Skills for Hydrogen Safety

Erasmus+ KA202 - Strategic Partnerships for vocational education and training

Learning Unit 7

Hydrogen Combustion

Contents

-------- BLOCK 1 --------

1.1. Combustion

Combustion is an exothermic chemical process in which a substance reacts with oxygen and gives off heat.

The original substance is called the fuel – it may be a solid, liquid, or gas. The source of oxygen is called the oxidizer – it is usually a gas (air). The new chemical substances that are created from the fuel and the oxidizer are called exhaust. When hydrocarbons are used as fuel, carbon dioxide is a common exhaust.

The activation energy must be overcome to initiate combustion, but the heat from a flame may provide enough energy to make the reaction self-sustaining.

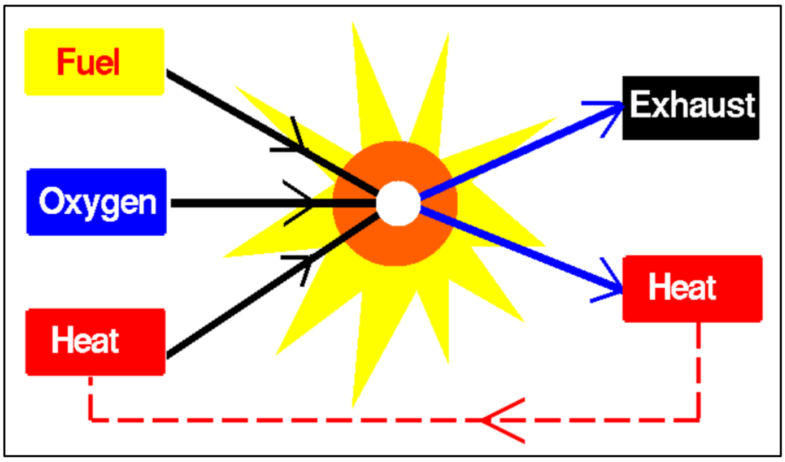

Figure 1. Basic schematic of combustion elements.

1.1.1. Types of Combustion

Combustion can be categorised in different forms: it can be complete (when there is an unlimited supply of oxygen) or incomplete (when there is a limited supply). Table 1 describes the key differences between these two forms.

Table 1. Complete vs Incomplete combustion.

	COMPLETE	INCOMPLETE
Also known as	Clean combustion	Dirty combustion
Condition	Unlimited supply of oxygen	Oxygen is in limited supply
Outcome	Fuel will burn completely	Fuel will not react completely
By-products	Water and CO_2	CO and soot
Example	Candle	Burning paper

Combustion can also be categorised in three different types:

- **Rapid**: Produces a large amount of heat and light energy, and does so rapidly. A stove flame is an example of rapid combustion.
- **Spontaneous**: Requires no external energy to start – a substance with a low ignition temperature self-heats and the heat is unable to escape. Many substances and even human beings can spontaneously combust in the right conditions.
- **Explosive**: Accompanied by sudden production of heat and sound, happening at an extremely rapid pace. Fireworks are an example of explosive combustion.

Discussion → An in-class discussion is recommended to highlight more examples of the abovementioned types of combustion.

1.1.2. Combustion FAQs

What are the factors that support the combustion process?

1. Sufficient supply of oxygen;
2. A fuel which burns during combustion;
3. Energy that helps the fuel reach the ignition point.

What is ignition temperature?

It is the temperature at which the fuel starts burning. Every substance has a different ignition point.

What are inflammable substances?

They are substances with very low ignition temperatures, which must be stored carefully.

1.2. The Combustion of Hydrogen

In the combustion of hydrogen, it reacts with oxygen to form water, with the release of energy, according to the equation:

$$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (g) + \text{energy}$$

This reaction is commonly used in the space sector to power rocket engines, given that hydrogen yields the highest specific impulse of any known propellant.

Hydrogen does not produce carbon emissions after combustion. However, when burned in air, Nitrogen Oxides (**NOx**) are produced due to the Nitrogen that is present in atmospheric air.

NOx = the sum of NO and NO_2

Note that this is not exclusive to the combustion of hydrogen, and also applies to the combustion of fossil fuels. NO_2 is a key air pollutant, and is a precursor to other pollutants of concern such as particulate matter.

Minimising NOx emissions from hydrogen engines and boilers is possible by controlling certain combustion conditions, and after-treatment and removal of NOx is also possible. However, these strategies invariably increase the <u>cost</u> and <u>complexity</u> of hydrogen combustion systems.

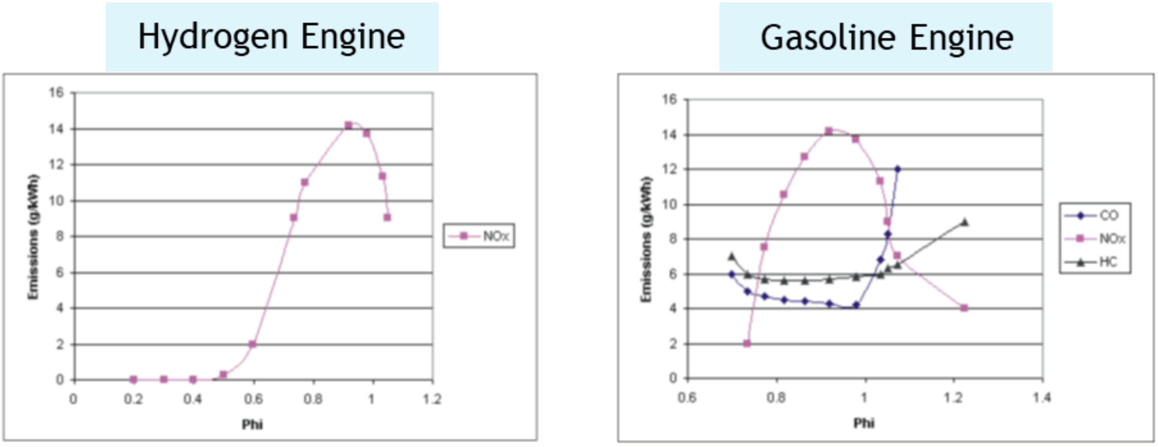

Figure 2. Comparison of emissions of a hydrogen combustion engine versus a standard petrol engine.
[Source: https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf]

Burning hydrogen is a way of generating energy from it. However, this is different from the electrochemical process that takes place inside a fuel cell, which also generates energy from hydrogen.

Discussion → An in-class discussion is recommended to highlight key differences and similarities between fuel cell systems and hydrogen combustion systems.

1.3. Applications of Hydrogen Combustion

Some examples of applications of hydrogen combustion, which will be discussed in more detail later in the course, include:

1.3.2. Hydrogen Internal Combustion Engines

They work in a very similar way to traditional spark-ignition engines, but are modified to use hydrogen as a combustion fuel.

Suggested Reading → How hydrogen combustion engines can contribute to zero emissions.
https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions

1.3.3. An Alternative to Methane

Hydrogen can be combusted and used for the same applications of fossil natural gas, such as industrial heating, home heating and cooking, as well as combustion in gas turbines.

Hydrogen can be blended with fossil natural gas in many types of existing pipelines, augmenting it or, ultimately, replacing it altogether. Some gas grid injection projects around the world include:

- ✓ H21 Leeds City Gate (United Kingdom), a 100% hydrogen grid plan for a UK city that is technically feasible and economically viable. More information at https://h21.green/projects/h21-leeds-city-gate/

- ✓ HyDeploy (United Kingdom), the world's first hydrogen grid injection project. More information at https://hydeploy.co.uk

- ✓ Evolugen/Gazifère (Canada), a green hydrogen green injection project in North America. More information at https://evolugen.com/evolugen-and-gazifere-announce-one-of-canadas-largest-green-hydrogen-injection-projects-to-be-located-in-quebec/

Suggested Reading → Zero Emission Hydrogen Turbine Center: A closed loop of the energy future. https://www.powerengineeringint.com/hydrogen/zero-emission-hydrogen-turbine-center-a-closed-loop-of-the-energy-future/

CONTINUOUS ASSESSMENT 1: QUIZ

-------- End of Block 1 --------

-------- **BLOCK 2** --------

2.1. Flammability of Hydrogen

Flammability is the ease with which a combustible substance can be ignited. Hydrogen has a very broad flammability range: between 4% and 74% concentration in air, and 4% to 94% concentration in pure oxygen.

This means it is flammable when mixed even in small amounts with air, and keeping air or oxygen from mixing with hydrogen inside confined spaces is very important. Table 2 and Figure 3 compare hydrogen and other fuels in terms of flammability.

Table 2. Flammability ranges of hydrogen and other fuels.

Fuel	Flammable Range in air (%)
Hydrogen	**4.0 – 74**
Methane	5.3 – 15
Propane	2.2 – 9.6
Methanol	6.0 – 36
Gasoline	1.0 – 7.6
Diesel	0.6 – 5.5

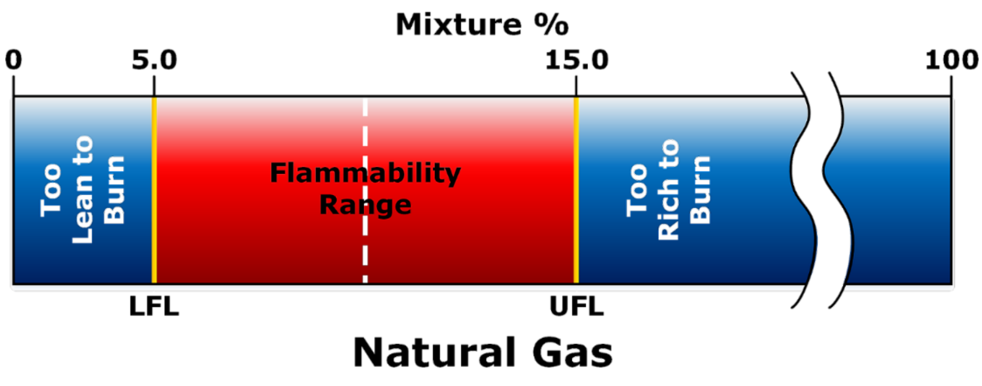

Figure 3. The flammability range of natural gas (methane), illustrated, for comparison.

The NFPA 704 is the "Standard System for the Identification of the Hazards of Materials for Emergency Response". Hydrogen has the NFPA 704's highest rating of **4** on the flammability scale, however, it has the lowest rating of **0** for innate hazard for reactivity or toxicity.

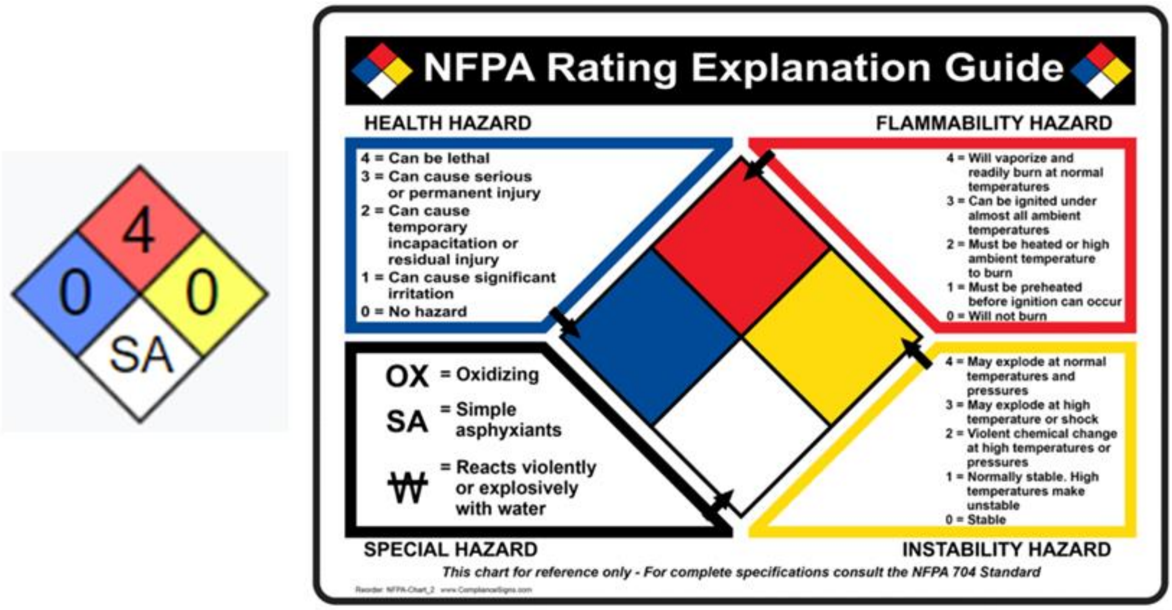

Figure 4. Hydrogen's fire diamond (left) and detailed explanation of a fire diamond (right).
[Source: https://myusf.usfca.edu/environmental-health-safety/nfpa-hazard-diamond]

According to Figure 4, hydrogen's flammability hazard means it will "rapidly or completely vaporize at normal atmospheric pressure and temperature, or is readily dispersed in air and will burn readily". Its health classification states that hydrogen "poses no health hazard, no precautions necessary", and its instability/reactivity classification is "normally stable".

As a special notice, hydrogen is considered a Simple Asphyxiant Gas which may reduce/displace the normal oxygen concentration in breathing air. This is a standard classification for many gases, and hydrogen is not hazardous in this sense unless at elevated concentrations.

2.2. The Hydrogen Flame

Hydrogen burns with a pale blue flame that is nearly invisible in daylight, although the flame may appear yellow if there are impurities in the air such as dust. A pure hydrogen flame will not produce smoke, and the flame temperature is relatively high – table 3 compares the flame temperature of hydrogen with other fuels.

Table 3. Flame temperature comparison.

Fuel	Flame Temperature in the air
Hydrogen	2,045 °C
Methane	1,957 °C
Propane	1,980 °C
Candle	1,000 °C

Hydrogen flames have low radiant heat, which means you may not feel any heat until you are very close to (or in) the flame. A video will better illustrate the characteristics of a hydrogen flame, using a propane flame as means of comparison.

Video → Hydrogen Safety: Hydrogen Flame Prop Demonstration https://www.youtube.com/watch?v=r-8H5u4YzuY

Lab Experiment → At this point a simple lab experiment is recommended so that learners can visualise a hydrogen flame and compare it with the flame from other common fuels, highlighting the relevant safety aspects.

2.3. Hydrogen Combustion Management

Hydrogen combustion management and safety consists of three key areas: preventing, detecting and suppressing (undesired/uncontrolled) combustion.

2.3.1. Preventing Combustion

Since hydrogen has a very wide flammability range and low ignition energy, it should be assumed that any hydrogen release is likely to result in fire.

The best way to prevent unwanted combustion (fire) is to remove one or more of its three key elements: heat, fuel and oxygen. As a rule, when dealing with hydrogen, controlling heat and keeping it away from the fuel is the best way to prevent undesired combustion. Common sources of heat include:

- **Plant and equipment**: a planned maintenance programme should be used to maintain plant and equipment clean, serviced and ventilated.

- **Hot work**: work such as welding and soldering must follow a strict permit system including protective clothing, spark control and routine checks.

- **Electrical equipment**: the installation and maintenance of electrical equipment and fittings should always be done by qualified electrical contractors.

- **Smoking**: non-smoking signs must be provided and enforced.

- **Arson**: the possibility of deliberately started fires should also be part of the risk assessment.

2.3.2. Detecting Combustion

Since hydrogen is colourless, odourless, burns with a nearly invisible flame and gives off relatively little radiant heat, a hydrogen fire is often difficult to detect.

Using flame detectors (such as the one illustrated in Figure 5) and thermal imaging cameras is the best way to detect if flames are present. If these tools are not available, a suspected leak should be cautiously approached in search for thermal waves. A combustible object such as a broom or dust particles can also be carefully put into the suspected flame to detect its presence.

Figure 5. The Honeywell FSL100 Flame Detector.
[Source: https://sps.honeywell.com/us/en/products/safety/gas-and-flame-detection/industrial-fixed/fsl100-flame-detectors]

2.3.3. Suppressing Combustion

Although hydrogen fires do not produce smoke, burning of nearby combustible materials can result in smoke, and its inhalation can be a danger in a hydrogen fire.

Hydrogen fires can ignite nearby objects through heat transmitted by radiation and/or convection. Usually, a hydrogen fire is not extinguished until the supply of hydrogen has been shut off or exhausted, and there is always a danger of re-ignition and even explosion.

The best way of handling a hydrogen fire is to let it burn under control until the supply has been shut off, as unburned gaseous hydrogen can result in an explosion. Best practices include the following actions:

1. From a safe distance or by remote operation, stop the flow of hydrogen by closing the block or isolation valve;

2. Use water sprays to extinguish any secondary fires and keep the fire from spreading;

3. Do not attempt to move a burning cylinder;

4. Carbon dioxide can be used on a hydrogen fire, but dry chemicals work better as they make the flames more visible.

In sum, hydrogen is no more or less dangerous than other flammable fuels, but has specific safety aspects. Further information can be found at: https://h2tools.org/bestpractices.

> "Hydrogen safety concerns are not cause for alarm; they simply are different than those we are accustomed to with gasoline or natural gas."
>
> –Air Products and Chemicals, Inc.

Discussion → An in-class discussion is recommended on the management of hydrogen combustion, emphasising particularities and generalities as well as comparing it with the learners' potential existing knowledge of the combustion of other fuels.

CONTINUOUS ASSESSMENT 2: QUIZ

-------- End of Block 2 --------

-------- **BLOCK 3** --------

3.1. Hydrogen Combustion Engines

Hydrogen internal combustion engines (Hydrogen ICEs) are nearly identical to traditional spark-ignition engines. In this case, gaseous or liquid hydrogen, instead of a fossil fuel, is burned to generate thrust.

Figure 6. A hydrogen internal combustion engine.
[Source: https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf]

In general, while fuel cells are most efficient at lower loads, ICEs tend to be most efficient under high loads, in a way that may enable both technologies to be successful for different applications.

Hydrogen ICEs have the same four-stroke combustion cycle as petrol engines, comprising intake, compression, ignition and exhaust, and generating rotational motion. This is illustrated in Figure 7.

1. **Intake**: air and fuel are mixed and drawn into the cylinder;
2. **Compression**: the mixture is compressed in the chamber;
3. **Ignition**: the compressed mixture is fired and ignited, forcing the piston back down;
4. **Exhaust**: the exhaust leaves the cylinder, and the cycle is complete.

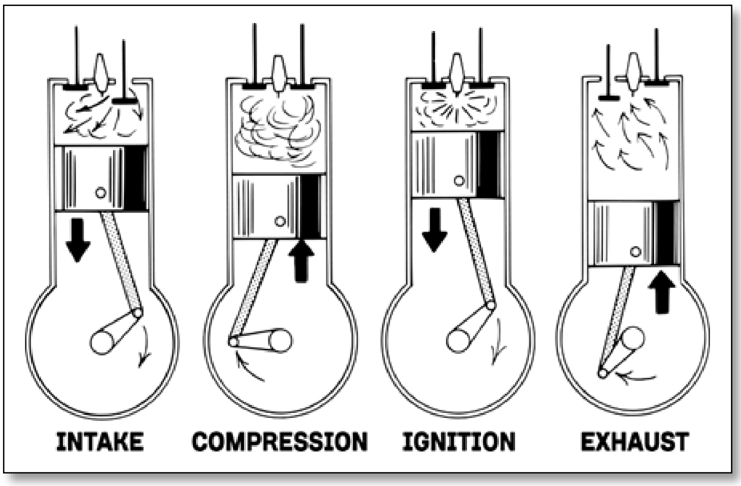

Figure 7. The standard four-stroke combustion cycle of an engine.

In relation to the combustive properties of hydrogen, its wide range of flammability is an advantage: it means hydrogen ICEs are easy to start, provide greater fuel economy and a more complete combustion. Additionally, hydrogen's ignition energy is an order of magnitude less than that required for gasoline, meaning lean mixtures and prompt ignition. However, this can lead to premature ignition, a well-known hydrogen ICE challenge. Other peculiarities related to hydrogen's combustive properties include:

- Hydrogen's **autoignition temperature** is relatively high, requiring a different compression ratio;
- Hydrogen's high **flame speed** means hydrogen engines can more closely approach a thermodynamically ideal cycle;
- Hydrogen's high **diffusivity** (ability to disperse in air) provides a more uniform mixture, but is a disadvantage if a leak develops;
- Hydrogen's **low density** poses challenges in terms of fuel storage and reduced energy density of the fuel-air mixture.

The safety aspects of vehicles powered by a hydrogen combustion engine also presents some particularities. For instance, attention is needed regarding enclosed spaces (such as garages) and ventilation, as well as crash behaviour.

Suggested Reading → A useful publication by H2 tools about safety aspects of hydrogen-fuelled vehicles with combustion engines. https://h2tools.org/sites/default/files/2019-09/310002.pdf

3.2. Hydrogen Boilers

In the near future, it is expected that boilers capable or burning 100% hydrogen will be available commercially in countries such as the UK and Ireland. However, most modern boilers – and other gas appliances we use today – are already able to run on a blend of up to 20% hydrogen. Companies who manufacture gas appliances and that may provide hydrogen systems soon include Worcester (part of the Bosch group), Viessmann and Baxi.

Figure 8. The concept of a 100% hydrogen boiler.

One of the most frequently asked questions – and source of worry – about hydrogen boilers is regarding their cost. However, manufacturers believe they will not cost more than the natural gas equivalent: roughly between £600 (€700) for a budget model and £2,000 (€2,400) for a premium model. The installation process is also expected to be very similar to that of natural gas boilers, with similar costs forecasted.

Projects and programmes in many countries are currently investigating the use of hydrogen as a fuel for residential and industrial appliances. For example, the **HyDeploy** programme being run at Keele University, in England, is testing the effects of blending hydrogen and natural gas. The project facilitated the injection of hydrogen in a part of the UK's natural gas network for the first time ever, with larger demonstrations planned for the near future. More information is available at www.hydeploy.co.uk.

Similarly, the new Innovation Centre of Gas Networks Ireland (GNI), in Dublin, is also testing different blends of hydrogen and methane (up to 10% hydrogen), and their applications in appliances such as boilers, stoves and gas fireplaces. More information is available at https://www.gasnetworks.ie.

3.2.1. Operation of Hydrogen Boilers

Although the overall process of a hydrogen boiler is the same as a traditional one, some modifications are needed. A schematic its main components can be seen in Figure 9.

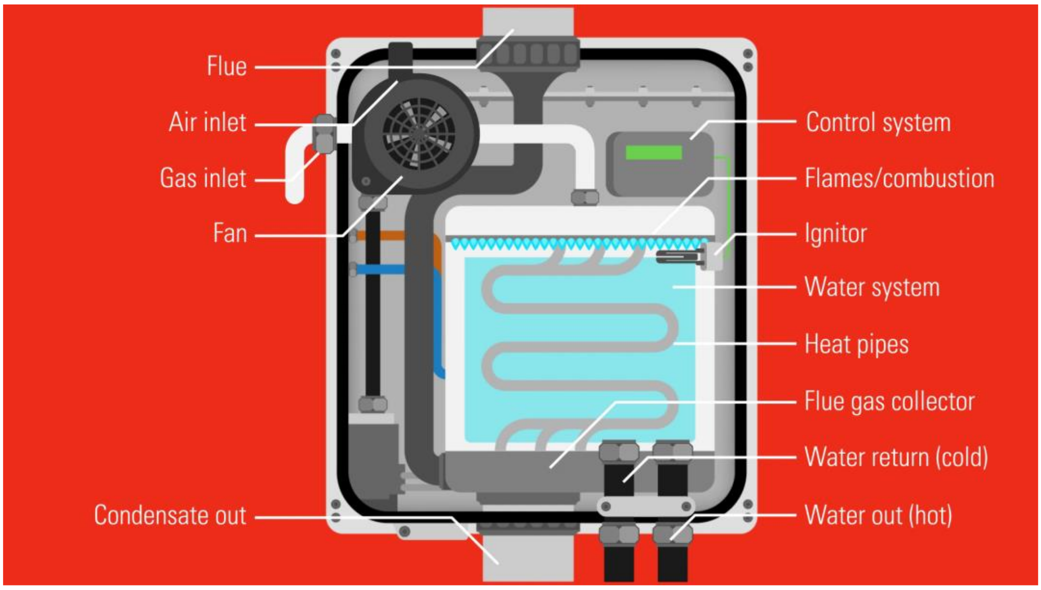

Figure 9. Key components of a hydrogen boiler.
[Source: https://youtu.be/241Ltw7B8ZA]

The operation of a hydrogen boiler comprises four steps:

1) **Hydrogen and oxygen enter the boiler.**
   - ✓ Hydrogen (coming from the main supply) and oxygen (from the air) enter through inlets that contain valves controlling their amounts.
   - ✓ The amount of gas impacts the size of the flame.

2) **The two gases are mixed and burned**.
   - ✓ Hydrogen and oxygen are mixed together and combusted in a catalytic burner.
   - ✓ Due to hydrogen's flammability, burners need to be specially designed to be able to limit flames.
   - ✓ Also, a flame detector is needed, since hydrogen flames are nearly invisible.

3) **The hot mixture enters the heat exchanger**.
   - ✓ The heat exchanger consists of several pipes through which the hot gases travel, surrounded by cold water.
   - ✓ This water, when heated, is sent to taps and heating systems.

4) **The by-products exit the system**.
    - ✓ The direct by-product of hydrogen combustion (water) escapes the system.
    - ✓ The hot flue gases (hydrogen and oxygen) also escape.
    - ✓ The small amount of NOx produced during combustion can also exit the system via the flue.

Video → How a hydrogen boiler works (by Viessmann). https://youtu.be/241Ltw7B8ZA.

Discussion → An in-class discussion is recommended on the extra components of a hydrogen boiler, and on general safety considerations.

CONTINUOUS ASSESSMENT 2:
PRODUCTION OF A HYDROGEN BOILER DIAGRAM

-------- End of Block 3 --------

References

Best Practices - Hydrogen Tools. Available at: https://h2tools.org/bestpractices.

Hydrogen Use in Internal Combustion Engines. rep. Available at: https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf.

NFPA Hazard Diamond. Available at: https://myusf.usfca.edu/environmental-health-safety/nfpa-hazard-diamond.

Viessmann. Available at: https://www.viessmann.co.uk.

Figures and tables are referenced in caption when applicable.