



Accidental Release of Hydrogen Blends in Pipelines - Numerical Analysis and Safety Implications

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Table of Contents

Section	Page
1. Introduction and Executive Summary	12
2. Safety Aspects of Hydrogen Blends in Pipelines.....	15
3. Review of Studies on Hydrogen Blends Releases from Pipelines	16
3.1 Gas Dispersion	16
3.1.1 Open Environment.....	16
3.1.2 Closed Environment.....	23
3.2 Fire and Explosion	26
3.3 Risk Analysis	31
3.4 Summary	33
4. Reference Scenarios and Numerical Models	34
4.1 Reference Scenarios.....	34
4.1.1 Scenario 1: Outdoor Pipeline Leaks in Rural Areas.....	34
4.1.2 Scenario 2: Outdoor Pipeline Leaks in Urban Areas	34
4.1.3 Scenario 3: Indoor Pipeline Leaks	35
4.2 Computer Models and Codes	36
4.2.1 CNL Hydrogen Risk Analysis Toolkit.....	36
4.2.2 STAR-CCM+	36
4.2.3 GOTHIC.....	36
4.3 Modeling Methodology	36
5. Scenario 1: Outdoor Pipeline Leaks in Rural Areas.....	37
5.1 Model Verification and Validation	37
5.1.1 Unignited Jet Cloud	37
5.1.2 Jet Flame	38
5.2 Sensitivity Study Results and Discussions.....	39
5.2.1 Leak Rate.....	40

Accidental Release of Hydrogen Blends in Pipelines - Numerical Analysis and Safety Implications	
153-126510-REPT-004665 Rev. 1	Page 6 of 83
5.2.2	Jet Fire 40
5.2.3	Fire and Explosion 43
5.3	Implications for Safety 46
6.	Scenario 2: Outdoor Pipeline Leaks in Urban Areas 47
6.1	Model Setup..... 47
6.2	Model Verification 49
6.3	Sensitivity Study Results and Discussion 50
6.3.1	Dispersion Behaviour 50
6.3.2	Flammable Area and Energy 52
6.3.3	Hydrogen Blending Ratio 54
6.3.4	Wind Velocity 56
6.3.5	Distance Between Buildings..... 56
6.4	Implications to Safety 59
7.	Scenario 3: Indoor Pipeline Leaks 59
7.1	Model Setup..... 60
7.2	Model Verification 60
7.3	Sensitivity Study Results and Discussion 61
7.3.1	Reference Case 63
7.3.2	Effect of Ventilation 64
7.3.3	Effect of Hydrogen Blending Ratio and Ventilation..... 67
7.3.4	Implications for Safety 69
8.	Summary and Considerations 69
9.	Acknowledgements..... 70
10.	References 71
Appendix A	Pipeline Infrastructure 75
Appendix B	Overview of Hydrogen Blending Projects 78
Appendix C	Effect of Pressure and Blending Ratio on Gas Density 80
Appendix D	Coupled Effect between Pipeline Pressure and Hydrogen Blending Ratio on

Safety Parameters.....	81
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Figures

Figure 1: Event sequence diagram following a hydrogen leak [28].	16
Figure 2: CFD model geometry (240 m wide and 80 m high) showing velocity field for hydrogen natural dispersion. Two 30 m wide and 20 m high structures representing factory buildings were placed in the domain, from Ref. [18].	16
Figure 3: Concentration profile for methane release at 7.5 s: (a) with wind (10 m/s) and (b) without wind (0 m/s), from Ref. [18].	17
Figure 4: Concentration profile for hydrogen release at 4 s: (a) with wind (10 m/s) and (b) without wind (0 m/s).	17
Figure 5: 3D model domain of the gas station during a hydrogen blend leak [29].	18
Figure 6: Flammable gas cloud at (a) 1 MPa and (b) 4 MPa [29].	19
Figure 7: 3D model domain of urban streets with 70 m long traffic [30].	19
Figure 8: Distribution of flammable cloud with 50% hydrogen blending ratio [30].	20
Figure 9: Maximum explosion overpressure versus hydrogen blending ratio [30].	21
Figure 10: 3D model domain for a hydrogen blended mixing station [31].	21
Figure 11: Development of flammable methane gas cloud (5% methane iso-surface, 109.61 kg/s release rate, 5.28 m/s west wind, 15% hydrogen blending ratio) [31].	22
Figure 12: Development of flammable hydrogen gas cloud (4% hydrogen iso-surface, 109.61 kg/s release rate, 5.28 m/s west wind, 15% hydrogen blending ratio) [31].	23
Figure 13: Steady-state methane flammable clouds at different blending ratios (109.61 kg/s release rate, 5.28 m/s west wind) [31].	23
Figure 14: Steady-state hydrogen flammable clouds at different blending ratios (109.61 kg/s release rate, 5.28 m/s west wind) [31].	23
Figure 15: 3D model domain of an indoor environment [32].	24
Figure 16: Gas distribution of indoor leak of 20% hydrogen blended gas on z = -0.6 m plane at 300 s for (a) methane and (b) hydrogen [32].	24
Figure 17: Effect of blending ratio on flammable volume of blended gas mixture [32].	25
Figure 18: 3D model domain of a domestic kitchen [17].	25
Figure 19: 3D concentration distribution of the hydrogen blended gas at different times in a domestic kitchen (5.5×10^{-5} kg/s leak rate, 10% hydrogen blending ratio, no ventilation) [17].	26
Figure 20: Mean flame height for different hydrogen blends [33].	27

Figure 21: Air entrainment for free and wall hydrogen blends fire [34].	27
Figure 22: Flame length for free and wall hydrogen blends fire [34].	28
Figure 23: Test 1 - Flame profile during ignition of the methane-hydrogen mixture [15].	29
Figure 24: Test 2 - Flame profile during ignition of methane only [15].	30
Figure 25: Flame lengths for tests with methane and hydrogen blends [16].	31
Figure 26: Individual risk from ignited releases for different types of houses [19].	32
Figure 27: Combined individual risk from carbon monoxide and ignited releases for different types of houses [19].	33
Figure 28: Schematic of a full pipeline rupture.	34
Figure 29: Schematic of the model domain adapted from [18].	35
Figure 30: 3D model domain of a domestic kitchen [17].	35
Figure 31: Mole fraction of (a) hydrogen and (b) methane varying with distance from the nozzle for different H ₂ blending ratio. Comparison between experiments from [39] (symbol), CNL toolkit (solid line), and HyRAM (dashed line).	38
Figure 32: Flame length varying with hydrogen blending ratio. Comparison between experiments from Ref. [33] (symbol), CNL toolkit (solid line), and HyRAM (dashed line).	39
Figure 33: Leak rate changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.	40
Figure 34: Flame length predicted by the CNL toolkit changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.	41
Figure 35: Heat flux contour profiles for different leak diameters and hydrogen blending ratio. Leak diameters of 14 mm, 44 mm, and 139 mm correspond to 1%, 10%, and 100% of the pipeline cross-sectional area (A _c).	42
Figure 36: Contour profiles of fuel concentration with different leak diameter and blending ratio. The colour range was depicted based on the LFL and UFL of each hydrogen blend.	43
Figure 37. Explosive mass changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.	44
Figure 38: Overpressure contour profiles for different leak diameters and hydrogen blending ratio.	45
Figure 39: Mesh distribution along the numerical domain.	48
Figure 40: (a, b) Methane volume fraction for 100% CH ₄ at 7.5 s and (c, d) hydrogen volume fraction for 100% H ₂ at 4.0 s both at wind velocity = 10 m/s. (a, c) Results from CNL and (b, d) results from Ref. [18].	49

Figure 41: Velocity profile for methane release for 100% CH ₄ , wind velocity = 10 m/s at 1 s. (a) Results from CNL and (b) results from Ref. [18].	49
Figure 42: Fuel volume fractions between the LFL and UFL varying with time for 100% CH ₄ (left side) and 100% H ₂ (right side) with wind velocity = 10 m/s.	51
Figure 43: Areas analyzed: upwind (Region 1), building canyon (Region 2), and downwind (Region 3).	52
Figure 44: Flammable area within the computation domain for 100% CH ₄ (case 1) and 100% H ₂ (case 5) with wind = 10 m/s within (a) entire domain, (b) region # 1, (c) region # 2, and (d) region # 3.	53
Figure 45: (a) Total energy available for combustion and (b) flammable energy within the flammability range for 100% CH ₄ (case 1) and 100% H ₂ (case 5).	54
Figure 46: Hydrogen blending volume fraction between LFL and UFL at 7.5 s for (a) 0% H ₂ , 100% CH ₄ , (b) 20% H ₂ , 80% CH ₄ , (c) 50% H ₂ , 50% CH ₄ , (d) 75% H ₂ , 25% CH ₄ , and (e) 100% H ₂ , 0% CH ₄ , wind velocity = 10 m/s. The coloured bar shows the LFL and UFL limits for each case.	55
Figure 47: (a) Area containing the flammable fuel concentration and (b) Fuel energy per unit depth in the flammable area varying with hydrogen blending ratio at wind velocity of 10 m/s.	55
Figure 48: Hydrogen blending volume fraction between LFL and UFL at 7.5 s for (a) wind velocity = 10 m/s, (b) wind velocity = 5 m/s, (c) wind velocity = 0 m/s with hydrogen blending ratio of 20% H ₂ , 80% CH ₄ .	57
Figure 49: (a) Area containing the flammable fuel concentration and (b) fuel energy per unit depth in the flammable area varying with wind velocity for 20% H ₂ and 80% CH ₄ .	57
Figure 50: Hydrogen blending volume fraction between LFL and UFL varying the distance between the buildings (80, 60, and 40 m) at 7.5 s, wind velocity = 10 m/s, and hydrogen blending ratio of 20% H ₂ , 80% CH ₄ .	58
Figure 51: (a) Normalized area containing the flammable fuel concentration and (b) fuel energy per unit volume in the flammable area in between the buildings for hydrogen blending ratio of 20% H ₂ , 80% CH ₄ and wind velocity = 10 m/s.	58
Figure 52: Mesh layout for the GOTHIC simulations.	60
Figure 53: 3D and 2D distributions of fuel concentration following a release of hydrogen blends inside a kitchen at 3000 s. Comparison between CNL results (left side) and results from Ref. [17] (right side).	61
Figure 54: Locations in the kitchen where the fuel concentration was analyzed. P2 and P3 are located above the leak, P1 and P4 are located at the back wall, and P5-P9 are located at the back left corner.	62

Figure 55: 3D contours of the fuel concentration at different times for the reference case.	63
Figure 56: Fuel concentration varying with (a) time for all locations shown in Figure 54 and (b) height (P5-P9) at 3000 s for Case 1 (reference case). Dashed line shows the LFL.	64
Figure 57: 2D contours showing the fuel concentration at different times for 0 ACH (no ventilation, left side) and 0.5 ACH (right side).	65
Figure 58: Fuel concentration varying with time for different ventilation rates (Cases 1-4): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).	66
Figure 59: Fuel concentration varying with height (P5-P9) at 3000 s for different ventilation rates (Cases 1-4).....	66
Figure 60: Fuel concentration varying with time for different hydrogen blending ratios without ventilation (Cases 1 and 5-8): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).....	67
Figure 61: Fuel concentration varying with time for different hydrogen blending ratios (Cases 3 and 9-12): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).....	68
Figure 62: Fuel concentration varying with height (P5-P9) at 3000 s for different hydrogen blending ratios and ventilation: (a) no ventilation (Case 1 and 5-8) and (b) 1 ACH (Cases 3 and 9-12).....	68
Figure 63: Representation of a pipeline network: gathering, transmission and distribution pipelines [49]. Note that the figure is not to scale.	75
Figure 64: Representation of gathering pipelines shown in green [49]. Note that the figure is not to scale.	76
Figure 65: Representation of transmission pipelines shown in red [49]. Note that the figure is not to scale.....	77
Figure 66: Representation of distribution pipelines shown in blue [49]. Note that the figure is not to scale.....	77
Figure 67: Hydrogen blending activities in Canada [57].	78
Figure 68: Hydrogen blending activities around the world [57].....	79
Figure 69: Density of the mixture changing with hydrogen blending ratio and pressure.	80
Figure 70: (a) Leak rate, (b) explosive mass, and (c) flame length changing with hydrogen blending ratio and leak diameter at a given energy content.	82
Figure 71: Heat flux varying with hydrogen blending ratio and pressure.	82
Figure 72: Overpressure varying with hydrogen blending ratio and pressure.....	83

Tables

Table 1: Operational conditions applied in pipeline blends studies.....	33
Table 2: Flame length for different hydrogen blending ratio.....	38
Table 3: Separation distances based on heat flux thresholds for different hydrogen blending ratio and leak diameters at 7 MPa.....	42
Table 4: Separation distances based on overpressure thresholds for different hydrogen blending ratio and leak diameters at 7 MPa.....	46
Table 5: Sensitivity to key model variables.....	47
Table 6: Test conditions for the scenario 2 sensitivity study.....	50
Table 7: Test conditions for the scenario 3 sensitivity study.....	62
Table 8: Pipeline operational conditions [2, 4, 49-52].....	75
Table 9: Status of ongoing blending projects worldwide [57].....	79
Table 10: Calculation of the pipeline pressure and blend density at a fixed volumetric energy content.....	81

1. Introduction and Executive Summary

On December 16, 2020, Natural Resources Canada (NRCan) released “The Hydrogen Strategy for Canada” [1]. This strategy identifies strategic partnerships, de-risking investments, and international collaboration as key pillars of action required to grow the domestic hydrogen market and position Canada as a supplier of choice to the world. Furthermore, Canada’s 2030 emissions reduction plan highlights the next steps for clean air and a strong economy while stating that Canada’s heavy industry emissions currently rank as the fourth highest emitting sector.

To reduce the heavy industry sector's environmental footprint, the adoption and widespread utilization of clean fuels (such as low-carbon intensity hydrogen) will decrease greenhouse gas emissions across Canada. In addition, Canada has the potential to produce large amounts of low-cost, clean hydrogen (H_2), which will be an essential part of a low-carbon economy.

Blending hydrogen into existing natural gas pipelines has been considered as a promising method to distribute hydrogen over long distances without the development of new infrastructure [2-7]. There are several advantages of using existing natural gas pipelines to transport hydrogen. Natural gas pipelines have well-established operational, maintenance, and safety protocols, and relatively good public acceptance [4, 8]. While pipelines transporting hydrogen at low blending ratios (i.e., up to 20% H_2) may require minimal modifications to hardware [2, 4, 9-11], the introduction of hydrogen could impact the safe operating envelope. Thus, modifications to the operating conditions, regulatory processes (oversight, permitting and approvals), and infrastructure may be required to mitigate safety concerns arising from material degradation, such as hydrogen embrittlement, and the effect on end-use appliances [2, 4, 12]. In Canada, the hydrogen blending ratio is currently limited to 5% for a specific suite of gas appliances [13].

A short overview of the pipeline infrastructure and hydrogen blending projects in Canada and around the world are presented in Appendix A and Appendix B, respectively. Moreover, a detailed discussion of pipeline infrastructure, hydrogen blending projects, and regulations, codes, and standards can be found in a recent report conducted by the Canadian Standards Association [14].

NRCan signed a Memorandum of Agreement with Atomic Energy of Canada Limited (AECL) for a project titled “Safety Analysis of Hydrogen Systems in Pipelines for Transporting Hydrogen versus Hydrogen and Natural Gas Blends.” For this project, CNL acts as a contractor for AECL. The overall goal of this work was to provide insights on the safety aspects involving accidental releases of hydrogen blends from pipelines.

The project was executed in three steps:

1. Conduct a literature review of the experimental and numerical studies on the dispersion, fire, and explosion behaviour associated with accidental release of hydrogen blends from pipelines to gain a better understanding on these areas of interest.

2. Identify representative scenarios, and define sensitivity parameters, for further numerical analysis of pipelines transporting hydrogen blends.
3. Perform numerical analysis (computational fluid dynamics – CFD – codes and/or engineering models) to evaluate the hazards related to accidental release of hydrogen blends from pipelines.

In Step 1, the literature review identified several conclusions and remarks regarding the safety of blending hydrogen into natural gas pipelines (see Section 2):

- When the volume of hydrogen in the natural gas exceeds 20%, additional measures may be required to maintain the safe operating envelope of the pipeline, including strategies to mitigate and manage risks, and preventions of leaks, embrittlement, fire, and explosion [2, 4, 9-11]. Note most of these literature studies were carried out with blending ratios less than 20%.
- Large-scale experiments with pure natural gas or less than 20% H₂ showed minor difference in jet flame dimensions, radiant heat flux, and overpressure generated [15, 16].
- The accumulation of combustible gas has the potential for fire and explosion when the gas concentration is within the flammability (or explosion) limits [17].
- The hazard (e.g., fire or explosion) associated with a pipeline leak depends on the environment conditions (e.g., open space with or without obstructions, confined or semi-confined space, wind, natural and forced ventilations) into which the gas is leaking [18].
- The risk of a hazard depends on the likelihood of an event to occur (e.g., pipeline or components failure frequency, probability of ignition, and probability of mitigation failures) and the severity of the consequence (e.g., heat flux and overpressure) [19].
- A risk assessment systematically evaluates controls and mitigation measures to foresee if they can prevent the incident from turning into an accident with damaging consequences. Risk assessment tools, such as PIPESAFE or other software, can be used to calculate individual and societal risks of pipelines transporting hydrogen blends [20].

In Step 2, three scenarios involving experimental and numerical studies on the dispersion, fire, and explosion behaviour related to the accidental release of hydrogen blends from pipelines were identified for further safety analysis (see Section 3). In Step 3, a numerical analysis was performed using CFD codes and engineering models (see Section 4). Each of the three scenarios was taken as a base case to evaluate the hazards related to accidental releases of hydrogen blends from pipelines. The main conclusions of this numerical analysis were the following:

- Scenario 1: Outdoor pipeline leaks in rural areas (see Section 5)

The pipeline release in a free open space examined in Reference [15] was taken as the benchmark case for a sensitivity study. The key findings of the present study are:

- The addition of hydrogen in natural gas pipelines did not largely affect the potential hazards associated with accidental releases with blending ratios up to 20% H₂

- (e.g., leak rate, flame length, heat flux, explosive mass, and overpressure) at a given pipeline pressure and leak size. This observation is consistent with the literature finding [2, 4, 9-11]. It also suggests that the existing natural gas pipeline infrastructure could require minimal modifications for hydrogen blends up to 20%.
- Increasing the hydrogen content in the blends led to a decrease in the overall density due to the lower molar weight of hydrogen. To maintain the same volumetric energy content in the pipeline, pressure must also increase. Above 20% blending ratios, this raise in pressure increased the severity of hazards (leak rate, flame length, explosive mass, heat flux, and overpressure) at a given volumetric energy content.
 - Without adequate mitigation measures, a higher pipeline pressure could increase the risk of fire and explosion, therefore, the effect of elevated pipeline pressure needs to be carefully considered for blending ratios greater than 20% hydrogen.
- Scenario 2: Outdoor pipeline leaks in urban areas (see Section 6)
- The pipeline release and interaction with the surroundings in an open atmosphere presented in Reference [18] was taken as the benchmark case for a sensitivity study. The key findings of the present study are:
- The simulations showed that for 100% H₂, the jet plume dispersed more quickly from the source due to the greater density difference between hydrogen and air when compared to 100% CH₄. The flammable cloud of the 100% H₂ case also occupied a larger area due to the wider hydrogen flammability limit. However, the total flammable mass for methane (CH₄) was larger than hydrogen due to higher methane density, but the total energy released in a potential explosion was still higher for 100% H₂ than 100% CH₄ due to higher hydrogen heat of combustion.
 - When hydrogen blends are considered, the volume of flammable cloud for up to 20% H₂ was similar to that of 100% CH₄, suggesting that the risk of fire and explosion for hydrogen blends up to 20% is similar to 100% CH₄. However, when the hydrogen blending ratio is greater than 20%, there is a potential for larger accumulation of flammable gas near the ground and in between the buildings mainly due to the increase in the flammability limit range of the mixture, potentially increasing the risk of fire and explosion if mitigating measures are not applied.
- Scenario 3: Indoor pipeline leaks (see Section 7)
- The pipeline release in a closed atmosphere presented in Reference [17] was taken as a reference case for a sensitivity study. The key findings of the present study are:
- Without ventilation, the fuel rises to the ceiling as a plume, spreads laterally and downwards, and entirely fills the space. The fuel concentration can exceed the low flammability limit (LFL) at the ceiling under the given modelling conditions. However, ventilation was effective in reducing the maximum fuel concentration to levels below the LFL.

- At the same volumetric leak rate, the fuel distribution in the enclosure, and the maximum fuel concentration at the ceiling, were the same for different hydrogen blending ratios, suggesting the maximum fuel concentration would be greater when a higher pipeline pressure (higher leak rate) is applied depending on the design pressure of end user appliances. Nonetheless, the risk can be mitigated with sufficient ventilation.

It should be noted that the distribution of a buoyant gas in an enclosure depends on the leak rate, momentum and buoyancy fluxes, volume of the enclosure, location of the leak, and ventilation conditions.

The next sections describe the safety aspects of hydrogen blends in pipelines, including a detailed discussion of the literature experimental and numerical studies on hydrogen blends in pipelines, details on the three scenarios selected for further numerical analysis, and the numerical simulation of these cases along with discussions and their relevance to safety. It should be noted that the simulation results presented in this report are intended to provide a qualitative view of the potential hazards for hydrogen blends. Specific conditions are required for quantitative analysis.

2. Safety Aspects of Hydrogen Blends in Pipelines

Hydrogen has different physical and chemical properties than natural gas, that is, much lower density, smaller molecular size, lower ignition energy, and wider flammability limits [21, 22]. When hydrogen is added to natural gas pipelines, the energy content by volume of the mixture decreases. Therefore, to achieve the same volumetric energy content would require a higher volumetric flow rate, and therefore, a higher operating pressure [9-11, 21, 23].

Before injecting hydrogen into natural gas infrastructure, it is necessary to review the safety considerations for this change, and mitigate the risks associated with the introduction of hydrogen, including leaks and embrittlement as well as potential for fire and/or explosion [5]. A good understanding of the hazards associated with hydrogen blending is important for the transportation of hydrogen in natural gas pipelines.

Concerning the safety of hydrogen blending in natural gas pipelines, analysis has shown that the risk of fire and explosion can be reduced significantly with appropriate mitigation measures in case of leaks or ruptures [2, 6, 22]. Leaks and/or ruptures can occur due to corrosion failure, natural forces (e.g., floods, winds, snow/ice accumulation), excavation damage, equipment failure, incorrect operation, and other outside forces (e.g., vandalism, terrorism, and theft) [24, 25]. Leaks can also occur due to hydrogen embrittlement, which decreases the pipeline material toughness, leading to brittle fracture [2, 21, 23, 26].

The event sequence diagram presented in Figure 1 explains the possible consequences of a pipeline leak [27, 28]. The first outcome can be categorized as an unignited release, which can occur if a leak is detected and isolated before ignition. If the leak is not isolated, there is the potential for an immediate ignition at the break, resulting in a jet fire. When immediate ignition does not occur, hydrogen blends can mix with air, forming a flammable cloud. Delayed ignition in such a cloud can result in fire or explosion.

The literature review conducted in this project was focused on the topics relevant to the above hazard events. The numerical analysis was also focused on characterizing the dispersion, jet fire and explosion behaviour involving the accidental release of hydrogen blends from pipelines.

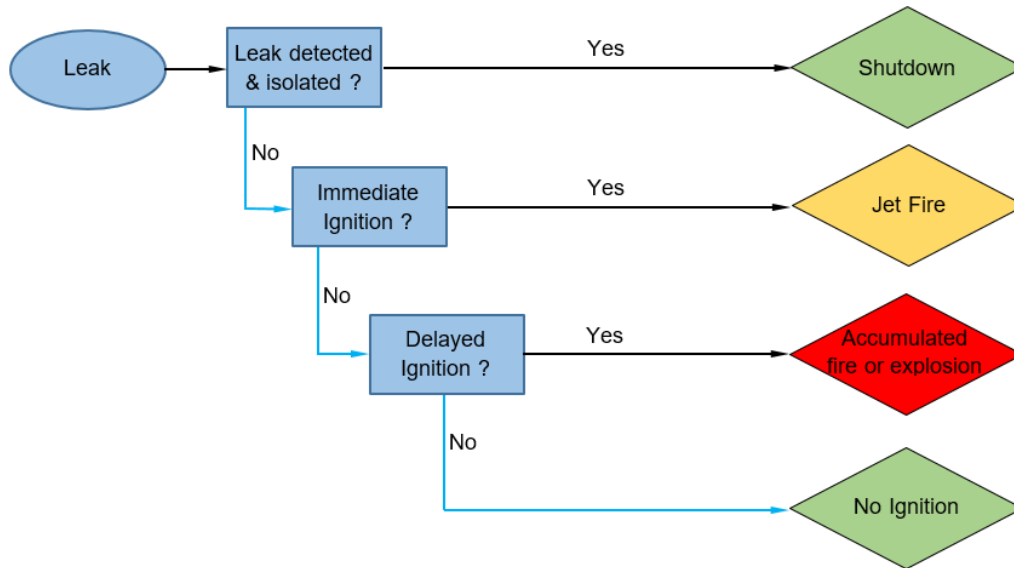


Figure 1: Event sequence diagram following a hydrogen leak [28].

3. Review of Studies on Hydrogen Blends Releases from Pipelines

3.1 Gas Dispersion

3.1.1 Open Environment

Wilkening and Baraldi [18] analyzed the safety aspects of high-pressure hydrogen and methane pipeline ruptures using a CFD software (CFD-ACE). The authors investigated dispersion effects due to different properties of hydrogen and methane, such as density, diffusivity, viscosity, and flammability limits. The model geometry and velocity field are shown in Figure 2.

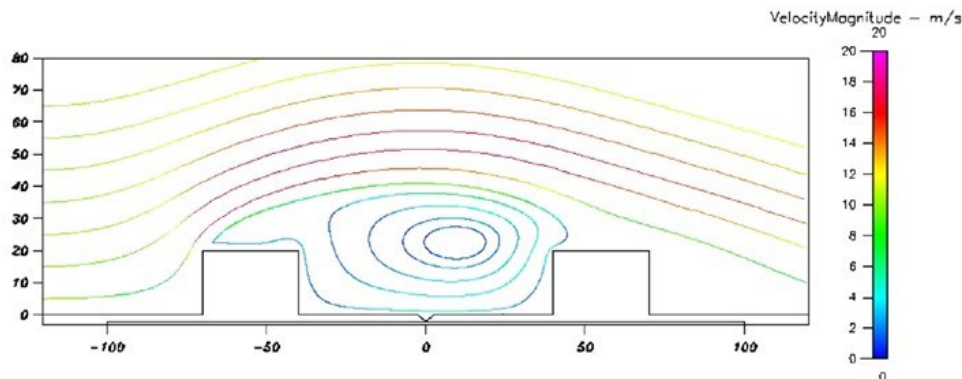


Figure 2: CFD model geometry (240 m wide and 80 m high) showing velocity field for hydrogen natural dispersion. Two 30 m wide and 20 m high structures representing factory buildings were placed in the domain, from Ref. [18].

The pipeline was filled with either methane or hydrogen at a pressure of 1.1 MPa. The leak had a diameter of 0.2 m, and it was located at $x = 0$ m. Below the ground level, a pipeline (–10 and +100 m long, 1 m diameter) was modelled as the leak source. Two wind profiles were chosen, i.e., with wind (10 m/s) and without wind (0 m/s).

Figure 3 compares the effect of wind on gas concentration profiles for methane release. With wind (Figure 3a), the methane cloud recirculates at lower elevations, resulting in the accumulation of flammable methane-air mixtures close to the ground and near the buildings, creating conditions for ignition. With no wind (Figure 3b), the regions with methane concentrations in the flammability range are located mostly far from the ground and above the building, which reduces the risk of ignition.

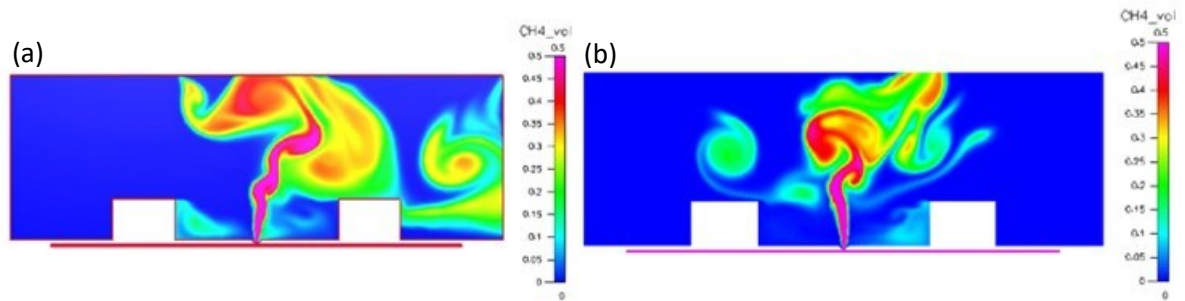


Figure 3: Concentration profile for methane release at 7.5 s: (a) with wind (10 m/s) and (b) without wind (0 m/s), from Ref. [18].

Figure 4 shows the simulation results for the hydrogen release. Hydrogen is more buoyant than methane. Therefore, even with wind (Figure 4a), less flammable hydrogen-air mixtures were found near the ground and buildings. With no wind (Figure 4b), hydrogen moves upwards due to buoyancy. However, in both conditions, the hydrogen release results in a more flammable mixture when compared to methane due to the wider flammability limits of hydrogen.

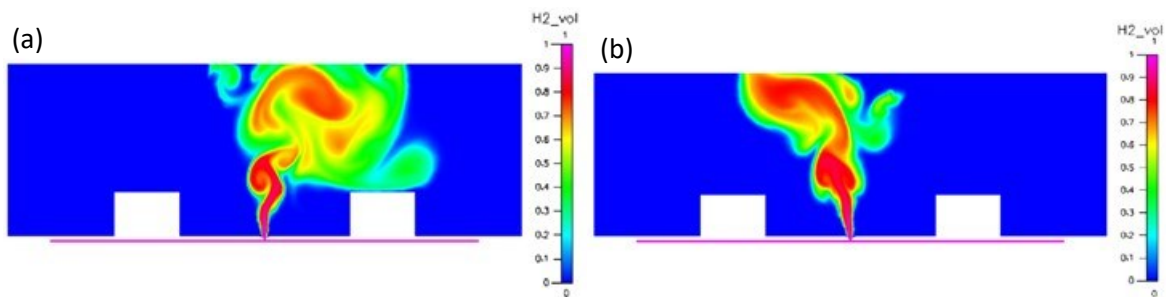


Figure 4: Concentration profile for hydrogen release at 4 s: (a) with wind (10 m/s) and (b) without wind (0 m/s).

Tong et al. [29] conducted 3D large-scale simulations on FLACS software of gas leakage in a hydrogen blended natural gas station. The computational domain is $100 \times 62 \times 40$ m. The study aimed to evaluate the impact of pipeline pressure and leakage direction on the accident consequences. Two scenarios were simulated: gas leakage and gas cloud explosion. A 20% hydrogen concentration was introduced to the natural gas station, with a leakage rate varying from 12.70 to 50.79 kg/s and wind speed at 2 m/s. Figure 5 shows the 3D model domain of the gas station.

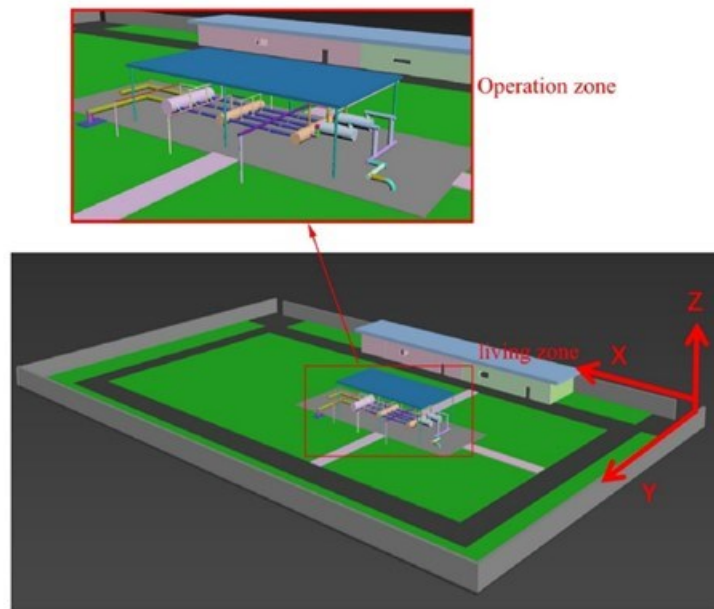


Figure 5: 3D model domain of the gas station during a hydrogen blend leak [29].

Figure 6 shows the evolution of flammable gas clouds for hydrogen blend release at two different pipeline pressures. When the leak started, the blended gas mixed with air, creating a flammable gas cloud, which expanded towards the living zone. Under the same leakage conditions (i.e., same leak size), a higher pressure led to a greater leak rate, which increased the accumulation of flammable gas, causing a higher explosion intensity. The ignition of the flammable cloud triggered a rapid explosion and created a local high-pressure area. The peak explosion overpressure increased from approximately 6 kPa to 16 kPa when the pipeline pressure increased from 1 to 4 MPa.

Zhou et al. [30] conducted a 3D CFD simulation using FLACS software of urban streets (70 m long traffic) to study the dispersion and explosion characteristics of hydrogen-blended natural gas with hydrogen concentrations varying from 10-100%, leakage rates from 1.95 to 5.27 kg/s, pressures equal to 0.4 MPa, and wind speed from 0 to 7 m/s. The hydrogen blending ratio and ambient wind speed were analyzed to check the consequences of explosions. Figure 7 shows the 3D model domain of urban streets.

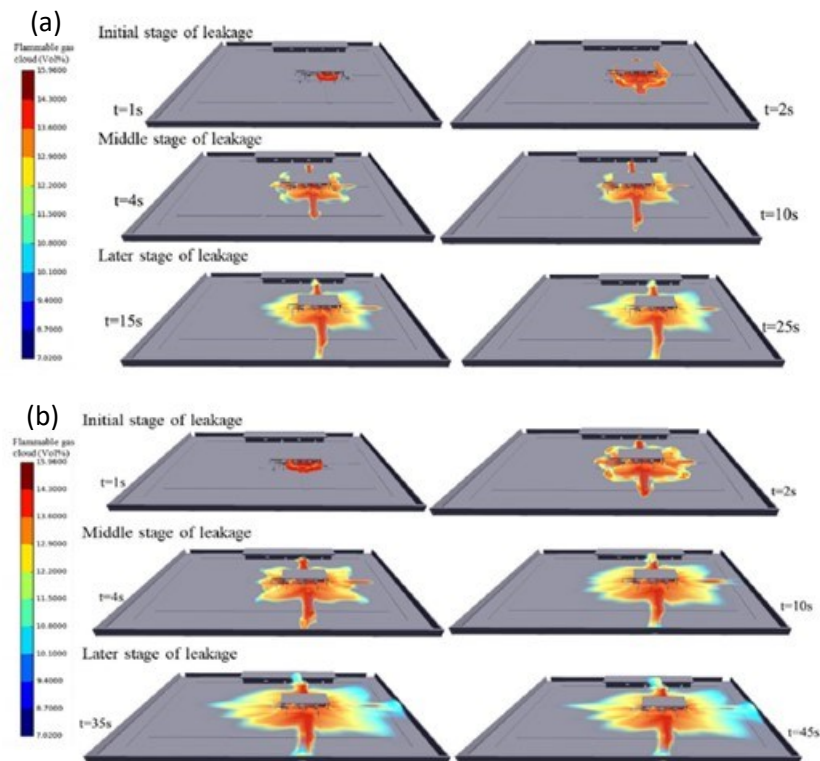


Figure 6: Flammable gas cloud at (a) 1 MPa and (b) 4 MPa [29].

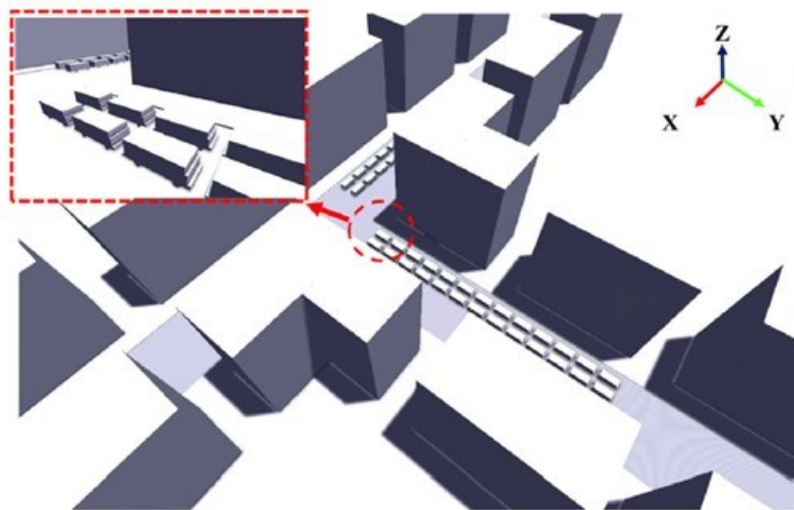


Figure 7: 3D model domain of urban streets with 70 m long traffic [30].

Figure 8 shows the dispersion of a flammable cloud with a 50% hydrogen blending ratio. The dispersion path of the cloud changes depending on the traffic flow and obstacles. High traffic levels led to more serious explosion accidents. The effect of wind was important, as it kept the flammable cloud near the vehicle due to recirculation, creating conditions for ignition. An increase in hydrogen blending ratio beyond 40% resulted in a rapid increase in the maximum overpressure.

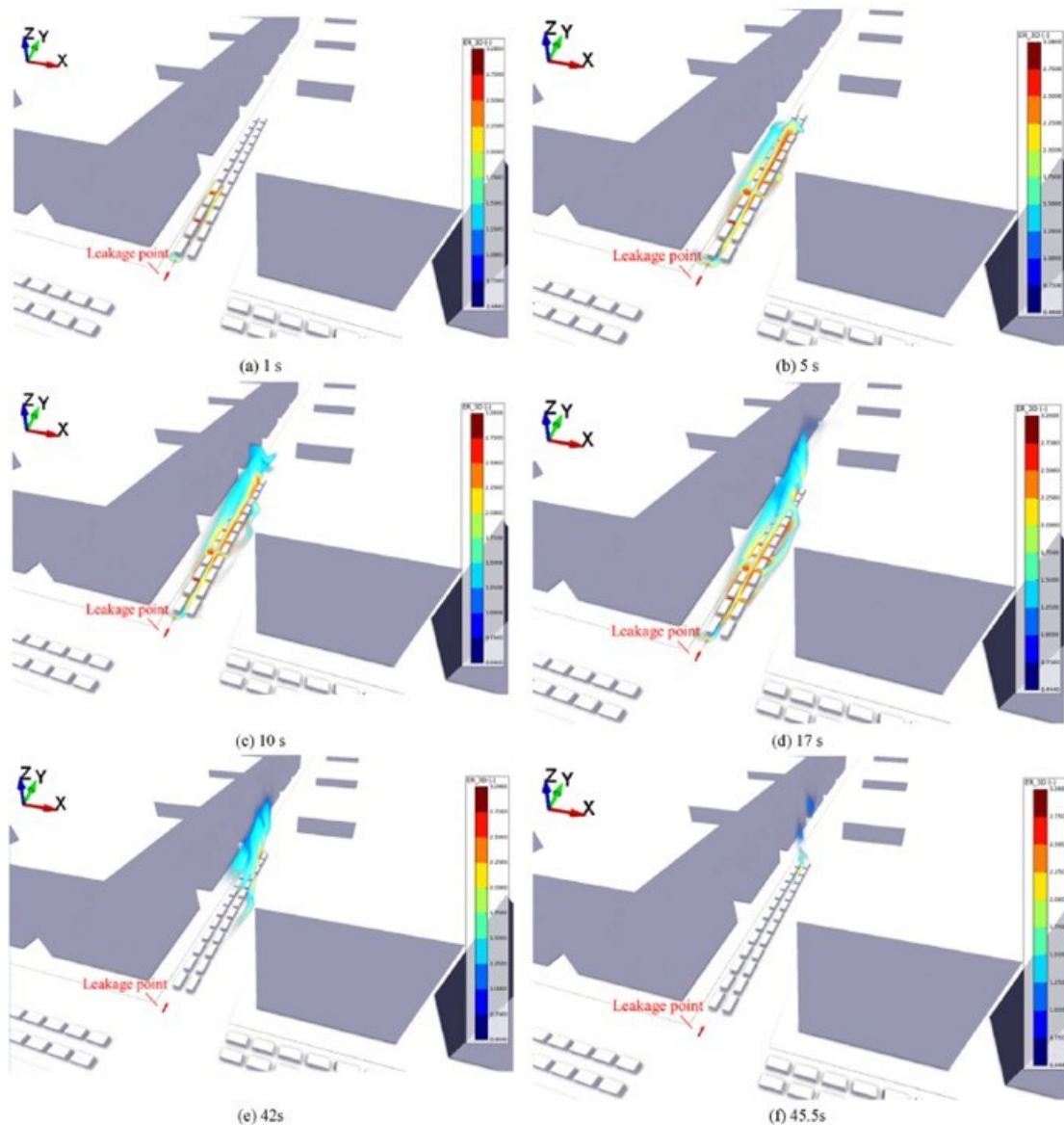


Figure 8: Distribution of flammable cloud with 50% hydrogen blending ratio [30].

When the hydrogen blending ratio increased from 0% to 40%, the maximum explosion overpressure increased 6.5 times without the effect of wind. With a wind speed of 3 m/s, the maximum explosion overpressure increased 2.3 times. When the hydrogen blending ratio is greater than 40%, the maximum overpressure of the explosion increases almost exponentially with the increase of the hydrogen blending ratio (Figure 9).

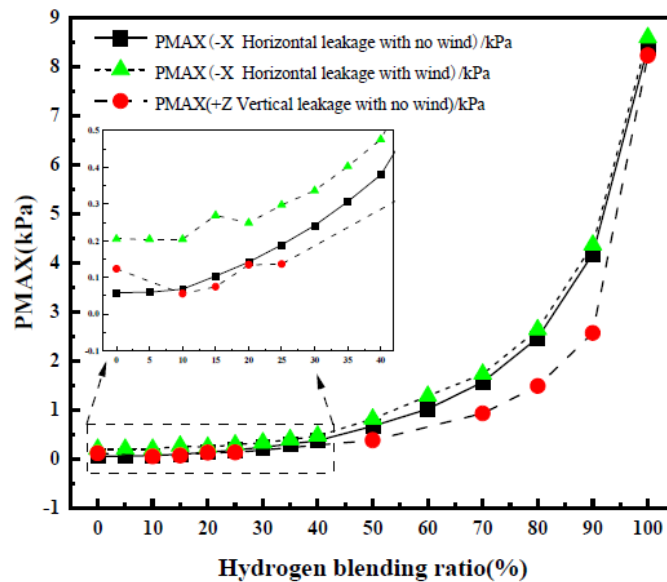
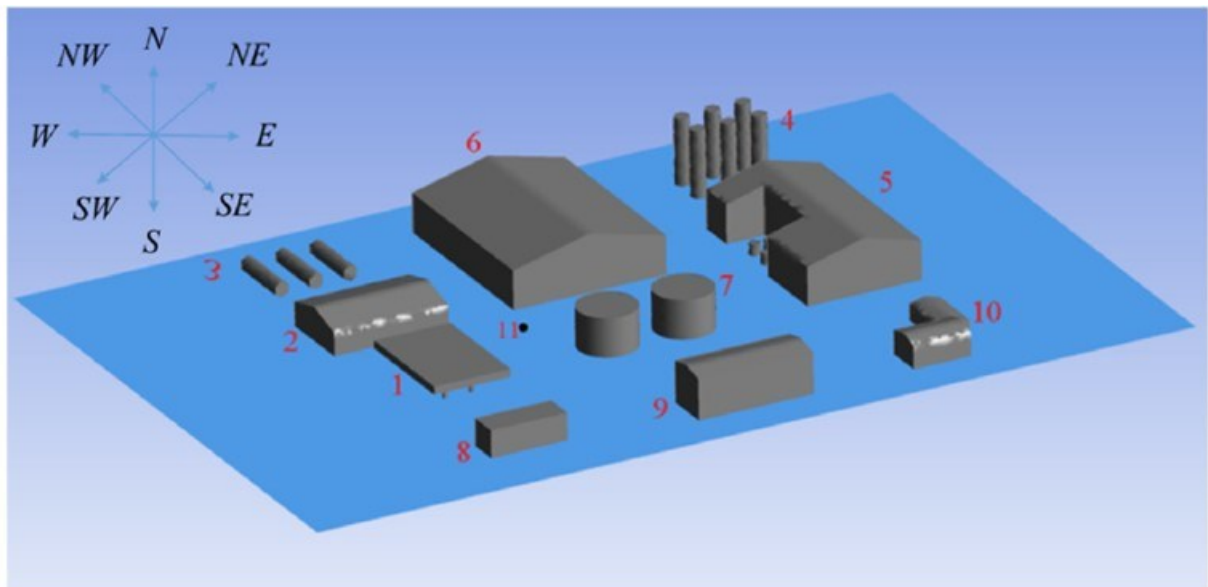


Figure 9: Maximum explosion overpressure versus hydrogen blending ratio [30].

Li et al. [31] performed 3D CFD simulations of the dispersion of hydrogen blends released from transmission pipelines into a gas mixing station. Figure 10 shows the model domain (230×150×50 m) for the hydrogen blending mixing station.



1 - hydrogen receiving station, 2 - hydrogen process workshop, 3 - hydrogen tank area, 4 - natural gas tank area, 5 - natural gas process workshop, 6 - hydrogen-enriched natural gas process workshop, 7 - hydrogen-enriched natural gas tank area, 8 - power distribution room, 9 - hydrogen-enriched natural gas distribution station, 10 - fire pump room, 11 - gas release location (leak diameter of 700 mm)

Figure 10: 3D model domain for a hydrogen blended mixing station [31].

The simulations were performed with different hydrogen blending ratios from 5 to 30%, leak rates from 87.69 to 131.53 kg/s, and wind speeds from 1.5 to 15.5 m/s in various directions.

Figure 11 and Figure 12 show an example of the development of methane and hydrogen flammable gas clouds for 15% hydrogen blending ratio at a release rate of 109.61 kg/s and a wind speed of 5.28 m/s. The LFL is 5% for methane and 4% for hydrogen. The flammable gas cloud is represented by the LFL iso-surface for each gas. In the early stage of release and dispersion, flammable gas is sprayed out in the form of a high-speed jet. The surrounding air mixes with flammable gas and disperses under the action of wind. The cloud size reaches a steady state after 30 s for methane, but 2 s for hydrogen. The flammable gas cloud for hydrogen is smaller because of the lower hydrogen content in the mixture.

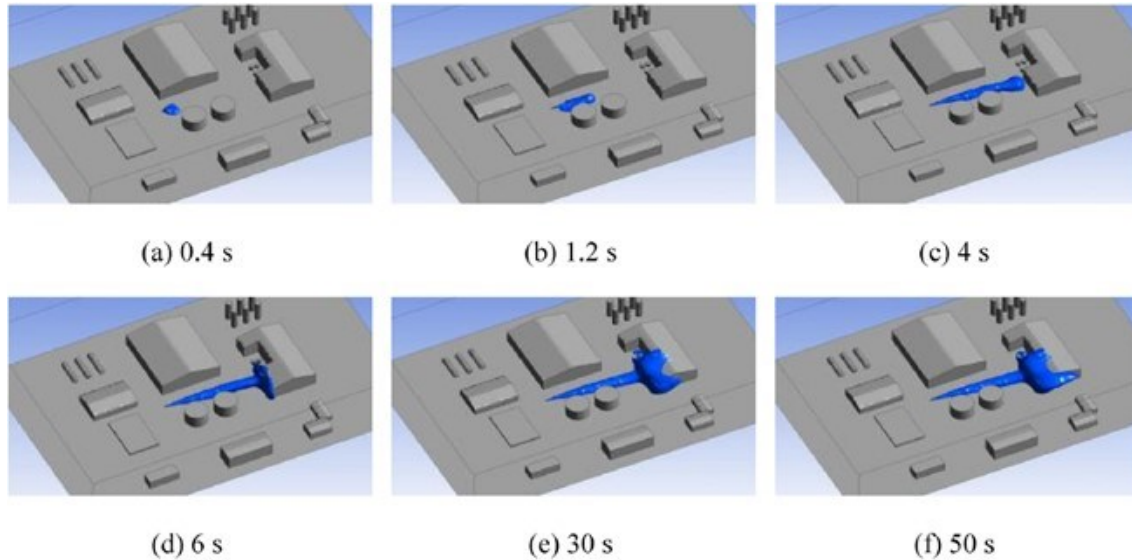


Figure 11: Development of flammable methane gas cloud (5% methane iso-surface, 109.61 kg/s release rate, 5.28 m/s west wind, 15% hydrogen blending ratio) [31].

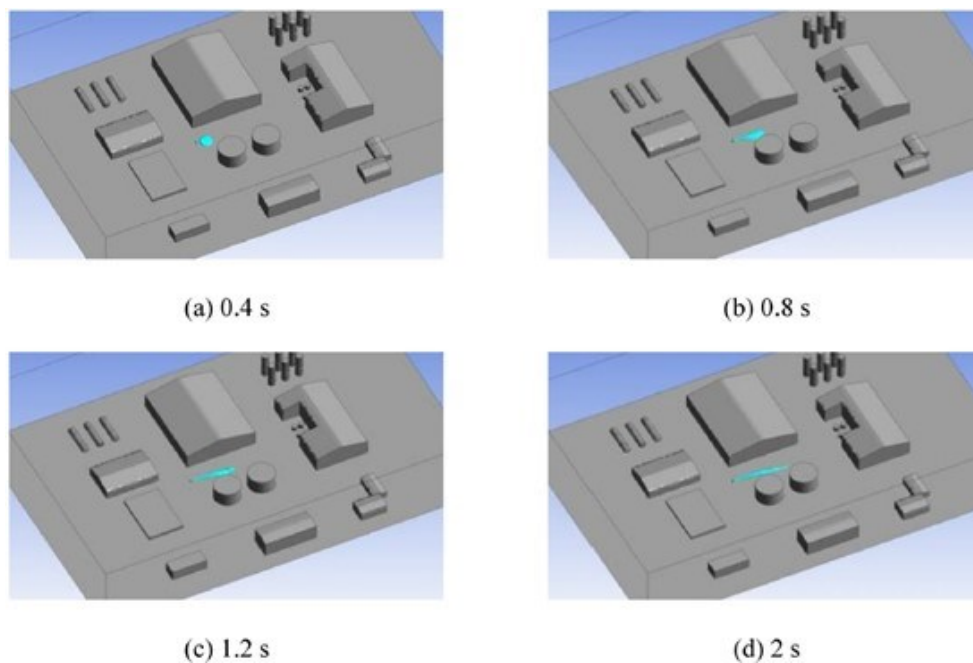


Figure 12: Development of flammable hydrogen gas cloud (4% hydrogen iso-surface, 109.61 kg/s release rate, 5.28 m/s west wind, 15% hydrogen blending ratio) [31].

The effect of the blending ratio on the steady-state flammable gas clouds is shown in Figure 13 for methane and Figure 14 for hydrogen. The shape and location of the flammable clouds are very similar for methane at different blending ratios, whereas the flammable gas cloud for hydrogen increases significantly at a larger blending ratio. Therefore, the hydrogen blending ratio has a large influence on the dispersion of flammable hydrogen clouds.

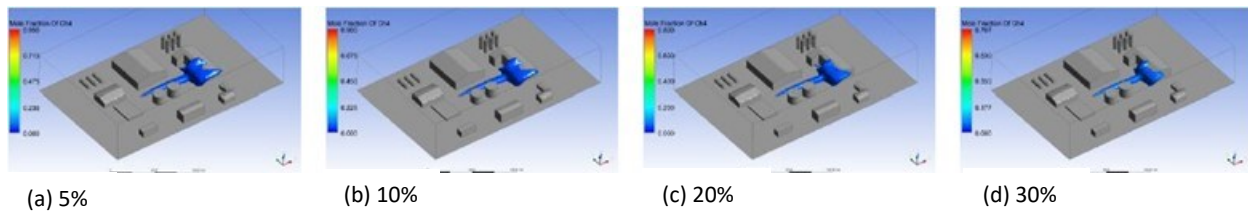


Figure 13: Steady-state methane flammable clouds at different blending ratios (109.61 kg/s release rate, 5.28 m/s west wind) [31].

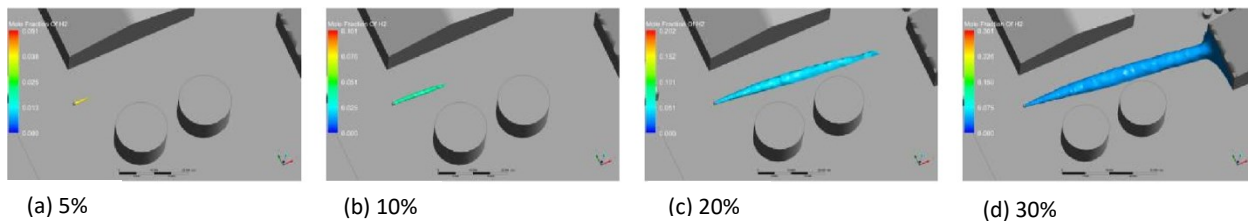


Figure 14: Steady-state hydrogen flammable clouds at different blending ratios (109.61 kg/s release rate, 5.28 m/s west wind) [31].

3.1.2 Closed Environment

Sun et al. [32] conducted 3D simulations using ANSYS Fluent to examine the leakage and dispersion of hydrogen-methane blended natural gas into an indoor environment (Figure 15). The hydrogen blended mixture dispersed from the leak hole (5 mm diameter) into the indoor environment with both the door and window closed. The blending ratio varied from 5 to 23% hydrogen. The distribution of methane and hydrogen and the effects of the hydrogen blending ratio on the flammable volume of gas mixture were investigated.

At ambient temperature and pressure, the density of methane and the density of hydrogen are both lower than air. When the blended gas is released, the jet is sprayed horizontally first, then impacts the wall and mixes with air. The gas mixture then moves upward due to buoyancy, accumulates in the ceiling, and then expands downward. Figure 16 shows an example of the accumulation of flammable gas for a continuous release of 20% hydrogen blended gas. At 300 s, the upper volume is filled with a flammable methane-air mixture, while the envelope of flammable hydrogen is much smaller because there is only 20% hydrogen in the blended mixture, and hydrogen quickly mixes with air. The effect of the blending ratio on the flammable volume of the blended gas mixture is shown in Figure 17. The flammable volume increases rapidly during the initial release, growing faster for a larger blending ratio. After 180 s, the

flammable volume is smaller for a larger blending ratio because methane contributes a major portion of the flammable volume.

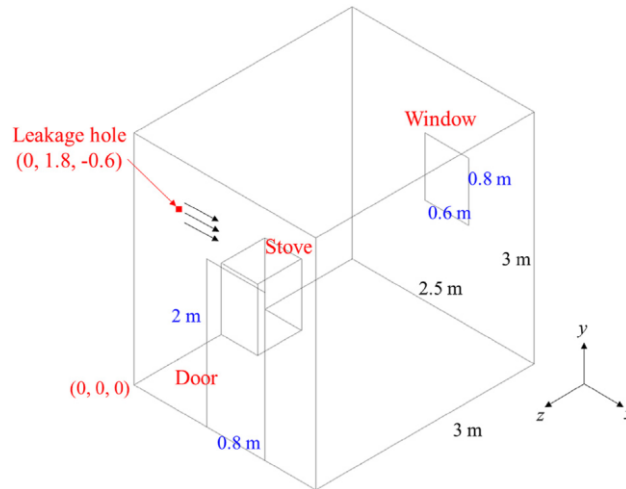


Figure 15: 3D model domain of an indoor environment [32].

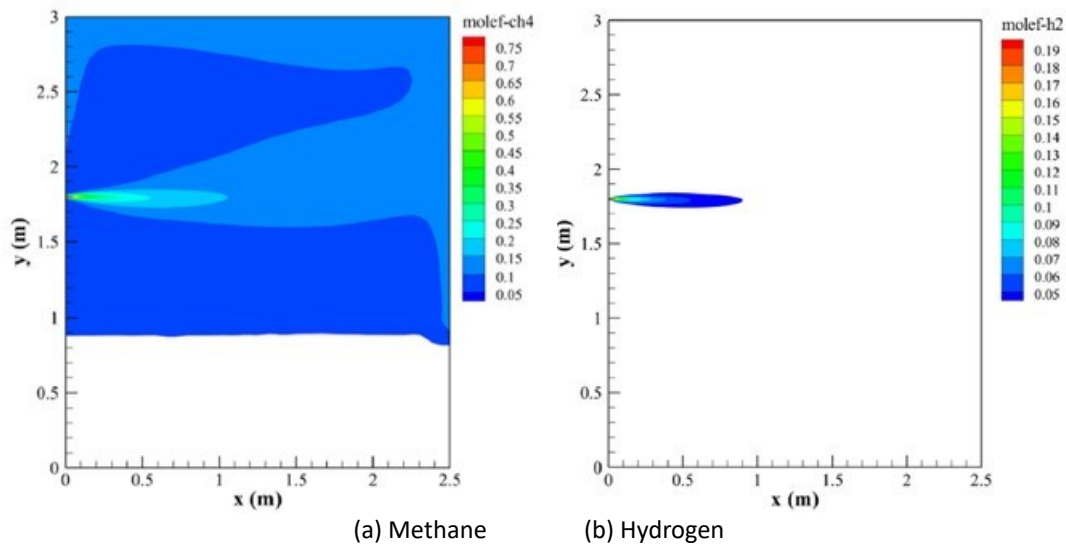


Figure 16: Gas distribution of indoor leak of 20% hydrogen blended gas on $z = -0.6$ m plane at 300 s for (a) methane and (b) hydrogen [32].

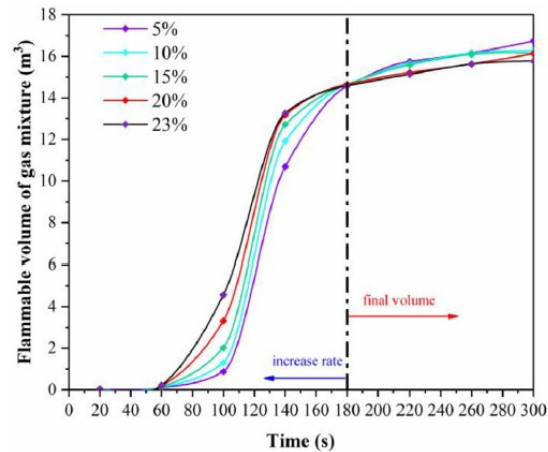


Figure 17: Effect of blending ratio on flammable volume of blended gas mixture [32].

Su et al. [17] performed 3D numerical simulations using ANSYS Fluent to analyze the leakage and diffusion characteristics of hydrogen-blended natural gas in a real domestic kitchen. The 3D model domain is presented in Figure 18. It was assumed that the leaks come from a gas stove with leak rates varying between 5.5×10^{-5} and 2.7×10^{-4} kg/s and gradually fill the kitchen space through diffusion and convection. In this study, the concentration distribution of flammable gas, explosion risk area, and alarm response time were analyzed. As the blending ratio varied from 2.5 to 20% hydrogen, the LFL of blended gas decreased slightly from 4.97 to 4.76%.

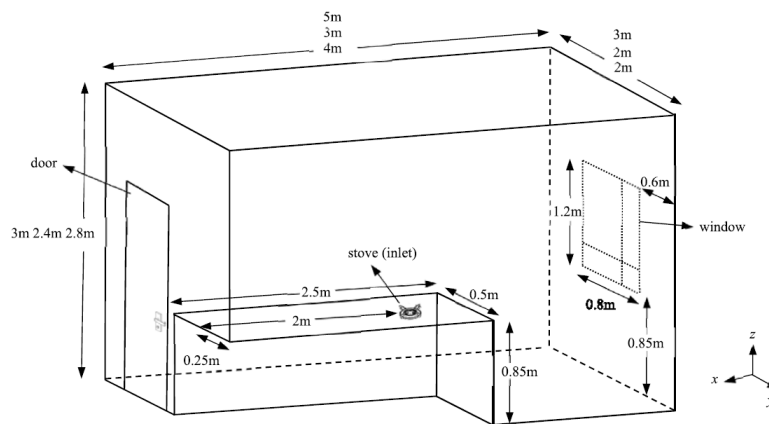


Figure 18: 3D model domain of a domestic kitchen [17].

Figure 19 shows an example of accumulation of flammable gas in the kitchen during a release of 10% hydrogen blended gas at 5.5×10^{-5} kg/s. Initially the flammable concentration was located above the leak hole. Over time, the concentration gradually tends to be uniform, and a combustible cloud was accumulated in the kitchen ceiling.

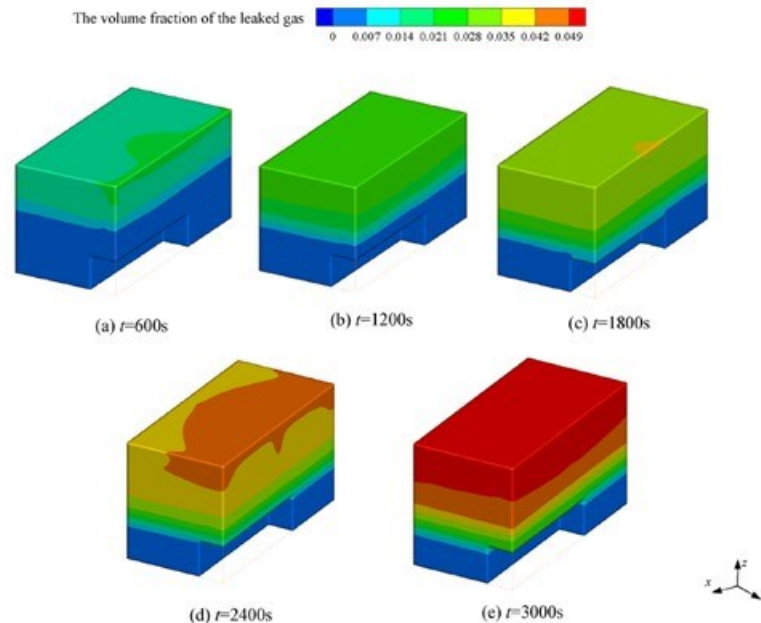


Figure 19: 3D concentration distribution of the hydrogen blended gas at different times in a domestic kitchen (5.5×10^{-5} kg/s leak rate, 10% hydrogen blending ratio, no ventilation) [17].

This flammable gas accumulation triggered the alarm, closing the leakage source and opening the door and window at the same time to create natural ventilation. The flammable cloud quickly dispersed out of the kitchen. Therefore, natural ventilation was efficient in removing the flammable cloud.

3.2 Fire and Explosion

Ramachandran and Hecht [33] studied the dispersion, ignition, and flame characteristics of blended jets of hydrogen and methane at near-atmospheric pressure. The release rate was fixed at 0.75 L/min, and the nozzle diameter was fixed at 1 mm. Five mixtures with blending ratios of 0, 25%, 50%, 75%, and 100% were tested. The results indicated that the flame height was reduced at higher blending ratios (Figure 20) due to the increase in flame speed of hydrogen, which caused an increase in fuel consumption (i.e., the products are consumed near the nozzle), confining the flame to a shorter region.

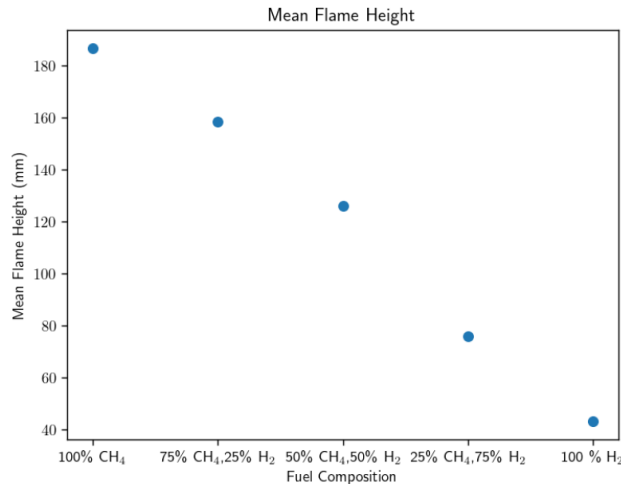


Figure 20: Mean flame height for different hydrogen blends [33].

He et al. [34] experimentally measured the temperature profile of a hydrogen blended jet fire (maximum 12% hydrogen) under free fire and wall fire (sidewall restricted), as depicted in Figure 21. Different hydrogen blend ratios (0-12%), nozzle diameters (4-9 mm), and fire heat release rates were considered in the experimental conditions. It was found that the wall fire temperature was higher than that in the free fire at a fixed height. The temperature along a vertical line above the nozzle increased when the hydrogen blend ratio increased while the flame height decreased.

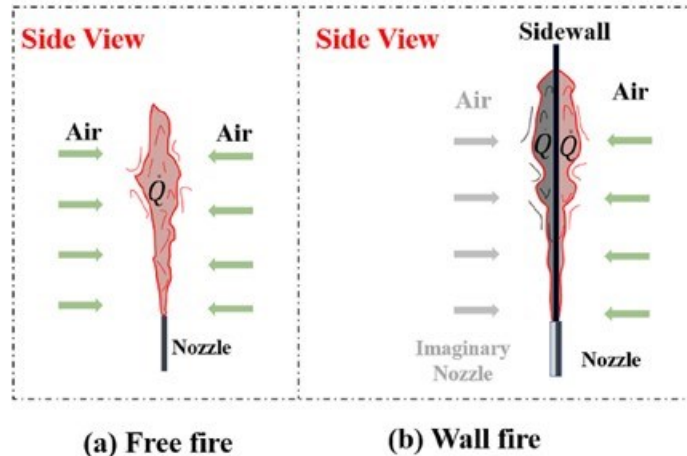


Figure 21: Air entrainment for free and wall hydrogen blends fire [34].

It was found that the vertical temperature increased with increasing volume flow rate, and the wall fire vertical temperature was higher than the free fire vertical temperature with a maximum difference of 140 °C. Moreover, the sidewall restricted the wall fire flames, resulting in higher flames than those of free fire. This behaviour was related to the restriction of air entrainment at one side, which had a significant influence on the flame height (Figure 22).

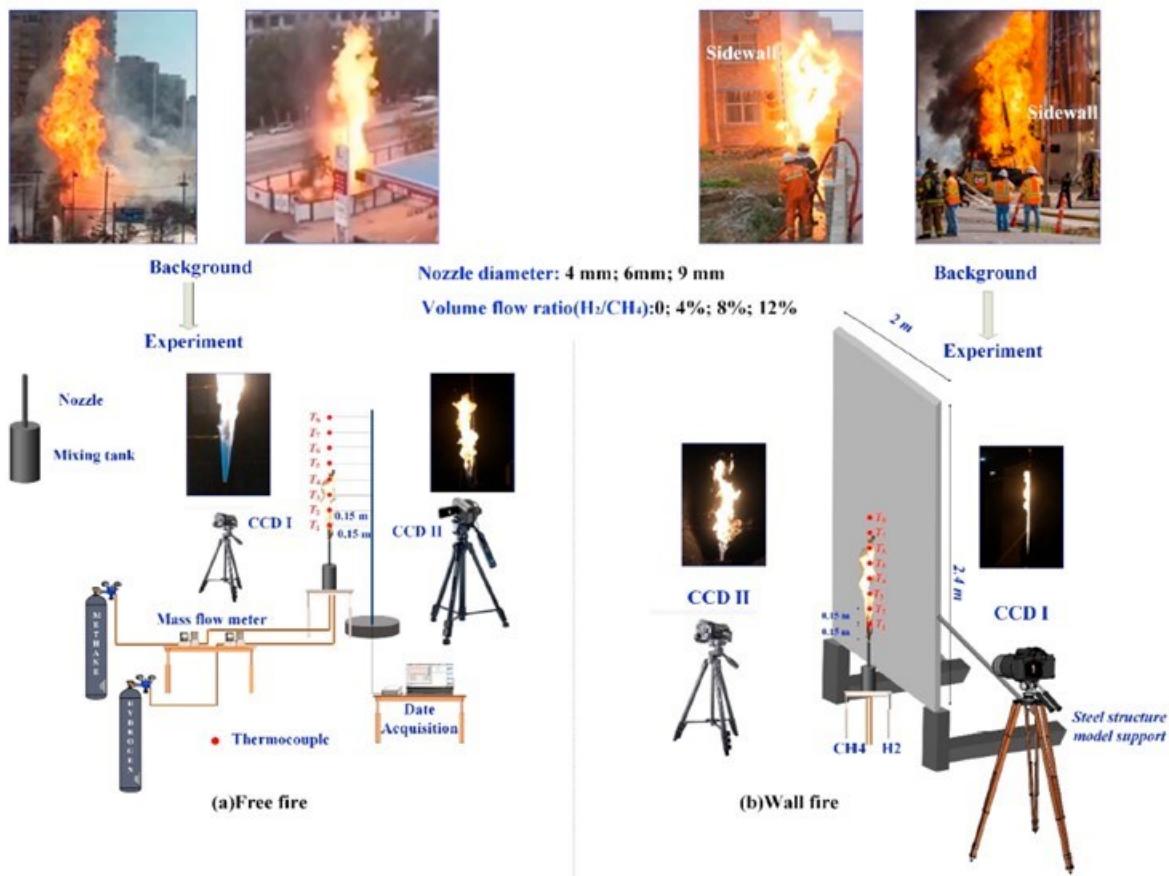


Figure 22: Flame length for free and wall hydrogen blends fire [34].

Lowesmith and Hankinson [15] conducted two large-scale experiments to study the complete rupture of high-pressure transmission pipelines (150 mm diameter, 7 MPa) carrying a methane/hydrogen mixture with approximately 22% hydrogen (Test 1) or 100% methane (Test 2). The leak rates varied from 150 to 215 kg/s from a 150 mm leak diameter. The wind speed varied from 1.2 to 2.1 m/s. Thermal radiation and overpressure due to gas ignition were measured.

Test 1 resulted in an immediate ignition of the hydrogen/methane mixture after rupture of the pipeline (Figure 23). The ignited mixture expanded quickly and formed a fireball of 46-56 m height after 4 s. The fireball burned out, but the flame length continued to increase, reaching 100 m height, between 5 and 8 s. A jet fire was formed, which gradually decreased in length with time. The flame was vertical due to negligible wind effects.

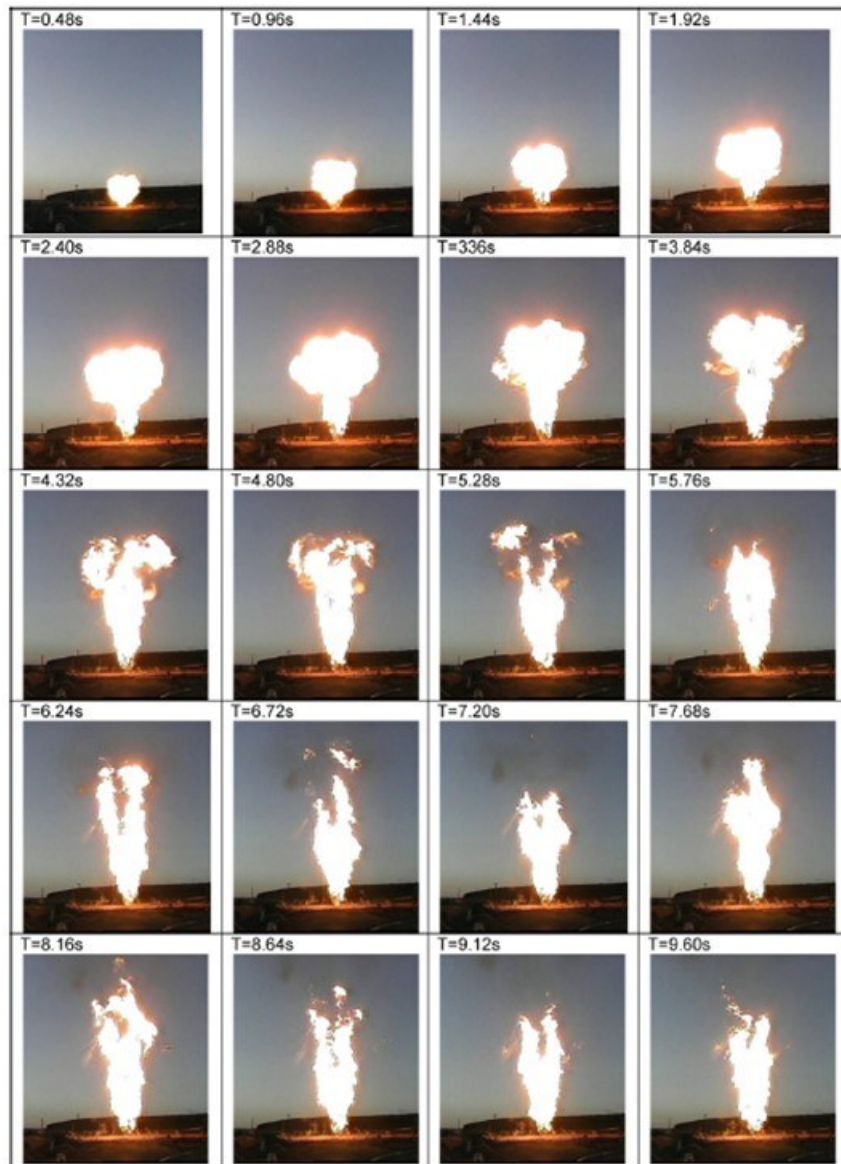


Figure 23: Test 1 - Flame profile during ignition of the methane-hydrogen mixture [15].

Test 2 was ignited as soon as the pipeline was ruptured to compare with Test 1. The ignited mixture expanded quickly, forming a fireball with 41–56 m height after 4 s (Figure 24). The fireball also burned out, but the flame length continued to increase, reaching 100 m height at 5.5 s. The effect of wind tilted the flame. Therefore, the results of both tests showed that the addition of hydrogen to methane resulted in little difference in flame dimensions. The measured heat radiated demonstrated no difference between methane and the methane/hydrogen mixture. Moreover, there was no significant difference between the overpressures generated in the two experiments.

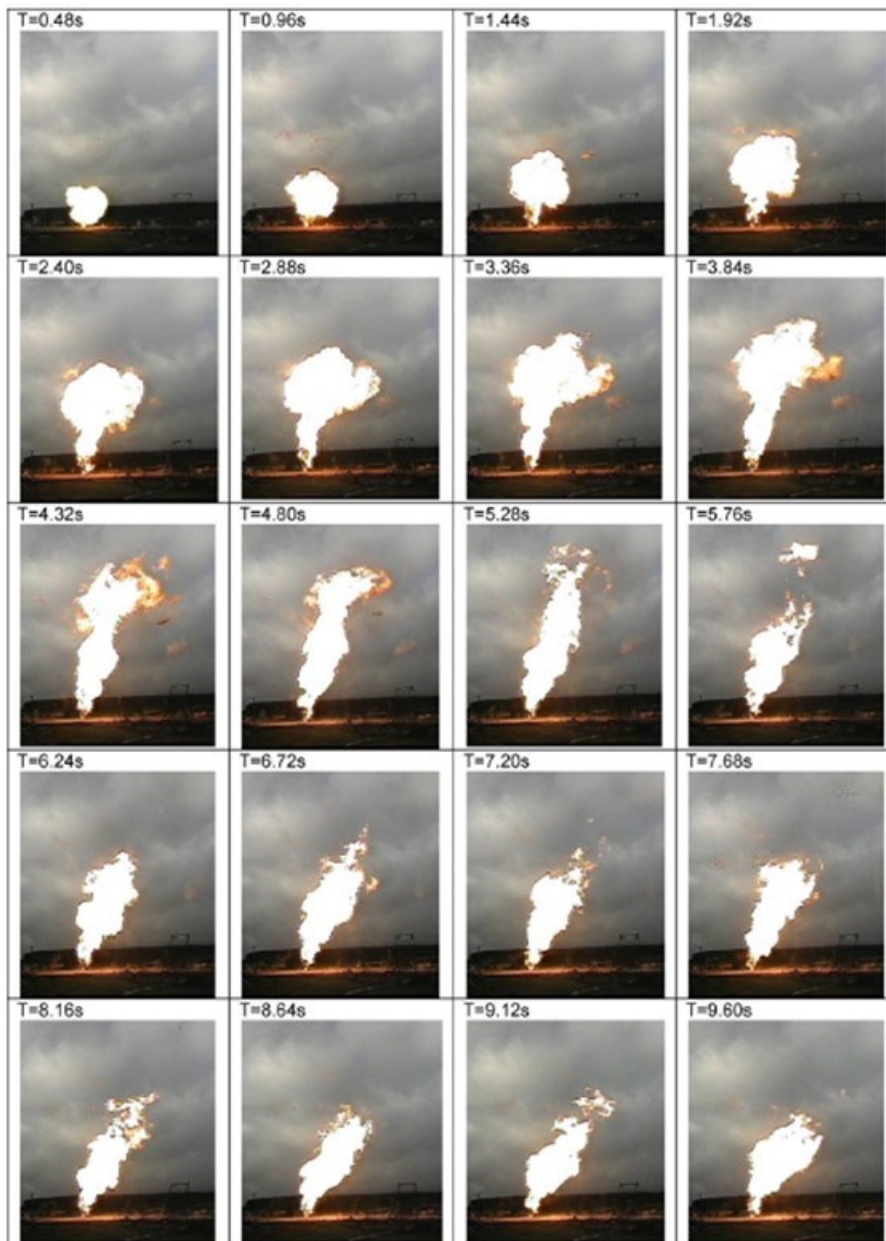


Figure 24: Test 2 - Flame profile during ignition of methane only [15].

Lowesmith and Hankinson [16] also performed six large-scale high-pressure horizontal jet fire experiments at 6 MPa (20, 35, and 50 mm leak diameter) using methane (3 tests) and methane/hydrogen (3 tests) mixtures (24% hydrogen). The leak rates varied from 2.7 to 18.4 kg/s, and the wind speed varied from 1.7 to 6.3 m/s. The experiments measured the flame length and the incident radiation field from the fire.

The flames for both methane and methane/hydrogen mixture looked very similar and were independent of leak orifice size. The flames were momentum-dominated, with high velocity (turbulent), with some flame tip elevation (Figure 25). However, the flames for the methane/hydrogen mixture were slightly shorter than the methane flames with the same leak

diameter. Moreover, there was no significant difference in the incident radiation field for the two different fuels for comparable leak diameters.

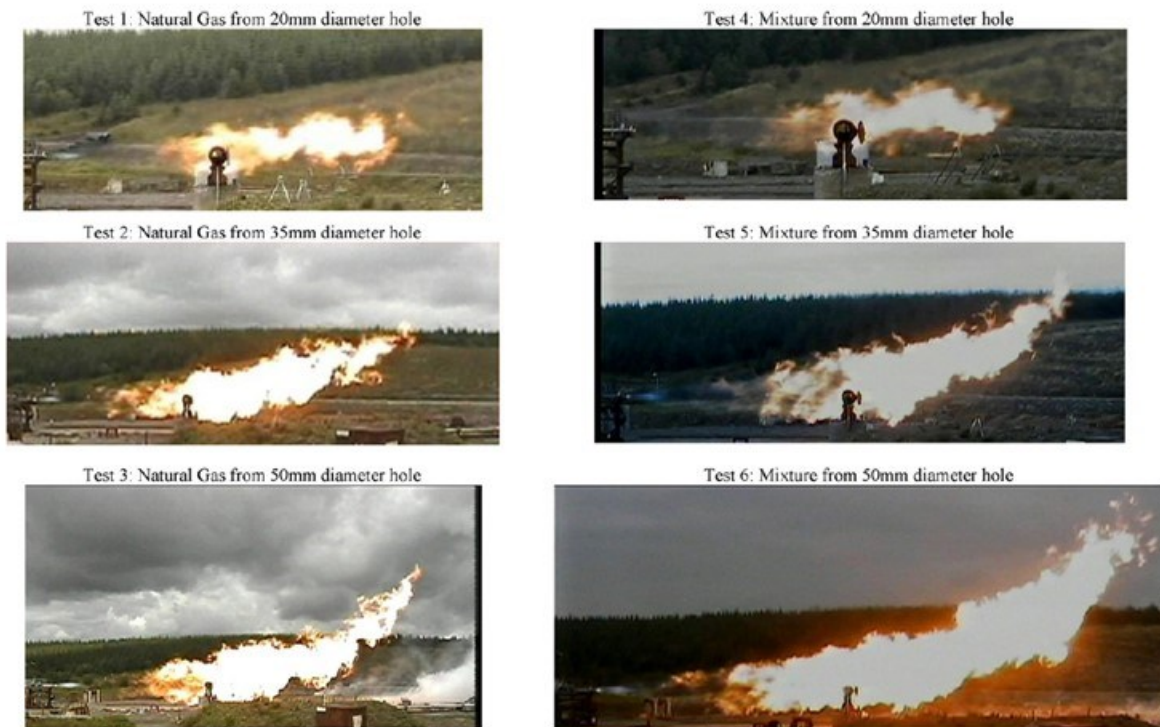


Figure 25: Flame lengths for tests with methane and hydrogen blends [16].

3.3 Risk Analysis

Acton et al. [20] studied the use of PIPESAFE as a software package that contains a range of mathematical models to calculate individual and societal risk. PIPESAFE considered failure cause, frequency, mode, gas outflow, dispersion, ignition, thermal radiation, and thermal effects. Moreover, PIPESAFE includes separate fireball and quasi-steady jet fire (or crater fire) models. All of the consequence models in PIPESAFE have been validated by comparison with results from comprehensive experiments carried out at a large scale.

Wattis et al. [19] studied the Quantitative Risk Assessment (QRA) analysis via the CONIFER risk assessment package for the ATCO Gas and Pipelines Ltd. Project in Canada, which started delivering a 5% blend of hydrogen into natural gas pipelines (Fort Saskatchewan, Alberta). The quantitative risk assessment had the objective to understand any risks associated with the introduction of blended gas into its existing distribution system and to its customers. The authors analyzed the risks associated with hydrogen-blended natural gas at concentrations of 5% and 20% hydrogen, along with the impact of operating pressure. An individual risk (IR) level of 1×10^{-6} per year was used as a reference threshold.

The QRA was divided into two components: gas distribution (mains and services operating at 550 kPa/80 psi) and the end-user (customer meter, internal pipework, and end-use appliances, operating at 1.7 kPa/0.25 psi). Both QRA components considered large-scale (e.g., full line

break) and small-scale (e.g., failed fittings or pinhole leak) releases, the impact of gas migration, housing types (bungalow, semi-detached, detached, multi-attached) and finished vs. unfinished basements. The end-user QRA also considered the impact of the floor plan and the type of end-use appliance (furnace, boiler, cooking range, etc.). The QRA considered the individual risk (IR) from the perspective of fire and explosion and carbon monoxide (CO) poisoning.

The results showed that adding 5% or 20% hydrogen to the natural gas distribution system resulted in an increase in the absolute individual risk relative to natural gas. However, even for the 20% blend, the combined IR for the mains and services was still significantly below the reference criterion (Figure 26). Therefore, there were no significant risks associated with the conversion of the existing natural gas distribution system to a hydrogen blended gas service.

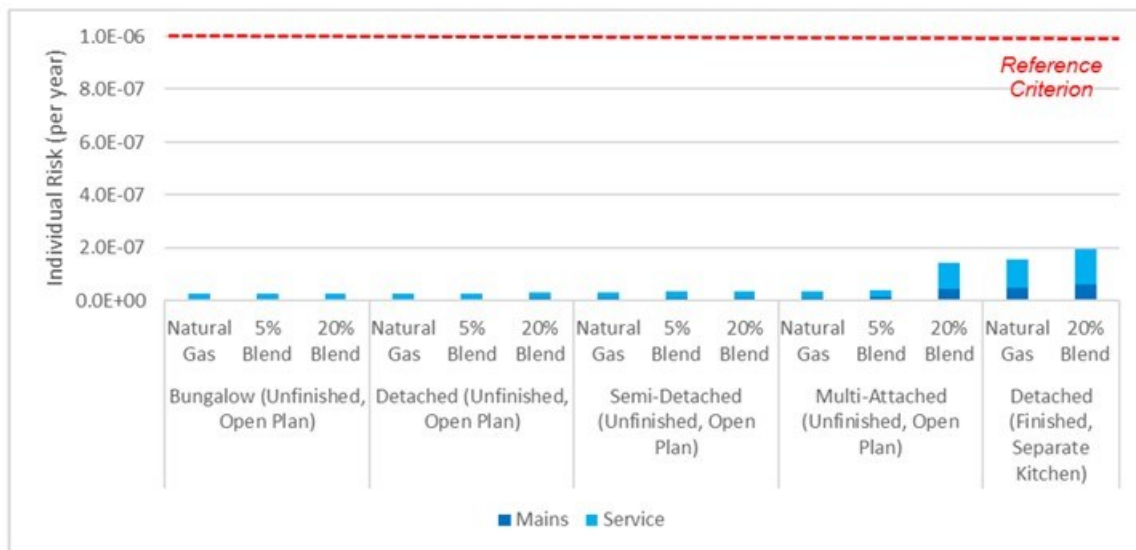


Figure 26: Individual risk from ignited releases for different types of houses [19].

Figure 27 shows that by adding 5% or 20% hydrogen, the IR was increased due to ignited releases from the customer meter, internal pipework, and appliances (green bars) relative to natural gas. However, the total IR for the end-user is comprised of the risk from both CO poisoning (grey bars) and ignited gas. This resulted in an overall decrease in IR for end-users. The IR for the end-user is dominated by the risk associated with CO poisoning (between 70% and 89% of the total IR). Therefore, the increase in IR due to ignited releases as a result of introducing hydrogen is minimal.

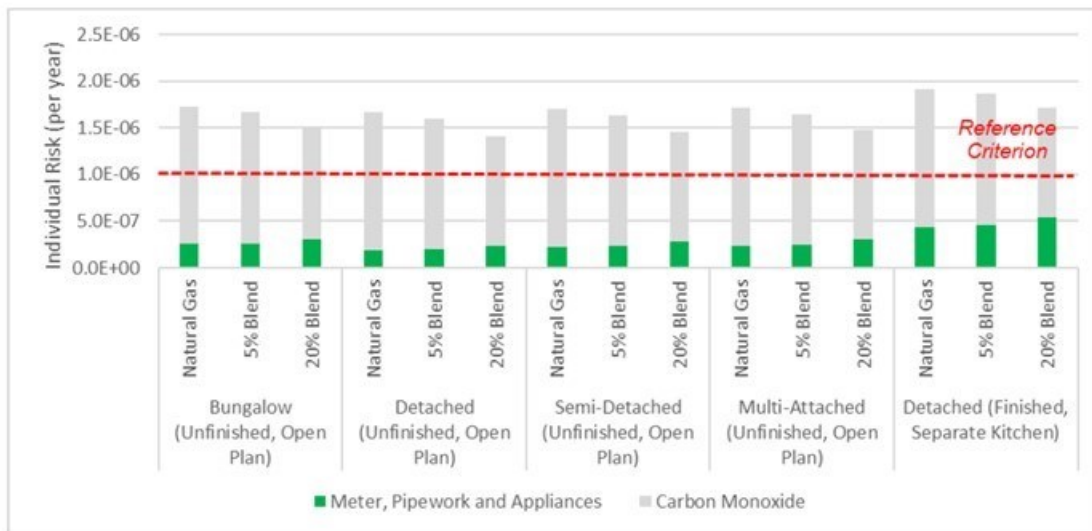


Figure 27: Combined individual risk from carbon monoxide and ignited releases for different types of houses [19].

3.4 Summary

This review examined studies with operational conditions varying according to Table 1. There were studies with hydrogen and methane concentrations varying from 0 to 100%, leak diameters from 1-200 mm, leakage rates from 5.5×10^{-5} to 215 kg/s, pressures from 0.002 to 7 MPa, and wind speeds from 0 to 15.5 m/s. The pressure used in these studies falls in the operating range of transmission and distribution pipelines shown in Table 8 in Appendix A. The leak diameter is representative of small leaks (i.e., less than 1% pipe diameter) or large releases (full bore rupture).

Table 1: Operational conditions applied in pipeline blends studies.

Hydrogen Concentration (vol. %)	Methane Concentration (vol. %)	Leak diameter (mm)	Leakage Rate (kg/s)	Pressure (MPa)	Wind speed (m/s)	Ref.
Release and Dispersion						
2.5-100	0-97.5	5-200	5.5×10^{-5} -131.53	0.002-4	0-15.5	[17, 18, 29-32]
Fire and Explosion						
0-100	0-100	1-150	2.7-215	6-7	1.2-6.3	[15, 16, 33, 34]

4. Reference Scenarios and Numerical Models

4.1 Reference Scenarios

Three reference scenarios were selected from the literature review (Section 3) for further numerical analysis. Their geometry setups and operating conditions are described in this section.

4.1.1 Scenario 1: Outdoor Pipeline Leaks in Rural Areas

Lowesmith and Hankinson [15] conducted two large-scale experiments to study the complete rupture of high-pressure transmission pipelines (140 mm diameter, 7 MPa - see Figure 28) carrying either a methane/hydrogen mixture with approximately 22% hydrogen or 100% methane. The leak rates varied from 150 to 215 kg/s from a 140 mm leak diameter. The wind velocity varied from 1.2 to 2.1 m/s. This scenario is representative of pipeline leaks in rural (unpopulated) areas.

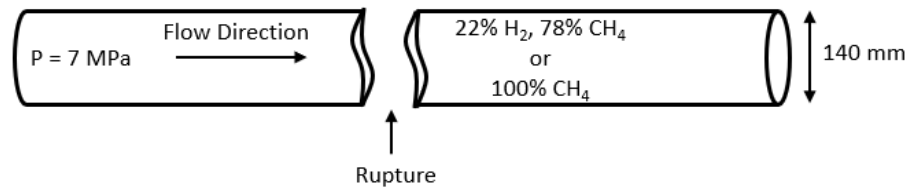


Figure 28: Schematic of a full pipeline rupture.

Lowesmith and Hankinson [15] did not address the effects of blending ratios, pipeline pressure, and leak diameters on the consequences of accidental releases. Therefore, the effects of these parameters on jet and cloud characteristics, including leak rate, flame length, radiant heat flux, and explosion pressure, were examined in the present study.

4.1.2 Scenario 2: Outdoor Pipeline Leaks in Urban Areas

Wilkening and Baraldi [18] conducted a CFD analysis of high-pressure hydrogen and methane releases from a pipeline. Figure 29 shows the schematic of the model domain. The pipeline was filled with either methane or hydrogen at a pressure of 1.1 MPa. The leak had a diameter of 0.2 m, and it was located at $x = 0$ m. Below the ground level, a pipeline (–100 and +100 m long, 1 m diameter) was modelled as the leak source. The source was placed between two buildings to study the effect of cloud dispersion and accumulation near the ground. Two wind profiles were chosen, i.e., with wind (10 m/s) and without wind (0 m/s). This scenario is representative of pipeline leaks in urban (populated) areas.

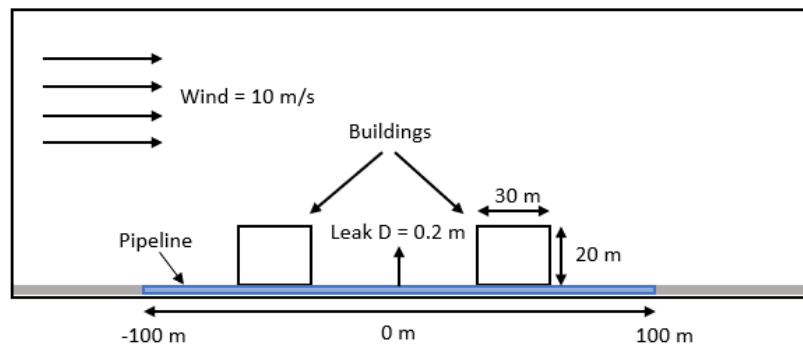


Figure 29: Schematic of the model domain adapted from [18].

The authors did investigate the influences of hydrogen blending ratios and distances between buildings on the gas dispersion behaviour. Therefore, the pipeline modelled in Reference [18] was used as a reference case to further examine the effect of hydrogen blending ratio, wind velocity, and distance between the buildings on gas dispersion behaviour.

4.1.3 Scenario 3: Indoor Pipeline Leaks

Su et al. [17] performed 3D numerical simulations using ANSYS Fluent to analyze the leakage and diffusion characteristics of hydrogen-blended natural gas in a real domestic kitchen. The 3D model domain is reproduced in Figure 30. It was assumed that the leaks come from a gas stove with leak rates varying between 5.5×10^{-5} and 2.7×10^{-4} kg/s and gradually fill the kitchen space through diffusion. As the blending ratio varied from 0 to 20% hydrogen, the LFL of blended gas decreased slightly from 4.97 to 4.76%. This scenario is representative of pipeline leaks in a closed space (end-user applications).

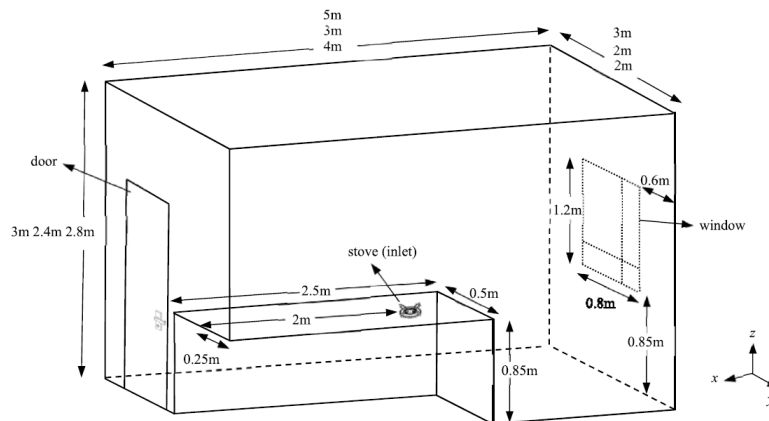


Figure 30: 3D model domain of a domestic kitchen [17].

The authors did not analyze the effect of hydrogen blending ratios higher than 20% and the effects of forced ventilation on the flammable gas accumulation. Therefore, the indoor environment modelled in Reference [32] was used as a reference case to further examine the these effects on flammable gas accumulation.

4.2 Computer Models and Codes

4.2.1 CNL Hydrogen Risk Analysis Toolkit

CNL developed an engineering toolkit in MATLAB for conducting quantitative risk assessment and consequence modelling for hydrogen containing systems [35]. This toolkit follows the same approach as the HyRAM code developed by the Sandia National Laboratories [36]. The toolkit integrates the models that calculate the physical consequence of jet release, fire and explosions, and probabilistic data to generate a risk matrix. The physics models can analyze pure hydrogen and methane, or their blends. They have been verified and validated with numerical and experimental data from literature. Only the physics models of the CNL toolkit were used for simulating scenario 1 (Section 4.1.1). The results of this analysis are provided in Section 5.

4.2.2 STAR-CCM+

Simcenter STAR-CCM+ [37] is a commercial CFD software developed by Siemens Digital Industries Software based on the finite volume discretization approach. This software allows the modeling and analysis of a range of engineering problems involving fluid flow, heat transfer, stress, particulate flow, electromagnetics and related phenomena. STAR-CCM+ was used for modelling scenario 2 (Section 4.1.2). The results of this analysis are provided in Section 6.

4.2.3 GOTHIC

GOTHIC™ [38] is a commercial software developed by Numerical Advisory Solutions (NAS) Engineering, Inc. (formerly Numerical Applications, Inc.). It is a versatile, general-purpose thermal-hydraulics software package that solves the conservation equations for mass, momentum, and energy for multicomponent, multi-phase compressible flow in lumped parameter and/or multi-dimensional (1, 2, or full 3D) geometries. It has been used for the design, licensing, safety, and operating analysis of nuclear power plant systems including primary system, containment, and equipment performance. GOTHIC 8.2 was used for modelling scenario 3 (Section 4.1.3). The results of this analysis are provided in Section 7.

4.3 Modeling Methodology

The numerical simulations were conducted according to the following steps:

- Step 1: Model verification and validation
- Step 2: Sensitivity study

Model verification is an important step to check if the equations are solved correctly. This step was implemented by comparing the simulated results with either analytical solutions or calculations generated by other software. In Scenarios 1, 2, and 3, the CNL results (i.e., from the toolkit, STAR-CCM+, and GOTHIC) were verified by comparing the results with simulations conducted with HyRAM [27], CFD-ACE [18], and ANSYS Fluent [17], respectively.

Model validation is necessary to ensure that the underlying physics have been captured correctly. This step was implemented by comparing the simulated results with experiments. In Scenario 1, the CNL results were compared with experiments on unignited and ignited hydrogen blends available in the literature [15, 33, 39].

In the sensitivity study, a base case was chosen from each of the three identified scenarios, and several model parameters were varied and compared with the base case.

5. Scenario 1: Outdoor Pipeline Leaks in Rural Areas

This section presents the analysis results for the first reference scenario (Section 4.1.1) using the CNL hydrogen risk analysis toolkit (Section 4.2.1). Here, an outdoor pipeline leak in a rural (unpopulated) area will be studied.

5.1 Model Verification and Validation

5.1.1 Unignited Jet Cloud

Leak of hydrogen blends from a high-pressure source can form a turbulent jet that entrains air from the ambient environment. Entrainment of the ambient air causes the concentrations of hydrogen and methane within the jet to fall as they mix with air. Ramachandran and Hecht [39] measured the hydrogen and methane concentration decay along the centreline of a vertical jet cloud released from a 1 mm nozzle at 1 MPa (10 bar) and 25 °C. The hydrogen blending ratio varied between 0% H₂ (100% CH₄), 25% H₂ (75% CH₄), 50% H₂ (50% CH₄), 75% H₂ (25% CH₄), and 100% H₂ (0% CH₄).

Figure 31 shows that the results calculated with the CNL toolkit were in good agreement with HyRAM simulations and experiments conducted in Ref. [39]. There is a slight difference in the results for 100% H₂. Both the CNL toolkit and HyRAM are not able to accurately predict the experimental data near the nozzle (< 0.15 m) for this condition. Far from the nozzle (> 0.15 m), the results are more similar to the experimental data. The reasons for this discrepancy for 100% H₂ are unknown, but it can be related to experimental uncertainties and different set of equations, assumptions and physical properties used in the CNL toolkit and HyRAM.

It is worth noting that the 100% H₂ release decreases slower with distance (Figure 31a) than the 100% CH₄ release (Figure 31b). Schefer et al. [40] observed similar behaviour, indicating that lighter gases (i.e., hydrogen) decrease slower than heavier gases (i.e., methane). This behaviour occurs due to the difference in molecular weight between hydrogen and methane - hydrogen has a considerably lower molecular weight (2.016 g/mol); therefore, it is more buoyant than methane (16.043 g/mol). When air is entrained into the jet flow, the molecular weight of the mixture increases, approaching the molecular weight of air (28.9 g/mol). Therefore, the increase in molecular weight for 100% H₂ is higher than 100% CH₄, causing a slower decrease with distance. For the blends, the data suggests a similar rate of decrease in the mole fraction of either hydrogen or methane, showing negligible effect of the blending ratio.

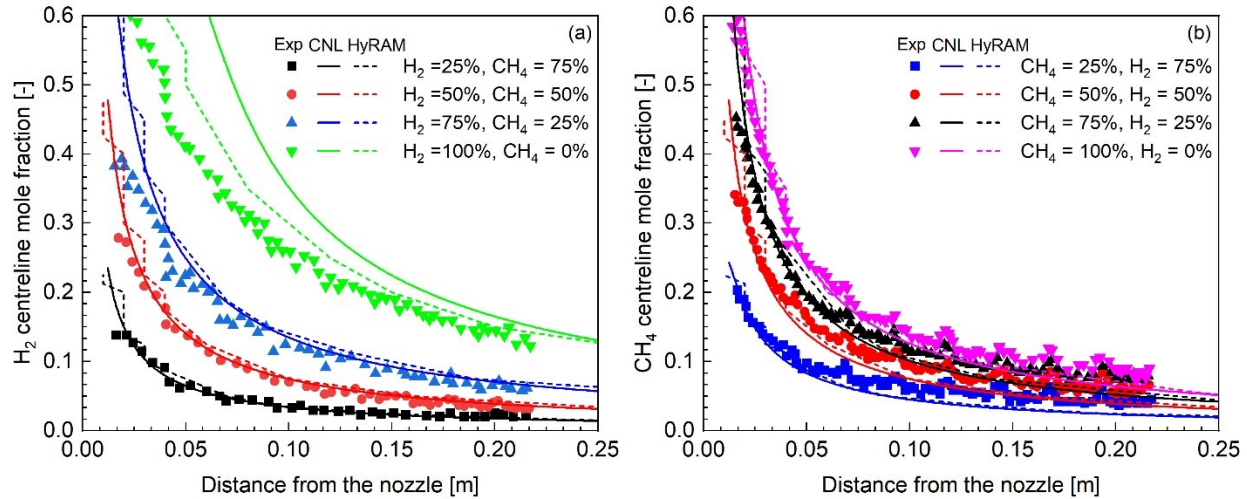


Figure 31: Mole fraction of (a) hydrogen and (b) methane varying with distance from the nozzle for different H₂ blending ratio. Comparison between experiments from [39] (symbol), CNL toolkit (solid line), and HyRAM (dashed line).

5.1.2 Jet Flame

Flame length is defined as the distance from the jet orifice to the point at which all the jet fluid has mixed with the atmosphere and has reacted. In both the CNL toolkit and HyRAM, flame length is determined as the distance where the radiative heat flux drops to 10% of the maximum value. Table 2 and Figure 32 show the flame length values varying with hydrogen blending ratio comparing experimental data from Ref. [33], HyRAM and CNL toolkit simulations for a vertical jet flame from a 1 mm nozzle at 0.101 MPa and 25 °C.

Table 2: Flame length for different hydrogen blending ratio.

H ₂ [vol.%]	CH ₄ [vol.%]	Flame Length (Exp. [33]) [m]	Flame Length (CNL Toolkit) [m]	Flame Length (HyRAM) [m]
0	100	0.187	0.183	0.182
25	75	0.159	0.168	0.167
50	50	0.126	0.150	0.150
75	25	0.076	0.130	0.130
100	0	0.043	0.103	0.103

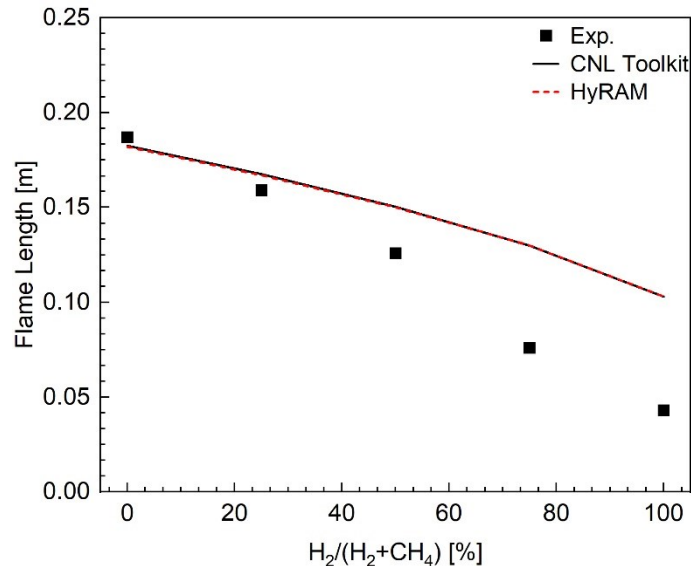


Figure 32: Flame length varying with hydrogen blending ratio. Comparison between experiments from Ref. [33] (symbol), CNL toolkit (solid line), and HyRAM (dashed line).

First, the experimental data revealed that the flame length decreased with an increase in the hydrogen blending ratio due to higher flame velocity of hydrogen, as described by Ramachandran and Hecht [33]. The increase in the flame velocity causes an increase in the fuel consumption near the nozzle, thus a shorter flame length. The results for HyRAM and CNL toolkit are identical and showed similar trends as compared to experimental data. However, they both only agree with experimental data up to 20% hydrogen blending ratio. Above 20%, both HyRAM and CNL toolkit overpredicted the flame length. One possible reason for this discrepancy is the approach used to determine the flame length, which was based on the flame images in the experiments, but calculated by the heat flux in the model. Nevertheless, the model predictions are conservative for risk assessment.

5.2 Sensitivity Study Results and Discussions

A sensitivity study was conducted using the CNL toolkit for the large scale pipeline release scenario taken from Ref. [15]. The base case was 22% H₂ and 78% CH₄ released from a 140 mm diameter leak at 7 MPa. The sensitivity parameters are:

- Blending ratio (% H₂):
0, 10, 20, 22, 25, 50, 75, 100
- Leak diameter (mm):
1, 4, 14, 44, 70, 100, 139
- Pressure (MPa): 1, 3, 7, 10

The leak diameters of 1, 4, 14, 44, and 139 mm were chosen to correspond to 0.01, 0.1, 1, 10, and 100% of the pipeline cross-sectional area, respectively. A 1 mm leak diameter indicates a very small leak that may exist during normal operation, and 139 mm leak diameter shows a full rupture of the pipeline. Pressures and blending ratios were chosen based on the conditions presented in Table 1 and Table 8.

5.2.1 Leak Rate

Figure 33 shows the effects of leak diameter, hydrogen blending ratio, and pipeline pressure on the mass flow rate of the leak (referred to as leak rate). In general, the leak rate increases significantly with leak diameters at smaller blending ratios, while it increases linearly with pipeline pressure (due to an increase in density), but it decreases with an increase in the hydrogen blending ratio (due to a decrease in density).

For small leak diameters up to 14 mm, the leak rate remains small (less than 2.5 kg/s) when increasing the hydrogen blending ratio from 0 to 100% H₂ (Figure 33a) and pipeline pressure from 1 to 10 MPa (Figure 33b). However, for the full pipeline rupture (a leak diameter equal to 139 mm), an increase in the hydrogen blending ratio from 0 to 100% H₂ decreases the leak rate from 192 to 66 kg/s (Figure 33a). This means that a pipeline with 100% CH₄ will leak a larger amount of gas by mass than that with 100% H₂. Note that a more detailed interpretation of these results is presented in Section 5.2.3, considering the flammable cloud size. On the other hand, an increase in the pipeline pressure from 1 to 10 MPa increases the leak rate from 24 to 245 kg/s (Figure 33b). This is an important finding because pipelines transporting hydrogen blends for long distances usually require high pressures.

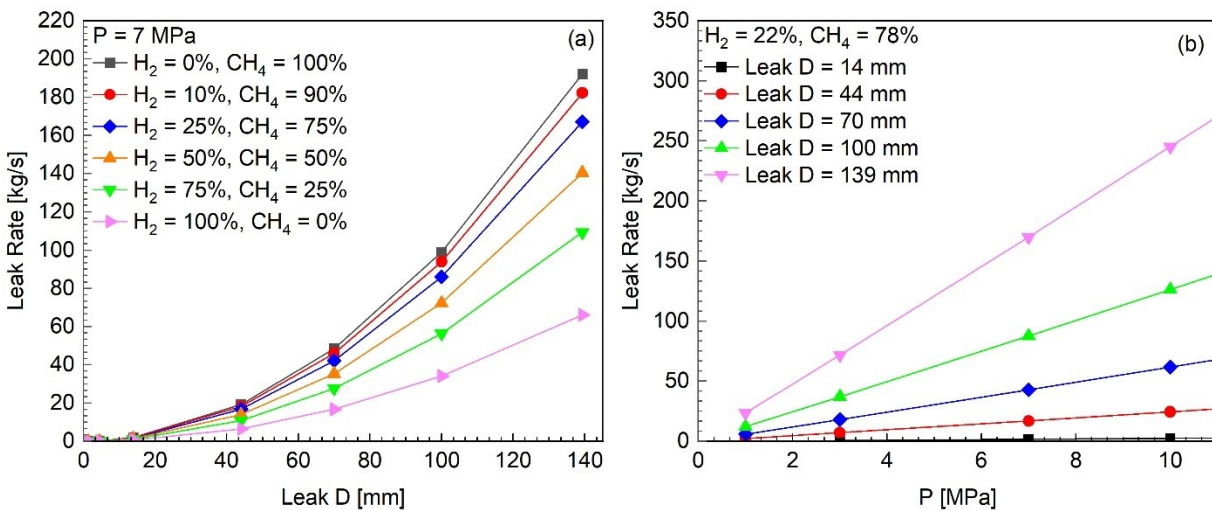


Figure 33: Leak rate changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.

5.2.2 Jet Fire

When an immediate ignition occurs at the rupture, a jet fire can be created, and the visible flame length is an important safety parameter to define the safe separation distance for people and structures. Figure 34 shows the flame length varying with leak diameter, hydrogen blending

ratio and pressure. The flame length linearly increases with leak diameter and pressure because of the larger leak rate as explained in Section 5.2.1. However, it is weakly related to the hydrogen blending ratio, decreasing from 21 to 15 m and 153 m to 121 m for $D = 14$ mm and $D = 139$ mm, respectively, when the hydrogen blending ratio increases from 0% to 100% H_2 (Figure 34a) due to an increase in the flame velocity, as explained in Section 5.1.2. For the base case (22% H_2 , 78% CH_4), an increase in the pipeline pressure from 1 to 10 MPa results in a weak increase in the flame length (from 8 to 23 m) for small leak diameters (e.g., $D = 14$ mm), but it shows a strong relationship for large leak diameters (e.g., $D = 139$ mm), increasing from 63 to 170 m.

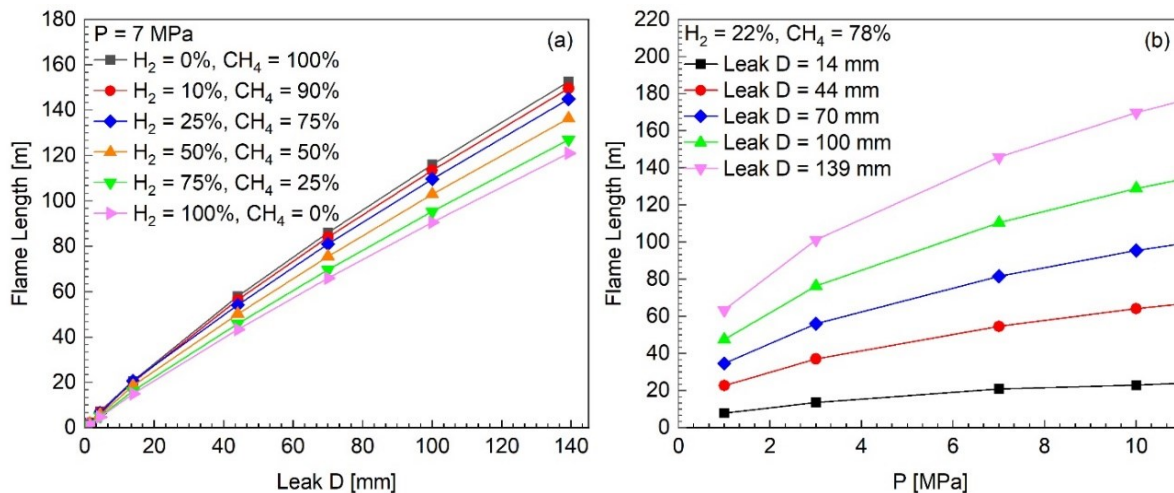


Figure 34: Flame length predicted by the CNL toolkit changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.

Figure 35 shows the heat flux contours created by the jet fire. The heat flux was analyzed for three leak diameters (14, 44, and 139 mm) and hydrogen blending ratios (0%, 20%, and 100% H_2), but the pipeline pressure was kept constant at 7 MPa. As shown in Section 5.2.2, the area affected by heat fluxes larger than 2 kW/m^2 increases with leak diameter due to an increase in the flame length. However, the area remains relatively the same for hydrogen blending ratios up to 20% H_2 and slightly decreases at 100% H_2 . These results show that the heat flux area is highly sensitive to the leak diameter, but only slightly sensitive to the hydrogen blending ratio.

Table 3 shows the separation distance correspondent to “no harm for long exposures” ($q < 2 \text{ kW/m}^2$) and “second-degree burn” ($2 \leq q \leq 10 \text{ kW/m}^2$) [41] varying with hydrogen blending ratio and leak diameter. For a leak diameter equal to 14 mm, the separation distance for “no harm” is within 20-28 m for hydrogen blending ratios varying from 0% to 100% H_2 . However, when there is a full rupture of the pipeline ($D = 139$ mm), the separation distance increases to values more than 200 m. Within 10-14 m, there is a risk of second-degree burn for leak diameters up to 14 mm, whereas this distance increases to more than 100 m for the full pipeline rupture ($D = 139$ mm).

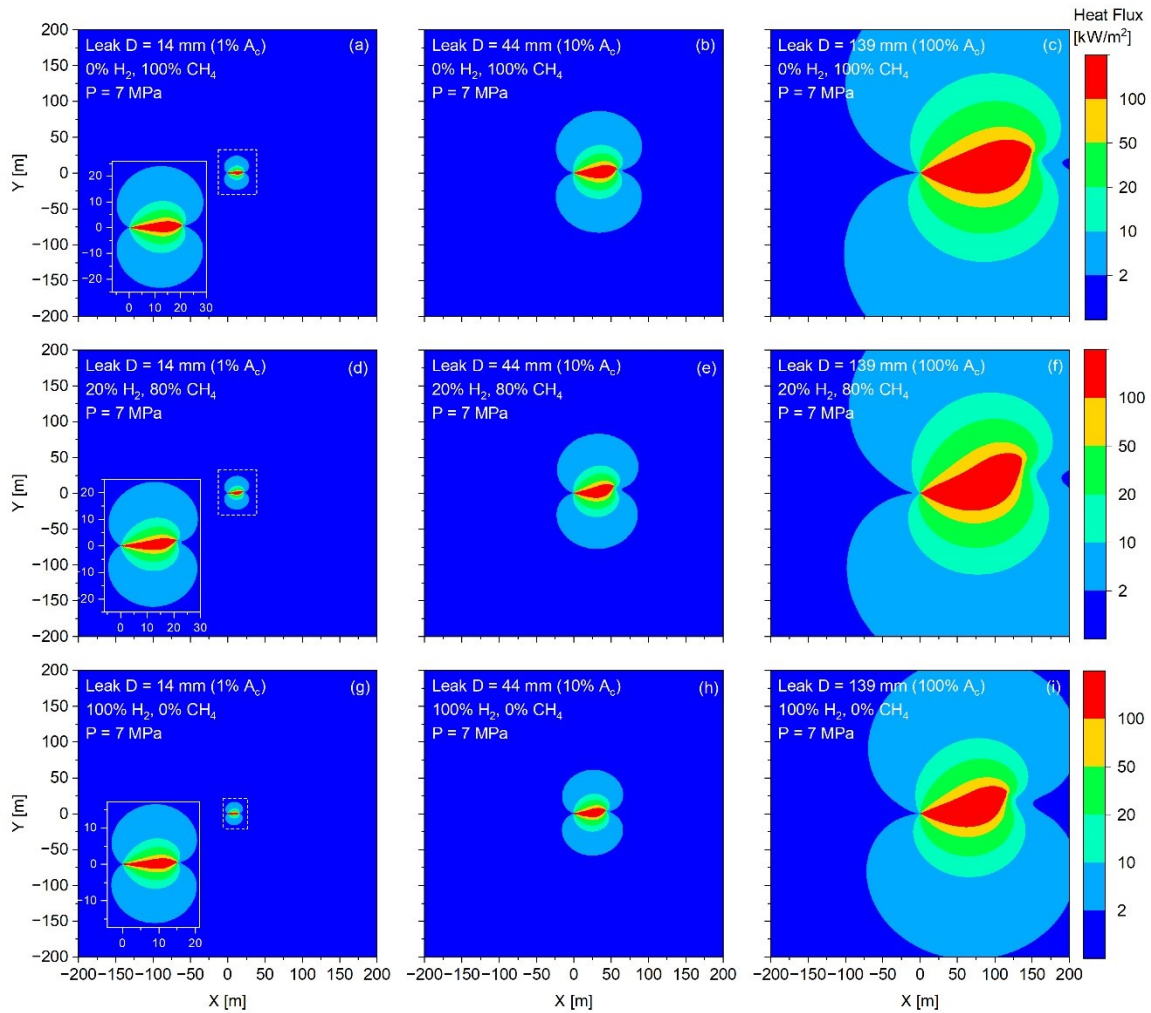


Figure 35: Heat flux contour profiles for different leak diameters and hydrogen blending ratio.
Leak diameters of 14 mm, 44 mm, and 139 mm correspond to 1%, 10%, and 100% of the pipeline cross-sectional area (A_c).

Table 3: Separation distances based on heat flux thresholds for different hydrogen blending ratio and leak diameters at 7 MPa.

Heat Flux Threshold (q) [kW/m ²]	Consequences	H ₂ [vol.%]	CH ₄ [vol.%]	Separation Distance [m]		
				D = 14 mm	D = 44 mm	D = 139 mm
$q < 2$	No harm for long exposures	0	100	28	93	> 200
		20	80	28	86	> 200
		100	0	20	66	> 200
$2 \leq q \leq 10$	Second-degree burn	0	100	14	47	> 100
		20	80	14	46	> 100
		100	0	10	35	> 100

5.2.3 Fire and Explosion

If a jet release is not immediately ignited, a flammable cloud can be formed. Figure 36 shows the contour plots of fuel concentrations for three hydrogen blending ratios (top to bottom: 0%, 20%, and 100% H₂), and three leak diameters (left to right: 14, 44, and 139 mm) at 7 MPa. The flammability range varies between 4.4% and 16.6% for 0% H₂, 4.3% and 26.6% for 20% H₂, and 4% and 75% for 100% H₂. The lower and upper flammability limits (LFL, UFL respectively) of hydrogen blends were calculated by applying the Le Chatelier rule, which states that any mixture of limiting gas mixtures is itself a limiting gas mixture:

$$\frac{y_{H_2}}{LFL_{H_2}} + \frac{y_{CH_4}}{LFL_{CH_4}} = 1 \text{ and } \frac{y_{H_2}}{UFL_{H_2}} + \frac{y_{CH_4}}{UFL_{CH_4}} = 1 \quad (1)$$

where y is the volume % of hydrogen and methane in air, $LFL_{H_2} = 4\%$, $UFL_{H_2} = 75\%$, $LFL_{CH_4} = 4.4\%$, $UFL_{CH_4} = 16.6\%$. The flammability limit (sum of y_{H_2} and y_{CH_4}) of blends is dependent on the blending ratio.

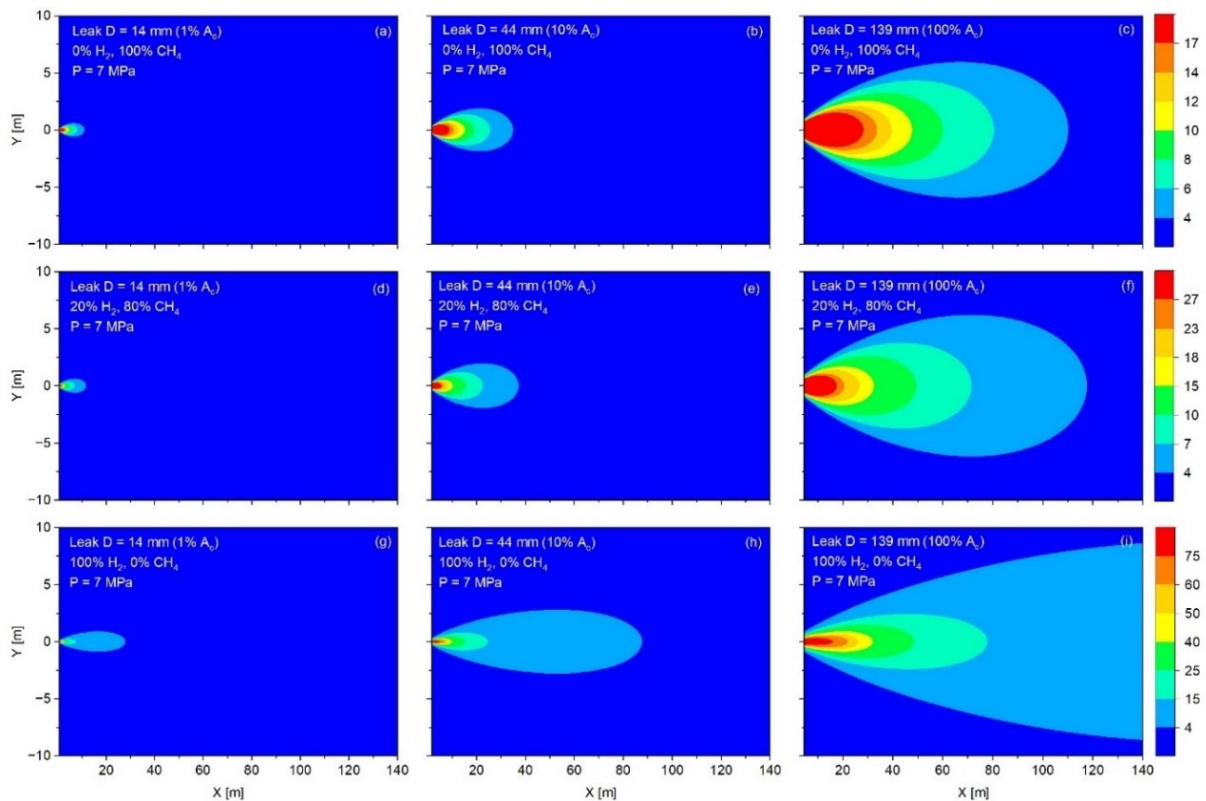


Figure 36: Contour profiles of fuel concentration with different leak diameter and blending ratio. The colour range was depicted based on the LFL and UFL of each hydrogen blend.

Figure 36 also shows that the size of the flammable cloud increases with leak diameter and hydrogen blending ratio from 10 m ($D = 14$ mm) to 110 m ($D = 139$ mm) at 0% H₂ and from 30 m ($D = 14$ mm) to more than 140 m ($D = 139$ mm) at 100% H₂. As the flammability limit of hydrogen is significantly wider than methane, an increase in the hydrogen blending ratio increases the size of the flammable cloud. The highest fuel concentrations were found near the

nozzle, decreasing with distance due to air entrainment.

The flammable cloud was used to calculate the explosive mass showed in Figure 37. The explosive mass of unignited release is the total hydrogen blend mass along the cloud length between the flammability limits at the instant of jet release. The results follow the same trend as the leak rate (Figure 33). The explosive mass increases with leak diameter and pressure and decreases with hydrogen blending ratio. Up to 44 mm leak diameter, the explosive mass varies from 6-10 kg. For the full pipeline rupture case (139 mm leak diameter), the explosive mass considerably increases when compared to the 44 mm leak diameter case, varying from 306 to 163 kg for 0% and 100% H₂, respectively. A pressure increase does not significantly increase the explosive mass for small leak diameters up to 44 mm, varying between 0.5 and 17.0 kg. However, the explosive mass largely increases from 16 to 530 kg at 139 mm leak diameter for pressures changing from 1 to 10 MPa.

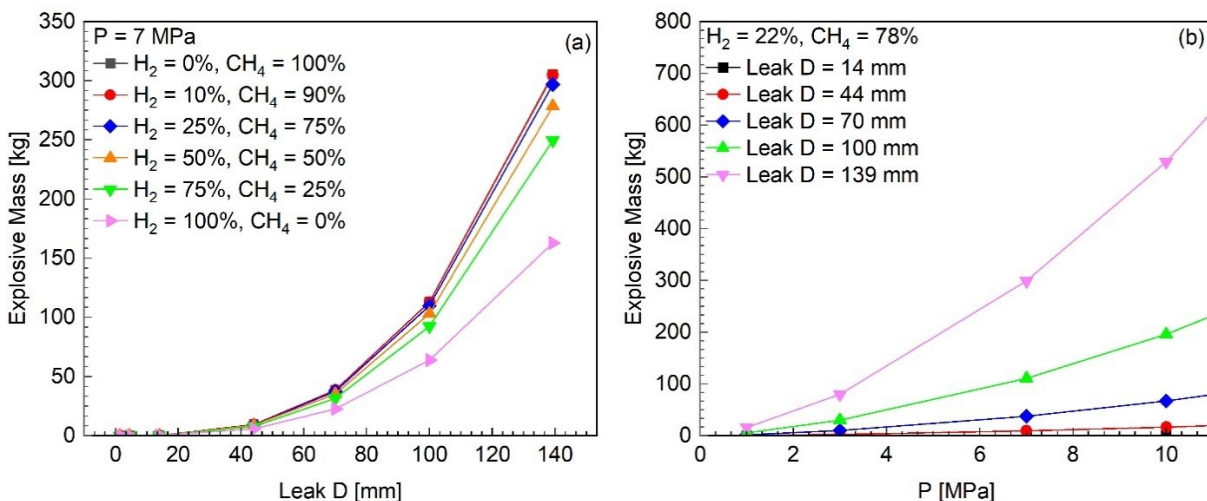


Figure 37. Explosive mass changing with (a) leak diameter and hydrogen blending ratio and (b) pressure and leak diameter.

Ignition of the flammable cloud will likely generate overpressures that can affect people and structures. The explosion overpressure is a function of the distance measured from the origin and explosive energy, which depends on the total explosive mass of hydrogen blend, calculated through the heat of combustion (120 MJ/kg and 50 MJ/kg for hydrogen and methane, respectively, using the lower heating value), and the ground reflection factor (assumed to be 2). It is assumed that all available energy in the initial mixture will be converted into blast wave energy, and a reflecting ground surface is taken into account through the reflection factor [42]. This energy is used to scale the distance from the origin into a dimensionless distance, which calculates scaled overpressure from the blast curves by Baker-Strehlow-Tang (BST) curves [43].

Figure 38 shows the overpressure contours for the cases with 14, 44, and 139 mm leak diameters and 0, 20, and 100% hydrogen blending ratios. The overpressures follow the same trend as the heat fluxes, i.e., increase when the leak diameter increases, but are not too sensitive to an increase in the blending ratio. Moreover, the highest overpressures are concentrated near the leak and then decreases with distance.

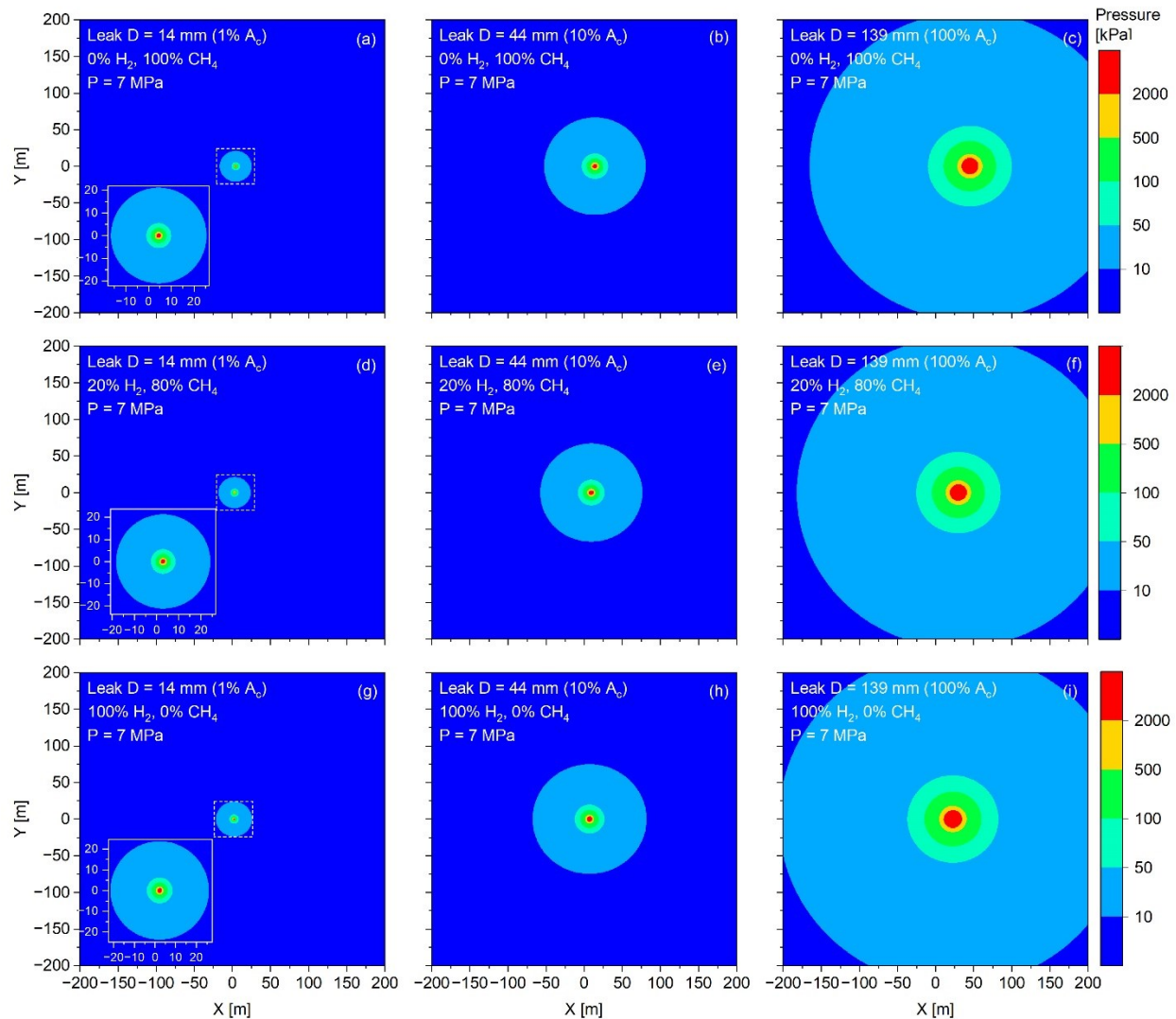


Figure 38: Overpressure contour profiles for different leak diameters and hydrogen blending ratio.

Table 4 shows the separation distance for overpressures that can cause “*eardrum rupture*” ($P > 14$ kPa) and “*lung haemorrhage*” ($14 \leq P \leq 100$) [41]. The separation distance for “*eardrum rupture*” increased from 15 to 18 m and from 156 to 167 m for $D = 14$ mm and $D = 139$ mm, respectively, and 0 to 100% hydrogen blending ratio. The separation distance for “*lung haemorrhage*” is much lower and varied from 2 m to 22-35 m for $D = 14$ mm and $D = 139$ mm, respectively.

Table 4: Separation distances based on overpressure thresholds for different hydrogen blending ratio and leak diameters at 7 MPa.

Overpressure Threshold (ΔP) [kPa]	Consequences	H ₂ [vol.%]	CH ₄ [vol.%]	Separation Distance [m]		
				D = 14 mm	D = 44 mm	D = 139 mm
$\Delta P > 14$	Eardrum rupture	0	100	15	49	156
		20	80	16	50	158
		100	0	18	55	167
$14 \leq \Delta P \leq 100$	Lung haemorrhage	0	100	2	7	22
		20	80	2	7	22
		100	0	2	6	35

5.3 Implications for Safety

Table 5 summarizes the sensitivity study presented in Section 5.2, indicating the trend of key model variables to an increase in the input parameters. The results showed that either an increase in the leak diameter at a given pipeline pressure or an increase in the pipeline pressure at a given leak diameter (Study #1-2, Table 5) increased the characteristic parameters for dispersion, fire, and explosion, which is expected as larger leak diameters and/or pipeline pressures increase the leak rate, flame length, heat flux, explosive mass, and overpressure. On the other hand, an increase in the hydrogen blending ratio (Study #3, Table 5) at a given pipeline pressure and leak diameter decreased the leak rate, flame length, heat flux, explosive mass, and overpressure. It seems these results favour an increase in the hydrogen blending ratio. In fact, for hydrogen blending ratio up to 20%, the addition of hydrogen in natural gas pipelines does not largely affect the characteristic parameters for dispersion, fire, and explosion, indicating that the existing natural gas pipeline infrastructure could handle hydrogen blends with minimal modifications. However, for hydrogen blending ratios larger than 20%, a further analysis was conducted.

An increase in the hydrogen blending ratio larger than 20% significantly decreased the blend density (results provided in Appendix C), requiring larger pressures to transport hydrogen with the same volumetric energy content in the natural gas pipelines. The coupled effect between pipeline pressure and hydrogen blending ratio was conducted in Study #4 (Table 5). In this study, the volumetric energy content of the pipeline was fixed (i.e., pipeline pressure increased along with hydrogen blending ratio, providing the same volumetric energy content). The results showed that the leak rate, flame length, explosive mass, heat flux, and overpressure increased when hydrogen blending ratio and pipeline pressure increased. This suggests a potential increase in the risk of fire and explosion. Note that, the results relevant to Study #4 are presented in 0. Therefore, there is an interplay between hydrogen blending ratio and pipeline pressure that needs to be carefully considered before increasing the hydrogen blending ratio.

Table 5: Sensitivity to key model variables.

Study #	Input Parameter	Variable	Sensitivity
1	Leak diameter increasing from 1 mm to 139 mm at a given pipeline pressure and hydrogen blending ratio	Leak rate	Increased
		Flame length	Increased ^a
		Heat flux	Increased
		Explosive mass	Increased ^a
		Overpressure	Increased
2	Pipeline pressure increasing from 1 to 10 MPa at a given leak diameter and hydrogen blending ratio	Leak rate	Increased
		Flame length	Increased ^a
		Heat flux	Increased ^c
		Explosive mass	Increased ^a
		Overpressure	Increased ^c
3	Hydrogen blending ratio increasing from 0 to 100% at a given pipeline pressure and leak diameter	Leak rate	Decreased
		Flame length	Decreased ^a
		Heat flux	Decreased ^b
		Explosive mass	Decreased ^b
		Overpressure	Decreased ^d
4	Hydrogen blending ratio increasing from 0 to 100% at a given energy content of the pipeline blends ^e	Leak rate	Increased
		Flame length	Increased ^a
		Heat flux	Increased ^b
		Explosive mass	Increased ^a
		Overpressure	Increased ^b

^a More sensitive to large leak diameters (> 44 mm).

^b More sensitive to hydrogen blending ratios higher than 20%.

^c Not directly simulated (expected according to the change in the leak rate).

^d Only slightly sensitive.

^e Energy content calculated by multiplying the density by the heat of the combustion of the blend. The pipeline pressure increases due to a decrease in the blend density at higher blending ratios. See more details in 0.

6. Scenario 2: Outdoor Pipeline Leaks in Urban Areas

This section presents the analysis results for the second scenario (Section 4.1.2) using STAR-CCM+ (Section 4.2.2). In this case, an outdoor pipeline leak in an urban (populated) area will be studied.

6.1 Model Setup

The numerical simulations were conducted with the finite volume discretization approach. A 2D domain based on Figure 3 was created with dimensions of 240 m wide and 80 m high. 2D calculations provide a qualitative view of potential hazards for hydrogen blends due to domain size limitations. For large transient profiles, simulations should be conducted with a larger domain. Two 30 m wide and 20 m buildings were considered in the domain. The model used a mesh size of 5 cm at the release location coarsening into a 1 m resolution far from the release location (Figure 39).

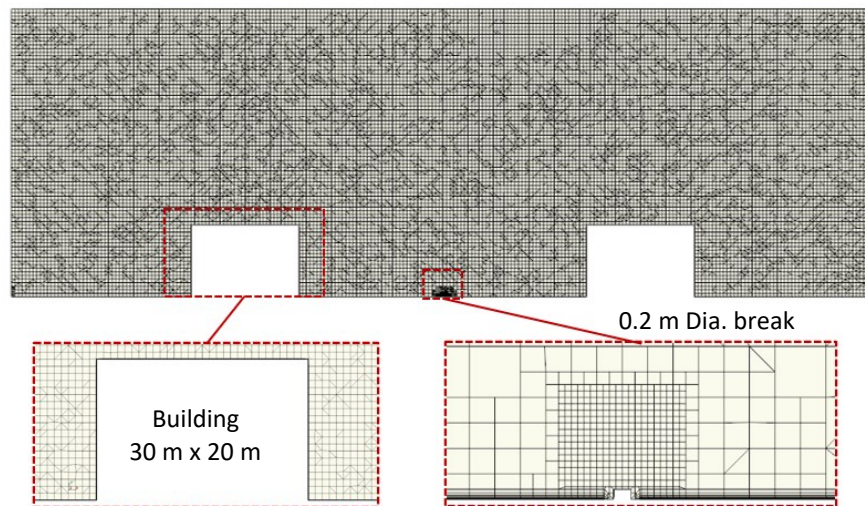


Figure 39: Mesh distribution along the numerical domain.

The simulation solved the Navier-Stokes continuity and momentum equations, along with the energy equation. Turbulence was modelled using the LES (Large-Eddy Simulation) approach described in Wilkening and Baraldi [18], and the dynamic Smagorinski sub-grid model. Though the LES approach adopted by Wilkening and Baraldi [18] uses a two-dimensional domain and course grid sizes not traditionally used in LES studies, this model was adopted for its fast run-time which facilitates numerous scoping tests to capture broad general trends and identify problematic cases that can be investigated in greater detail in future studies. Either 100% hydrogen, 100% methane, or blended hydrogen and methane was simulated with the species transport equation. Density was calculated by assuming the ideal gas law.

The simulation was first initialized with the steady-state solution without a gas leak for the background flow. An implicit unsteady solver and a segregated flow solver approach, with the SIMPLE algorithm for the pressure-velocity coupling, was used. A timestep size of 0.001 s was used in the 10 s simulation timespan; 100 inner loop iterations were used in the first two seconds and 20 inner loop iterations were used thereafter.

The top of the domain was modelled as a pressure outlet while the building surfaces and floor of the domain were modeled as no-slip boundaries. The left-side wall was modelled as an inlet (Dirichlet) boundary with a specified velocity (see Table 6) when wind is considered, and a pressure outlet boundary when wind is not considered, whereas the right-side wall was modelled as a pressure outlet boundary. The pipeline leak had a diameter of 0.2 m, and it was modelled as a mass flow inlet boundary. The mass flow rates from the pipeline were obtained from Ref. [18] for 100% methane and 100% hydrogen pipeline releases. The mass flow rate of the blended gas (Table 6) was estimated based on the mass fractions of hydrogen and methane gas from these reported values.

6.2 Model Verification

The CFD model was verified with the simulation results from Ref. [18] for 100% CH₄ and 100% H₂, both with wind velocity (left to right) equal to 10 m/s. Figure 40 shows the verification results for the contour plots of hydrogen and methane volume fractions at 7.5 s; whereas Figure 41 shows the velocity profiles at 1 s. CNL simulations for both 100% CH₄ and 100% H₂ cases (Figure 40a and Figure 40c) showed reasonable agreement with the results from Ref. [18] (Figure 40b and Figure 40d).

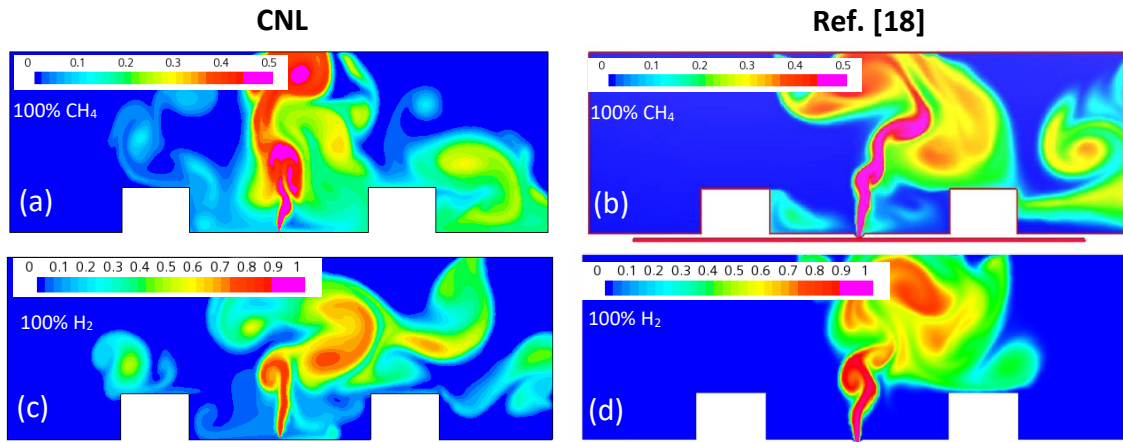


Figure 40: (a, b) Methane volume fraction for 100% CH₄ at 7.5 s and (c, d) hydrogen volume fraction for 100% H₂ at 4.0 s both at wind velocity = 10 m/s. (a, c) Results from CNL and (b, d) results from Ref. [18].

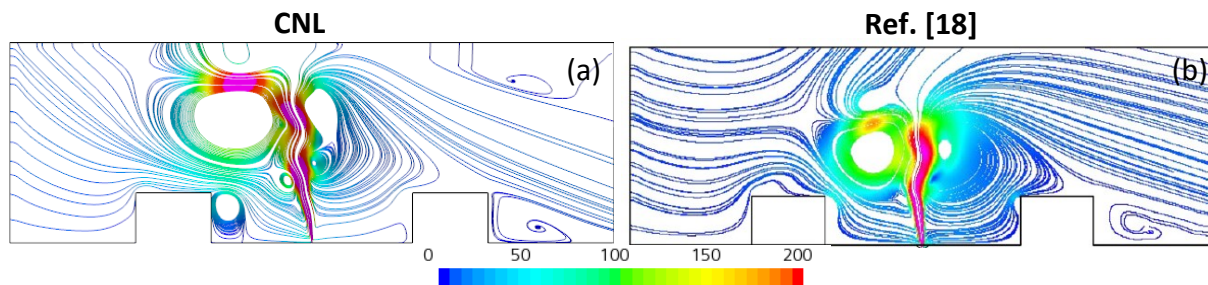


Figure 41: Velocity profile for methane release for 100% CH₄, wind velocity = 10 m/s at 1 s. (a) Results from CNL and (b) results from Ref. [18].

In both cases, the jet cloud rises and spreads downwind (see Section 6.3.4). For 100% CH₄, there was an accumulation of a flammable mixture near the ground and around the buildings; however, the CNL results showed a higher accumulation of the flammable mixture in between the buildings than the results from Ref. [18]. Finer grid sizes used in this study, and differences in sub-grid modelling, may explain these discrepancies. For 100% H₂, CNL results also showed a slight accumulation in between the buildings, which was not seen in Ref. [18]. Moreover, there was a slight recirculation of the flammable cloud to the left of the buildings, contrary to the wind direction for both cases (100% CH₄ and 100% H₂) conducted by CNL. This recirculation might be a result of the different velocity magnitudes between the gas release (200 m/s) and wind (10 m/s) as shown in Figure 41 for the 100% CH₄ case. CNL results also showed velocities

in the order of 50-100 m/s above the left building (Figure 41a), whereas the magnitude of the velocities in Ref. [18] are more similar to the wind velocity. These packets of high-speed fluid observed in the CNL study are produced as a minority of separated vortices, which have much higher momentum than the freestream, traveling upstream after shedding. Note that the differences in the concentration profiles between CNL and Ref. [18] can be related to different modeling techniques such as numerical solver, mesh, assumptions used, and the fact that turbulence is random and chaotic. Moreover, the results from Ref. [18] were not experimentally validated. Therefore, all these reasons make the comparison challenging.

6.3 Sensitivity Study Results and Discussion

A sensitivity study was conducted using the CFD model developed at CNL, and the cases tested are presented in Table 6. The objective of this sensitivity study was to identify the influence of different hydrogen blending ratios, wind velocities, and distance between buildings on the accumulation of flammable gas cloud, and risk of fire and explosion according to the size of the cloud. The leak rate was determined based on the pipeline pressure of 1.1 MPa and leak diameter of 0.2 m.

Table 6: Test conditions for the scenario 2 sensitivity study.

Case #	H ₂ [%]	CH ₄ [%]	Leak Rate [kg/s]	Distance Between Building [m]	Wind Velocity [m/s]
1	0	100	34.2	80	10
2	20	80	29.7	80	10
3	50	50	22.8	80	10
4	75	25	17.2	80	10
5	100	0	11.5	80	10
6	20	80	29.7	80	5
7	20	80	29.7	80	0
8	20	80	29.7	60	10
9	20	80	29.7	40	10

6.3.1 Dispersion Behaviour

Figure 42 shows the time evolution of the flammable cloud between LFL and UFL for 100% CH₄ (Case 1) and 100% H₂ (Case 5). For 100% CH₄ (Figure 42 left) LFL and UFL are 4.4 and 16.4, respectively. Initially (at 0.5 s), most of the cloud is located near the leak location and methane concentrations are higher than the UFL. Therefore, the flammable concentrations only cover a small fraction of the cloud. When the cloud starts to mix with air due to air entrainment, diffusion, and turbulence (i.e., wind - 2.5 s), methane concentration decreases, reaching values within the flammability range. The flammable cloud spreads over a larger area mostly located above the buildings. After 4.5 s, the flammable cloud quickly accumulates near the ground and

in between buildings. Therefore, the release of 100% CH₄ in an urban area could result in an accumulation of a flammable cloud near the ground due to gas recirculation and entrapment after 4.5 s, increasing the risk of fire and explosion.

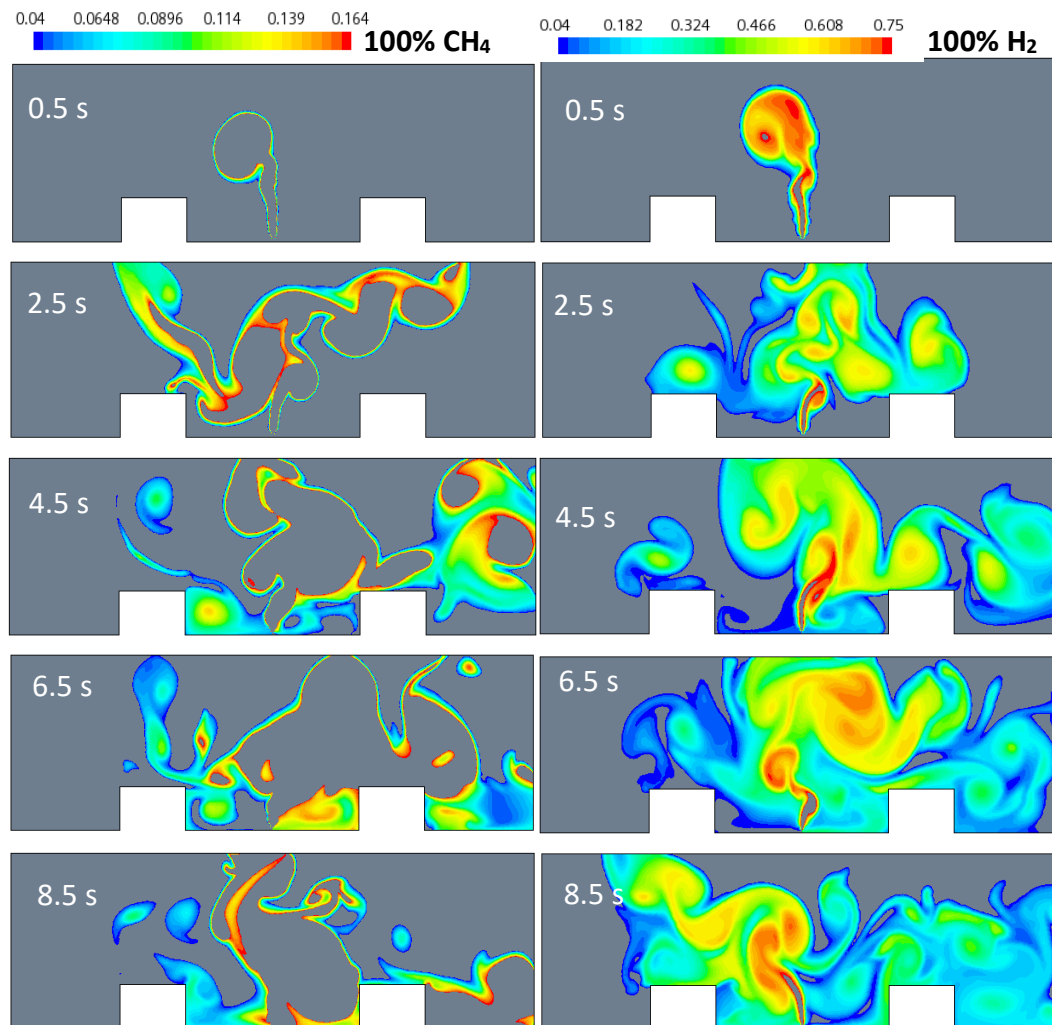


Figure 42: Fuel volume fractions between the LFL and UFL varying with time for 100% CH₄ (left side) and 100% H₂ (right side) with wind velocity = 10 m/s.

For 100% H₂ (Figure 42 right), the flammable cloud spreads faster when compared to 100% CH₄. Although hydrogen is lighter than methane, flow expansion around building geometry creates gas recirculation, which promotes mixing, resulting in a decrease in the hydrogen concentration. As the hydrogen flammable range gets wider, from 4 (LFL) to 75% (UFL), the hydrogen flammable cloud occupies a larger area than methane. After 6.5 s, the cloud is covering most of the area in between, above, and to the right side of the buildings. This behaviour could lead to a higher potential for ignition, thus a larger risk of fire and explosion when compared to 100% CH₄ due to the larger flammable volume.

6.3.2 Flammable Area and Energy

The total flammable area was evaluated by calculating the area of the entire domain that contains hydrogen/methane within the flammability limit. Moreover, three other regions shown in Figure 43 were evaluated: region # 1 (upwind), region # 2 (building canyon), and region # 3 (downwind).

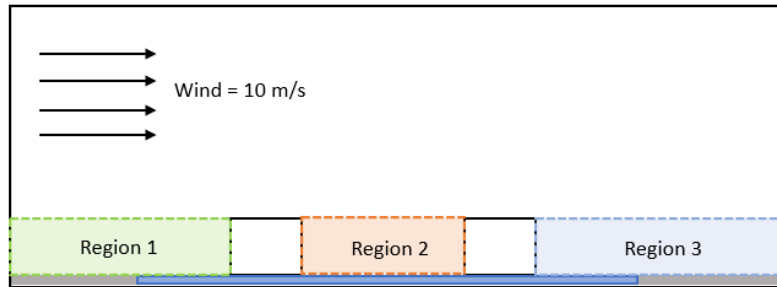


Figure 43: Areas analyzed: upwind (Region 1), building canyon (Region 2), and downwind (Region 3).

Figure 44 shows the total flammable area in the entire domain and the flammable area in each of the regions specified in Figure 43 for cases 1 and 5 (see Table 6). The total flammable area (Figure 44a) increases with time due to the mixing of fuel with air; however, the increase in the flammable area for 100% H₂ is larger and faster than that with 100% CH₄ due to the wider hydrogen flammability range. For 100% H₂, the increase in the flammable area with time is relatively linear, whereas for 100% CH₄, the increase is slow up to 1.5 s and then quickly increases due to air dilution, reaching flammable concentrations. Quasi steady-state conditions are reached at about 6 s for 100% H₂ and 4 s for 100% CH₄. The peaks and valleys in the curves correspond to vortex shedding, transport, and gas recirculation effects. Figure 44b shows that region # 1 contains almost no methane and hydrogen. This is expected as the gas velocities in this region are of the same order as the wind velocity. As the wind is blowing from left (upwind) to right (downwind), it tends to move the cloud to the right (downwind). Therefore, the higher flammable gas concentrations are located in regions # 2 (Figure 44c) and # 3 (Figure 44d) due to gas recirculation, entrapment, and wind effect.

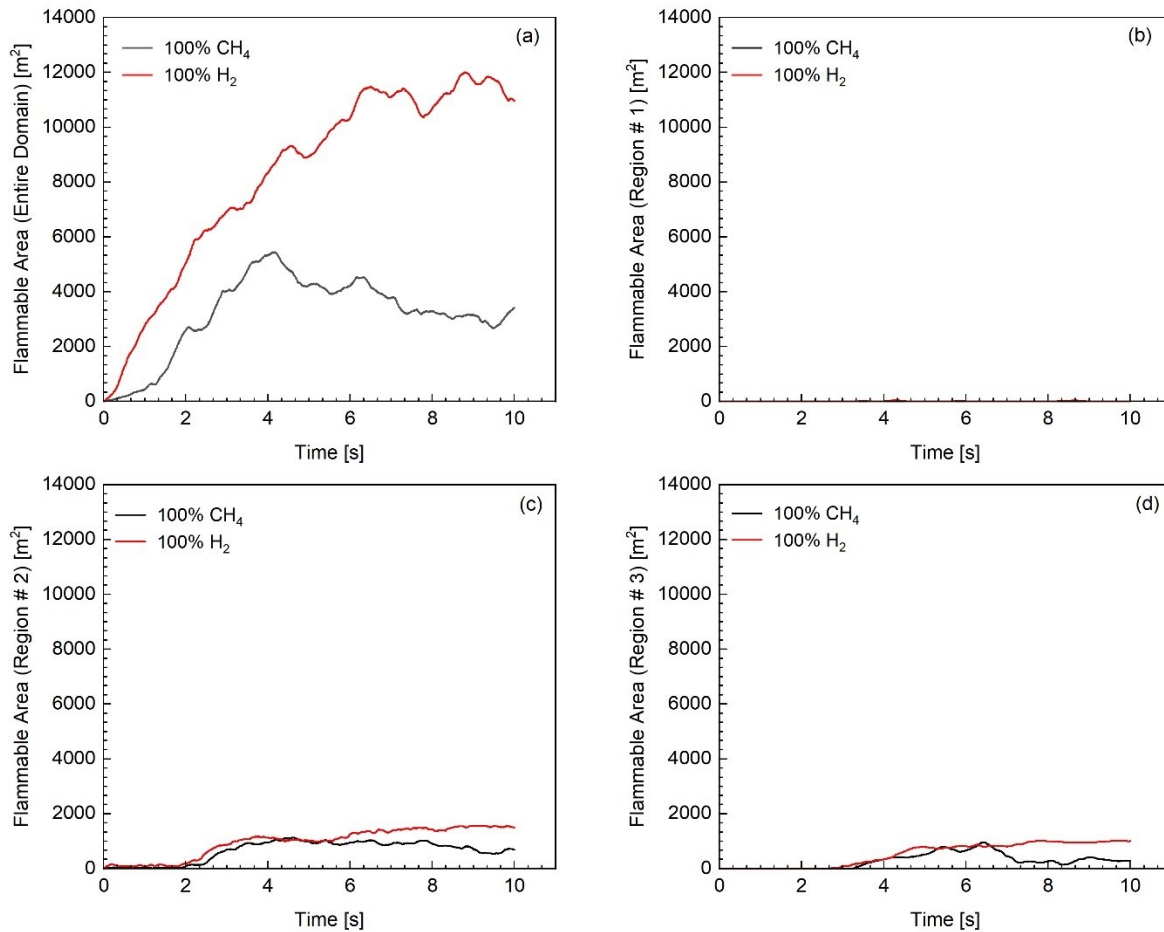


Figure 44: Flammable area within the computation domain for 100% CH₄ (case 1) and 100% H₂ (case 5) with wind = 10 m/s within (a) entire domain, (b) region # 1, (c) region # 2, and (d) region # 3.

The total energy (E) available that eventually can be released in case of an explosion was calculated by multiplying the heat of combustion of the blend ($\Delta H_{c,blend}$) by the total mass of the blend (m) in the computation domain:

$$E = m \cdot \Delta H_{c,blend} \text{ and } \Delta H_{c,blend} = \frac{\sum_i y_i \cdot \Delta H_{c,i} \cdot MW_i}{\sum_i y_i \cdot MW_i} \quad (2)$$

where y_i , MW_i , and $\Delta H_{c,i}$ are the volume fraction, molar weight, and heat of combustion of each species i.e., ΔH_c is equal to 120 MJ/kg for hydrogen and 50 MJ/kg for methane.

Figure 45a shows that the total energy increases with time for both 100% CH₄ and 100% H₂ and then reaches quasi steady-state conditions. The total available energy is lower for 100% H₂ than for 100% CH₄ due to the lower density of hydrogen. When the flammable energy is considered (i.e., the energy accounted within the flammability limit), 100% H₂ has a larger flammable energy than 100% CH₄ due to the wider hydrogen flammability range and larger heat of combustion - see Figure 45b. These results imply that for certain conditions, 100% H₂ would be more dangerous than 100% CH₄; however, most of the hydrogen total energy (Figure 45a) is

accounted as flammable energy (Figure 45b), whereas only a fraction of the methane total energy is accounted as flammable energy. It is expected that over time, the methane flammable energy will eventually increase due to air entrainment, decreasing the methane concentrations to flammable conditions. Then, the flammable area for 100% CH₄ will likely approach the 100% H₂ flammable area. A detailed analysis needs to be conducted before reaching further conclusions.

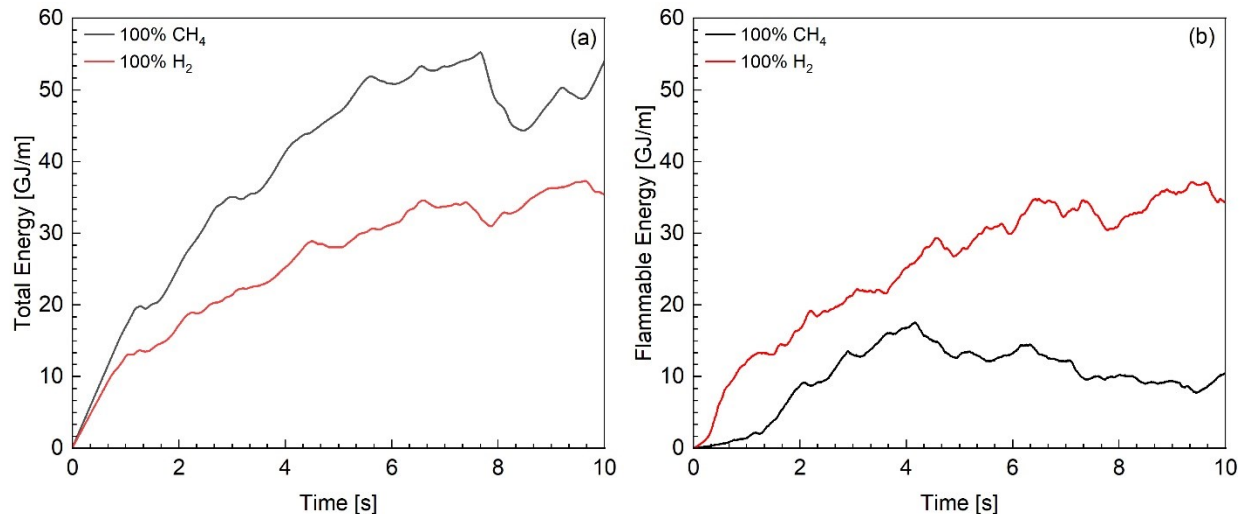


Figure 45: (a) Total energy available for combustion and (b) flammable energy within the flammability range for 100% CH₄ (case 1) and 100% H₂ (case 5).

6.3.3 Hydrogen Blending Ratio

Figure 46 shows the results for cases 1-5, where the hydrogen blending ratio varied from 0 to 100%. The results were depicted at 7.5 s, where a quasi-steady-state condition was reached. Up to 20% H₂ (Figure 46b), the flammable cloud looks similar to pure methane (100% CH₄) at this specific time. However, when the hydrogen blending ratio is higher than 20% (Figure 46c-e), there is a large accumulation of flammable gas near the ground and in between the buildings. When the flammable area and energy are taken into account over the entire simulation time, Figure 47a and Figure 47b, it is possible to see that both flammable area and energy increases when the blending ratio increases. Up to 20% hydrogen blending ratio, this increase is relatively small, but it is almost four times higher for 75% hydrogen blending ratio (Figure 47b). Therefore, these results suggest that the risk of fire and explosion for hydrogen blending ratios up to 20% should be similar but still slightly higher than 100% CH₄. More dangerous conditions are reached when the blending ratio increases, which can potentially increase the risk of fire and explosion, if corrective measures are not applied.

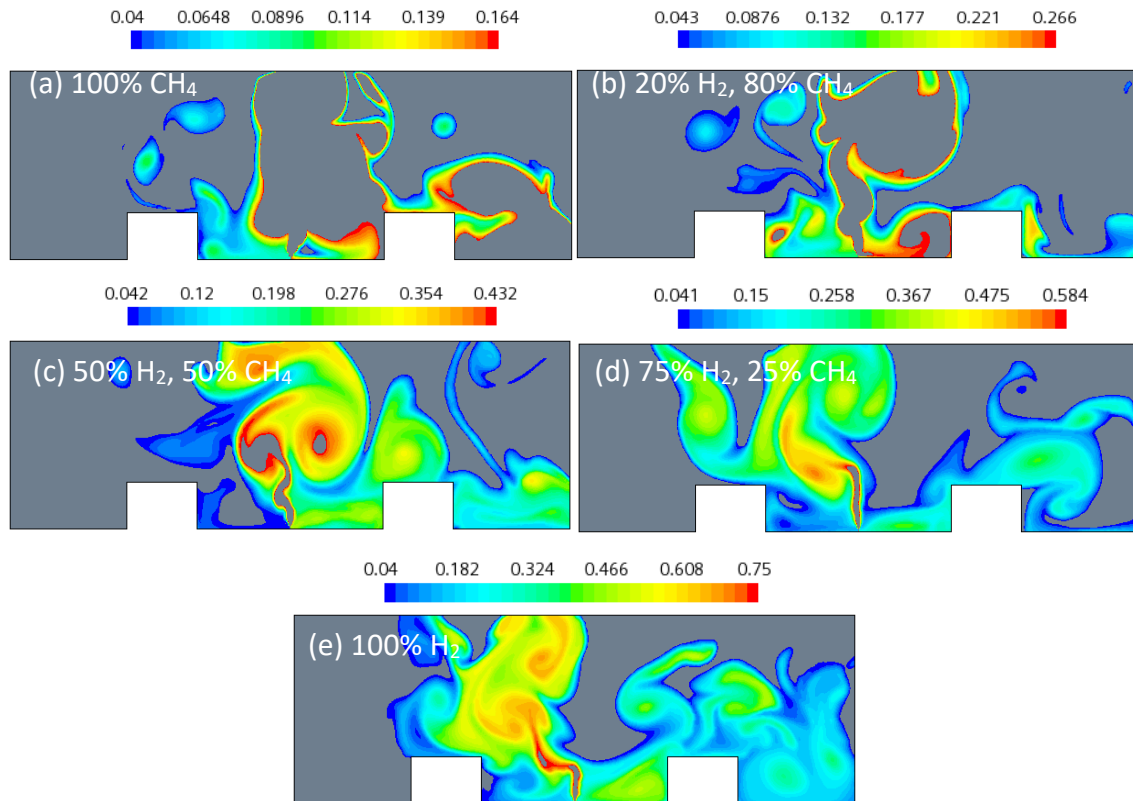


Figure 46: Hydrogen blending volume fraction between LFL and UFL at 7.5 s for (a) 0% H₂, 100% CH₄, (b) 20% H₂, 80% CH₄, (c) 50% H₂, 50% CH₄, (d) 75% H₂, 25% CH₄, and (e) 100% H₂, 0% CH₄, wind velocity = 10 m/s. The coloured bar shows the LFL and UFL limits for each case.

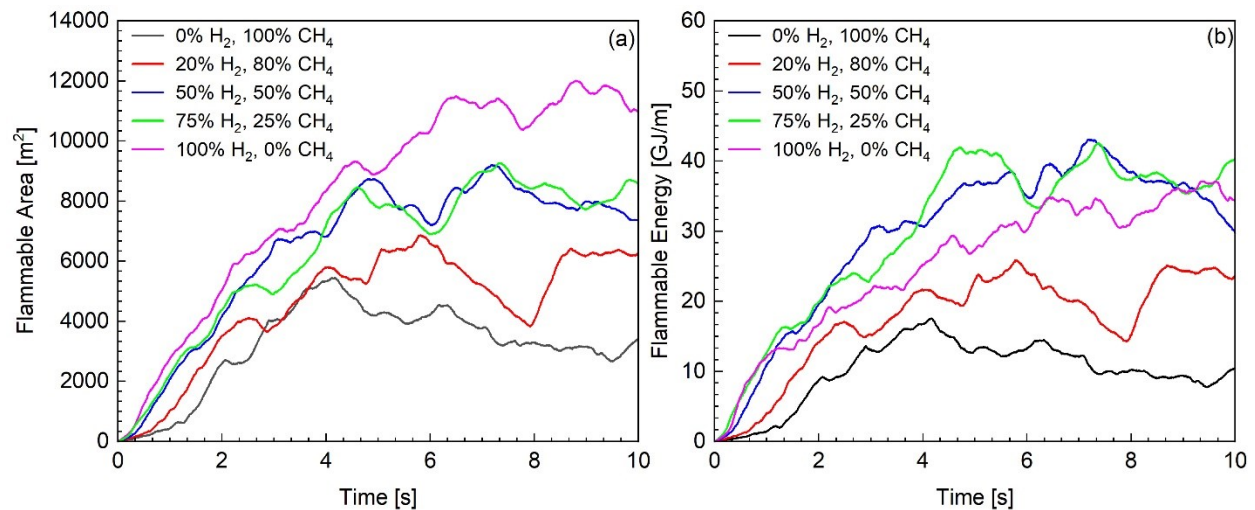


Figure 47: (a) Area containing the flammable fuel concentration and (b) Fuel energy per unit depth in the flammable area varying with hydrogen blending ratio at wind velocity of 10 m/s.

6.3.4 Wind Velocity

Figure 48 and Figure 49 show the sensitivity of the flammable cloud, flammable area, and flammable energy to the wind velocity. The velocity varied from 10 m/s (base case) to 0 m/s (no wind). The hydrogen blending ratio is 20% H₂ and 80% CH₄ and the results are also depicted at 7.5 s. Figure 48 shows a flammable gas accumulation in the recirculation region in between buildings, which possibly caused a delay in the increase in the flammable area (Figure 49) for conditions with no wind when compared to 10 m/s wind velocity. The steady-state flammable area for the higher wind velocity (10 m/s) is lower than the lower one (5 m/s). This suggests that after the fuel exits in the recirculation region, high wind speeds purge more of the fuel away from the buildings. However, a simulation with a longer time and a larger domain should be performed for further conclusions.

6.3.5 Distance Between Buildings

Figure 50 shows the effect of the distance between buildings on the flammable cloud. When the distance decreases from 80 to 40 m, there is less accumulation of the flammable gas in between the buildings at 7.5 s and a large fraction of the cloud is transported to the right side of the buildings (downwind).

Figure 51a shows the normalized flammable area (flammable area divided by the total area between buildings) and Figure 51b shows the volumetric flammable energy available (energy per unit depth divided by the total area between buildings). A decrease in the distance between buildings from 80 to 40 m increases the normalized flammable area and consequently the volumetric flammable energy available. This indicates that there is more flammable gas accumulation in a smaller area, which can potentially increase the risk of fire and explosion, and consequently cause more damage to people and structures, if corrective measures are not applied.

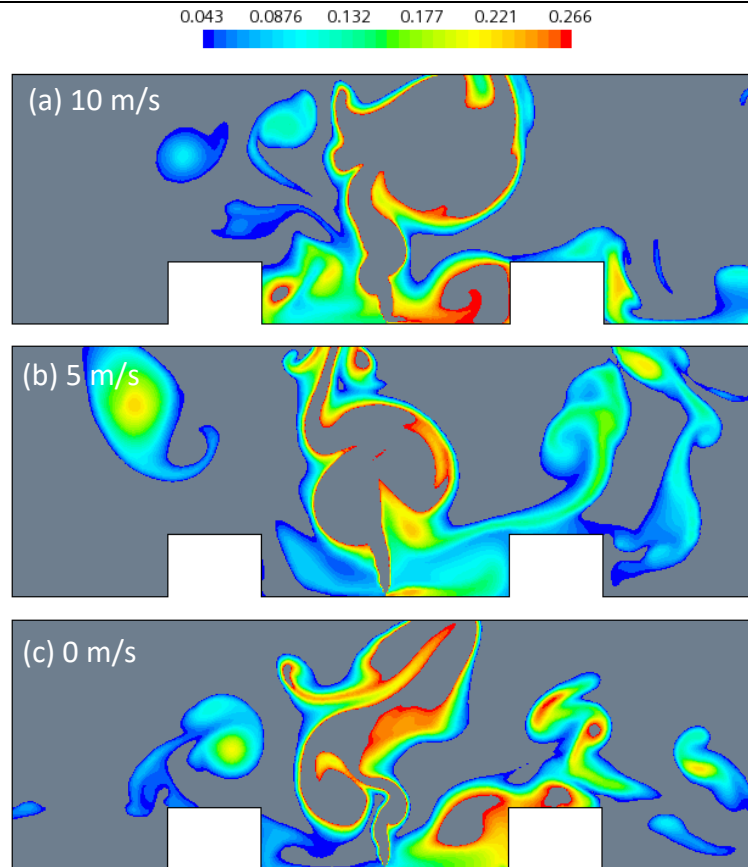


Figure 48: Hydrogen blending volume fraction between LFL and UFL at 7.5 s for (a) wind velocity = 10 m/s, (b) wind velocity = 5 m/s, (c) wind velocity = 0 m/s with hydrogen blending ratio of 20% H₂, 80% CH₄.

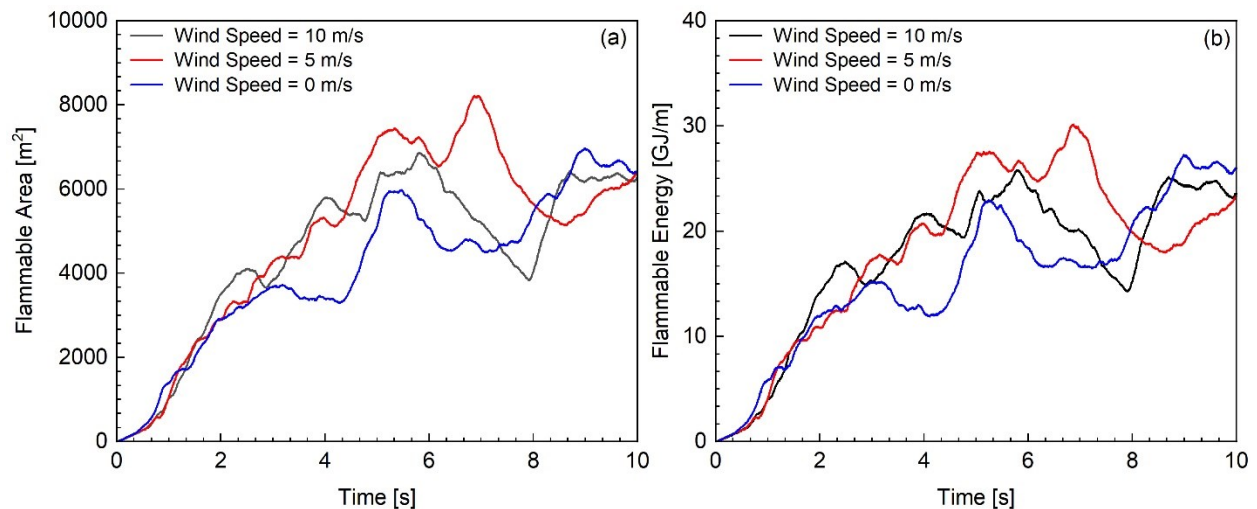


Figure 49: (a) Area containing the flammable fuel concentration and (b) fuel energy per unit depth in the flammable area varying with wind velocity for 20% H₂ and 80% CH₄.

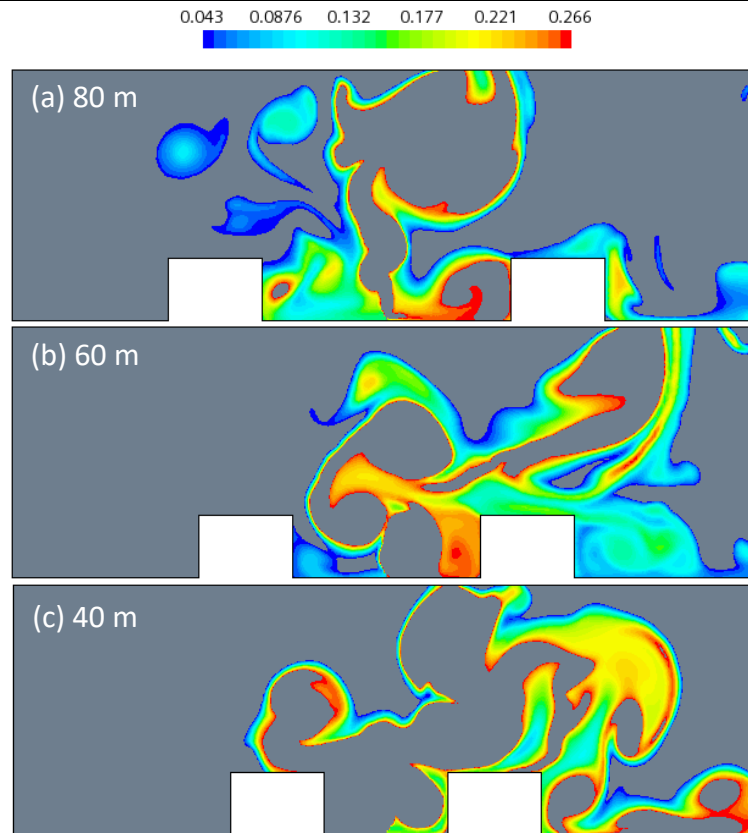


Figure 50: Hydrogen blending volume fraction between LFL and UFL varying the distance between the buildings (80, 60, and 40 m) at 7.5 s, wind velocity = 10 m/s, and hydrogen blending ratio of 20% H₂, 80% CH₄.

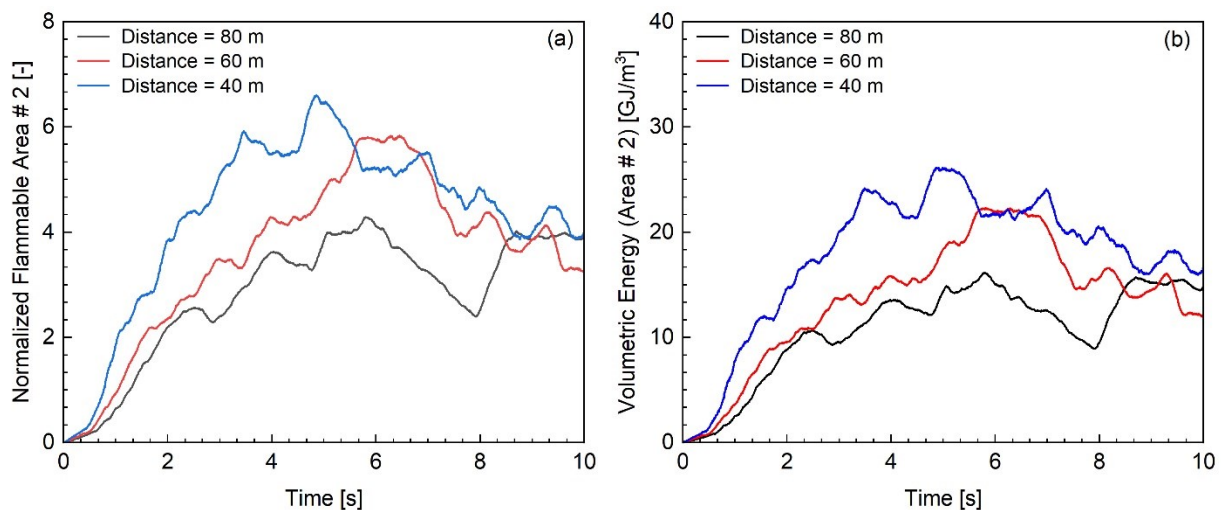


Figure 51: (a) Normalized area containing the flammable fuel concentration and (b) fuel energy per unit volume in the flammable area in between the buildings for hydrogen blending ratio of 20% H₂, 80% CH₄ and wind velocity = 10 m/s.

6.4 Implications to Safety

The accidental release of methane, hydrogen, or hydrogen blends in urban areas can result in an accumulation of a flammable cloud near the ground and around buildings due to gas recirculation and entrapment, increasing the risk of fire and explosion. The simulations showed that for 100% H₂, the flammable cloud dispersed more quickly and occupied a larger area when compared to 100% CH₄ due to the wider hydrogen flammability limit. Moreover, the flammable energy released in a potential explosion was higher for 100% H₂ than 100% CH₄ due to the larger heat of combustion although the total flammable mass for 100% H₂ was less than 100% CH₄. As the total flammable thermal energy was much larger for hydrogen, the outcome of hydrogen fire or explosion might be worse as compared to methane considering the higher flame speed of hydrogen (higher chemical reactivity). However, over time, the methane flammable energy can eventually increase due to more dilution with air, reaching flammable conditions. A more detailed analysis needs to be conducted before reaching further conclusions.

When hydrogen blends are considered, the flammable cloud for up to 20% H₂ remains similar to 100% CH₄. However, when the hydrogen blending ratio is higher than 20%, there is a potential for large accumulation of flammable gas near the ground and in between the buildings, primarily due to wider flammability range of hydrogen. These results suggest that the risk of fire and explosion for hydrogen blends up to 20% is similar to 100% CH₄. However, when the blending ratio increases, more flammable gas accumulation can potentially increase the risk of fire and explosions.

This analysis also showed that wind can potentially move the flammable cloud away from the buildings. However, a simulation with a longer time and a larger domain should be performed for further conclusions. Moreover, a decrease in the distance between buildings resulted in a larger flammable gas accumulation in a smaller area, which can potentially increase the risk of fire and explosion, and consequently cause more damage to people and structures without corrective measures.

It should be noted that the results presented in this section provide a qualitative view of the potential hazards for hydrogen blends. The exact outcome of a fire or explosion depends on various factors, including area confinement and congestion, level of turbulence, and gas composition. Detailed analysis is required for specific cases.

7. Scenario 3: Indoor Pipeline Leaks

This section presents the analysis results for the third scenario (Section 4.1.3) using GOTHIC (Section 4.2.3). This scenario was focused on examining the effect of forced ventilations on the accumulation of flammable gases during an indoor pipeline leak in a kitchen.

7.1 Model Setup

The GOTHIC model layout and the mesh distribution are shown in Figure 52. A uniform mesh size was used throughout the domain ($\Delta x = \Delta y = \Delta z = 0.1$ m). A finer mesh size ($\Delta x = \Delta y = 0.03$ m) was used at the gas injection and exhaust to resolve the fuel gas buoyancy and shear at the outlet. The kitchen stove was modelled using a non-porous 3D blockage (this region was inactive in the simulation).

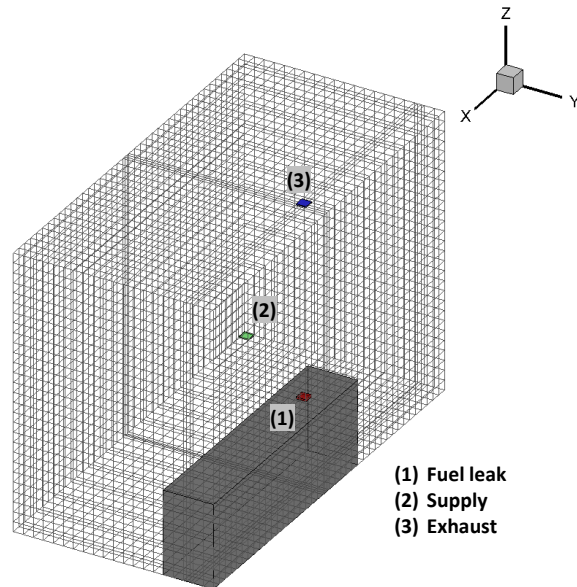


Figure 52: Mesh layout for the GOTHIC simulations.

A flow boundary condition (location #1 in Figure 52) was used to model the gas injection. The ventilation air supply (location #2 in Figure 52) was also modelled as a flow-inlet boundary and the ventilation exhaust (location #3 in Figure 52) was modelled as a pressure outlet boundary condition above the stove.

The FAVOR (Fractional Area/Volume Obstacle Representation) method was used to solve the governing equations of mass, momentum, and energy through the finite volume method. GOTHIC solves these equations on a fully rectangular grid, using a shifted grid for the momentum equation. The standard $k-\epsilon$ model was used to solve the turbulence kinetic energy and dissipation. The FAVOR method employs porosity functions to account for solid obstacles bounded in the rectangular mesh. The governing equations were solved through a conjugate gradient iterative technique using a first-order upwind semi-implicit scheme.

7.2 Model Verification

The GOTHIC model was verified with the simulation results from Ref. [17] for 10% H_2 (90% CH_4) representing a kitchen with no ventilation (windows and doors closed). The gas was released at $0.84 \text{ m}^3/\text{h}$ (0.5 kg/h) through a vertically placed nozzle (10 mm diameter) on the top of the stove (see Figure 30).

Figure 53 shows that the CNL GOTHIC results agreed well with the results from Ref. [17] for the 3D and 2D distributions of fuel concentration at 3000 s. The flammable gas concentration was defined by the flammability limit of the mixture calculated through Equation (1), Section 5.2.3. However, to be consistent with Ref. [17], LFL_{CH_4} in Equation (1) was assumed as 5. Therefore, the LFL was 4.9% for 10% hydrogen blends.

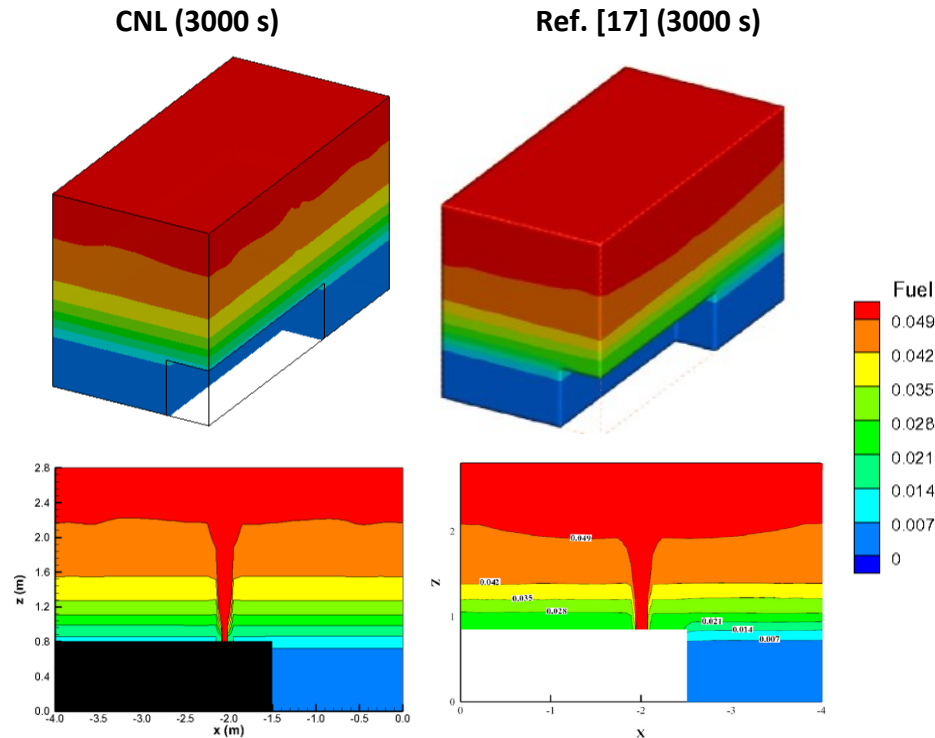


Figure 53: 3D and 2D distributions of fuel concentration following a release of hydrogen blends inside a kitchen at 3000 s. Comparison between CNL results (left side) and results from Ref. [17] (right side).

As observed in the 2D distribution (Figure 53 bottom), during the leak, the blended gas rose as a vertical plume, reached the ceiling, spread to the sidewalls, and descended in the space between the sidewalls and the vertical plume. After the blended gas had been released for 3000 s, the fuel was uniformly distributed on the horizontal plane, but stratified along the height. A layer of flammable gas mixture ($> 4.9\%$ fuel) formed at the ceiling. Without ventilation, this flammable layer would continue to grow with more gas released into the kitchen.

7.3 Sensitivity Study Results and Discussion

A sensitivity study was conducted using the above verified GOTHIC model, and the evaluated cases are presented in Table 7. Forced ventilation and different hydrogen blending ratios (0 to 100%) were tested to identify the conditions that favour flammable gas accumulation inside the kitchen. Case # 1 is the reference case with no ventilation and 10% hydrogen blending ratio. The leak diameter remained the same as the reference case. To maintain the same volumetric leak rate ($0.84 \text{ m}^3/\text{h}$), the mass leak rate decreased from 0.5 to 0.07 kg/h

when increasing the blending ratio from 0 to 100%. The forced ventilation (ACH - air exchange per hour) was chosen based on the ventilation ranges recommended by the Ontario Building Code and ASHRAE [44, 45]. The locations in the kitchen where fuel concentration was analyzed are presented in Figure 54.

Table 7: Test conditions for the scenario 3 sensitivity study.

Case #	H ₂ [%]	CH ₄ [%]	Leak rate (kg/h)	Ventilation [ACH]
1	10	90	0.50	0.0 ^a
2	10	90	0.50	0.5
3	10	90	0.50	1.0
4	10	90	0.50	1.5
5	20	80	0.45	0.0 ^a
6	50	50	0.31	0.0 ^a
7	75	25	0.19	0.0 ^a
8	100	0	0.07	0.0 ^a
9	20	80	0.45	1.0
10	50	50	0.31	1.0
11	75	25	0.19	1.0
12	100	0	0.07	1.0

^a Worst-case scenario representing no ventilation.

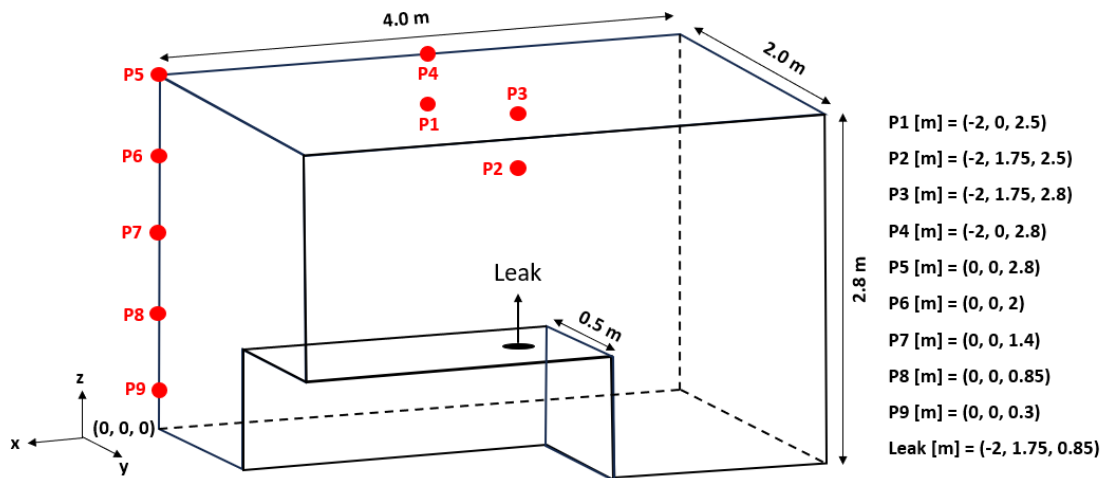


Figure 54: Locations in the kitchen where the fuel concentration was analyzed. P2 and P3 are located above the leak, P1 and P4 are located at the back wall, and P5-P9 are located at the back left corner.

7.3.1 Reference Case

Figure 55 shows the time evolution as a 3D distribution of fuel concentration inside the kitchen, and Figure 56 shows the fuel concentration at different locations in the kitchen and the vertical profile of fuel concentration for the reference case (Case 1, Table 7). Without ventilation, there is an accumulation of flammable gas at the ceiling (red region in Figure 55d, above 2.2 m height, and P1-P5 in Figure 56a) after 3000 s. With more gas leaked into the enclosure, the fuel concentration at other locations (P6-P9, Figure 56a) would eventually exceed the LFL, creating conditions for fire and explosion. Locations P2 and P3 always have the highest fuel concentrations as they are located close to the ceiling above the leak source, whereas P9 has the lowest concentration because it is close to the floor and away from the leak source. Figure 56b shows that the fuel concentration decreased along the height, i.e., high concentrations close to the ceiling and low concentrations near the floor. The concentration gradient was much larger below the 1.5 m height (Figure 56b), suggesting that the majority of the fuel accumulated in the upper region of the kitchen.

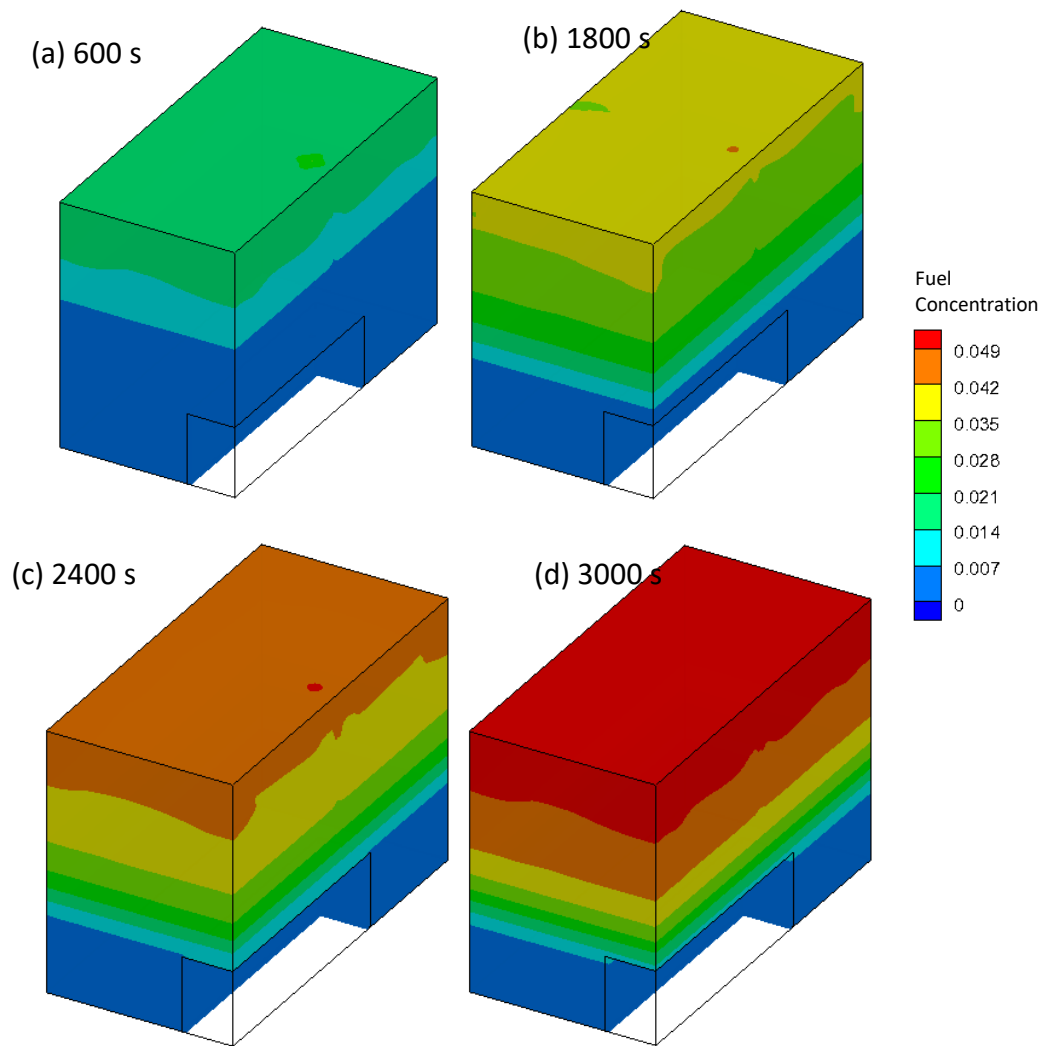


Figure 55: 3D contours of the fuel concentration at different times for the reference case.

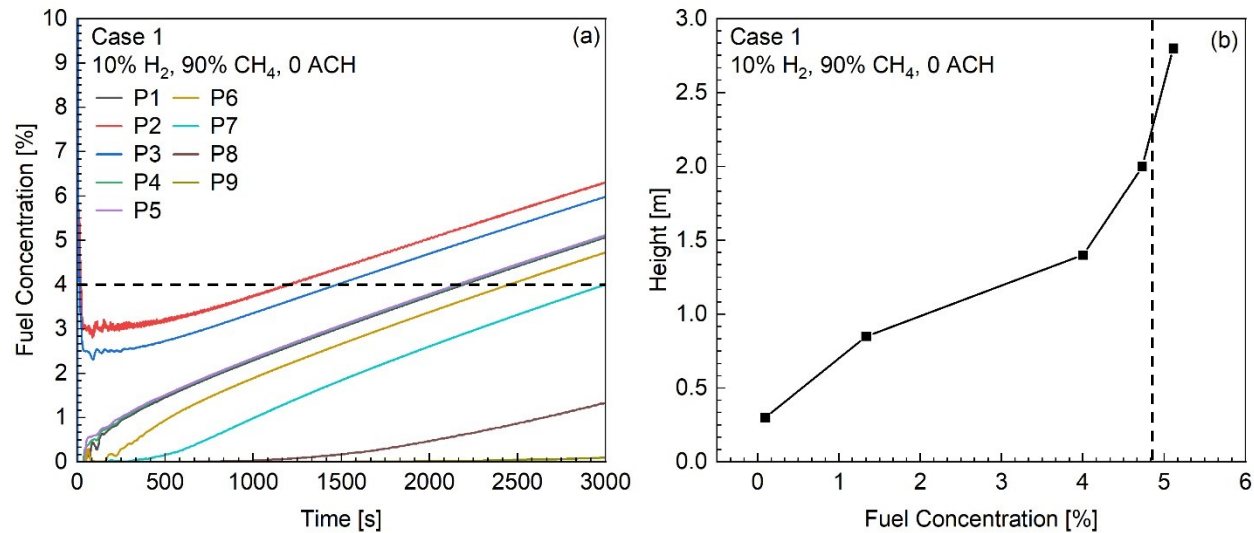


Figure 56: Fuel concentration varying with (a) time for all locations shown in Figure 54 and (b) height (P5-P9) at 3000 s for Case 1 (reference case). Dashed line shows the LFL.

7.3.2 Effect of Ventilation

The effect of ventilation in the kitchen with rates varying from 0.5 to 1.5 ACH is shown in Figure 57, Figure 58, and Figure 59. As described in Section 7.1, the ventilation air was supplied through an inlet flow boundary located at the floor, and the exhaust gas was transported out through a pressure boundary at the ceiling above the leak (see Figure 52). Note that these conditions represent the best-case scenario, as there are several locations where ventilation air and exhaust gas can be applied, producing different results. As it is known from literature [46], if the enclosure is vented through an opening close to the floor and another one close to the ceiling, the layer of buoyant fluid near the ceiling will drive a flow through the openings by natural convection.

Figure 57 shows that a ventilation rate of 0.5 ACH was sufficient to significantly reduce the fuel concentration at the ceiling after 3000 s. With forced ventilation, the fuel concentration remained stratified in the enclosure, but the variation along the height was significantly smaller at higher ventilation rates.

Figure 58a shows that the fuel concentration above the leak source (P3) decreased to levels below the LFL, approaching quasi-steady state at 3000 s. At this location, an increase in the ventilation rate from 0.5 to 1.5 ACH had a small effect on the fuel concentration. In the locations far from the leak source (P5-P9), ventilation also decreased the fuel concentration significantly below the LFL level.

Figure 59 shows that fuel stratification reduced at high ventilation rates (1.5 ACH), showing a more uniform distribution but below the LFL level along the height of the kitchen.

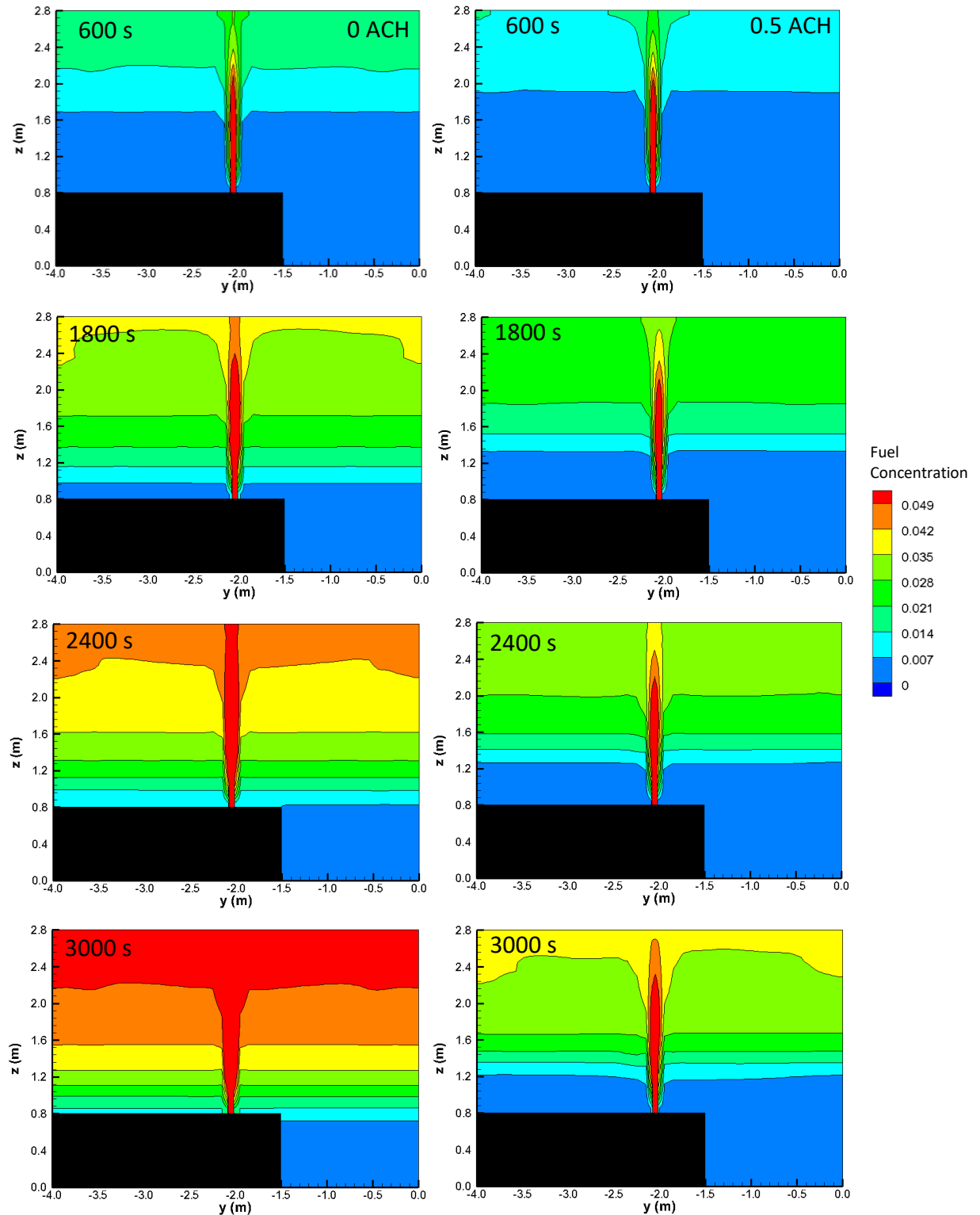


Figure 57: 2D contours showing the fuel concentration at different times for 0 ACH (no ventilation, left side) and 0.5 ACH (right side).

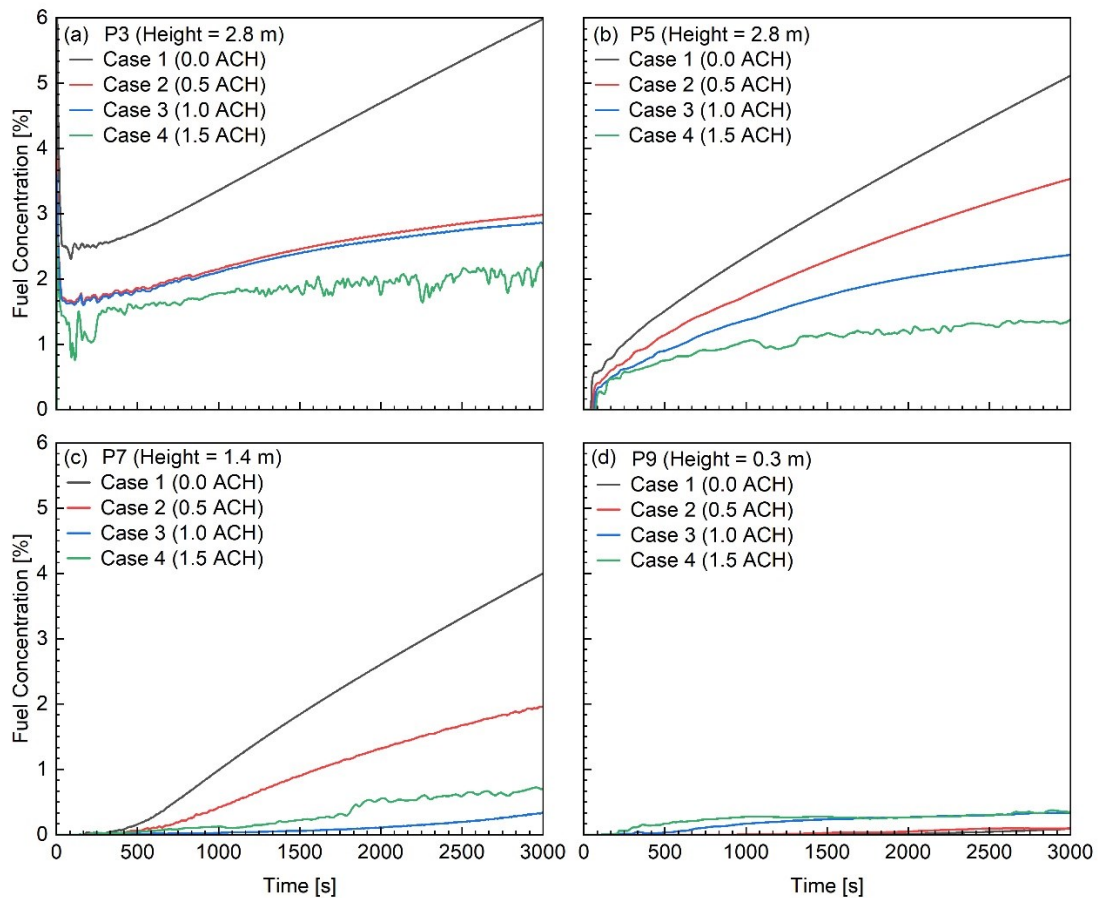


Figure 58: Fuel concentration varying with time for different ventilation rates (Cases 1-4): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).

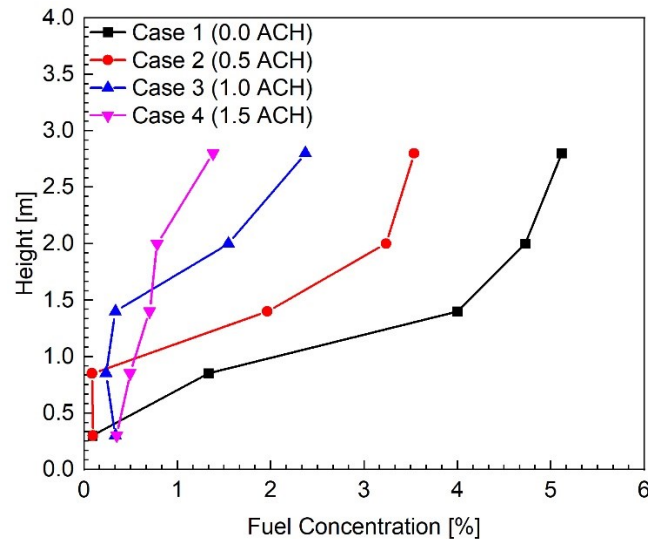


Figure 59: Fuel concentration varying with height (P5-P9) at 3000 s for different ventilation rates (Cases 1-4).

7.3.3 Effect of Hydrogen Blending Ratio and Ventilation

The effect of hydrogen blending ratio is presented in Figure 60 through Figure 62. It should be noted that the volumetric leak rate was maintained at $0.84 \text{ m}^3/\text{h}$ in these cases, therefore the mass rate decreased from 0.5 to 0.07 kg/h when increasing the hydrogen blending ratio from 0 to 100%.

The fuel concentration remained almost unchanged with an increase in the hydrogen blending ratio alone, with results similar to the reference case. The same conclusion can be reached when ventilation is applied for different hydrogen blending ratios (Figure 61). In this case, the effect of ventilation is an important parameter. Additionally, it appears that an increase in the hydrogen blending ratio would not cause more fuel accumulation at a given volumetric leak rate. When considering the lower density of hydrogen, a higher pipeline pressure would be required for hydrogen blends to maintain the same energy content, thus the volumetric leak rate would be higher for hydrogen blends. Therefore, it is expected that the fuel concentration would be higher in the ceiling with more hydrogen blended in the fuel for the same duration of leak.

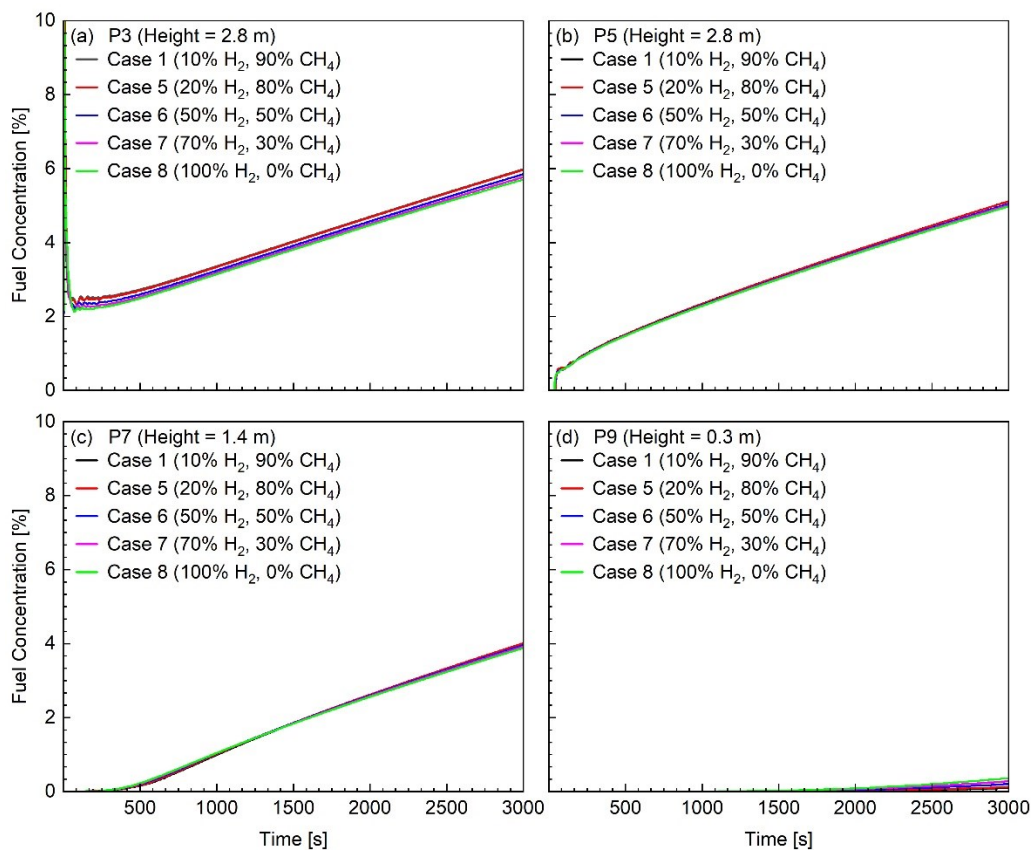


Figure 60: Fuel concentration varying with time for different hydrogen blending ratios without ventilation (Cases 1 and 5-8): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).

Accidental Release of Hydrogen Blends in Pipelines - Numerical Analysis and Safety Implications

153-126510-REPT-004665 Rev. 1

Page 68 of 83

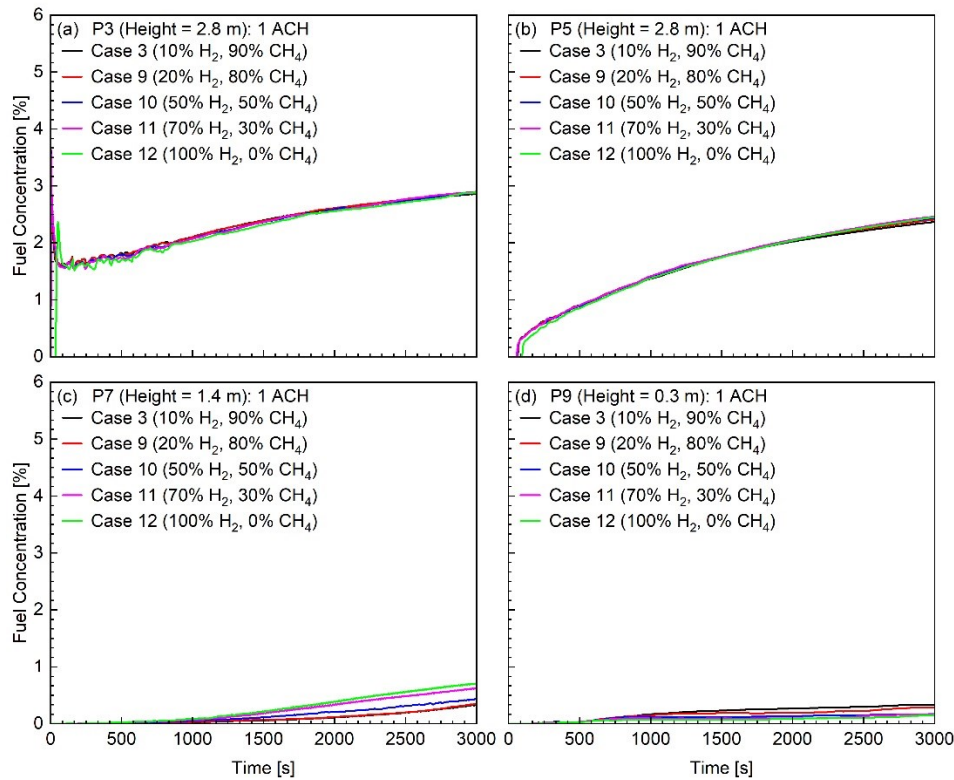


Figure 61: Fuel concentration varying with time for different hydrogen blending ratios (Cases 3 and 9-12): (a) P3 (height = 2.8 m, above the leak), (b) P5 (height = 2.8 m), (c) P7 (height = 1.4 m), and (d) P9 (height = 0.3 m).

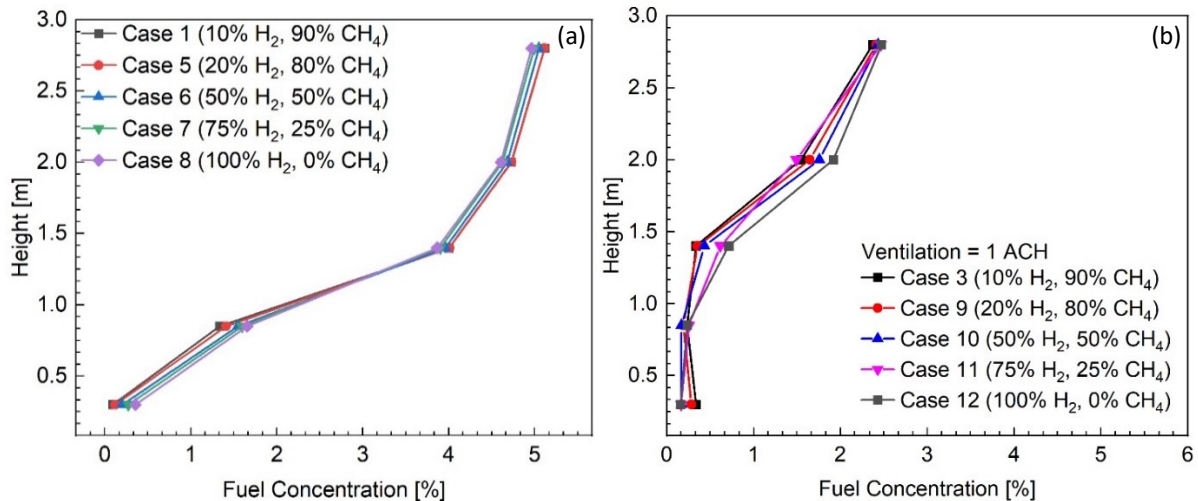


Figure 62: Fuel concentration varying with height (P5-P9) at 3000 s for different hydrogen blending ratios and ventilation: (a) no ventilation (Case 1 and 5-8) and (b) 1 ACH (Cases 3 and 9-12).

7.3.4 Implications for Safety

The accidental release of hydrogen blends in a kitchen can result in an accumulation of a flammable cloud near the ceiling without ventilation. The simulations showed that forced ventilation from 0.5 to 1.5 ACH can decrease the fuel concentration inside the kitchen to levels below the LFL at the given leak rate. This shows the importance of ventilation in houses where pure hydrogen, pure methane, or hydrogen blends will be considered. Moreover, at the same volumetric leak rate, changes in the hydrogen blending ratio from 0 to 100% had almost the same fuel accumulation in the upper region of the kitchen, suggesting that the hydrogen blends have a higher potential for fuel accumulation because a higher pipeline pressure is required to deliver the same volumetric energy content. It should be noted that the end user equipment, such as furnace, may not be designed to operate at higher pressures, thus the pipeline pressure to homes may remain the same.

It should also be noted that the distribution of a buoyant gas in an enclosure depends on the leak rate, momentum and buoyancy fluxes, volume of the enclosure, location of the leak, and ventilation conditions of the enclosure [47]. A more detailed analysis needs to be conducted for specific cases.

8. Summary and Considerations

Blending hydrogen into existing natural gas pipelines has been considered as a promising method to distribute hydrogen on a large scale, and over long distances without the development of new infrastructure. A good understanding of the hazards and safety issues associated with hydrogen blending is important for the use of hydrogen in natural gas pipelines.

In this report, a literature review of the studies on blending hydrogen into natural gas pipelines provided a good understanding of the dispersion, fire and explosion behaviour associated with accidental release of hydrogen blends. The review also identified three representative scenarios involving pipeline leaks in indoor and outdoor environments. In these three scenarios, a few gaps were identified, such as lack of analysis for different blending ratios, leak diameters, pipeline pressures, and weather conditions. These gaps were addressed in this report by conducting simulations with engineering models and CFD codes.

These simulations revealed that an outdoor pipeline leak with hydrogen blending ratio up to 20% did not largely affect the characteristic parameters related to dispersion, fire, and explosion (e.g., leak rate, volume of flammable gas, flame length, heat flux, explosive mass, and overpressure), suggesting that the consequences of these potential hazards did not vary significantly. The results also suggest that the existing natural gas pipeline infrastructure could require minimal modifications for hydrogen blends up to 20%. Above 20% hydrogen blending ratio, the characteristic parameters related to dispersion, fire and explosion increased at higher blending ratios due to the reduction in the gas density, which required an increase in the pipeline pressure to maintain the same volumetric energy content.

For a leak occurring in an urban area, there is a potential for a wider spread of flammable gas near the ground and buildings, potentially increasing the risk of fire and explosion. A release of 100% H₂ resulted in a total available energy lower than for 100% CH₄ due to the lower density

of hydrogen. However, 100% H₂ has a larger flammable energy than 100% CH₄ due to the wider hydrogen flammability range and larger heat of combustion. These results imply that for certain conditions, 100% H₂ would be more dangerous than 100% CH₄. However, it is expected that over time, the methane flammable energy will eventually increase due to air entrainment, decreasing the methane concentrations to flammable conditions, and then increasing its flammable area to levels close to 100% H₂. Further simulations with a taller domain and larger computational time are required to confirm this hypothesis.

When a hydrogen blend release occurs in a closed environment (e.g., kitchen) without ventilation, flammable gas accumulates at the ceiling, spreading downwards until it entirely fills the space. Numerical simulations showed that ventilation was effective in reducing the fuel concentration to levels below the LFL. The effect of hydrogen blending ratio is negligible for a given volumetric leak rate, suggesting that hydrogen blends could have a higher potential for accumulation when a higher pipeline pressure (higher volumetric leak rate) is to be applied depending on the design pressure of end user appliances. However, a more detailed analysis needs to be performed for specific cases.

It is important to note that the risk of a hazard (fire and explosion) depends on the likelihood of an event to occur (e.g., pipeline or components failure frequency, probability of ignition, and probability of mitigation failures) and the severity of the consequence (e.g., heat flux and overpressure). Therefore, a quantitative risk assessment should be implemented to systematically evaluate, control, and mitigate such risks, preventing an incident from turning into an accident with damaging consequences. Risk assessment tools, such as PIPESAFE, HyRAM, and the CNL toolkit, can be used to calculate individual and societal risks of pipelines transporting hydrogen blends. The use of such risk assessment tools, combined with detailed analysis of CFD simulations, can provide a good view of the hazards involving hydrogen blends.

It should be noted that the numerical simulations presented in this report are not representative of real pipeline accidents, rather they are intended to provide insights for potential hazards associated with pipeline leaks. Detailed analysis is required for specific accidental scenarios.

9. Acknowledgements

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Appendix A Pipeline Infrastructure

According to CSA Z662:23, a pipeline is defined as “those items through which oil or gas industry fluids are conveyed, including pipe, components, and any appurtenances attached thereto, up to and including the isolating valves used at stations and other facilities” [48]. CSA Z662:23 also describes that a pipeline system is defined as “pipelines, stations, and other facilities required for the measurement, processing, storage, gathering, transportation, and distribution of oil or gas industry fluids” [48]. A pipeline network is used for connecting the fuel production site to end-user appliances [22], and it is composed of three main classifications: gathering, transmission, and distribution (Figure 63)[2, 4, 49-52]. Table 8 shows the typical operational conditions of each type of pipeline.

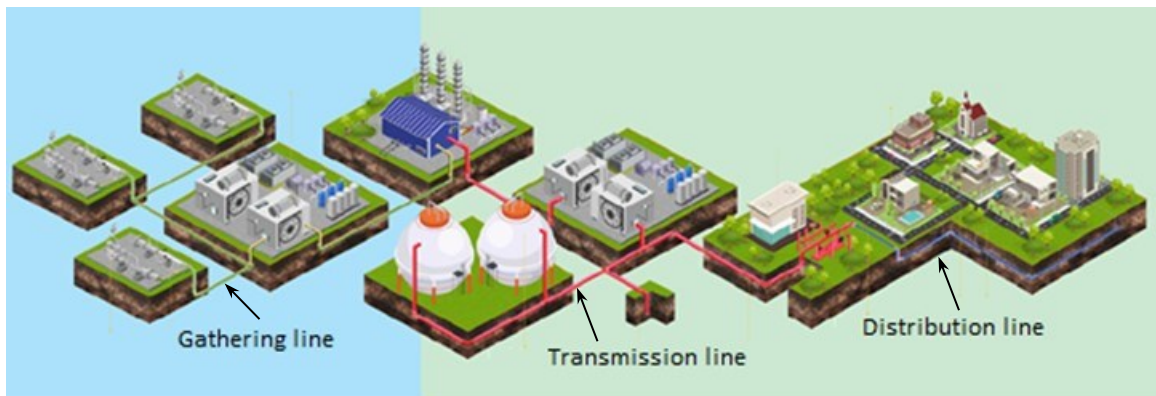


Figure 63: Representation of a pipeline network: gathering, transmission and distribution pipelines [49]. Note that the figure is not to scale.

Table 8: Pipeline operational conditions [2, 4, 49-52].

Pipeline	Diameter (in/mm)	Pressure (psi/MPa)	Cause of Leaks
Gathering	4-36/100-914	N/A	Corrosion, structural stress, failed joints
Transmission	6-48/150-1200	200-1200/1.38-8.27	Corrosion, outside forces, rupture
Distribution	0.5-2/15-50	0.25-60/0.0017-0.41	Outside forces

Gathering pipelines are used to transport gas from production facilities to processing facilities and transmission pipelines (Figure 64). This type of pipeline usually operates at low pressures (the exact range of operating pressure was not found in the literature) and has a diameter between 4 and 36 in (100-914 mm). Leaks usually occur due to corrosion, structural stress, and failed joints [2, 4, 49-52].

Transmission pipelines usually operate at high pressures ranging from 200 to 1,200 psi (1.38-8.27 MPa) and are used for long-distance gas transportation to the distribution lines (Figure 65). This type of pipeline has a diameter ranging from 6 to 48 in (152.4-1,219.2 mm) and typically needs compressor stations to increase the line pressure to achieve long distances. Incidents are usually related to corrosion and outside forces causing catastrophic rupture due to the high internal pressure, which can cause fire and explosions [2, 4, 49-52].

Distribution pipelines transport gas to end-users such as residences, commercial and industrial buildings, etc. (Figure 66). This type of pipeline usually has low pressures of 0.25 to 60 psi (0.0017-0.41 MPa) and small diameters of 0.5 to 2 in (12.7-50.8 mm). Incidents in these pipelines occur mostly due to leaks and outside forces. Leaks from these pipelines can be associated with higher risks, owing to the higher severity of the hazard due to higher population densities typically in the area. [2, 4, 49-52].

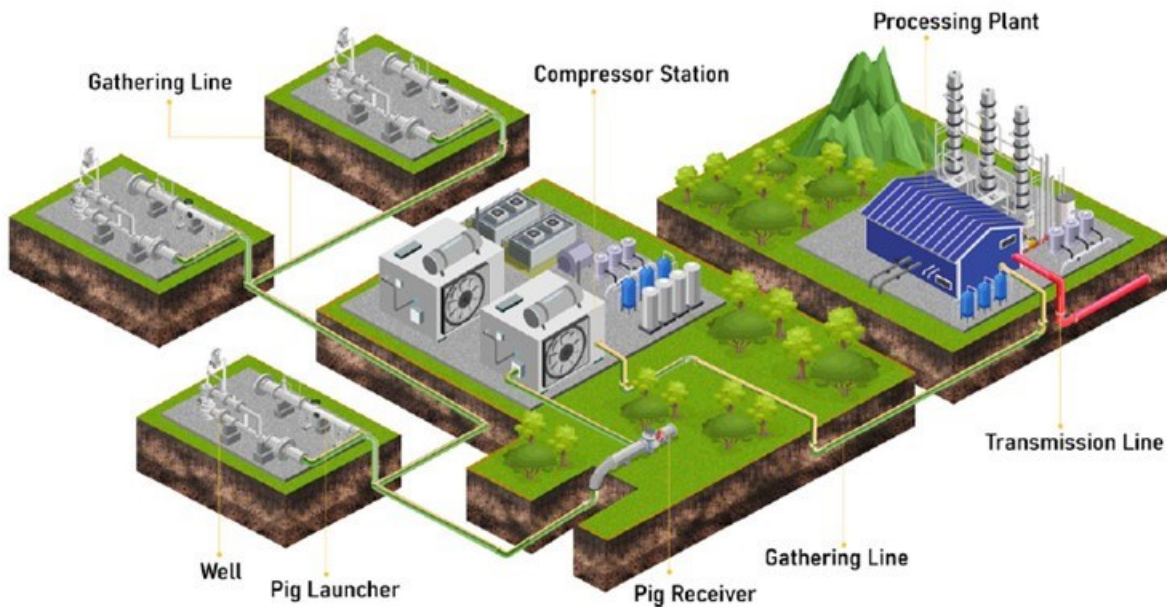


Figure 64: Representation of gathering pipelines shown in green [49]. Note that the figure is not to scale.

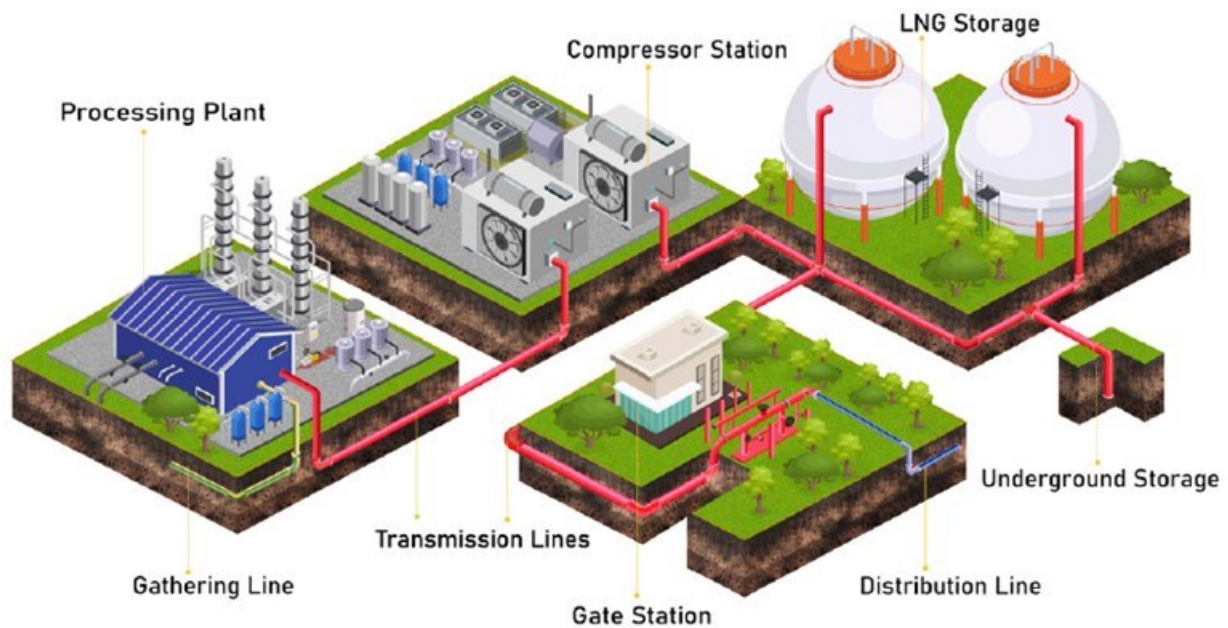


Figure 65: Representation of transmission pipelines shown in red [49]. Note that the figure is not to scale.



Figure 66: Representation of distribution pipelines shown in blue [49]. Note that the figure is not to scale.

Appendix B Overview of Hydrogen Blending Projects

The purpose of this appendix is to show a few (and not all) hydrogen blending projects in Canada and around the world. There are several ongoing hydrogen blending projects currently in the pilot phase [53-56]. However, the available technical information about the success and/or challenges of these projects is limited.

Figure 67 shows the hydrogen blending activities in Canada. A few provinces in Canada, such as Alberta, Ontario, and Quebec, already have ongoing hydrogen blends projects, with hydrogen blending ratios varying from 2 to 20%, whereas British Columbia has established blending policies for future implementation [57].

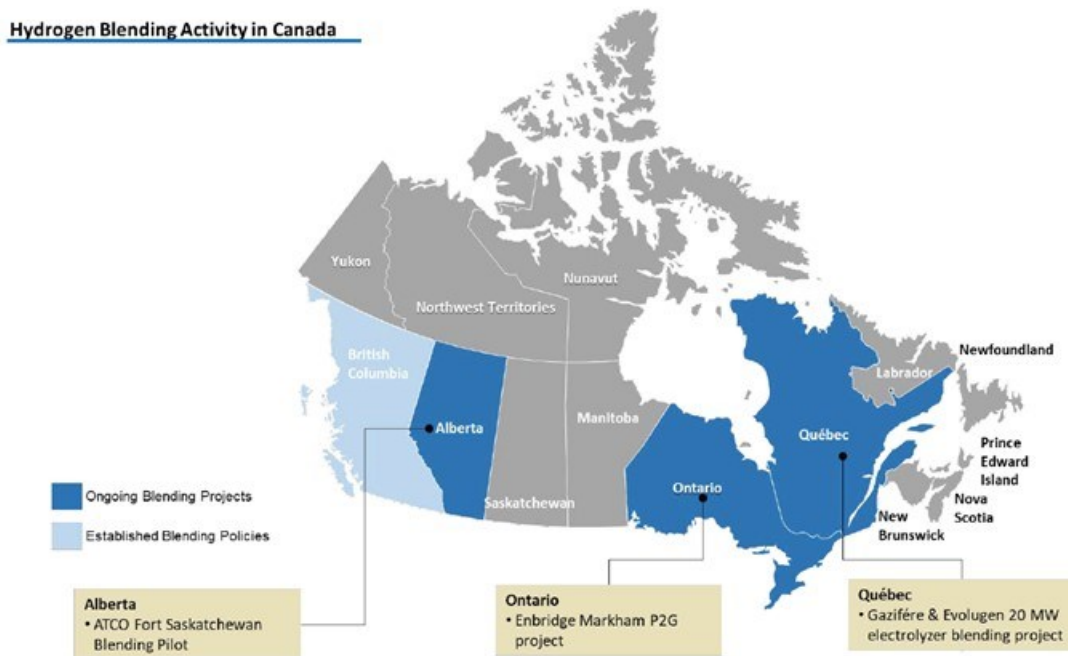


Figure 67: Hydrogen blending activities in Canada [57].

Around the world, Ref. [57] (Figure 68) shows that several countries have ongoing hydrogen blending projects, with maximum hydrogen concentrations of 20%, except in the United Kingdom and The Netherlands, where full conversion of natural gas pipelines to 100% hydrogen has been tested. A more detailed and recent review of hydrogen blending projects was conducted by the Canadian Standards Association [14], where more projects were included and discussed.

Accidental Release of Hydrogen Blends in Pipelines - Numerical Analysis and Safety Implications

153-126510-REPT-004665 Rev. 1

Page 79 of 83

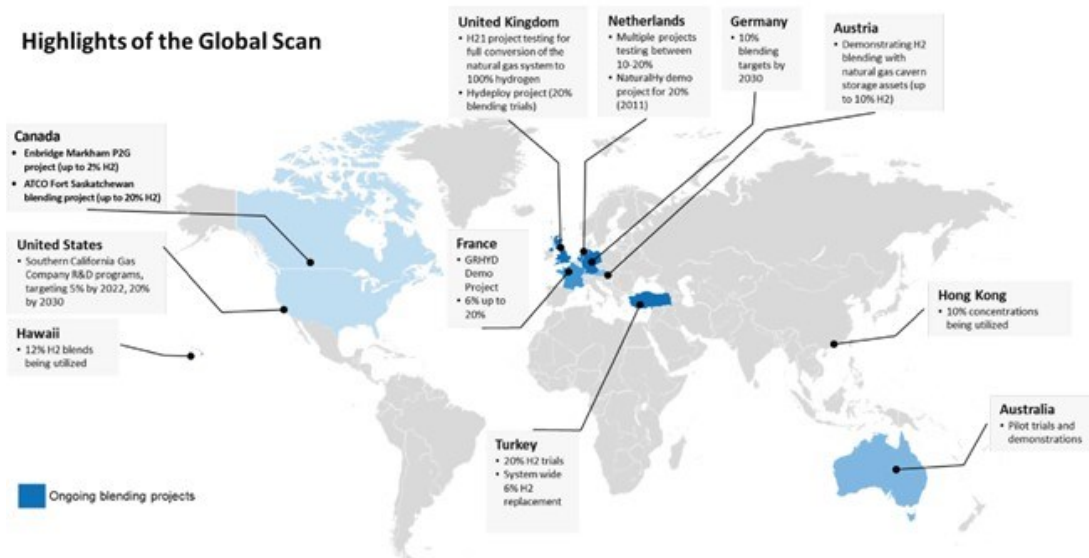


Figure 68: Hydrogen blending activities around the world [57].

Table 9: Status of ongoing blending projects worldwide [57].

Country	Ongoing Blending Projects
Australia	Pilot trials and demonstrations.
Austria	Demonstrating hydrogen blending with natural gas cavern storage assets (up to 10% H ₂ blending ratio).
Canada	Enbridge Markham P2G project (up to 2% H ₂ blending ratio). ATCO Fort Saskatchewan blending project (up to 20% H ₂ blending ratio). Gazifere & Evolugen (Quebec): 20 MW electrolyser blending project.
France	GRHYD demonstration project (from 6% to 20% hydrogen blending ratio).
Germany	10% H ₂ blending ratio targets by 2030.
Hong Kong	10% H ₂ blending ratio being utilized.
Netherlands	Multiple projects testing between 10-20% blending ratio and some pilots testing 100% H ₂ .
Turkey	20% H ₂ blending ratio trials with 6% hydrogen blending ratio replacement.
United Kingdom	H21 project testing for full conversion of the natural gas system to 100% H ₂ . HyDeploy project (20% H ₂ blending ratio).
United States	Southern California gas company R&D programs targeting 5% hydrogen blending ratio by 2022 and 20% H ₂ blending ratio by 2030. Hawaii: 12% H ₂ blending ratio being utilized.

Appendix C Effect of Pressure and Blending Ratio on Gas Density

Figure 69 shows the effect of hydrogen blending ratio and pipeline pressure on gas density. The density was evaluated inside the pressurized pipeline. This figure shows that the gas density decreased from 21.0 to 2.5 kg/m³ at 3 MPa and from 80 to 8 kg/m³ at 10 MPa when the hydrogen blending ratio increased from 0 to 100% H₂. However, when the pipeline pressure increased from 1 to 10 MPa, the gas density increased from 5 to 59 kg/m³.

The hydrogen density at atmospheric pressure (0.083 kg/m³) is lower than the methane density (0.659 kg/m³). Therefore, when more hydrogen is added, the mixture density decreases. On the other hand, pressure and density are directly proportional. So, an increase in pressure results in an increase in the gas density. This density increase due to an increase in pressure is more evident for low hydrogen blending ratios. When the hydrogen blending ratio is 100%, density is not too sensitive to pressure, which means that for pipelines with 100% hydrogen, pressure does not play a large role in the gas density. The opposite occurs for 100% CH₄, where the density is highly sensitive to pressure.

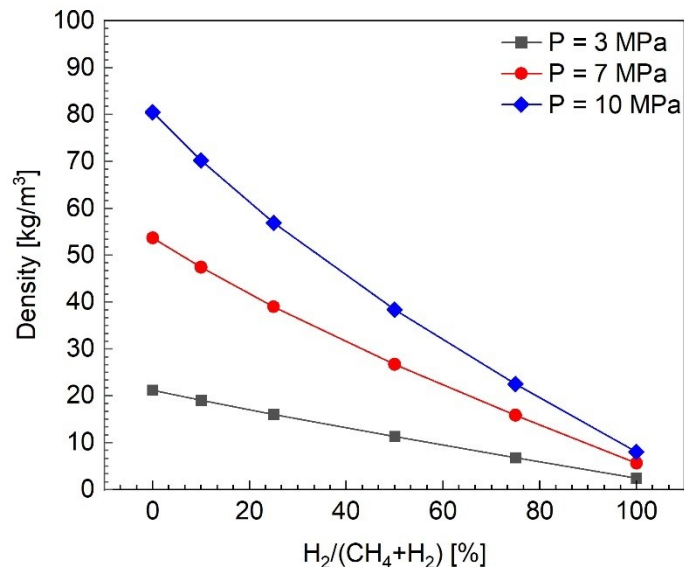


Figure 69: Density of the mixture changing with hydrogen blending ratio and pressure.

Appendix D Coupled Effect between Pipeline Pressure and Hydrogen Blending Ratio on Safety Parameters

To analyze the coupled effect between pipeline pressure and hydrogen blending ratio, the volumetric energy content (blend density multiplied by the heat of combustion of the blend) was fixed, i.e., as the density decreased due to the increase in the hydrogen blending ratio, the pressure was also increased to deliver the same volumetric energy content.

The reference case for the energy calculations was considered as 100% CH₄ with pipeline pressure equal to 3 MPa (Table 10), i.e., an increase in the hydrogen blending ratio should result in the same volumetric energy content as 100% CH₄. The reference volumetric energy was then calculated by multiplying the methane density at 3 MPa (21.16 kg/m³) by the heat of combustion of methane (50 MJ/kg), which gives 1058 MJ/m³. Then, this reference value was used as basis for the calculation of the blend density and pipeline pressure required to maintain the same volumetric energy. Table 10 shows that up to 20% hydrogen blending ratio, there was only a slight increase in pressure and decrease in blend density. However, for large hydrogen blending ratios (75%) density decreased approximately 40%, requiring two times increase in pressure to maintain the same volumetric energy. For 100% H₂, the density decrease is about three times, requiring almost four times increase in pressure.

Table 10: Calculation of the pipeline pressure and blend density at a fixed volumetric energy content.

Volumetric Energy [MJ/m ³]	H ₂ [%]	Pipeline Pressure [MPa]	Blend Density [kg/m ³]
1058 ^a	0 ^a	3.00 ^a	21.16 ^a
1058	20	3.73	20.30
1058	50	4.95	18.30
1058	75	6.75	15.30
1058	100	10.65	8.82

^a Reference case.

Figure 70 shows the results of the leak rate, explosive mass, and flame length varying with hydrogen blending ratio and leak diameter at a given volumetric energy content. These results were simulated with the CNL hydrogen risk analysis toolkit presented in Section 4.2.1.

When the hydrogen blending ratio increased up to 75%, leak rate, explosive mass, and flame length also increased. However, between 75 and 100% H₂, there is a shift in the values of the leak rate and explosive mass for leak diameters higher than 100 mm, i.e., leak rate decreased, and explosive mass increased with an increase in the hydrogen blending ratio. This shift is caused by the interplay between the decrease in density and increase in pressure (Table 10). For 100% H₂, the increase in pressure, although almost four times higher than the reference pressure, is not enough to increase the leak rate to levels shown in the 75% H₂ case (139 mm leak diameter). Consequently, the explosive mass decreased, which directly linked to the leak rate, also decreased. The flame length, on the other hand, is not affected by the leak rate; therefore, it increased with leak diameter, pressure, and hydrogen blending ratio.

However, the increase is higher for 100% H₂ due to the higher heat of combustion of pure hydrogen as compared to the heat of combustion of the blend.

The results for the heat flux and overpressure are presented in Figure 71 and Figure 72. Both heat flux and overpressure increased when pressure and hydrogen blending ratio increased. Up to 20% H₂, this increase is not very significant, but for hydrogen blending ratios larger than 20%, the increase is substantial.

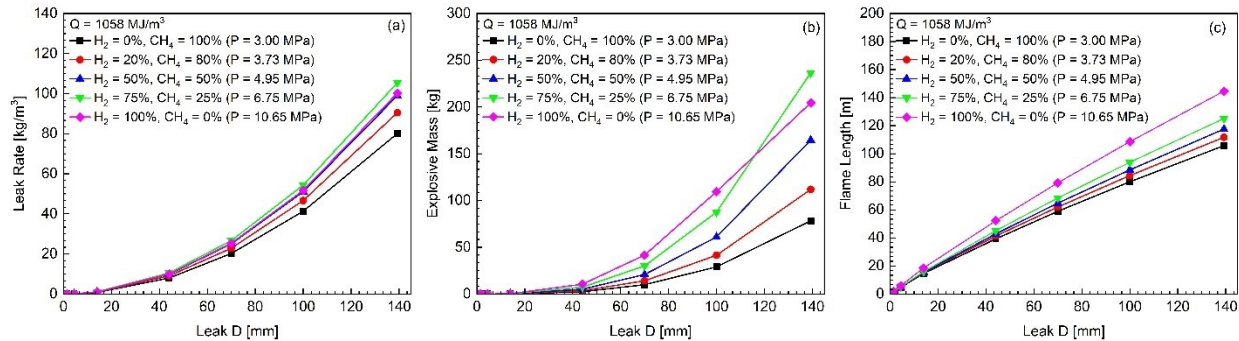


Figure 70: (a) Leak rate, (b) explosive mass, and (c) flame length changing with hydrogen blending ratio and leak diameter at a given energy content.

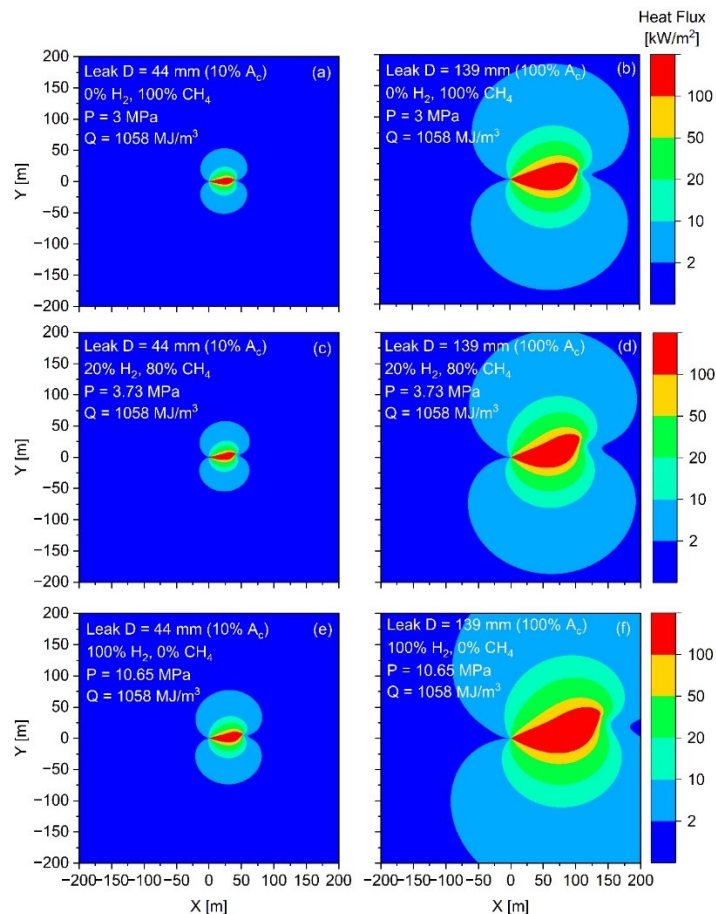


Figure 71: Heat flux varying with hydrogen blending ratio and pressure.

Accidental Release of Hydrogen Blends in Pipelines - Numerical Analysis and Safety Implications

153-126510-REPT-004665 Rev. 1

Page 83 of 83

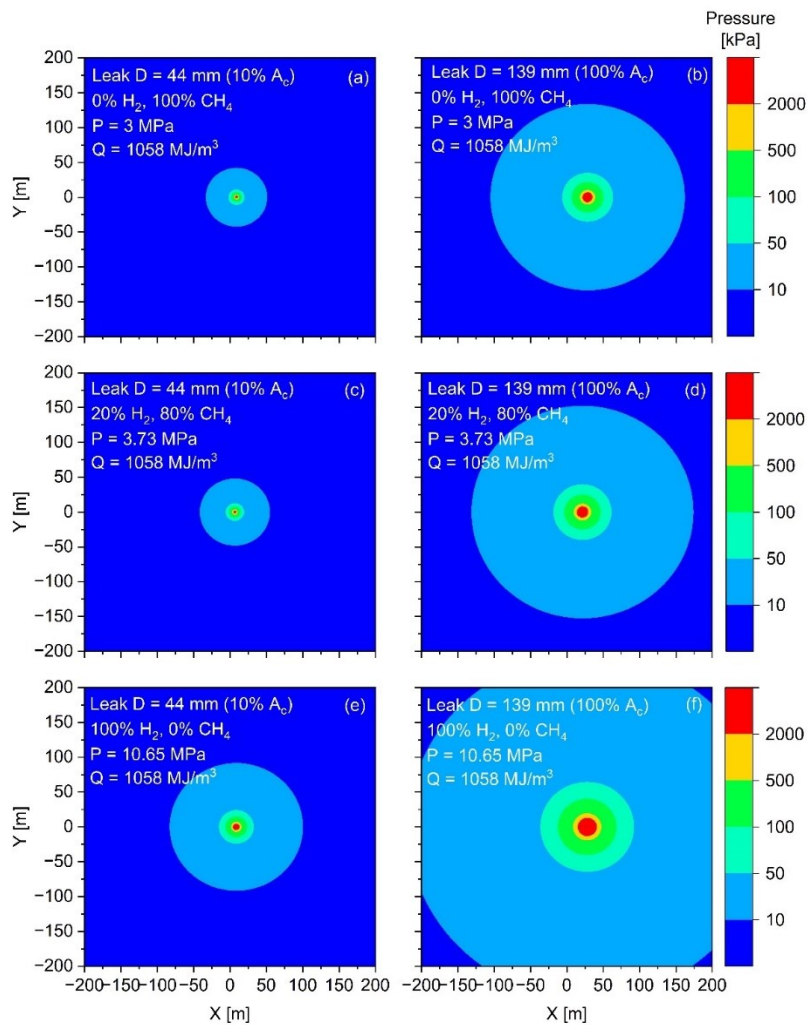


Figure 72: Overpressure varying with hydrogen blending ratio and pressure.