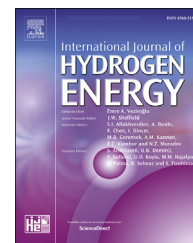


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Assessing the pressure losses during hydrogen transport in the current natural gas infrastructure using numerical modelling

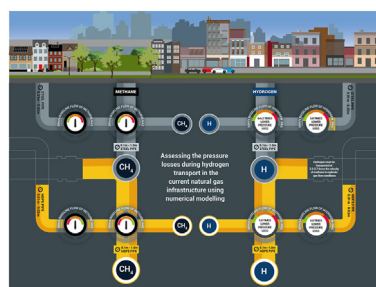
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HIGHLIGHTS

- Hydrogen is expected to replace methane by 2035 for domestic heating applications.
- Analytical and computational models were used to compare flow of hydrogen and methane.
- Hydrogen velocity must be up to 2.7 times faster than methane to replicate flow.
- MDPE pipes showed lower pressure losses than steel pipes due to reduced roughness.

GRAPHICAL ABSTRACT



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ABSTRACT

The UK government aims to transition its modern natural gas infrastructure towards Hydrogen by 2035. Since hydrogen is a much lighter gas than methane, it is important to understand the change in parameters when transporting it. While most modern work in this topic looks at the transport of hydrogen-methane mixtures, this work focuses on pure hydrogen transport. The aim of this paper is to highlight the change in gas distribution parameters when natural gas is replaced by hydrogen in the existing infrastructure. This study uses analytical models and computational models to compare the flow of hydrogen and methane in a pipe based on pressure loss. The Darcy-Weisbach and Colebrook-White equations were used for the analytical models, and the $k-\epsilon$ model was used for the computational approach. The variables considered in the comparison were the pipe material (X52 Steel and MDPE) and pipe diameters (0.01m–1m). It was observed that hydrogen had to be transported 250–270% the velocity of methane to replicate flow for a fixed length of pipe. Furthermore, it was noted that MDPE pipes has 2–31% lower pressure losses compared to X52 steel for all diameters when transporting hydrogen at a high velocity.

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Lastly, it was noted that the analytical model and computational model were in agreement with 1–5% error in their findings.

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Introduction

The UK government aims to transition its modern natural gas network (post 1970) to hydrogen by 2035 and this would require the shift from the use of natural gas to hydrogen for domestic heating applications [1,2]. The main advantage for the use of hydrogen is that it has no carbon emissions, making it an environmentally friendly option. Here, the term environmentally friendly refers to the minimal global warming potential of unburnt hydrogen and its combustion products (water vapour) [3,4]. In addition to this, hydrogen has a higher flame temperature; burning velocity; and consequently, higher thermal efficiency than natural gas [5] (Schiro, Stopato and Benato, 2020).

Currently, there are three prominent methods of hydrogen production, as shown in Fig. 1 [6]. The most prominent method for hydrogen production is through steam reforming. This method uses the reaction of hydrocarbons (mainly methane or coal) with steam to form hydrogen gas (also known as grey hydrogen) with CO_2 as a by-product being released into the atmosphere [7]. The modified approach to this process captures the carbon by products at the end of the steam reformation process and stores them underground. This process is a low emission process and does not affect the production of hydrogen (known as blue hydrogen) [7]. The production of grey and blue hydrogen is dependent on

hydrocarbons, suggesting that while hydrogen is a carbon neutral fuel, its production is not. To make the production of hydrogen more eco-friendly, the use of renewable energy and electrolysis has been suggested. Since the source of this hydrogen (also known as green hydrogen) is not hydrocarbon dependent, the production process is carbon neutral [7]. While green hydrogen production is environmentally sustainable, it is not cost effective due to the cost of renewable energy [7–9].

The use of hydrogen as an energy vector in combination with renewable energy sources (Wind, solar, geothermal etc.) has also been proposed [10–12,15]. The benefit of coupling hydrogen fuel (as an energy vector) to the renewable energy sector is that it has the potential to improve the reliability of this sector by reducing the issues caused due to weather dependency [10,8,11]. Consequently, using excess renewable energy to produce, and store hydrogen is a step towards reducing the carbon footprint of the hydrogen production process [13,14].

While Hydrogen has shown great potential as a fuel, it does bring its own challenges in terms of safety. Hydrogen has a very low ignition energy (0.019 mJ), and a very wide flammability range (4–75%) in air [15–17]. These two factors, combined with the environmental cost of producing hydrogen have played a large part in the slow transition away from natural gas. With the development of technologies to make hydrogen safer and more affordable, a shift in government policy and

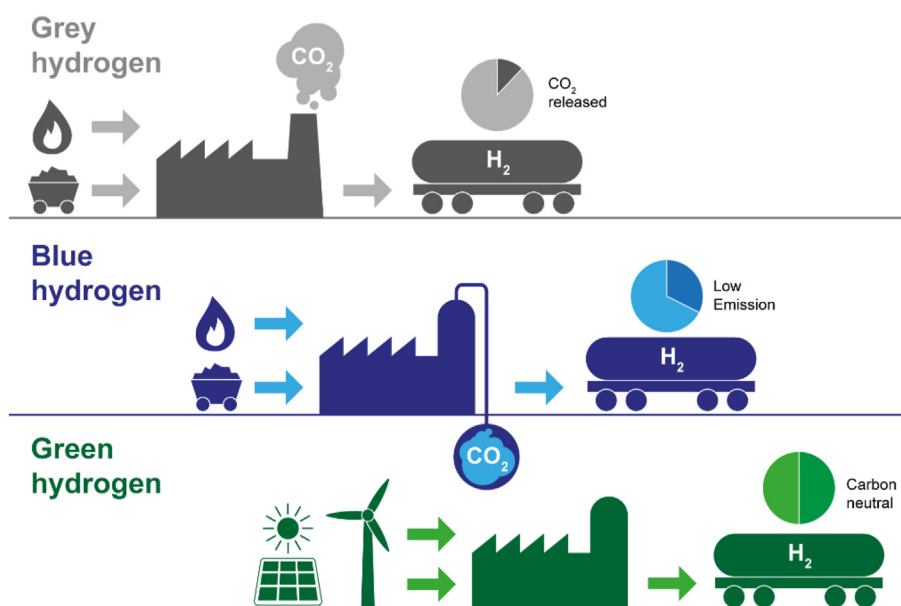


Fig. 1 – Simplified processes for the production of grey, blue, and green hydrogen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

public opinion are just as important. Currently, the Paris agreement has been a great driving force for multiple countries to shift towards energy solutions that slow down the effects of climate change [9,18]. Additionally, the decision of the UK government to create schemes to provide subsidies to organisations for investing and shifting towards renewable sources creates an incentive for the energy market to further diversify [19–21,12]. Consequently, investments in the renewable energy market are expected to reduce the cost of providing energy to the consumer thus making it more affordable and aiding the alleviation of the energy crisis [22,23]. The result of making an energy source like hydrogen more affordable is that it is likely to help improve public opinion, causing people to shift away from hydrocarbon fuels [24,12,25].

While it is important to improve public opinion on fuel sources like hydrogen, ensuring consumer safety while the fuel is used should be of utmost priority. Other than the fire and explosive risk of hydrogen, another factor that must be considered is the risk of hydrogen embrittlement when being used within the existing national gas network. Hydrogen embrittlement is the process in which hydrogen is diffused and absorbed into the metal microstructure at high temperature and pressure resulting in its embrittlement [26–28]. The embrittlement leads to formation and propagation of cracks, followed by material failure under high stress conditions [29–31,32]. This information is of key value and must be considered when understanding the implications of shifting from a natural gas based infrastructure to a hydrogen gas infrastructure. Hydrogen is much lighter than natural gas, resulting in higher mechanical requirements when being pumped. These two factors combined with the explosive risk posed by hydrogen create the need to assess the overall safety of the gas infrastructure in its readiness to shift to pure hydrogen by 2035.

Literature review

In its current state, majority of the research is focused on the short-term goal of understanding the flow of a natural gas and hydrogen mixture being transported through existing natural gas pipelines [11,33,34]. Looked at a range of different pipeline steels and their embrittlement behaviour when exposed to hydrogen and natural gas mixtures at high pressures. It was noted that the presence of hydrogen at pressures plays a role in the formation of critical defects in pipeline steels. This was caveated by the point that proper maintenance and repair can keep the pipeline functional – although alternative solutions must be considered on the long term [27]. Studied the effects of hydrogen on C–Mn steels used for natural gas transport. The key research from this study showed that these pipes are still suitable for natural gas-hydrogen mixtures (up to 30% v/v) but will not be a sustainable choice when the shift to pure hydrogen happens [35]. discussed the observation of hydrogen induced cracking in pipeline steels in the case of oil and gas drilling applications. The notable point from this study was that hydrogen diffusion is governed by the presence of traps in the microstructure. Consequently, irreversible trapping of hydrogen results in the crack formation and propagation in steels.

Kurz et al. [36] focused on the effect of natural gas-hydrogen mixtures and pure hydrogen on the compressor

network used to pressurise and transport the gas in pipelines. The key understanding derived from this study was that the use of hydrogen is bound to significantly increase the load on the compressors, thus increasing the transport costs. Alternatively, the use of re-staging compressors was suggested as a cost-effective solution [30]. Looked at the effect of pure hydrogen on high strength steels used in pipeline applications to understand influence of hydrogen embrittlement on mechanical properties of the steel. It was understood that hydrogen significantly reduces the ductility of high strength steels and is detrimental to the mechanical properties of steel.

Briottet et al. [29] summarised the hydrogen embrittlement process in pipeline steels (X80) and whether they could be a viable option when hydrogen is pumped through them. The major conclusion was that high strength steels were not a viable solution for hydrogen transport on the long term because of their loss in mechanical performance due to embrittlement. The authors also pointed out that the cost of hydrogen transport was costlier than that of natural gas for a given amount of energy [37]. Looked at the life cycle assessment of the natural gas network and how transport of pure hydrogen through this system would affect it from a logistical and economic point of view. This study verifies claims that once the cost of producing hydrogen reduces, and the process becomes more sustainable, the transport of hydrogen via pipelines longer than 100 km is at a competitive cost with natural gas transport [38]. Specifically looked at the conversion of the UK gas system for hydrogen transport and highlighted the concern that structures built before 1970 have iron or copper piping, which makes them unsuitable for hydrogen transport.

Objective

Based on the literature, a large portion of the studies over the past 10 years focus on the effects of natural gas-hydrogen mixtures on pipelines instead of pure hydrogen. Furthermore, these studies focused on the behaviour of the pipe material in a high-pressure environment as opposed to the performance of the pipe while being used for its intended application. Subsequently, the focus of all these studies was on gas transport over long distances with little or no focus on local or domestic transport.

Consequently, this numerical study looks at the how the transport performance of the hydrogen is affected in a fixed length of pipe (100 m) of different materials as compared to methane. Methane (largest component of natural gas) has been selected instead of natural gas to allow for replicability and reduce the potential error caused by the varied composition of natural gas. This further allows for a better comparison in performance between two pure gases. The pipe materials being compared are X52 steel, and Medium Density Polyethylene (MDPE). These materials are being considered due to their widespread usage in local and domestic gas transport networks (BSI Standards 6891, 2015; [39,36]. The objective of this study is to compare the flow of these two gases at various levels of the transport network and understand the different conditions required for successful transport of hydrogen in the natural gas network. Mathematical and computational modelling tools will be used to compare

gas flow performance based on pressure loss over a fixed distance.

Methodology

This study looks to understand the flow of gases through pipes using both mathematical and computational modelling. The comparative study allows for understanding the gap between empirical models (Darcy-Weisbach equation) and computational models (k- ϵ model) for fluid flow in confined conditions [40].

Mathematical modelling

Mathematical modelling of the gas flow in a pipe was done to theoretically estimate the pressure loss of a gas when it flows through a pipe of a given material. The Darcy-Weisbach equation (Equation (1)) was used to calculate pressure loss (P). The Colebrook-White model (Equation (2)) was used to estimate the friction factor. These equations were selected for the mathematical modelling due to their widespread applications and easy replicability [41–44].

$$\frac{\Delta P}{L} = f_D \cdot \frac{\rho}{2} \cdot \frac{v^2}{D} \quad (1)$$

$$\frac{1}{\sqrt{f_D}} = -2 \cdot \log \left(\frac{2.51}{Re \sqrt{f_D}} + \frac{\epsilon}{3.7D} \right) \quad (2)$$

In equation (1), pressure loss (P) was calculated as a function of friction (f_D), gas velocity (v), gas density (ρ), and pipe diameter (D). In equation (2), the friction factor (f_D) was calculated as a function of the turbulence of the gas (Reynold's number – Re), pipe roughness (ϵ), and pipe diameter (D).

Mathematical modelling was done to calculate the difference in pressure loss of hydrogen and methane when flowing through pipes for different materials and diameters (Table 1). The pipe materials considered were X52 steel, and MDPE [45,46]. The roughness of the X52 steel and MDPE pipes were taken as 0.04572 mm and 0.0015 mm respectively (Engineering ToolBox, 2003; [47,48]). These materials were chosen because the current UK government policy dictates the use of these materials for gas transport at various levels of distribution (National, local, and domestic – Table 2) [38]. Based on the level of distribution, different pipe diameters (nominal) were considered (0.01 m–1 m) [49,50].

Table 2 – Nominal pipe diameters and their corresponding scale of application.

Nominal Pipe Diameter (m)	Application
1	National level gas transport
0.914	National level gas transport
0.5	Local gas distribution
0.1	Local gas distribution
0.02	Domestic level transport
0.01	Domestic level transport

Simulation setup

Computational Fluid Dynamics (CFD) software ANSYS Fluent (2020R2) was used to simulate gas flow in X52 steel and MDPE [51,36,27]. Fig. 2 shows the setup of the simulation. The model geometry consists of the pipe body (100 m length) and the fluid domain. The key assumptions made were that (i) gas transport was a constant temperature process for the chosen length of pipe; (ii) the length of pipe was not near terminal points of the transport system – i.e. gas behaviour during start and stopping of flow was ignored; and (iii) The flow parameters were chosen to reflect adverse transport conditions. The different geometries designed for the simulation were based on the dimensions in Table 1 to allow comparison between the mathematical and computational modelling.

The k- ϵ model for turbulent flow was selected for the simulation of gas flow in the fluid domain of the geometry. This model was selected because of its popularity for use in confined flow problems, and minimal boundary condition requirements [52,40]. Additionally, this model provides key data with regards to the transfer of turbulent kinetic energy due to diffusive transport, and energy fluctuations. While the Darcy-Weisbach equation focuses on the pressure losses of the fluid due to velocity and friction, the k- ϵ model focuses on the work done by the fluid due to turbulence [40]. Given the turbulence conditions (Reynold's number) selected for the mathematical and computational modelling, the k- ϵ model was the preferred choice due to its efficiency with handling high Reynolds flows. While the computational model does not directly include the Reynold's number term, a boundary condition for Turbulence Intensity (Equation (3)) was used to include the influence of turbulence. Here, I is the Turbulence Intensity and Re is the Reynold's number.

$$I_D = 0.16(Re)^{-\frac{1}{8}} \quad (3)$$

Table 1 – Nominal pipe diameters for MDPE and X52 Steel pipes.

Nominal Diameter (mm)	MDPE – Inner diameter (mm)	MDPE – Outer diameter (mm)	Steel – Inner diameter (mm)	Steel – Outer diameter (mm)
10	9.46	11.64	9.23	13.7
20	18.92	23.28	18.846	26.67
100	101.2	125	102.26	114.3
500	494.8	560	533.6	559
914	915.6	1000	939.6	965
1000	1006.6	1100	996.94	1016

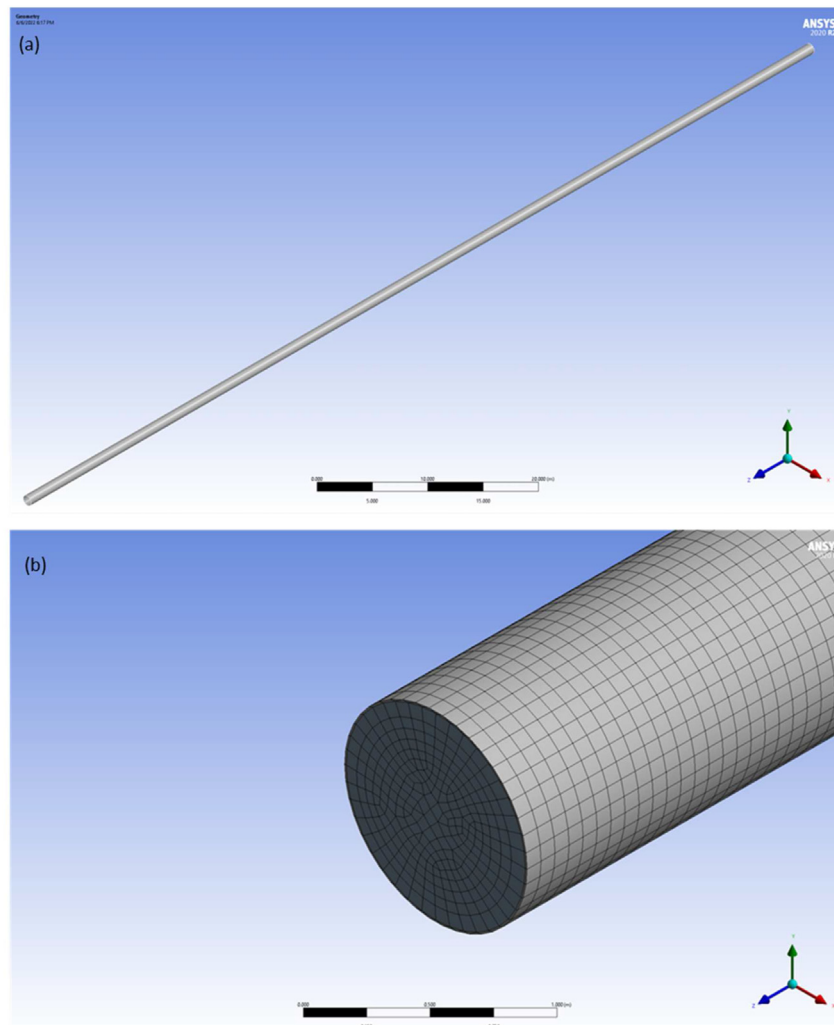


Fig. 2 – Model of problem geometry consisting of pipe and fluid domain. (a) Isometric view of 100 m pipe of 0.1 m diameter; (b) close-up of pipe outlet for mesh visualisation.

Fidelity study

A fidelity study was conducted on the computer (Lenovo Thinkstation; Intel i9 processor 3.10 GHz; 64 GB RAM) used for the simulations to understand the effect of the cell size used in the problem domain on the accuracy and computation time of the simulation. The fidelity study was conducted on a pipe of diameter 0.1 m with hydrogen flow velocity of 30 m/s. Gas velocity of 30 m/s was chosen as it represents a high load on the distribution system and can be used to assess the system performance in adverse conditions. The accuracy of the

simulation results was measured against results of the mathematical modelling to determine the error for a given cell size. Table 3 shows the initial results of the fidelity study. It highlights the element size, number of elements, number of processor cores used, computation time for the simulation, number of iterations, and the estimation of error using the value of pressure loss in the pipe.

From Table 3, the computation time is directly proportional to the number of elements for a fixed set of processor cores. The results from the computational model were within 7% of the mathematical model for the corresponding geometry. To

Table 3 – Results of fidelity study to determine the mesh size and measure computation time for the estimation of pressure loss in a fixed length of pipe.

Element size (m)	Number of Elements	Number of cores	Number of iterations	Computation Time (s)	Pressure loss (Pa)	Error %
0.5	3,959,963	8	624	1949	873.29	6.45
1.0	426,589	8	306	61	888.21	4.85
2.0	108,256	8	129	4	926.29	0.77
2.5	58,581	8	156	2	939.62	0.66

ensure mesh independence, the residual error was set to 10^{-6} for all initial tests. The solutions for all initial tests converged and the result for the higher fidelity meshes (0.5 m and 1 m) was within 2% of each other. This was suggestive of mesh independence. The coarse meshes (2 m and 2.5 m) were not considered because they were not adequately representative of the problem domain being considered. While mesh independence was established for the finer mesh sizes, it had a larger error in relation to the mathematical models. The cause for the error in relation to the mathematical model is quite possibly the factors considered in the calculation of pressure loss, and the difference in computation method. In the mathematical modelling, the calculation of pressure loss is based on the friction and interaction of the gas with the pipe walls. Conversely, the estimation of pressure loss in the computational modelling is dependent on the conversion of kinetic energy to other forms due to pressure differences and diffusive forces. In addition to this, the mathematical model computes the pressure loss as a bulk value based on the boundary conditions provided whereas the computational model has an iterative approach to estimate pressure loss

relative to the previous element in the problem domain. This observation implies that the number of elements in the simulation directly influences the calculation of pressure loss. Based on this, a trade-off between the computation time and error was established, resulting in the decision to keep the number of elements constant between all the simulations, to account for the variation in geometry. Table 4 shows the list of simulations and the number of elements for a given geometry used in each of the simulations.

Results and discussion

Estimating pressure loss

Darcy-Weisbach equation (Equation (1)) used with Colebrook-White equation (Equation (2)) for the prediction of pressure loss for a fixed straight length of pipe.

Fig. 3 shows the pressure loss per meter for the two gases being transported in steel and MDPE pipes of different diameters (0.01 m, 0.02 m, 0.1 m, 0.5 m, 0.914 m, 1.0 m). The

Table 4 – Element size and numbers for models of Steel and MDPE pipes for nominal diameters 0.01 m–1 m.

Serial Number	Gas Type	Gas Velocity (m/s)	Nominal Pipe Diameter (m)	Pipe Material	Element Size (m)	Number of elements
1	Methane	30	0.01	X52 Steel	0.5	374,814
2	Methane	30	0.02	X52 Steel	0.75	256,747
3	Methane	30	0.1	X52 Steel	1	410,916
4	Methane	30	0.5	X52 Steel	0.5	778,814
5	Methane	30	0.914	X52 Steel	0.5	444,768
6	Methane	30	1.0	X52 Steel	0.5	441,947
7	Methane	30	0.01	MDPE	0.5	423,969
8	Methane	30	0.02	MDPE	0.75	285,138
9	Methane	30	0.1	MDPE	1.0	415,206
10	Methane	30	0.5	MDPE	0.5	803,088
11	Methane	30	0.914	MDPE	0.5	440,947
12	Methane	30	1.0	MDPE	0.5	407,330
13	Hydrogen	30	0.01	X52 Steel	0.5	374,814
14	Hydrogen	30	0.02	X52 Steel	0.75	256,747
15	Hydrogen	30	0.1	X52 Steel	1	410,916
16	Hydrogen	30	0.5	X52 Steel	0.5	778,814
17	Hydrogen	30	0.914	X52 Steel	0.5	444,768
18	Hydrogen	30	1.0	X52 Steel	0.5	441,947
19	Hydrogen	30	0.01	MDPE	0.5	423,969
20	Hydrogen	30	0.02	MDPE	0.75	285,138
21	Hydrogen	30	0.1	MDPE	1.0	415,206
22	Hydrogen	30	0.5	MDPE	0.5	803,088
23	Hydrogen	30	0.914	MDPE	0.5	440,947
24	Hydrogen	30	1.0	MDPE	0.5	407,330
25	Hydrogen	80	0.01	X52 Steel	0.5	374,814
26	Hydrogen	80	0.02	X52 Steel	0.75	256,747
27	Hydrogen	80	0.1	X52 Steel	1	410,916
28	Hydrogen	80	0.5	X52 Steel	0.5	778,814
29	Hydrogen	80	0.914	X52 Steel	0.5	444,768
30	Hydrogen	80	1.0	X52 Steel	0.5	441,947
31	Hydrogen	75	0.01	MDPE	0.5	423,969
32	Hydrogen	75	0.02	MDPE	0.75	285,138
33	Hydrogen	75	0.1	MDPE	1.0	415,206
34	Hydrogen	75	0.5	MDPE	0.5	803,088
35	Hydrogen	75	0.914	MDPE	0.5	440,947
36	Hydrogen	75	1.0	MDPE	0.5	407,330

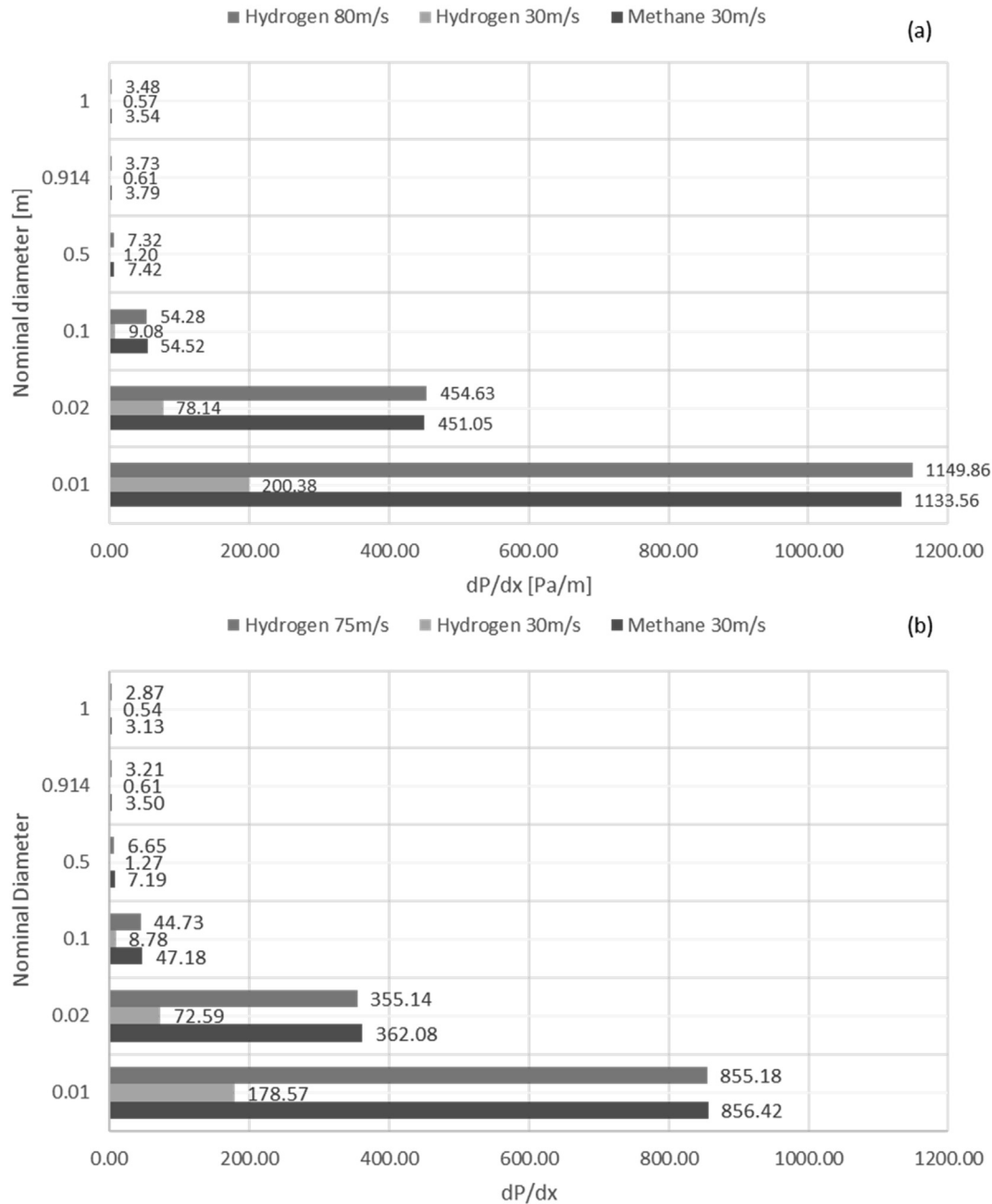


Fig. 3 – Estimation of pressure loss using the Darcy-Weisbach equation for methane and hydrogen gas flow in (a) Steel and (b) MDPE Pipes of different nominal diameters (0.01m–1m).

mathematical model was applied to estimate the velocity of hydrogen required to replicate similar flow conditions as methane based on pressure loss. Methane flowing at 30 m/s was selected as the baseline for comparison as it represents a high energy demand and is a case for adverse gas distribution conditions due to high load on the distribution network. The similarity in flow between the gases is measured based on the pressure loss per unit length [53]. The change in velocity results in changes in the turbulence (Reynold's number) of the gas and the friction factor [53]. The different pipe diameters are inversely proportional to the relative roughness of the pipe materials, resulting in an inversely proportional relationship

between the relative roughness and the estimation of friction factor (Equations (1) and (2)). Based on this, pressure losses have been compared for a fixed set of diameters.

From Fig. 3, it was noted that hydrogen being transported at the same velocity as methane (30 m/s) has significantly lower pressure losses (approximately 6 times), caveated by significantly lower operating pressures. Comparing Fig. 3a and b, similar trends were observed in the calculation of pressure loss against different diameters for pipes of different materials. From Fig. 3a, it was noted that the pressure loss for hydrogen at 30 m/s was 6–6.2 times lower than that of methane at the same velocity, for pipe diameters 0.1m–1.0 m.

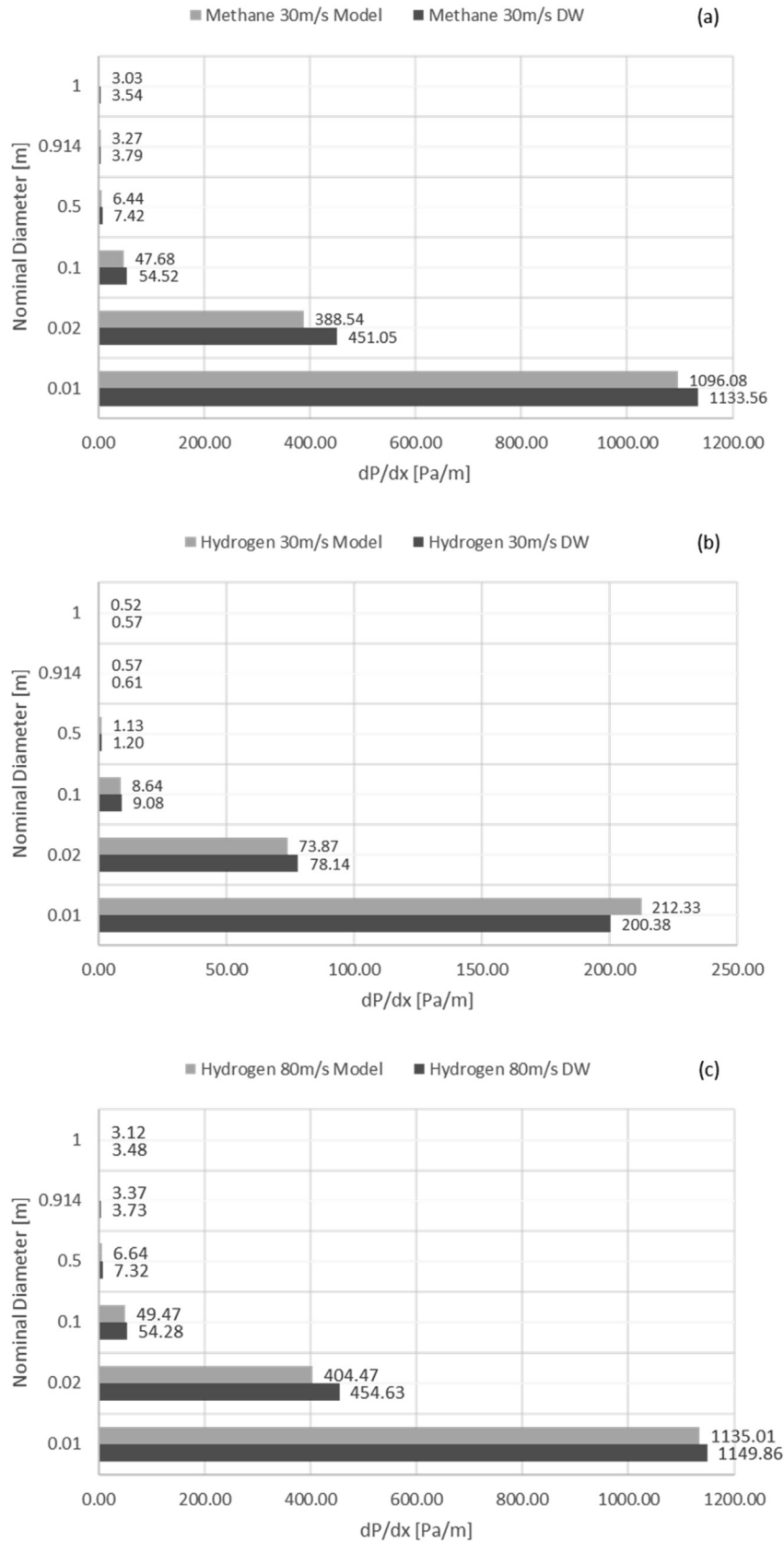


Fig. 4 – Comparing mathematical model (DW equation) to computational model (k-e model) based on pressure losses observed for (a) Methane with velocity 30 m/s; (b) Hydrogen with velocity 30 m/s (smaller x-axis scale used for readers' convenience); and (c) Hydrogen with velocity 80 m/s in a steel pipe.

Due to computational errors, the pressure loss for hydrogen at 30 m/s was approximated 5.8 times lower than methane at 30 m/s for smaller diameters (0.01 m, 0.02 m). Fig. 3b showed a similar trend to Fig. 3a, but the pressure loss for hydrogen at 30 m/s was 5.8 times lower than methane at 30 m/s (for pipe diameters 0.1 m, 0.5 m, 0.914 m, and 1.0 m), and 4.8 times lower for pipe diameters (0.01 m and 0.02 m). The difference in pressure losses for methane and hydrogen at 30 m/s was lower for MDPE pipes (Fig. 3b) because MDPE is a smoother material than steel, which results in lower pressure losses. The pressure loss per unit length reduces for larger diameters because of the reduced interaction of the fluid with the pipe walls. The reduced interaction of the fluid with the pipe walls results in lower frictional losses of the fluid, thus resulting in lower pressure losses per unit length of pipe. Furthermore, it was noted that steel pipes showed higher pressure losses than MDPE pipes for all diameters and gas velocities. The higher frictional losses in steel pipes were observed due to the higher roughness of steel compared to MDPE (X52 steel has a roughness of 4.57×10^{-5} m; while MDPE has a roughness of 1.5×10^{-6} m).

Additionally, Hydrogen must be transported at approximately 2.5–2.7 times the velocity of methane to create comparable flow conditions. The factors influencing this are the density and viscosity of the two gases. Hydrogen being a lighter (Density = 0.0832 kg/m^3), and less viscous gas (viscosity = 0.00000876 Pa s) than methane (Density = 0.664 kg/m^3 ; viscosity = 0.00001084 Pa s) has 84% lower turbulence at 30 m/s. This is due to the lower Reynold's number of hydrogen (2629) compared to methane (16,961) at 30 m/s. These density and viscosity influence the estimation of friction factor which in turn affects the calculation of pressure losses in pipes (Equation (2)). In addition to the physical properties of the gases, the pipe material also affects the flow of gases. MDPE is a smoother material (lower absolute roughness) compared to steel, which results in lower friction factors for gases travelling at the same velocity (Equation (1)). Lower friction factors combined with lower absolute roughness further bolster the fact that MDPE pipes have lower pressure losses due to friction, but lower operating pressures as well.

The consequence of increasing the velocity of hydrogen is the proportional increase in volumetric flowrate for a fixed pipe cross-section. The increase in volumetric flowrate suggests an increased mass flowrate of hydrogen through a given point in the pipe. Consequently, this would increase the energy supplied by the gas network. The increase in mass flow rate of hydrogen is likely to influence the onset and propagation of cracking and embrittlement in steel pipes over a fixed duration of time [38,54,32]. While embrittlement is a known concern with hydrogen transport in steel pipes, it is out of scope for the purpose of this study.

Comparing gas flow performance

The computational model (k- ϵ model) was used to verify and compare findings from the mathematical model (Darcy-Weisbach and Colebrook-White equations). The computational model simulates turbulent fluid flow using additional parameters like diffusive transport in conjunction with

mechanical factors like friction from pipe walls. The comparison of the gas flow performance was done based on the dP/dx . Facet averages of pressure were used at the inlet and outlet of the computational model to calculate the pressure loss (dP) in the pipe, and the dP/dx (by dividing dP with the length of the pipe i.e., 100 m). dP/dx was used as the metric for comparison of the two gases because it is representative of the influence of mechanical factors on the gas flow performance.

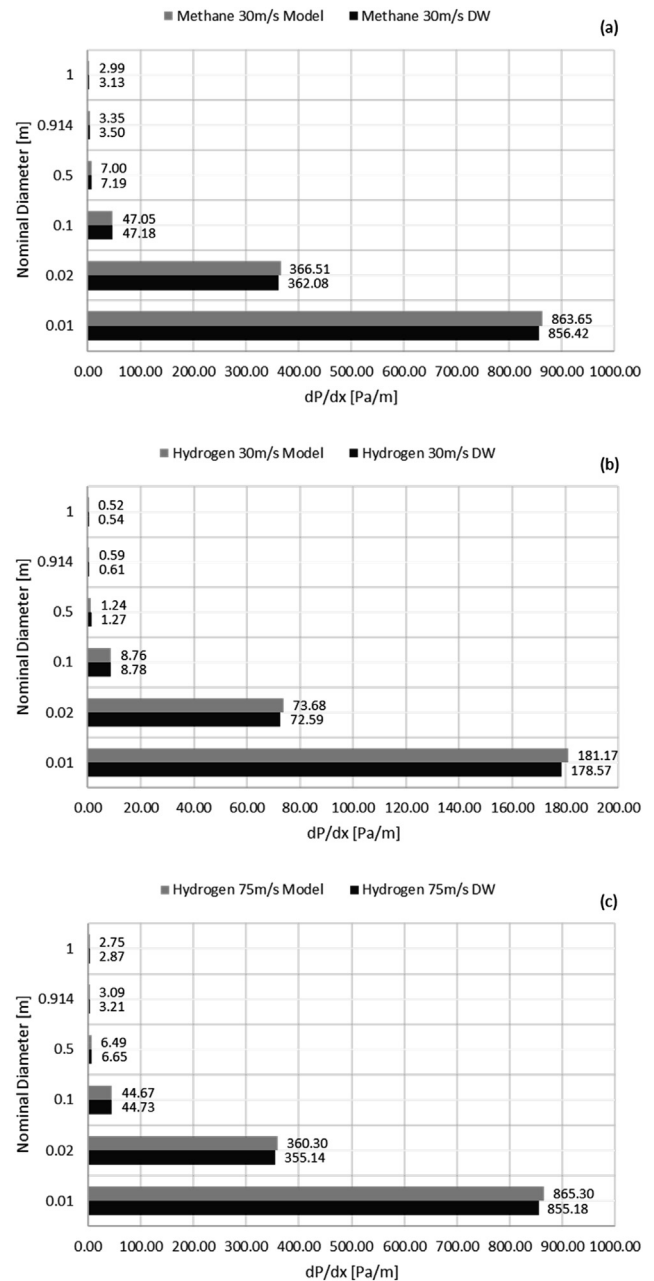


Fig. 5 – Comparing mathematical model (DW equation) to computational model (k- ϵ model) based on pressure losses observed for (a) Methane with velocity 30 m/s; (b) Hydrogen with velocity 30 m/s (smaller x-axis scale used for readers' convenience); and (c) Hydrogen with velocity 75 m/s in a MDPE pipe.

Additionally, it is a common metric to both models, thus making it a preferred choice for comparing the flow performance of methane and hydrogen.

Figs. 4 and 5 show the comparison of dP/dx for the mathematical and computational models for the flow of hydrogen and methane in steel and MDPE pipelines, respectively.

When comparing the pressure losses of methane and hydrogen at different velocities in different pipe materials, it was noted that there was an inconsistency in the $k-\epsilon$ model values for pipe diameters of 0.01 and 0.02 m. The primary cause for this observation is the limited capability of this model to compute transitional flows [40]. The Reynold's numbers of both the gases at the velocities being considered are suggestive of transitional flow instead of turbulent flow ($2000 < Re < 4000$). The $k-\epsilon$ model is most effective when computing high turbulent flows (high Reynold's number), and

that can be noted from the consistent pressure loss results observed for pipe diameters 0.1 m–1 m.

When comparing the pressure loss of the gases for pipe diameters 0.1 m–1 m, it was noted that the $k-\epsilon$ model consistently under-predicted the pressure loss when compared to the Darcy-Weisbach model. One potential reason for this observation is the influence of gas diffusion at high velocities combined with the roughness of the pipe. Additionally, the computation method used by the $k-\epsilon$ model is a step-based method, whereas the D-W model uses a bulk estimation method, resulting in the differences in predicted pressure losses.

When comparing the results from both models, it was observed that they were in agreement. The difference in values between the D-W model and $k-\epsilon$ model is between 1 and 5%. Additionally, the computational model showed

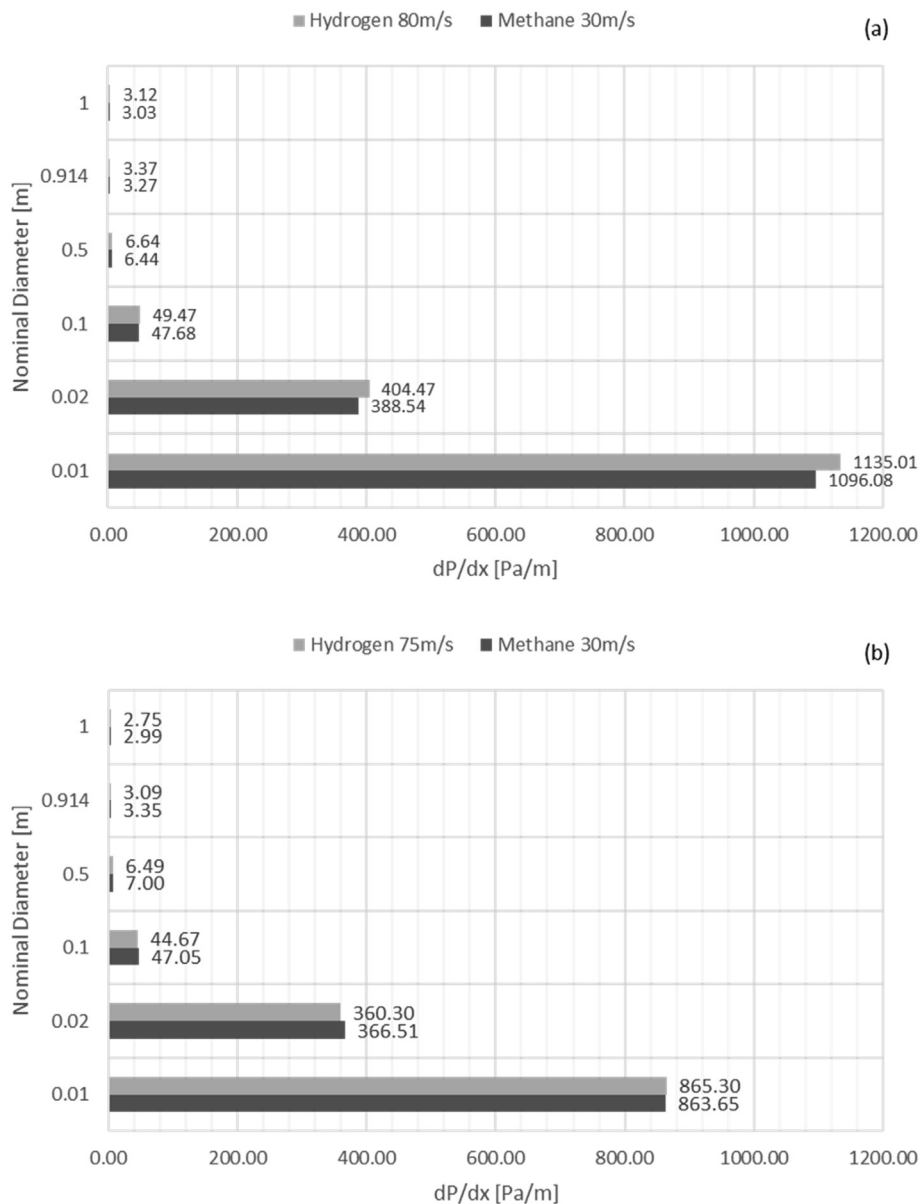


Fig. 6 – Comparison of gas flow and pressure loss in hydrogen (80 m/s, 75 m/s) and methane (30 m/s) in (a) steel pipes; and (b) MDPE pipes.

similar trends in pressure loss when comparing the two materials, with higher pressure losses in steel pipes. While the models used generate an approximate value for pressure loss in both gases, the weightage of the mechanical factors in these models is the same. The influence of factors such as gas diffusion, combined with the stepwise computational method plays a role in the under-prediction of pressure loss from the $k-\epsilon$ model.

Comparing pipe material performance

The pipe material has a direct influence on the flow of gas through the pipeline. The absolute roughness of the pipe is a key variable in the determination of the friction factor which in turn influences the pressure loss. The two materials have vastly different absolute roughness (X52 steel has a roughness of 4.57×10^{-5} m; while MDPE has a roughness of 1.5×10^{-6} m) and this is an influencing factor in deciding the kind of pipe being used at various stages of the transport process. Fig. 6 shows the gas flow performance for the two different pipe materials based on the pressure loss.

From Fig. 6, MDPE being smoother than steel, has lower dP/dx values for all pipe diameters. It was noted that the dP/dx for methane and hydrogen was lower in MDPE pipes compared to steel pipes. Subsequently, it was noted that the velocity required for hydrogen to replicate the flow characteristics of methane is also slightly lower in MDPE pipes (75 m/s) as compared to steel pipes (80 m/s). In both cases, the gas velocity required to replicate the flow of methane is much higher than 30 m/s. This implies that, in both types of pipes, the amount of energy required to transport hydrogen is much larger than the energy required to transport methane. This can also be attributed to the lower density and viscosity of hydrogen compared to methane. Furthermore, the lower pressure losses in MDPE pipes make it preferable for use in local and domestic transport of gas while steel pipes are used for long distance transport. The lower energy consumption in gas transport combined with a reduced risk of embrittlement make MDPE pipes a preferred choice of pipe material for gas distribution on the consumer part of the grid. The lower dP/dx for MDPE pipes make it more compliant with safety regulations with regards to gas transport to appliances in a domestic setup (BSI Standards 6891, 2015).

The key findings of this study suggest that transporting hydrogen at the same velocity as methane would require modifications given hydrogen's low density and viscosity. The suggested changes need to be made to the long-distance transport network in accordance with the findings by Refs. [36,55,37]. At the local and domestic scale minor changes are required at the user end to make the network and user appliances compatible and safer for hydrogen use in accordance with the findings from the Hy4Heat project [56,57].

Conclusions

Mathematical and computational modelling was done to compare the flow of hydrogen and methane in the natural gas

infrastructure. Understanding the flow of hydrogen in the natural gas infrastructure is important because of the potential shift in policy in favour of using hydrogen as an energy vector. The flow conditions of the two gases were compared for pipes of two different materials (X52 steel and MDPE), and different diameters (0.01m–1m). The broad range of diameters was selected to represent the various stages of gas distribution from long distance transport to domestic distribution. The key results are as follows.

- Based on the mathematical and computational modelling, the primary observation is that hydrogen must be pumped at a much higher velocity (~2.5–2.7 times) than methane to replicate similar flow conditions. This is because hydrogen is a much lighter gas (~8 times less dense) and has a lower viscosity at the same temperatures.
- The velocity of hydrogen required to replicate the pressure loss of methane was lower in MDPE pipes (75 m/s) compared to steel pipes (80 m/s).
- The roughness of the pipe material plays a key role in the estimation of pressure loss during gas flow. MDPE pipes being a factor of 10 smoother than steel pipes showed lower pressure losses during gas flow.
- The roughness of the pipe material influences pressure losses during turbulent flow. X52 steel being rougher than MDPE, showed larger pressure losses for both gases, and all the different pipe diameters considered.
- Based on the computational models, hydrogen had 2–31% lower pressure loss when transported in MDPE pipes at high velocity (75 m/s) for different pipe diameters (0.01m–1m). Based on the mathematical models, hydrogen had 9–34% lower pressure loss when transported in MDPE pipes at high velocity (75 m/s) for different pipe diameters (0.01m–1m).
- It was observed that the pressure losses were lower in larger diameter pipes due to reduced interaction of the gas with the pipe wall, resulting in reduced losses due to friction.

Follow on studies because of this work aim to look at the transport of methane/hydrogen blends within the existing infrastructure, and the influence of internal pipe coatings on the transport of hydrogen within the gas distribution infrastructure. Additionally, studies will also look to assess the challenges created by hydrogen embrittlement when the natural gas infrastructure transitions towards pure hydrogen transport. Future parametric studies will also consider the effect of changing temperature and humidity on transport conditions.

In conclusion, it is important to highlight the fact that shifting towards the use of hydrogen in the natural gas infrastructure is relatively feasible, but specific considerations must be made. The change in energy consumption for gas transport must be accounted for, alongside the change in policy regarding the safety and maintenance of the infrastructure. Lastly, provisions must be made to ensure the safe transportation and consumption of hydrogen at a local and domestic scale to ensure the safety of the consumers.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2023.05.208>.

REFERENCES

- [1] Dnv GL. Testing paves the way for hydrogen use in homes - DNV. 2020. *Perspectives* - DNV GL Available at: <https://www.dnv.com/oilgas/perspectives/testing-paves-the-way-for-hydrogen-use-in-homes.html>. [Accessed 4 June 2022].
- [2] Kwarteng K, Trevelyan A-M. UK government launches plan for a world-leading hydrogen economy - gov.UK. 2021. Available at: <https://www.gov.uk/government/news/uk-government-launches-plan-for-a-world-leading-hydrogen-economy>. [Accessed 4 June 2022].
- [3] Derwent RG. Hydrogen for heating: ATMOSPHERIC IMPACTS A literature review. 2018 [Newbury].
- [4] Sherwood SC, Dixit V, Salomez C. The global warming potential of near-surface emitted water vapour. *Environ Res Lett* 2018;13(10) [Institute of Physics Publishing].
- [5] Shiro F, Stoppato A, Benato A. Modelling and analyzing the impact of hydrogen enriched natural gas on domestic gas boilers in a decarbonization perspective. *Carbon Resources Conversion*, 3 KeAi Publishing Communications Ltd., 2020:122–9.
- [6] Hermesmann M, Müller TE. Green, turquoise, blue, or grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems Progress in Energy and Combustion Science, 90; 2022. p. 01–28 [Elsevier Ltd.].
- [7] Abrafi Awuah MY. Hydrogen safety. Milton-Keynes: Cranfield University; 2018.
- [8] Demirbas A. Future hydrogen economy and policy *energy sources, Part B: economics, Planning and policy*. Taylor and Francis Inc.; 2017.
- [9] Koneczna R, Cader J. Hydrogen in the strategies of the European Union member states. *Gospodarka Surowcami Mineralnymi/Mineral Resources Management* 2021;37(3):53–74. Polska Akademia Nauk.
- [10] Akhtari MR, Shayegh I, Karimi N. Techno-economic assessment and optimization of a hybrid renewable earth - air heat exchanger coupled with electric boiler, hydrogen, wind and PV configurations. *Renew Energy* 2020;148:839–51. Elsevier Ltd.
- [11] Liu J, Teng L, Liu B, Han P, Li W. Analysis of hydrogen gas injection at various compositions in an existing natural gas pipeline. *Front Energy Res* 2021;9 [Frontiers Media S.A.].
- [12] Nastasi B. Hydrogen policy, market, and R&D projects. In: *Solar hydrogen production: processes, systems and technologies*. Elsevier; 2019. p. 31–44.
- [13] Ballo A, Valentin KK, Korgo B, Ogunjobi KO, Agbo SN, Kone D, Savadogo M. Law and policy review on green hydrogen potential in ECOWAS countries. *Energies* 2022;15(7):2304. MDPI AG.
- [14] Tholen L, Leipprand A, Kiyar D, Maier S, Küper M, Adisorn T, Fischer A. The green hydrogen puzzle: towards a German policy framework for industry. *Sustainability* 2021;13(22) [MDPI].
- [15] Cirrone DMC, Makarov D, Molokov V. Simulation of thermal hazards from hydrogen under-expanded jet fire. *Int J Hydrogen Energy* 2019;44(17):8886–92. Elsevier Ltd.
- [16] Hooker P, Hall J, Hoyes JR, Newton A, Willoughby D. Hydrogen jet fires in a passively ventilated enclosure. *Int J Hydrogen Energy* 2017;42(11):7577–88. Elsevier Ltd.
- [17] Schefer RW, Merilo EG, Groethe MA, Houf WG. Experimental investigation of hydrogen jet fire mitigation by barrier walls. *Int J Hydrogen Energy* 2011;36(3):2530–7.
- [18] UNFCCC. Adoption of the paris agreement - Paris agreement. 2015. Available at: Must specify DOI or URL if using the accessed field (Accessed: 4 June 2022).
- [19] Collins L. UK to finalise world's first national subsidy for clean hydrogen production by end of the year | Recharge. Recharge, Available at: 2022. <https://www.rechargenews.com/energy-transition/uk-to-finalise-worlds-first-national-subsidy-for-clean-hydrogen-production-by-end-of-the-year/2-1-1200842> (Accessed: 4 June 2022).
- [20] Hands G. Government launches new scheme for technologies producing hydrogen from biomass - gov.UK. 2022. Available at: <https://www.gov.uk/government/news/government-launches-new-scheme-for-technologies-producing-hydrogen-from-biomass>. [Accessed 4 June 2022].
- [21] Hands G, Kwarteng K. Biggest ever renewable energy support scheme opens - gov.UK. <https://www.gov.uk/government/news/biggest-ever-renewable-energy-support-scheme-opens>. [Accessed 4 June 2022].
- [22] Birol F. What does the current global energy crisis mean for energy investment? – Analysis - IEA. International Energy Agency 2022. <https://www.iea.org/commentaries/what-does-the-current-global-energy-crisis-mean-for-energy-investment>. [Accessed 10 September 2022].
- [23] Kåberger T. The energy crisis and the role of renewables. Renewable Energy Institute 2022. <https://www.renewable-ei.org/en/activities/column/REupdate/20220622.php>. [Accessed 10 September 2022].
- [24] Andreasen KP, Sovacool BK. Mapping and interpreting critical hydrogen stakeholders in Denmark. *Int J Hydrogen Energy* 2014;39(15):7634–7. Elsevier Ltd.
- [25] Peter Andreasen K, Sovacool BK. Energy sustainability, stakeholder conflicts, and the future of hydrogen in Denmark *Renewable and Sustainable Energy Reviews*. Elsevier Ltd; 2014.
- [26] Lutostansky E, Creitz L, Jung S, Schork J, Worthington D, Xu Y. Modeling of underground hydrogen pipelines. *Process Saf Prog* 2013;32(2):212–6.
- [27] Østby E, Høvik D, Hugaas B-A, Agnes N, Horn M. Hydrogen's peculiar effect on material properties: do we need to be concerned about hydrogen transport in pipelines?. 2021.
- [28] Zhang T, Zhao W, Deng Q, Jiang W, Wang Y, Wang Y, Jiang W. Effect of microstructure inhomogeneity on hydrogen embrittlement susceptibility of X80 welding HAZ under pressurized gaseous hydrogen. *Int J Hydrogen Energy* 2017;42(39):25102–13. Elsevier Ltd.
- [29] Briottet L, Batisse R, De Dinechin G, Langlois P, Thiers L. Recommendations on X80 steel for the design of hydrogen

- gas transmission pipelines. *Int J Hydrogen Energy* 2012;37(11):9423–30.
- [30] Briottet L, Moro I, Lemoine P. Quantifying the hydrogen embrittlement of pipeline steels for safety considerations. *Int J Hydrogen Energy* 2012;37(22):17616–23.
- [31] Chen H, Mao Z. The study on the results of hydrogen pipeline leakage accident of different factors. In: IOP conference series: earth and environmental science. 64; 2017. Institute of Physics Publishing.
- [32] Stalheim D, Boggess T, Bromley D, Jansto S, Ningileri S. Continued microstructure and mechanical property performance evaluation of commercial grade api pipeline steels in high pressure gaseous hydrogen. In: International pipeline conference. Calgary: ASME; 2012.
- [33] Papadimas DD, Peng JK, Ahluwalia RK. Hydrogen carriers: production, transmission, decomposition, and storage. *Int J Hydrogen Energy* 2021;46(47):24169–89. Elsevier Ltd.
- [34] Pluvinage G. Mechanical properties of a wide range of pipe steels under influence of pure hydrogen or hydrogen blended with natural gas. *Int. J. Pres. Ves. Pip* 2021;190. Elsevier Ltd.
- [35] Findley KO, O'Brien MK, Nako H. Critical assessment 17: mechanisms of hydrogen induced cracking in pipeline steels. *Mater Sci Technol* 2015;31(14):1673–80. Maney Publishing.
- [36] Kurz R, Lubomirsky M, Bainier F. Hydrogen in pipelines: impact of hydrogen transport in natural gas pipelines. 2020.
- [37] Wulf C, Reuß M, Grube T, Zapp P, Robinius M, Hake JF, Stolten D. Life Cycle Assessment of hydrogen transport and distribution options. *J Clean Prod* 2018;199:431–43. Elsevier Ltd.
- [38] Dodds PE, Demoullin S. Conversion of the UK gas system to transport hydrogen. *Int J Hydrogen Energy* 2013;38(18):7189–200.
- [39] Kuczynski S, Łaciak M, Olijnyk A, Szurlej A, Włodek T. Thermodynamic and technical issues of hydrogen and methane-hydrogen mixtures pipeline transmission. *Energies* 2019;12(3) [MDPI AG].
- [40] Tu J, Yeoh G-H, Liu C. Computational fluid Dynamics: a practical approach. 3rd ed. Oxford, United Kingdom: Elsevier; 2018.
- [41] Botros KK, Shouman A. Relationship between roughness height in use with Colebrook roughness function and the internal wall surface roughness parameters for stainless steel pipes. *Elsevier J Nat Gas Sci Eng* 2016;35:197–202. Available at: 10.1016/J.JNGSE.2016.08.044 (Accessed: 8 March 2023).
- [42] Čojbašić Ž, Brkić D. Very accurate explicit approximations for calculation of the Colebrook friction factor. *Int J Mech Sci* 2013;67:10–3. Available at: 10.1016/J.IJMECS.2012.11.017 (Accessed: 8 March 2023).
- [43] Dyachenko SA, Zlotnik A, Korotkevich AO, Chertkov M. Operator splitting method for simulation of dynamic flows in natural gas pipeline networks. *North-Holland Phys Nonlinear Phenom* 2017;361:1–11. Available at: 10.1016/J.PHYSD.2017.09.002, . [Accessed 13 September 2022].
- [44] More AA. Analytical solutions for the Colebrook and White equation and for pressure drop in ideal gas flow in pipes. *Chem Eng Sci* 2006;61(16):5515–9. Available at: 10.1016/J.CES.2006.04.003 (Accessed: 8 March 2023).
- [45] Matmatch. Medium density Polyethylene (MDPE) alternative and trade names. 2022.
- [46] Peninsular Steel Tubes. X52-X52N - material data sheet. 2014.
- [47] ToolBox Engineering. Roughness & surface coefficients. https://www.engineeringtoolbox.com/surface-roughness-ventilation-ducts-d_209.html. [Accessed 18 September 2022].
- [48] SimScale. Surface roughness & porosity. SimScale 2022. <https://www.simscale.com/docs/analysis-types/pedestrian-wind-comfort-analysis/advanced-modelling/>. [Accessed 18 September 2022].
- [49] ASME. AMERICAN national standard for welded and seamless wrought steel pipe. 2015. ANSI 836.10 .. 1979).
- [50] European Standards. Plastics piping systems for water supply, and for drainage and sewerage under pressure- Polyethylene (PE)-Part 2: pipes. 2011.
- [51] BSI Standards 6891. Specification for the installation and maintenance of low pressure gas installation pipework of up to 35 mm (R1 1/4) on premises. 2015.
- [52] Bopp J, Weiss DA. On the origin of the centreline velocity overshoot in the entrance region of a turbulent pipe flow. *Elsevier Masson Int J Therm Sci* 2022;172:107256. Available at: 10.1016/J.IJTHEMALSCI.2021, . [Accessed 26 July 2022].
- [53] Toolbox Engineering. Darcy-weisbach equation - major pressure and head loss due to friction. Engineering Toolbox, https://www.engineeringtoolbox.com/darcy-weisbach-equation-d_646.html. [Accessed 26 September 2022].
- [54] Jack TA, Pourazizi R, Ohaeri E, Szpunar J, Zhang J, Qu J. Investigation of the hydrogen induced cracking behaviour of API 5L X65 pipeline steel. *Int J Hydrogen Energy* 2020;45(35):17671–84. Elsevier Ltd.
- [55] Reuß M, Welder L, Thürauf J, Linßen J, Grube T, Schewe L, Schmidt M, Stolten D, Robinius M. Modeling hydrogen networks for future energy systems: a comparison of linear and nonlinear approaches. *Int J Hydrogen Energy* 2019;44(60):32136–50. Elsevier Ltd.
- [56] Ryan N, Roberts S. Safety assessment: experimental testing-domestic pipework leakage. 2020.
- [57] Simpson G, Allason D, Johnson M. Safety assessment: experimental testing-cupboard level leakage and accumulation. 2019 [Brampton].