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Purging hydrogen distribution pipelines: literature review, description of recent experiments and proposed future work

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Overview

- H21 project
- Review of natural gas pipeline purging: current practice
- Scientific basis supporting current practice
- Implications of switching to hydrogen
- Review of related guidance and research on hydrogen purging
- H21 experimental programme
- Current status and future activities

H21 Project

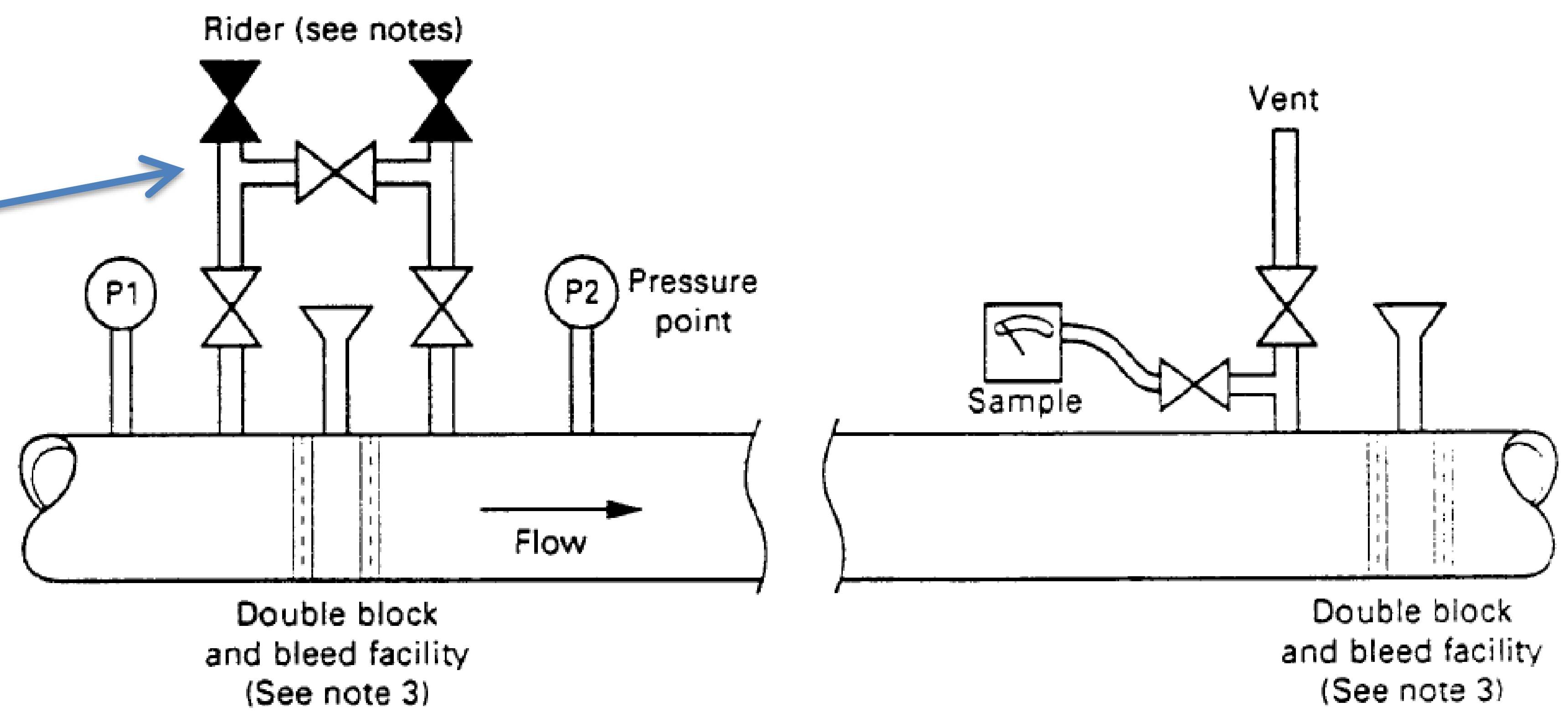
- Aim: to assess the feasibility of converting the existing UK natural gas distribution network to transport 100% hydrogen
- H21 Phase 2 aims: to provide safety critical evidence to support the viability of a 100% hydrogen live community trial, which will be undertaken later in Phase 3
- Funded by energy regulator for Great Britain (OFGEM) under the Network Innovation Competition (NIC)
- Led by Northern Gas Networks (NGN), partners include all the GB gas distribution network operators (GDNOs) and National Gas Transmission
- Work presented here undertaken collaboratively by the Health and Safety Executive's Science and Research Centre (HSE) and DNV
- Focus of this presentation: purging the < 7 barg gas distribution network
  - Assess current basis of safety for purging natural gas pipelines
  - Examine implications of switching to 100% hydrogen
  - Scope exclude purging downstream of the emergency control valve

https://h21.green/

Current Natural Gas Pipeline Purging

- Institute of Gas Engineers and Managers Safety Recommendations IGEM/SR/22
- British Standard BS EN 12327 on pressure testing, commissioning and decommissioning of gas infrastructure
- Gas distribution company procedures on main laying and service laying, and associated other procedures
- Direct purging between natural gas and air is used in the majority of applications

“Rider” or bypass connection to feed in gas from upstream pipeline



Notes:

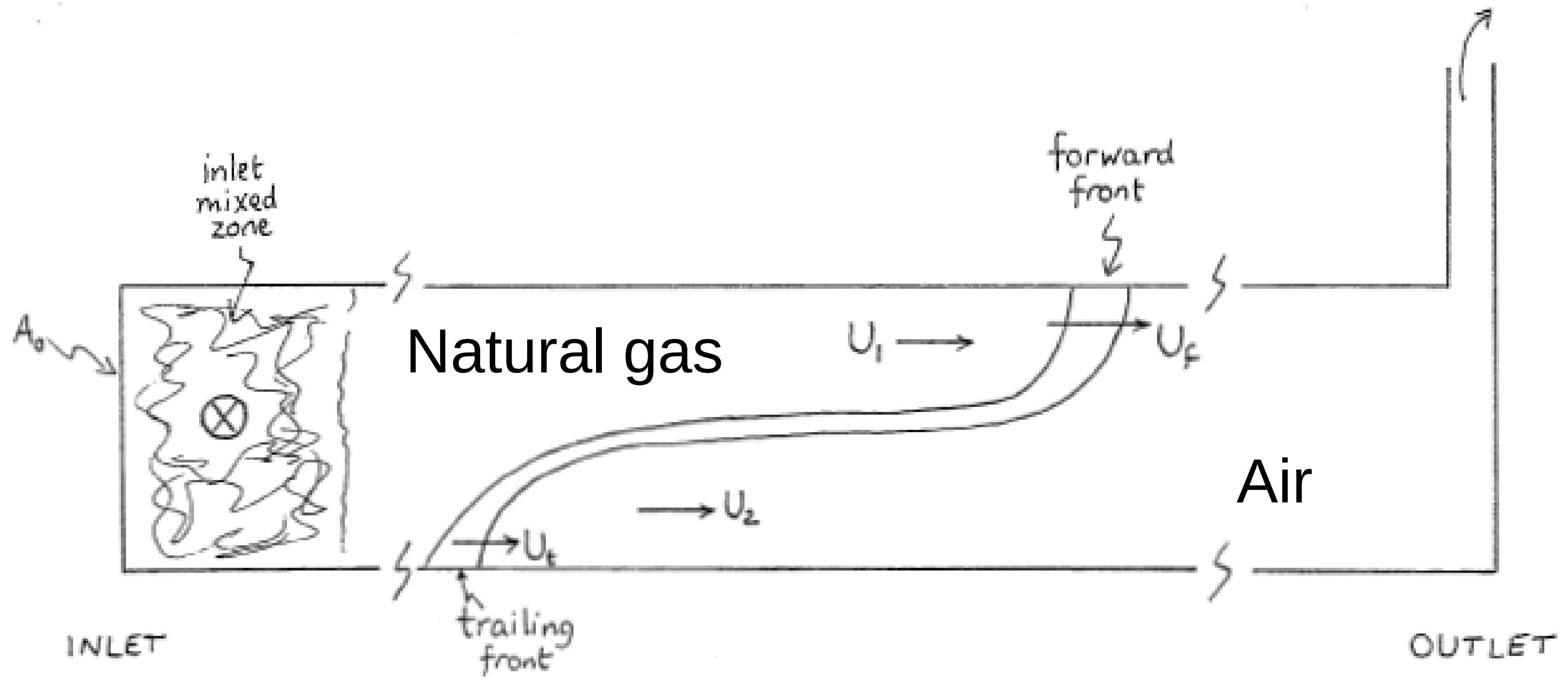
1. *Purge rider connections should be as close as possible.*
2. *Rider may be omitted at the discretion of the engineer.*
3. *Low pressure mains not greater that 150 mm n.b. may be isolated by a single faced valve or squeeze off if the isolation is sound.*

Principles of Distribution Pipeline Purging

- Gas distribution pipelines operate at relatively low pressures
- Three pressure tiers:

Low Pressure (LP)	< 75 mbarg
Medium Pressure (MP)	75 mbarg – 2 barg
Intermediate Pressure (IP)	2 barg – 7 barg

- Displacement purging is used to commission and decommission pipelines with direct transfer between air and natural gas in most cases
- Purging velocity must be sufficient to produce piston-type flow and avoid the buoyant natural gas stratifying in the pipeline



Source: Daish & Linden (1991)

NGN Procedure on main and service laying NGN/PM/MSL/1

- Example of direct purging requirements: rider and vent sizes needed to achieve the minimum purging velocity, for given upstream driving pressures

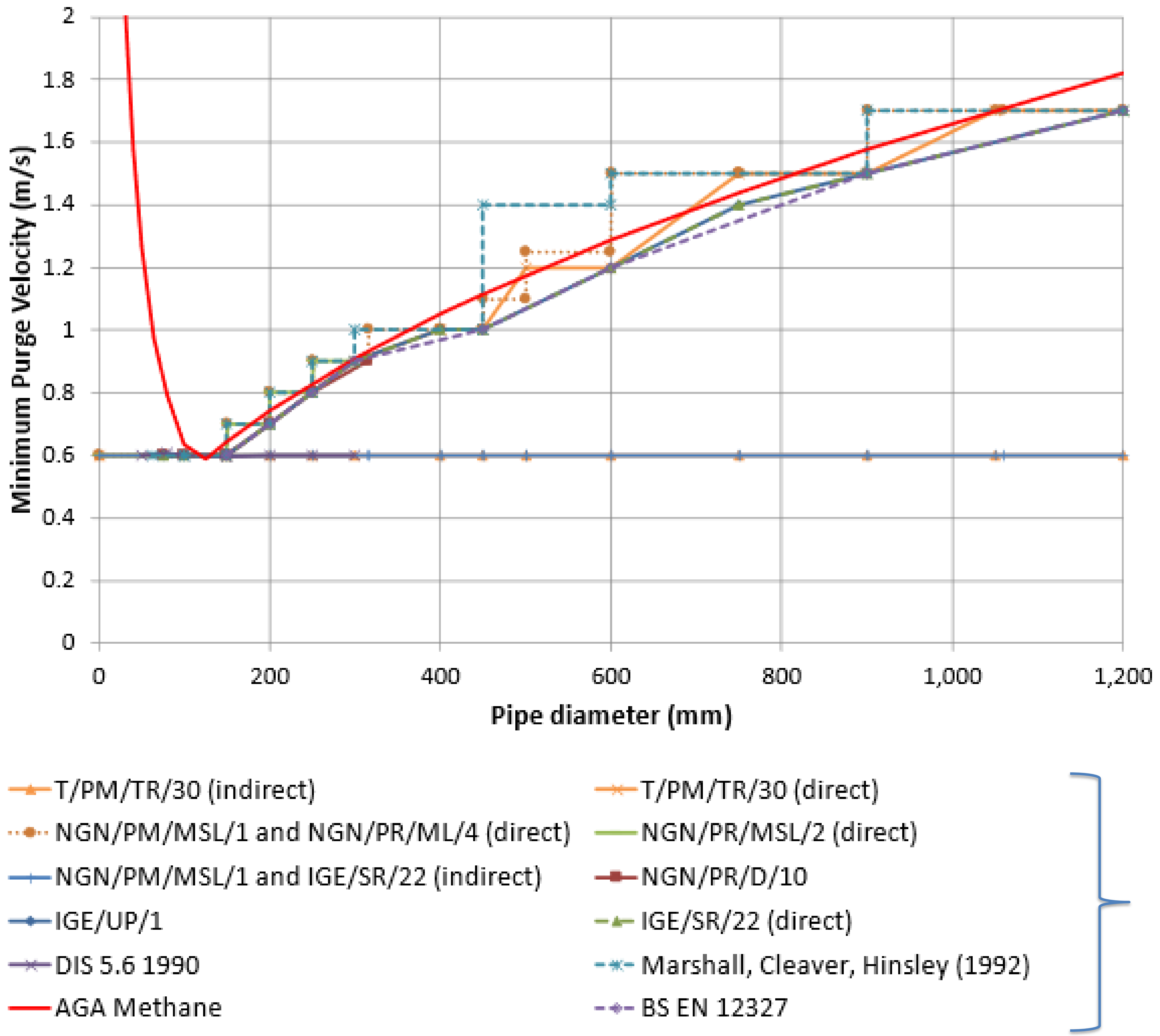
Nominal pipe diameter or equivalent pipe diameter	Recommended rider and vent diameters (mm) for rider inlet pressures of					Minimum distance for release of squeeze-off from the fully closed position (mm)
	21 mbar	30 mbar	75 mbar	350 mbar	2 bar	
0 to 150mm (0 to 180 mm PE) (0-6in.)	32	32	32	32	32	15
151 to 200mm (8in.)	63	63	63	32	32	15
201 to 250mm. (10in.)	63	63	63	63	63	30
251 to 301mm (12in)	63	63	63	63	63	30
301 to 450mm (18in)	90	90	90 (2x63)	63	63	45
451 to 600mm (24in)	180	180 (2x125)	125 (2x90)	90 (2x63)	63	60 (see note 1)
601 to 900mm (36in)	180	180 (2x25)	180 (2x25)	125 (2x90)	90 (2x63)	-
901 to 1200mm (48in)	-	250 (2x180)	250 (2x180)	180 (2x125)	90 (2x63)	-

Commissioning mains by direct purging

Nominal pipe dia or equivalent pipe dia. D	Min. purge velocity m/s	Typical Purge velocity m/s	Min air inlet hole & vent/ejector diameters		Min. size of compressor used on inlet		or	Min. size of compressor used on ejector		Ejector size mm
			PE mm	Met In.	m³/min	ft³/min		m³/min	ft³/min	
0 to 150mm 0 to 180mm PE 0 to 6in	0.6	1.5	32	1	1.9	(70)	-	N/A		50mm
151 to 200mm (8in)	0.7	1.4	63	1.5	2.8	(100)	OR	2X2.0	(2X70)	50mm
201 to 250mm (10in)	0.8	1.2	63	2	3.9	(140)	OR	2X2.0	(2X70)	50mm
251 to 315mm (315mm PE) (12in)	0.9	1.1	63	2	n/a		-	2x2.8	(2x100)	50mm
316 to 400mm (355 PE) (14 & 16 in)	1.0	1.5	90 or 2x63	3	N/A		-	2x2.8	(2x100)	150
401 to 450mm (18 in)	1.0	2.0	-	4			-	2x3.9	(2x140)	150
451 to 500mm (20 in)	1.1	2.0	-	5			-	2x3.9	(2x140)	150
501 to 600mm (24 in)	1.25	2.0	-	6			-	2x3.9	(2x140)	150
601 to 750mm (30 in)	1.5	1.7	-	6			-	2x7.8	(3x275)	250
751 to 900mm (36in)	1.5	2.0	-	6 inlet 8 ejector			-	2x7.8	(4x275)	250
901 to 1060mm (42 in)	1.7	1.8	-	8			-	2x7.8	(4x275)	250
1051 to 1200mm (48 in)	1.7	1.8	-	12 inlet 8 ejector			-	2x7.8	(4x275)	250

Table C15 - De-commissioning mains by direct purging

Minimum purging velocity requirements for natural gas

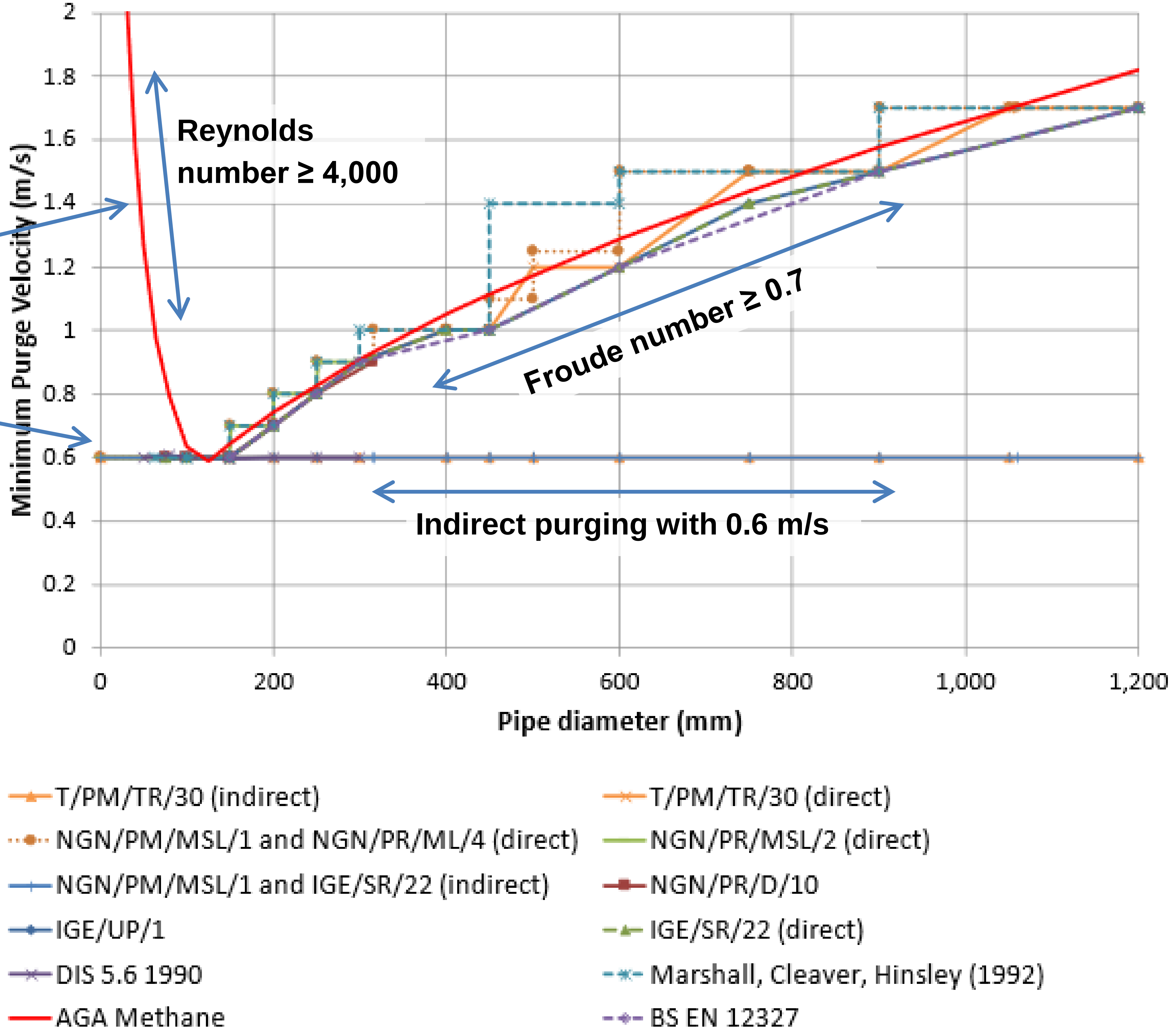


Gas industry procedures, standards and research publications

Minimum purging velocity requirements for natural gas

AGA requires
$Re \geq 4{,}000$

British standards require velocity ≥ 0.6 m/s



Froude number:
to avoid stratification

$$Fr = \frac{Inertial\ forces}{Buoyancy\ forces} = \frac{V}{\sqrt{g'd}} \geq 0.7$$

Reynolds number:
to keep flow turbulent

$$Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho V d}{\mu} \geq 4{,}000$$

Properties of methane and hydrogen

	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 (1963)

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

[d] Source: Drysdale (1998)

[e] Babrauskas (2003)

Implications of switching to hydrogen

- Froude number requirement

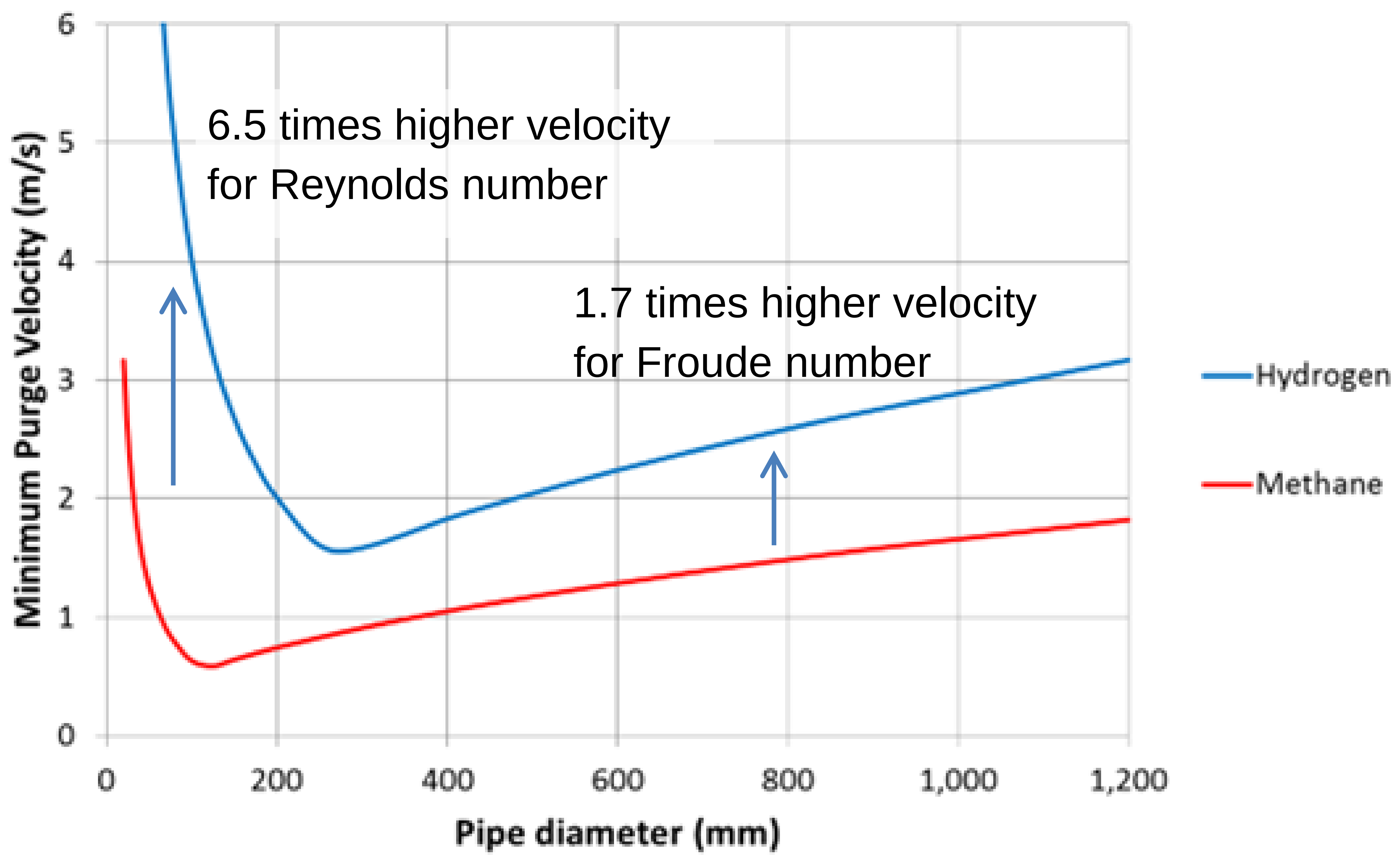
$$Fr = \frac{V}{\sqrt{g'd}} \qquad g' = 2g\left(\frac{\rho_{air} - \rho_{gas}}{\rho_{air} + \rho_{gas}}\right)$$

$$V = 0.7\sqrt{2dg\left(\frac{\rho_{air} - \rho_{gas}}{\rho_{air} + \rho_{gas}}\right)}$$

$$\frac{V_{H2}}{V_{CH4}} = \sqrt{\left(\frac{\rho_{air} - \rho_{H2}}{\rho_{air} + \rho_{H2}}\right)\left(\frac{\rho_{air} + \rho_{CH4}}{\rho_{air} - \rho_{CH4}}\right)} = \sqrt{\left(\frac{29-2}{29+2}\right)\left(\frac{29+16}{29-16}\right)} = \sqrt{3.0} = 1.7$$

- Reynolds number requirement

$$Re = \frac{\rho V d}{\mu} \qquad \frac{V_{H2}}{V_{CH4}} = \frac{\mu_{H2}}{\mu_{CH4}}\frac{\rho_{CH4}}{\rho_{H2}} = \frac{(0.87)}{(1.07)}\frac{(16)}{(2)} = 6.5$$

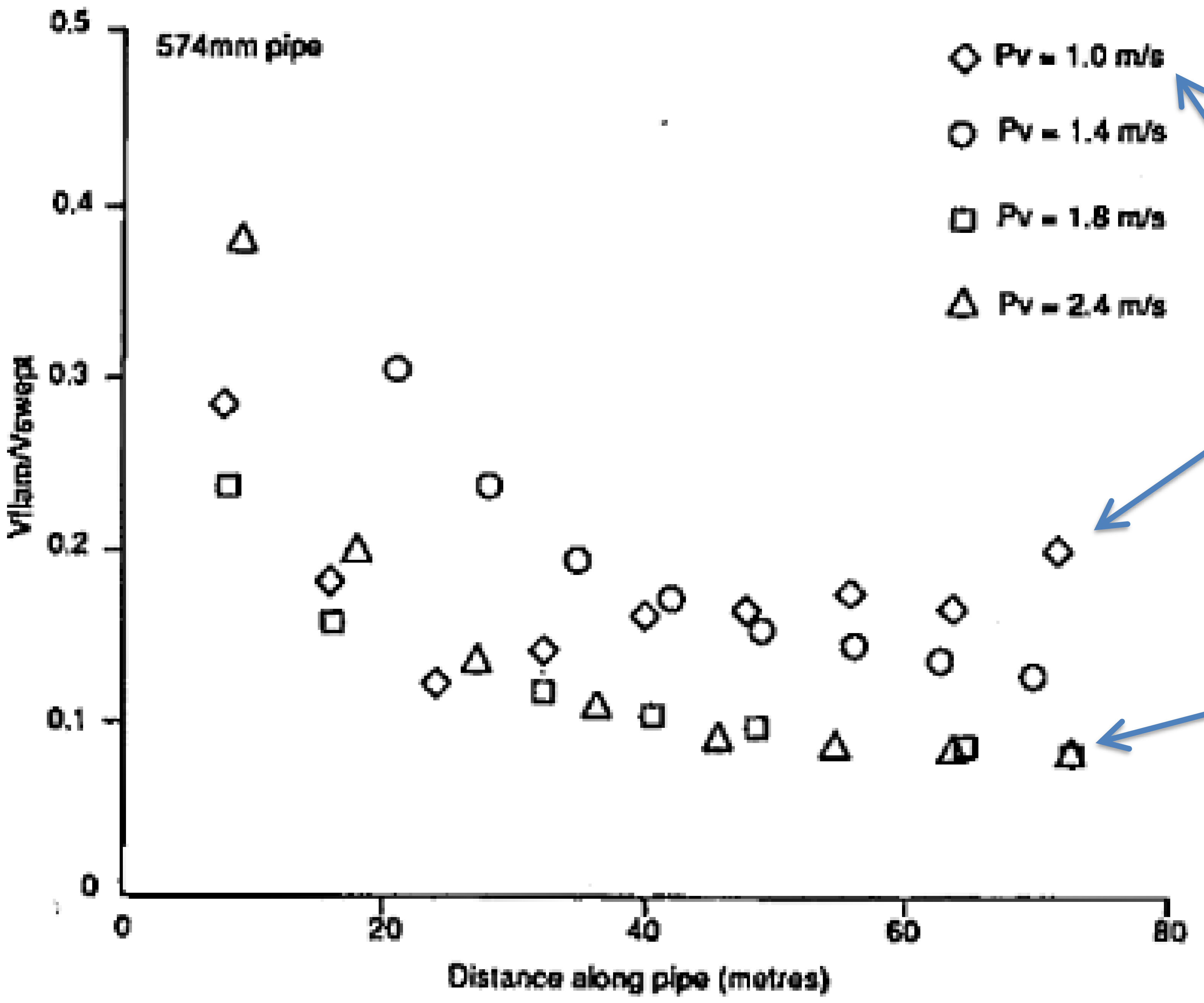


Scientific basis for natural gas purging practices

- Purging research undertaken by British Gas and CERC in 1990's
  - Marshall, Cleaver & Hinsley (1992), Darby (1993), Daish & Linden (1991)
  - Laboratory experiments to visualise stratification in pipes using saline and fresh water
  - Purging experiments in polyethylene (PE) pipes with diameters of 50 mm, 75 mm, 150 mm and lengths 40 m to 260 m, with purging velocities in the range 0.1 to 1.5 m/s
  - Tests included straight, horizontal pipes, pipes fitted with 90-degree and 180-degree bends, and pipes angled upwards/downwards with 3° and 6° slopes
  - Flammable gas mixtures ignited in the largest diameter pipes
  - Horizontal steel pipes with diameters 305 mm and 574 mm and lengths 100 m, purging velocities from 0.3 m/s to 2.4 m/s, some mixtures ignited
  - Tests on longer 300 m pipes fitted with several bends and inclined sections
  - Measurements during actual purging operations on the gas network (3.6 km and 10 km)
- Research undertaken by American Gas Association and Southwest Research Institute
  - Johnson, Svedman & Kuhl (1997), AGA (2001)

Scientific basis for natural gas purging practices

- Results from British Gas experiments on natural gas (Marshall, Cleaver & Hinsley, 1992)



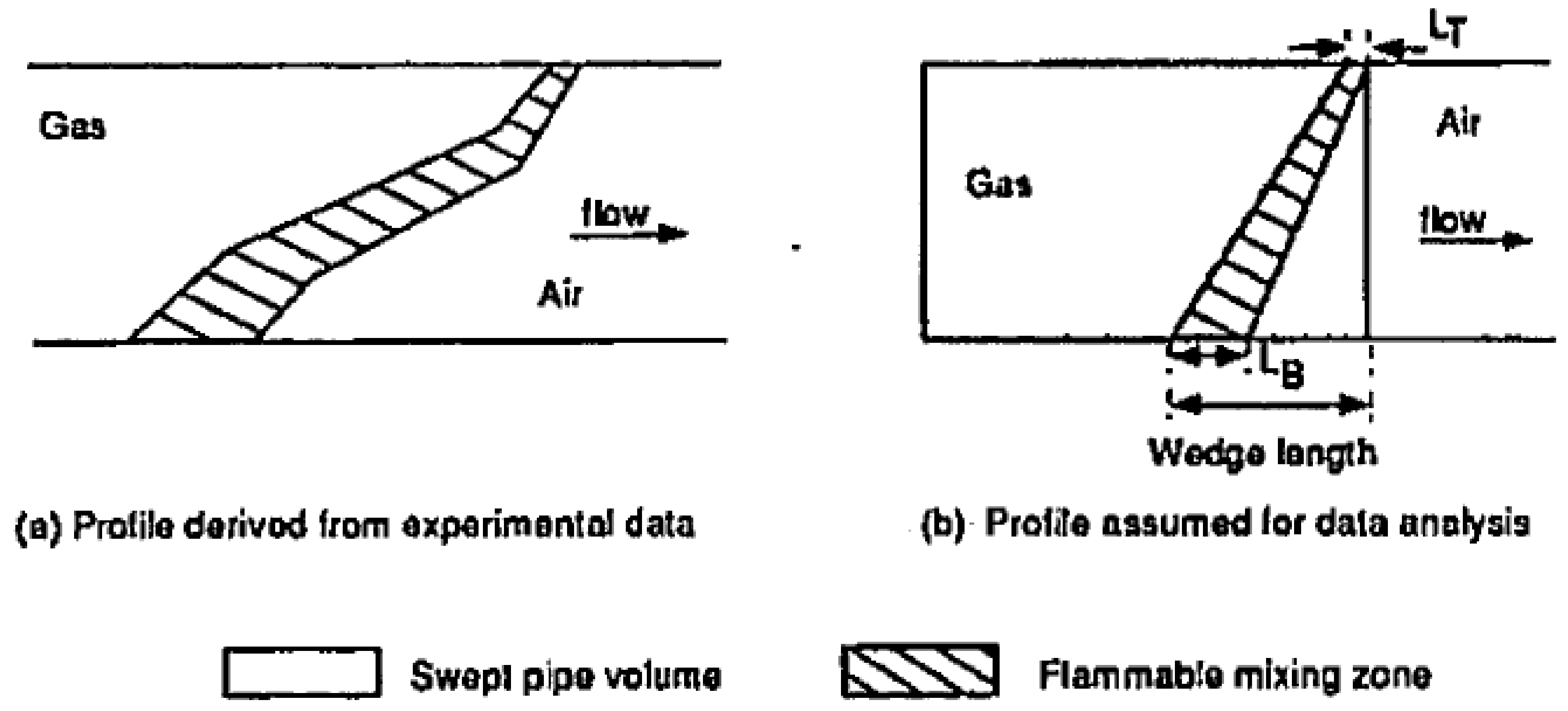
Purging velocity too low, gas cloud growing due to stratification and mixing

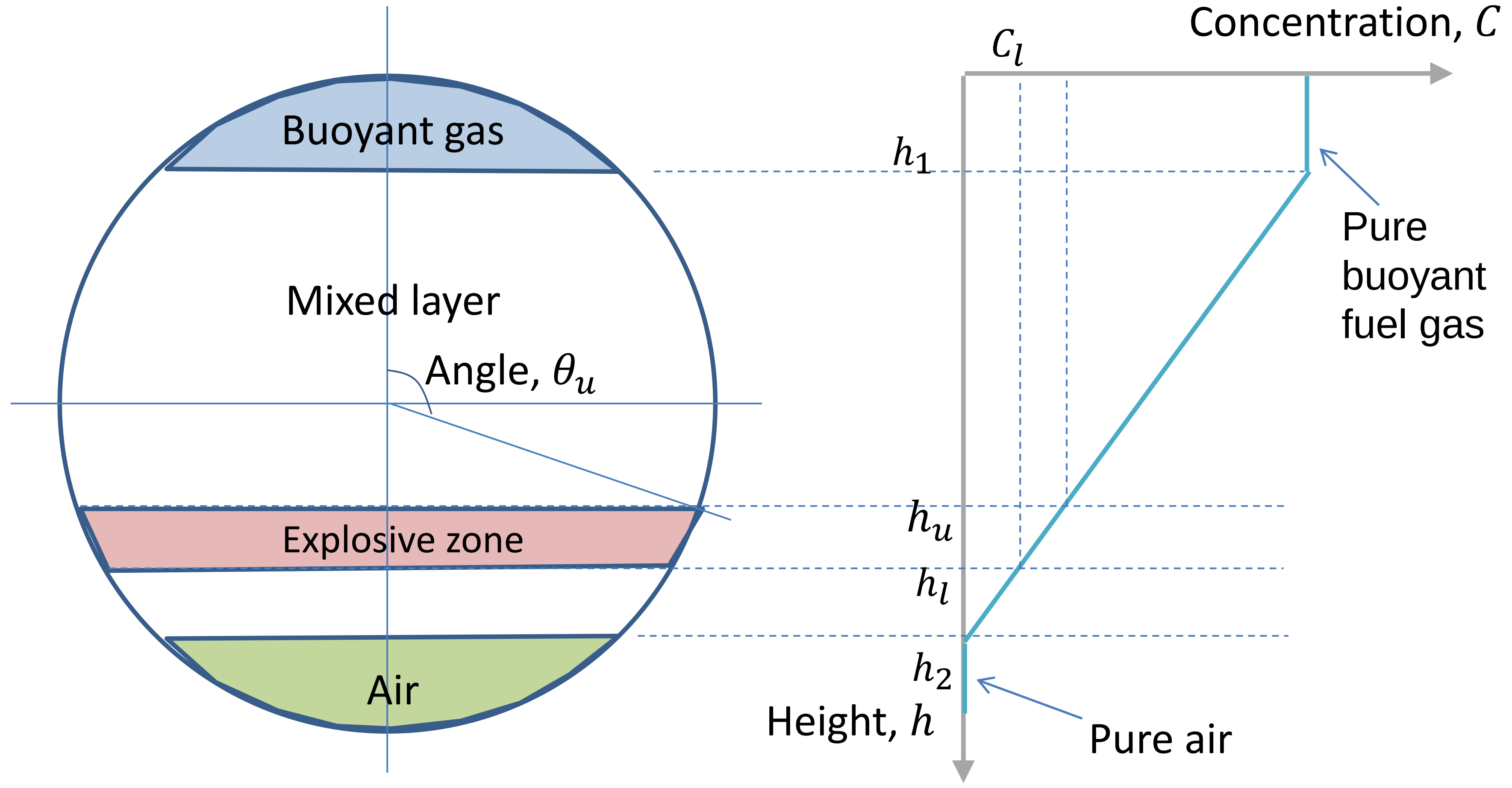
Higher purging velocities give stable flammable cloud size as a fraction of swept length, i.e., flammable cloud occupies approximately 8% of swept volume at later stages

Effect of purge velocity on ratio of flammable volume to swept volume (Vflam/Vswept)

Scientific basis for natural gas purging practices

- Mathematical model developed by Daish & Linden (1991) to predict flammable gas cloud size during direct purging operations





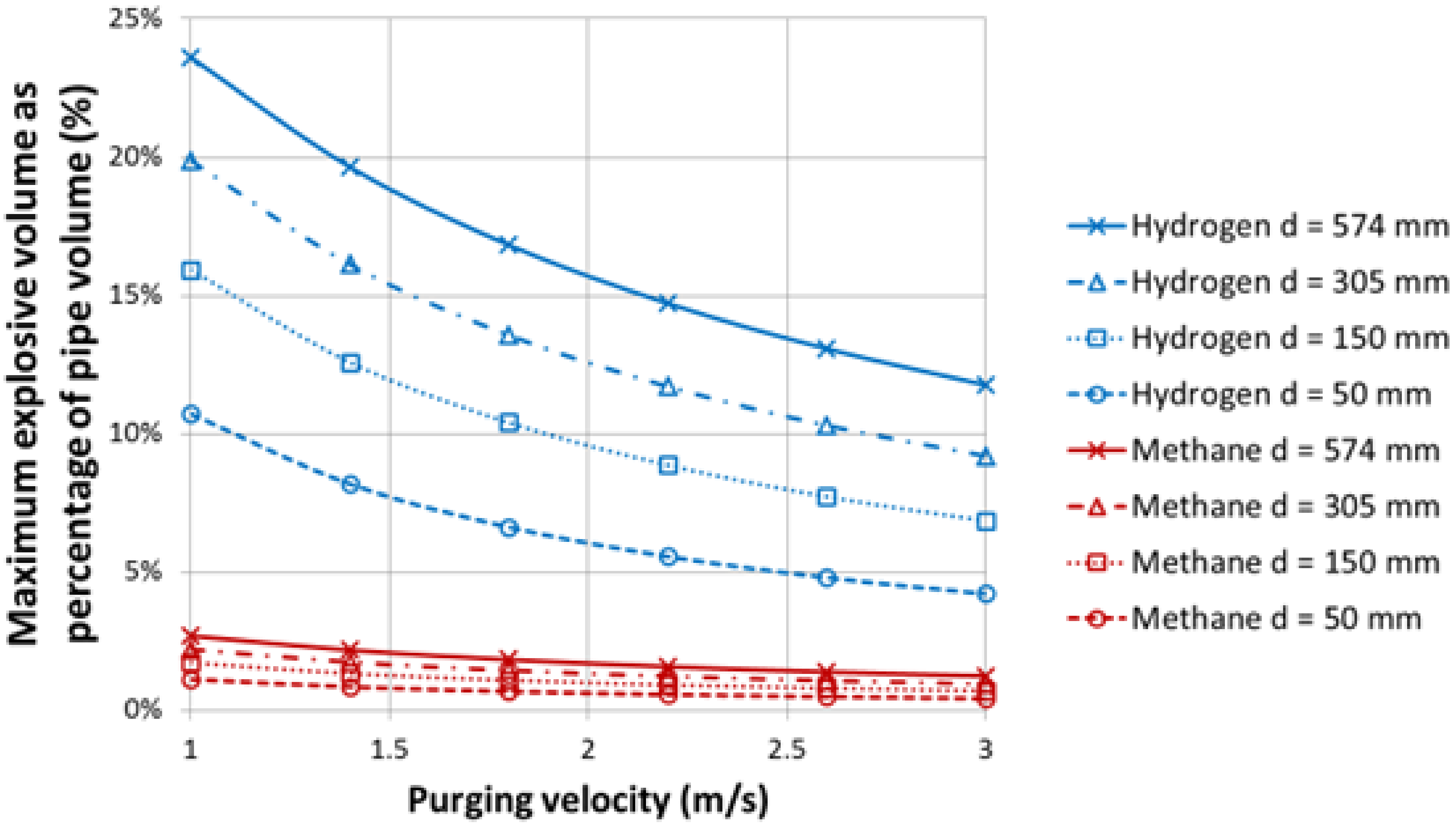
$$Q_{sl}^{*} = (A_2^{*} - \beta)\left[U_1^{*} + \left(\frac{h_1^{*} - \frac{1}{2}}{h_2^{*} - h_1^{*}}\right)(U_1^{*} - U_2^{*})\right] - \frac{(U_1^{*} - U_2^{*})}{3\pi(h_2^{*} - h_1^{*})}(\sin^3\theta_1 - \sin^3\theta_2)$$

- Original Fortran implementation of Daish & Linden (1991) model purchased by HSE
- Verification tests undertaken and substance properties then altered from natural gas to hydrogen

Implications of switching to hydrogen

- Model predicts a much larger flammable volume for hydrogen

Explosive volume as a percentage of the pipe volume for purging hydrogen and methane through four pipes of different diameter with a pipe length of 80 m



- Example: 305 mm diameter pipeline
  - Minimum purging velocity to avoid stratification: V_{CH4} = 0.9 m/s, V_{H2} = 1.6 m/s
  - Explosive volume is 2% of the pipe volume for methane, 13% of the pipe volume for hydrogen

Ignition likelihood and potential consequences

- Lower minimum ignition energy: 0.01 mJ for hydrogen, 0.26 mJ for methane
- Unable to rule out potential for electrostatic ignition of flammable gases in pipe
- Flame could also propagate into pipe from ignited airborne cloud (flame arrestors?)
- Run-up from deflagration to detonation within approximately 60 pipe diameters
- Basis of safety for natural gas is that maximum overpressure inside pipeline of < 2 bar can be withstood by pipeline without damage
- Higher pressures likely in hydrogen detonations: possible projectile damage?
- Detonation observed in ignition tests with stoichiometric hydrogen mixtures in 10 m long lengths of 180 mm diameter main and (separate) 32 mm diameter service pipes
- Decision taken to proceed with indirect purging of hydrogen distribution pipelines, using nitrogen to avoid producing flammable mixtures in the pipeline
  - Avoids need for flame arrestors, with their associated large pressure drop
  - Introduces additional risks from handling high-pressure nitrogen gas supply

Related research on hydrogen pipeline purging

- HyDelta (https://hydelta.nl)
  - KIWA Netherlands purging experiments using two pipelines 200 m long, with nominal diameters of 100 mm and 200 mm
  - "*the use of nitrogen is (for the time being) recommended for safety-technical reasons in order to avoid flammable mixtures in the pipeline*"

- HyPurge
  - SGN commissioned Steer Energy to conduct a series of hydrogen pipeline purging experiments to support the H100 Fife neighbourhood hydrogen trials in Scotland (https://www.sgn.co.uk/H100Fife)
  - Evidence supporting H100 trials is currently being reviewed by HSE
  - Proposed to purge mains using indirect purging with nitrogen

Related standards

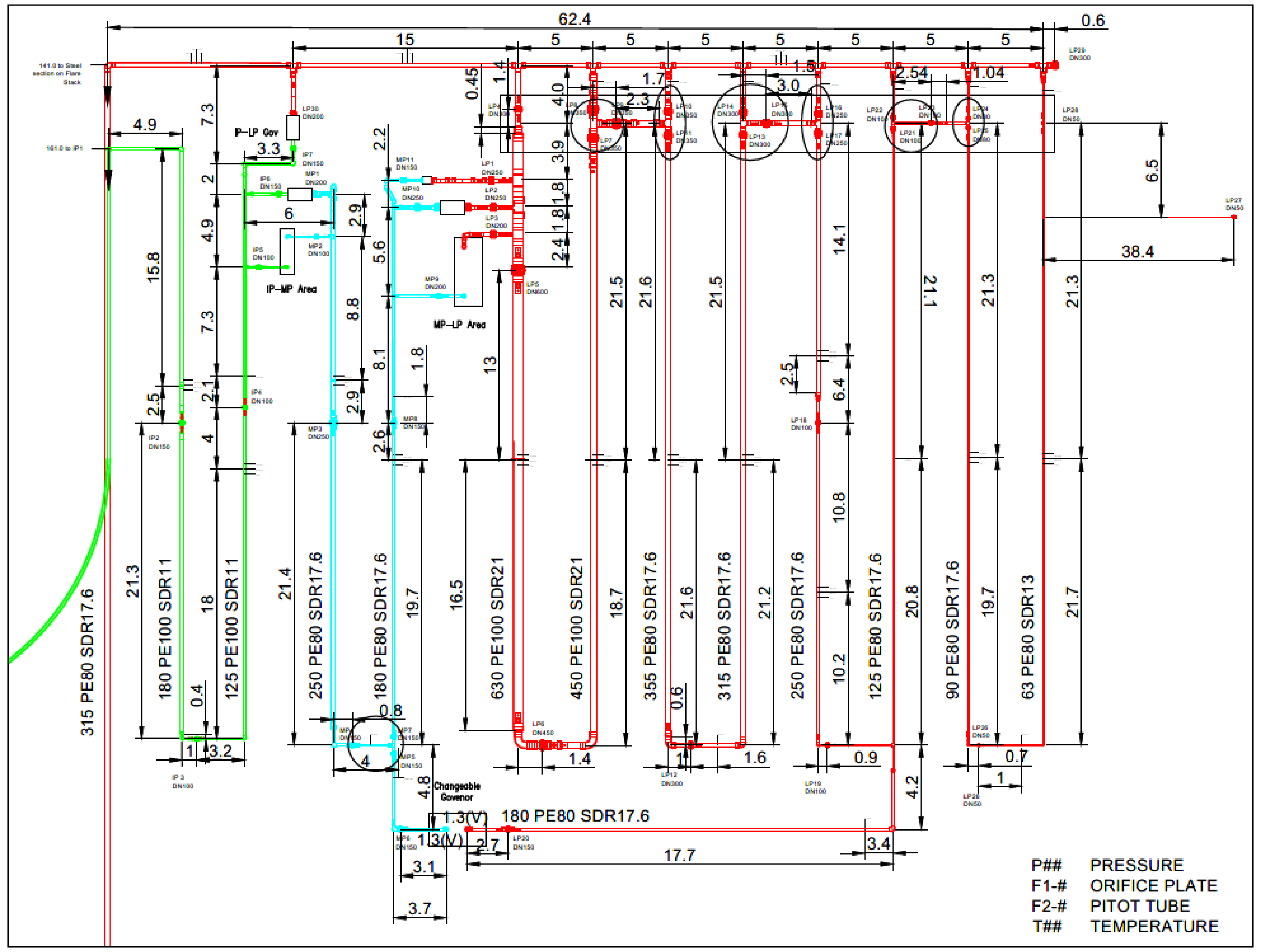
- European Industrial Gas Association (EIGA) Doc 121/14.
  - “*Nitrogen or other inert gas shall be used to purge hydrogen from the pipeline before loosening or disconnecting flanges, instruments, etc. Dead ended legs of the pipeline system that cannot be swept by nitrogen shall be pressure purged. The number of pressure purging cycles shall be evaluated for each specific job*.”

- ASME B31.12 code on Hydrogen Piping and Pipelines
  - *“Before cutting by torch or welding on a line that may contain a mixture of hydrogen and air, it shall be made safe by displacing the mixture with hydrogen, air, or an inert gas. Caution must be taken when using an inert gas to provide adequate ventilation for all workers in the area*.”

H21 Experimental Programme

- Two series of experiments at the DNV Spadeadam test site
  1. "Microgrid" network of interconnected PE pipelines from 63 mm to 630 mm in diameter, and lengths of a few tens of metres with parts operating at LP, MP and IP pressures



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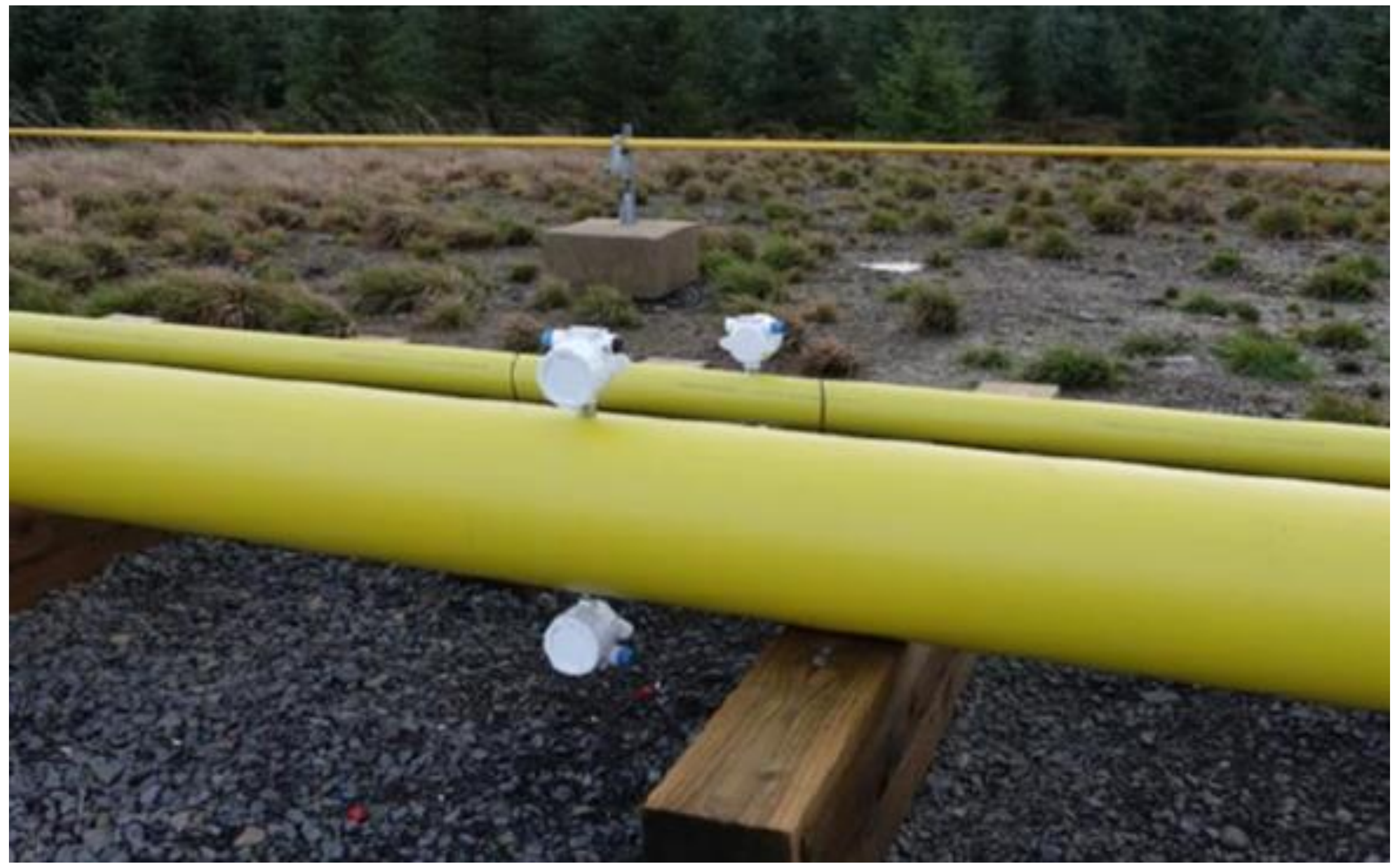
  - Designed primarily for various operational and demonstration purposes (not principally for purging measurements)
  - No direct measurements of concentration within the pipelines
  - Purging conditions inferred from pressure drop measurements and concentrations measured at the vent exit

https://h21.green/news/hydrogen-testing-on-the-h21-microgrid-has-begun/

H21 Experimental Programme

2. Dedicated pipeline purging rig: two straight 100 m lengths of PE pipe with diameters of 125 mm and 315 mm
   - 32 tests including both direct and indirect purges (with nitrogen) of both hydrogen and natural gas, commissioning and decommissioning purges, and conversion-style purges from natural gas to hydrogen
   - Range of purging velocities corresponding to Froude numbers ranging from 0.3 to 1.3
   - Concentrations measured at top and bottom of pipeline to assess stratification



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H21 Experimental Programme

- Analysis of experimental data completed in June 2023
- Results indicated that hydrogen did not stratify at low velocities, i.e., at low Froude number and low Reynolds numbers
- Results appear to be consistent with findings from HyDelta and HyPurge experiments
- Postulated that this effect is due to high molecular diffusivity of hydrogen

	Methane, CH_4	Hydrogen, H_2
Molecular diffusivity in air (cm^2/s)	0.196	0.611

- Final report on H21 purging work submitted as evidence for regulatory review to support future procedures used in hydrogen village trial https://www.redcarhydrogencommunity.co.uk/
- Currently awaiting feedback from HSE regulatory review
- Report to be published in due course on https://h21.green/

Molecular diffusivity effects

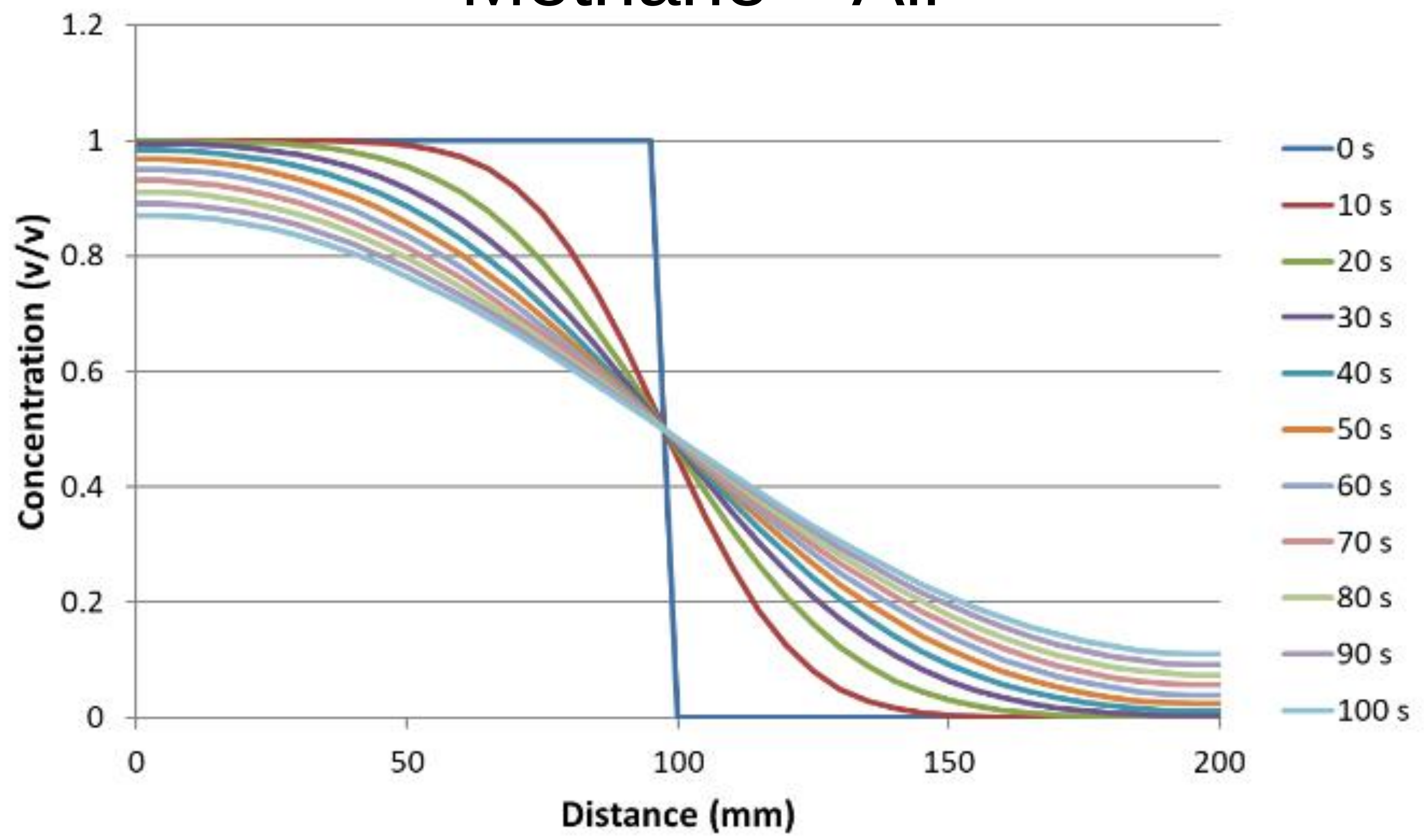
- Preliminary analysis: one-dimensional molecular diffusion

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

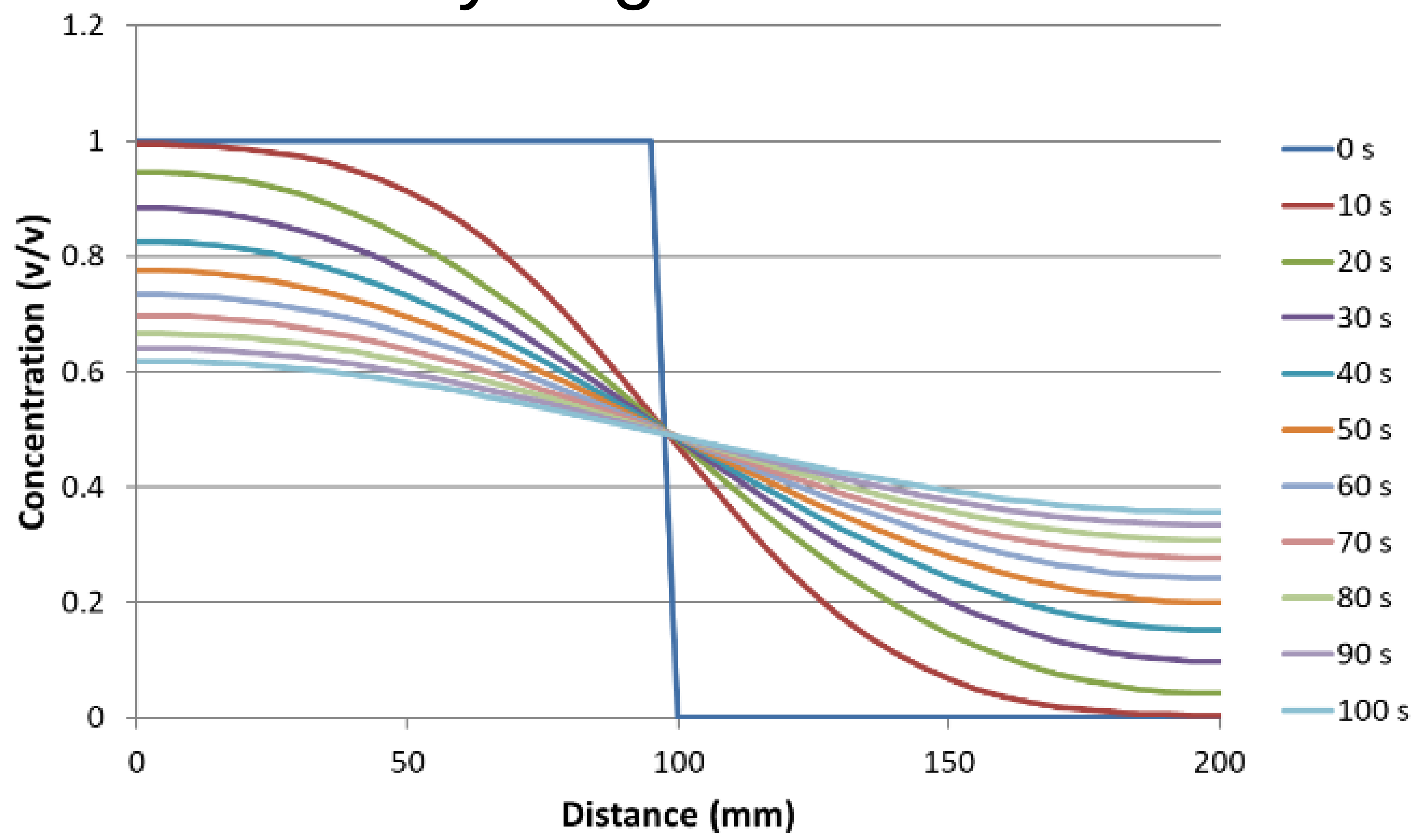
- Key parameter controlling the rate of diffusion is: $D\frac{t}{x^2}$

- 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, 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

Methane – Air



Hydrogen – Air



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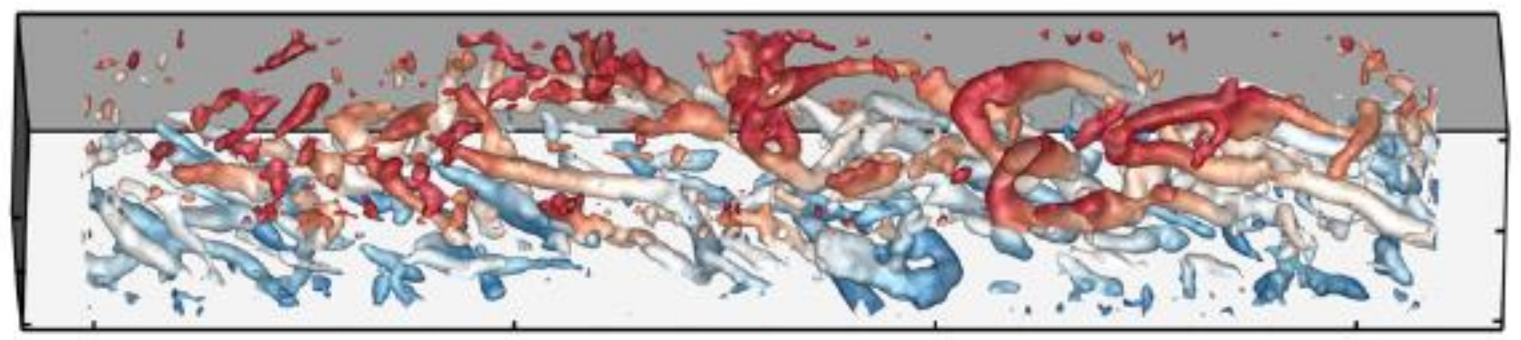
Future Work

- Mathematical model for purging of natural gas previously developed for British Gas in the 1990s did not take into account molecular diffusion effects
- Recent experiments indicate that these effects improve the efficiency of hydrogen purging, especially in small diameter pipelines
- Useful to develop a new purging model that accounts for molecular diffusion to improve our understanding of the physics and enable results to be extrapolated from purging experiments to wider range of cases
- Model could also be used to explore use of direct purging for hydrogen
- Aim to partner with stratified flows research group at the University of Cambridge
  - High-performance computing
  - World-class laboratory facilities



http://dx.doi.org/10.1017/jfm.2022.588

http://www.damtp.cam.ac.uk/user/pfl4/Publications_2_files/56hld96.pdf

Conclusions

- Reviewed scientific basis of current natural gas distribution pipeline purging practice
- Examined implications of switching to hydrogen
- Concluded that indirect purging with nitrogen is necessary, at least in the immediate future for hydrogen trials
- H21 experiments undertaken to support development of new purging procedures for hydrogen: final reports to be published soon
- Tests indicated that hydrogen does not stratify at low purging velocities
- Future work to examine the impact of molecular diffusion effects

Thank you for listening

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