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Hydrogen-Natural Gas Co-Blending: Performance Analysis with CFD and Static Mixers

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The integration of hydrogen into natural gas infrastructure is a viable transitional strategy for decarbonizing energy systems without requiring major pipeline modifications. However, achieving uniform mixing of hydrogen and natural gas remains a significant challenge due to differences in gas properties. Additionally, poor mixing of hydrogen-natural gas blends can result in uneven flow distribution and pose potential safety risks. In this study, a T-junction pipeline model was developed, with hydrogen injected perpendicularly into a natural gas stream using computational fluid dynamics (CFD). Simulations were performed at a fixed natural gas flow velocity of 8 m/s, while varying hydrogen pipe diameters (0.1–0.4 m) and injection velocities (4–10 m/s) to evaluate the uniformity of the gas mixture. A Kenics-type static mixer was installed downstream of the injection point to assess its impact on blending performance. Results indicated that a hydrogen pipe diameter of 0.2 m and an injection velocity of 8–10 m/s yielded optimal blending, achieving a hydrogen blending ratio (HBR) of 20.00–23.81 % and a uniform hydrogen mole fraction distribution. The static mixer further improved blending quality, reducing the coefficient of variation (CoV) to 6.71 %. These results demonstrate the potential of CFD-guided optimization to ensure safe and efficient hydrogen–natural gas blending in the development of future energy networks.

1. Introduction

The global energy transition represents a transformative shift from fossil fuel dependence toward low-carbon alternatives. The transition is driven by growing environmental concerns arising from rapid urbanization, industrial expansion, and energy consumption. Among various clean energy carriers, green H_2 has emerged as a promising option, offering a high energy content and zero carbon emissions during end-use applications (Rosa et al., 2025). Although H_2 holds significant potential, the majority of its production facilities are located in remote areas rich in renewable energy sources and geographically distant from major demand centres (Yue et al., 2021). The construction of dedicated H_2 pipeline infrastructure can be costly and time-intensive, owing to substantial upfront capital requirements for production, transport, and storage facilities (Cui and Aziz, 2023). In response to these constraints, the adoption of H_2–natural gas blending (HBNG) has been proposed as a practical and cost-effective pathway for hydrogen distribution.

The HBNG method leverages existing natural gas infrastructure to enable partial H_2 integration without substantial retrofitting. This approach has been implemented in several countries through pilot and full-scale projects. According to the International Energy Agency (IEA), approximately 40 HBNG pipeline projects have been completed or are under construction worldwide (Mahajan et al., 2022). Most countries have adopted a 5–20 % hydrogen blending ratio (HBR) for residential applications, while ongoing research is examining higher blends of up to 30 % and beyond for dedicated infrastructure. Nevertheless, blending H_2 with natural gas introduces several limitations that significantly affect the properties of the blended gas. The addition of H_2 alters key characteristics such as energy density, flame speed, Wobbe index, and thermal conductivity, which in turn pose safety risks and operational challenges in blended gas systems (Islam et al., 2024). Furthermore, achieving

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a uniform H_2–natural gas mixture at the desired HBR remains a major challenge due to differences in gas properties and flow dynamics (Ouyang et al., 2025). Hence, CFD simulations were conducted to evaluate flow interactions and mixing behavior in H_2–natural gas pipeline systems.

CFD tools provide an effective method for modelling the complex behavior of blended gases in pipelines. By simulating real-world conditions, researchers can visualize flow fields, assess turbulence intensity, and predict pressure drops across different blending scenarios. Previous studies have evaluated the effects of H_2 injection velocity (Fang et al., 2024), HBR (Lu et al., 2024), and pipeline geometry (Eames et al., 2022) on flow dynamics and mixing performance using T-junction configurations. However, conventional T-junction injection methods frequently result in inadequate mixing due to abrupt momentum differences and limited turbulence development. Passive mixing technologies, such as static mixers, are being investigated to improve flow homogenization without external energy input. Limited research has incorporated static mixing devices into CFD models for HBNG, indicating a significant gap in the literature.

In this study, the mixing behavior of H_2 and natural gas within a T-junction pipeline model is analyzed using CFD ANSYS FLUENT. A Kenics-type static mixer was installed downstream of the H_2 injection point to evaluate its effectiveness in improving blend uniformity. The investigation examined the effects of key parameters, including H_2 inlet diameter, injection velocity, and mixer geometry. Mixing uniformity was assessed through contour visualization and H_2 concentration distribution. The impact of the mixer was quantitatively evaluated using the coefficient of variation (CoV). The findings of this research are expected to provide valuable insights into the feasibility and performance of HBNG co-blending.

2. Methods

2.1 Geometric model and meshing strategy

A T-junction model was generated using CFD software ANSYS Fluent 2025 to simulate H_2 injection into a natural gas pipeline. The geometry consisted of a 0.4 m diameter main pipe and a perpendicular H_2 inlet pipe. A pipeline length of 15 m was employed to adequately capture the downstream evolution of gas mixing. The T-shaped configuration is strategically selected to create a controlled mixing zone and replicate practical hydrogen injection scenarios. Structured hexahedral meshing was generated using ANSYS Meshing to ensure accurate boundary layer resolution, as shown in Figure 1(a). A specific case study incorporating the mixer was also conducted to assess its effect on H_2–natural gas blending uniformity. A Kenics-type static mixer, matching the 0.4 m pipeline diameter, was installed downstream of the H_2 injection point as depicted in Figure 1 (b). The 0.6 m long mixer consists of six alternating left and right-handed helical elements, each twisted at 90°. The mixer was centrally aligned and tested along a 50 m pipeline.

(a) (b)

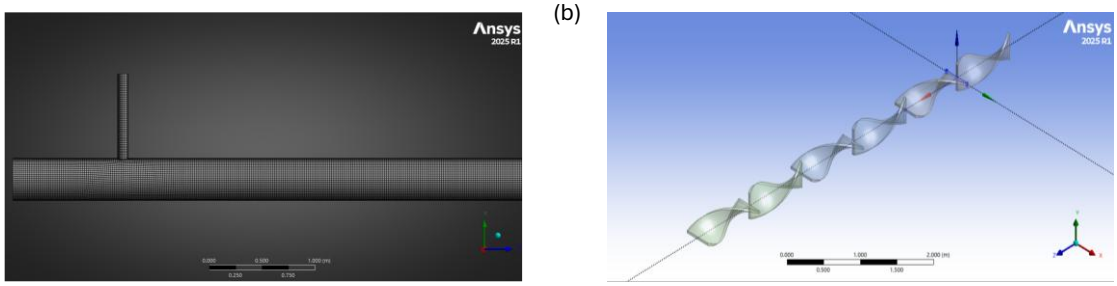

Figure 1: (a) T-junction pipeline geometric and mesh (b) Kenics-type static mixer configuration

2.2 Numerical methods and boundary conditions

Simulations were conducted using a pressure-based solver under steady-state, isothermal conditions. The realizable k–ε turbulence model and species transport equations were applied to the model. The Reynolds-Averaged Navier–Stokes (RANS) equations of the realizable k–ω turbulence model were employed in this study to improve accuracy in predicting swirling and recirculating flows (Azizi et al., 2022). In contrast, Direct Numerical Simulation (DNS) was not feasible for practical engineering problems involving high-Reynolds-number natural gas flows, while Large Eddy Simulation (LES) was not pursued due to higher computational cost (Di et al., 2024). The natural gas flow velocity was fixed at 8 m/s, and H_2 was injected at 6 m/s. Wall boundaries were defined as smooth, adiabatic, and subject to no-slip conditions, with gravity set to 9.81 m/s² along the Z-axis. All equations were discretized using a second-order upwind scheme, with a convergence threshold of 10^{-6} (Fang et al., 2024). Material properties were sourced from the FLUENT database, and the reference pressure was set to 101,325 Pa. Parametric studies analyzed the effects of H_2 inlet diameter, velocity, and static mixer presence

on mixing performance. Post-processing focused on the contour plot and H_2 mole fraction distribution. For a static mixer, mixing uniformity was also quantified using the CoV, with lower values suggesting better homogeneity.

3. Result and Discussions

3.1 Effects of hydrogen diameter on mixing distribution

Figure 2 illustrates the contour plots of H_2 mole fraction at different downstream locations for varied H_2 inlet diameters. At a diameter of 0.1 m, the H_2 remains concentrated in the upper region of the pipe. Radial penetration into the natural gas stream is minimal, indicating insufficient turbulent mixing and a low HBR of 4.48 %. Increasing the diameter to 0.2 m (HBR 15.79 %) enhances diffusion and allows deeper penetration into the core flow. The pipe cross-section at x = 15 m shows a symmetric distribution with a wider green band, suggesting a more uniform mole fraction. Further increases to 0.3 m and 0.4 m may lead to excessive jet momentum, achieving higher HBRs of 29.67 % and 42.85 %. These findings are consistent with the numerical studies of Eames et al. (2022) and Liu et al. (2023), which reported that larger pipe diameters promote stratification near pipe walls and reduce mixing efficiency. Hence, selecting an appropriate inlet diameter is crucial to balance H_2 content and blending uniformity.

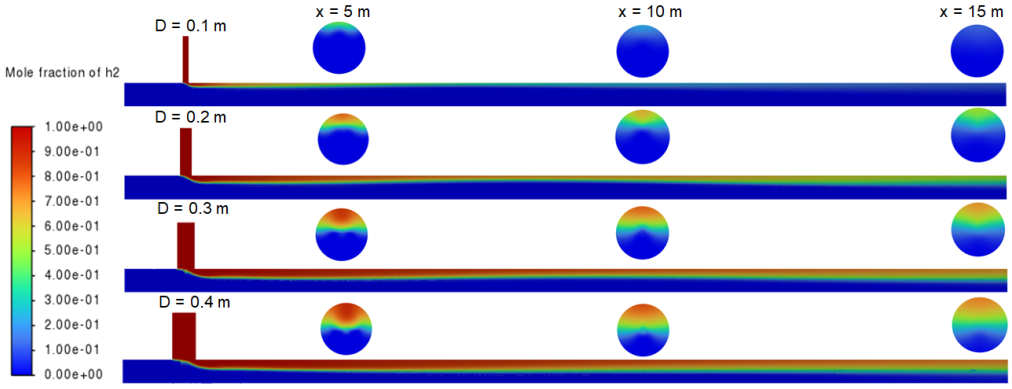

Figure 2: Contours of the hydrogen mole fraction and cross-sections at varied hydrogen diameter

The H_2 mole fractions for different inlet diameters are depicted in Figure 3. As the H_2 diameter increases, the initial H_2 concentration at 1 m downstream rises from 0.254 (0.1 m) to 0.733 (0.4 m). Large diameters generate a stronger H_2 jet with greater momentum, allowing deeper penetration into the natural gas stream (Eames et al., 2022). Beyond 1 m, the H_2 mole fraction decreases for all pipe sizes, reflecting natural mixing and dispersion within the pipeline.

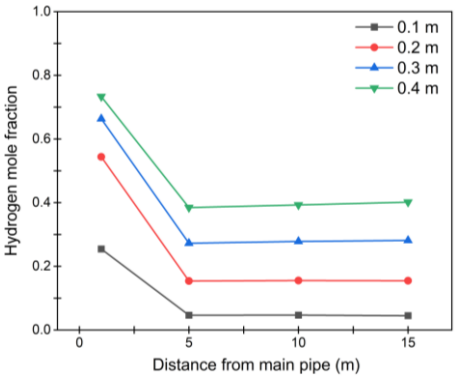

Figure 3: Hydrogen mole fraction distribution for different hydrogen pipeline diameters

Figures 2 and 3 demonstrate that increasing the H_2 inlet diameter improves the blending ratio but reduces mixing uniformity due to stratification effects. An inlet diameter of 0.2 m was found to provide the optimal balance between hydrogen penetration and downstream blend uniformity for safe and effective mixing performance.

3.2 Effects of hydrogen velocity on mixing distribution

The contour plot in Figure 4 demonstrates the effect of H_2 injection velocity on the mole fraction distribution and blending performance under a fixed H_2 inlet diameter of 0.2 m. At 4 m/s, hydrogen remains concentrated in the upper region with minimal radial dispersion. The low HBR of 11.11 % revealed inefficient integration of H_2 into the natural gas stream. As the velocity increases to 6 m/s (HBR 15.79 %), the H_2 jet penetrates deeper into the pipeline. When the H_2 velocity was set at 8 m/s and 10 m/s, the blending performance improved markedly, resulting in more uniform mole fraction distributions that extended up to 15 m downstream. These conditions correspond to elevated HBRs of 20.00 % and 23.81 %. The comparison between the 8 m/s and 10 m/s cases reveals no significant difference in contour patterns or mixing quality. Both exhibit similar uniformity, suggesting that increasing the H_2 injection velocity beyond 8 m/s yields minimal additional benefits in blending performance. Fang et al. (2024) similarly observed that higher H_2 injection velocities enhance initial mixing by improving jet penetration and interaction with the natural gas flow, though the effect plateaus beyond a certain threshold.

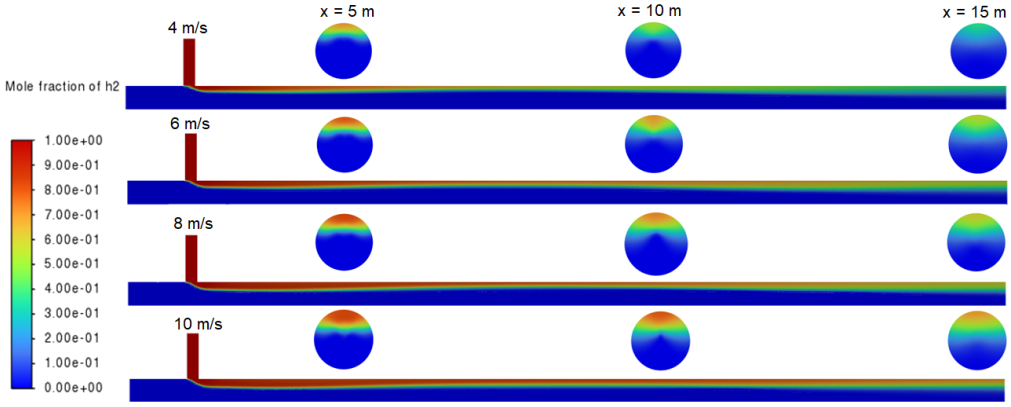

Figure 4: Contours of the hydrogen mole fraction and cross-sections at different hydrogen velocities

Figure 5 shows the distribution of H_2 mole fraction at varying injection velocities along the pipeline. At 1 m, all velocities yield similarly high initial mole fractions around 0.416. As the flow progresses, dispersion behavior diverges. The mole fraction decreases sharply at 4 m/s and stabilizes at 0.115. As the velocity increases to 6 m/s and 8 m/s, the mole fractions also decline initially but stabilize at higher values, reflecting improved radial mixing and dispersion. The 10 m/s case exhibits the most uniform and sustained H_2 distribution, with the mole fraction increasing from 0.215 at 5 m to 0.250 at 15 m. These results confirm that higher H_2 injection velocities (≥8 m/s) promote deeper mixing across the pipeline cross-section.

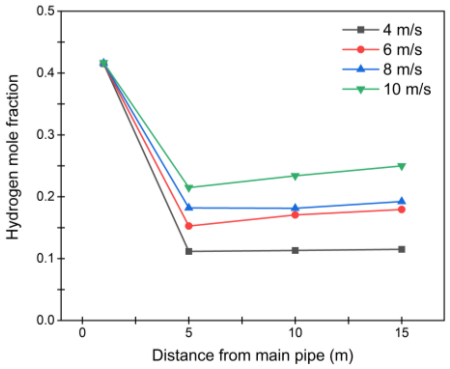

Figure 5: Hydrogen mole fraction distribution at varied hydrogen velocity

The increase in H_2 injection velocity from 4 m/s to 10 m/s enhanced radial penetration and blending performance. However, the improvements plateaued beyond 8 m/s, as both 8 m/s and 10 m/s resulted in similarly uniform downstream flow. Therefore, a hydrogen injection velocity of 8 m/s or greater represents the optimal condition for effective and efficient mixing.

3.3 Influence of static mixer integration on hydrogen-natural gas mixing efficiency

Figure 6 illustrates the effect of incorporating a static mixer on the H_2 mole fraction distribution along the pipeline. The cross-sectional contour plots at various downstream positions depict a gradual improvement in the uniformity. At x = 5 m, the cross-section reveals a distinctly non-uniform profile, with high H_2 concentrations indicated by red to green regions in the upper part of the pipe. The different gas layers show minimal mixing and strong stratification. As the flow progresses downstream, the influence of the static mixer becomes increasingly evident, enhancing mixing performance and improving the uniformity of H_2 distribution throughout the pipeline. At x = 10 m and x = 20 m, the H_2 distribution spreads more evenly across the pipe cross-section, with the concentration gradient transitioning from sharp to more diffuse. By x = 30 m and x = 40 m, the mole fraction becomes largely uniform, reflected in the dominant light blue-green coloration, suggesting successful H_2 blending with natural gas. Similar contour patterns were observed by Du et al. (2024), where red zones near the injection point indicated high H_2 concentrations that gradually transitioned to blue-green tones downstream with the use of a static mixer.

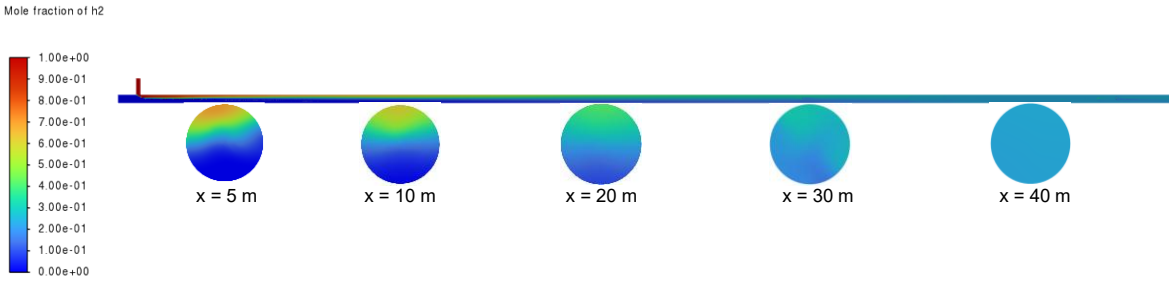

Figure 6: Hydrogen distribution contours with static mixer addition

This visual observation is further supported by the quantitative H_2 mole fraction data presented in Figure 7. The mole fraction at 1 m is 0.219. As the distance increases to 5 m and 10 m, the mole fraction rises to 0.235 and 0.245, respectively, indicating progress in mixing. The peak value of 0.249 is observed at 20 m, emphasizing the mixer's optimal effectiveness in dispersion. Beyond this point, the mole fraction shows a slight decline and stabilizes around 0.247 at 30 m and 0.245 at 40 m. This plateau suggests that the gas mixture has reached a nearly homogeneous state. Furthermore, the mixing uniformity is verified by a reduction in CoV value to 6.71 %, implying excellent blend consistency.

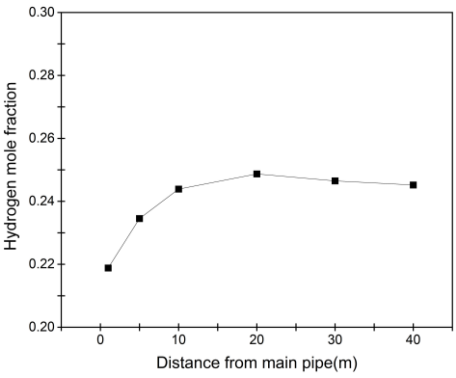

Figure 7: Hydrogen mole fraction distribution along the pipeline with static mixer integration

The visual pattern, H2 mole distribution, and CoV results further validate the static mixer's role in promoting H2–natural gas homogenization. The helical elements of the Kenics mixer induce strong swirl and generate controlled turbulence for radial mixing. The helical design also promotes a transition from steady to unsteady flow at relatively low Reynolds numbers for effective mixing even under laminar and transitional flow conditions (Nyande et al., 2021). Ultimately, the static mixer enhances blend uniformity, mitigates stratification, and accelerates the mixing process.

4. Conclusion

Hydrogen–natural gas blending in a T-junction pipeline model was evaluated using CFD simulations. The analysis focused on injection parameters and the effectiveness of a static mixer. Optimal blending was achieved with a 0.2 m H_2 inlet diameter and an injection velocity of 8–10 m/s, which enhanced radial dispersion and improved blending uniformity. At higher H_2 inlet diameters and velocities, contour visualizations of H_2 mole fraction revealed pronounced stratification in upstream sections, characterized by distinct H_2-rich and natural gas-rich layers with limited mixing. This stratification arises from the high jet momentum of the injected H_2 and its lower density, which restricts radial penetration and hinders uniform mixing. The incorporation of a Kenics-type static mixer mitigated this stratification by promoting a gradual transition toward a more uniform distribution downstream. The static mixer further accelerated homogenization by reducing the CoV value. Collectively, the combination of optimized injection parameters and passive mixing strategies demonstrates that HBNG co-blending can be effectively achieved using existing pipeline infrastructure. These findings reinforce low-carbon transition efforts by supporting safer and more cost-effective H_2 integration into current natural gas systems. Although the current investigation emphasizes technical performance, future research incorporating detailed economic analysis is required to complement the results and support the practical deployment of hydrogen blending strategies.

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