a particle and notes

3.9 Settling Velocity

Although Stokes Law can calculate settling velocity in laminar flow, it is worthwhile taking into account of turbulence for larger particles at higher velocities). Note that in the flows that we are examining, the settling (vertical) flows will be, in general, caused by turbulent effects (minimum) as well as connections (potentially significant).

The settling velocity of a spherical particle suspended in a vertical flow can be expressed for each of the main flow regimes as below.

	Turbulent (Re > 500)	**Transition**	**Laminar (Re < 2)**
Equation	Newton's Law $V_t \propto \sqrt{\frac{(\rho_p - \rho_f)}{\rho_f}}$	Intermediate Law $V_t \propto \frac{(\rho_p - \rho_f)^{0.71}}{\rho_f{}^{0.29}\mu^{0.43}}$	Stoke's Law $V_t \propto \frac{(\rho_p - \rho_f)}{\mu}$
Ratio	1 : 3.0	1 : 2.2	1 : 1.25

Figure 10: Settling velocity comparisons of Hydrogen against Natural Gas. It should be noted that the values of the Reynolds number at which the fluid flow regimes transition from laminar to turbulent are different than the more ubiquitous values applied to pipe systems[7].

If we seek to consider the effect of the shift between regimes occurring for each gas at a different diameter, we can plot the following chart (N.B. with logarithmic axes).

[7] https://neutrium.net/unit-operations/terminal-velocity-of-particles-for-gravity-separation/

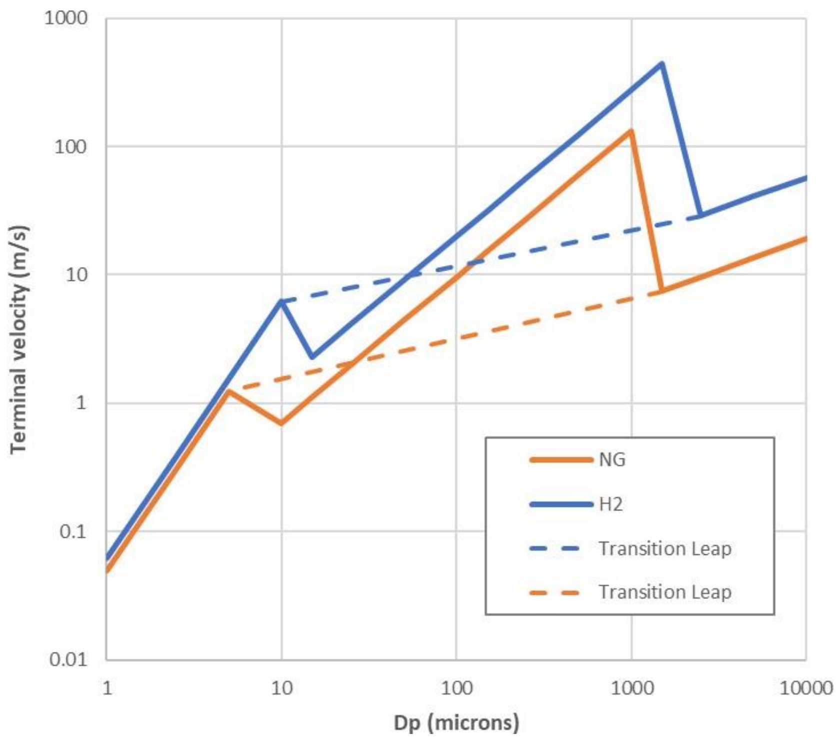


Figure 11: Terminal Velocity comparisons between Natural Gas and Hydrogen

Figure 11 highlights:

- The gases are most often imposing the same flow regime on a given particle size.
- The steps at regime change indicate that there is significant uncertainty in behaviour in the transition regime values. This is the likely regime of interest in network pipes.

This work shows that particles fall more easily through Hydrogen than Natural Gas as would be expected based on their physical properties. This would mean that if the flow rates of Hydrogen and Natural Gas were the same, Natural Gas would be expected to transport a suspended particle further.

This indicates that Hydrogen must be flowing at a higher velocity to 'hold a particle up'.

3.10 Rouse Number[8,9]

The forces on a particle in a pipe can be appraised in terms of the ratio of particle settling velocity to the shear velocity that the particle is exposed to in the gas stream. In its simple terms, this is the rate of a particle's free-fall to the strength of turbulence acting to suspend particles. This ratio is a non-dimensional number known as the Rouse Number:

$$P = \frac{w_s}{\beta \kappa u_*}$$

[8] https://en.wikipedia.org/wiki/Rouse_number

[9] https://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-163-surface-processes-and-landscape-evolution-fall-2004/lecture-notes/4_sediment_transport_edited.pdf

When the Rouse number is above 7.5, particles will not be moved. When the Rouse number is between 2.5 and 7.5, particles will be transported as bedload; 50% of the particles will be transported by suspension between Rouse Numbers of 1.2 and 2.5; 100% of the particles will be transported by suspension between Rouse Numbers of 0.8 and 1.2; and all particles will be contained within the 'wash load' when the Rouse number is lower than 0.8.

In this context, we can take u_* (shear velocity) to be:

$$u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{\frac{\mu}{\rho}}\sqrt{\frac{du}{dy}}$$

using the established relationship,

$$\tau = \mu \frac{du}{dy}$$

and assuming that

$$\frac{du}{dy} \propto u \ ,$$

i.e. assuming the same flow regime and same velocity profile in both Hydrogen and Natural Gas at identical calorific flow rates (x3.5).

Figure 12 puts the physical properties of the two gases into the component parts of this equation and then brings them together.

Regime	Turbulent Re > 500	Transition	Laminar Re < 2
Settling velocity Ratio ($W_{s.H2}$ / $W_{s.CH4}$)	3.0	2.2	1.25
$\sqrt{\frac{\mu}{\rho}}_{H2} \Big/ \sqrt{\frac{\mu}{\rho}}_{NG}$	2.7	2.7	2.7
$\sqrt{\frac{du}{dy}}_{H2} \Big/ \sqrt{\frac{du}{dy}}_{NG}$	1.9	1.9	1.9
Shear velocity Ratio ($u_{*.H2}$ / $u_{*.CH4}$)	5.0	5.0	5.0
Rouse Number ratio (P_{H2} / P_{CH4})	**0.6**	**0.4**	**0.25**

Figure 12: Rouse Number ratio comparisons

The values indicate that particles being transported by Hydrogen are **more likely to be suspended,** when compared with Natural Gas, due to the significantly increased pipeline flow velocity.

3.11 Ability of the flow to move a particle (Shields Parameter)

The Rouse number, examined above, looks at the likelihood of particles being carried i.e. remaining suspended. However, it does not consider the preceding matter of starting to move any given particle.

The Shields parameter[10] (τ_*) is a nondimensional number which is used to calculate the initiation of motion of sediment in a fluid flow:

$$\tau_* = \frac{\tau}{(\rho_s - \rho_f)gD}$$

The shear in a fluid can be determined from:

$$\tau = \mu \frac{du}{dy}$$

So that the first equation becomes:

$$\tau_* = \frac{\mu \frac{du}{dy}}{(\rho_s - \rho_f)gD}$$

Noting that for a low-pressure gas:

$$\rho_s \gg \rho_f$$

We can re-write this as:

$$\tau_* = \frac{\mu \frac{du}{dy}}{\rho_s g D}$$

Once again assuming that,

$$\frac{du}{dy} \propto u$$

i.e. the same flow regime and same velocity profile in both Hydrogen and Natural Gas at identical calorific flow rates, then,

$$\tau_* \propto \frac{\mu u}{\rho_s g D}$$

Grouping by those parameters that vary with the gas, and those that do not,

$$\tau_* \propto (\mu u)\left(\frac{1}{\rho_s g D}\right)$$

And finally inserting the gas property values and comparing for Hydrogen and natural gas

$$\frac{\tau_{*Hydrogen}}{\tau_{*Natural\ Gas}} = 2.8$$

This would indicate that the initiation of motion occurs earlier (at lower calorific flowrate) in the case of Hydrogen than compared with Natural Gas due to the high velocity Hydrogen must flow at.

[10] https://en.wikipedia.org/wiki/Shields_parameter

3.12 Ability of the flow to move a particle by Saltation

Two different approaches to assessing the ability of the gas flows to move a particle by saltation were used and both are reported below.

3.12.1 Bagnold Formula

The Bagnold formula relates the amount of sand moved by the wind to wind speed. In its simplest form[11], this equation can be expressed as:

$$q = C \frac{\rho_f}{g} \sqrt{\frac{d_p}{D_B}}\, u_*^3$$

Using the established relationship,

$$\tau = \mu \frac{du}{dy}$$

and assuming that

$$\frac{du}{dy} \propto u \ ,$$

i.e. assuming the same flow regime and same velocity profile in both Hydrogen and Natural Gas at identical calorific flow rates (x3.5), we see that,

.

$$q \propto C \frac{\rho_f}{g} \sqrt{\frac{d_p}{D_B}}\, (\mu u)^{\frac{3}{2}}$$

Grouping by those parameters that vary with the gas, and those that do not:

$$q \propto \left(\frac{C}{g} \sqrt{\frac{d_p}{D_B}}\right) \left(\rho_f \, (\mu u)^{\frac{3}{2}}\right)$$

So, in the case that the Hydrogen is flowing 3.5 times faster than the natural gas, but in the same flow regime (such that the velocity gradient is 3.5 times higher in the Hydrogen) the ratio of the Bagnold number of Hydrogen versus natural Gas is 0.5.

Therefore, the mass transport in Hydrogen is said to be half that of natural gas as a result of Hydrogen's much lower density.

NOTE: the Bagnold equation was derived for air and the low density of hydrogen may be beyond the validity of the model. Indeed, this is arguably the very reason for this present piece of work – to extend debris transport knowledge into very low gas density realms.

[11] It is noted that the formula is valid in dry (desert) conditions. The effects of sand moisture at play in most coastal dunes, therefore, are not included.

3.12.2 Rizk

The Rizk equation is recommended by a review of particle transport[12] as the only option for saltation of fine particles and an option for larger particles (>200µm). It calculates the solids mass flowrate achieved in a pipe in stated flow conditions. The equation takes the form,

$$\frac{W_s}{\rho_f U_s A} = \left(\frac{1}{10^d}\right)\left(\frac{U_s}{\sqrt{gD_T}}\right)^{1.1d_p+2.5}$$

where $d = 1.44d_p + 1.96$, and noting that d and d_p are in millimetres.

Re-arranging, and grouping by those parameters that vary with the gas, and those that do not:

$$W_s = \left(\left(\frac{A}{10^{1.44d_p+1.96}}\right)\left(\sqrt{gD_T}\right)^{-1.1d_p-2.5}\right) \rho_f {u_s}^{1.1d_p+3.5})$$

Now comparing Hydrogen with Natural Gas, for any given particle and pipe sizes, and noting the ratio of the gas velocity in the pipe for Hydrogen versus natural gas (i.e. 3.5),

$$\frac{W_{s_{H2}}}{W_{s_{NG}}} = 0.11(3.5)^{1.1d_p+3.5}$$

A plot can therefore be made of the ratio of (N.B **not** the absolute) mass transport achieved by the gases for 'any' given particle size.

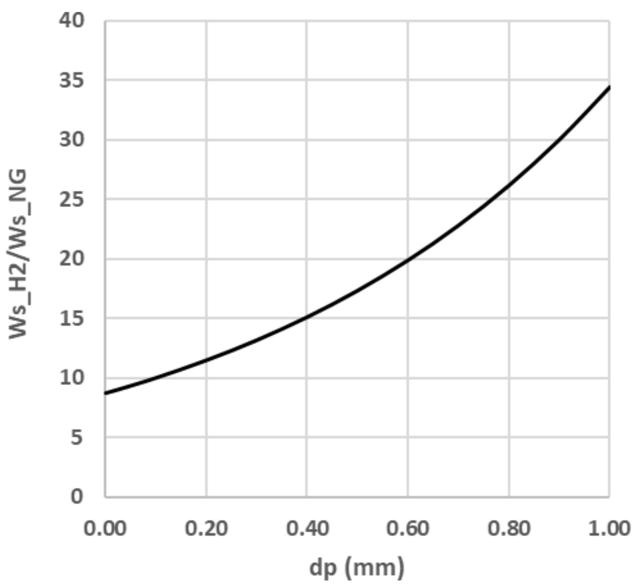


Figure 13: Ratio of mass transport capacity of Hydrogen versus Natural Gas predicted by Rizk versus particle diameter

This would indicate that the capacity of the Hydrogen flows to transport debris are significantly greater than those of natural gas.

NOTE: Care should be taken not to infer from this graph increasing carrying capacity with increasing diameter. The capacity of any gas to transport particles decreases with particle size but this affects **both** the Hydrogen and the natural gas **equally**. This is incorporated in the original equation in the form of the (1 / 10^d) term.

12 L. M. Gomes and A. L. Amarante Mesquita, Braziian Journal of Chemical Engineering, 2014

3.13 Ability of the flow to pickup and transport particles by suspension (Kalman)

The Kalman equation is recommended as the only option for determining pickup velocity in a review paper on particulate transport[13]. It is expressed in a segregated manner in the paper using the following equation (and values for *a* and *n* that vary with flow regime),

$$Re_{p^*} = a.\, Ar^n$$

By manipulation, and grouping by those parameters that vary with the gas and those that do not, it can be expanded out to:

$$u_p = \left(\frac{a}{k_{pd}} \cdot (\rho_p\, g)^n \cdot d_p^{\,3n-1}\right) \cdot \left(\frac{\rho_f^{\,n-1}}{\mu^{2n-1}}\right)$$

The table in the following figure (Figure 14) was developed by evaluating Hydrogen relative to natural gas for a range of specific particle sizes. The two rows in the table consider:

- the ratio of the pickup velocities for Hydrogen and natural gas, and then
- the same ratio of the pickup velocities for Hydrogen and natural gas but normalised with respect to the necessarily faster flow speed in Hydrogen pipes to deliver the equivalent calorific value (i.e. 3.5 times faster).

d_p (micron)	1	2.5	5	10	25	50	100	250	500	1000	2500
$\frac{u_{p\,H2}}{u_{p\,CH4}}$	4.0				8.9	4.9	3.4				
$\frac{u_{p\,H2}}{u_{p\,CH4}} / 3.5$	1.1				2.6	1.4	1.0				

Figure 14: Particle pick-up velocity comparison: the second row taking into account need for Hydrogen to be travelling 3.5 times faster to deliver the same calorific rate

This indicates that particle pick-up and suspension may be noticeably lower in the Hydrogen compared to Natural Gas around the 50micron particle scale.

4 Conclusion

This work presented in this Report indicates that the “erosiveness” of debris carried by Hydrogen, when compared to Natural Gas, can be determined by two key factors:

- The relative gas flow velocity
- The relative mass flow rate of the debris (how much debris can be transported by the gas).

The relative gas flow velocity of Hydrogen, versus natural gas, is calculated to be up to 3.5 times that for Natural Gas due to the decision to run network at the same pressure whilst sustaining calorific delivery rate. This therefore increases the likelihood of erosion.

The relative mass flow rate of debris in Hydrogen, versus natural gas, was explored with a range of models. These, and their results, are summarised in Figure 15 below.

[13] L. M. Gomes and A. L. Amarante Mesquita, Braziian Journal of Chemical Engineering, 2014

Models	Aim	Comment	+ / -
Particle Settling velocity	Used to indicate if	This is a first demonstration that Hydrogen must be travelling at a higher speed to 'hold a particle up'.	+
Rouse Number	This is used to indicate if the particles are to be transported, and if so, what regime (bedload, suspension, wash load)	The results indicate that particles being transported by Hydrogen are **more likely to be suspended** when compared with Natural Gas due to the significantly increased main flow.	-
Shields Parameter	Used to calculate the initiation of motion of sediment	This would indicate that the initiation of motion occurs earlier in the case of Hydrogen than compared with Natural Gas.	-
Bagnold Formula	Used to understand the amount of mass that will be transported in the fluid	This would indicate that the mass transport in Hydrogen versus Natural Gas is said to be about half.	+
Rizk	Used to indicate the likelihood of the flow to pick up debris	This would indicate that the transport capacity of the Hydrogen flows are significantly greater than those of Natural Gas.	-
Kalman	This is used to indicate the ability of the flow to transport particles by suspension	This indicates that particle suspension **may be noticeably lower** in Hydrogen compared to Natural Gas in the transition range around the 50micron particle scale.	+

Figure 15: Summary table regarding Mass flow of debris

This theoretical work would therefore indicate that when moving from natural gas to Hydrogen:

1. The propensity to initiate particle motion and to pick up particles (Shields Parameter, Rizk) would be greater, but that particles would then be more likely to drop out of the flow (settling velocity) before again being picked-up and transported (saltation increases).
2. That particles would more likely to be transported as a suspension (Rouse number), but for very fine debris (circa 50µm diameter) the particle suspension may be appreciably lower (Kalman). This is significant because suspended particles will tend to cause more erosion than if they were transported as bedload.
3. The total mass transport of debris would be around 50% lower (Bagnold).

The particle transportation regime will be significantly different for Hydrogen compared to Natural Gas, primarily due to the higher velocities at which it will be flowing. The analysis suggests, with significant reservations over its reliability, that there will be increased wall collisions as the gas is more likely to cyclically pick up and dropout particles, increasing the likelihood of pipe wall erosion.

5 Recommendations

It is clear from the work that the high velocities of Hydrogen are a key factor. The option exists to extend this work to consider increased pressures and reduced flow rates.

2.1.1. Computational Fluid Dynamics

Options exist to explore the phenomenon further by running Computational Fluid Dynamics (CFD) models. However, the anecdotal understanding is that the debris loading of the current gas flows is relatively low and that the ability of CFD to account for particle interactions would be of limited benefit.

2.1.2. Validity of Models

As has already been indicated, the models and understanding used in this work have come from the oil and gas industry, and from research into wind-blown transportation and river hydraulics. It is therefore inevitable that assumptions have been made to use these to evaluate low density gas transport of spare debris: the validity of the models in such cases is not proven. There are options of going back to the original papers to further assess the models and peer reviews of them. However, that is likely to be a significant undertaking and would not significantly improve confidence in them of the conclusions made.

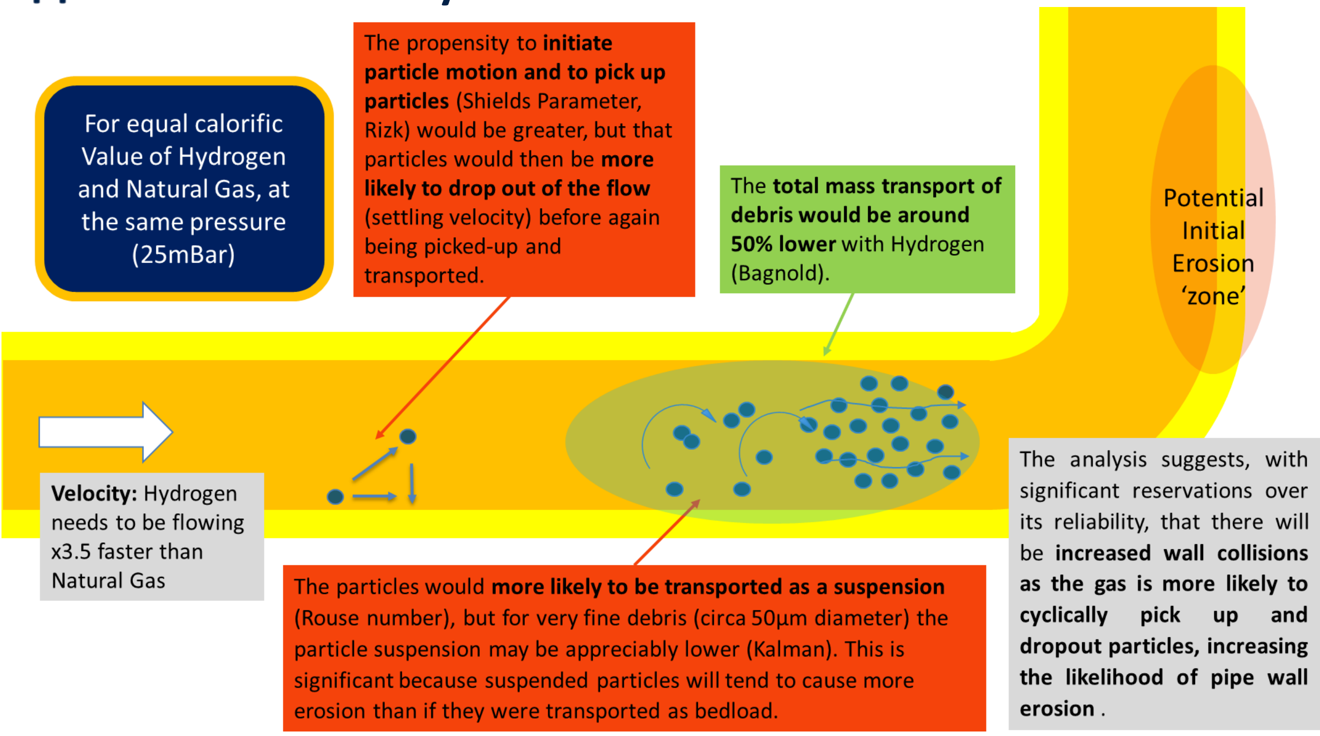
There is also a need to develop and use a dynamic model of the gas network to look at the impact of the change in fuel gas upon the calorific capacity of the network. It is expected that operating pressure limits may constrain the delivery of hydrogen and thus also the periods at which the very highest velocities are experienced.

Therefore, in the absence of Hydrogen specific data and amid concerns about the strict validity of the models used, there is a gap in the industry's understanding.

2.1.3. Exploratory Experimental work

It is recommended that exploratory experimental work is carried out on a small scale to re-assess the theoretical indications reported. This will provide much needed confidence in subsequent estimates of the risks (or otherwise) of erosion within the gas network in the switch to Hydrogen.

Appendix A - Summary Slide



Appendix B - List of Symbols

Ar	Archimedes Number	[-]
At	Area exposed to erosion.	[m^2]
β	Eddy Factor, taken as 1 unless otherwise stated	[-]
$Cunit$	Unit conversion factor (m/s → mm/year).	[-]
C_S	A dimensionless constant of order unity that depends on the sediment sorting	[-]
c	An empirical constant (Erosional Velocity equation)	[-]
CV	Calorific Value	[MJ/m^3]
D	Inner pipe diameter.	[m]
D_B	Nearly uniform grain size originally used in Banold's experiments (250 micrometers)	[m]
D_T	Pipe Diameter	[m]
dp	Particle diameter.	[m]
$\cdot EL$	Erosion rate referred to depth.	[mm/year]
$F(\alpha)$	Function characterising ductility of the material.	[-]
g	Local gravitational acceleration	[m/s^2]
κ	von karamn constant, taken to be 0.4 unless otherwise stated	[-]
K	Material constant.	[(m/s)-n]
mp	Mass of sand particle.	[kg]
ρ	density	[kg/m^3]
ρ_f	Density of fluid.	[kg/m^3]
ρm	Density of fluid mixture.	[kg/m^3]
ρp	Density of particle.	[kg/m^3]
ρt	Density of target material	[kg/m^3]
q	Mass transport of sediment across a lane of unit width	[kg/ms]
Re	Reynolds number	[-]
u_*	Shear Velocity	[m/s]
u	Velocity	[m/s]
Up	Particle impact velocity (equal to the fluid velocity).	[m/s]
US	Saltation velocity	[m/s]
Vt	Settling Velocity	[m/s]
Ve	Erosion Velocity	[m/s]
μ	Dynamic Viscosity	[kg/ms]
w_s	Solids mass flow rate	[kg/s]

Appendix C - List of Key Equations

Reynolds Number

$$Re = \frac{\rho u D}{\mu}$$

Erosional Velocity

$$V_e = \frac{c}{\sqrt{\rho_m}}$$

< *From API RP 14E*

Erosion rate

$$E_L = \frac{\dot{m}_p K U_p^n F(\alpha)}{\rho_t A_t} C_{unit}$$

< *From DNV PR O501*

Newton's Law

$$_t = 1.74\sqrt{\frac{g d_p(\rho_p - \rho_f)}{\rho_f}}$$

Intermediate Law

$$V_t = \frac{3.54 g^{0.71} D_p^{\ 1.14} (\rho_p - \rho_f)^{\ 0.71}}{\rho_f^{\ 0.29} \mu^{0.43}}$$

Stoke's Law

$$V_t = \frac{d_p^2(\rho_p - \rho_f) g}{18\mu}$$

Rouse Number

$$P = \frac{w_s}{\beta \kappa u_*}$$

Bagnold formula

$$q = C_S \frac{\rho_f}{g} \sqrt{\frac{d_p}{D_B}} u_*^3$$

Rizk

$$\frac{W_s}{\rho_f U_s A} = \left(\frac{1}{10^d}\right) \left(\frac{U_s}{\sqrt{g D_T}}\right)^{1.1 d_p + 2.5}$$

Kalman

$$Re_{p^*} = a.\, Ar^n$$

Archimedes

$$Ar = \frac{g L^3 \rho_f (\rho - \rho_f)}{\mu^2}$$