NRC·CNRC Clean Energy Innovation

Data Collection and Analytics for Hydrogen Blending Testing on End-use Appliances and Related Controls

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Author(s): Yeong Yoo*, Aminul Islam**, and Francois Girard**

CBI: *NRC-AST, **NRC-CEI

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Executive Summary

This report summarizes the analysis on "Hydrogen Blending on End-use Appliances and Related Controls," aggregates findings without disclosing sensitive information, and includes recommendations for future research based on unbiased analytical results. This data was collected from various interested and affected parties participating in CSA Group's standardization activities. This work aims to enable the CSA applicable committees or associated members to develop detailed plans for further research.

NRC conducted data analytics based on responses from eight participants, that tested a total of 74 appliances. The hydrogen blending percentages ranged from 5-100 vol%, with nearly two-thirds of tests conducted at 30-40 vol% H2 or 70 vol% H_2. Over 95% of tests were conducted on a single appliance unit, limiting the dataset's reliability.

Out of the 74 tested appliances, 14 were tested with less than 20 vol% hydrogen. For the remaining 60 appliances, the test fuel contained 20-100 vol% hydrogen. Fifty-seven appliances indicated a safe upper limit of 20 vol% or higher based on the parameters measured by the participants. In this document, the ‘safe upper limit’ refers to the maximum vol% hydrogen that individual participants considered safe based on their specific test parameters. Only three appliances—a storage water heater, an atmospheric boiler, and a cooktop—exhibited flashback or burner overheating at higher hydrogen concentrations and indicated a safe upper limit of 10 or 15 vol% hydrogen.

With fuel blends of 10-80% H_2, flashback was observed under various conditions such as steady state, cold start, re-ignition, and shutdown. Among the 74 tested appliances, flashback was not measured or information was unavailable for 25 appliances. Of the remaining 49 appliances, 18 had no issues, while 31 exhibited flashback problems. One appliance exhibited flashback at 10% H_2 under steady sate condition while three appliances exhibited flashback at 20% H_2 during cold start and re-ignition. Flashback issues were more prominent during cold start and re-ignition compared to steady state or shutdown conditions.

Burner overheating can reduce appliance durability over time. Hence. it is important to assess overheating temperatures to evaluate potential degradation. In all cases where overheating was observed, the blended fuel contained 30-70% hydrogen. Among the 74 tested appliances, burner overheating was not measured or information was not provided for 50% of the appliances. Of the remaining appliances, 30% showed overheating issues. Eleven appliances exhibited burner overheating over 5°C (9°F) compared to the burner deck temperature measured without hydrogen.

Certain burners, such as direct-fired burners, power flame burners, and staged fuel burners, have a relatively flexible safe upper limit exceeding 30 vol% hydrogen. Most burner types have a lower safe upper limit, typically between 20 and 25 vol% hydrogen. Notably, three burner types exhibited issues at lower hydrogen levels: the atmospheric burner (in cooktops) showed flashback, the pre-mixed burner (in storage water heaters) showed flashback, and the tube burner (in atmospheric boilers) experienced burner overheating. These burners had a safe upper limit below 20 vol% hydrogen. Detailed information on these three cases is tabulated in Table 4-3.

Most cases showed ignition times within 4 seconds, but 3 appliances showed ignition delays exceeding 4 seconds with a blended fuel containing 40% hydrogen. There was no significant change in ionization or UV signals as hydrogen content increased; however, many cases did not report or measure ionization signal changes during hydrogen blending tests.

CO emissions are usually affected by factors such as the Wobbe index, oxygen concentration in flue gas, equivalence ratio, flame temperature, burner deck temperature, appliance type, burner type, and primary and secondary air flows. Over two-thirds of the tested appliances showed constant or decreased CO emissions compared to tests without hydrogen in the fuel.

Similarly, over two-thirds of the tested appliances displayed constant or decreased NOx emissions compared to tests without hydrogen. Less than one-third exhibited an increase in NOx emissions with higher hydrogen content. Specific burners, such as staged fuel burners and power flame burners, showed only constant or increasing NOx emissions and higher combustion temperatures than other burner types. Some burner types, including ultra-low NOx burners, dry low NOx burners, atmospheric burners, IR burners, and tip-jet burners, only exhibited decreased NOx emissions with increasing hydrogen content.

Depending on the tested appliances, different participants utilized different standards, while some performed tests without following any specific standard. Since 77% of the tested appliances were residential, the CSA ANSI Z21 series standards for residential appliances were the most commonly used, applied in almost 84% of cases that reported utilizing a standard testing procedure. The CSA ANSI Z83 series of standards for industrial or commercial appliances and the CSA B149 Gas codes were also utilized but accounted for a limited number of reported cases.

Following are some recommendations for future research:

1. Ignition, burner overheating, and flashback (steady-state, cold-start, re-ignition, and shutdown) are the key factors that needs to be considered during testing.
2. Out of 60 appliances tested with more than 20 vol% H_2, only three indicated a safe upper limit below 20 vol% H_2. Detailed investigation of these appliances would help generalize any safe upper limit for various end-use appliances with hydrogen blends.
3. Different studies have controlled variables such as air-to-fuel ratios and gas inlet pressure, which affect emission levels (e.g., CO, NOx, and UHC). Standardized controls on air, fuel flows and pressures for different appliance types should be specified to enhance reliability and allow objective comparison of datasets.
4. To enhance reproducibility, test and collect data from multiple units of the same model for accurate assessment of combustion performance and safety issues.
5. Further research on the performance and safety of appliances for reproducibility and mid- to long-term durability is required to conclusively report safe upper limits of hydrogen blending and identify causes of safety issues (ignition, burner overheating, and flashback).

1 Introduction

NRC launched its Advanced Clean Energy (ACE) Program to accelerate the development of clean renewable fuels, and energy storage materials and devices to allow for fuel switching and electrification across all sectors to support Canada's net-zero target by 2050. Hydrogen R&D, one of three pillars under the ACE program includes hydrogen production, distribution, storage and conversion.

NRC published a review paper, "Review of hydrogen tolerance of key Power-to-Gas (P2G) components and systems in Canada" in July 2017 [1]. This report presented the codes, standards, and regulations (CSR), R&D needs and gaps, hydrogen tolerance of key components and systems, demo cases, and Technology Development Matrix (TDM) analysis identified and determined for P2G technology. A detailed investigation of CSR on the injection of renewable hydrogen and renewable natural gas (RNG) into natural gas (NG) pipelines has clarified current constraints and safety considerations in terms of gas injection, transport and end-use systems. It was determined that a hydrogen concentration limit up to 20% might pose some challenges with regard to end-use appliances and gas analysis methods. Further research is needed to address end-user concerns regarding process control, emissions and safety.

In addition, an updated report, "H2 blending into the Canadian NG grid network and H_2 tolerances in end-use appliances" was also published in March 2022, that includes CSR for H_2 blending into NG grid and H_2 blends-fueled end-use appliances. This report reports that the H2 blending limit in NG pipelines may be uncertain and system specific, limited by grid integrity, safety, energy transport capacity, and the specifications of end-use applications. It is important to determine how hydrogen blending thresholds impacts certification of existing appliances, especially legacy appliances, and whether further tests are required on new appliances.

As a leader in standards development, CSA is engaged in multiple initiatives supporting the development of standards related to hydrogen. CSA is exploring hydrogen technologies that touch the entire value chain of the hydrogen ecosystem. In addition, CSA has an extensive hydrogen standards portfolio for the transportation sector that includes fuel cells, storage, and fueling stations.

CSA Group published the Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases research report in May 2021. This study examined the performance of space and water heating appliances fueled by methane as a natural gas proxy, and methane/hydrogen blends containing up to 15% hydrogen. The appliances were tested for input rate, ignition and burner operating characteristics, combustion products properties, and gas leakage, using three gas mixtures (pure methane, 5% hydrogen/methane blend, and 15% hydrogen/methane blend mixtures) per applicable CSA/ANSI Z21 series Standards. Effects of gas composition on furnaces were also tested for temperature rise and heating tube temperatures. Condensing appliances were additionally assessed for dew point temperatures and acidity. Overall, appliances showed no major operable issues and consistent trends of decreased heat output and CO_2 emissions with increase of hydrogen content in methane/hydrogen blends. Consequently, to meet the same heat demand, the appliances would need to operate for longer periods which would result in additional carbon dioxide emissions. However, the overall CO_2 emissions for the same heat output are still expected to be lower with the use of blends compared to natural gas. Carbon monoxide and nitrogen oxide measurements were in the acceptable ranges regardless of the type of fuel used. No consistent trends were observed for other measured properties, indicating that hydrogen mixtures up to 15% do not significantly affect these parameters. Future testing of gas blends containing 5% and 15% of hydrogen as examined herein, as well as higher hydrogen amounts, ought to incorporate natural gases to determine more representative results.

Interest was expressed by industry to conduct a follow up project to evaluate additional product categories and increased blend rates. It was determined that an initial task would be required to review what testing and research has been done related to Hydrogen blending on end-use appliances and related controls, before a test plan could be developed for the research project.

The objective of this project is to conduct data collection and analysis to review hydrogen blend testing and research on end-use appliances and related controls conducted by North American gas utilities, interested and affected parties and relevant research groups. The project aims at providing unbiased analytical results and aggregated findings without disclosing any specifically sensitive information. This work may enable CSA standard development committees to develop detailed plans for the preparation of a collaborative research proposal on “Hydrogen Blending on End-use Appliances and Related Controls” that might be supported by a consortium of gas utilities and other interested and affected parties. For data collection and analytics, CSA coordinated the preparation and distribution of the data collection request and provided NRC with feedback of analyzed data. NRC had developed the technical information request, excel-based template for detailed appliances and testing conditions, and additional data collection template for in-depth interviews with the participants.

This report summarizes the analysis of “Hydrogen Blending on End-use Appliances and Related Controls”, aggregated findings obtained through data collection and analytics, and recommendations for future research.

2 Suitability of Appliances for Natural Gas and Hydrogen Blends

Several North American hydrogen/natural gas blending pilot projects are underway. In Alberta, ATCO Gas has started to inject 5% hydrogen by volume into a section of its network serving about 2000 customers starting in late 2022 [2]. Enbridge Gas in Ontario is injecting 2% hydrogen by volume into a network serving approximately 3600 customers in the Toronto metropolitan area from 2021, abating up to 117 tons of carbon dioxide (CO_2) from the atmosphere every year [3]. In California, San Diego Gas & Electric and SoCalGas are conducting multiple demonstrations, blending hydrogen from 1% to 5% by volume and up to 20% in various network sections from 2021 to 2026 [4]. Dominion Energy in Utah has started with a 5% hydrogen injection at a training facility [5]. NW Natural in Oregon is testing a 5% hydrogen blend at a training facility with potential expansion into customer networks [6]. Lastly, Hawaii Gas operates a distribution network on Oahu delivering manufactured gas with 10-15% hydrogen by volume, serving about 30,000 customers [7].

2.1 Gas Appliance Combustion Fundamentals

2.1.1 Combustion System

A gas appliance combustion system controls and regulates the flow of gas, premixes fuel and air, and ignites the gas mixture. Figure 2-1 shows the schematic of typical natural gas burner system. The appliance combustion systems consist of five major components [8]:

- Gas supply,
- Air supply and fuel mixing,
- Burner head,
- Ignition,
- Controls and safety devices.

2.1.1.1 Gas Supply

The gas supply system typically consists of gas supply line, gas regulator, gas valve and burner supply line. The gas supply line extends from the meter outside the home to the gas valve within the appliance and usually includes an external shut-off valve at the entrance to the appliance. The gas regulator reduces and maintains the gas pressure from the supply line to the burner supply line within a narrow range of the design operating pressure across various gas input rates. Typically, there are three types of regulating devices: adjustable, multi-stage, and non-adjustable. Adjustable regulators allow for external adjustment of outlet pressure; multi-stage regulators offer multiple outlet pressure settings; and non-adjustable regulators are preset to a single pressure. The gas valve controls the gas flow rate, either operating as a simple on/off device or modulating the gas flow gradually. The burner supply line runs from the gas valve to the manifold, which distributes gas to the burners. The pressure through the manifold remains constant, and the manifold orifices regulate the gas flow to individual burners based on the orifice size and upstream pressure.

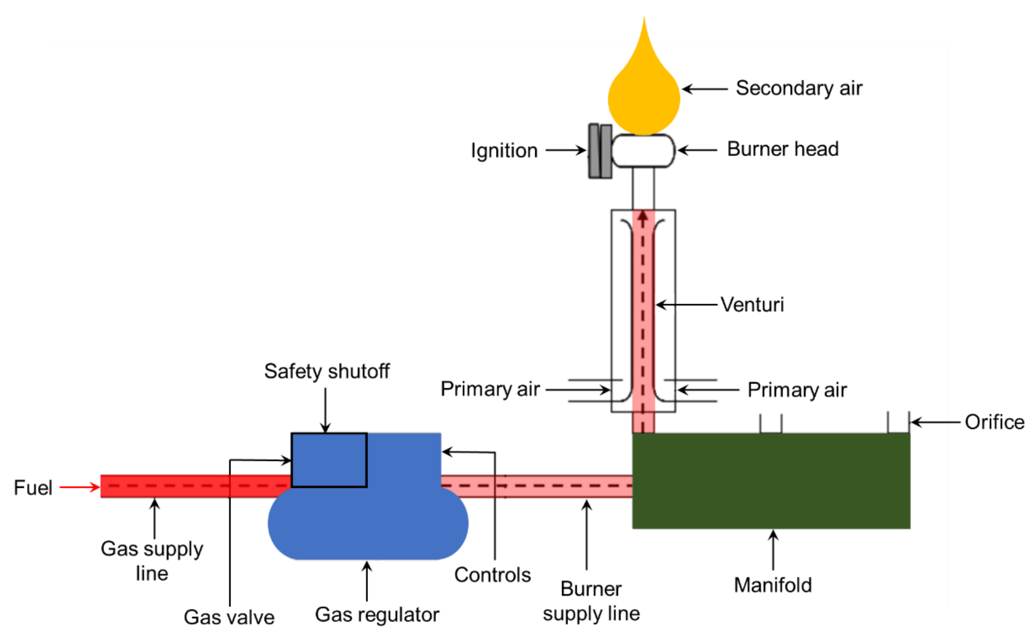


Figure 2-1 Schematic of natural gas burner system [8].

2.1.1.2 Air Supply and Fuel Mixing

To achieve complete combustion and stable flames, burners are designed for proper air and fuel mixing. Figure 2-2 illustrates a schematic of typical burner design, showing primary and secondary air flows and fuel mixing. It's important to distinguish between 'primary' air, added before combustion, and 'secondary' air, drawn in from around the flame. Some burners have fixed primary air openings, with adjustable devices controlling air flow. Fuel enters the burner through the orifice, and the volume and velocity of gas injected into the burner are controlled by the combination of gas pressure and orifice size. Adjusting the gas supply (manifold) pressure changes the velocity of the gas stream, altering the Venturi effect and thereby adjusting the amount of primary air drawn into the burner. The Venturi, a short tube with a constricted throat-like passage, increases velocity and creates negative pressure relative to the air surrounding the burner. This negative pressure draws in atmospheric air, mixing it with the high-velocity gas flow. The mixing tube, positioned between the Venturi and the burner head, is where gas and primary air are mixed as they move along the tube.

2.1.1.3 Burner Head

The burner head is the point where the area is greatest and the velocity is at its lowest point. As a result, the pressure is at its highest point within the burner. The increased pressure allows the gas/air mixture to be uniformly distributed to the burner ports with enough velocity to match the flame speed of the fuel gas. The burner port is an opening that discharges the air-gas mixture for ignition, distributes flames for even heat transfer, and spreads the flames to reach secondary air. Based on the extent to which combustion air is mixed burners can be classified as partial (rich) premix, full premix, and non-premix (non-aeration) burners. In partial premix burners, a fraction of the air required for complete combustion is provided upstream of the burner head. The remainder of the air is drawn in from around the flame (secondary air). In full premix burners, fuel and all required air are mixed upstream of the combustion zone, allowing control of the fuel-air ratio, flame temperature, and NOx and CO production. These burners typically use blowers to ensure adequate combustion. Non-premix burners mix gas with air after passing through the burner head, eliminating the need for small air supply openings prone to blockage by dirt, lint, or cooking residues.

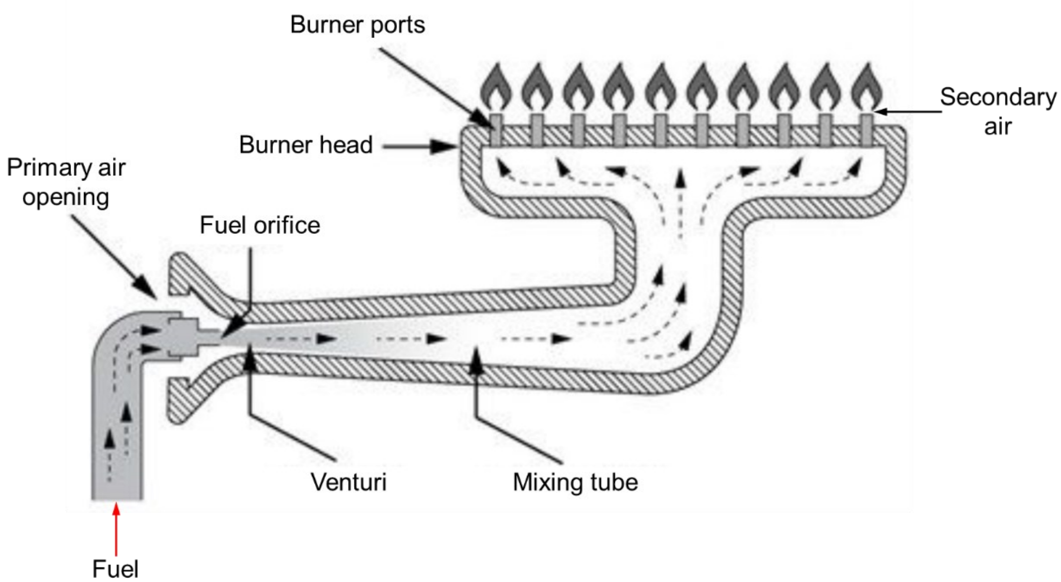


Figure 2-2 Atmospheric burner design illustrating primary and secondary air flows and fuel mixing [9]**.**

2.1.1.4 Ignition

There are three common ignition systems in residential gas appliances; standing pilot (found in most storage water heaters), electronic ignition (used in cooking equipment and tankless water heaters), and manual ignition (seen in older fireplaces and ovens). Standing pilot systems use a small auxiliary burner to maintain a constant flame to ignite the main burner. Electronic ignition systems, widely used in residential appliances, include intermittent pilot ignition, intermittent direct ignition, and hot surface ignition. Intermittent pilot ignition uses a spark to ignite a temporary pilot flame, which then lights the main burner. Intermittent direct ignition sparks directly to light the main burner, often used in cooktops. Hot surface ignition, common in ovens and furnaces, uses a silicon carbide element that glows red-hot when an electric current passes through it to ignite the main burner. Older appliances still utilize manual ignition, where the user manually lights a pilot flame with a match to ignite the main burner.

2.1.1.5 Controls and Safety Devices

A safety shutoff device stops the gas supply to the burner(s) if the ignition source fails. This device can turn off the gas supply in main burners, pilots, or both. Residential gas appliance burners feature two types of controls; on/off and modulating. On/Off controls are used in devices that are turned on/off manually, such as clothes dryers, or automatically, such as water heaters. Modulating controls allows variable fuel input rates, commonly found in cooktops and occasionally in space heating appliances. Tankless water heaters have modulating controls that operate 2–3 banks of burners, which can be used in various combinations.

There are different types of safety devices available for natural gas appliances. Common safety devices include flammable vapor ignition resistance, safety shutoffs, thermal cutoffs, and oxygen depletion sensors. A flammable vapor ignition resistance device utilizes a sensor inside the combustion area to detect the ignition of flammable vapor and shut off the gas flow to the burner and pilot light. This type of safety device is specific to water heaters. A thermal cutoff fuse, also known as an 'over-limit switch', is designed to electrically shut down the unit when it senses excessive temperatures either inside the combustion chamber or, in the case of some water heaters, inside the storage tank. Oxygen depletion sensors, on the other hand, are designed to prevent accidental carbon monoxide poisoning by shutting down the appliance when the oxygen concentration in the air drops below a specified level.

A properly functioning burner should have uniform heat and flame distribution, complete combustion without carbon or carbon monoxide escape, stable flames that do not lift from the burner ports, ready ignition with flames that travel easily across the burner, and quiet operation. Simple adjustments can help a well-designed burner perform satisfactorily under varying conditions: a small hard blue flame or flames blowing off the burner ports indicates too much primary air, necessitating closing the air shutter, while a soft, blurred, or yellow-tipped flame indicates insufficient primary air, requiring the air shutter to be opened [9].

2.1.2 Burners

Burners are designed in various shapes and sizes to meet diverse combustion requirements. Two main categories of atmospheric burners used in residential gas appliances are:

- Main burners and
- Pilot burners.

Typical main burners include two types: single-port and multi-port (circular, tube, or other geometries). In single-port burners, fuel and air mix inside the burner tube, ignite at the outlet, and then flow into a heat exchanger. Single-port or mono-port burners consist of a single pipe or nozzle in in-shot or up-shot designs. An in-shot burner typically fires horizontally, with gas burning at the end of the mixer tube extension, as depicted in Figure 2-3 (a). Conversely, in an up-shot burner, the air-gas mixture flows through a bend into a riser tube where it burns vertically. Sometimes, a flame spreader deflects flames in a predetermined pattern (Figure 2-3 (b)). Up-shot burners are commonly found in domestic storage-type water heaters. Multi-port burners are widely used in appliances and come in various shapes and types, such as drilled ports, ribbon burners, slotted ports, or bar burners. The term 'burner bed' refers to a grouping of multiple multi-port burners. Figure 2-3 (c) illustrates a schematic of different types of multi-port burners. Multi-port burners with circular heads are common in storage water heaters and cooktops. Long tubes multi-ports are used in ovens and grills, and blade-type burners are used in boilers.

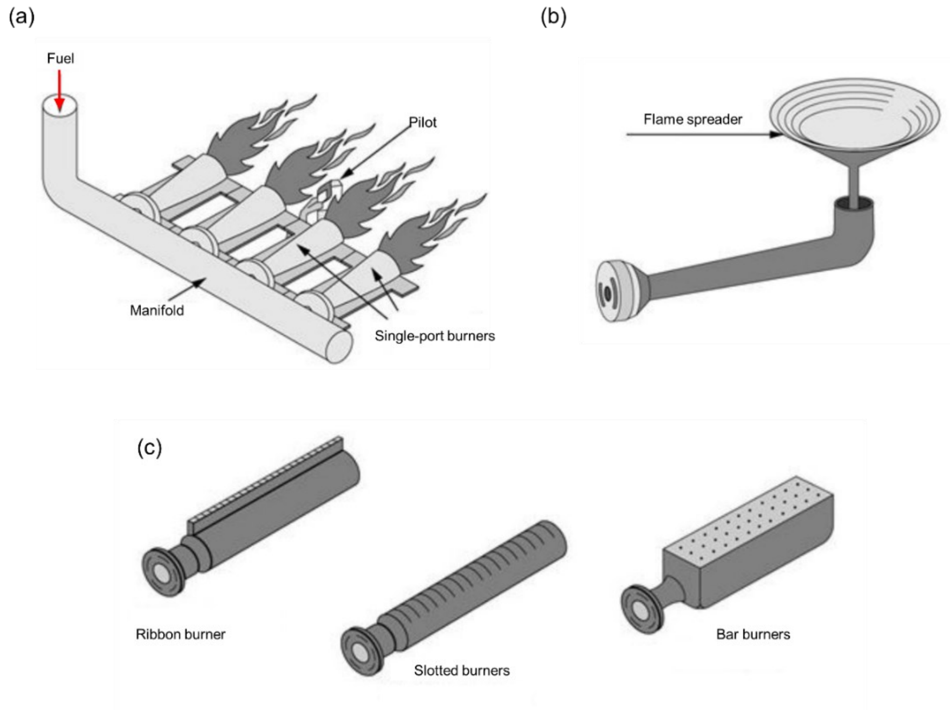


Figure 2-3 (a) Four in-shot single-port burners and (b) Up-shot single-port burner and (c) Different types of multi-port up-shot burners [9]**.**

Other types of burners include ring, spoon, staged fuel, tip-jet, tube and IR, direct-fired, dry low NOx, ultra-low NOx, log set, mesh, IR, pancake, perforated, power flame, and range burner. Figure 2-4 shows the schematic of four types of burners as a representative example. A pancake burner (Figure 2-4 (a)), named for its flat disk shape, is commonly used in storage-tank water heaters. In these burners, primary air travels through a nozzle fuel stream, and secondary air is established when the flame premixes with fuel in an air-rich enclosure, leading to flame formation on the 'pancake'. As depicted in Figure 2-4 (b), an in-shot partially premixed burner from a modern residential furnace operates horizontally, with gas burning at the end of the extended mixer tube. An ultra-low NOx burner is designed to minimize nitrogen oxide emissions by optimizing the fuel-air mixture and incorporating advanced combustion technologies. This type of burner achieves significantly lower NOx levels compared to standard burners, making it ideal for applications requiring stringent emissions control [10]. Figure 2-4 (c) shows the schematic of a premixed ultra-low NOx burner typically used in a storage water heater. Figure 2-4 (d) shows a typical cooktop burner configuration. As fuel injects into the burner head, it entrains surrounding air, mixes within the burner head, and flows out through flame ports.

Radiant gas burners, also known as infrared burners, are common in heating and cooking appliances, where combustion happens on a surface like perforated ceramic or stainless-steel mesh [11]. This design evenly disperses the fuel/air mixture, with all needed combustion air provided through the burner, making them fully premixed. On the other hand, ribbon burners are typically found in tankless water heaters, although there is no clear consensus on whether they are full, partial, or non-premix burners. Range burners are found in most gas stovetops and typically use partially premixed fuel and oxidizer blends. Fuel is injected into the burner head, where it mixes with surrounding air before flowing out through the flame ports. Mesh burners commonly use ceramic fiber for surface-stabilized combustion [12]. A premixed fuel and air mixture flows through the porous fiber, heats up, and combusts on the outer surface, with combustion products diffusing back to the mesh surface to sustain stable combustion.

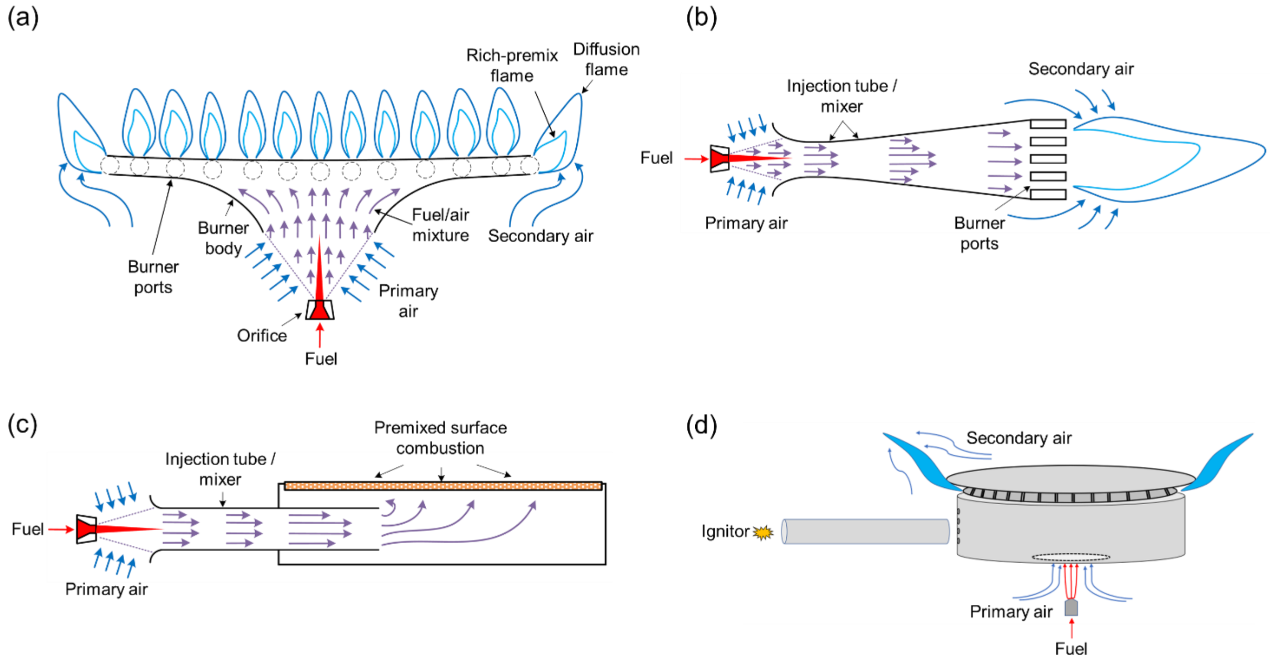


Figure 2-4 Schematic of (a) Pancake burner, (b) In-shot burner, (c) Ultra-low NOx burner and (d) Cooktop burner [13], [14].

The primary function of a pilot burner is to ignite the main burner flame. Due to the variety of main burner designs, there are numerous pilot burner designs available, each with different mounting styles and directional hoods. Most pilot burners also serve as a component in the flame safety circuit, monitored by a device that shuts off the gas supply to the main burner if the pilot flame extinguishes. Pilot burners are often categorized by their ability to premix primary air or their ignition sequence. Similar to main burners, pilot burners can be classified based on their ability to premix gas with air. There are two basic types: aerated pilots and non-aerated pilots. Aerated pilots premix air and gas, resulting in a sharp blue flame that is relatively stable and generally unaffected by drafts or main burner variations. In contrast, non-aerated pilots produce a softer flame with a slight yellow tint and can be influenced by drafts and main burner changes. A deflector target is commonly used to direct the flame toward the main burner port and shield the pilot flame. For non-aerated pilots, the target shield is often tapered to create a venturi effect on the secondary air, improving air/gas mixing and achieving stable characteristics similar to an aerated pilot flame.

2.1.2.1 Burner Operation Issues

Lamellar flame propagation refers to the movement of a flame front through a fuel/air mixture. Figure 2-5 shows the schematic of the lamellar flame propagation. As shown in the figure, the fuel/air mixture flows from left to right with a bulk flow velocity denoted as ϑ_f. An ignition initiates the flame propagation, and the flame propagates from right to left at a lamellar flame speed, S_L. The flame front, represented by the boundary between the burnt fuel and the unburnt fuel/air mixture, moves from right to left with a speed S_L. Simultaneously, the fuel/air mixture is moving from left to right with a velocity ϑ_f.

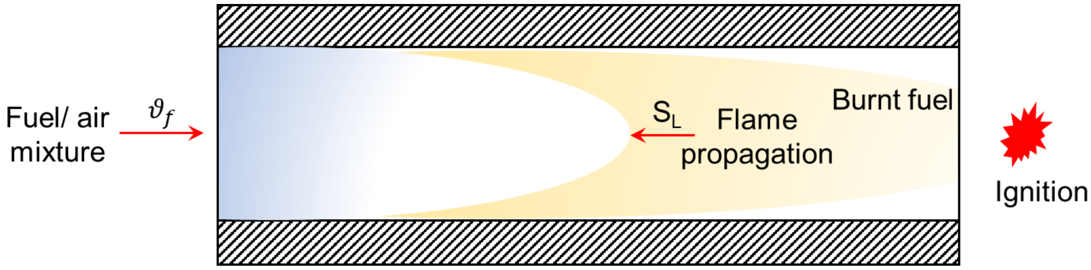


Figure 2-5 Schematic of lamellar flame propagation.

$$S_L \gg \vartheta_f \qquad \text{(Flashback)}$$

$$\vartheta_f \gg S_L \qquad \text{(Blowoff/ Flame Liftoff)}$$

Flashback occurs when the lamellar flame speed S_L is greater than the bulk fuel flow velocity ϑ_f. In this situation, the flame front can move upstream into the burner, which can lead to hazardous conditions as the flame travels back into the system supplying the fuel/air mixture. This usually occurs when the fuel/air mixture velocity is too low to prevent the flame from propagating back into the fuel supply line. Flashback can occur at various stages of burner operation:

- Cold start and re-ignition: Cold start is when the burner is first turned on with no prior heat source. Re-ignition happens shortly after shutdown, typically retaining some residual heat.
- Steady state conditions: This stage starts after the cold start when the burner has reached its usual operating conditions.
- Shutdown: This stage is when the ignition source is cut off. Re-ignition shortly after shutdown retains residual heat, whereas a longer interval before re-ignition is considered a cold start.
- Extinction pop: Flashback can occur spontaneously with a 'pop' sound when the burner is fully shut off. This can disturb the pilot flame. Reducing the primary air supply can mitigate this issue.

On the other hand, blowoff occurs when the bulk fuel flow velocity ϑ_f is greater than the lamellar flame speed S_L. In this case, the flame is unable to stabilize and is 'blown off' from the burner as the fuel/air mixture flows too quickly for the flame to propagate back through it. This results in the flame being extinguished as it cannot maintain its position relative to the burner. Maintaining a proper balance between the lamellar flame speed and the bulk fuel flow velocity is crucial to ensure stable combustion.

Typical terminologies used in burner operation are tabulated in Table 2-1. Figure 2-6 shows some schematics of different types of flames.

Table 2-1 Typical terminologies used in burners.

Terminology	Description
Flashback	Flashback is a combustion phenomenon where the flame propagates backward into the burner or fuel supply system, instead of remaining at the designated point of combustion.
Blowoff/ flame liftoff	Blowoff, or flame liftoff, is a combustion phenomenon where the flame is blown away from the burner port and cannot maintain its position at the designated point of combustion.
Floating flames	Floating Flames refer to a combustion phenomenon where the flame is not anchored or attached to the burner port, but instead appears to hover or float above it. Floating flames, unlike lifted flames with well-defined shapes, have a less structured geometry, appearing long and quiet. This instability causes them to roll around in combustion chambers and sometimes completely detach from the burner ports. They produce a characteristic strong aldehyde scent and are typically caused by an inadequate supply of secondary and excess air.
Waving flames	A waving flame moves or sways like an air dancer, appearing unstable due to air drafts across the burners. These flames can be problematic if they contact cool surfaces. Drafts can cause pilot flames to go out or drift away from the flame safeguard.
Flame rollout	Flame rollout is a type of floating flame that extends beyond the combustion chamber, seeking additional air due to inadequate combustion air. The primary danger of flame rollout is its potential to extend several feet, posing a risk of burns to operators.
Fluctuating flames	Fluctuating flames refer to flames that vary in intensity or size unpredictably over time. This fluctuation can occur due to several reasons, such as unstable gas pressure, blockages in gas orifices, or issues with pilot burner operation. It's a condition commonly observed in gas-fired equipment where the combustion process is not stable, leading to inconsistent flame characteristics.
Flame carry-over	Flame carry-over, whether smooth or uneven, refers to a situation where flames from a burner or combustion chamber extend beyond their intended area or flow in an irregular manner.
Shoot formation	Shoot formation refers to the accumulation of solid residues or deposits that can occur within the appliance, particularly in combustion chambers, burner ports, or flue passages. These deposits often consist of by-products from the combustion process, such as soot, carbon, or other particulate matter.

Table 2-1 Typical terminologies used in burners (continued).

Terminology	Description
Yellow tipping	Yellow tipping occurs when the tips of gas burner flames appear yellow due to incomplete combustion, often caused by insufficient primary air supply or improper air-to-fuel ratio. This incomplete combustion can produce soot particles, which may accumulate on downstream surfaces, potentially blocking gas passages.
Burner overheating	Burner overheating refers to a condition where the burner assembly or components associated with combustion reach excessively high temperatures during operation.
Radiation flux	Radiation flux refers to the heat energy emitted in the form of electromagnetic waves (radiation) from the surfaces of the appliance, particularly from the combustion chamber or heat exchanger. This flux of radiant heat is a crucial aspect of the appliance's heat transfer process, contributing significantly to its overall efficiency and performance.
Ionization probe	The ionization probe is a sensor typically positioned near the burner or flame area of a gas appliance. Its primary function is to detect the presence of a flame by sensing the ionization generated by the combustion process. When a flame is present, ions (charged particles) are produced within the flame due to the intense heat and chemical reactions of combustion. The ionization probe detects these ions, which allows it to confirm that the burner has ignited and that the flame is stable.
Equivalence ratio	The equivalence ratio is the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. During stoichiometric combustion, all the oxygen is consumed in the reaction, leaving no molecular oxygen (O2) in the products.

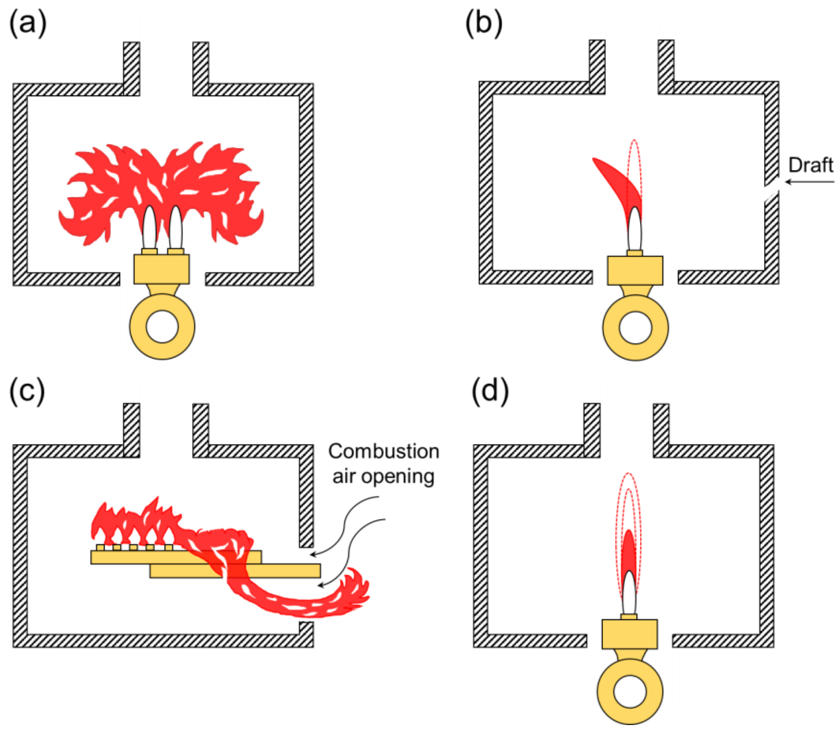


Figure 2-6 Schematic of (a) Floating flame, (b) Waving flame, (c) Flame rollout and (d) Fluctuating flames.

2.1.3 Emissions

2.1.3.1 CO Emissions

CO emission refers to the release of carbon monoxide (CO) as a by-product of the combustion process. Carbon monoxide is a colorless, odorless, and toxic gas that is produced when carbon-based fuels, such as gasoline, natural gas (methane), kerosene, propane, charcoal are burned incompletely. Proper combustion of natural gas typically produces carbon dioxide (CO_2) and water vapor (H_2O) as the main by-products. Various factors can lead to incomplete combustion, resulting in CO emissions. This includes insufficient oxygen during combustion, malfunctioning or improperly adjusted burners, obstructions in the flue or poor ventilation, appliance malfunction or failure and the accumulation of soot, debris, or damage to burner components, all of which can prevent complete fuel burning and lead to higher CO levels. Appliances are designed and regulated to minimize CO emissions, adhering to safety standards set by regulatory bodies. For example, California's Carbon Monoxide Poisoning Prevention Act of 2010 mandates that all residential properties with fossil fuel-burning appliances, fireplaces, or attached garages have an approved carbon monoxide alarm in each sleeping area and on every level of the home [15].

Since CO is primarily formed due to incomplete combustion of carbon-containing fuels in the presence of insufficient oxygen, the temperature at which combustion occurs influences the extent of incomplete combustion and thus the production of CO. Generally, CO emissions tend to decrease with increasing combustion temperatures up to a certain point. At lower temperatures, incomplete combustion is more likely due to inadequate mixing of fuel and air or insufficient residence time in the combustion zone. There is typically an optimal temperature range for combustion where CO emissions are minimized. This range varies depending on the specific fuel, burner design, and combustion conditions. However, at high temperatures, CO emissions can increase again due to thermal decomposition of CO_2 or other combustion intermediates, leading to secondary production of CO. Typical trends of CO and NOx emissions with respect to temperature are illustrated in Figure 2-7.

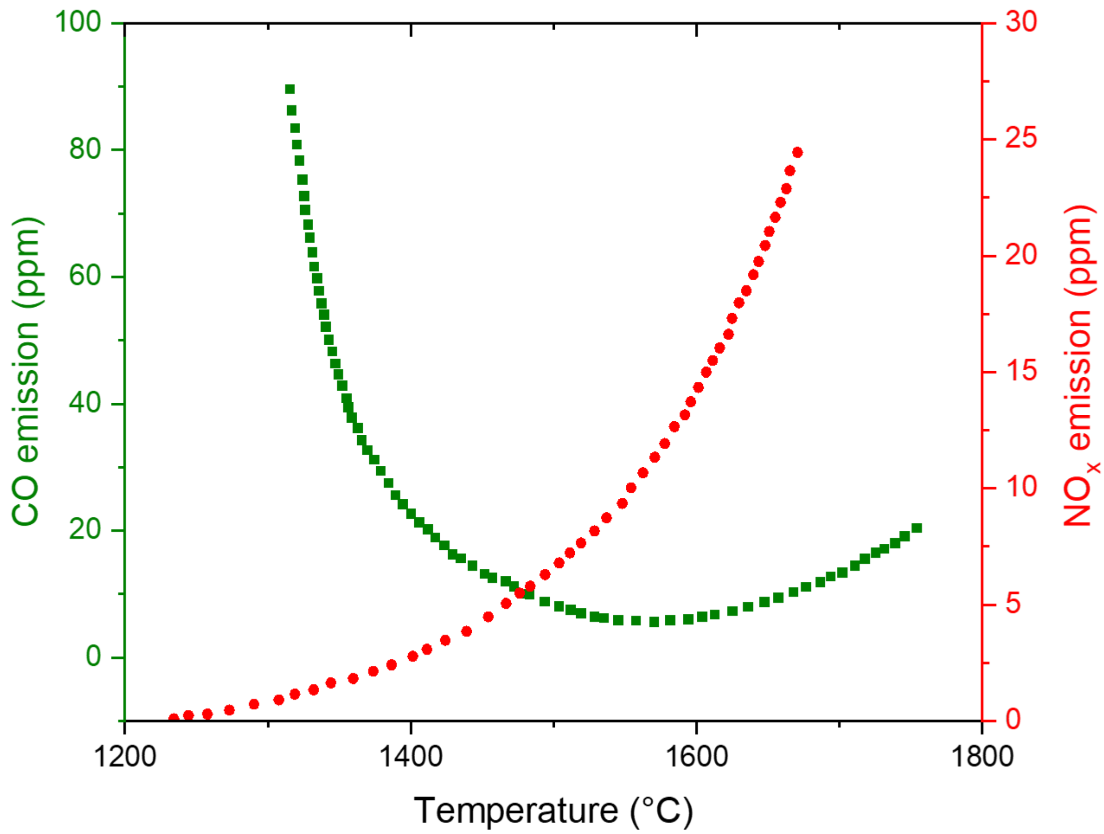


Figure 2-7 Typical CO and NOx trends with respect to temperature [16], [17], [18].

2.1.3.2 NOx Emissions

NOx emissions refers to the release of nitrogen oxides (NO and NO_2) during the combustion process. These gases are collectively referred to as NOx and are formed when nitrogen and oxygen in the air react at high temperatures within the combustion chamber. NOx emissions contribute to air pollution, including smog and acid rain, and can harm human health by causing respiratory problems. Many regions regulate NOx emissions to mitigate these impacts. Although, there are no U.S. indoor exposure guidelines for NO_2, but Canada limits it to 90 ppb over 1 hour and 11 ppb long-term [19]. In 2021, the WHO set the outdoor standard at 13 ppb over 24 hours. Indoor NO_2 levels can exceed 100 ppb if stoves are used without adequate ventilation due to low exhaust hood efficiency or user inactivation [20], [21]. These regulations may be leading manufacturers to design burners and combustion systems to minimize NOx production.

NOx emissions generally increase with higher combustion temperatures. This is because nitrogen (N_2) and oxygen (O_2) from the air react more readily at elevated temperatures to form nitrogen oxides (NO and NO_2). At high temperatures, nitrogen and oxygen molecules in the combustion air break apart more easily due to increased kinetic energy. Lowering combustion temperatures is an effective strategy to reduce NOx emissions. Other mitigation techniques include optimizing combustion conditions, combustion staging and air-fuel ratio adjustment. Engineering solution involves optimizing burner design (i.e. low-NOx burners), fuel injection strategies, and implementing exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) systems to further mitigate NOx emissions.

2.1.3.3 Unburned Hydro Carbon (UHC) Emissions

Unburned Hydrocarbon (UHC) emissions refer to the release of hydrocarbon compounds that have not undergone complete combustion. UHC emissions occur when hydrocarbon fuels, such as natural gas, are not fully burned in the combustion process [22], [23]. This can happen due to insufficient oxygen, improper air-fuel ratios, or incomplete mixing of fuel and air. UHCs include various volatile organic compounds (VOCs) and other hydrocarbons that are released into the atmosphere. Similar to CO and NOx, UHC emissions also contribute to air pollution. They can react in the atmosphere to form ground-level ozone and other secondary pollutants, which can affect air quality and human health.

At lower combustion temperatures, incomplete combustion is more likely to occur due to insufficient oxygen availability or inadequate mixing of fuel and air. This results in higher UHC emissions as some hydrocarbon molecules do not fully react and combust. Similar to CO emission, there is typically an optimal temperature range for combustion where UHC emissions are minimized. This range varies depending on factors such as the specific fuel composition, burner design, and combustion conditions. UHC emissions increases at high temperature due to thermal decomposition of hydrocarbons or other combustion intermediates.

2.1.4 Rich and Lean Fuel Mixture

The ‘rich’ and ‘lean’ fuel mixture refer to the air-fuel ratio specific to combustion processes using natural gas. A rich fuel mixture occurs when there is more natural gas (fuel) supplied relative to the amount of air needed for complete combustion. This results in an excess of fuel compared to the available oxygen. A fuel-rich mixture can lead to incomplete combustion, where some natural gas molecules do not fully burn due to insufficient oxygen. This incomplete combustion can result in higher emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC). Lean fuel mixture on the other hand occurs when there is less fuel supplied relative to the amount of air needed for complete combustion. In this case, there is excess oxygen compared to the available natural gas. Lean mixtures are used in natural gas appliances to promote more efficient combustion and reduce emissions of CO and UHC. However, lean mixtures can also lead to higher nitrogen oxide (NOx) emissions due to the higher combustion temperatures associated with leaner conditions.

2.2 Impacts of Hydrogen Blends on Combustion

Dong et al. [24] studied the laminar flame speeds of hydrogen/natural gas/air mixtures over a full range of fuel compositions (0–100% volumetric fraction of H_2) and a wide range of equivalence ratios using a bunsen burner at 293 K and 1 atm. It was found that the laminar flame speeds of hydrogen/air and natural gas/air mixtures reach their maximum values of 2.933 m s^{-1} and 0.374 m s^{-1} at equivalence ratios of 1.7 and 1.1, respectively. The laminar flame speeds of hydrogen/natural gas/air mixtures increase with the volumetric fraction of hydrogen, showing an exponential increasing trend. Figure 2-8 shows the laminar flame speed vs. equivalence ratio obtained from this study. The comparison between hydrogen and natural gas flame is tabulated in Table 2-2.

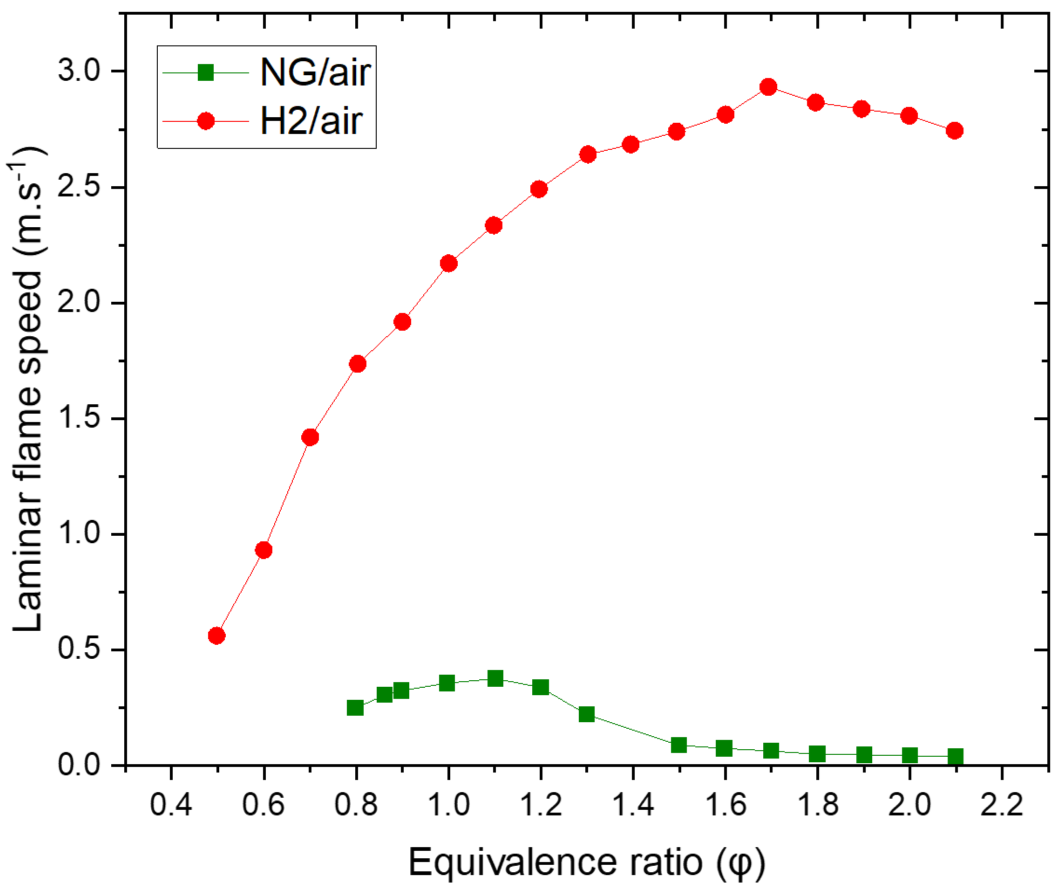


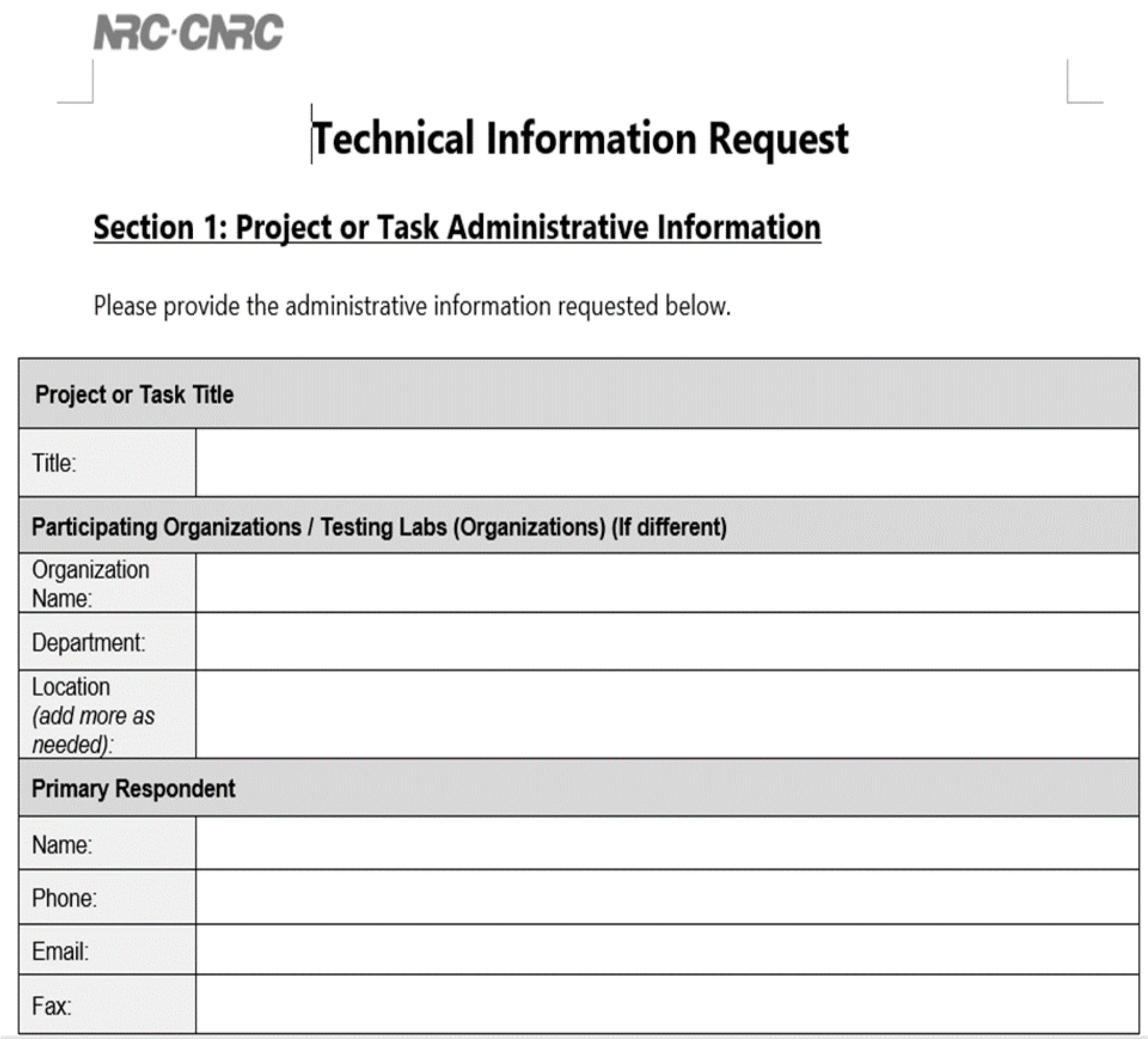
Figure 2-8 Laminar flame speed vs equivalence ratio [24].

Table 2-2 Comparison of hydrogen and natural gas [24], [25]**.**

Properties	**Hydrogen**	**Natural gas**
Flammability limit	4%/75%	7%/20%
Flame speed	~2.2 m.s^{-1}	~0.4 m.s^{-1}
Adiabatic Flame Temperature	~ 2127°C	~ 2055°C

3 Data Collection from Interested and Affected Parties

Data collection from interested and affected parties such as North American gas utilities, industry interested and affected parties and relevant research groups has been conducted for reviewing hydrogen blends testing/research of end-use appliances and related controls. For the data collection process, CSA coordinated the preparation and distribution of the data collection request and NRC has developed a technical information request, an excel-based template for detailed appliances and testing conditions, and an additional data collection template for in-depth interviews with respondents as shown in Figure 3-1 to Figure 3-3, respectively.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Technical Information Request

Section 1: Project or Task Administrative Information

Please provide the administrative information requested below.

Project or Task Title	
Title:	
Participating Organizations / Testing Labs (Organizations) (If different)	
Organization Name:	
Department:	
Location *(add more as needed):*	
Primary Respondent	
Name:	
Phone:	
Email:	
Fax:	

Figure 3-1 Technical information request for data collection from interested and affected parties

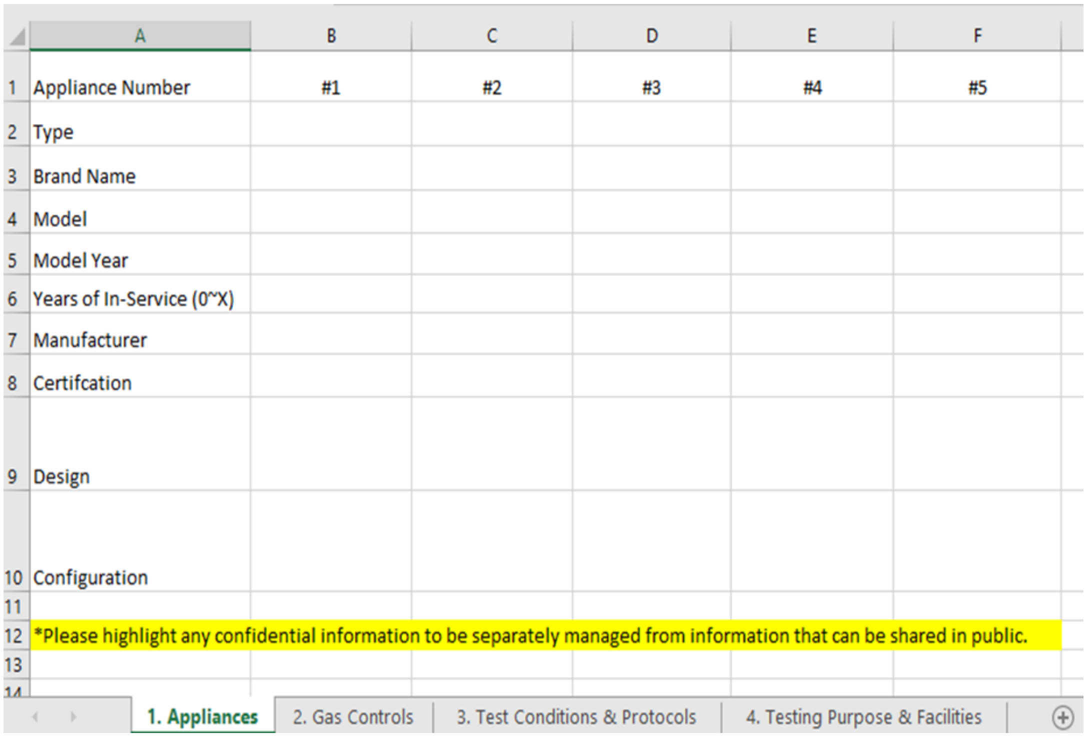

Figure 3-2 An Excel-based template for detailed appliances and testing conditions.

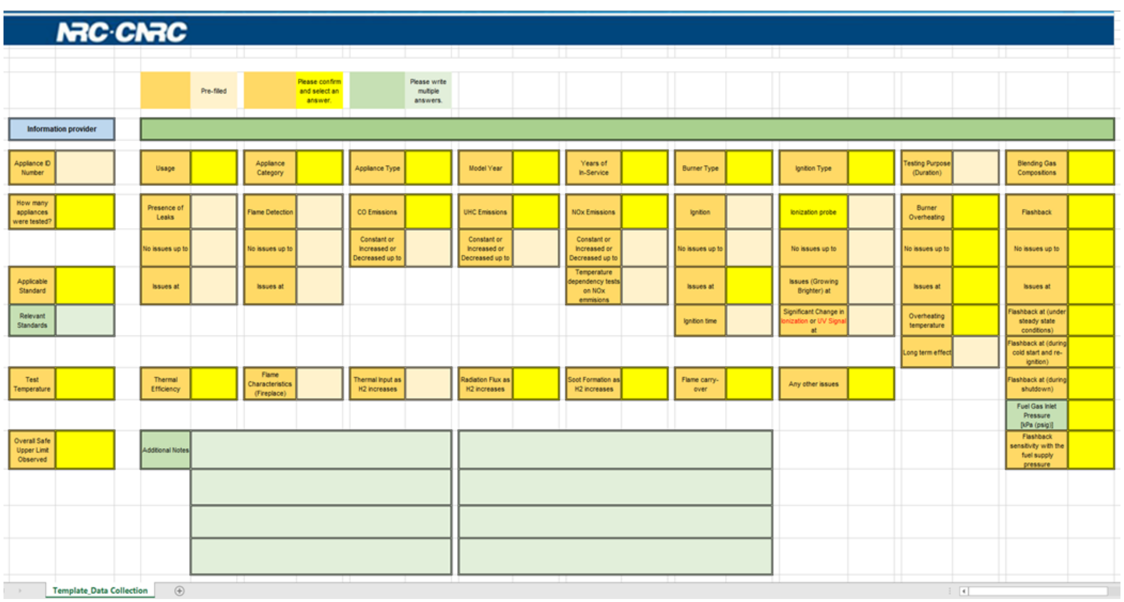

Figure 3-3 An additional data collection template for interview process.

The technical information request is comprised of five sections as follows;

- Section1: Project or Task Administrative Information;
- Section 2: Appliances and Gas Controls for H_2 Tolerance Testing with four sub-sections, including Testing Conditions and Protocols Applied, Testing Purpose and Facilities, etc.;

- Section 3: Results and Findings with five sub-sections, including Impact on Combustion Performance and Emissions, Operability Issues and Limiting Factors, Safety Issues, etc.;
- Section 4: Additional Information with four questions, including Knowledge Gaps, H_2 Blending Limits, Durability Testing, and Interview Acceptance;
- Section 5: Data and References.

Any contents provided from interested and affected parties are disclosed to NRC only and used for data analytics purposes to extract aggregated findings without disclosing specifically sensitive information.

An Excel-based spreadsheet template for the section 2 of the technical information request as shown in Figure 10 was provided to interested and affected parties, in order to collect detailed appliances and testing conditions for multiple appliances tested. The template is comprised of four tabs, including appliances, gas controls, testing conditions & protocols, and testing purpose & facilities.

These two types of templates were circulated to various interested and affected parties for data collection. NRC received data from the data collection respondents via an individual content collaboration platform created for each stakeholder to keep security and confidentiality for the data collection from interested and affected parties.

After receiving two templates filled by respondents, an additional data collection template prefilled by NRC was provided to each respondent for in-depth interview process as shown in Figure 11. The additional data collection template pre-filled by NRC for each appliance was updated and corrected by each respondent before an individually scheduled interview that was held online for 1.5~2 hours to clarify and confirm all the responses reported in three types of templates as the last step on data collection.

4 Data Analytics for Aggregated Findings

4.1 Appliances and Burners Tested

NRC conducted data analytics, based on all the responses from 8 respondents. The total number of appliances tested was 74 as shown in Table 4-1.

Table 4-1 Total number of appliances tested.

Information provider	Number of appliances tested
A	24
B	18
C	13
D	9
E	6
F	2
G	1
H	1
Total	**74**

The appliances tested for hydrogen blending in methane or natural gas can be categorized as residential, industrial, and commercial appliances. The main category of appliances tested was residential appliances with 77%, much greater than the percentage of industrial or commercial appliances as shown in Figure 4-1.

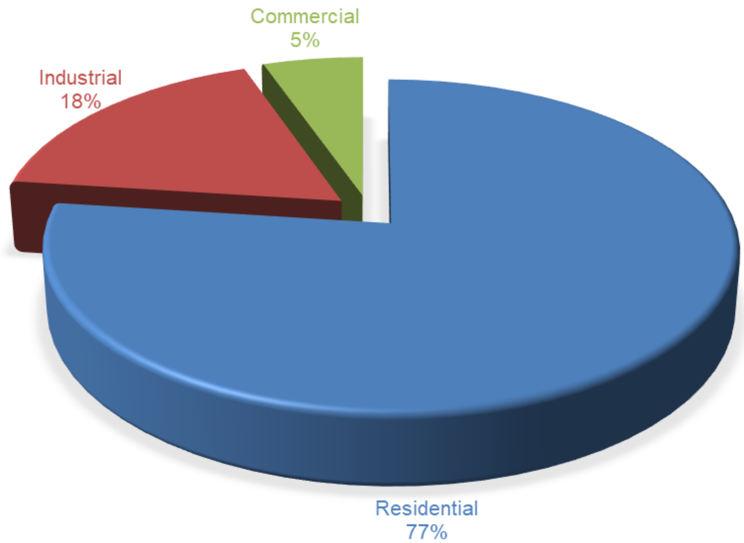

Figure 4-1 Percentile of residential, commercial and industrial appliances being tested.

In the case of appliance category, water heater/boiler and residential cooking appliances were tested with the first and second highest percentages of 30% and 21%, respectively, resulting in the sum of these two types over 50% as shown in Figure 4-2.

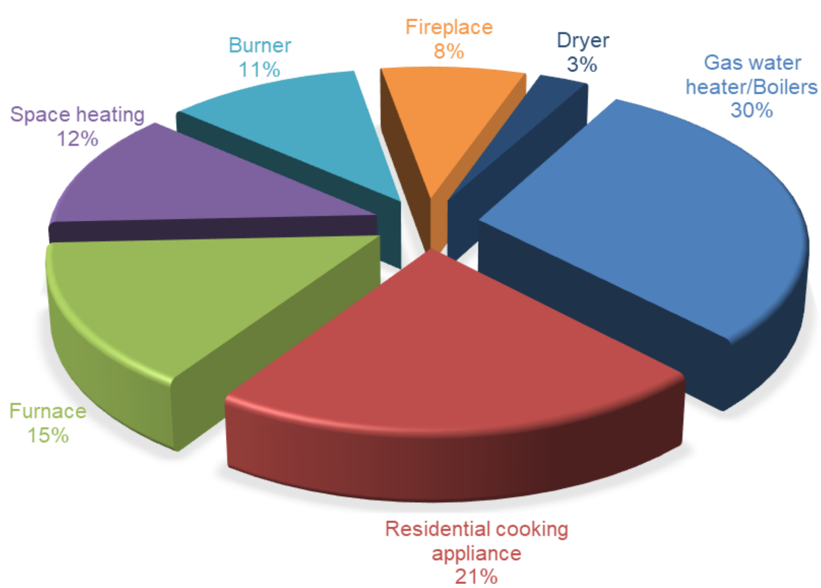

Figure 4-2 Percentile of appliance category being tested.

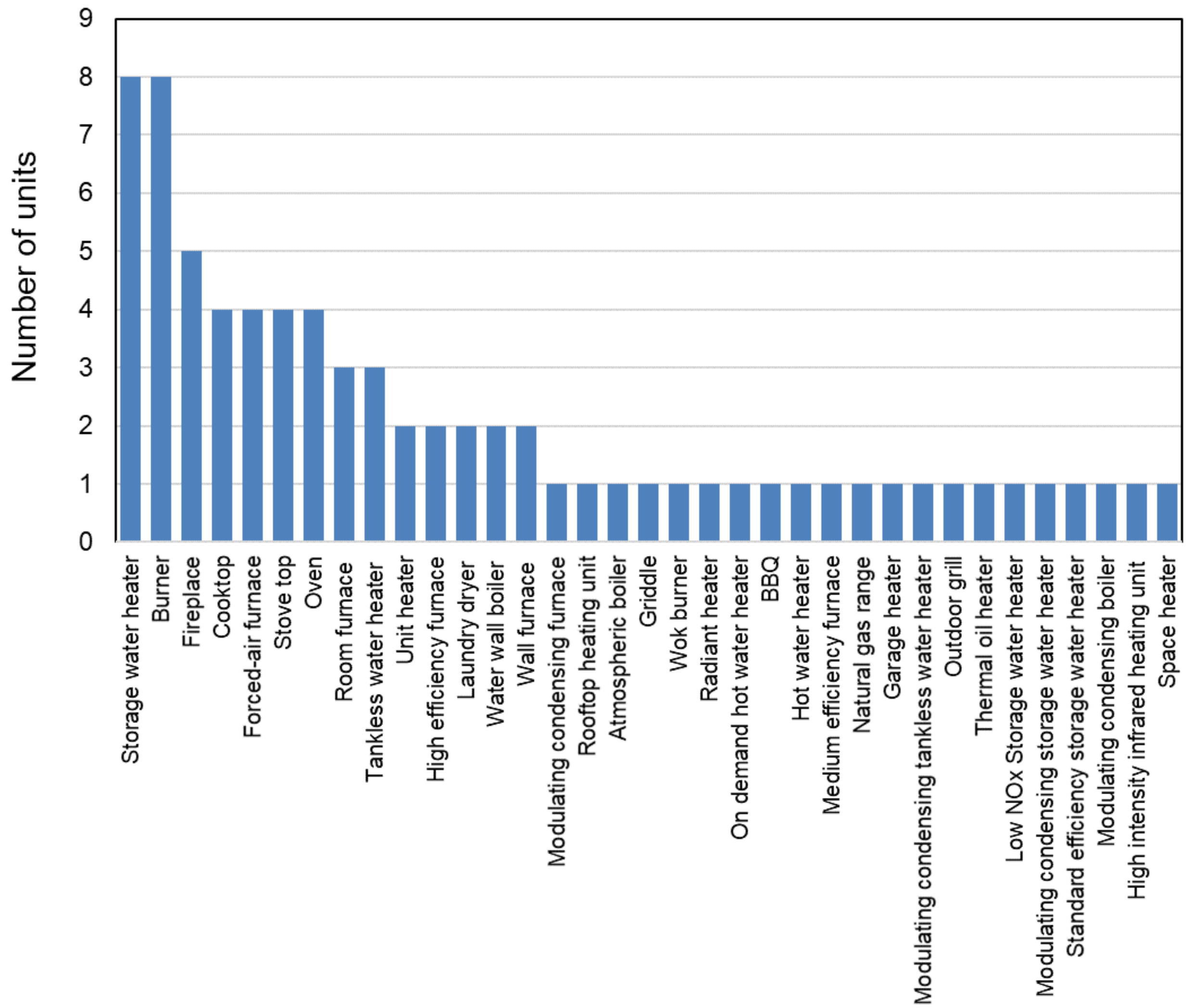

Figure 4-3 Types of appliances tested.

Figure 4-3 illustrates the different types of appliances being tested by the participants, along with the corresponding number of units for each appliance type. Figure 4-4 shows the years of service prior to the appliance testing. The ratio of new and used appliances utilized for blending tests was almost 1:1 (new 39% and used 35%). In the case of used appliances, over 90% had 'unknown' years of service prior to testing.

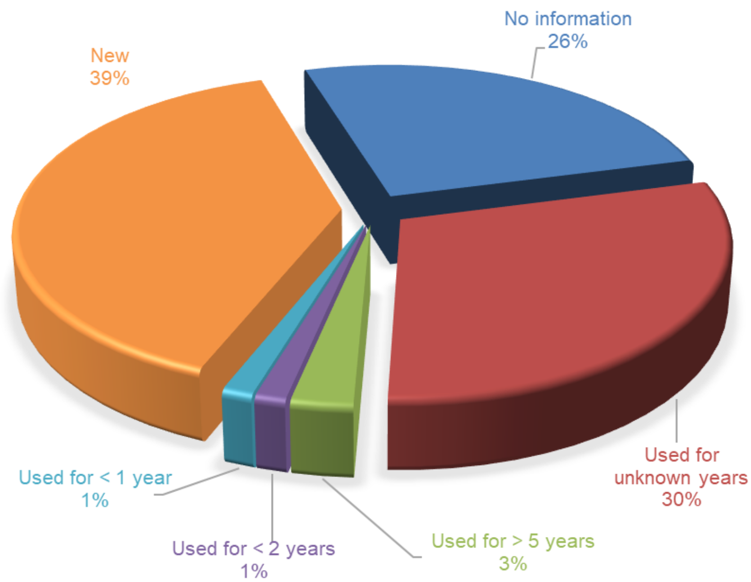

Figure 4-4 Years of service prior to the appliance testing.

The burner types of appliances tested can be seen in Figure 4-5. Main burner types used are in the order of in-shot, premixed, tube, and pancake burners. The potential correlation between burner types of appliances and observed safe upper limits can be found in Section 4.7.

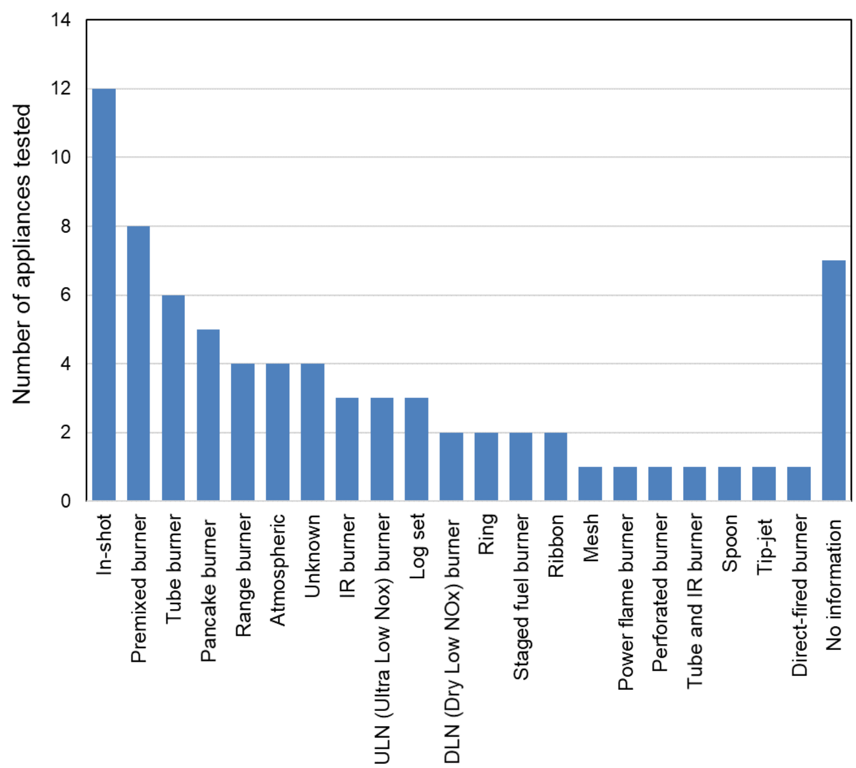

Figure 4-5 Burner types of appliances tested.

Figure 4-6 shows the ignition types of appliances tested. The term 'Unknown' in the graph means that the participants do not know the type of ignition on the tested appliances, while 'No information' means that no information regarding the ignition type was provided by the participants. The main type of ignition in appliances tested was electric spark, and the portion of standing pilot in ignition types was very minor.

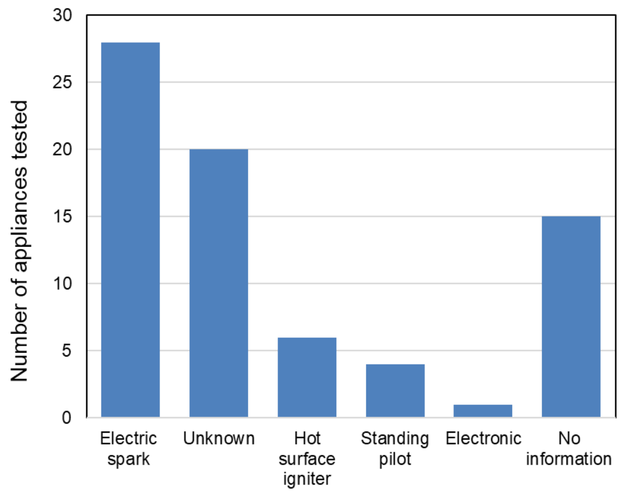

Figure 4-6 Ignition types of appliances tested.

4.2 Test Conditions

Hydrogen blending percentages applied for tested appliances are shown in Figure 4-7. The range of hydrogen blending percentages was 5-100 vol% H_2, with almost two-thirds of cases tested at 30-40 vol% H_2 or 70 vol% H_2. Fifteen appliances were tested with 5-20 vol% hydrogen. For the remaining 59 appliances, which were tested with blended fuel containing more than 20 vol% hydrogen, were also evaluated at lower hydrogen concentrations.

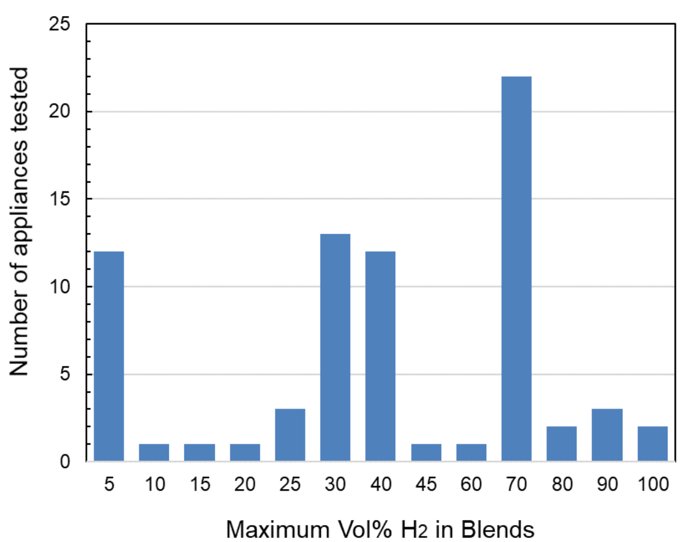

Figure 4-7 Blending gas compositions for appliances tested.

Figure 4-8 shows the number of identical appliance units tested for reproducibility. Over 95% of tests were conducted on only one appliance unit, resulting in limited reliability of the datasets.

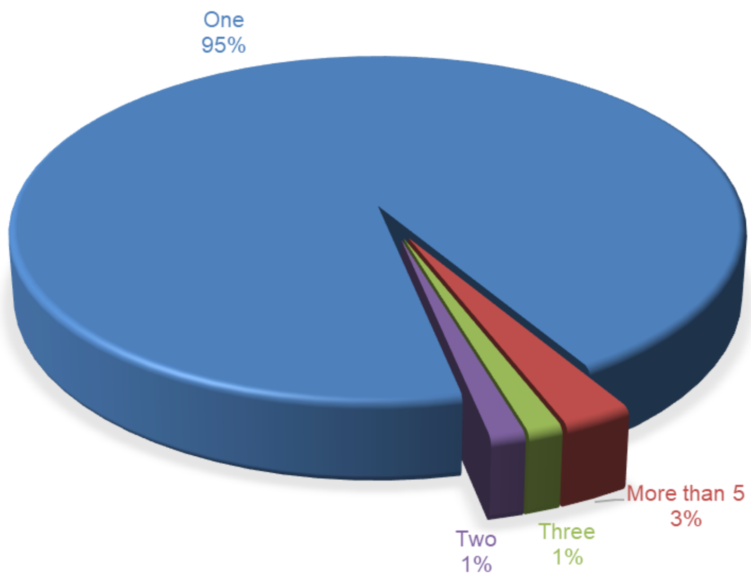

Figure 4-8 Number of same appliance units tested for reproducibility.

There was no gas leakage detected during hydrogen blending tests for two-thirds of all cases. The remaining one-third of the test cases were related to "not measured" gas leakage detection or "no information" reported, as shown in Figure 4-9.

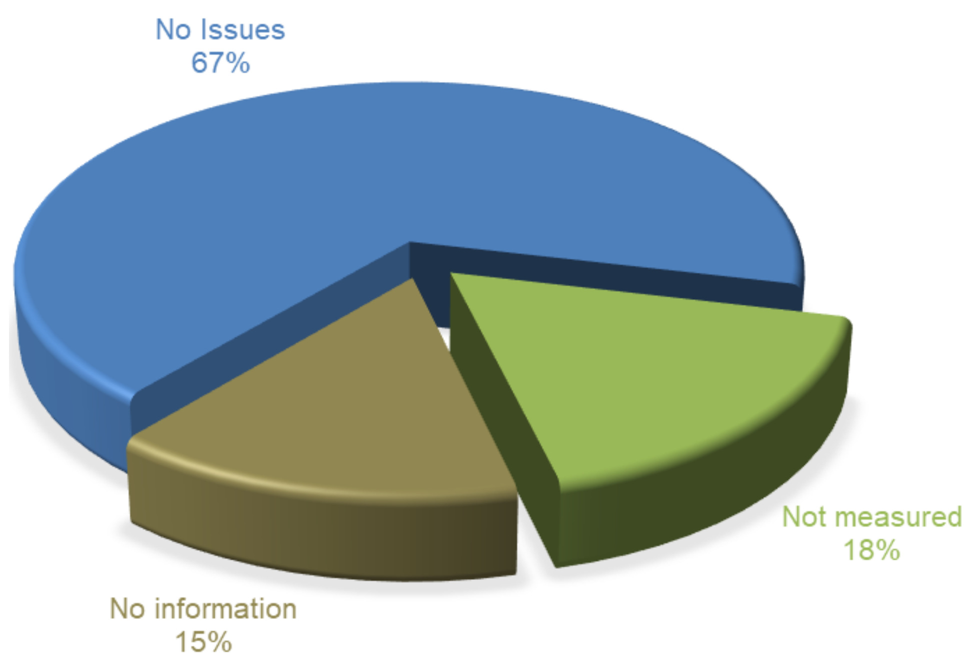

Figure 4-9 Presence of gas leakage.

4.3 Applicable Standards

In this study, participants followed the current standard test procedures for each appliance type. Thirty-seven appliances were tested using the standard procedure, while the remaining thirty-seven appliances were tested without following any standard. Figure 4-10 shows the different standards that were used and the number of appliances that utilized each of these standard procedures. The CSA/ANSI Z21 series of standards for residential appliances were the most commonly used, applied in almost 84% of reported cases. The CSA ANSI Z83 series of standards for industrial or commercial appliances and the CSA B149 Gas codes are also utilized, but these account for a limited number of reported cases. Table 4-2 shows other relevant standards applicable to the use of appliances with hydrogen blends.

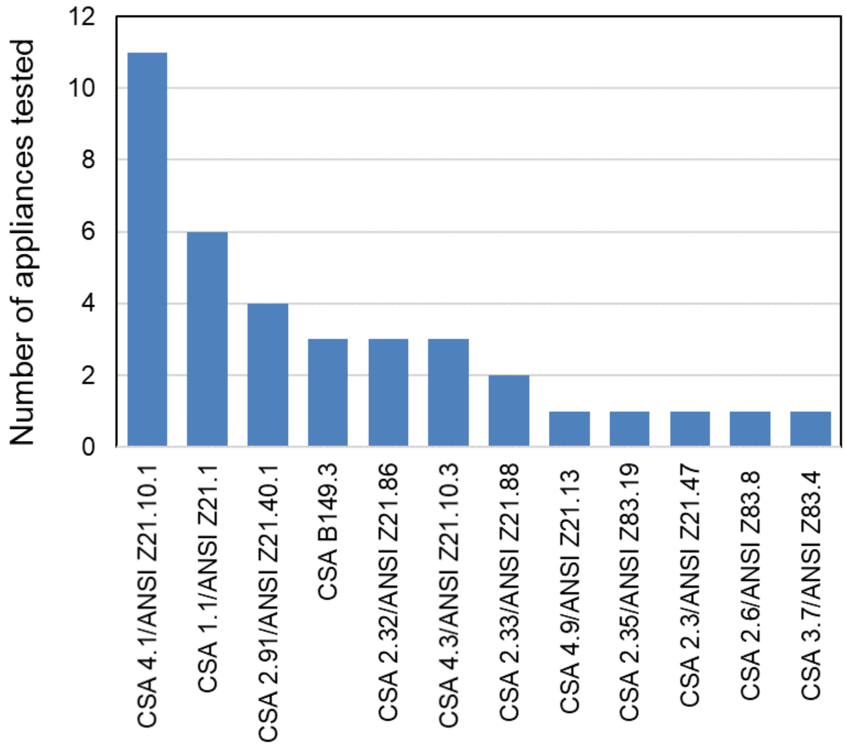

Figure 4-10 Applied standards vs. number of appliances tested using each standard.

Table 4-2 Other relevant standards.

Relevant Standards	Standard title
ASME B31.3	Process Piping
CSA B149.1	Natural gas and propane installation code
CAN/CSA-P.3-15 (R2020)	Testing method for measuring energy consumption and determining efficiencies of gas-fired and fuel oil-fired water heaters
CAN/CSA-P.2-13 (R2022)	Testing method for measuring the annual fuel utilization efficiency of residential gas-fired or oil-fired furnaces and boilers
CSA P.4.1:24	Testing method for measuring fireplace efficiency
CGA 3.4-1973 (R2020)	Industrial and Commercial Gas-Fired Conversion Burners
ASME B31.12-2023	Hydrogen Piping and Pipelines
CAN/CSA-P.7-10 (R2015)	Test method for measuring energy loss of gas-fired instantaneous water heaters
San Diego County Air Pollution Control District Rule 69.5.1	Natural gas fired water heaters and repeal of existing rule 69.5.1
SCAQMD rule 1153, 1138, 1131, 1153.1, 4692	Emissions of oxides of nitrogen from commercial food ovens
SCAQMD rule 1111 and 4905, HSC-19881	Reduction of NOx emissions from natural gas fired, fan-type central furnaces
RULE 1146.2	Emissions of Oxides of Nitrogen from Large Water Heaters and Small Boilers and Process Heaters

4.4 Safety Test Results (Flashback)

Flashback is generally characterized as '*an uncontrolled upstream propagation of the flame, due to a local imbalance in the flow velocity and flame speed*' [26].

Figure 4-11 illustrates the distribution of appliances experiencing flashback in the presence of hydrogen within the test fuel. Among the 74 appliances tested, flashback observation was either not considered or information was unavailable for 34% of the cases. Of the remaining 66%, 24% exhibited no issues, while 42% experienced flashback problems. In all instances where flashback was observed, the blended fuel contained between 25% and 80% hydrogen. Consequently, flashback emerges as a critical factor to monitor for the safe operation of appliances using hydrogen blends.

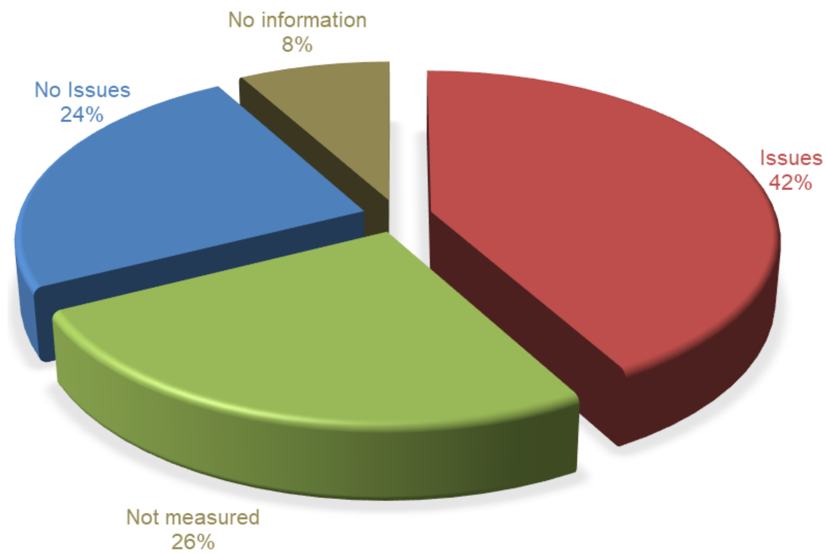

Figure 4-11 Flashbacks observed during hydrogen blending tests.

Flashback can occur under various operational conditions, including steady-state conditions, cold start and re-ignition, and the shutdown process, as illustrated in Figure 4-12-Figure 4-14, respectively. Under steady-state conditions, flashback was observed in only one instance below 20 vol% H_2, as shown in Figure 4-12. During cold start and re-ignition, flashback occurrences were relatively evenly distributed between 20 vol% and 50 vol% H_2, as depicted in Figure 4-13. During shutdown, flashback issues were observed in one case at 25 vol% H_2 and in other cases between 40 vol% and 50 vol% H_2, as shown in Figure 4-14. It was found that flashback issues were more prevalent during cold start and re-ignition compared to steady-state conditions or shutdown. Therefore, these specific operational conditions for observing flashback in hydrogen blending tests could be considered to enhance the reliability of safety testing protocols and potentially relevant testing standards.

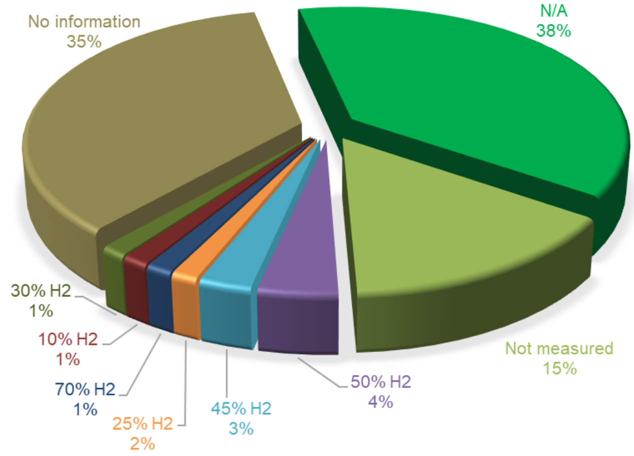

Figure 4-12 Flashback observed under steady state conditions.

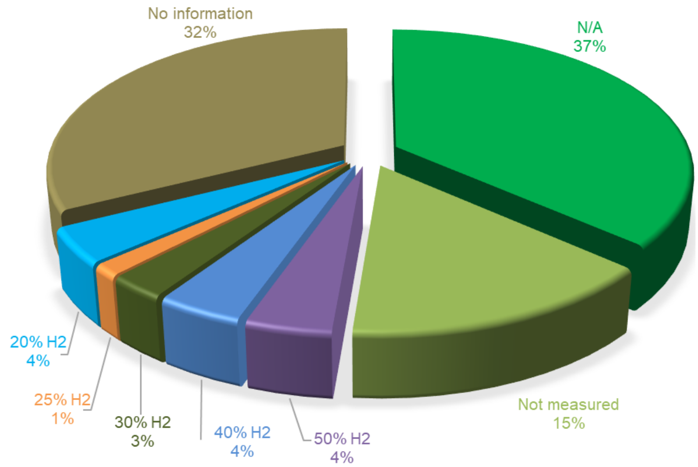

Figure 4-13 Flashback observed during cold start and re-ignition.

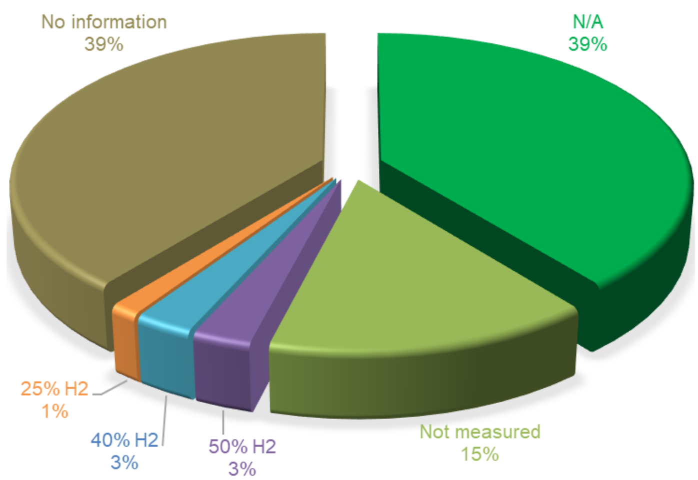

Figure 4-14 Flashback observed during shutdown.

4.5 Operability Issues and Limiting Factors (Flame, Burner, Ignition)

4.5.1 Flame Detection

Figure 4-15 illustrates flame detection issues during hydrogen blending tests. All reported cases, except those with no information or where measurements were not taken, indicated no flame detection issues.

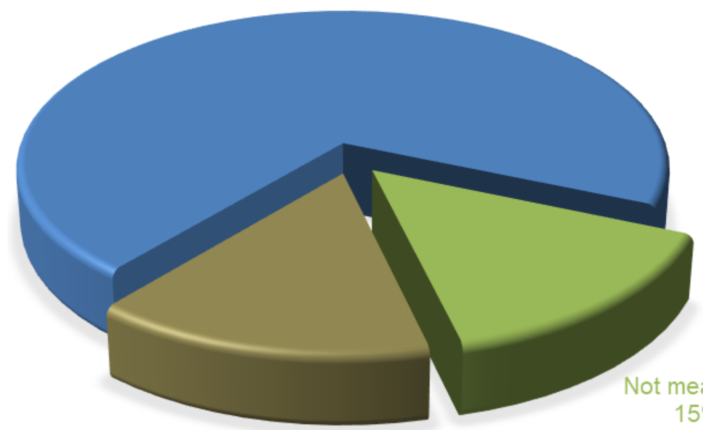

Figure 4-15 Flame detection issues during hydrogen blending tests.

4.5.2 Burner Overheating

Figure 4-16 depicts burner overheating issues during hydrogen blending tests. In 30% of all cases, burner overheating was observed within the maximum hydrogen percentage blended for each case. In all instances where overheating was observed, the blended fuel contained between 30% and 70% hydrogen. Burner overheating may reduce the durability of appliances over long-term use; therefore, it is important to monitor the range of overheating temperatures to assess the potential impact on the degradation of appliance components.

Figure 4-17 presents the burner overheating temperatures, defined as deviations greater or less than 5°C (9°F), recorded during testing. Approximately one-third of the cases showed burner overheating exceeding 5°C (9°F) relative to the burner deck temperature during operation without hydrogen in the fuel gas. In instances where overheating surpassed 5°C (9°F), the blended fuel contained more than 40% H2. While there is no formally established limit for allowable burner overheating temperatures, it is observed that when propane is used in appliances designed for natural gas, the burner temperature may increase by approximately 5°C (9°F) compared to natural gas operation. Given this precedent, a 5°C (9°F) increase may be considered an acceptable threshold for long-term use. Consequently, it is advisable to consider burner overheating temperature as an important parameter when determining a safe upper limit for the hydrogen volume percentage in fuel blends used for appliance operation.

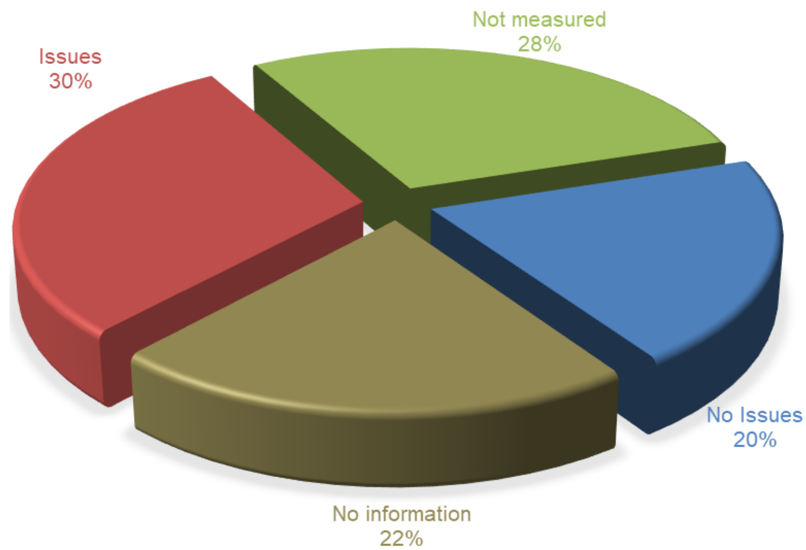

Figure 4-16 Burner overheating issues during hydrogen blending tests.

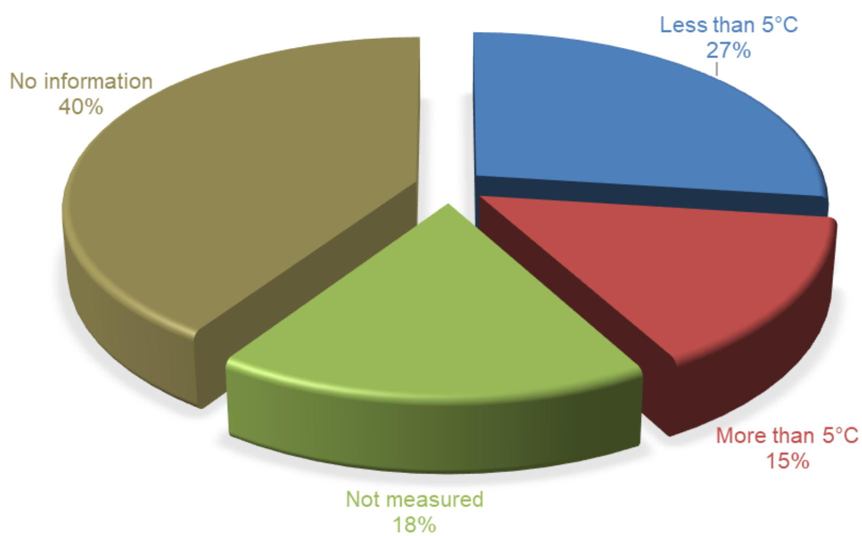

Figure 4-17 Burner overheating temperatures measured during testing (more or less than 5°C).

4.5.3 Ignition

Figure 4-18 illustrates that approximately 19% of all tested appliances exhibited ignition issues in the presence of hydrogen. About one-quarter of the reported cases, excluding those with missing or unmeasured data, showed ignition problems when the hydrogen concentration in the fuel reached or exceeded 30 vol% H_2.

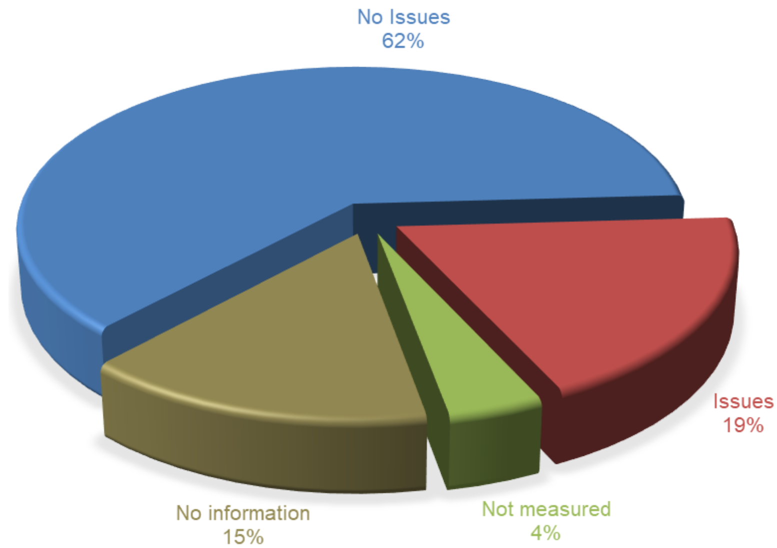

Figure 4-18 Ignition issues detected during hydrogen blending tests.

Ignition time was measured to determine whether ignition took longer than 4 seconds in the presence of hydrogen, as shown in Figure 4-19. While most cases demonstrated ignition times within 4 seconds, 4% of the cases exhibited ignition delays exceeding 4 seconds when the blended fuel contained 40 vol% or more hydrogen. Factors such as increased primary air, fuel accumulation in the chamber, acoustic instability, or a weaker pilot could have contributed to the ignition delay, either individually or in combination [26]. Ignition delay is a critical factor to monitor for the safe and reliable operation of appliances using hydrogen blends.

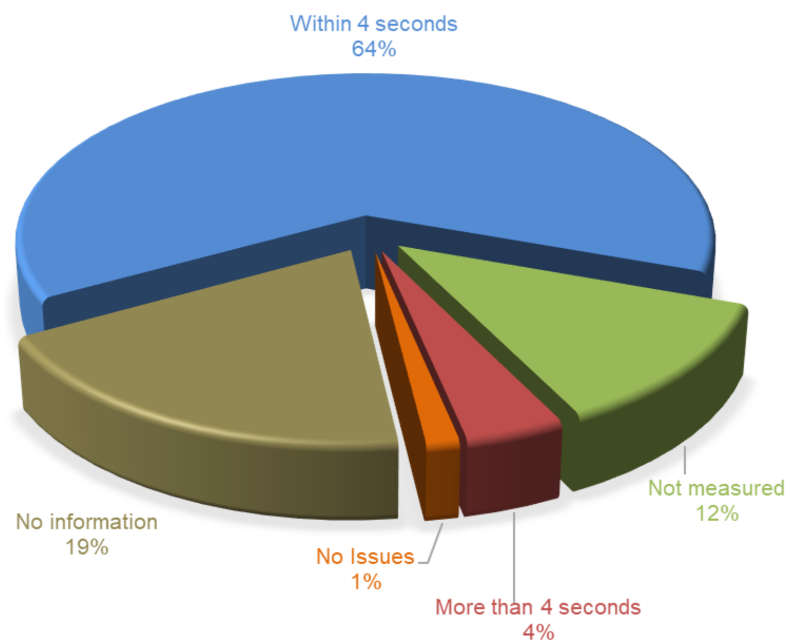

Figure 4-19 Ignition time measured during hydrogen blending tests (more or less than 4 seconds).

4.5.4 Ionization probe

As depicted in Figure 4-20, no significant change in ionization or UV signal was observed with the introduction of hydrogen into the blended fuel; however, many cases did not report or measure ionization signal changes during hydrogen blending tests.

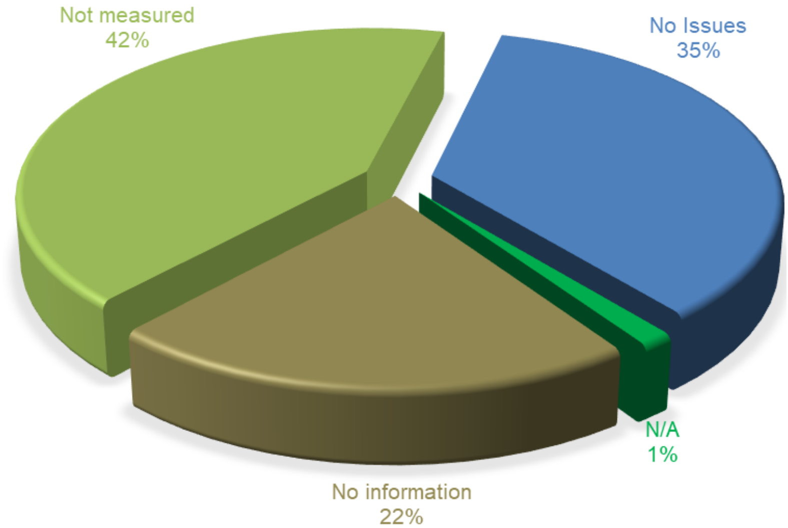

Figure 4-20 Ionization probe issues monitored during hydrogen blending tests.

4.6 Combustion Performance and Emissions Test Results

4.6.1 CO Emission

Figure 4-21 illustrates the CO emissions from appliances when hydrogen is present in the test fuel. As the hydrogen content increases in blends with methane or natural gas, the carbon content in the fuel gas decreases. This reduction leads to a lower Wobbe index (and thus, lower thermal input) and an increase in oxygen concentration (excess air) in the flue gas, promoting complete combustion. These changes typically result in reduced CO emissions.

As hydrogen content increases, over two-thirds of all cases showed either constant or decreased CO emissions compared to results without hydrogen in the fuel. Excluding cases with missing or unmeasured data, the percentage of cases showing constant or decreased CO emissions rises to slightly over 85%. Therefore, fewer than 15% of cases exhibited increased CO emissions with hydrogen addition.

The addition of H_2 promotes the formation of OH and H intermediates which gives the overall mixture a higher burning velocity. This facilitates the flame anchoring closer to the surface as compared to natural gas flame, thus promoting efficient heat transfer and, hence cooling the flame. Lower flame temperature aided with higher primary and secondary air entrainment with H_2 addition increases the CO emissions slightly [27].

CO emissions are influenced by a variety of factors, including the Wobbe index, oxygen concentration in flue gas, equivalence ratio, flame temperature, burner deck temperature, appliance type, burner type, and primary and secondary airflows.

While it is challenging to identify specific reasons for the increase in CO emissions for certain appliances, such as griddles, rooftop units, (maladjusted) high-efficiency furnaces, low-NOx water heaters, etc. [26], [28], several potential factors could contribute to the observed increases in CO emissions in this study. These include decreased flame temperature, decreased burner temperature, inadequate mixing of fuel and air, and insufficient residence time in the combustion zone. However, more detailed investigations into specific appliances and operational conditions are needed to identify the reproducible causes.

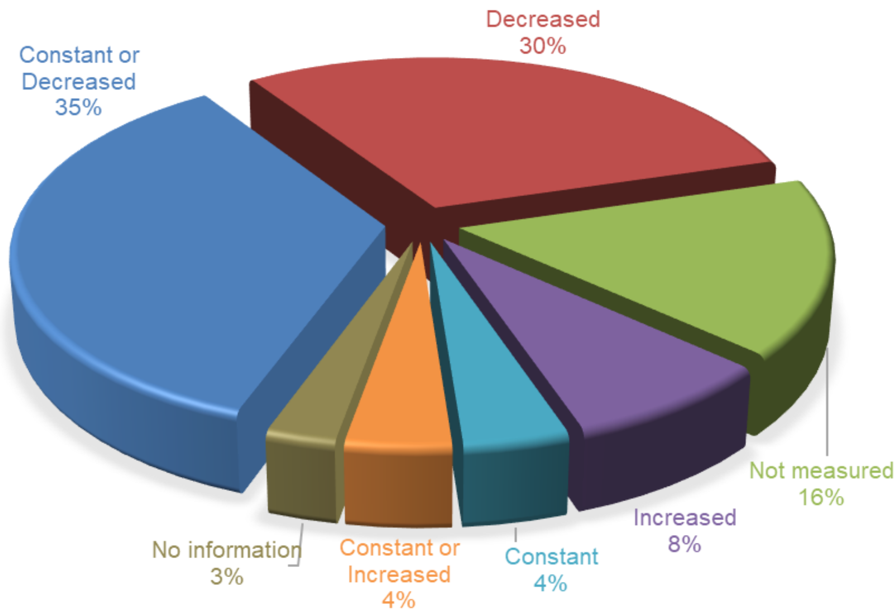

Figure 4-21 CO emissions from appliances with hydrogen in the test fuel.

4.6.2 NOx Emission

Figure 4-22 presents the measured NOx emissions from appliances when hydrogen is included in the test fuel. The addition of hydrogen to natural gas enhances heat transfer, resulting in lower flame temperatures and, consequently, reduced NOx formation via the Zeldovich mechanism [29]. In the presence of hydrogen, over two-thirds of the cases showed either constant or decreased NOx emissions compared to testing results without hydrogen in the fuel.

Unlike CO emissions, specific burners, such as staged fuel burners and power flame burners, showed only constant or increasing NOx emissions with increasing hydrogen content, indicating higher combustion temperatures compared to other burner types.

Certain burner types, including ultra-low NOx burners, dry low NOx burners, atmospheric burners, IR burners, and tip-jet burners, consistently produced decreasing NOx emissions in the presence of hydrogen in the blends. Other burner types, such as pancake burners, in-shot burners, ribbon burners, range burners, premixed burners, tube burners, and log set burners, exhibited either decreasing or increasing NOx emissions.

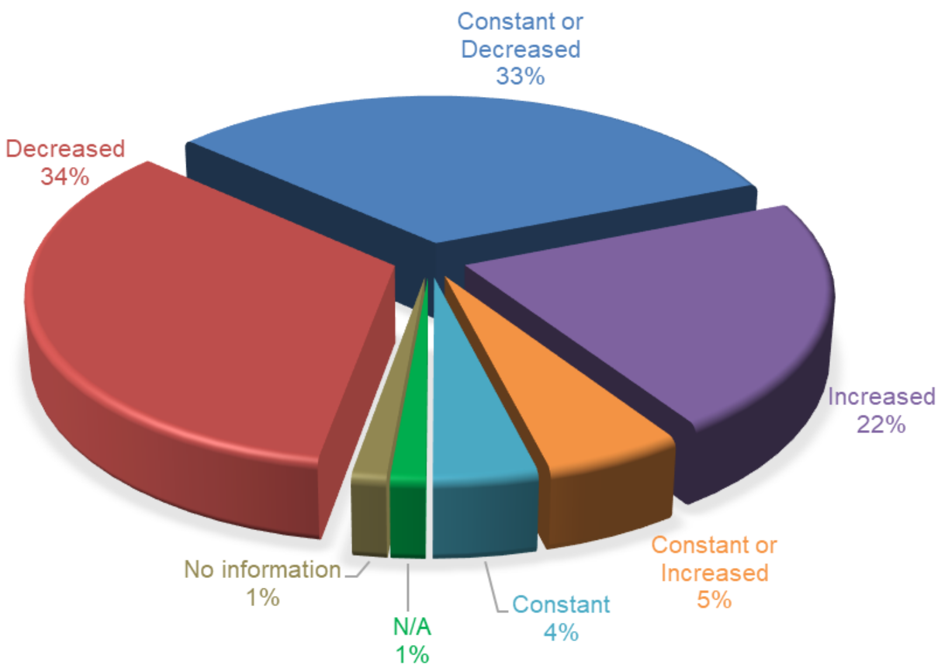

Figure 4-22 Measured NOx emissions from appliances with hydrogen in the test fuel.

4.6.3 UHC Emission

Figure 4-23 shows the measured unburned hydrocarbon (UHC) emissions with hydrogen in the test fuel. For over 50% of the appliances, UHC emissions were either not measured or not reported by the participants. Excluding these cases, less than 10% showed increased UHC emissions with hydrogen present, indicating that only a limited number of cases exhibited higher UHC emissions.

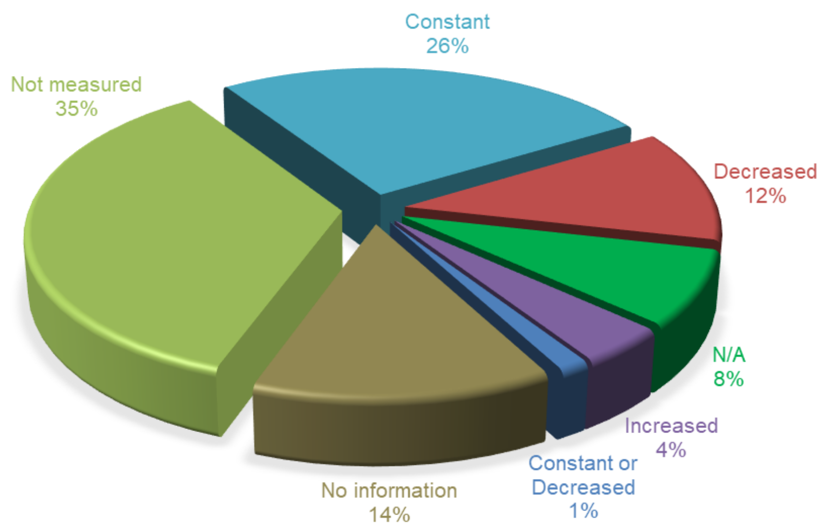

Figure 4-23 UHC emissions from appliances with hydrogen in the test fuel.

4.7 Overall Safe Upper Limits

It has been reported that the failure propensity and maximum H_2 tolerance of residential appliances vary depending on the model, age, and maintenance level. The maximum allowable H_2 in gas-fired appliances also varies significantly based on the mode of operation and equivalence ratio [26]. Figure 4-24 shows the overall safe upper limit of the tested appliances. The 'safe upper limit' refers to the maximum vol% hydrogen that individual participants considered safe based on their specific test parameters. Appliances with a safe limit of less than 20 vol% were tested below 20 vol% H_2.

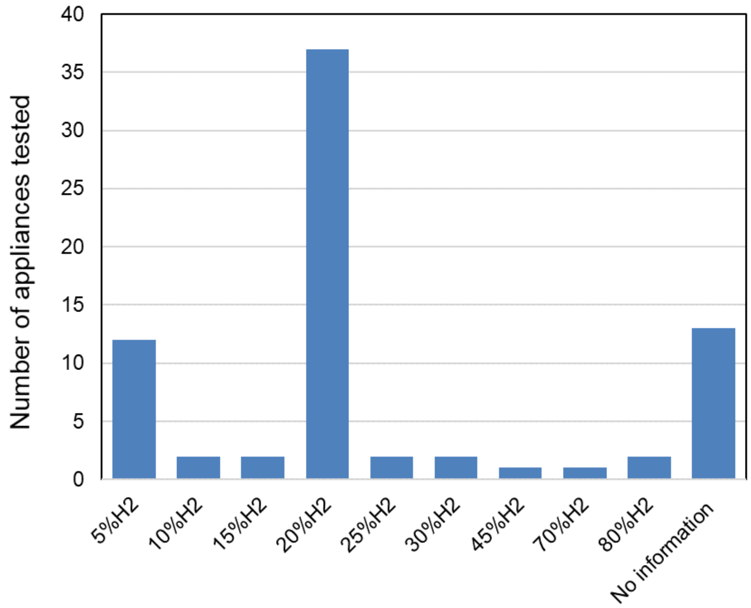

Figure 4-24 Overall safe upper limit vs. number of appliances tested (including those tested below 20vol% H_2).

Figure 4-25 shows the percentages of the overall safe upper limit of hydrogen vol% for tested appliances. In 50% of all cases, 20 vol% H_2 was identified as the overall safe upper limit. As mentioned earlier, appliances with a safe limit of less than 20 vol% were tested below 20 vol% H_2.

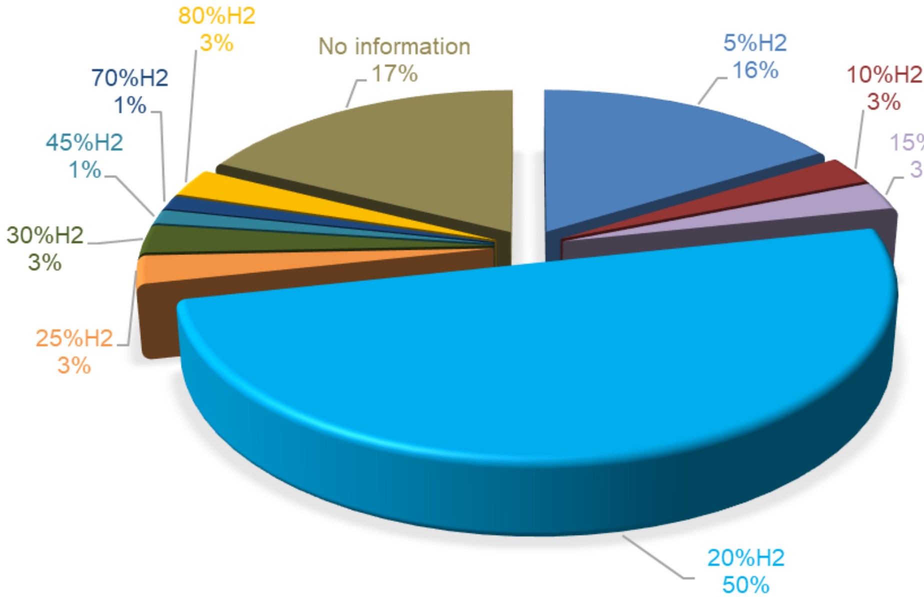

Figure 4-25 Overall safe upper limits of hydrogen vol% for tested appliances (including those tested below 20vol% H_2).

Figure 4-26 presents the observed overall safe upper limit versus the maximum vol% H_2 in the tested fuel. The yellow bars in the graph represent test results with a maximum of 5-10 vol% H_2 in the fuel. Out of the 74 tested appliances, 14 were tested with less than 20 vol% hydrogen. For the remaining 60 appliances, the test fuel contained between 20-100 vol% hydrogen.

Figure 4-27 shows the overall safe upper limit data, excluding tests with less than 20 vol% hydrogen. As illustrated, 94% of the tests indicate a safe upper limit of ≥20 vol% hydrogen. In other words, fifty-seven appliances demonstrated a safe upper limit of 20 vol% or higher based on the parameters measured by the participants.

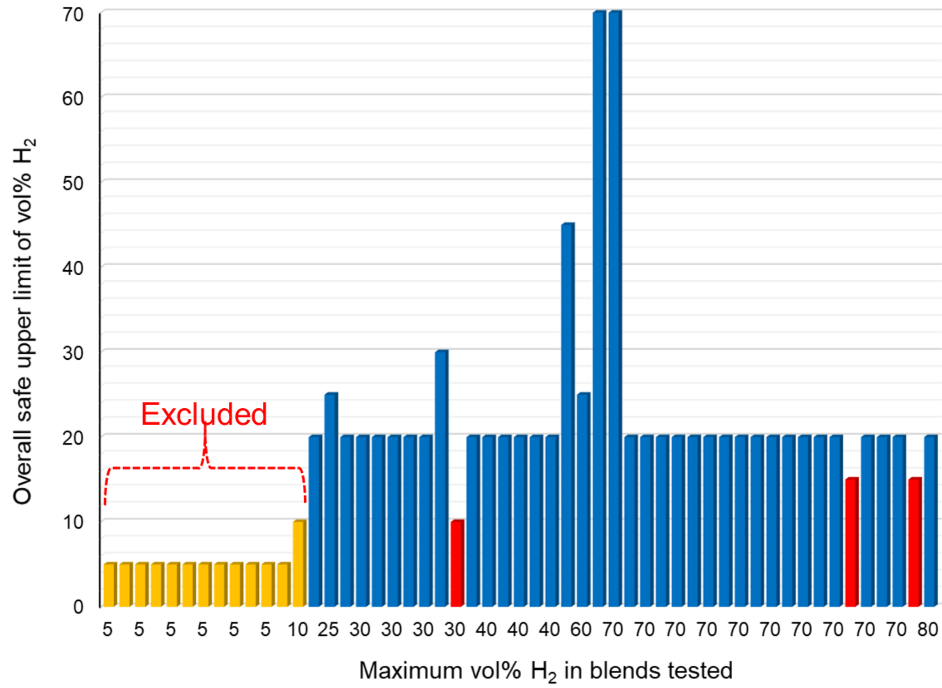

Figure 4-26 Overall safe upper limits vs. maximum vol% H_2 in the tested blends.

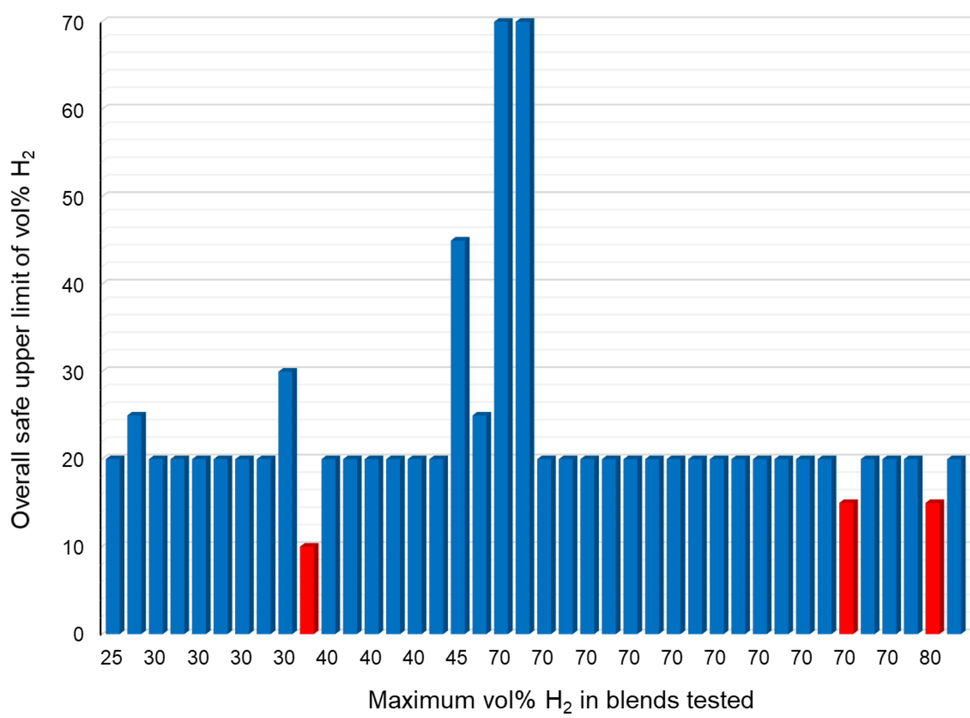

Figure 4-27 Overall safe upper limits vs. maximum vol% H_2 in the tested blends (excluding < 20%H_2).

Only three appliances—a storage water heater, an atmospheric boiler, and a cooktop (indicated by red bars in Figure 4-27)—exhibited flashback or burner overheating at higher hydrogen concentrations, resulting in a safe upper limit of 10 or 15 vol% hydrogen. Table 4-3 provides detailed information on these specific cases where the safe upper limit is lower than 20 vol% H_2.

Table 4-3 Detailed information on the three cases with safe upper limits lower than 20vol% H_2.

No.	Appliance Type	Burner Type	Max. vol% H_2 Tested	Safe Upper Limit	Safety Issues Observed
Case 1	Storage Water Heater	Premixed Burner	30vol% H_2	10vol% H_2	Flashback under steady state conditions
Case 2	Atmospheric Boiler	Tube Burner	70vol% H_2	15vol% H_2	Burner overheating >5°C at 20vol% H_2
Case 3	Cooktop	Atmospheric Burner	80vol% H_2	15vol% H_2	Flashback at 20vol% H_2 during cold start and re-ignition

4.8 Potential Correlation between Appliances and Safety Issues

Potential correlations between different appliances and some associated safety issues are presented in Table 4-4 and Table 4-5. Table 4-4 highlights the potential correlation between burner type and the safe upper limit for hydrogen. Certain burners, such as direct-fired burners, power flame burners, and staged fuel burners, exhibit a safe upper limit exceeding 30 vol% H_2. However, most burner types have a relatively lower safe upper limit, ranging between 20 and 25 vol% H_2. Notably, the current study found that three burner types—atmospheric burners, pre-mixed burners, and tube burners—pose potential risks and should be used with caution in hydrogen blends, as their safe upper limits were observed to be below 20 vol% H_2. Table 4-5 lists different appliances with their respective burner types that exhibited burner overheating temperatures exceeding 5°C in the presence of hydrogen in the tested fuel.

Table 4-4 Burner types vs. safe upper limits.

Safe Upper Limit	Burner Type
Relatively Flexible Safe Upper Limits with > 30vol% H_2	Direct-fired burner, power flame burner, and staged fuel burner
Relatively Low Safe Upper Limits with 20~25vol% H_2	Pancake burner, ultra-low NOx burner, in-shot burner, IR burner, range burner, log set burner, ring burner, spoon burner, tip-jet burner, atmospheric burner, pre-mixed burner, and tube burner
Potentially Risky Lower Safe Upper Limits with < 20vol% H_2	Atmospheric burner, pre-mixed burner, and tube burner

Table 4-5 Appliance/burner type with burner overheating temperature over 5°C.

No.	Appliance	Burner Type
1	Storage water heater	Pancake Burner
2	NG Range	Atmospheric Burner
3	Fireplace	Atmospheric Burner
4	Unit Heater	IR Burner
5	Cooktop	Ring Burner
6	Furnace (High Efficiency)	In-shot Burner (2 Cases)
7	Hot Water Heater	Pancake Burner
8	Dryer (Laundry)	Spoon Burner
9	Wok Burner	Tip-jet
10	Boiler (Atmosphere)	Tube Burner

5 Conclusions and Recommendations

5.1 Conclusions

This report provides a comprehensive analysis demonstrating some of the impacts of hydrogen blending on various appliances. The study involved testing 74 appliances with hydrogen blending percentages ranging from 5% to 100%. The key findings indicate that:

- Most appliances tested (77%) were residential, and the majority showed a safe upper limit of 20 vol% hydrogen or higher. The 'safe upper limit' refers to the maximum vol% hydrogen that individual participants considered safe based on their specific test parameters. However, three specific appliances (a storage water heater, an atmospheric boiler, and a cooktop) exhibited safety issues such as flashback and burner overheating at lower hydrogen concentrations (10-15 vol%).
- Flashback was observed in 31 of the 74 appliances tested with hydrogen blends of 10-80% H_2 under various conditions, including steady state, cold start, re-ignition, and shutdown. One appliance exhibited flashback at 10% H_2 during steady state, while three appliances experienced flashback at 20% H_2 during cold start and re-ignition.
- Burner overheating occurred in appliances using fuel blends with 30-70% hydrogen. Overheating was not measured or reported for 50% of the 74 appliances tested. Among the remaining appliances, 30% exhibited overheating, with 11 showing burner temperatures over 5°C (9°F) higher than without hydrogen.
- Over two-thirds of the tested appliances showed constant or decreased CO and NOx emissions with increasing hydrogen content. However, certain burner types, such as staged fuel burners and power flame burners, exhibited constant or increasing NOx emissions.
- Different standards were used by different participants for different types of appliances, with the CSA ANSI Z21 series being the most commonly applied. The lack of standardized testing protocols and the limited number of identical appliance units tested reduced the reliability of the dataset.

5.2 Recommendations

Based on data collected from various interested and affected parties involved in this project's data collection and analytics for H_2 blending testing on end-use appliances and related controls, the B149 Hydrogen WG, the Binational Gas TC Hydrogen WG, and NRC's data analytics conducted to provide unbiased results and aggregated findings without disclosing sensitive information, the following recommendations can be made:

- Ignition, burner overheating, and flashback (under various conditions such as steady-state, cold start, re-ignition, and shutdown) are the important parameters during testing to identify potential safety issues.
- Conduct detailed investigations on appliances that indicated a safe upper limit below 20 vol% hydrogen to identify safe upper limits for various end-use appliances.
- To enhance the reliability of the results, it is recommended to test multiple units of the same appliance model. This will provide a more accurate assessment of combustion performance and safety issues.

- Implement standardized controls on air, fuel flows, and pressures for different appliance types to ensure consistent and reliable data. This will facilitate objective comparisons across different studies.
- Further research is needed to assess the mid- to long-term durability and performance of appliances using hydrogen blends.

Previous investigations into materials compatibility with hydrogen have shown that other constituents, such as water vapor, hydrogen sulfide (H_2S), carbon dioxide, nitrogen, helium, and various impurities in natural gas, also interact with hydrogen and may influence the results. Therefore, it is recommended to use a standard natural gas composition for testing when studying the effects of hydrogen blends. By addressing these recommendations, future research can provide more robust and reliable data, aiding in the development of standards and regulations for hydrogen blending in end-use appliances.

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