

Article

3D-CFD Analysis of Direct Hydrogen Feed-In into Natural Gas Pipelines

Nejc Klopčič ^{1,*}, Karin Rainwald ¹, Martin Krennböck ¹, Dominik Schiffer ¹, René Regenfelder ¹,
Thomas Stöhr ¹, Franz Winkler ¹ and Alexander Trattner ^{1,2,*}

¹ HyCentA Research GmbH, Inffeldgasse 15, A-8010 Graz, Austria

² Institute of Thermodynamics and Sustainable Propulsion Systems, Graz University of Technology, Inffeldgasse 19, A-8010 Graz, Austria

* Correspondence: klopcc@hycenta.at (N.K.); trattner@tugraz.at (A.T.); Tel.: +43-316-873-9492 (N.K.); +43-316-873-9500 (A.T.)

Abstract

To supply hydrogen to the geographically decoupled demand sites, efficient hydrogen transport is necessary. The existing natural gas pipelines represent a promising transport solution, with the blended hydrogen content expected to steadily increase. An open issue of hydrogen blending is the mixing behavior. Therefore, the effects of different geometric parameters (diameters, angles), operating conditions (velocities, concentrations), and injection layouts (single- and multi-point) on the mixture quality during direct injection of hydrogen into a natural gas pipeline are studied using 3D CFD. The main goal is to find parameters and layouts leading to sufficient mixing quality over a range of operating conditions. The mixing quality is determined based on the coefficient of variation (COV). The results show that the momentum flux ratio is a key parameter governing the mixing behavior. However, a high momentum flux ratio alone does not guarantee sufficient uniformity for all operating conditions. For the investigated range, single-point injection cannot ensure reliable mixing quality, whereas multi-point layouts with higher hydrogen inlet velocities achieve sufficient uniformity.

Keywords: 3D CFD; pipelines; hydrogen feed-in; hydrogen blending

1. Introduction

Achieving an independent and sustainable energy supply is crucial for the resilience and growth of Europe's economy. In this context, green hydrogen plays a pivotal role in ensuring 100% sustainability and energy independence [1]. Projections for hydrogen demand across Europe by 2030 and 2040 underscore the urgent need for robust hydrogen transportation infrastructure to connect production hubs with consumption regions. According to the European Hydrogen Backbone Initiative (EHB), a hydrogen demand of 580 TWh (17.5 Gt of H₂) is expected by 2030 across Europe, with Central Europe alone accounting for 197 TWh (6 Gt of hydrogen) [2]. However, this region is currently projected to produce only 82 TWh of hydrogen, highlighting a significant gap between supply and demand. Therefore, developing hydrogen pipeline infrastructure is viewed as essential for bridging these disparities. Addressing this challenge necessitates the development of efficient hydrogen pipeline networks. Typical transport capacities of such pipelines range from 10.6 to 22.5 GW via DN1100 and DN800 pipelines operating at 70 bar maximum pressure [3].



Academic Editor: Isabel Cabrita

Received: 17 April 2026

Revised: 17 June 2026

Accepted: 24 June 2026

Published: 30 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Repurposing existing natural gas pipelines presents an economically viable pathway to facilitate hydrogen transport on a broad scale [4–6]. Supported by initiatives such as the European Hydrogen Backbone (EHB), HyDelta, and the German Gas and Water Association (DVGW), considerable progress has been made in adapting pipeline infrastructure for hydrogen compatibility [7–10]. Significant research efforts have focused on the mechanical and material challenges of retrofitting pipelines, leading to the development of fracture-mechanical assessment frameworks [11–18]. Additionally, studies comparing the flow properties of hydrogen and natural gas have uncovered opportunities to optimize pipeline operations and improve transport efficiency [19–25]. Further research has been conducted on the economic viability of constructing and operating hydrogen pipelines, analyzing various scenarios to exploit technological advances for both pure and mixed hydrogen transport [26–34]. Safety considerations have also been a critical focus, with advancements in leak detection, inspection technologies, and material testing to ensure pipeline integrity under hydrogen conditions [35–37]. Tests on pipeline materials, valves and equipment used in European high-pressure gas networks have been carried out by Sánchez-Láinez et al. [38]. Furthermore, a comprehensive review on pipeline resilience when faced with hydrogen-induced degradation has been done by Qin et al. [39]. A further important point is the need for regulations and standards to assess existing pipelines. Sánchez et al. [40] have recently reviewed current standards and testing protocols relevant to pipeline systems targeted for repurposing.

Our research group has specifically examined the quality of hydrogen after exposure to refurbished pipelines [41].

One of the critical steps in transitioning to hydrogen pipelines involves gradually increasing the permissible hydrogen concentrations in the existing natural gas grid, currently capped at 10 vol% in countries like Austria and Germany [42]. However, injecting hydrogen into natural gas grids introduces significant challenges due to differences in density and potential separation, particularly in inclined or vertical pipelines under specific operational conditions. These issues can lead to regulatory non-compliance, component failure, or safety risks due to local hydrogen concentrations exceeding allowable limits [43–45]. Potential effects of this issue include material and component failure, hydrogen leakage, or inaccuracies in flow measurements. The challenge is twofold. On one hand, effective mixing of natural gas and hydrogen needs to be ensured downstream as quickly as possible. On the other hand, gas separation during operation needs to be prevented. Under standard conditions, separation is not expected [44]. However, under specific circumstances such as very low flow rates or when the flow is halted, separation may occur after a period of inactivity, particularly in inclined or vertical aligned pipeline sections, where stratification is more pronounced [46]. Consequently, ensuring a homogeneous mixture immediately after hydrogen injection is imperative to avoid operational inefficiencies and safety hazards.

As shown in Figure 1, hydrogen can be injected into the pipeline either directly or via a bypass injection [47]. Direct injection (Figure 1a) is only permitted for dedicated pure hydrogen pipelines, while the hydrogen feed-in for the NG gas grid happens via a bypass (Figure 1b) to ensure homogeneous mixture. The bypass injection functions as follows. The natural gas is extracted from the pipeline (7) and mixed with the hydrogen within the bypass stream (5). A static mixer element (8) is positioned in the bypass to ensure a homogeneous mixture [47]. The blending process is controlled by regulated flow rates of hydrogen and natural gas (4, 7) depending on the actual hydrogen conditions (3) and composition of natural gas (6) to meet target hydrogen content. The Austrian demonstration project Wind2Hydrogen [48] employs the bypass feed-in approach, injecting hydrogen produced via electrolysis from renewable energy sources into the NG grid.

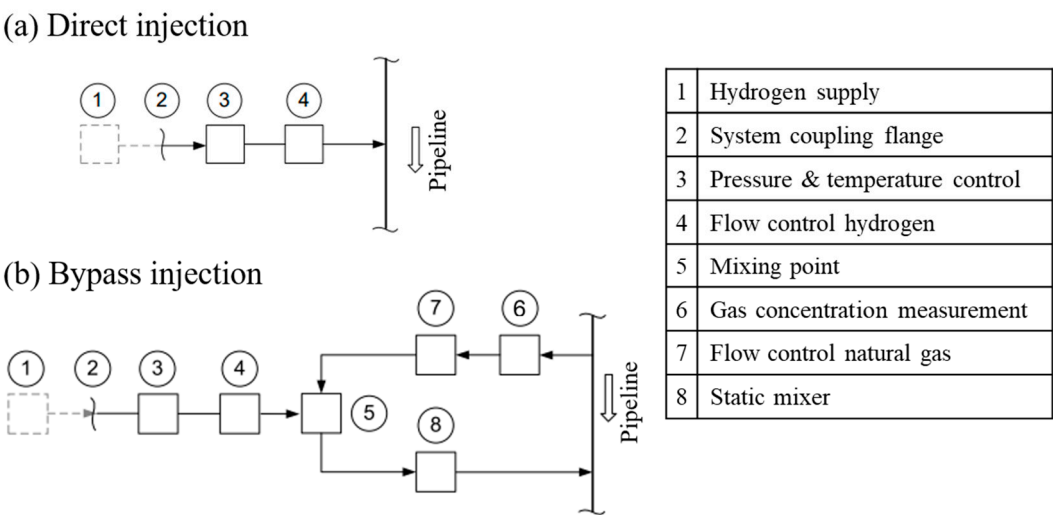


Figure 1. Schematics of (a) direct injection and (b) bypass injection. Adapted from ref. [47].

While bypass injection ensures good mixture quality, the approach has a significant economic drawback. The feed-in station operator and the gas grid operator are typically two separate entities. The exit–entry pricing model, standard in EU, leads to costs for both the extracted natural gas required for pre-mixing as well as the grid feed-in of the hydrogen–NG mixture [49]. Additional costs for measurement systems and complexity of reimbursement indicate either the need to adjust this pricing model as part of the hydrogen transition or explore the viability of direct blending to circumvent the NG extraction fees.

Different authors investigated hydrogen–NG blending behavior, including both bypass concepts with static mixers and direct injection mixers. Direct injection is understood as configurations in which hydrogen is introduced directly into the main gas stream through T-junctions, side, top or bottom injection, injection lances, orifice-based injectors, or multi-point injection arrangements, with or without additional downstream mixing elements. 3D CFD simulation studies presented in the literature show good mixing behavior for bypass feed-in with static mixers, while direct injection concepts show a stronger dependence on injector geometry, operating conditions, and available downstream mixing length [43–45].

Kong et al. [45] studied the mixing behavior of hydrogen and natural gas in a pipeline with a T-junction and a three-dimensional helical static mixer using CFD simulation. The pipeline had a diameter of 50 mm. The simulation study evaluated the effect of the number of mixing units and geometry of the mixing unit. The study concluded that three mixing units are an optimum number for sufficient mixing while keeping the pressure loss low. Mixing uniformity increased with increasing torsion angle but decreased when the angle becomes too high. Regarding the mixing length, the best results were found when the distance of the mixing units was the shortest. The blending behavior using static mixers was studied by Liu et al. [50]. Hydrogen was injected directly into the natural gas pipeline with a diameter of 310 mm via a porous injection with multiple injection holes. Following the injection, several mixing elements were positioned. The study concluded that with respect to the number of mixing elements, four elements were found to be optimal in terms of pressure drop and mixing uniformity. The mixing became more uniform as the hydrogen content increased. The uniformity decreased as the inlet velocity increased. This can be attributed to the reduced residence time, which is an important parameter for mixing.

Another study regarding the blending behavior of hydrogen and natural gas was done by Yan et al. [51]. The hydrogen injection was performed using a hydrogen pipe with a 90° bend inside the main pipeline. The number of injection pipes varied and were arranged in a circle with a certain radial distance from the pipe’s center when two or

more pipes were used. The operating pressure was atmospheric. The study concluded that the distance where uniform mixing was achieved could be reduced by increasing the number of injection pipes and by adding a turbulator after the injection pipes. The radial distance had a significant effect on the mixing process, i.e., a greater distance shortens the uniform mixing length. Su et al. [52] studied a T-junction hydrogen injection into a natural gas pipeline with an operating pressure of 3 bar and developed a deep neural network model to predict the coefficient of variation (COV) based on the CFD data. The accuracy of the deep neural network model in predicting the COV was confirmed in the study with an average error of 4.53%, which is in line with the requirements of engineering applications. In addition, the computational efficiency for predicting COV was at least two orders of magnitude faster when the deep neural network model was used instead of CFD simulations.

Different injection configurations for injecting hydrogen into a natural gas pipeline were investigated by Eames et al. [43]. Topside and bottom-side T-junction injections, as well as a hillside injection, were compared. The study concluded that bottom-side injection has clear advantages in terms of uniform mixing. This injection configuration allows the hydrogen to rise through the natural gas, improving the mixing behavior. Additionally, a T-junction hydrogen injection into a natural gas pipeline with a diameter of 0.8 m and 18 bar operating pressure was simulated by Fernandes et al. [53]. The blending process was simulated with and without static mixer elements. The mixing lengths to achieve uniform mixture could be reduced with static mixers, but for the price of additional pressure loss. Further investigations of different blending structures and systems were done by Ouyang et al. [54] and Du et al. [55]. More recently, Grácio et al. [56] investigated high-pressure T-junction configurations and direct injection layouts for hydrogen blending, further demonstrating that injector arrangement and local momentum transfer are key design parameters for direct blending systems. An overview of some injection types is presented in Figure 2.

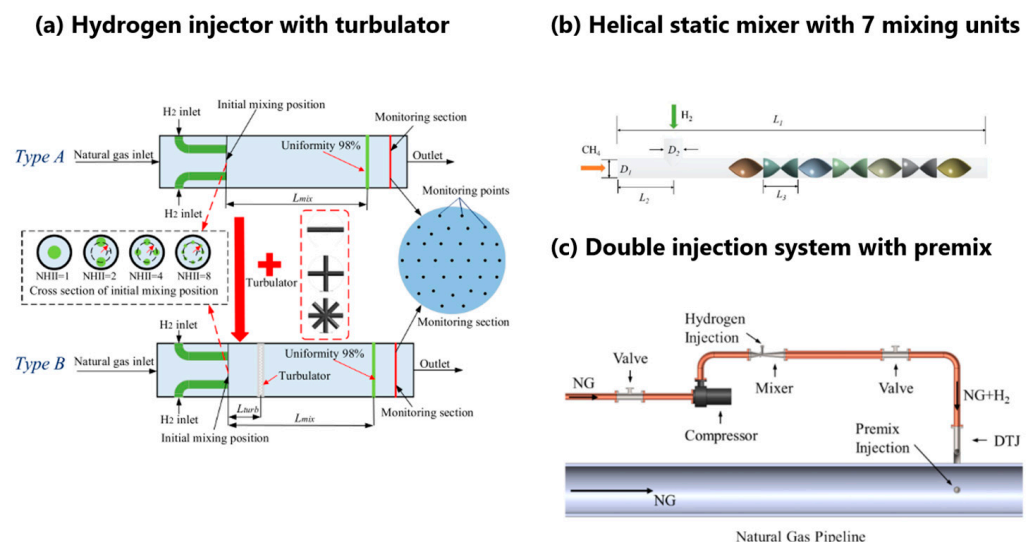


Figure 2. Overview of hydrogen blending solutions investigated in the literature: (a) hydrogen injector with turbulator by Yan et al. [51], (b) helical static mixer with seven units by Kong et al. [45], and (c) double injection system with premix by Gracio et al. [56]. All figures republished under CC-BY 4.0.

These studies show that direct injection mixers are not limited to a single injector type but include a broad range of laboratory-scale and application-oriented concepts. At the same time, the published results indicate that their performance is highly case-specific and

depends on the interaction between injector design, pipeline operating conditions, pipe geometry, and available mixing length.

While bypass injection has been widely investigated and demonstrated as a reliable route to achieve rapid mixing, the evidence base for direct injection across realistic operating envelopes and system constraints remains limited. In particular, most published work targets low-pressure, small-diameter pipelines, which only partially represents the hydraulic, operational, and regulatory realities of transnational transmission corridors (grid level 1). Insights from our expert interviews with Austrian gas transmission system operators highlight additional constraints that are especially relevant at this scale, including the need for bidirectional operation and the requirement to keep the main pipeline free of internal obstructions to enable routine pigging, inspection, and cleaning. As a result, concepts such as static mixers or internal flow-conditioning elements can improve mixture quality where their installation is feasible, but they are typically not compatible with grid level 1 infrastructure when pigging, inspection, and unrestricted pipeline operation must be maintained. Their application therefore requires a case-specific trade-off assessment, whereas the present study specifically focuses on direct injection concepts without internal mixing elements for pipeline sections where such components are not desirable or technically feasible.

This work closes these gaps by assessing hydrogen–natural gas blending via direct injection, where turbulence is the sole mixing mechanism and no intrusive internals are introduced. Using CFD, we systematically quantify the influence of key geometric and operational parameters (injection angle, bulk flow velocity, and pipeline diameter) on mixing performance. On this basis, we derive practical criteria for achieving target mixing lengths and concentration uniformity without incurring additional pressure losses or constraining operational flexibility. Importantly, the analysis spans both grid level 1 (transnational transmission) and grid level 3 (national distribution) contexts, enabling a structured comparison of feasibility and design implications across pressure levels, diameters, and operating modes.

In addition, the study extends the analysis to the exact blending layout of an existing real-world hydrogen blending station in the national distribution grid (grid level 3). The specific station geometry, boundary conditions, and operating ranges are reproduced in the CFD model to evaluate mixing behavior under realistic distribution-level constraints. This allows a direct assessment of how design features such as injection configuration, pipe layout, and downstream network interfaces influence mixing uniformity, providing insights into how distribution-scale blending stations can be designed or retrofitted to ensure compliant and robust hydrogen admixture under practical operating conditions.

By combining CFD-based evidence with operator requirements and expert feedback, the study provides new insight into the boundary conditions under which direct injection can be a viable blending strategy at transmission and scale, while also identifying transferability and limitations for distribution networks. The results support the development of scalable, cost-effective blending concepts and inform infrastructure optimization pathways aligned with Europe's transition toward hydrogen integration.

2. Methodology

In order to investigate the mixing behavior of hydrogen injection into the natural gas grid, 3D CFD simulations were performed using Ansys Fluent 2024R2. The study consists of three main scenarios:

- In the first scenario focusing on grid level 1, a simple geometrical model consisting of a topside T-junction with two pipes, namely the main pipeline and the hydrogen injection pipeline, was prepared. The aim of this model was to investigate the effects

of geometrical parameters (injection angle and diameter) and operational parameters (natural gas velocity and target hydrogen volume fractions of mixture) on mixing quality. Furthermore, a simple topside injection would potentially represent the best case for blending from a construction standpoint; thus, this configuration was chosen as the starting point of the investigations. A design of experiments (DoE) approach, which will be described in the subsequent sections, was used for the parameter study in the first scenario.

- Based on the results of the first scenario, it was decided to investigate multi-point injection in more detail in the second scenario. Since current pipeline regulations in Austria and Germany limit the hydrogen content to 10 vol%, we focused on this limiting scenario only in the second scenario. Different geometrical layouts and hydrogen pipe diameters were compared to assess their impact on the mixing process. The aim was to identify suitable geometries leading to good mixing behavior of the gases.
- In the third scenario, different orifice geometries and their effect on blending were examined for a real-life application within the national distribution network (grid level 3) in Austria. Furthermore, the effects of bends in the pipeline on the mixing quality due to secondary mixing effects was examined. The simulations were done at grid level 3 for a DN600 pipeline with single-point injection and an operating pressure of 4.2 bar.

In the following subsections, the underlying mathematical and geometrical models and boundary conditions are presented.

2.1. Mathematical Model

The mathematical model employed by the Ansys Fluent 2024R2 software includes solving a set of conservation equations for continuity, momentum, energy, turbulence, and species transport. The mathematical equations solved by the software are presented below [57].

- Continuity:

$$\rho \frac{\partial p}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

- Momentum:

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (2)$$

where ρ is the density, $\vec{v}$ is the velocity vector, p is the static pressure, $\bar{\tau}$ is the stress tensor, $\rho \vec{g}$ is the gravitational body force, and $\vec{F}$ are the external body forces from model-dependent source terms ($\vec{F} = 0$ in our case).

The stress tensor with μ as the molecular viscosity and I the unit tensor can be calculated as:

$$\bar{\tau} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^t \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \quad (3)$$

- Energy:

$$\frac{\partial}{\partial t} \left(\rho \left(e + \frac{v^2}{2} \right) \right) + \nabla \cdot \left(\rho \vec{v} \left(h + \frac{v^2}{2} \right) \right) = \nabla \cdot \left(\lambda_{\text{eff}} \nabla T - \sum h_j \vec{J}_j + \bar{\tau}_{\text{eff}} \cdot \vec{v} \right) + S_h \quad (4)$$

Here, e and h represent the internal energy and enthalpy, respectively. λ_{eff} is the effective thermal conductivity and $\vec{J}_j$ the flux diffusion of species j . The first three terms on

the right-hand side represent (in order from left to right) heat transfer due to conduction, species diffusion, and viscous dissipation. The user-defined source term S_h is zero in this work.

- Turbulence:

The realizable $k - \epsilon$ model was chosen within the software (based on the literature [53]), which solves two separate conservation equations for the turbulent kinetic energy k and turbulent dissipation rate ϵ .

- Turbulent kinetic energy:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (5)$$

- Turbulent dissipation rate:

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon \quad (6)$$

These equations include several empirical factors and model constants, where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_2 = 1.9$ and $C_1 = 1.44$ are constants, $\sigma_k = 1.0$ and $\sigma_\epsilon = 1.2$ are the turbulent Prandtl numbers, and S_k and S_ϵ represent additional source terms (again being zero in the present work).

The terms G_k and G_b are calculated as follows:

$$G_k = \mu_t S^2 \quad (7)$$

$$G_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (8)$$

Here, $S = \sqrt{2S_{ij}S_{ij}}$ is the modulus of the mean rate of stress tensor, $Pr_t = 0.85$ is the turbulent Prandtl number, g_i the component of the gravitational vector in the i -th direction, $\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p$ is the coefficient of thermal expansion, and $\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$ is the turbulent viscosity with a standard value for C_μ of 0. Lastly:

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right] \quad (9)$$

$$\eta = S \frac{k}{\epsilon} \quad (10)$$

$$C_{3\epsilon} = \tanh \left| \frac{v}{u} \right| \quad (11)$$

where v is the component of flow velocity parallel to the gravitational vector and u is the component of flow velocity perpendicular to the gravitational vector.

- Species transport:

In the present study, natural gas was represented by pure methane. This represents a simplification since real natural gas does not exclusively comprise methane, and its composition can vary substantially depending on origin, processing, and supply route. Reported methane contents range from methane-rich gas qualities of approximately 97% to lower values of around 83%, with the remaining fraction consisting mainly of higher hydrocarbons, nitrogen, carbon dioxide, and other minor constituents [58,59]. Including this

compositional variability would introduce additional input parameters and uncertainties that are not central to the scope of this work. Therefore, pure methane was selected as a stable and reproducible baseline gas in order to isolate the influence of hydrogen admixture and mixing behavior. With methane and hydrogen thus being the only species used within the mixture model, only one equation for species transport is solved for methane:

$$\frac{\partial}{\partial t}(\rho y_{\text{CH}_4}) + \nabla \cdot (\rho \vec{v} y_{\text{CH}_4}) = -\nabla \cdot \vec{J}_{\text{CH}_4} + R_{\text{CH}_4} + S_{\text{CH}_4} \quad (12)$$

where $\vec{J}_{\text{CH}_4}$ is the diffusion flux based on Fick's law, R_{CH_4} is the production rate by chemical reaction, and S_{CH_4} represents any user-defined sources. Both the reaction rate and user-defined sources do not apply in this case and are thus zero. The hydrogen mass fraction can then simply be calculated as:

$$y_{\text{H}_2} = 1 - y_{\text{CH}_4} \quad (13)$$

The fluid properties in each cell, such as density, which are used in the governing equations, are calculated using a mixing law from the properties and mass/mole fractions of the corresponding species; thus, only one set of governing equations is solved for the mixture.

2.2. Physical Model

In the first scenario of the study, the simple geometry consisted of the transmission line for methane with a diameter of 1 m (typical for transnational pipelines [58]) and an injection line for hydrogen, as seen in Figure 3a. Uniform flow field conditions were set at both pipe inlets. To ensure a reasonable flow field was established at the injection point, the distance between pipe inlet and injection point was set as 10 times the diameter. The diameter of the hydrogen pipe was one of the varied parameters; thus, the geometry and mesh slightly changed for different simulation runs. The length of the hydrogen pipe was 10 times its diameter parameter. The mixing length was defined as 15 times the diameter of the main pipe.

In the second scenario of the study, hydrogen was simultaneously blended through a one-stage multi-point injection geometry using four pipes. The angle α between the axis of the injection pipe and the surface of the main pipeline was varied, resulting in three different injection directions at 0° , 45° , and 90° . In addition, the diameter of the hydrogen injection pipes was adjusted between 0.2 m and 0.07 m, resulting in hydrogen flow velocities of 6.5 m/s and 53 m/s, respectively, for a target blend of 10 vol% hydrogen and a methane velocity of 8 m/s. Six different layouts were created due to the varying pipe angles and diameters. Figure 3b shows the volume body of the pipeline with a perpendicular ($\alpha = 90^\circ$) inlet and a diameter of 0.07 m. Additionally, the front view of the three different injection direction layouts, namely the perpendicular ($\alpha = 90^\circ$), 45 degree ($\alpha = 45^\circ$), and tangential ($\alpha = 0^\circ$) inlets, are shown. The main pipeline was fixed at a diameter of 1 m and a mixing length of 20 m. Both gas streams had an inlet temperature of 10°C and an operating pressure of 70 bar. The length of the main pipeline before the mixing point is 5 m and the hydrogen pipes were each 1 m long.

Furthermore, a layout consisting of two stages with four perpendicular pipes each was designed (Figure 3c). The second stage was arranged with a 45° offset 3 m after the first stage. The diameters of the hydrogen pipes were 0.07 m, resulting in an inlet velocity of 26.5 m/s for this configuration with a total of 8 pipes.

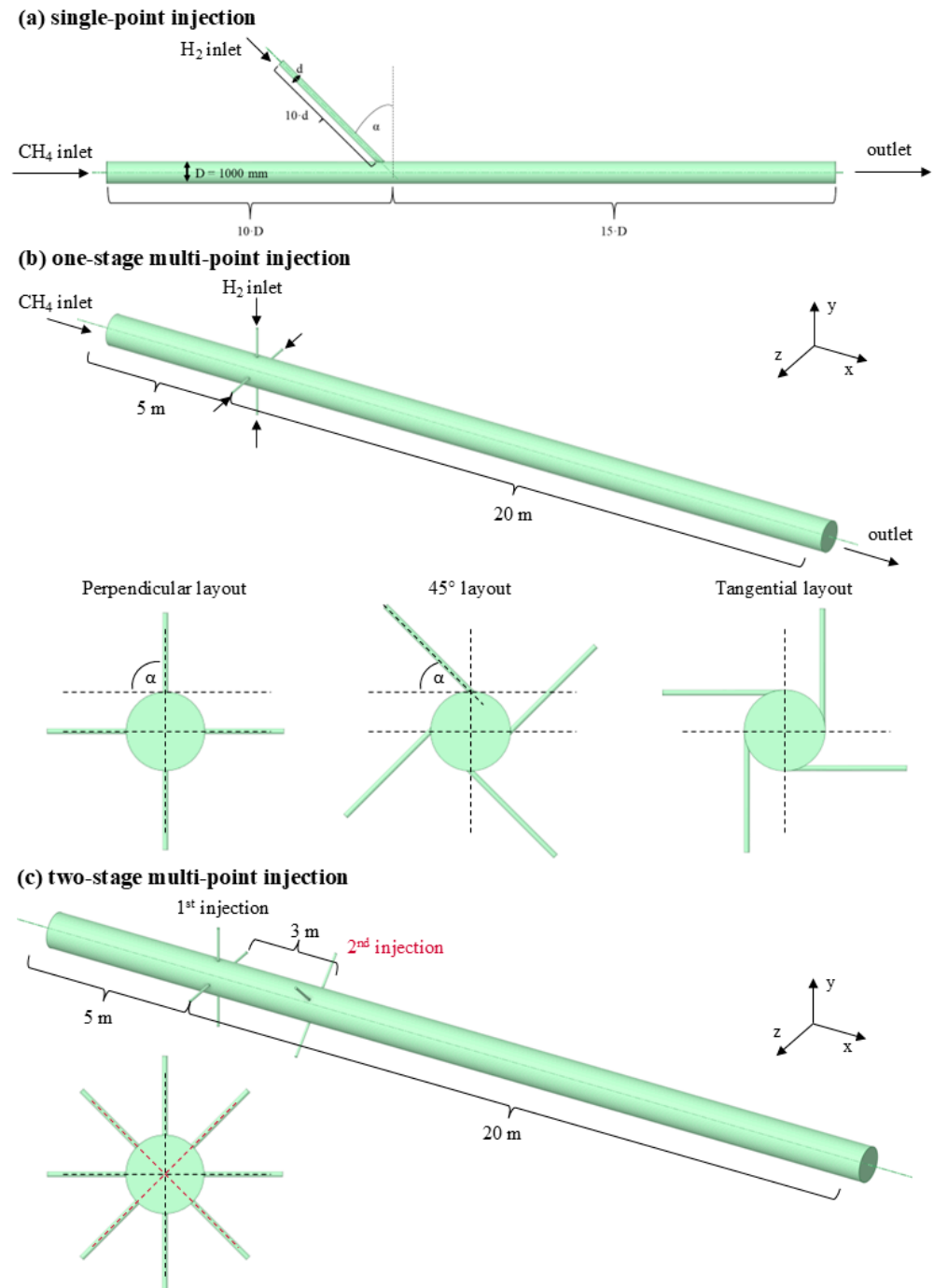


Figure 3. (a) Single-point injection; (b) one-stage multi-point injection with varying injection angles α and an injection pipe diameter of 0.07 m: perpendicular layout ($\alpha = 90^\circ$), 45 degree layout ($\alpha = 45^\circ$), and tangential layout ($\alpha = 0^\circ$); (c) two-stage multi-point injection with staggered perpendicular inlets and an injection pipe diameter of 0.07 m.

The model in the third scenario consisted of an approximately 50 m long DN600 pipeline section and an injection pipe with a diameter of 0.08 m and length of about 1 m. The pipeline section with the exact dimensions is shown in Figure 4. At the end of the section under consideration, there is a 90° bend, which is intended to provide a secondary mixing effect. Therefore, the mixing quality was evaluated both before and after the bend in order to quantify this effect. Since the operating pressure was at a lower level of 4.2 bar compared to the first two scenarios, different velocities were produced in the pipeline. The natural gas entered the pipeline section at a constant velocity of 3.6 m/s, and the mass

flow of hydrogen was calculated using Equation (21) to achieve the desired hydrogen concentrations of 2, 10, 20, and 50 vol%. The temperature remained unchanged at 10 °C.

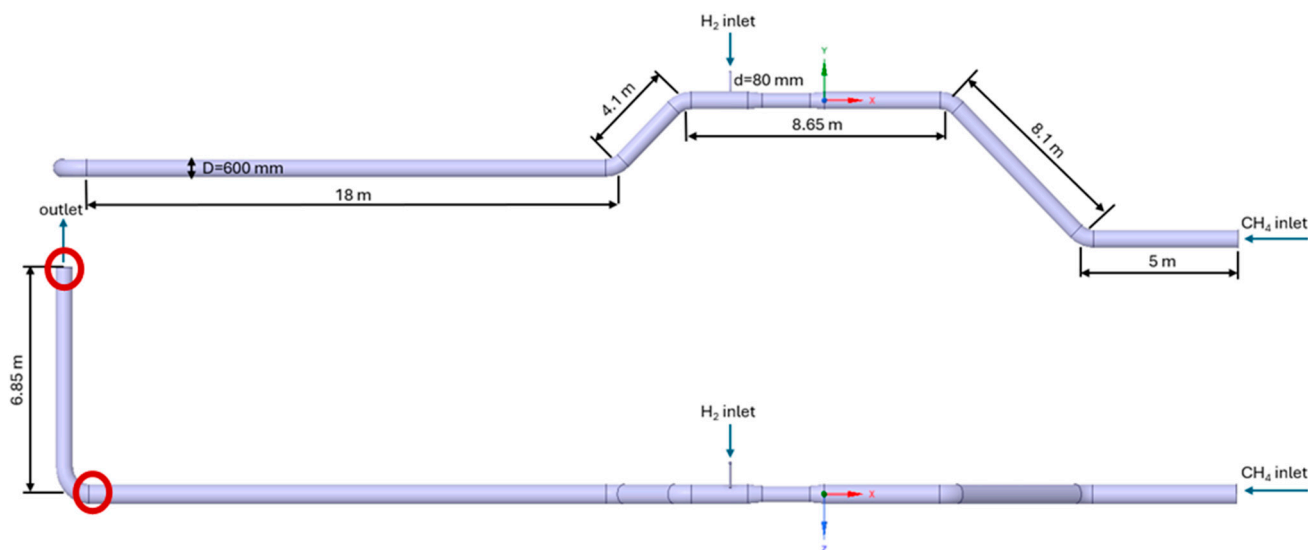


Figure 4. Scenario 3—real-life application of a national distribution (grid level 3) pipeline section with an injection pipe for hydrogen blending in xy - and zx -plane views. Two red circles mark the locations of cross-sections used to evaluate the uniformity of the hydrogen–methane mixture.

The following orifice geometries are simulated and the effect on the quality of mixture investigated: perforated plates with large and small boreholes and single circular openings with large and small diameters. In addition, two different thicknesses of the orifices are investigated. Simulations are also performed for converging and diverging injection pipes.

2.3. Mixing Uniformity

To characterize the mixing uniformity of the hydrogen–methane blend, the coefficient of variation (COV) was applied. COV is defined in Equation (14) and is the ratio between the standard deviation σ and the mean μ of the data. In this study, the density was chosen as the characteristic parameter. The literature sources typically define $\text{COV} \leq 5\%$ as the threshold for a sufficiently uniform mixture of H_2 and CH_4 [52]. To the best of the authors knowledge, no such thresholds for local concentration variability are currently defined in regulatory frameworks (i.e., ÖVGW H E310, DVGW G 262, etc.).

$$\text{COV} = \frac{\sigma(\rho)}{\mu(\rho)} = \frac{\sqrt{\frac{\sum_{i=1}^n (\rho_i - \frac{1}{n} \sum_{i=1}^n \rho_i)^2}{n-1}}}{\frac{1}{n} \sum_{i=1}^n \rho_i} \quad (14)$$

In this case, the density of the mixture ρ_i was chosen as the characteristic physical quantity, but other authors have also employed the mass or mole fraction of one of the phases. This density-based COV was selected because density is a mixture-level scalar that is directly affected by local H_2/CH_4 composition differences. H_2 -rich regions correspond to lower local density, while CH_4 -rich regions correspond to higher local density. The density-based COV therefore provides a practical indicator of scalar non-uniformity across the outlet cross-section. Concentration-based COV values depend on the selected reference species and target concentration since the standard deviation is normalized by the mean mole fraction. Thus, H_2 -based COV is more restrictive at low hydrogen fractions, whereas CH_4 -based COV is more restrictive at high hydrogen fractions. The density-based COV avoids selecting one species as the reference and provides a consistent mixture-level evaluation

across all investigated blending ratios. Additionally, in the majority of the cases, density-based COV was the most restrictive with a 5% threshold.

The terms σ and μ represent the standard deviation and mean values, respectively, which are well-known statistical quantities. The mixture density ρ_i was calculated within the CFD program for each cell or face with an index i . By defining a reference plane at a desired pipeline cross-section, the mixing quality on that plane could be calculated. The number of regions n on the plane depends on the refinement of the computational mesh. Fluent already includes functions that can calculate an area-weighted average value and standard deviation on a surface.

2.4. Mesh and Grid Independence

The polyhedral mesh (Figure 5—exemplary scenario 2) was created with five boundary layers using the Fluent Meshing tool. To ensure reliable results, a grid sensitivity analysis was conducted by calculating and comparing the average density using meshes of approximately 1.5, 2.5, and 3 million cells. Figure 6 displays COVs across various cross-sections downstream of the hydrogen inlet. It is evident that COV at 2.5 million cells matches the results at 3 million cells. For further simulations, a mesh size of approximately 2.5 million cells was chosen. The meshing process was analogous for all three scenarios, with the final cell count after the mesh sensitivity study being approx. 2 million cells for scenario 1, the aforementioned 2.5 million for scenario 2, and approx. 3 million cells for scenario 3.

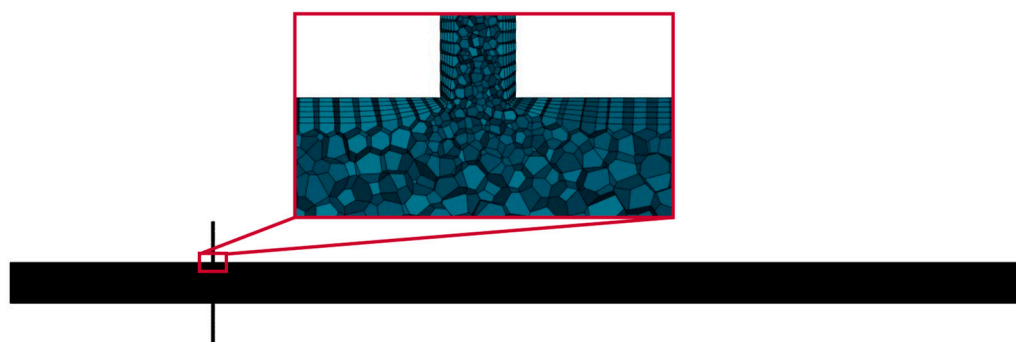


Figure 5. Polyhedral mesh of the one-stage perpendicular inlet with a diameter of 0.07 m.

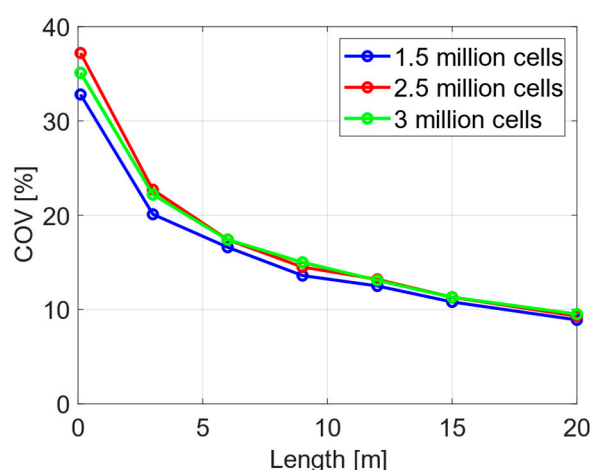


Figure 6. COVs along the mixing length for different mesh sizes for scenario 2.

2.5. Boundary Conditions and Solver Settings

Velocity was specified as the boundary conditions for simulation models in all three scenarios at the methane inlet. For the hydrogen inlet boundary condition, an inlet mass

flow rate was specified for the first and third scenarios with single-point injection (see Equation (21)), which was changed to an inlet velocity for the multi-point injections in the second scenario (see Equation (18)). For both boundary conditions at the methane inlet and the hydrogen inlet, the turbulence intensity was set to 10% and the hydraulic diameter corresponds to the pipe diameter. To verify the impact of this assumption, a representative sensitivity study with inlet turbulence intensities of 5%, 10%, and 20% at both the methane and hydrogen inlets was carried out, which showed nearly identical outlet COV values. The prescribed inlet turbulence intensity therefore has a negligible influence on the evaluated COV, which is attributed to the sufficiently long pipe sections allowing the turbulence field to develop before the mixing region.

The realizable k - ϵ model was used for all simulations, as it has proven to be a suitable and established model in other publications on similar topics [52,53]. The turbulence model sensitivity study showed that the realizable k - ϵ and SST k - ω models led to the same overall interpretation of the investigated mixing configurations. For the representative scenario 2 cases (see Figure 7), both models predicted that the larger hydrogen inlet diameter did not achieve the target value of $\text{COV} \leq 5\%$, whereas the smaller inlet diameter fulfilled the criterion after 20 m. Quantitative differences were observed mainly at intermediate downstream positions, where the SST k - ω model predicted a faster COV reduction, particularly for the smaller inlet diameter. However, the final COV-based design classification remained unchanged, and the corresponding two-dimensional cross-sections showed no visible qualitative differences in the predicted concentration distribution. Based on this comparison, the realizable k - ϵ model was retained for the parametric simulations. The results should therefore be interpreted as a RANS-based engineering assessment of overall mixing behavior and COV trends rather than as a fully resolved description of instantaneous turbulent jet-in-crossflow structures. Within this scope, the turbulence model choice did not affect the main design conclusions.

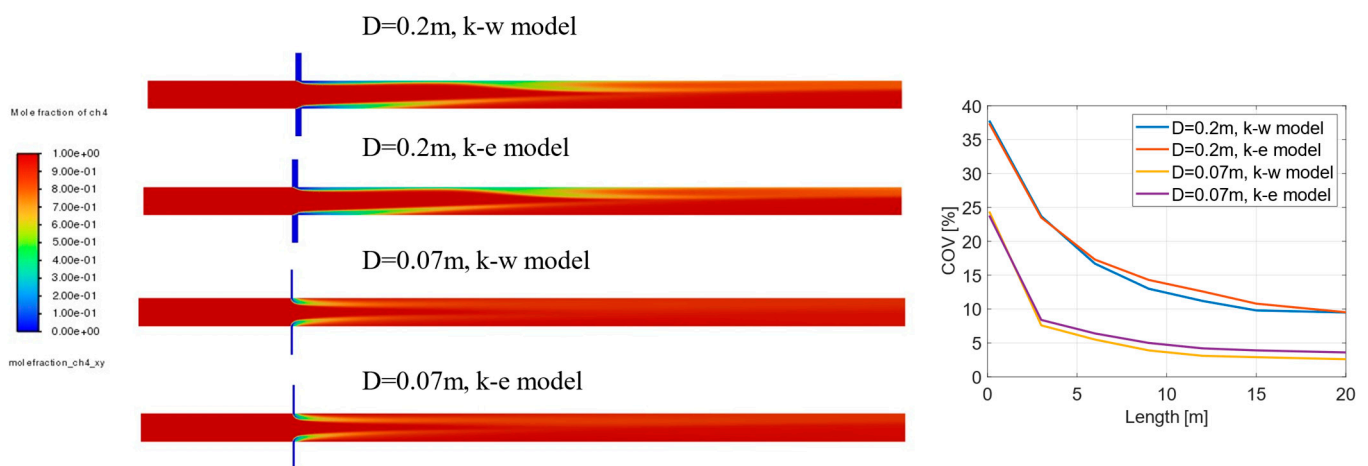


Figure 7. Comparison of CH₄ mole fraction cross-sections and COV profiles along the length between the realizable k - ϵ and SST k - ω models for two different diameters based on scenario 2 with perpendicular injection.

For the outlet boundary conditions, a constant pressure of 70 bar was set for the simulation cases in scenarios one and two. In the simulation model of the third scenario, the outlet boundary condition was set with a constant pressure of 4.2 bar due to the national distribution pipelines on grid level 3 operating at lower pressure levels. A constant temperature of 10 °C was set, which is a plausible value for pipelines [19]. The simulation was steady-state, and the convergence of the solution was determined by monitoring both

the residuals and the standard deviation of density, as well as the mean density on the outlet face. The solver settings for the ANSYS Fluent CFD simulations are listed in Table 1.

Table 1. Settings in ANSYS Fluent.

Item	ANSYS Fluent Settings
Turbulence Model	Realizable k- ϵ ; buoyancy effects—only turbulence production
Near-Wall Treatment	Standard wall functions
Pressure–Velocity Coupling	Coupled
Spatial Discretization Gradient	Least squares cell-based
Spatial Discretization Pressure	Second order
Spatial Discretization Density	Second order upwind
Spatial Discretization Momentum	Second order upwind
Spatial Discretization Turbulent Kinetic Energy	Second order upwind
Spatial Discretization Turbulent Dissipation Rate	Second order upwind
Spatial Discretization CH ₄	Second order upwind
Spatial Discretization Energy	Second order upwind

To calculate the hydrogen inlet velocity for the multi-point injections, the mass flow of methane $\dot{m}_{\text{CH}_4}$ was calculated with the following formula, in which w_{CH_4} is the flow velocity of methane; A_{CH_4} is the cross-sectional area of the main pipeline; p and T are the operating pressure and temperature, respectively; z_{CH_4} is the real gas compressibility factor, which was calculated using the real gas database CoolProp [60,61]; and R_{CH_4} is the gas constant of methane.

$$\dot{m}_{\text{CH}_4} = \frac{w_{\text{CH}_4} \cdot A_{\text{CH}_4} \cdot p}{T \cdot z_{\text{CH}_4} \cdot R_{\text{CH}_4}} \quad (15)$$

The mass flow after the hydrogen inlet, $\dot{m}_{\text{mixture}}$, was calculated via the following formula:

$$\dot{m}_{\text{mixture}} = \frac{\dot{m}_{\text{CH}_4} \cdot M_{\text{mixture}}}{\nu_{\text{CH}_4} \cdot M_{\text{CH}_4}} \quad (16)$$

$$M_{\text{mixture}} = \nu_{\text{CH}_4} \cdot M_{\text{CH}_4} + \nu_{\text{H}_2} \cdot M_{\text{H}_2} \quad (17)$$

where M_{mixture} , M_{H_2} , and M_{CH_4} are the molar masses of the mixture, hydrogen, and methane, respectively; and ν_{CH_4} and ν_{H_2} are the volume concentrations of methane and hydrogen, respectively.

The mass flow of hydrogen can then be calculated as follows, wherein M_{H_2} is the molar mass of hydrogen and n_{pipes} is the number of hydrogen inlet pipes.

$$\dot{m}_{\text{H}_2} = \frac{\dot{m}_{\text{mixture}} \cdot \nu_{\text{H}_2} \cdot M_{\text{H}_2}}{n_{\text{pipes}} \cdot M_{\text{mixture}}} \quad (18)$$

The hydrogen inlet velocity w_{H_2} for multi-point injections was then calculated via the following formula from a constant total hydrogen mass flow, wherein A_{H_2} is the cross-sectional area of one hydrogen inlet pipe, R_{H_2} is the gas constant of hydrogen, and z_{H_2} is the real gas compressibility factor of hydrogen, which was calculated using CoolProp.

$$w_{\text{H}_2} = \frac{\dot{m}_{\text{H}_2} \cdot T \cdot z_{\text{H}_2} \cdot R_{\text{H}_2}}{A_{\text{H}_2} \cdot p} \quad (19)$$

2.6. Design of Experiments for Scenario 1

Design of experiments (DoE) methods offer a promising avenue for optimizing various industrial systems. While initially rooted in experimental studies, they can be effectively integrated in Computational Fluid Dynamics (CFD) simulations. Particularly in scenarios where multiple parameters impact the final solution and system efficiency, fractional factorial DoE methods present substantial time-saving benefits over full factorial designs [62–65].

The mixing behavior of hydrogen and methane is influenced by several parameters, including the methane velocity, the hydrogen inlet angle, and the diameter of the hydrogen inlet pipe. Furthermore, the volumetric fraction of hydrogen was varied and set to 10%, 20%, 30%, 50%, and 70%, which in turn impacts injection conditions, such as injection velocity. The objective was to rapidly achieve a well-mixed flow by optimizing these factors. It is crucial to prevent the hydrogen from forming into separated layers without adequately mixing with the main flow.

For each gas mixture, a DoE study was implemented via the Ansys Workbench. In contrast to a full factorial design, which necessitates a significantly larger number of simulations, the refined, face-centered Central Composite Design (CCD) was chosen in this study. This method provides the advantage of ensuring an adequate number of simulation points in the edge region of the control space within the defined limits. By selecting the refined option, additional points were inserted inside the range to improve overall coverage and increase the accuracy of the results. Figure 8 illustrates the applied DoE method. The circles and star denote the simulation points in the control space for a classic face-centered CCD, while the rectangles represent an example of additional points inserted through the refinement option [66].

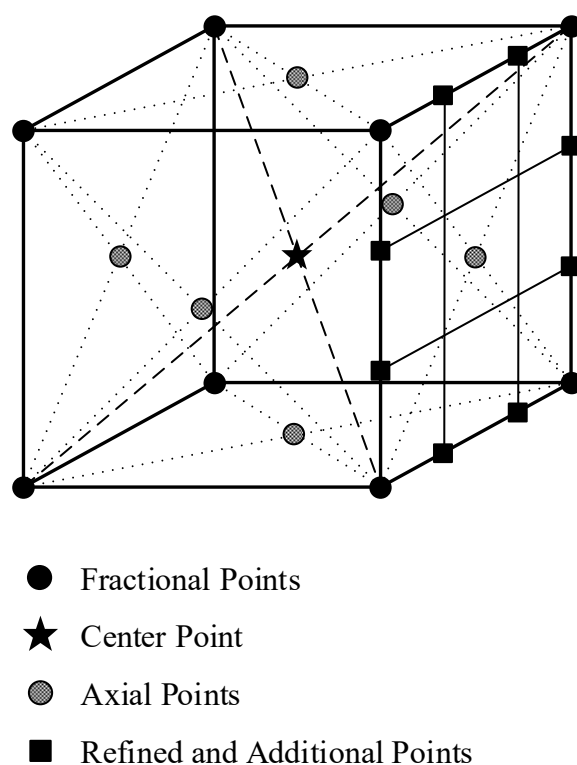


Figure 8. Refined, face-centered Central Composite Design.

The input parameters, i.e., the angle (0° denotes perpendicular pipes) and diameter of the hydrogen injection pipe, the gas velocity in the main NG pipe, and the target gas concentration, were varied, as summarized in Table 2.

Table 2. Variation parameters and limits for DoE in scenario 1.

Variation Parameter	Lower Limit	Upper Limit
H ₂ injection angle	0°	45°
H ₂ injection diameter	100 mm	300 mm
Flow velocity of CH ₄	2 m/s	25 m/s
Hydrogen volume concentration	10%	70%

Since the inlet velocity of natural gas was defined as an input parameter, the inlet mass flow of hydrogen for the inlet boundary condition needs to be calculated utilizing the following formula:

$$\frac{\dot{V}_{N,CH_4}}{\dot{V}_{N,H_2}} = \frac{\dot{m}_{CH_4} \cdot \rho_{N,H_2}}{\dot{m}_{H_2} \cdot \rho_{N,CH_4}} = \frac{w_{CH_4} \cdot A_{CH_4} \cdot \rho_{CH_4} \cdot \rho_{N,H_2}}{\dot{m}_{H_2} \cdot \rho_{N,CH_4}} = \frac{v_{CH_4}}{v_{H_2}} = x \quad (20)$$

where x is the ratio of volume fractions v_i of CH₄ and H₂, w_i is the flow velocity, A_i is the cross-sectional area of the respective pipes, and ρ_i is the density. The subscript N for density ρ_N and volume flow $\dot{V}_N$ denotes the values at normal conditions, whereas density without the subscript is calculated at the pipeline operating conditions of 70 bar and 10 °C. The mass flow can be calculated as a function of the CH₄ inlet velocity parameter w_{CH_4} as follows:

$$\dot{m}_{H_2} = \frac{w_{CH_4} \cdot A_{CH_4} \cdot \rho_{CH_4} \cdot \rho_{N,H_2}}{x \cdot \rho_{N,CH_4}} \quad (21)$$

2.7. Model Validation

As experimental validation was not feasible within the scope of this work, the CFD model was validated by comparison with the literature data for similar hydrogen injection and mixing problems. Two reference studies were used for this purpose. Firstly, the work by Hadi Sichani et al. [44] was used as a comparative reference, where the authors examined the injection of hydrogen into natural gas pipelines for 10 different scenarios at 70 bar. Of these 10 scenarios, three representative cases were selected, their geometries and boundary conditions replicated, and then simulated using our model. The hydrogen injection setup is the same for all three cases. A single injection pipe with a diameter of 6 mm is connected at a right angle to the pipeline and hydrogen is injected at a constant velocity of 24.16 m/s. The difference between the individual cases lies in the diameter of the pipeline and the velocity of CH₄ within it. Case 1 involves a DN20 pipeline in which the methane velocity is 8.7 m/s, resulting in a hydrogen volume fraction of 20%. Additionally, Case 4 was selected with a DN50 pipeline and a methane flow velocity of 8.35 m/s, resulting in a 4% hydrogen content. The final comparison case is Case 9 from the study, which uses a DN100 pipeline with a methane velocity of 0.78 m/s, leading to a 10% hydrogen volume fraction.

The COV of the methane mass fraction was used as the comparison quantity and was evaluated at different downstream distances from the injection point. The evaluation positions correspond to 10, 20, 50, 100, and 200 pipe diameters. For the DN100 case, the evaluation was limited to 100 pipe diameters due to the shorter simulated pipeline geometry. The comparisons are shown in Figure 9a–c. Overall, the present CFD model reproduces the literature data well. The largest deviations occur close to the injection point, where the mixing field is still strongly governed by the jet structure and local gradients. The RMSE values of COV are 0.56%, 0.03%, and 0.14% for Cases 1, 4, and 9, respectively.

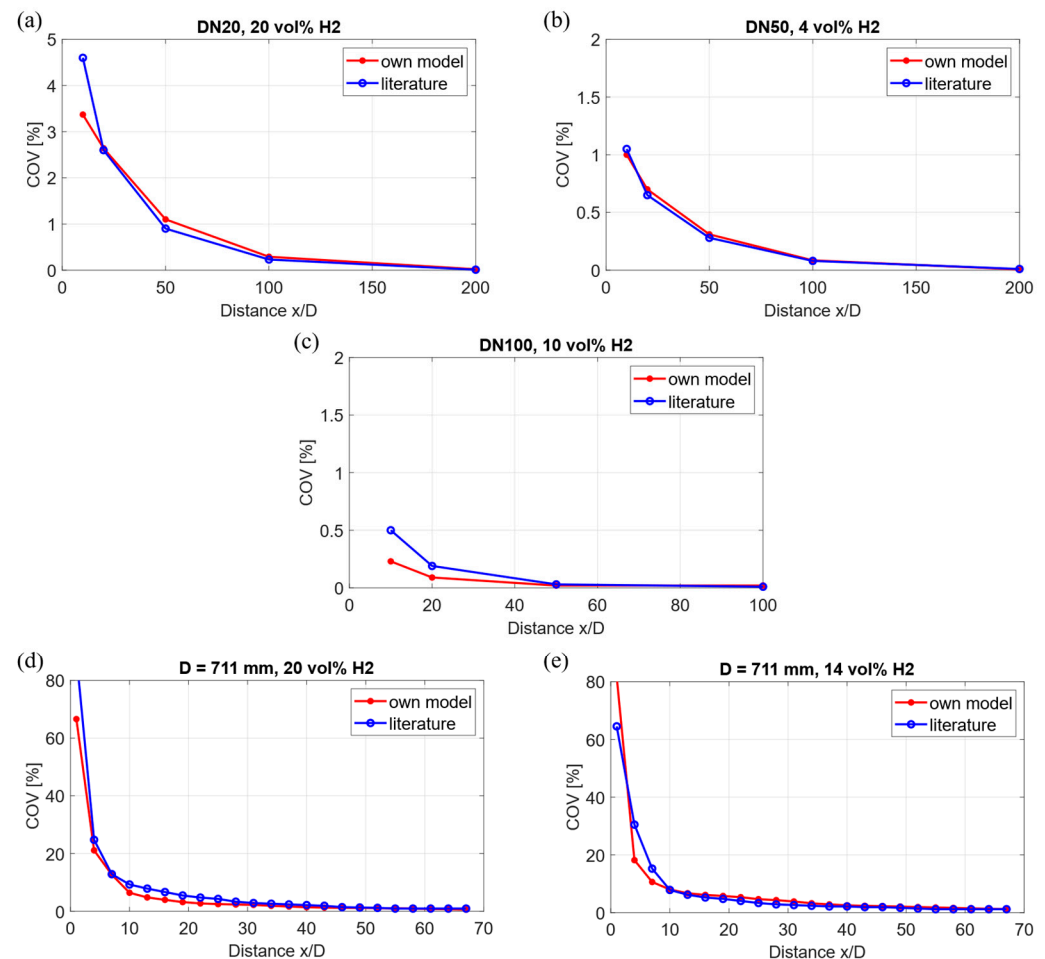


Figure 9. Validation of the CFD model against the literature data for hydrogen injection into natural gas pipelines. Subfigures (a–c) show comparisons with Hadi Sichani et al. [44] for three pipeline configurations at 70 bar: (a) DN20 with 20 vol% H₂, (b) DN50 with 4 vol% H₂, and (c) DN100 with 10 vol% H₂. Subfigures (d,e) show comparisons with Gracio et al. [56] for a 70 bar pipeline with a diameter of 711 mm and hydrogen volume fractions of (d) 20 vol% H₂ and (e) 14 vol% H₂.

In addition, the model was compared with the experimental and numerical data reported by Gracio et al. [56] for hydrogen injection into a larger pipeline with an inner diameter of 711 mm. Two cases with hydrogen volume fractions of 20% and 14% were reproduced. The corresponding results are shown in Figure 9d,e. The present simulations capture the downstream reduction in COV and therefore the progressive homogenization of the gas mixture. With the exception of the first data point after 1 m with a higher deviation, the RMSE values are 1.54% and 1.20% for the 20% and 14% hydrogen cases, respectively. The deviations are again most pronounced in the near-injection region, while the agreement improves with increasing downstream distance.

Based on comparisons with the literature sources, the employed CFD model is considered suitable for predicting hydrogen–methane mixing behavior in pipeline configurations relevant to this work.

3. Results and Discussion

The following section is divided into three parts for each of the three simulated scenarios. We start with the results of single-point injection before discussing the results of one- and two-stage multi-point injections, and then finally the results of the real-life application.

3.1. Scenario 1: Investigation of Single-Point Injection

The DoE simulation study comprised 164 simulation runs for the four input parameters of hydrogen injection angle, hydrogen inlet diameter, methane inlet velocity, and target hydrogen concentration. The output value of interest was the coefficient of variation, COV, at the outlet, which was used as a measure of mixing uniformity. Lower COV values corresponded to better mixing behavior, with the literature commonly defining good mixing in the range of 2–5%. In the present work, a threshold of $\text{COV} \leq 5\%$ was used as the criterion for sufficiently homogeneous mixing. Across these cases, the median COV was 4.88%, while the mean COV was 7.64%. In total, 50.7% of the investigated cases fulfilled the $\text{COV} \leq 5\%$ criterion.

The strongest influence on the outlet COV was observed for the hydrogen fraction and hydrogen inlet diameter (see Figure 10). Increasing the hydrogen fraction generally improved the mixing quality in the investigated parameter range. At 10% hydrogen, only 14.3% of the cases reached $\text{COV} \leq 5\%$, whereas this share increased to 89.7% at 50% hydrogen and 79.3% at 70% hydrogen. This trend does not imply that a higher hydrogen fraction intrinsically improves mixing. Instead, in the present boundary condition setup, the hydrogen mass flow was calculated from the methane pipe velocity and the target hydrogen concentration. Therefore, higher target hydrogen fractions resulted in higher hydrogen inlet velocities and higher jet momentum for the same inlet geometry.

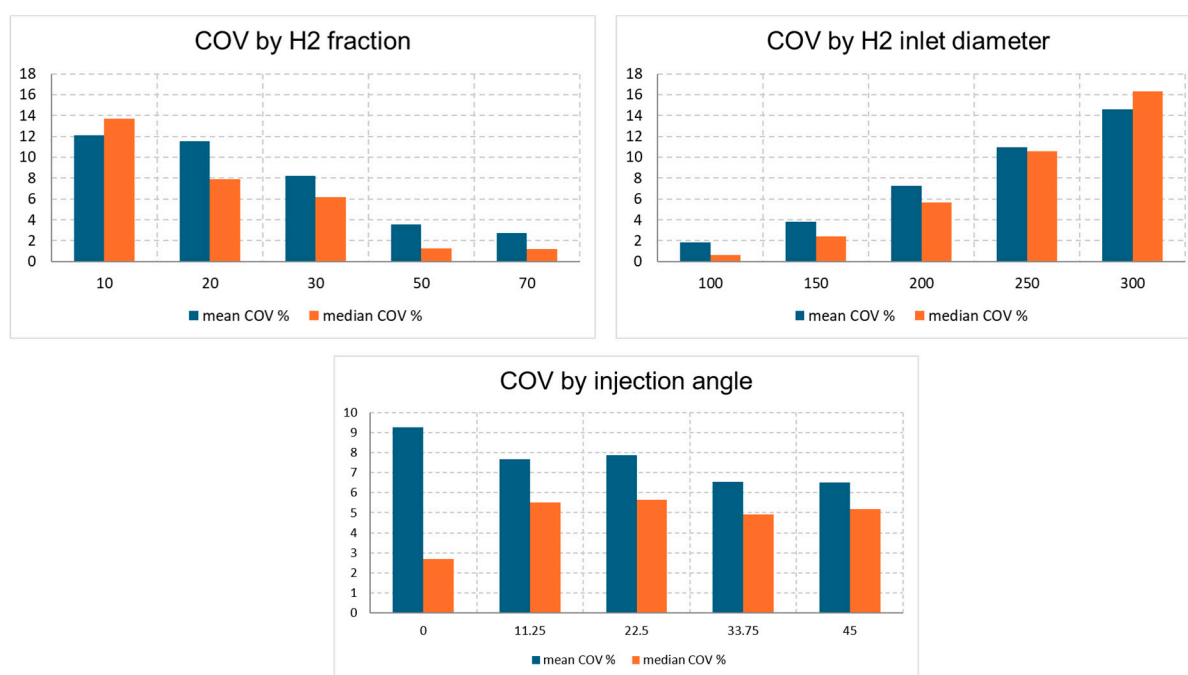


Figure 10. Mean and median COVs by H₂ fraction, inlet diameter, and injection angle.

In contrast, increasing the hydrogen inlet diameter reduced the mixing performance. For a hydrogen inlet diameter of 100 mm, 92.0% of the cases fulfilled the COV criterion, while only 24.0–25.0% of the cases with inlet diameters of 250–300 mm reached $\text{COV} \leq 5\%$. This confirms that the hydrogen inlet diameter influences COV primarily through the resulting hydrogen inlet velocity and jet momentum. Smaller inlet diameters increase hydrogen velocity at a given target concentration and therefore enhance jet penetration and turbulence generation.

Both the hydrogen fraction and hydrogen inlet diameter showed a statistically significant influence on COVs. In contrast, the methane inlet velocity and hydrogen inlet angle did not show a statistically significant global group effect when all cases were pooled. For

the methane inlet velocity, this weak global effect can be explained by the definition of the hydrogen mass flow boundary condition. Since the hydrogen mass flow was calculated from the methane pipe velocity and target hydrogen concentration, the methane velocity was not independently varied from the hydrogen inlet flow. Its influence is therefore partly embedded in derived quantities, such as the hydrogen inlet velocity, velocity ratio, and momentum flux ratio. Similarly, the effect of hydrogen inlet angle is strongly coupled to other parameters, particularly hydrogen inlet velocity and jet momentum, and should therefore not be interpreted independently.

To further interpret the observed mixing trends, characteristic dimensionless numbers were calculated for the inlet conditions. The Reynolds number was calculated using the inlet velocity, pipe diameter, and fluid properties. For the methane main pipe, the Reynolds number ranged from 9.2×10^6 to 1.15×10^8 , confirming fully turbulent flow in all investigated cases. The hydrogen inlet Reynolds number ranged from 4.8×10^5 to 3.8×10^8 , indicating turbulent hydrogen injection throughout the entire DoE. However, the methane Reynolds number showed only a weak correlation with the outlet COV, with a Spearman correlation coefficient of $s = -0.06$, whereas the hydrogen Reynolds number showed a stronger negative correlation of $s = -0.64$. This indicates that the mixing quality is governed primarily by the local hydrogen injection conditions rather than by the bulk turbulence level of the methane main flow.

A clearer physical trend was obtained from the velocity ratio, Reynolds number ratio, and momentum flux ratio. The momentum flux ratio was defined as $J = \frac{\rho_{H_2} v_{H_2}^2}{\rho_{CH_4} v_{CH_4}^2}$. Across the investigated cases, J ranged from 0.16 to 5796, with a median value of 13.0. The COV decreased strongly with increasing momentum flux ratio, with a Spearman correlation coefficient of $s = -0.81$. A similarly strong trend was found for the velocity ratio $\frac{v_{H_2}}{v_{CH_4}}$, with $s = -0.81$, and for the Reynolds number ratio $\frac{Re_{H_2}}{Re_{CH_4}}$, with $s = -0.74$. Cases fulfilling the target criterion of $COV \leq 5\%$ had a median momentum flux ratio of 68.3, compared with only 3.3 for cases that did not meet the target. Similarly, successful cases had a median velocity ratio of 25.6 and a median Reynolds number ratio of 0.70, whereas unsuccessful cases showed median values of 5.6 and 0.18, respectively. These results identify the momentum flux ratio as the most compact dimensionless indicator for mixing quality in the investigated geometry.

In addition to jet momentum, buoyancy effects must be considered because hydrogen has a substantially lower density than methane under the investigated operating conditions. However, for the present analysis, an inlet-based hydrogen Froude number was not used as the main buoyancy indicator, since it mainly describes the momentum-dominated character of the initial hydrogen jet. Instead, a bulk densimetric Froude number was introduced to assess the possible relevance of buoyancy-driven stratification in the main pipe after injection. The bulk densimetric Froude number was calculated as $Fr_{d,bulk} = \frac{v_{mix}}{\sqrt{g' \cdot D_{CH_4}}}$, with $g' = g \frac{\rho_{CH_4} - \rho_{H_2}}{\rho_{CH_4}}$, where v_{mix} is the mixture velocity, D_{CH_4} is the methane main pipe diameter, g is the gravitational constant, and $\rho_{CH_4} - \rho_{H_2}$ represents a conservative, maximum density contrast between a methane-rich lower region and a hydrogen-rich upper region.

This definition is more appropriate for assessing possible downstream stratification than an inlet-based hydrogen Froude number, because stratification in a horizontal pipe is governed by the inertia of the mixed bulk flow relative to the buoyancy force caused by density differences between hydrogen-rich and methane-rich regions. The bulk densimetric Froude number ranged from 0.75 to 28.10, with a median value of 6.86. It showed a moderate negative Spearman correlation with the outlet COV, with $s = -0.32$. This indicates that higher bulk flow inertia tended to reduce the outlet COV, but the influence was clearly weaker than that of the momentum flux ratio. Therefore, $Fr_{d,bulk}$ should be interpreted as a

supporting indicator for possible downstream buoyancy-driven stratification rather than as the primary predictor of mixing performance.

Table 3 summarizes the most relevant dimensionless parameters and their correlation with the outlet COV. The results confirm that mixing performance is primarily controlled by the hydrogen jet momentum relative to the methane main flow. Consequently, reducing the hydrogen inlet diameter improves mixing not because of the geometric change alone, but because it increases the hydrogen inlet velocity, hydrogen Reynolds number, velocity ratio, and momentum flux ratio. However, this design implication must be interpreted together with practical constraints of the injection system. While smaller hydrogen inlet diameters improve mixing by increasing the hydrogen inlet velocity, they also lead to higher pressure losses at high hydrogen mass flows. This can increase the required upstream pressure and, consequently, the compressor power demand of the mixing station. Therefore, the hydrogen inlet diameter should not be minimized solely from a mixing perspective but optimized as a trade-off between mixing quality, pressure loss, compressor power, and practical component design. In contrast, $Fr_{d,bulk}$ does not directly describe the injection process but rather the ability of the downstream bulk flow to suppress vertical separation of hydrogen-rich and methane-rich regions.

Table 3. Value ranges, median values, and Spearman correlations with COVs for different dimensionless parameters.

Dimensionless Parameter	Range	Median	Spearman Correlation with COV
Re_{CH_4}	9.2×10^6 – 1.15×10^8	6.23×10^7	−0.06
Re_{H_2}	4.8×10^5 – 3.81×10^8	1.87×10^7	−0.64
Re_{H_2}/Re_{CH_4}	0.052–3.31	0.33	−0.74
Velocity ratio	1.24–236.3	11.2	−0.81
Momentum flux ratio	0.16–5796	13.0	−0.81
Froude number hydrogen inlet	1.4–5964	103.6	−0.77
Bulk densimetric Froude number $Fr_{d,bulk}$	0.75–28.10	6.86	−0.32
Diameter ratio d_{H_2}/D_{CH_4}	0.10–0.30	0.20	+0.57

Evaluation of the momentum flux ratio further supports this interpretation. For $J < 1$, only 4.3% of cases achieved $COV \leq 5\%$, and for $1 < J < 5$, none of the cases fulfilled the mixing criterion. The intermediate range of $5 \leq J < 20$ represents a transition region, in which 50.0% of the cases met the COV target and the median COV was 5.22%. In contrast, for $J > 20$, 90.0% of cases met the COV target, with a median COV of 1.19%. This suggests that J is a suitable compact indicator for identifying injection configurations that are likely to provide sufficient mixing in the investigated pipeline geometry.

The effect of hydrogen inlet angle was analyzed separately. When all cases were considered together, the overall angle effect was weak (see Figure 10). The median COV values ranged from 2.68% for 0° to 5.64% for 22.5° , and the share of cases fulfilling $COV \leq 5\%$ varied only between 48.0% and 58.6%. This confirms that the injection angle alone is not a reliable predictor of mixing quality. Its effect depends strongly on the jet momentum, inlet diameter, and target hydrogen fraction.

These results show that the hydrogen inlet angle can influence the local mixing behavior, but it is not the primary design parameter. A perpendicular injection maximizes the transverse momentum component of the hydrogen jet and can therefore improve penetration into the methane main flow. However, this does not necessarily lead to the lowest

outlet COV. In particular, if the jet momentum is too high, the perpendicular jet can impinge on the opposite pipe wall and generate recirculating or swirling flow structures, which may delay homogenization within the available mixing length.

This behavior is visible in the detailed post-processing of the selected simulation cases shown in Figure 11. Figure 11a,b represent the simulation cases with the lower-momentum configurations, with a hydrogen pipe diameter of 300 mm, methane inlet velocity of 19.25 m/s, and hydrogen concentration of 30%. For both cases, the momentum flux ratio was 2.37. In Figure 11a, the perpendicular 0° injection led to stronger penetration into the pipe cross-section and resulted in a more homogeneous outlet density distribution. In contrast, Figure 11b, with 45° inclined injection, introduced the hydrogen more parallel to the methane main flow. The hydrogen therefore remained closer to the upper region of the pipe, leading to a hydrogen-rich layer near the top and a less homogeneous outlet density field.

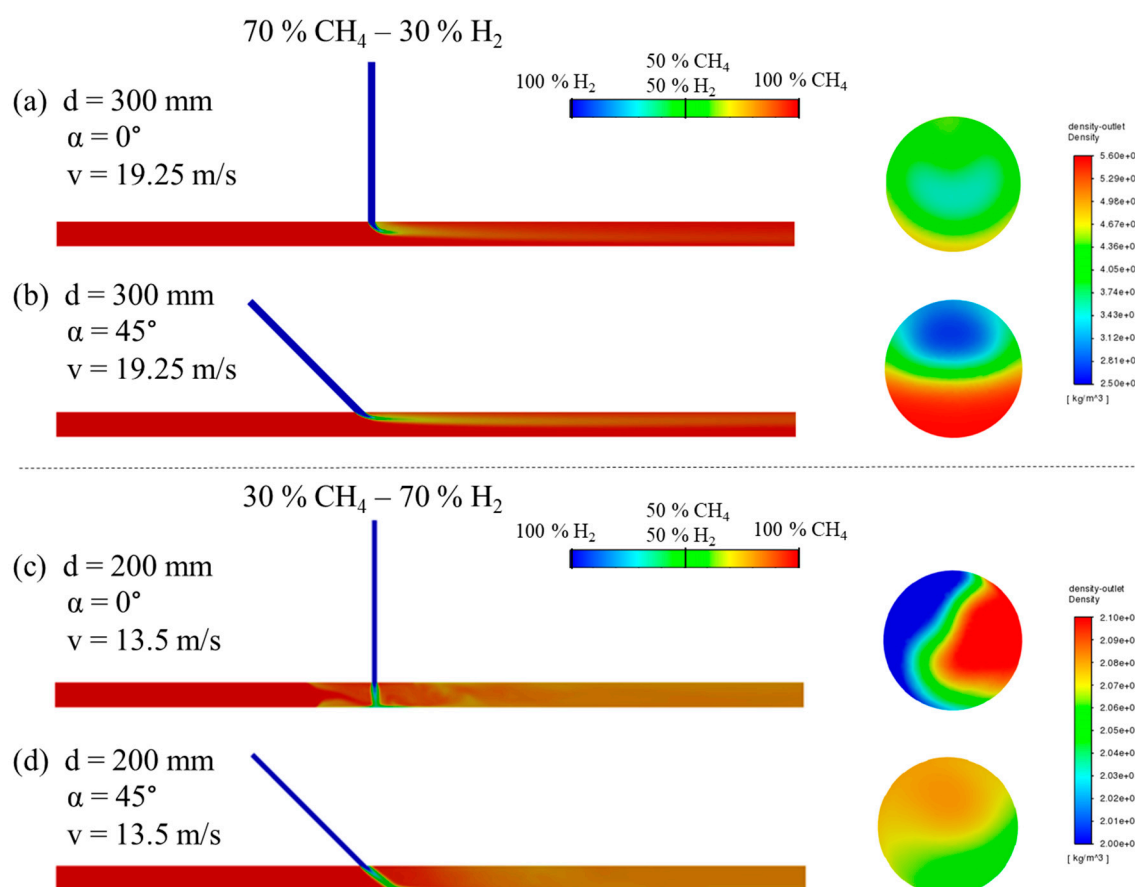


Figure 11. Cross-section of methane distributions and density distributions at the outlet of models for four select simulation cases: (a) 30% H_2 , diameter 300 mm, velocity 19.25 m/s, and angle 0° ; (b) 30% H_2 , diameter 300 mm, velocity 19.25 m/s, and angle 45° ; (c) 70% H_2 , diameter 200 mm, velocity 13.5 m/s, and angle 0° ; and (d) 70% H_2 , diameter 200 mm, velocity 13.5 m/s, and angle 45° . Adapted from ref. [67].

Figure 11c,d represent the higher-momentum configurations, with a hydrogen pipe diameter of 200 mm, methane inlet velocity of 13.5 m/s, and hydrogen concentration of 70%. For these cases, the momentum flux ratio was significantly higher at 355.6. In this configuration, the behavior changed. In Figure 11c, the perpendicular 0° jet penetrated deeply into the main pipe and interacted strongly with the opposite wall. This caused a swirled flow pattern and a comparatively poor outlet COV despite the high momentum flux ratio. In Figure 11d, the 45° inclined injection introduced the hydrogen more gradually

in the downstream direction and avoided excessive wall impingement, resulting in a more homogeneous outlet density distribution.

Comparisons of Figure 11a–d show that high jet momentum is beneficial only up to the point where it enhances penetration and turbulence without creating unfavorable large-scale recirculation structures. At lower momentums, perpendicular injection can improve cross-sectional penetration, as observed in Figure 11a. At higher momentums, however, perpendicular injection can lead to excessive wall interactions and swirls, as observed in the case of Figure 11c. Overall, neither perpendicular nor inclined injections are universally optimal. The inlet angle should therefore be optimized together with the hydrogen inlet diameter, inlet velocity, and available mixing length. For pipeline sections requiring bidirectional operation, inclined injection may be disadvantageous because it favors one main flow direction. In such cases, a perpendicular or rotationally symmetric injection concept is preferable to ensure comparable mixing behavior for both flow directions.

Overall, the analysis shows that the outlet COV is best explained by the relative momentum of the hydrogen jet, represented by the momentum flux ratio J , and by the hydrogen inlet diameter through its influence on inlet velocity. Buoyancy effects are physically relevant for interpreting possible downstream stratification, but the bulk densimetric Froude number shows that they are secondary compared with injection-driven turbulence in the investigated cases.

3.2. Scenario 2: Investigation of Multi-Point Injection

To investigate the mixing effect of hydrogen and methane with the multi-point injection layout, the injection pipe diameter, injection direction, and number of injection pipes were varied. Figure 12 shows the COV along the mixing length for the six single-stage layouts, providing information on the state of mixing for the different layouts and diameters of the hydrogen injection pipes. While the solid lines represent different layouts with an injection tube diameter of 0.2 m, the dashed lines represent layouts with the smaller injection tube diameter of 0.07 m.

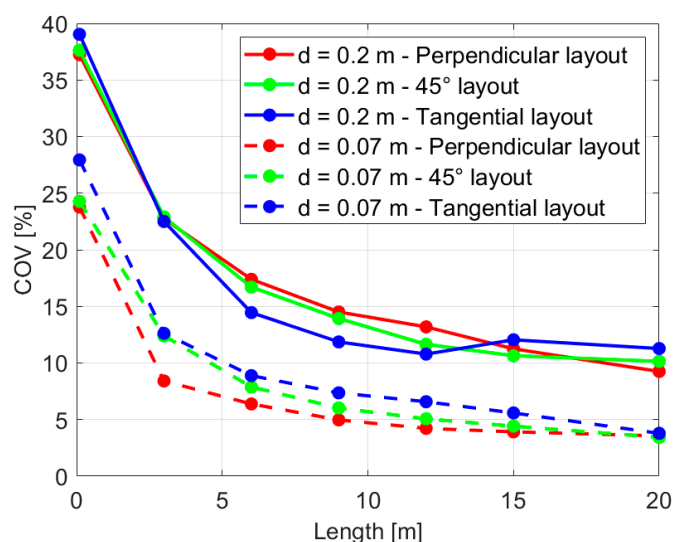


Figure 12. COV of different injection layouts and injection pipe diameters from cross-sections along the mixing length.

A clear difference between the two diameters can be observed. For the smaller injection diameter of 0.07 m, all three investigated layouts reached COVs below 5% after 20 m. The perpendicular injection showed the most promising result, reaching the target COV already after approximately 10 m, and maintained the lowest COV over most of the mixing length.

This was followed by the 45° injection and tangential injection layouts. In contrast, none of the layouts with the larger injection diameter of 0.20 m reached the target COV of 5% within the investigated mixing length. For this larger diameter, the ranking between the layouts was less consistent along the pipe. Between the second and fifth evaluated cross-sections, the tangential layout showed the lowest COV, followed by the 45° layout, whereas at the final evaluation point at 20 m, the perpendicular layout again showed the lowest COV, followed by the 45° and tangential configurations. At the final evaluation position of 20 m, the influence of the hydrogen inlet diameter was substantially stronger than the influence of the injection layout. For the larger hydrogen inlet diameter of 0.20 m, hydrogen inlet velocity was low, and the corresponding momentum flux ratio J was only about 0.068. As a result, all three layouts remained above the target value of $\text{COV} \leq 5\%$, with final COV values of approximately 9–11%. In contrast, reducing the hydrogen inlet diameter increased the hydrogen inlet velocity and raised the momentum flux ratio to about $J = 4.54$. Under these conditions, all three layouts achieved the COV criterion after 20 m, with final COV values of approximately 3.5–3.7%.

Compared with the single-injection configurations in scenario 1, the multi-point layouts achieved sufficient mixing at a lower momentum flux ratio. In scenario 1, cases with $J < 5$ generally did not meet the $\text{COV} \leq 5\%$ criterion, and even the intermediate range of $5 \leq J < 20$ represented only a transition region with mixed success. In scenario 2, however, all multi-point layouts with 0.07 m reached final COV values below 5% at $J = 4.54$. This indicates that distributing hydrogen over several injection points can reduce the jet momentum required from each individual inlet because hydrogen is introduced more uniformly across the pipe cross-sections. Nevertheless, the 0.20 m cases with $J = 0.068$ show that a minimum level of injection momentum is still required and that the observed improvement is specific to the investigated geometries and mixing lengths.

Figures 13 and 14 show the density distribution for cross-sections at distinct downstream positions in a contour plot from ANSYS Fluent of the smaller and larger diameters, respectively. The deeper penetration of hydrogen (blue) into methane (red) of the layouts with the smaller diameter can be clearly seen in all injection direction layouts when comparing Figures 13 and 14, especially at the cross-sections of 0.1 m and 3 m.

The figures show that, in all cases, the hydrogen content rose upwards, leading to higher hydrogen concentrations at the top wall and lower hydrogen concentrations at the bottom wall. This was a result of the buoyancy forces and density difference between hydrogen and methane. However, compared to the larger diameter layouts, the hydrogen build-up on the top wall was less pronounced with the smaller diameter. For the larger diameter layouts shown in Figure 13a,b, stratification occurred immediately after the inlet, indicating that too little turbulence was achieved with the given inlet velocity.

When comparing the mixing uniformity of three different injection tilts, perpendicular injection had a clear advantage over the other layouts since the flow direction is already towards the center of the pipe by design. More turbulence can be created with this injection tilt, resulting in lower COVs mentioned above. With tangential injection, the hydrogen flow interacted with the wall and was therefore slowed down. In addition, the hydrogen did not penetrate as deeply or as quickly as for perpendicular injection, as the flow direction was along the walls and not towards the center of the pipeline. This can be clearly seen in the smaller diameter in cross-section images (Figure 14a). The mixing effect was reduced compared to the perpendicular injection. This is in agreement with the study conducted by Eames et al. [43], which investigated the mixing effect for T-junction injections on the top and bottom wall, as well as a hillside injection. Their scenario aligns with our tangential inlet on the side wall with injection from the top, where the hillside injection showed a reduced mixing effect. The 45° injection is midway between the perpendicular and

tangential inlets. There was more hydrogen penetration observed than for tangential inlet, but as it is directed towards the wall rather than the center, the mixing effect was not as good as with the perpendicular inlet. These effects were much more pronounced when smaller diameter layouts and a sufficiently high injection velocity were considered.

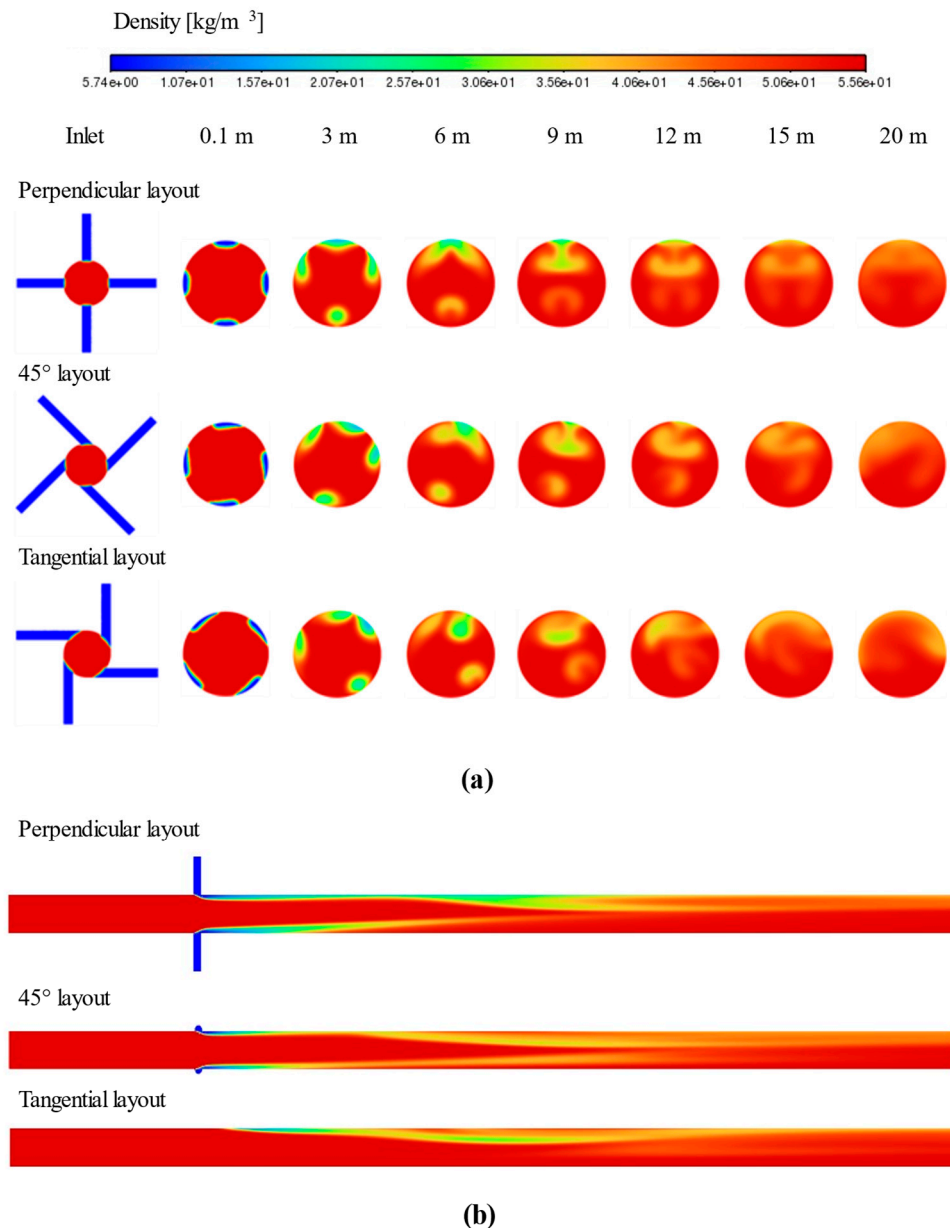


Figure 13. Density distributions of the one-stage layout with varying injection directions and an injection diameter of 0.2 m on various cross-sections (yz-plane) (a) and along the whole mixing length (xy-plane) (b).

Figure 15 compares the two-stage configuration with the one-stage perpendicular layout with the smaller diameter of 0.07 m. The one-stage layout reached a COV below 5% after a mixing length of approximately 9 m and further decreased to 3.6% at 20 m. In contrast, the two-stage layout did not reach the 5% COV criterion within the investigated mixing length and still showed a COV of approximately 5.8% at 20 m.

It should be noted that the comparison between the one-stage and two-stage layouts does not isolate the effect of staging alone. In the two-stage configuration, the same total hydrogen mass flow was distributed over eight injection pipes instead of four, while the individual pipe diameter remained unchanged. This increased the total hydrogen inlet

area and therefore reduced the hydrogen inlet velocity and momentum flux ratio. The investigated two-stage layout was chosen deliberately to assess whether a distributed injection concept could maintain sufficient mixing while lowering the required injection velocity. From a practical perspective, this is relevant because lower injection velocities can reduce pressure losses in the hydrogen injection system and may reduce the required upstream pressure and compressor power at the mixing station. The comparison should therefore be interpreted as a design-oriented trade-off between mixing quality and injection system requirements. For the investigated configuration, the reduced inlet velocity and lower momentum flux ratio outweighed the potential benefit of spatially distributed injection, and the two-stage layout did not achieve the target COV within the available mixing length.

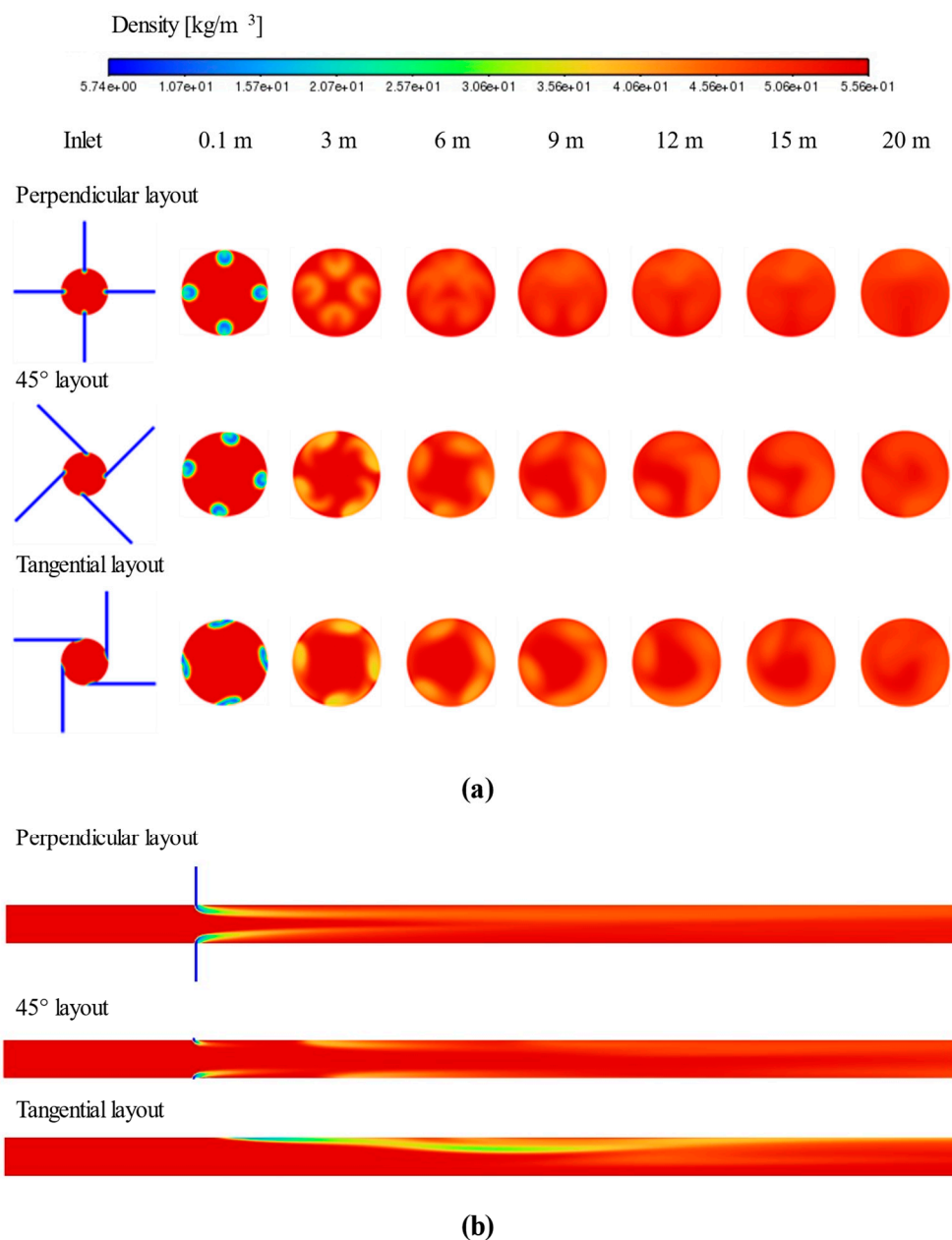


Figure 14. Density distributions of the one-stage layout with varying injection directions and an injection diameter of 0.07 m on various cross-sections (yz -plane) (a) and along the whole mixing length (xy -plane) (b).

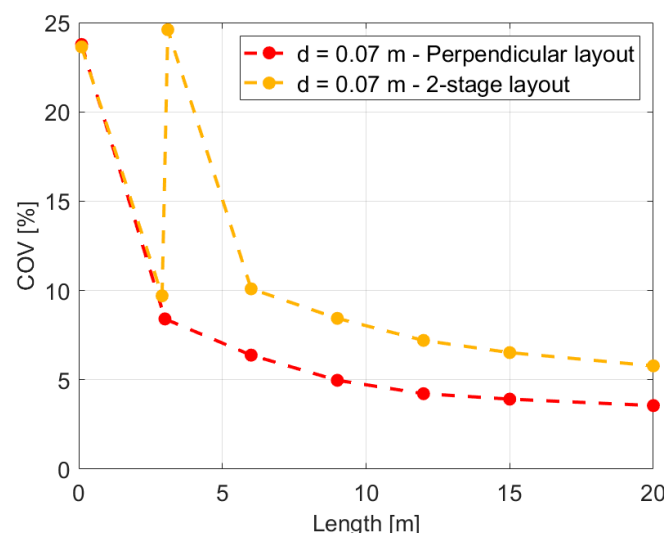


Figure 15. COVs of the one-stage perpendicular inlet with an injection diameter of 0.07 m and the two-stage layout on cross-sections along the mixing length.

3.3. Scenario 3: Real-Life Application of Hydrogen Blending Station with Single-Point Injection at Grid Level 3

In order to determine whether the mixing quality for a real-life application with a single-point injection and with different hydrogen concentrations and orifice geometries of the hydrogen inlet pipe is sufficient, the average density and COV were evaluated after the blending point but before the 90° bend (see location marked with red circle in Figure 3), as well as at the end of the simulated pipeline section at the outlet boundary. Any secondary mixing effects that may occur due to the bend can therefore be evaluated. Although differences in the quality of the mixture are evident due to the different geometries and secondary mixing effects caused by pipe bends, the COV target value of less than 5% was achieved for all investigated geometries and hydrogen concentrations. Figure 16 shows the density distribution in the pipeline cross-section when hydrogen is blended in at 2 vol% with different orifice geometries. The best mixing is achieved in case (a), a single opening with a small diameter. From this case, there is hardly any observable difference in the quality of the mixture. However, if the opening is larger, as in case (b), or if there are several smaller openings, as in the case of a perforated plate in case (c), the quality of the mixture is slightly worse. In both cases, the density distribution after the blending point is not uniform, with a higher local hydrogen concentration observed on the right side of the cross-section. However, after the 90° bend and secondary mixing effects, it can be seen that the quality of the mixture is sufficient at the end of the pipeline section for all three cases.

For case (a), with the best mixture quality (small-diameter single opening), and case (c), with the worst mixture quality (perforated plate), the concentration of hydrogen was increased to determine whether the mixture quality would still be sufficient or whether a certain orifice geometry would eventually become unsuitable for use.

Figure 17 shows the density distribution at a hydrogen concentration of 50 vol% for the two orifices at pipeline cross-sections before and after the pipeline bend. Once again, it can be seen that the mixture quality is poorer in the case with the perforated plate than with a single small opening. The secondary mixing effect caused by the pipeline bend can be seen in both cases, as the mixing quality increases after the bend for both cases. For the perforated plate, a local enclosed area with higher density (thus higher local methane content) can be observed before the bend. For both hydrogen concentrations, it can be seen that, although the geometry of the orifice has an influence on mixing, the overall mixing quality is completely sufficient (COV < 5%) for every orifice geometry used in this study.

Hence, it can be noted that secondary mixing effects caused by bends in the pipelines have a significant positive influence on the mixing quality at this grid level.

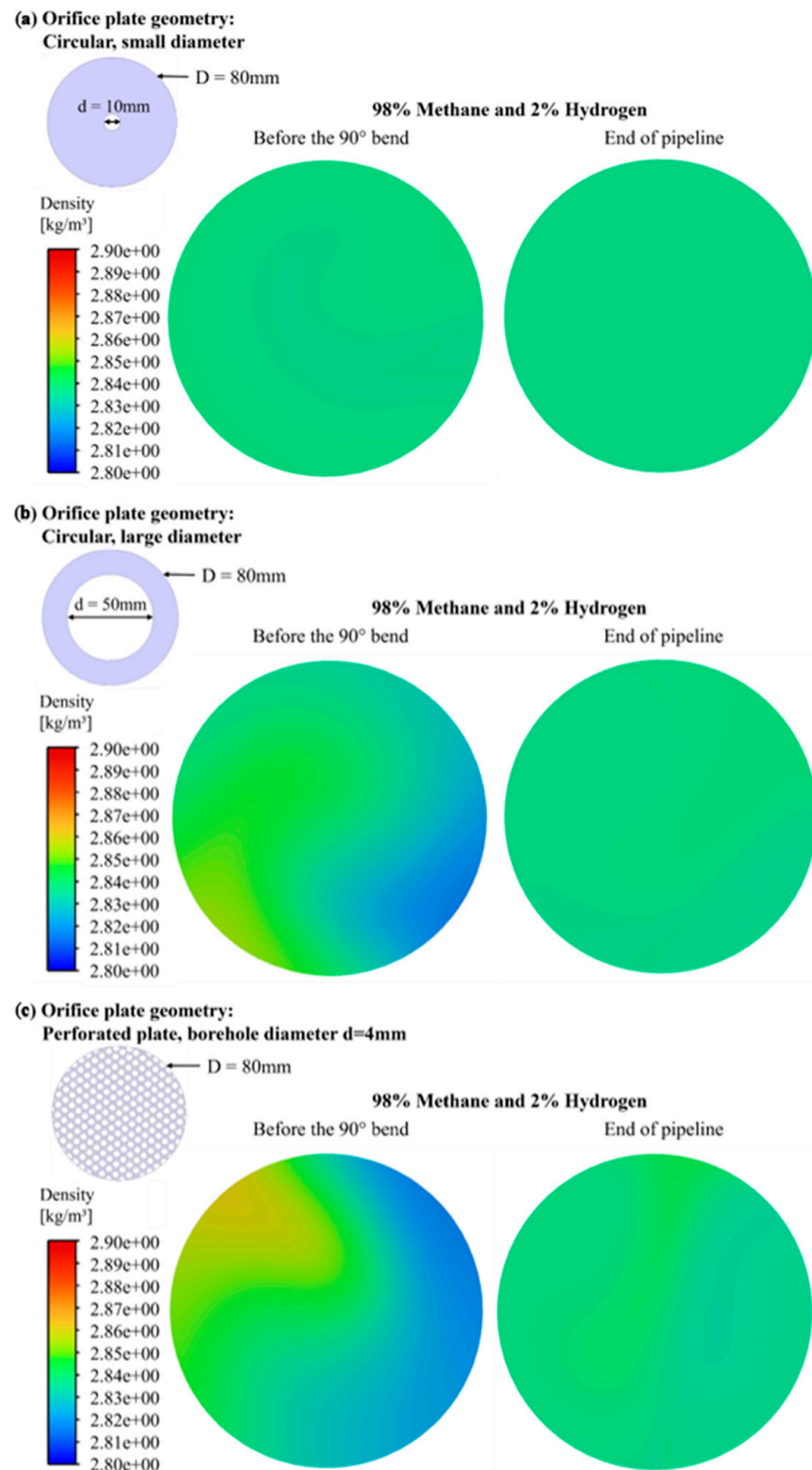


Figure 16. Density distributions in two different pipeline cross-sections for different orifices geometries at 2 vol% of hydrogen: (a) a single circular opening with a small diameter, (b) a single circular opening with a large diameter, and (c) a perforated plate.

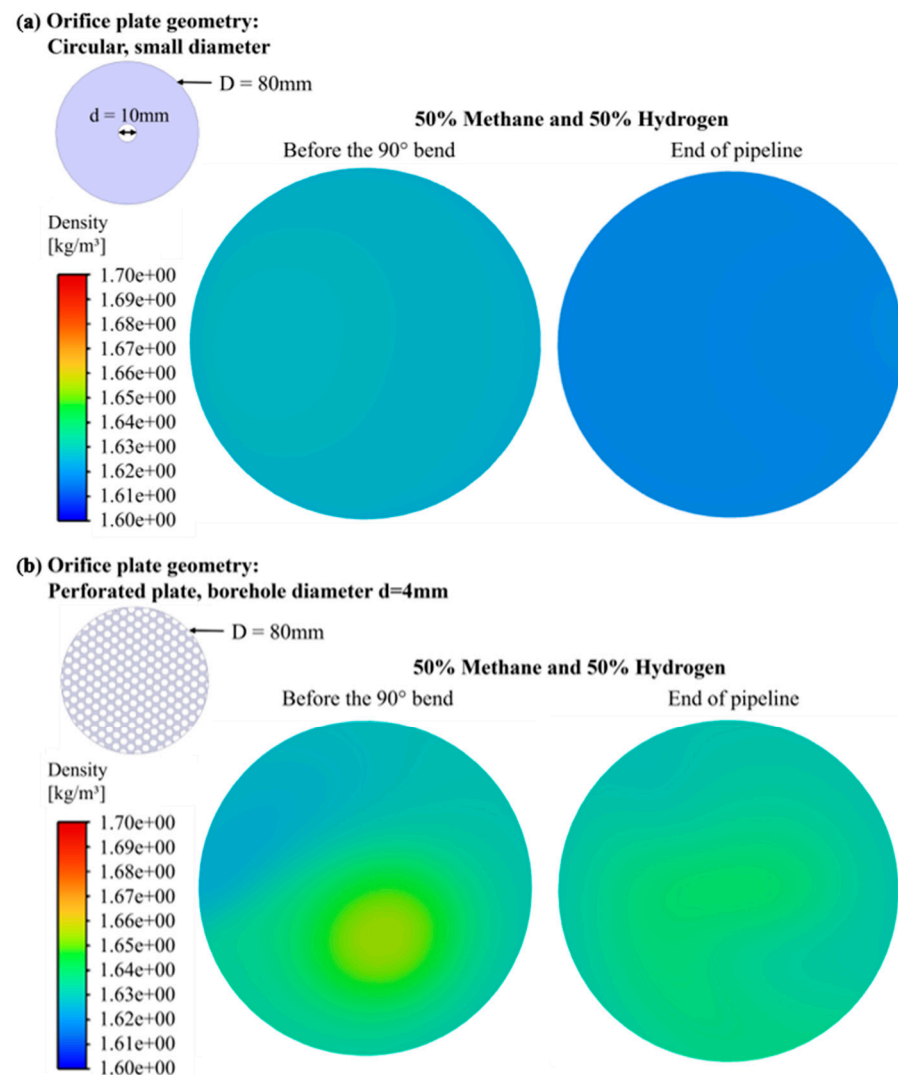


Figure 17. Density distributions in two different pipeline cross-sections for different orifices geometries at 50 vol% of hydrogen: (a) a single circular opening with a small diameter and (b) a perforated plate.

4. Conclusions

This study explored the feasibility of directly injecting hydrogen into natural gas pipelines, focusing on mixing behavior under realistic operational conditions. Using 3D CFD simulations and a systematic DoE approach, we evaluated the effects of key parameters, such as injection geometry (angle, diameter) and operating conditions (natural gas velocity, hydrogen concentration). For scenario 1, the statistical evaluation of the single-injection cases showed that only 50.7% of the investigated configurations achieved the target value of $\text{COV} \leq 5\%$, with a median COV of 4.88% and a mean COV of 7.64%. The analysis further showed that the momentum flux ratio is a suitable compact indicator for the expected mixing quality. Cases with $J < 5$ rarely or never fulfilled the COV criterion, whereas the range of $5 \leq J < 20$ represented a transition region with 50.0% successful cases, and for $J \geq 20$, 90.0% of the cases achieved $\text{COV} \leq 5\%$, with a median COV of 1.19%. The initial investigation of simple topside injection revealed that while high hydrogen velocity, high hydrogen content, and smaller injection pipe diameters generally improved mixing, they were insufficient to guarantee uniform blending across all scenarios. This finding underscores the limitations of simple topside injection for ensuring adequate mixing in diverse pipeline operating conditions.

To address the limitations of simple topside injection, a multi-point injection strategy was investigated in scenario 2. The results showed that the layouts with the smaller hydrogen pipe diameter of 0.07 m achieved the target COV of 5% over shorter mixing lengths due to the higher injection velocities and increased jet momentum. Among these configurations, the perpendicular layout performed best and reached the COV target after approximately 10 m. At the final evaluation position of 20 m, all multi-point layouts with 0.07 m diameter achieved final COV values of approximately 3.5–3.7% at $J = 4.54$. This is notable because comparable single-injection cases in scenario 1 did not reliably meet the COV target at similar momentum flux ratios, indicating that multi-point injections can improve mixing efficiency by distributing hydrogen more uniformly across pipe cross-sections. However, layouts with 0.20 m diameter corresponding to $J = 0.068$, as well as the two-stage designs with reduced inlet velocities, did not meet the COV target within the investigated mixing length.

For hydrogen blending at grid level 3, the simulations showed that for all orifice geometries, the quality of the mixture is sufficient and the target COV of below 5% is achieved. Although the orifice geometries have an influence on the quality of the mixture, all investigated geometries met the target COV value. This was also achieved because the existing bends in the pipeline section under consideration ensured further mixing than purely straight pipeline sections due to secondary mixing effects.

Overall, this work advances the understanding of direct hydrogen injection into large-scale natural gas pipelines and provides design-oriented guidance for blending stations under realistic operational constraints. Unlike prior studies that often focus on static mixers or idealized conditions, this study evaluates direct injection concepts based on practical COV targets and dimensionless mixing indicators. The results show that direct injection at grid level 1 requires a careful balance between injection diameters, jet momentum, pressure-loss considerations, and injection layouts. Simple topside injections may be sufficient only under favorable momentum conditions, whereas optimized multi-point injections can achieve adequate mixing at lower momentum flux ratios. At grid level 3, existing pipeline elements, such as bends, can contribute substantially to homogenization and may reduce the need for additional mixing devices. A summary of the investigated cases and derived recommendations is provided in Table 4. It should be noted that, while not within the scope of this study, static mixers combined with direct injections remain a technically effective option for improving mixture quality where their installation is feasible. However, for grid level 1 infrastructure, direct injection concepts avoiding internal obstructions may be preferable due to pigging, inspection, and bi-directional operational flexibility.

The demonstrated feasibility of direct injection under certain flow conditions is also economically relevant, as bypass injection may create additional costs under the EU exit–entry pricing model due to the extraction of natural gas for pre-mixing and the subsequent re-injection of the hydrogen–natural gas blend. Direct injection avoids this additional extraction step and may therefore reduce system complexity and blending-related costs. Future work should build on these findings by quantifying the cost-saving potential of direct injection in a dedicated techno-economic analysis, considering operator-specific tariff structures, metering concepts, and pipeline infrastructure data.

Table 4. Summary of COV-based mixing performance and design recommendations for the investigated injection scenarios.

Scenario	Grid Level	Operating Conditions	Main Configuration	Key COV Result	Design Recommendation
Scenario 1	Grid level 1	70 bar, 10 °C, 1 m main pipe diameter, base case natural gas velocity of 8 m/s	Simple topside injection with varied angles, diameters, natural gas velocities, and hydrogen concentrations	In total, 50.7% of cases achieved $\text{COV} \leq 5\%$. For $J \geq 20$, 90.0% reached the target, with a median COV of 1.19%.	The momentum flux ratio can be used as a compact screening parameter. Simple injection is robust only at sufficiently high jet momentum, yet high momentum flux does not guarantee sufficient mixing in all cases.
Scenario 2		70 bar, 10 °C, 1 m main pipe diameter, 10 vol% hydrogen	Single-stage multi-point injection with perpendicular, 45° and tangential layouts	$dH_2 = 0.07$ m achieved approximately 3.5–3.7% COV at 20 m and $J = 4.54$; $dH_2 = 0.20$ m remained at approximately 9–11% COV.	Multi-point injection can reduce the required momentum level compared with simple injection, though sufficient local jet momentum remains necessary.
Scenario 2—two-stage variant			Two-stage multi-point injection with reduced inlet velocity	The target COV was not reached within 20 m.	Additional injection points do not improve mixing if inlet velocity and jet momentum are reduced too strongly.
Scenario 3	Grid level 3	4.2 bar, 10 °C, 50% H_2 , 600 mm main pipeline diameter	Orifice-based injection into a pipeline section with bends	All investigated orifice geometries achieved $\text{COV} < 5\%$.	Existing bends and secondary flow structures can support homogenization and may reduce the need for additional mixing devices.

Author Contributions: Conceptualization, N.K. and T.S.; methodology, N.K. and D.S.; software, K.R., M.K. and D.S.; validation, N.K. and M.K.; formal analysis, N.K., K.R., M.K. and D.S.; investigation, N.K., K.R., M.K. and D.S.; resources, R.R. and F.W.; data curation, N.K., K.R., M.K. and D.S.; writing—original draft preparation, N.K., K.R. and M.K.; writing—review and editing, N.K., M.K. and R.R.; visualization, N.K., K.R. and M.K.; supervision, N.K. and A.T.; project administration, R.R.; funding acquisition, F.W. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Climate and Energy Fund (KLIEN) and the Austrian Research Promotion Agency (FFG) for funding and managing the project H2Real (Nr. 894621). Furthermore, part of this work was done within the research project “HyTechnomy” (Nr. 882510) and was funded within the COMET program by the Federal Ministry of the Republic of Austria (BMIMI, BMWET), the “Steirische Wirtschaftsförderungsgesellschaft”, and the province of Upper Austria. The HyCentA COMET Centre (Nr. 892427) is funded within COMET—Competence Centers for Excellent Technologies—by BMIMI and BMWET, as well as the co-financing from federal provinces of Styria, Upper Austria, Tyrol, and Vienna. The COMET program is managed by FFG.

Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing research project and require prior additional consent from the project partners. Requests to access the datasets should be directed to corresponding authors.

Acknowledgments: During the preparation of this work, the authors used OpenAI's ChatGPT-5.5 in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of Interest: All authors were employed by HyCentA Research GmbH. As HyCentA is a non-profit extra-university research center, the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Abbreviations

3D	Three-dimensional
CFD	Computational fluid dynamics
COV	Coefficient of variation
DoE	Design of experiments
NG	Natural gas

References

1. Trattner, A.; Klell, M.; Radner, F. Sustainable hydrogen society—Vision, findings and development of a hydrogen economy using the example of Austria. *Int. J. Hydrogen Energy* **2022**, *47*, 2059–2079.
2. European Hydrogen Backbone. Five Hydrogen Supply Corridors for Europe in 2030. 2022. Available online: <https://ehb.eu/files/downloads/EHB-Supply-corridor-presentation-Full-version.pdf> (accessed on 24 October 2022).
3. Tezel, G.; Robert, H. HyWay 27: Hydrogen Transmission Using the Existing Natural Gas Grid? Final Report for the Ministry of Economic Affairs and Climate Policy. 2021. Available online: <https://www.entsog.eu/sites/default/files/2021-11/1.2.%20HyWay27%20Final%20report%20%28UK%29.pdf> (accessed on 15 December 2021).
4. International Renewable Energy Agency (IRENA). *Geopolitics of the Energy Transformation: The Hydrogen Factor*; IRENA: Abu Dhabi, United Arab Emirates, 2022. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf (accessed on 9 June 2023).
5. Ortiz Cebolla, R.; Dolci, F.; Weidner, E. *Assessment of Hydrogen Delivery Options: Feasibility of Transport of Green Hydrogen Within Europe*; Publications Office of the European Union: Luxembourg, 2022.
6. European Commission. *Hydrogen Generation in Europe: Overview of Costs and Key Benefits*; Publications Office of the European Union: Luxembourg, 2020. Available online: <https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1> (accessed on 10 February 2022).
7. van Rossum, R.; Jens, J.; La Guardia, G.; Wang, A.; Kühnen, L.; Overgaag, M. European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries. 2022. Available online: <https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf> (accessed on 5 April 2022).
8. Wang, A.; van der Leun, K.; Peters, D.; Buseman, M. European Hydrogen Backbone: How Dedicated Hydrogen Infrastructure Can Be Created. 2021. Available online: https://ehb.eu/files/downloads/2020_European-Hydrogen-Backbone_Report.pdf (accessed on 9 November 2021).
9. Jansma, S.; Rekers, D. *D1C.3 The Influence of the Existing Natural Gas Distribution Networks on the Purity of Hydrogen*; Zenodo: Geneva, Switzerland, 2022.
10. Steiner, M.; Marewski, U.; Silcher, H. *DVGW-Projekt SyWeSt H2: Stichprobenhafte Überprüfung von Stahlwerkstoffen für Gasleitungen und Anlagen zur Bewertung auf Wasserstofftauglichkeit*; DVGW: Bonn, Germany, 2023.
11. Fink, S. Untersuchung zur Wasserstoffversprödung von Gasrohrleitungen. Diploma Thesis, Technische Universität Graz, Graz, Austria, 2021.
12. Drexler, A.; Helic, B.; Silvayeh, Z.; Mraczek, K.; Sommitsch, C.; Domitner, J. The role of hydrogen diffusion, trapping and desorption in dual phase steels. *J. Mater. Sci.* **2022**, *57*, 4789–4805. [CrossRef]
13. Drexler, A.; Konert, F.; Sobol, O.; Rhode, M.; Domitner, J.; Sommitsch, C.; Böllinghaus, T. Enhanced gaseous hydrogen solubility in ferritic and martensitic steels at low temperatures. *Int. J. Hydrogen Energy* **2022**, *47*, 39639–39653. [CrossRef]
14. Drexler, A.; Vandewalle, L.; Depover, T.; Verbeken, K.; Domitner, J. Critical verification of the Kissinger theory to evaluate thermal desorption spectra. *Int. J. Hydrogen Energy* **2021**, *46*, 39590–39606. [CrossRef]
15. Mohtadi-Bonab, M.A. Effect of different parameters on hydrogen affected fatigue failure in pipeline steels. *Eng. Fail. Anal.* **2022**, *137*, 106262. [CrossRef]

16. Laureys, A.; Depraetere, R.; Cauwels, M.; Depover, T.; Hertelé, S.; Verbeken, K. Use of existing steel pipeline infrastructure for gaseous hydrogen storage and transport: A review of factors affecting hydrogen induced degradation. *J. Nat. Gas Sci. Eng.* **2022**, *101*, 104534. [\[CrossRef\]](#)
17. Jia, G.; Lei, M.; Li, M.; Xu, W.; Li, R.; Lu, Y.; Cai, M. Hydrogen embrittlement in hydrogen-blended natural gas transportation systems: A review. *Int. J. Hydrogen Energy* **2023**, *48*, 32137–32157. [\[CrossRef\]](#)
18. Ronevich, J.; Shrestha, R.; San Marchi, C. Misconceptions of hydrogen degradation of pipeline steels in existing natural gas infrastructure. In Proceedings of the Fourth International Conference on Metals & Hydrogen, Ghent, Belgium, 11–13 October 2022.
19. Klopčič, N.; Stöhr, T.; Grimmer, I.; Sartory, M.; Trattner, A. Refurbishment of natural gas pipelines towards 100% hydrogen—A thermodynamic-based analysis. *Energies* **2022**, *15*, 9370.
20. Sodwatana, M.; Kazi, S.R.; Sundar, K.; Zlotnik, A. Optimization of hydrogen blending in natural gas networks for carbon emissions reduction. In Proceedings of the 2023 American Control Conference (ACC), San Diego, CA, USA, 31 May–2 June 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 1229–1236.
21. Tsiklios, C.; Hermesmann, M.; Müller, T.E. Hydrogen transport in large-scale transmission pipeline networks: Thermodynamic and environmental assessment of repurposed and new pipeline configurations. *Appl. Energy* **2022**, *327*, 120097. [\[CrossRef\]](#)
22. Tan, K.; Mahajan, D.; Venkatesh, T.A. Computational fluid dynamic modeling of methane-hydrogen mixture transportation in pipelines: Understanding the effects of pipe roughness, pipe diameter and pipe bends. *Int. J. Hydrogen Energy* **2024**, *49D*, 1028–1042.
23. Peet, Y.; Sagaut, P.; Charron, Y. Pressure loss reduction in hydrogen pipelines by surface restructuring. *Int. J. Hydrogen Energy* **2009**, *34*, 8964–8973. [\[CrossRef\]](#)
24. Zhang, C.; Li, Z.; Li, C.; Wu, X.; Sun, L.; Chen, C. Insight into the effects of hydrogen on inside-valve flow and Joule-Thomson characteristics of hydrogen-blended natural gas: A numerical study. *Int. J. Hydrogen Energy* **2024**, *49D*, 1056–1074. [\[CrossRef\]](#)
25. Wang, C.; Zhou, D.; Xiao, W.; Shui, C.; Ma, T.; Chen, P.; Hao, J.; Yan, J. Research on the dynamic characteristics of natural gas pipeline network with hydrogen injection considering line-pack influence. *Int. J. Hydrogen Energy* **2023**, *48*, 25469–25486. [\[CrossRef\]](#)
26. André, J.; Auray, S.; Brac, J.; De Wolf, D.; Maisonnier, G.; Ould-Sidi, M.M.; Simonnet, A. Design and dimensioning of hydrogen transmission pipeline networks. *Eur. J. Oper. Res.* **2013**, *229*, 239–251. [\[CrossRef\]](#)
27. Lee, H.; Lee, S. Economic analysis on hydrogen pipeline infrastructure establishment scenarios: Case study of South Korea. *Energies* **2022**, *15*, 6824. [\[CrossRef\]](#)
28. Galyas, A.B.; Kis, L.; Tihanyi, L.; Szunyog, I.; Vadaszi, M.; Koncz, A. Effect of hydrogen blending on the energy capacity of natural gas transmission networks. *Int. J. Hydrogen Energy* **2023**, *48*, 14795–14807. [\[CrossRef\]](#)
29. Lipiäinen, S.; Lipiäinen, K.; Ahola, A.; Vakkilainen, E. Use of existing gas infrastructure in European hydrogen economy. *Int. J. Hydrogen Energy* **2023**, *48*, 31317–31329. [\[CrossRef\]](#)
30. Prinzhofer, A.; Cacas-Stentz, M.C. Natural hydrogen and blend gas: A dynamic model of accumulation. *Int. J. Hydrogen Energy* **2023**, *48*, 21610–21623. [\[CrossRef\]](#)
31. Bellocchi, S.; De Falco, M.; Facchino, M.; Manno, M. Hydrogen blending in Italian natural gas grid: Scenario analysis and LCA. *J. Clean. Prod.* **2023**, *416*, 137809. [\[CrossRef\]](#)
32. Kazi, S.R.; Sundar, K.; Zlotnik, A. Dynamic Optimization and Optimal Control of Hydrogen Blending Operations in Natural Gas Networks. In 2024 American Control Conference (ACC); IEEE: Piscataway, NJ, USA, 2024.
33. Zhang, C.; Shao, Y.; Shen, W.; Li, H.; Nan, Z.; Dong, M.; Bian, J.; Cao, X. Key technologies of pure hydrogen and hydrogen-mixed natural gas pipeline transportation. *ACS Omega* **2023**, *8*, 19212–19222. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Ekhtiari, A.; Flynn, D.; Syron, E. Investigation of the multi-point injection of green hydrogen from curtailed renewable power into a gas network. *Energies* **2020**, *13*, 6047. [\[CrossRef\]](#)
35. Li, J.; Song, F.; Zhang, X. A review on hazards and risks to pipeline operation under transporting hydrogen energy and hydrogen-mixed natural gas. *Sci. Tech. Energ. Transit.* **2024**, *79*, 9. [\[CrossRef\]](#)
36. Ouyang, B.; Sun, D.; Yu, Y.; Hu, Z.; Wu, M. Simulation and analysis of leakage characteristics in hydrogen-blended natural gas pipelines. *Int. J. Hydrogen Energy* **2025**, *99*, 888–897. [\[CrossRef\]](#)
37. Cristello, J.; Dang, Z.; Hugo, R.; Park, S.S. Artificial intelligence based leak detection in blended hydrogen and natural gas pipelines. *Int. J. Hydrogen Energy* **2024**, *91*, 744–764. [\[CrossRef\]](#)
38. Sánchez-Lañez, J.; Cerezo, A.; Storch de Gracia, M.D.; Aragón, J.; Fernandez, E.; Madina, V.; Gil, V. Enabling the injection of hydrogen in high-pressure gas grids: Investigation of the impact on materials and equipment. *Int. J. Hydrogen Energy* **2024**, *52*, 1007–1018.
39. Qin, G.; Li, R.; Wang, B.; Wang, Y.; Cheng, Y.F. Enhancing hydrogen pipeline safety: Perspectives on resilience against hydrogen-induced degradation. *J. Pipeline Sci. Eng.* **2025**, *6*, 100314.
40. Sánchez, M.; Marinova, N.; Silveira, E.; Larrosa, N. Standards and codes for hydrogen in pipeline infrastructure: Testing, qualification, and integrity assessment. *J. Pipeline Sci. Eng.* **2025**, *5*, 100296. [\[CrossRef\]](#)
41. Stöhr, T.; Reiter, V.; Scheikl, S.; Klopčič, N.; Brandstätter, S.; Trattner, A. Hydrogen quality in used natural gas pipelines: An experimental investigation of contaminants according to ISO 14687:2019 standard. *Int. J. Hydrogen Energy* **2024**, *67*, 1136–1147. [\[CrossRef\]](#)

42. Roland Berger. *Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities: Hydrogen Injection into the Natural Gas Grid*; Fuel Cells and Hydrogen Joint Undertaking: Brussels, Belgium, 2017.
43. Eames, I.; Austin, M.; Wojcik, A. Injection of gaseous hydrogen into a natural gas pipeline. *Int. J. Hydrogen Energy* **2022**, *47*, 25745–25754. [\[CrossRef\]](#)
44. Hadi Sichani, P.; Zonta, F.; Soldati, A. *Analyse des Mischens und Entmischens von Wasserstoff in Erdgasleitungen*; TU Wien: Vienna, Austria, 2021.
45. Kong, M.; Feng, S.; Xia, Q.; Chen, C.; Pan, Z.; Gao, Z. Investigation of mixing behavior of hydrogen blended to natural gas in gas network. *Sustainability* **2021**, *13*, 4255. [\[CrossRef\]](#)
46. Liu, C.; Pei, Y.; Cui, Z.; Li, X.; Yang, H.; Xing, X.; Duan, P.; Li, L.; Li, Y. Study on the stratification of the blended gas in the pipeline with hydrogen into natural gas. *Int. J. Hydrogen Energy* **2023**, *48*, 5186–5196.
47. ÖVGW. *H E310—Wasserstoffeinspeiseanlagen*; ÖVGW: Vienna, Austria, 2023.
48. Salman, P.; Sartory, M.; Klell, M. wind2hydrogen—Umwandlung von erneuerbarem Strom in Wasserstoff zur Speicherung und zum Transport im Erdgasnetz. In Proceedings of the 14th Symposium Energieinnovation, Graz, Austria, 10–12 February 2016.
49. Hunt, P. *Entry-Exit Transmission Pricing with Notional Hubs: Can It Deliver a Pan-European Wholesale Market in Gas?*; Oxford Institute for Energy Studies: Oxford, UK, 2008.
50. Liu, Y.; Rao, A.; Ma, F.; Li, X.; Wang, J.; Xiao, Q. Investigation on mixing characteristics of hydrogen and natural gas fuel based on SMX static mixer. *Chem. Eng. Res. Des.* **2023**, *197*, 738–749. [\[CrossRef\]](#)
51. Yan, S.; Jia, G.; Xu, W.; Li, R.; Lu, Y.; Cai, M. Computational fluid dynamic analysis of hydrogen-injected natural gas for mixing and transportation behaviors in pipeline structures. *Energy Sci. Eng.* **2023**, *11*, 2912–2928. [\[CrossRef\]](#)
52. Su, Y.; Li, J.; Guo, W.; Zhao, Y.; Li, J.; Zhao, J.; Wang, Y. Prediction of mixing uniformity of hydrogen injection in natural gas pipeline based on a deep learning model. *Energies* **2022**, *15*, 8694. [\[CrossRef\]](#)
53. Fernandes, L.A.; Marcon, L.R.C.; Rouboa, A. Simulation of flow conditions for natural gas and hydrogen blends in the distribution natural gas network. *Int. J. Hydrogen Energy* **2024**, *59*, 199–213. [\[CrossRef\]](#)
54. Ouyang, X.; He, Q.; Chai, C.; Wang, Y.; Di, T.; Zhou, J.; Sun, X. A numerical study on hydrogen blending in natural gas pipeline by a T-pipe. *J. Pipeline Sci. Eng.* **2024**, *4*, 100186. [\[CrossRef\]](#)
55. Du, J.; Lv, X.F.; Zhao, H.J.; Qiao, S.W.; Chen, Z.H. Numerical study of the mixing process during hydrogen blending in natural gas pipelines. *J. Appl. Fluid Mech.* **2024**, *17*, 1618–1630. [\[CrossRef\]](#)
56. Grácio, G.; Rosa, N.; Martinho, N.; Gaspar, A.; Da Silva, M.G. CFD optimisation of hydrogen blending in high-pressure natural gas pipelines with T-junction configurations. *Fuel* **2026**, *422*, 139178. [\[CrossRef\]](#)
57. ANSYS. *Ansys Fluent Theory Guide 2023 R2*; ANSYS, Inc.: Canonsburg, PA, USA, 2023.
58. Horlacher, H.B.; Helbig, U. *Rohrleitungen 2*; Springer: Berlin/Heidelberg, Germany, 2018.
59. Suomalainen, M.S.; Arasto, A.; Teir, S.; Siitonen, S. Improving a pre-combustion CCS concept in gas turbine combined cycle for CHP production. *Energy Procedia* **2013**, *37*, 2327–2340. [\[CrossRef\]](#)
60. Bell, I.H.; Wronski, J.; Quoilin, S.; Lemort, V. Pure and Pseudo-Pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. Available online: www.coolprop.org (accessed on 26 June 2022).
61. Bell, I.H.; Wronski, J.; Quoilin, S.; Lemort, V. Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp. *Ind. Eng. Chem. Res.* **2014**, *53*, 2498–2508. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Kravos, A.; Ritzberger, D.; Hametner, C.; Jakubek, S.; Kutrašnik, T. Methodology for efficient parametrisation of electrochemical PEMFC model for virtual observers: Model-based optimal design of experiments supported by parameter sensitivity analysis. *Int. J. Hydrogen Energy* **2021**, *46*, 13832–13844. [\[CrossRef\]](#)
63. Rahim, Y.; Janßen, H.; Lehnert, W. Characterizing membrane electrode assemblies for high temperature polymer electrolyte membrane fuel cells using design of experiments. *Int. J. Hydrogen Energy* **2017**, *42*, 1189–1202. [\[CrossRef\]](#)
64. Charbonné, C.; Dhuitte, M.L.; Bouziane, K.; Chamoiret, D.; Candusso, D.; Meyer, Y. Design of experiments on the effects of linear and hyperelastic constitutive models and geometric parameters on polymer electrolyte fuel cell mechanical and electrical behaviour. *Int. J. Hydrogen Energy* **2021**, *46*, 13775–13790. [\[CrossRef\]](#)
65. Vairis, A.; Petousis, M. Designing experiments to study welding processes: Using the Taguchi method. *J. Eng. Sci. Technol.* **2009**, *4*, 99–103. [\[CrossRef\]](#)
66. Gregor, M.; Grznar, P.; Mozol, S.; Mozolova, L. Design of simulation experiments using central composite design. *Acta Simulatio* **2023**, *9*, 21–25. [\[CrossRef\]](#)
67. Klopčič, N. *Advancing Hydrogen Storage Technologies and Infrastructures*. Ph.D. Thesis, Technische Universität Graz, Graz, Austria, 2024.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.