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Maximum pipe transmission velocity for pure hydrogen gas flow

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PRCI LEADING PIPELINE RESEARCH
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Boxing bout n°1: H_2 against CO_2

Source: https://www.cleanenergywire.org/blog/cartoon-snapshot-whats-hot-energy-and-climate-year

Boxing bout n°1: H_2 transmission pipelines against HVDC

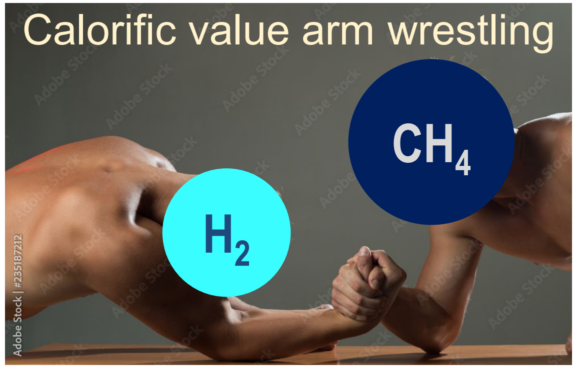
Source: https://medium.com/the-future-is-electric/hydrogen-pipeline-vs-hvdc-studies-keep-making-the-same-mistakes-dc91561c89bc

Pipelines are the most relevant answer to how transmit green energy in the future

What are the key gaps to transport H_2 by pipelines ?

- Guarantee that capacity of pipelines to deal with the embrittlement phenomenon of pipelines steel caused by hydrogen.
- Need of new compressions stations H_2 compatible.
- Ensure the compatibility of all the transmission network components (gas meters, valves, pressure reducers,…).
- **Overcame the fact: the calorific value of H_2 is 3 times less than natural gas**

⇒ Ensure a comparable transported energy as for natural gas.



Pipeline diameter Ø, Pressure, Flow velocity

Why do we need to know the V_{max} H_2 ?

- The maximum gas flow velocity transported is a key parameter in the design of future H2 networks:

⇒ It guarantees the network durability

⇒ It fixes the maximum amount of energy transportable. for a given pipe diameter and pressure

- The calorific value of hydrogen (3.55 kWh/Std.m^3) is 3 times lower than the natural gas (10.7 to 12.77 kWh/Std.m^3).

⇒ It leads to highly increase the hydrogen transmission flow velocity (for the same pipe diameter and operating pressure) to ensure a comparable amount of transported energy as for natural gas.

Which was determined the V_{max} for the natural gas ?

- **Historically, for natural gas V_{max} is 20 m/s.**

- **Where does this value come from?**

No one really knows!!!! Maybe using the API RP 14E standard, maybe not

- **To answer this question:**

A state of the art has been carried out to identify the main factors limiting the transmission flow velocity of natural gas and to understand "finally the true origin" of the "20 m/s".

State of the art – The limiting factors for the pipeline maximum transmission velocity V_{max} (1/2)

- **Few studies on the literature explain how the maximum transmission velocity was determined.**

- **The main limiting factors are:**

  – **The pressure drop:** The increase of the gas pipe velocity increases transmitted energy, increase the pressure drop and then, the compression power required. Therefore, an economic optimum must be identified.

  – **The pulsations generated by the flow:** The characteristics of hydrogen compared to natural gas are such that pulsations are likely to appear for the same operating points in energy flow, but in these cases, the speed of hydrogen and the frequency of pulsations will be three times higher.

State of the art – The limiting factors for the pipeline maximum transmission velocity V_{max} (2/2)

- **The main limiting factors are:**
  - **The external noise:** As for pulsations and for the same energy flow, the hydrogen flow generates sound noise level comparable to the case of natural gas, but with a frequency three times higher.
  - **The mechanical wear of pipelines induced by the acoustic noise:** The two previous sources of pressure fluctuations coupled with the effect of hydrogen, known to embrittlement behavior that weaken steel parts and accelerate the cracks propagation, lead to premature fatigue of the pipeline.
  - **The internal erosion:** The risk of erosion of the internal wall of the pipeline and/or the internal coating is the key factor that limits the speed of the fluid.

State of the art – The internal erosion – Facts

- **Upstream and midstream gas transmission pipeline presents a continuously risk of degradation of the different network components (by erosion-corrosion).**

  - The gas flow carries various types of contaminants (liquid or solid).

  - The particles diameters ranging from 1 µm to 2000 µm.

  - Particles between 30 µm and 100µm are difficult to completely remove and they are commonly known as sand particles and iron oxide.

  - Their high-speed drive, under the effect of gas flow, produces potentially serious erosion on the inner wall of the pipeline and network components.

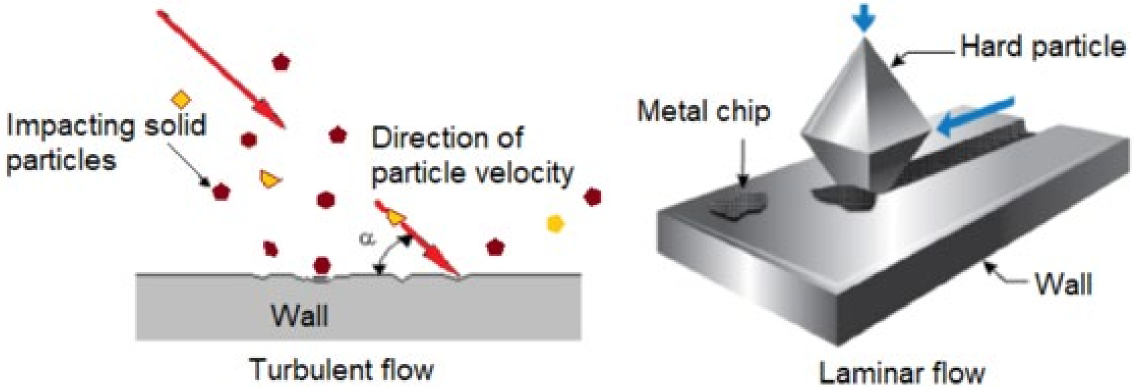
State of the art – The internal erosion – Parameters

- **The parameters influencing the speed of erosion are:**
  - the particle diameter and their density,
  - the density and viscosity of the gas flow,
  - the pipe diameter and thickness [18],
  - the material nature of the inner surface of the pipeline and the network components (gas meter, valves, pressure regulator…),
  - the particles predominant impact angle with the inner surfaces.

State of the art – The internal erosion – Flow regime

The erosion depends, also, strongly on the flow regime:

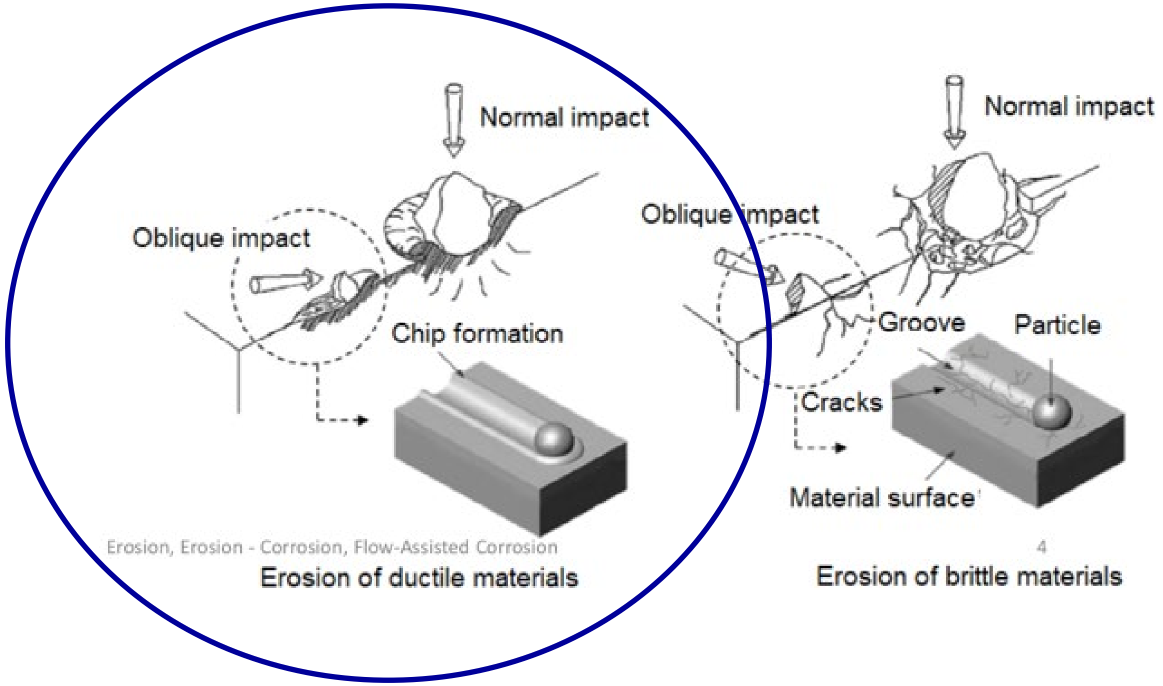
- for a laminar flow regime, the streamlines are parallel ⇒ the carried solid particles tend to wipe against the inner wall of pipes a speed lower than the flow velocity,
- for a turbulent flow regime, the streamlines are more chaotic ⇒ the solid particles directly strike the inner wall of pipes with an oblique or normal attack angle.



State of the art – The internal erosion – Pipeline material

On the other hand, the nature of the damage due to impacts depends on the material of pipeline inner wall:

- Brittle materials undergo cracking around the point of impact.
- Ductile materials, on the other hand, see the formation of chips located at impact points.



Case of the gas transmission pipeline

State of the art – The internal erosion – Prediction models

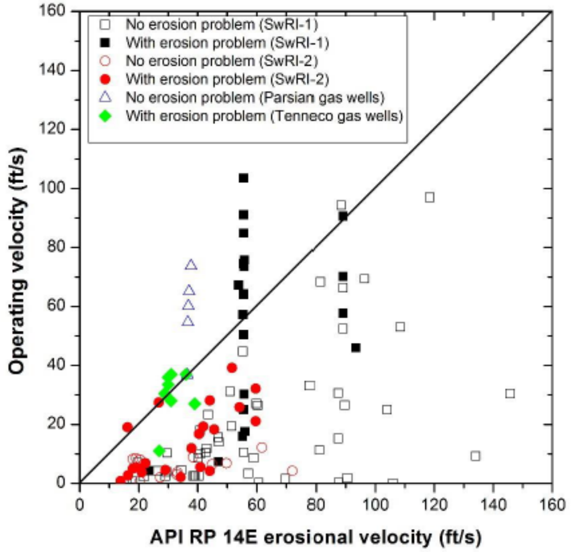
- **The prediction of the internal erosion for ductile materials is quantified by the amount of the ripped metal over a given period and the its quantification is carried out through models divided into three categories:**
  - Empirical models.
  - Semi-empirical models for single or two-phases flows.
  - Computational Fluid Dynamics (CFD) based models.

State of the art – The internal erosion – Empirical model

- The most known empirical model is presented in the API Standard RP 14E, or its modified version proposed by Salama et al.

- The API RP 14E determine the maximum flow velocity considering only the density of the fluid.

$$V_{max}[m/s] = 1.22\frac{C}{\sqrt{\rho_m}}$$



- This model is very simplistic

⇒ It leads to an important prediction error.

⇒ Natural gas operators' and academic researchers developed other models based on the theory of plastic deformation and the CFD.

State of the art – The internal erosion – Semi-empirical models

- **The Salama model** considers the pipe geometry and is based on experimental tests. It is usually used to predict erosion rate ER [mm/an] in elbows.

$$ER\,[mm/day] = \frac{1}{S_m}\frac{WV_m^2 d}{(D^2\rho_m)}$$

- **The Tulsa model** has been developed by the erosion/corrosion research center of the University of Tulsa. It estimates the erosion rate of gas transmission pipelines. Since the beginning of the 90th, this model is the most used ones by the oil and gas. This model determines the maximum erosion rate as a function of the mechanical properties relative to the strength of materials.

$$ER[mm/year] = F_M\ F_S\ F_P\ F_{\frac{r}{D}} \frac{W}{\left(\frac{D}{D_0}\right)}\ V_l^{1.73}$$

State of the art – The internal erosion – Semi-empirical models

- **The Oka model** is a modified version of the Tulsa model that combines the particle impact angle effect. It considers that erosion rate is a function of the impact angle "g(α)", and it is proportional to the erosion rate with an 90° angle "E90":

$$ER[mm/year] = g(\alpha)E_{90}$$

$$g(\alpha) = (\sin^{n1}(\alpha)\left(1 + H_v(1 - sin\alpha)\right)^{n_2}$$

State of the art – The internal erosion – CFD model

- The DNV GL-RP-0501 model is a predictive and management erosion model for the natural gas transmission networks. It based on CFD studies. It quantifies the erosion rate ER in a pipe according to of the flow velocity, the particles impact angle and the solid particle carried stream.

$$ER[mm/day] = K\, U_p^n F(\alpha) m_p$$

The F function characterizes the particles impact angle with the inner pipe wall.

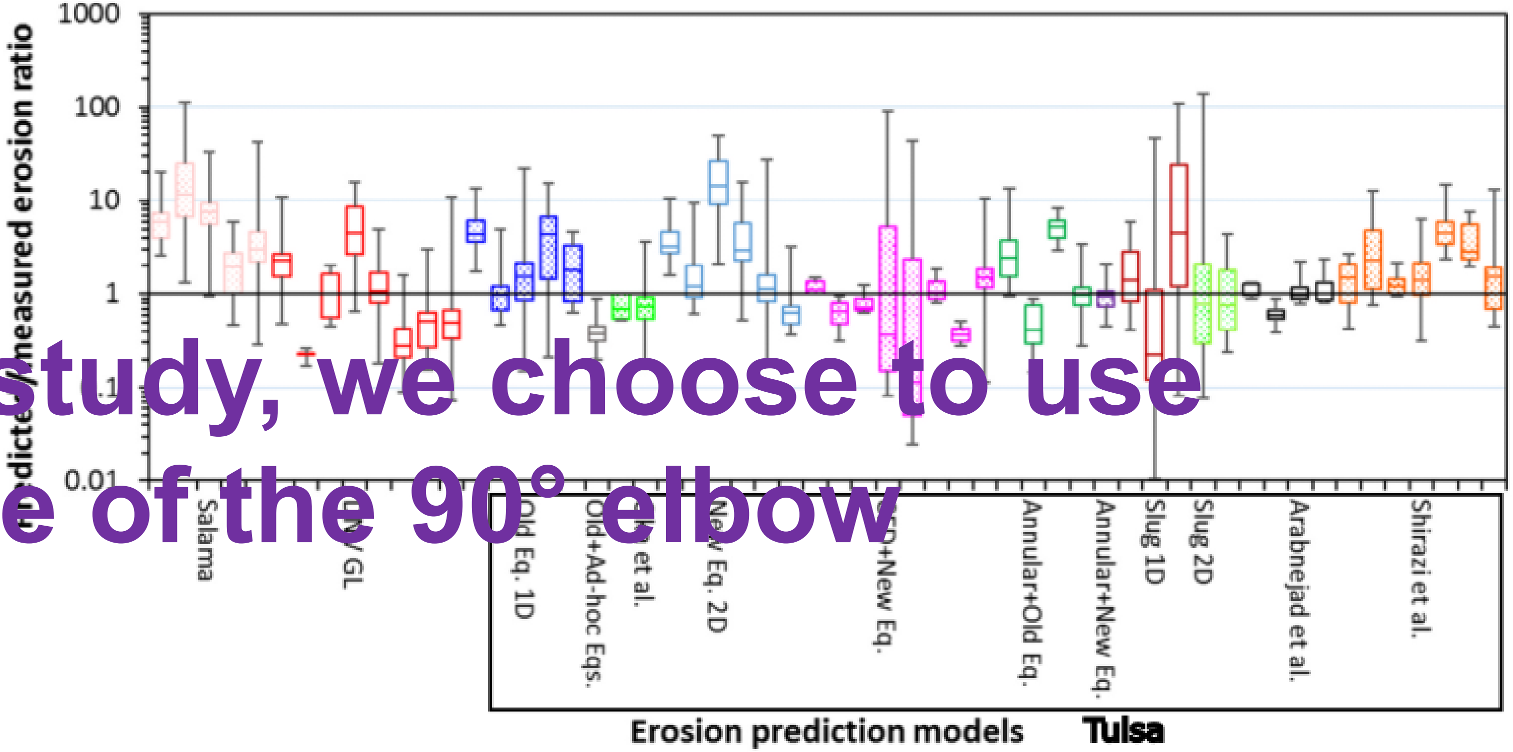
State of the art – The internal erosion – Models comparison

The four models are the most widely used models in literature to predict the erosion rate in the natural gas transmission networks.

They all agree that the 90° elbow is the sizing case.

The comparisons between the predictions of these different models and experimental measurements have shown that:

- The Salama model is the most conservative.
- The Tulsa models in their different versions also tend to overestimate erosion.
- The Oka model underestimates the rate of erosion compared to measurements (and).
- The DNV GL model predicts a wider margin for pipeline transmission velocity, but it remains equally conservative with an increase in erosion.



For our CFD study, we choose to use the case of the 90° elbow

CFD for the calculation of the erosion rate – Approach

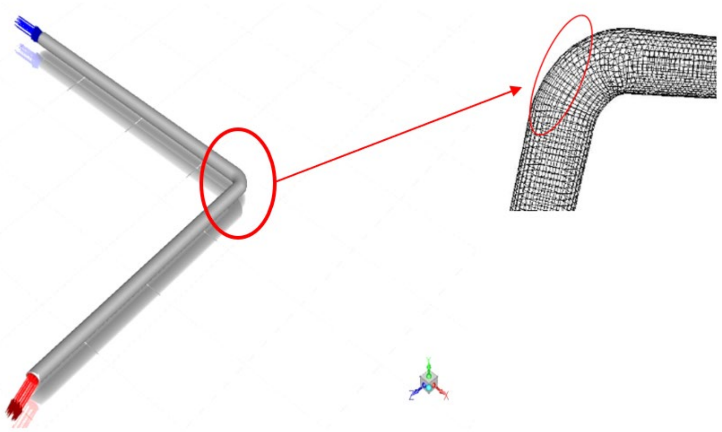
- We use the computation of fluid dynamics (CFD) to simulate the transport of particles in the gas flow.
- The integration of the velocity distribution ⇒ precisely calculate the path of the streamlines and therefore the solid particles trajectories.
- The CFD software used for this study is ANSYS FLUENT.
- The case study: injection of a constant quantity of solid particles into the flow.
- The erosion rate of the pipeline inner wall is calculated by integrating the erosion caused by each particle on surface units (i.e. 10^{-4} m2):

$$ER[mm/day] = \sum_{n=1}^{N_{particules}} \frac{\dot{m}_p C(d_p) f(\alpha) V_p^n}{A_{face}}$$

CFD for the calculation of the erosion rate – Application case

- 24” pipeline in with an internal diameter of 569 mm and a thickness of 31 mm.
- 90° elbow with abend radius of 1D.
- Upstream and downstream lengths of 20 D to ensure that the flow is fully developed before reaching the elbow.
- Carbon steel pipe material with thermophysical properties equivalent to those used on the French transmission network:

Thermodynamical properties	Valeur
Density [kg/m^3]	8030
Calorific capacity [j/kg.K]	502.48
Thermal Conductivity [W/m.K]	16.27



- Flow velocities: 20 m/s, 30 m/s, 40 m/s, 50 m/s, 60 m/s, 70 m/s and 80 m/s.

CFD for the calculation of the erosion rate – Gas properties

- The thermophysical properties of hydrogen and natural gas used in our simulations are calculated with REFPROP:

Thermodynamical properties	H2	GN
Density [kg/m³]	5.471391	56.93
Calorific capacity [j/kg.K]	14407.77	23400.0
Thermal Conductivity [W/m.K]	0.42439	0.041
Viscosity [Pa.s]	$8.641 \cdot 10^{-6}$	$1.789 \cdot 10^{-5}$
Flow pressure [bar abs]	67.7	
Flow temperature [°C]	10	

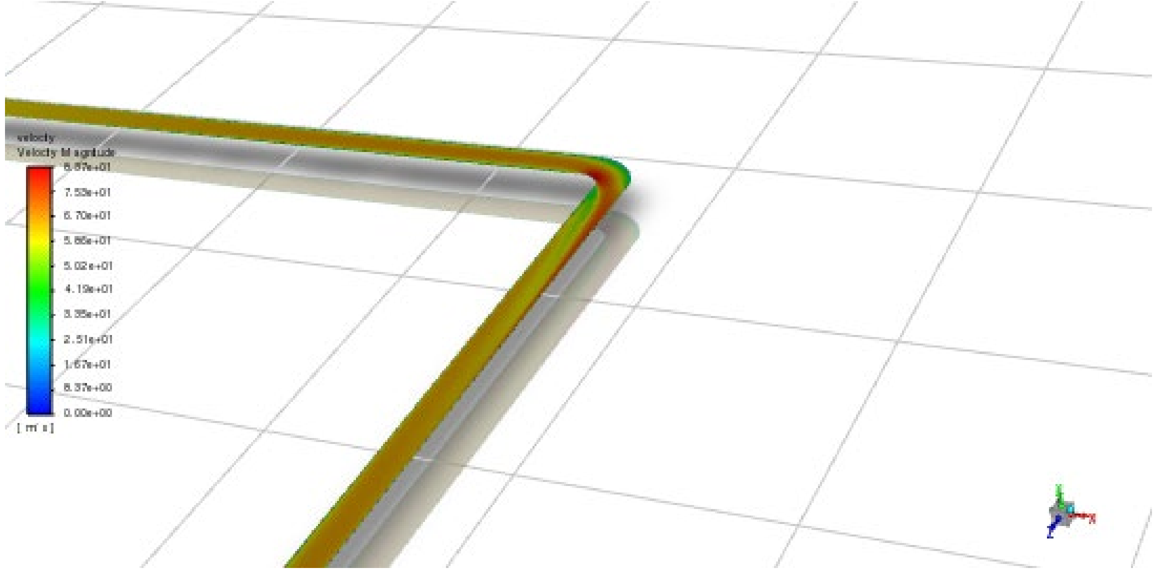
- The solid particles used are mainly composed of Fe2O3 (98%):

Density [kg/m3]	**5240**
Solid particles concentration [mg/Std.m³]	30

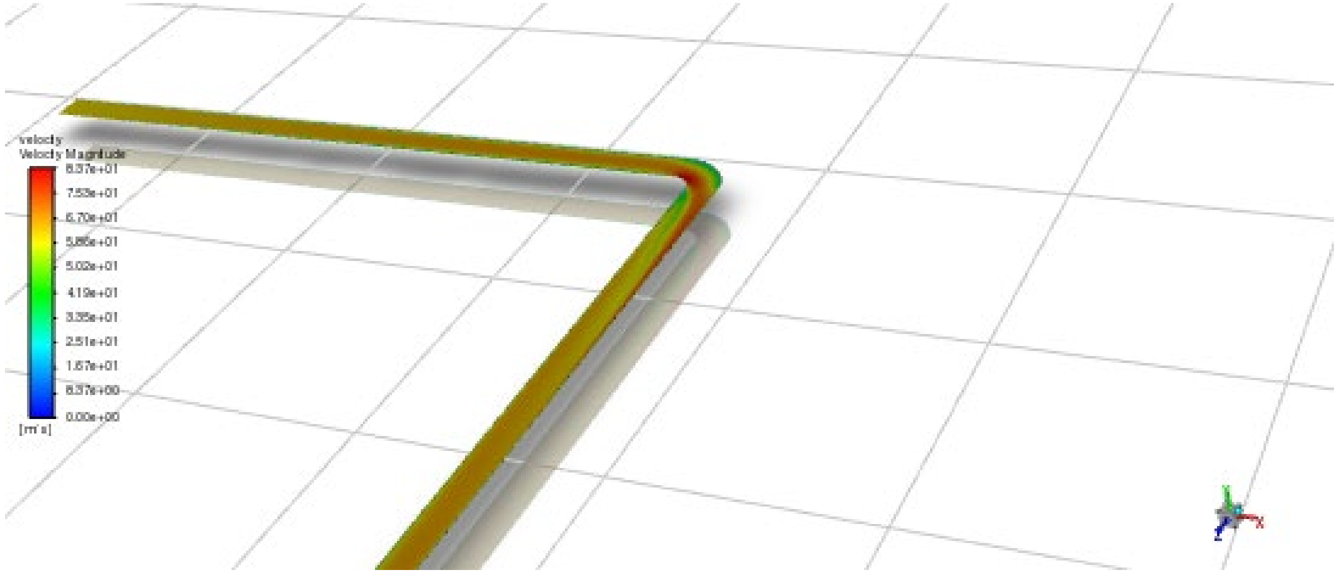
CFD for the calculation of the erosion rate – Models

- The velocity distribution in the pipe is calculated by solving the Navier-Stokes equations coupled to the k-w SST turbulence model.
- The used solid particle path tracking method is based on the LAGRANGE-EULER method.
- The fluid phase is considered a continuous medium by solving the Navier-Stokes equations
- The discrete phase (iron oxide particles) is solved by following the trajectory of the solid particles through the flow field.
- Gravity is considered negligible.

CFD for the calculation of the erosion rate – Velocity distribution



Natural gas – Flow velocity = 40 m/s

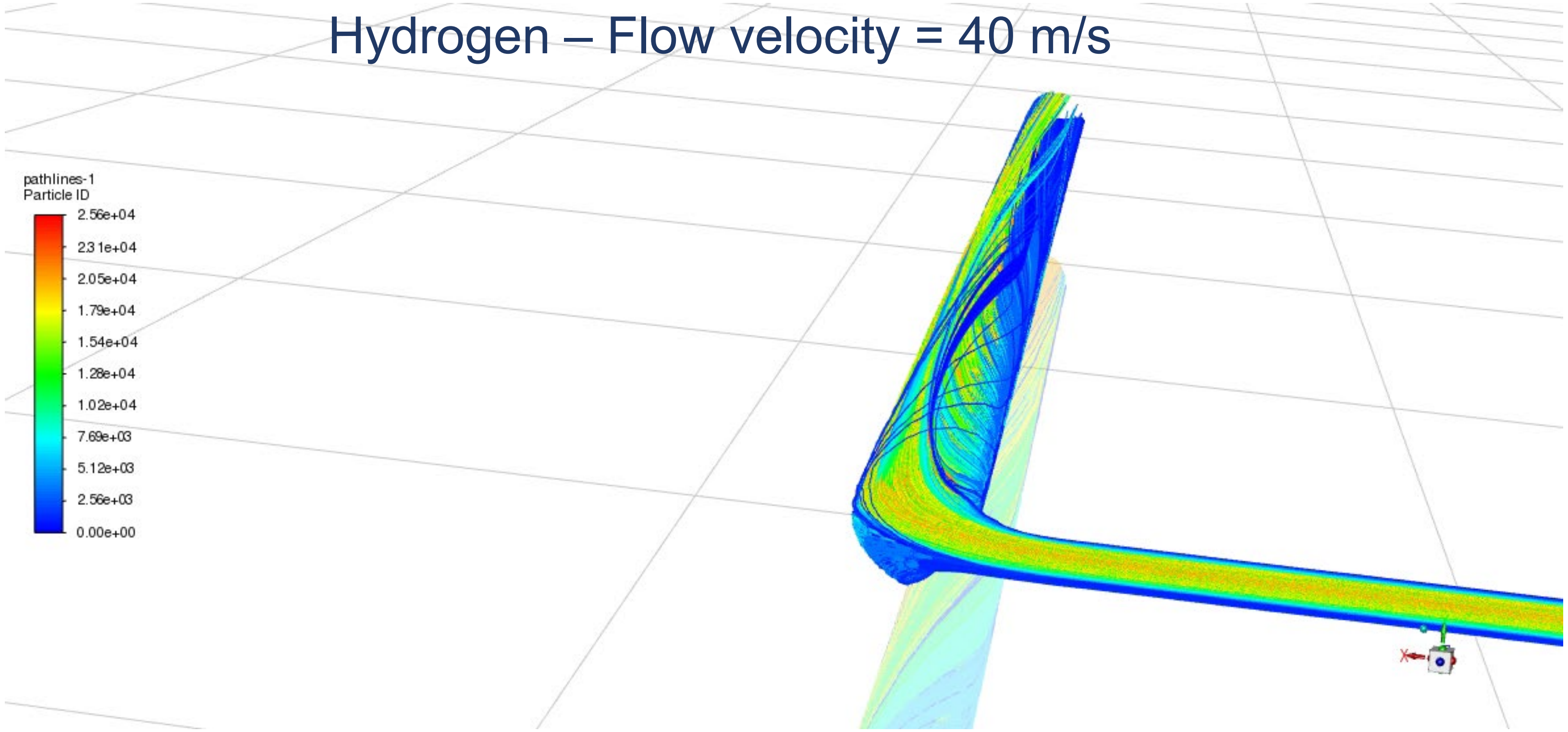


Hydrogen – Flow velocity = 40 m/s

- **A recirculation zone is observed in both cases at the outer area of the elbow bend.**
- **The gas velocity increases in the inner half of the elbow.**
- **The streamlines as well as the particles paths are carried to the outer area of the elbow bend.**

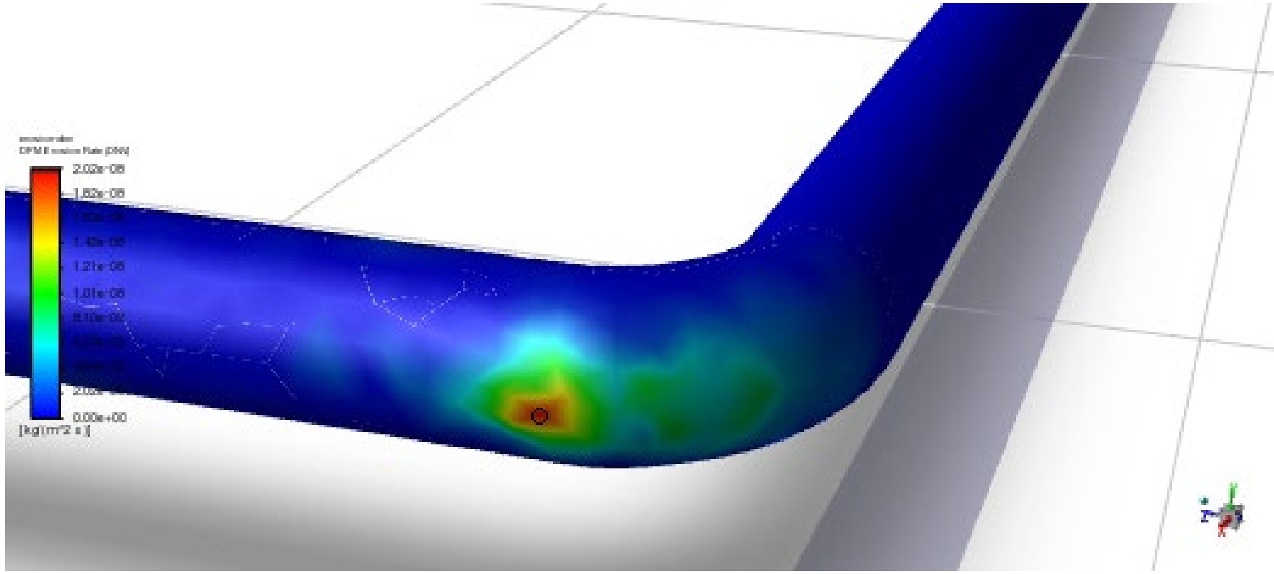
CFD for the calculation of the erosion rate – Solid particles path

Hydrogen – Flow velocity = 40 m/s

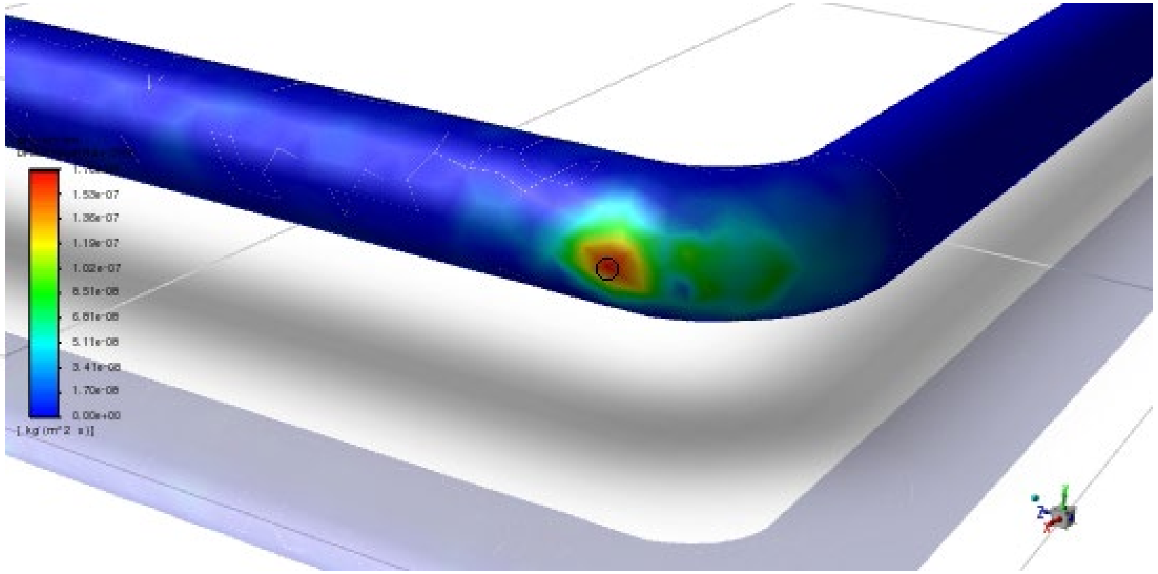


- **The streamlines concentration is maximum in the elbow bend outside area:**
  - ⇒ **the solid particles concentration impacting the pipeline inner wall is maximum.**
  - ⇒ **Highly increase the erosion in this area.**

CFD for the calculation of the erosion rate – Erosion rate distribution



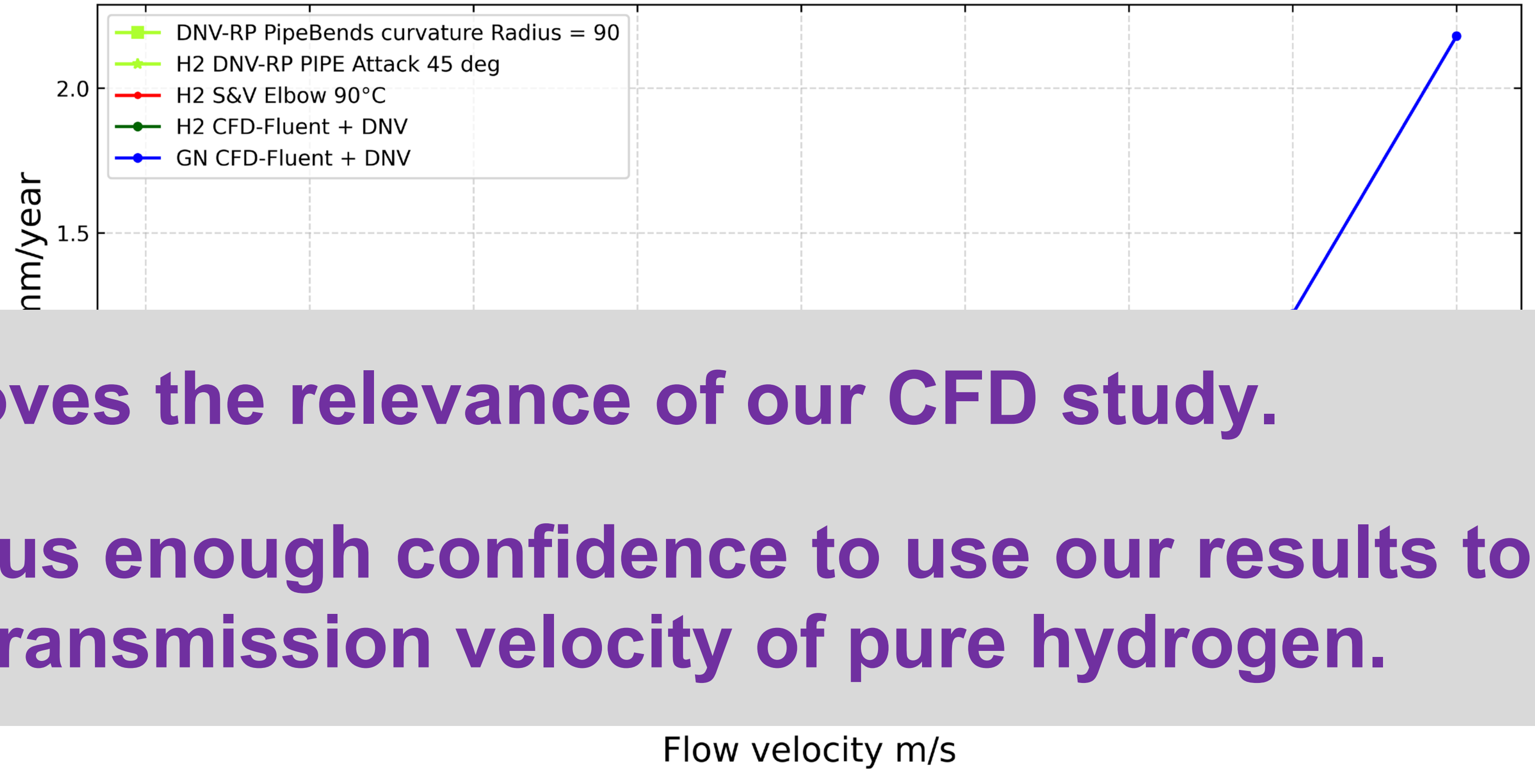
Natural gas – Flow velocity = 40 m/s



Hydrogen – Flow velocity = 40 m/s

- **The maximum point of impact is represented by the black circle.**
- **The location of the maximum erosion for both cases: natural gas and pure hydrogen, is almost the same.**
- **The erosion area is essentially defined by the streamlines which, the flow velocity, the gas thermodynamical properties and the pipeline geometry.**

CFD for the calculation of the erosion rate – Erosion rate



⇒ This proves the relevance of our CFD study.

⇒ It gives us enough confidence to use our results to assess the maximum transmission velocity of pure hydrogen.

- The annual erosion rates are almost 8 times lower, in pure hydrogen case compared to the natural gas case.
- The pure hydrogen erosion rate is perfectly comparable to the semi-empirical models (SLAMA and DNV models).

CFD for the calculation of the erosion rate – Erosion rate

Flow velocity [m/s]	Erosion rate [µm/year]		Percentage of thickness lost over 50 years for a 24" pipeline with a 31 mm thickness [%]	
	Natural gas	Hydrogen	Natural gas	Hydrogen
20	8.15	1.18	1.31	0.19
30	49.9	4.90	8.05	0.79
40	140	13.2	22.26	2.13

⇒ **This flow velocity can be easily extended to 60 m/s where the 50 years thickness loss is less than 13%. Which is perfectly acceptable knowing that we use a conservative approach.**

- **... a maximum annual acceptable erosion rate of 8.15 µm/year ⇒ 1.31% of thickness loss after 50 years of exploitation.**
- **For the case of pure hydrogen, up to a flow velocity of 40 m/s ⇒ 2.13% of thickness loss after 50 years of exploitation is equal to 2.13%.**

Conclusions & Overall Recommendations

- This paper presents a:
  - wide state-of-the-art on the main causes of limiting the natural gas pipeline transmission velocity,
  - CFD study carried out by RICE (Research and Innovation Center for Energy - GRTgaz) to assess the maximum velocity for the case of pure hydrogen.
- For the first time, a CFD study carried out in this study explain the limitation behavior of the natural gas transmission (20 m/s).
- The maximum erosion rate after 50 years of operation for pure hydrogen at a 90° elbow at 40 m/s is comparable with the erosion rate obtained for natural gas case at 20 m/s : 2,1%.

⇒ This flow velocity can be easily extended to 60 m/s where the 50 years thickness loss is less than 13%.

thank you

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