PURGING HYDROGEN DISTRIBUTION PIPELINES: LITERATURE REVIEW, DESCRIPTION OF RECENT EXPERIMENTS AND PROPOSED FUTURE WORK

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ABSTRACT

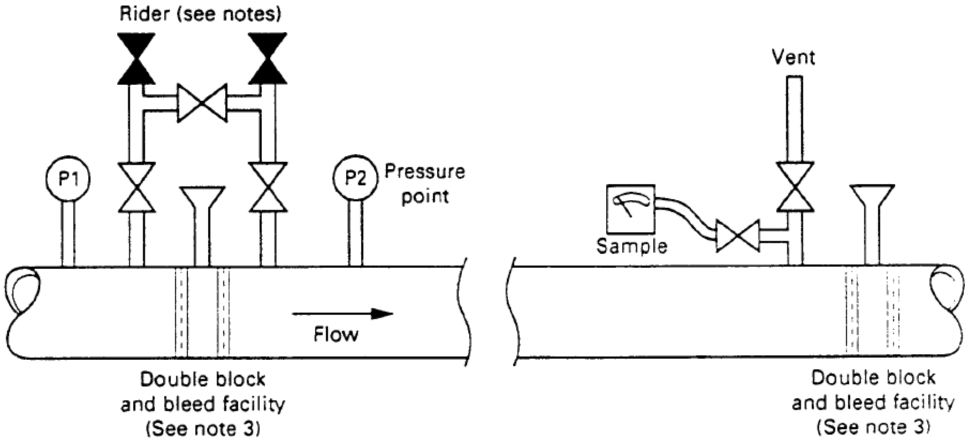
The aim of the H21 project is to undertake measurements, analysis and field trials to support the safe repurposing of Great Britain's natural gas distribution network for hydrogen. As part of this project, work has been ongoing to identify aspects of existing natural gas procedures that will need to be modified for hydrogen and to support the development of new procedures. This has included a review of the scientific basis of current displacement purging practices, analysis of the potential implications of switching from natural gas to hydrogen, and experimental support work. The reduced density and viscosity of hydrogen means that minimum purging velocities should (in principle) be higher for hydrogen to avoid stratification and ensure adequate removal of the purged gas during pipeline purging operations. A complicating factor is the high molecular diffusivity of hydrogen (roughly three times that of natural gas), which causes hydrogen to mix over short distances more rapidly than natural gas. Current models for pipeline purging do not take into account the mixing effect related to molecular diffusion. The wider flammable limits, lower ignition energy and greater potential for combustion to transition from deflagration to detonation with hydrogen means that indirect purging with nitrogen is currently being investigated for distribution pipelines. This paper reviews the ongoing analysis of hydrogen pipeline purging and discusses a potential future scientific programme of work aimed at developing a new pipeline purging model that accounts for molecular diffusion effects.

1.0 OVERVIEW OF H21 PROJECT

H21 is a UK project funded by the energy regulator, Ofgem. The project is led by Northern Gas Networks (NGN) on behalf of the four UK Gas Distribution Network Operators (GDNOs) and National Gas. It aims to undertake scientific research to support the safe repurposing of the existing natural gas distribution network for transporting hydrogen. Phase 1 of the project was completed in May 2021 and it included leakage tests on natural gas network assets and development of a preliminary Quantified Risk Assessment (QRA) model. Reports on these topics are available on the H21 website (www.h21.green). Phase 2 of the project is due to be completed in 2023 and involves further development of the QRA [1] and evaluation of network procedures, identifying which of these are suitable for a 100% hydrogen network and those that may require adjustments. The present paper describes the work undertaken to analyse one of these common network procedures, namely, purging of distribution pipelines. The distribution network in the UK currently includes pipelines operating up to a pressure of 7 bar. The present scope of work excludes purging of pipes downstream of the emergency control valve, i.e., in domestic, commercial or industrial premises.

2.0 CURRENT NATURAL GAS PURGING PRACTICE

The current UK natural gas purging procedures are described in the Institute of Gas Engineers and Managers Safety Recommendations document IGEM/SR/22 [2]. Each of the GDNOs incorporate these IGEM safety recommendations (with minor adjustments) into their own internal company procedures, which are used by operatives on the UK gas network. There is also a British Standard BS EN 12327 [3] on pressure testing, commissioning and decommissioning of gas infrastructure, which covers similar ground. These documents all contain a key table of information that stipulates the minimum purging velocity that must be achieved when purging pipelines of different diameters to give an efficient and complete purge, i.e., to prevent the gas from forming layers in the pipeline (stratifying). In most cases, information is also included on the rider and vent sizes needed to achieve this minimum purging velocity, based on the available upstream gas pressure. Different terminology is used in other countries for the pipeline purging configuration. The terminology "rider" is used here to refer to the bypass connection from the upstream pipeline (main) supplying the gas during commissioning purges. A schematic of the typical purging arrangement is shown in Figure 1. In North America, the vent is often called the blowoff pipe.



Notes:

1. *Purge rider connections should be as close as possible.*
2. *Rider may be omitted at the discretion of the engineer.*
3. *Low pressure mains not greater that 150 mm n.b. may be isolated by a single faced valve or squeeze off if the isolation is sound.*

Figure 1. Schematic showing typical purging arrangement of rider and vent, from IGEM/SR/22 [2]

In the US, equivalent guidance on minimum pipeline purging velocities is given in the American Gas Institute (AGA) document on "purging principles and practice" [4]. Figure 2 compares the minimum purging velocity for natural gas that is given in these various UK and US documents. The lines shown in the key as NGN/xx indicate internal company procedures used at Northern Gas Networks. T/PM/TR/30 and DIS 5.6 are historical UK gas industry standards and IGE/UP/1 is an IGEM standard on purging of industrial and commercial gas installations. The paper by Marshall *et al*. [5] presents the underpinning science behind the gas industry standards and is discussed in more detail below.

For direct purging between gas and air, the various standards and procedures follow a similar trend for the minimum purging velocity to increase with pipe diameter, which appears to be based on achieving a Froude number of 0.7. For pipeline diameters below 130 mm, the various UK documents all stipulate a minimum purging velocity of 0.6 m/s for direct purging, whereas the AGA guidance requires the velocity to increase as the pipeline diameter decreases to ensure that the flow remains turbulent, with a Reynolds number of 4,000. For indirect purging, the UK guidance stipulates a minimum purging velocity of 0.6 m/s, irrespective of the pipeline diameter.

The Froude number, Fr, expresses the ratio of inertial to buoyancy forces as follows:

$$Fr = \frac{U}{\sqrt{g'd}} \qquad ; \qquad g' = 2g\frac{(\rho_c - \rho_a)}{(\rho_c + \rho_a)} \tag{1}$$

where U is the velocity, d the pipeline diameter, g' is the reduced gravity, g is the gravitational acceleration (9.81 m/s^2), ρ is the density and subscripts c and a refer to the current of purge gas and the existing ambient gas in the pipeline. Slightly different definitions of g' exist in the literature. The version of g' presented here is used in the Gas Research Institute report by Johnson *et al*. [6].

The Reynolds number, Re, expresses the ratio of inertial to viscous forces, as follows:

$$Re = \frac{\rho U d}{\mu} \tag{2}$$

where μ is the dynamic viscosity.

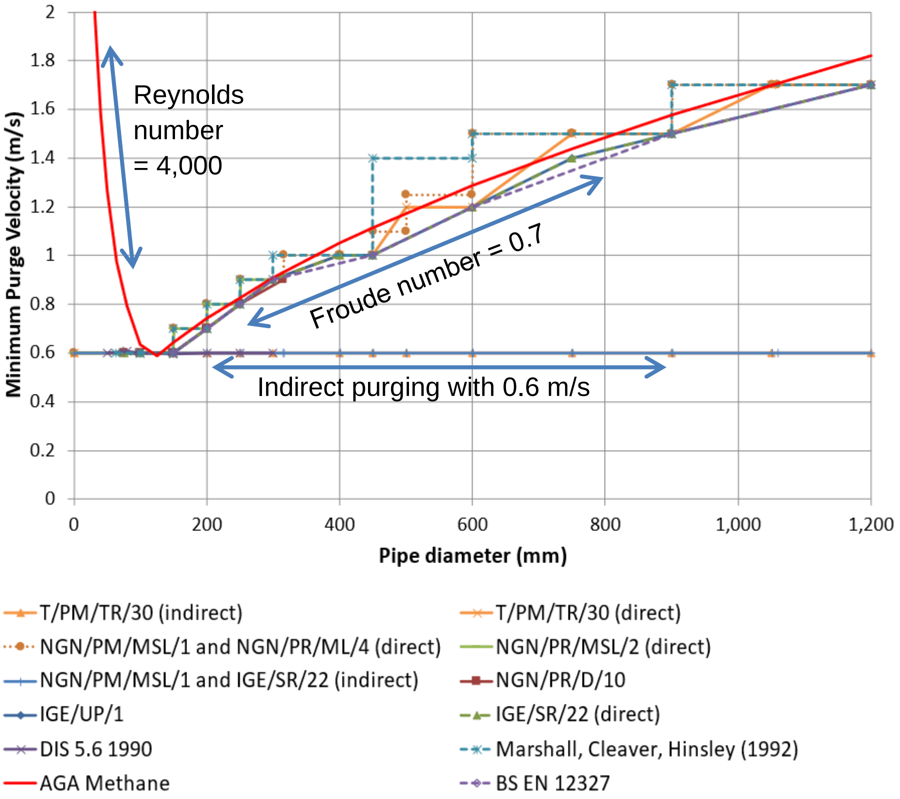


Figure 2. Comparison of minimum purging velocity in various gas industry publications

3.0 SCIENTIFIC BACKGROUND TO NATURAL GAS PIPELINE PURGING

3.1 British Gas Research

In the late 1980’s and early 1990’s, a programme of research on pipeline purging was undertaken by British Gas to assess the explosion hazard associated with direct purging of natural gas and to provide data that could be used to develop guidelines for safe direct purging [5, 7]. Prior to this research, when the gas network was operating on town gas, indirect purging appears to have been more commonly used. The research programme included:

- Laboratory experiments to visualise stratification in pipes using saline and fresh water.

- Large-scale experiments using polyethylene (PE) pipes with internal diameters of 50 mm, 75 mm, 150 mm and a range of pipe lengths from 40 m up to approximately 260 m and purging velocities in the range 0.1 to 1.5 m/s. Tests were undertaken on straight horizontal pipes, pipes fitted with 90-degree and 180-degree bends, and pipes angled upwards/downwards with 3° and 6° slopes. Concentrations were measured to examine the mixing of gas and air during direct purging operations. In the largest pipe, with an internal diameter of 150 mm and 15 mm wall thickness, ignition tests were also performed.

- Tests in two straight, 100 m long, horizontal steel pipes with internal diameters of 305 mm and 574 mm. Purging velocities were in the range 0.3 m/s to 2.4 m/s. Additional tests were performed using a longer 300 m pipe fitted with several bends and inclined sections. Gas concentrations were measured during purging operations and flammable gas mixtures in the pipes were also ignited.

- Measurements of gas concentrations were taken during actual purging operations on the gas network. Firstly, on a 3.6 km length of 400 mm diameter distribution main. Secondly, on a 10 km length of 300 mm diameter transmission pipe.

In parallel to this experimental work, British Gas commissioned Cambridge Environmental Research Consultants (CERC) to develop a mathematical model for direct purging that was capable of predicting several important parameters: the minimum purging velocity needed to avoid stratification, the volume of flammable gas produced in the pipeline during purging operations, and the arrival times of the interface between gas and air at the vent. The model was described in the report by Daish and Linden [8] and is based on propagation of buoyant and dense gravity currents along the pipeline during purging operations.

One of the main outputs of this combined programme of experimental work and modelling was a table of minimum purging velocities, which are plotted in Figure 2 above as the Marshall *et al.* data. Recommendations were also given on the maximum length of pipeline that should be purged at any one time. These limits were much larger for natural gas than had previously been applied for town gas. For example, the limits on pipelines with an internal diameter of between 250 mm and 300 mm was originally 30 m for town gas and this was increased to 500 m for natural gas (see [5]). The underpinning scientific basis for the limits on purging length for natural gas were not explained in the publications at the time [5, 7]. More recently, HSE’s calculations using the Daish and Linden [8] model suggest that these limits restricted the size of the flammable cloud generated inside the pipeline during purging operations to 2.5% of the pipeline volume. It is unclear why 2.5% of the pipeline volume was chosen as a limiting condition.

The basis of safety for the new guidelines on natural gas direct purging, as described in [5, 7], was that in the unlikely event of the flammable gas inside the pipeline igniting during the purging operation, the pipeline would be able to withstand the maximum overpressure generated in the resulting explosion. Marshall *et al.* [5] and Darby [7] described the results of “worst case” experiments involving ignition of an 80 m long 150 mm diameter pipeline filled with a stoichiometric natural gas mixture. The maximum overpressure generated in the explosion was 2 bar. Since 2 bar was less than the pressure rating of new steel and PE pipelines installed on the gas distribution network, it was concluded that it was “highly unlikely that any damage to pipes or the surrounding environment would occur as a consequence of an ignition within a pipe during a direct purging operation”.

The limits on the maximum length of pipeline that can be purged at any one time from Marshall *et al.* [5] are still applied in some current gas industry standards (e.g., IGE/UP/1) but these restrictions have since been dropped from the main purging standard, IGEM/SR/22. Similarly, restrictions on purging of branched pipeline networks have been relaxed over time.

3.2 Gas Technology Institute (GTI) Research

The AGA recommendations on minimum purging velocities for direct purging of natural gas differ from those given in IGEM/SR/22 and current UK gas industry procedures in one important respect, namely the AGA requires the purging flow to be fully turbulent. This requirement leads to a significant increase in the natural gas purging velocity for small diameter pipes (below 130 mm) – see Figure 2.

The AGA requirement for turbulent flow appears to be based on two arguments that were described in the report by Johnson *et al*. [6]. Their first argument was that turbulent flow helps to suppress stratification, due to the velocity profile in the pipe. Near the walls of the pipeline, the velocity is relatively low. Since the flow is moving slowly within this layer, density differences between the gas and the air could cause the two gases to form layers, due to buoyancy forces being greater than inertial forces. When the flow is turbulent, the velocity profile is more uniform across the cross-section of the pipe, and the boundary layer near the wall is very thin and sheared much more strongly. This should minimise the depth of the layer where the gas and air could stratify. Turbulent flows also involve greater mixing than laminar flows, so that any gas that does start to stratify near the walls should therefore mixed more readily into the bulk flow. The second argument presented by Johnson *et al*. [6] was made with reference to experimental data from the British Gas research programme [5, 7]. Specifically, there was one measurement point that indicated there was little change in the volume of gas-air mixture from increasing the purging velocity from 0.6 m/s to 1.0 m/s.

In addition to these requirements for turbulent flow, Johnson *et al*. [6] presented some analysis of the length of the mixed zone of flammable gases produced during purging operations, which was based on turbulent mixing theory and previous analysis by Perkins and Euchner [9].

4.0 POTENTIAL IMPACT FROM SWITCHING TO HYDROGEN

4.1 Gas properties

Table 1 summarises some of the properties of hydrogen and methane (the main component of natural gas) that have an impact on pipeline purging operations. The density of hydrogen is approximately eight times lower than methane, which clearly has an effect on the buoyancy of the purge gas. Hydrogen also has much wider flammable limits, a lower ignition energy, a higher laminar burning velocity and a smaller detonation cell size, which all have important implications in terms of the size of the flammable cloud produced during purging operations, its ease of ignition and potential consequences.

4.2 Froude and Reynolds Number Scaling

As noted earlier, the minimum purging velocities for natural gas are defined in the AGA guidelines using two criteria: a Froude number of 0.7 and a Reynolds number of 4,000. To assess how purging conditions may need to change for hydrogen, the properties of hydrogen can be substituted into Equations (1) and (2) to find the equivalent minimum purging velocities for hydrogen, assuming that these same criteria of $Fr = 0.7$ and $Re = 4000$ apply. The results are presented in Figure 3. To achieve the same Froude number of 0.7 for hydrogen, the minimum purging velocity would need to be 1.7 times higher than the equivalent velocity for methane. To achieve the Reynolds number of 4000, the velocity would need to be 6 times higher for hydrogen. From a practical perspective, there could be challenges in achieving these higher velocities for hydrogen, due to the need to use much larger rider and vent sizes (to minimise the pressure drop).

Table 1. Methane and hydrogen properties

	Methane, CH_4	**Hydrogen, H_2**
Molecular mass (g/mol)[a]	16.043	2.016
Density (kg/m^3)*[a]	0.68	0.08
Dynamic viscosity (µPa.s)*[a]	11	8.7
Molecular diffusivity in air (cm^2/s)[b]	0.196	0.611
Lower flammable limit (% v/v)[c]	4.4†	4.0
Upper flammable limit (% v/v)[d]	15	75
Detonation cell size (mm)[e]	250-310	15
Minimum ignition energy (mJ)[d]	0.26	0.01
Laminar burning velocity (m/s)[d]	0.37	3.2
Equipment Group[c]	IIA	IIC

* Properties given at 15°C and standard atmospheric pressure

† The lower explosive limit for methane is quoted in some sources[a,b] as 5.0 % v/v

[a] Source: https://encyclopedia.airliquide.com

[b] Source: Roberts [10]

[c] Source: BS EN 60079-20-1:2010 [11]

[d] Source: Drysdale [12]

[e] Babrauskas [13]

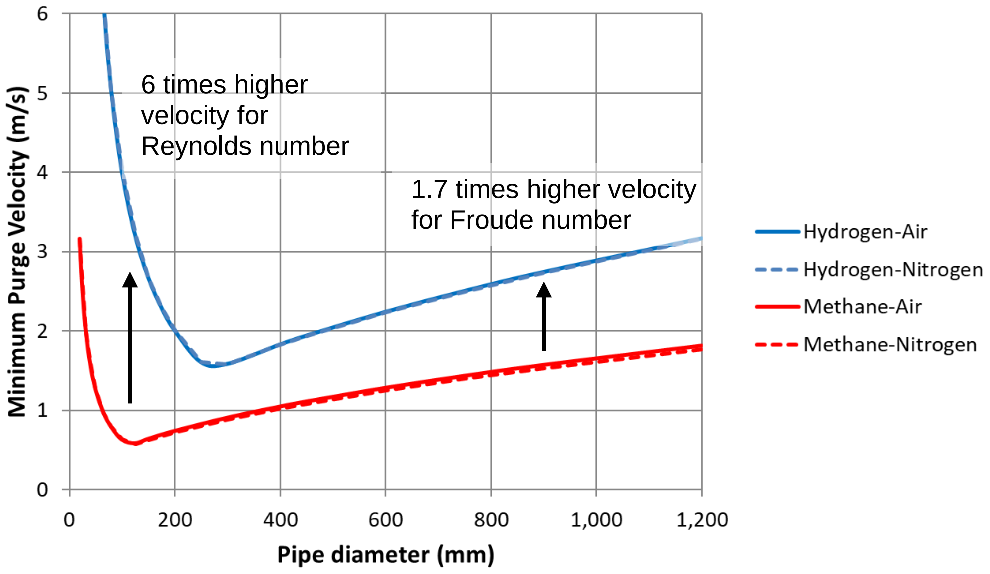


Figure 3. Minimum purging velocities of methane and hydrogen needed to achieve the Froude and Reynolds number criteria used by the AGA guidelines [4]

4.2 Molecular Diffusivity Effects

One of the factors that was not taken into account in the previous British Gas research nor the AGA Reynolds and Froude number criteria, is the effect of molecular diffusivity. Molecular diffusion causes gases to mix, due to the inherent random motion of molecules, and it occurs even in the absence of any laminar or turbulent flow. To assess the significance of molecular diffusion effects, the one-dimensional diffusion equation can be solved to assess the speed at which hydrogen and air diffuse across a distance comparable to the diameter of pipelines. The relevant equation is written as follows:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{3}$$

where C is the concentration, D the diffusivity, t time and x distance. Results are presented in Figure 4 from solving this equation numerically for diffusion of hydrogen and methane in air across distances of 50 mm and 200 mm. In the numerical model, at time zero, pure hydrogen (or methane) is located in one half of the space and pure air is located in the other half, with a sharp interface between the two gases. The model results in Figure 4 show how the concentration changes over a period of 100 seconds. These results do not account for any flow driven by pressure forces or buoyancy, the model simulates solely the effects of molecular diffusion.

The graphs in Figure 4 show that hydrogen diffuses across a distance of 50 mm and reaches nearly uniform concentrations within around 10 seconds. For methane, it takes around 30 – 40 seconds. Across a distance of 200 mm, it takes hydrogen longer to reach uniform concentrations (more than 100 seconds). For methane, concentrations still show a strong degree of stratification after 100 seconds.

The relative importance of diffusion depends on the molecular diffusivity, D, the time duration, t, and the distance over which the mixing occurs, x, according to the following relation:

$$D\frac{t}{x^2} \tag{4}$$

If it takes 10 seconds to reach uniform concentrations in the 50 mm space, and the 200 mm space is 4 times larger than the 50 mm space, then since x is squared in Equation (4), the time taken to reach uniform concentrations in the 200 mm space is not just 4 times longer but 4^2 = 16 times longer, i.e., 160 seconds.

This analysis of diffusion timescales is important when considering the recent results from hydrogen purging experiments (discussed below). In particular, in assessing the degree to which findings from purging tests in small diameter pipelines can be extrapolated to the behaviour of larger diameter pipelines. The results presented in Figure 4 are for hydrogen or methane diffusing in air. Similar results are expected for these fuel gases diffusing in nitrogen (i.e., when purging indirectly using nitrogen as the inert gas), given that air is composed of approximately 78% nitrogen.

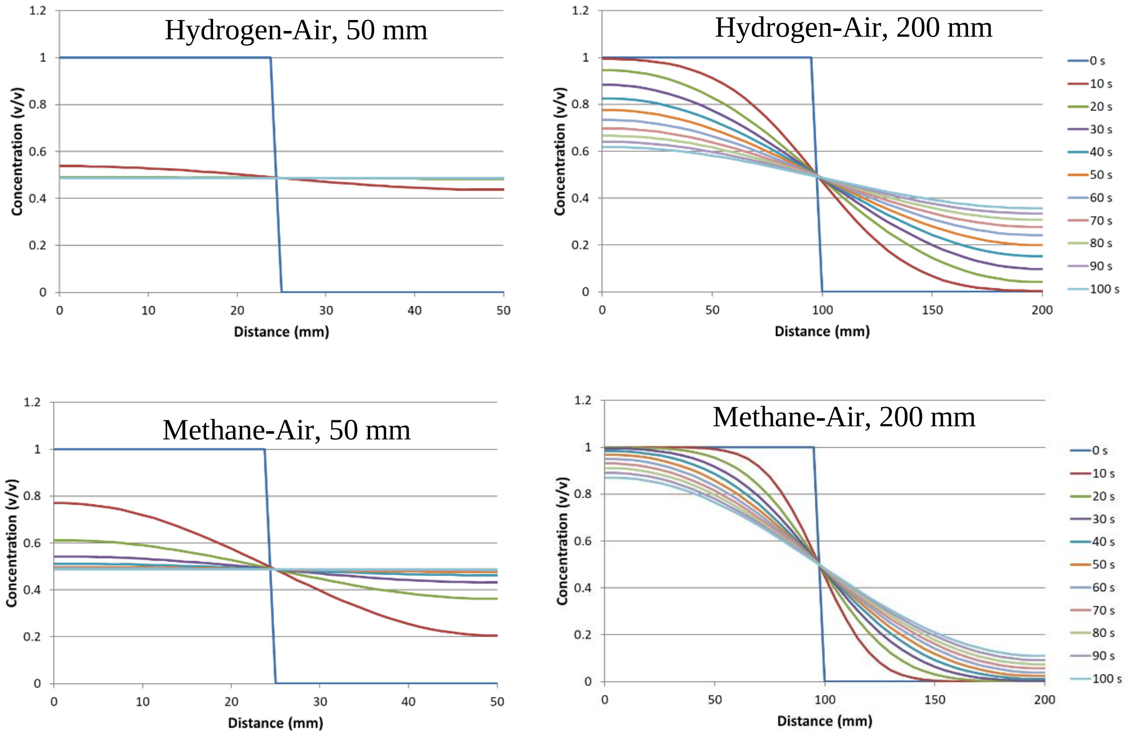


Figure 4. Solutions to the one-dimensional diffusion equation showing the change in hydrogen or methane concentrations over time in 50 mm wide or 200 mm wide spaces

5.0 RECENT RESEARCH ON HYDROGEN PIPELINE PURGING

5.1 HyDelta

HyDelta (https://hydelta.nl/) is a Dutch national research programme aimed at facilitating the large-scale implementation of hydrogen for heating in the Netherlands. Various useful HyDelta reports relating to repurposing of their existing natural gas network for hydrogen are available online[1]. The HyDelta study of hydrogen distribution pipeline purging was undertaken by KIWA NL [14] and it involved a series of experiments using two pipelines that were 200 m long, with nominal diameters of 100 mm and 200 mm. The pipelines were horizontal but at roughly the mid-point there was a raised bridge section 4.5 m higher than the upstream and downstream sections of pipeline. Concentrations were measured at three heights across the cross-section of the pipeline (top, middle and bottom) and at three locations along the length of the pipeline (upstream of the bridge, at the midpoint of the elevated bridge, and downstream of the bridge.

All of the tests were undertaken using indirect purging and Kooiman *et al*. [14] wrote that: “the use of nitrogen is (for the time being) recommended for safety-technical reasons in order to avoid flammable mixtures in the pipeline”. The tests showed that a purging velocity of 0.4 m/s was sufficient to purge the pipelines, but for practical reasons Kooiman *et al*. recommended that a minimum purging velocity of at least 1.0 m/s was used on the Dutch gas network. For larger diameter pipelines, they recommended to increase the purging velocity in proportion to the pipeline diameter. These velocities are well below the minimum velocity suggested by Figure 3, where the AGA criteria imply that the velocity would need to be around 2 m/s in the 200 mm pipeline and 4 m/s in the 100 mm pipeline.

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[1] https://zenodo.org/search?page=2&size=20&q=hydelta.

5.2 HyPurge

To support the H100 Fife neighbourhood hydrogen trials in Scotland (https://www.sgn.co.uk/H100Fife), SGN commissioned Steer Energy to conduct a series of hydrogen pipeline purging experiments in a project called “HyPurge” [15]. These direct purging trials (between hydrogen and air) used various pipeline configurations, with pipelines ranging in internal diameter (ID) from 51 mm to 238 mm, and lengths ranging from 6 m to 42 m.

The tests conducted using a 6 m long 51 mm ID pipeline involved very low purging velocities of between 0.08 m/s and 0.41 m/s. Concentration measurements in the vent indicated that hydrogen and methane purged completely, with a slightly more efficient purge for hydrogen. Tests on the 42 m long 200 mm and 250 mm ID pipelines used gas sensors located on the top and bottom of the pipeline at three locations to detect any layering of the gas. Three different venting arrangements were used to adjust the purging velocity. The smallest diameter vent restricted the velocity to the extent that it took around 20 minutes (1,200 seconds) for the hydrogen concentration to reach nearly 100% in the vent pipe. The molecular diffusion calculations presented above indicate that hydrogen will have diffused across the diameter of the 200 mm pipe within around 160 seconds. The purges did not show a persistent layer of stratified gas along the length of the pipe, but instead they all appeared to indicate that successful (complete) purges were eventually reached.

5.3 H21 Experiments

Two series of pipeline purging tests have been conducted in the H21 Phase 2 project. The first series of tests were undertaken by DNV using the “microgrid” at the Spadeadam test site. This consisted of a network of interconnected PE pipelines of various sizes, ranging from 63 mm to 630 mm outer diameter (OD), and lengths of a few tens of metres. Parts of the microgrid were operated at low, medium or intermediate pressures (i.e., within the range of 21 – 75 mbar, 75 mbar – 2bar, and 2 – 7 bar, respectively). The microgrid was designed primarily for various operational and demonstration purposes (not principally for purging measurements) and there were no direct measurements of concentration within the pipelines. Data from six trials have been assessed to date, which indicated that the purging efficiency increased as the Froude number was increased.

The second series of H21 pipeline purging tests is currently underway. They are being conducted on 100 m long lengths of 125 mm and 315 mm OD pipeline, with concentrations measured at five locations along the length of the pipelines, at both the top and the bottom of the pipeline, to assess the degree of stratification. All of these tests are being conducted using indirect purging of hydrogen with nitrogen, with some comparison tests using natural gas and some tests involving purging between natural gas and hydrogen, to simulate the conversion process on the network.

Additional experimental work on the H21 Phase 2 project has included ignition tests on 10 m lengths of buried PE pipe with a 180 mm diameter main and a separate 32 mm service. These were filled with stoichiometric hydrogen mixtures and ignited. In both cases, the hydrogen deflagration ran up to detonation, with a maximum overpressure of 50 bar. Given that the length to diameter ratios of the two pipelines were L/D = 63 and 385, detonation was expected. Neither the main nor the service suffered from catastrophic failure and there was no ground heave. However, a PE cap on the end of a pipe stub connected to the 180 mm diameter pipeline failed, and the measured over-pressure near the pipeline above ground was around 300 mbar. The test demonstrated that an internal hydrogen explosion in a relatively short length of pipe would have the potential to cause harm (due to impact injuries from projectiles, hearing damage, breaking of nearby windows etc.). For this reason, the H21 project is focusing on indirect purging of distribution pipelines, so that flammable mixtures of hydrogen are not present in pipelines during purging operations.

6.0 DISCUSSION

The preceding sections of this paper have described the scientific basis behind the current purging practices on the natural gas network, and the implications for hydrogen purging if the same AGA criteria used for natural gas were to be applied for hydrogen. Results from the Dutch HyDelta project and UK HyPurge project have then been discussed, which imply that much lower purging velocities could be used in practice than would be considered appropriate using the AGA criteria. Analysis of these results is still at a relatively early stage, but the results suggest that the high molecular diffusivity of hydrogen could explain some of the observed behaviour. Molecular diffusion could be helping to mix the hydrogen across the diameter of the pipelines over short timescales, avoiding stratification of hydrogen.

There are other reasons to expect the behaviour of hydrogen could differ from natural gas in purging operations. For example, the work by Gröbelbauer *et al*. [16] showed that in gravity currents generated by lock-exchange flows, the buoyant and dense currents exhibited similar characteristics when the difference in density between the two gases is small (e.g., for natural gas and air). However, for fluids with larger differences in density (e.g., hydrogen and air) the shape and speed of the buoyant and dense gravity currents was different (i.e., the speed of the dense gas along the floor of the channel was higher than the speed of the buoyant gas along the roof). This type of effect could, in principle, be taken into account in the purging model of Daish and Linden [8], which could use different critical Froude numbers for the leading and trailing edges of the mixed zone. However, the model would still be limited in not taking into account the effects of molecular diffusion.

7.0 OTHER PRACTICAL CONSIDERATIONS

There are other important practical issues that also need to be considered when purging hydrogen, in addition to the purging velocity. Currently, when purging natural gas, UK gas industry procedures dictate that the vent pipe must be located at least 5 m downwind from any ignition sources and care must be taken to ensure that vent gases are not drawn into nearby buildings. Due to the dispersion behaviour of hydrogen, it is expected that exclusion zones may need to increase in size. Guidance on the dispersion distances for hydrogen from vents is given in the recent hydrogen supplement to IGEM/SR/25 [17].

Measurements of noise levels have been made during hydrogen purging and venting operations as part of the H21 and SGN “LTS Futures” projects[2]. These indicate that noise levels will be higher for hydrogen than natural gas. It seems likely that at medium and/or intermediate pressures, throttling valves or silencers may be required to reduce noise levels, although it will be necessary to check that minimum purging velocities can still be achieved.

Ignition of vents during purging operations is likely to be more commonplace for hydrogen than for natural gas, due to its lower ignition energy. Experiments involving vent ignition with high-pressure hydrogen (relevant to transmission pipelines) have indicated that delayed ignition of vents can lead to airborne Vapour Cloud Explosions (VCE) with significant overpressures [18]. Tests undertaken by DNV at lower pressures relevant to the gas distribution network suggest that VCEs should be less of a concern, although an overpressure of 27 mbar was measured at a distance of 5 m following ignition of an intermediate pressure vent, which suggests that vents used in intermediate pressure (2 – 7 bar) purging operations will need to be located more than 5 m away from the nearest buildings.

Thermal radiation from ignited vents should be less of a concern for hydrogen than natural gas, due to the fact that hydrogen fires are less emissive. However, hydrogen fires can be more susceptible to flame tilt in crosswinds [19]. Since hydrogen flames are less visible than for natural gas, it may also be useful to provide gas network operatives with thermal cameras so that they can detect if the vent has ignited

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[2] https://www.sgn.co.uk/about-us/future-of-gas/lts-futures.

and to assess the size of the flame, as recommended in the recent report by Stedin for the Dutch hydrogen house conversion [20].

8.0 POSSIBLE FUTURE WORK

There is currently a knowledge gap in understanding the behaviour of hydrogen during purging operations. Models previously developed for natural gas (e.g., [8]) do not account for molecular diffusion effects, but recent purging tests appear to show these effects could play an important role in improving the purging efficiency, especially in smaller-diameter pipes. Whilst a pragmatic solution should be possible for the upcoming hydrogen trials, without this physical understanding, it is challenging to extrapolate results from recent experiments on relatively small diameter short pipelines to much larger and longer lengths of pipelines that are of practical interest on the gas distribution network. To address this issue, it would be useful to undertake further analysis, including a combination of theoretical/numerical studies, laboratory tests and carefully-monitored tests at larger scales.

The stratified flows research group at the University of Cambridge is well placed to develop a new model for hydrogen purging, given their research facilities (including access to high performance computing and world-class laboratory facilities) and their extensive background knowledge of stratified flows (which includes the original work undertaken for British Gas in the 1990's [8]). Improved understanding of the physics of pipeline purging would enable results from previous tests to be extrapolated with greater confidence. A new purging model would be useful to assess if and when direct purging could be used on the hydrogen network. Whilst the hydrogen village trial will use indirect purging with nitrogen, there are risks associated with use of high-pressure nitrogen gas cylinders on the wider gas network, with associated asphyxiation hazards plus issues around costs and training. An improved understanding of the physics could be used to refine the guidance on indirect purging (i.e., to maximise purging efficiencies and reduce costs associated with use of nitrogen and hydrogen) and also assess the risks and hazards associated with direct purging.

9.0 ACKNOWLEDGEMENTS

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