Testing **Hy**drogen admixture for **G**as **A**pplications

# Impact of hydrogen admixture on combustion processes – Part II: Practice

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# List of abbreviations

| | |
|---|---|
| CEN | European Committee for Standardization |
| CHP | combined heat and power |
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| DHW | Domestic Hot Water |
| EN | European Norm |
| GAR | Gas Appliance Regulation |
| GCV | gross calorific value |
| GHP | gas heat pump |
| GIWH | Gas Instantaneous Water Heater |
| GSHW | Gas Storage Water Heaters |
| $H_2$ | hydrogen |
| H2NG | Hydrogen/natural gas blend |
| $\lambda$ | air excess ratio |
| LCV | Lower calorific value |
| LNG | Liquefied natural gas |
| MN | Methane Number |
| $N_2$ | nitrogen |
| NCV | Net calorific value |
| $NO_x$ | nitrogen oxides |
| $O_2$ | oxygen |
| p | pressure |
| T | temperature |
| TC | Technical Committee |
| TIT | turbine inlet temperature |
| V | volume |
| $W_S$ | (superior) Wobbe Index, gross Wobbe Index |

# 1 Motivation and Scope

Climate change is one of today's most pressing global challenges. Since the emission of greenhouse gases is often closely related to the use and supply of energy, **the goal to avoid emissions requires a fundamental restructuring of the energy system** including all parts of the technology chains from production to end-use. Natural gas is today one of the most important primary energy sources in Europe, with utilization ranging from power generation and industry to appliances in the residential and commercial sector as well as mobility. As natural gas is a fossil fuel, gas utilization is thus responsible for significant emissions of carbon dioxide ($CO_2$), a greenhouse gas.

Today, the residential and commercial sector is the biggest end user sector for natural gas in the EU, both in terms of consumption and in the estimated number of more than 300 million installed appliances [FSCB20]. The most promising alternative fuels for decarbonising the gas sector are biogas and hydrogen. Producing hydrogen from green electricity and water could fulfil the demands and in parallel serve as a long-term energy storage option in chemically bound form, on the large scale. Thus, power-to-gas technologies can be a powerful tool for a European transition of the energy sector including all connected sectors while taking advantage of the existing gas grids as key components of the future energy infrastructure. However, the transformation of the gas sector, with its broad variety of technologies and end-use applications is a challenge, as a fuel switch is related to changing physical properties.

Technologies and materials need to be suitable for the new fuel, or, as an intermediate step, suitable to new blends. The injection of hydrogen into existing gas distribution will impact all gas-using equipment connected to the grids, since these devices were designed and optimized to operate safely, efficiently and with low pollutant emissions with natural gas as fuel. The **THyGA project**[1] focuses on technical aspects and the regulatory framework concerning the potential operation of domestic and commercial end user appliances with hydrogen / natural gas blends. The project deliverables start with a segmentation of the European appliance market (D2.1), an introduction to combustion theory including the impact of blending hydrogen with natural gas (D2.2), a background report on material science (D2.4) and a report on the impact of hydrogen admixture on appliances in practice (this report).

The structure of **this report** is organised in the following way. At first the authors explain the basic principles of the manifold existing gas appliance designs in the field and give qualitative indication on the expected impact of hydrogen admixture on these appliances. In a second part of this report, a systematic literature review is presented to gather the available information on the topic from literature and to disentangle what is known and what is so far unknown concerning the impact of hydrogen on the various appliance types in the market.

[1] For more information, please visit https://thyga-project.eu/

# 2 Working principles of appliances for gas combustion and expected impacts of hydrogen admixture

This chapter introduces the basics of various gas combustion technologies and their implementation in domestic and small-scale commercial appliances. The functional principles are explained and shown graphically, technology by technology. The focus is on aspects that are crucial for the influence of hydrogen admixture to natural gas, which will be discussed at the end of every subchapter.

Information on the market segmentation of gas end-use appliances can be found in deliverable D2.1 [FSCB20]. The fundamentals of combustion theory concerning hydrogen admixture to natural gas were recently published in deliverable D2.2 of the THyGA project [LSCA20].

## 2.1 Gas boilers

In the European Union a total of approximately 93 million gas boilers was installed in households and commercial contexts in 2014, used for room heating and warm water supply [VhBr19]. The numbers are rising continuously and can be expected to have exceeded 100 million appliances already, especially as a result of a fuel switch from oil-fired to gas-fired appliances. More data will be given in THyGA report D2.1 [FSCB20]. The appliance market consists of a broad variety of boiler technologies that exhibit different designs, different scales, and – very important in this context - different combustion technologies. Therefore, subcategories of gas boiler technologies are introduced in the following in order to discuss the impact of hydrogen admixture on these appliance types one by one.

The boilers of the following sub-categories are regulated under EN 15502 [En1512].

The basic working principle of a premixed gas boiler is depicted in the schematic in the Figure 2-1. The fuel gas passes the gas inlet valve and is mixed with air in a mixing zone. In this example, a fan-assisted design is shown where the air is actively blown into mixing zone, where fuel and air will mix homogeneously to form the gas/air mixture. The thoroughly mixed fuel/air mixture reaches the burner surface, which in this case consists of a perforated metal surface. The mixture moves through the small openings into the reaction zone. Here, the actual combustion takes place. During start-up, the ignitor initiates the combustion process. During operation, the flow velocity of the premixed gas/air mixture and the laminar combustion velocity (residential gas appliances generally operate in the laminar flow regime [Warn01]) on the surface of the plate will balance each other so that a stable flame is formed. A typical flame shape, a so-called “flame carpet”, for this kind of surface burner is shown in the photograph on the bottom Figure 2-1. A large surface area is covered by a multitude of small laminar flames. This burner design allows for a very compact combustion chamber. The hot flue gas is used to heat water in a heat exchanger which in turn delivers the heat for the designated end-use purposes such as space heating or warm water. The cooled-down flue gas is finally conveyed to the outlet, typically connected to a chimney.

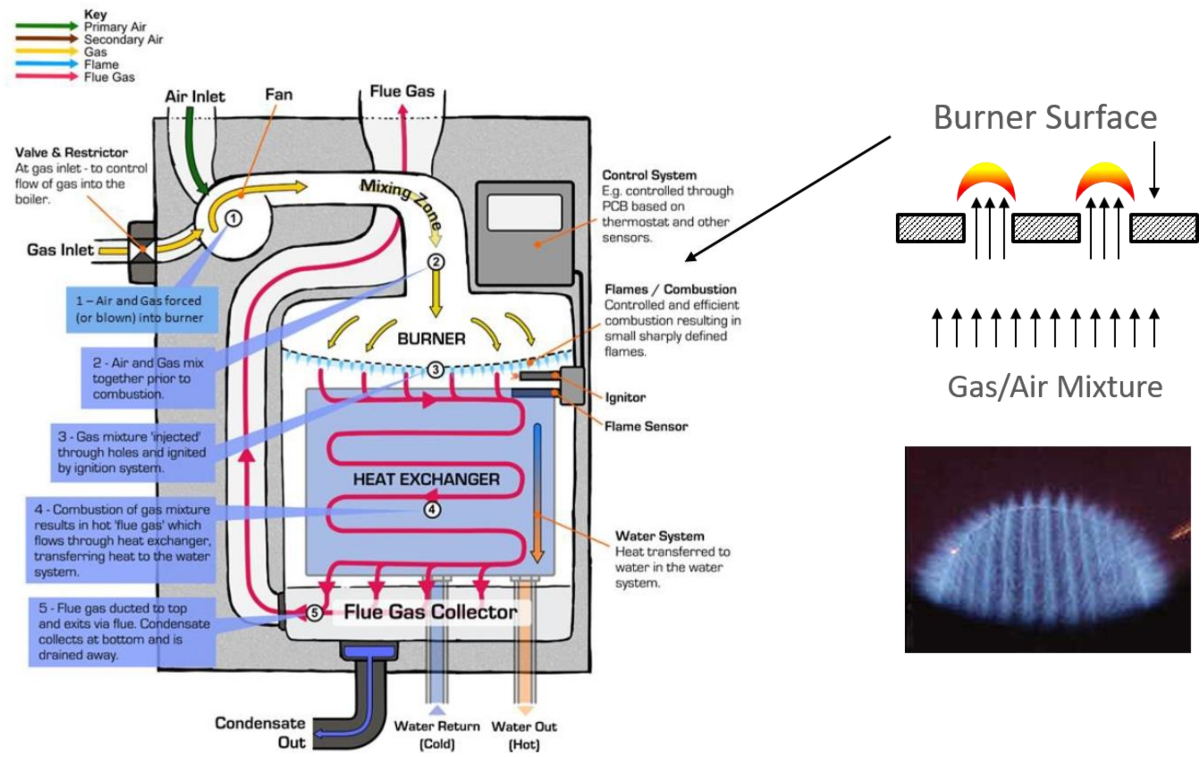


*Figure 2-1 Left: Schematic drawing of a gas-fired boiler system. Gas and air are mixed in a fan-assisted mixing zone (full premix-burner) [Fraz18] Right: Zoomed representation of a burner surface [GWI] and photograph of a surface burner in operation [Riel00].*

This general working principle can be found as well in several variations, as presented in the following. They vary especially with respect to the fuel gas / air mixing strategy.

The design depicted above is an example for a **fully premixed** boiler system. That means air and fuel gas are thoroughly mixed prior to the burner (see Figure 2-2).

In a **partially premixed** system, a similar mixing strategy would also be found, but in addition, a second air inlet, referred to as 'secondary air' exists as well. Thus, the local mixture in the primary zone is usually sub-stoichiometric.

In the third category, the so called **non-premixed** burners there is no fuel gas / air mixing strategy implemented before the fuel gas enters the reaction zone. This is the case for a classic non-premixed combustion system where both mixing of fuel and oxidizer as well as the actual combustion process take place in the combustion chamber. Within the combustion space, a flame will stabilize where there is a stoichiometric local mixture of fuel and air as well as a local balance of flow velocity and laminar combustion velocity.

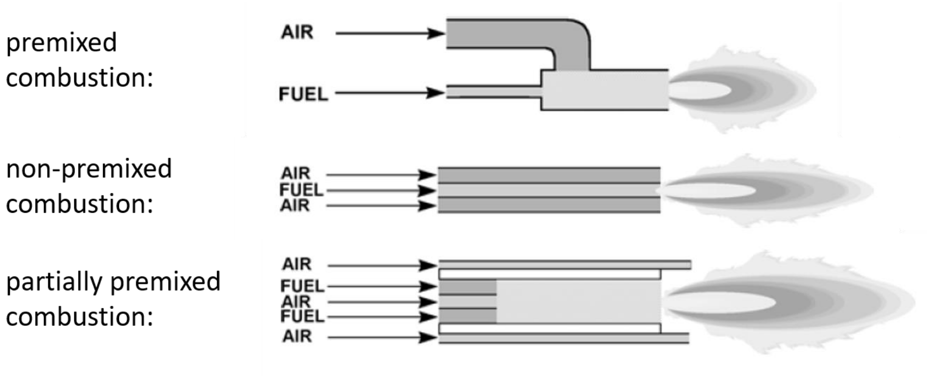


*Figure 2-2 Comparison of different air/fuel mixing strategies: Premixed combustion, non-premixed combustion, partially premixed combustion [Bauk00].*

### 2.1.1 Open flued boiler

The term 'open flued' describing an appliance design refers to the handling of the flue gas, which is in this case mixed with air from the room while being fed into the chimney. The additional amount of air is referred to as 'secondary air'. The installation site must have ventilation i.e. air vents allowing permanent air supply from outside the building to the installation site.

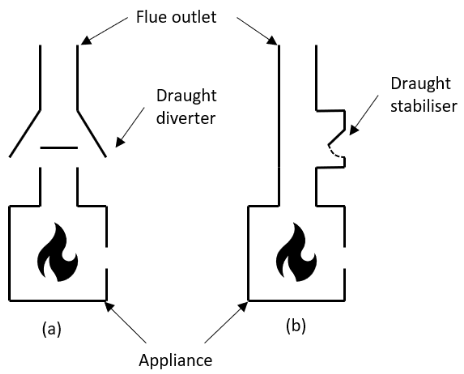


*Figure 2-3 Left: Open flued appliances with (a) draught diverter and (b) draught stabiliser [GWI].*

Draught diverters or draught stabilizers support the control of the chimney draft (see Figure 2-3). Once the hot flue gas / secondary air mixture enters the chimney it flows upwards and is let into the atmosphere[2]. Figure 2-4 shows an illustration of an open flued boiler. Blue arrows indicate the primary air (bottom) and secondary air (top) flow.

[2] If several appliances are connected to the same chimney, the flue gases mix and the chimney draught caused by each operating appliance influence each other.

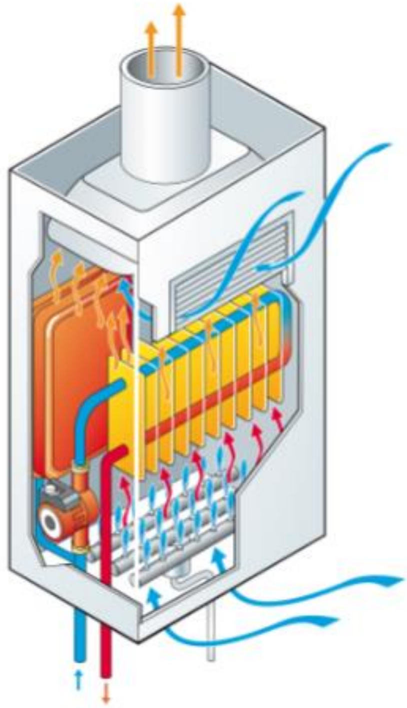

*Figure 2-4 Illustration of an open flued boiler [GRDF/CEGIBAT].*

## ➢ Impact of hydrogen admixture

For the boiler operation with notable hydrogen admixture levels there is a number of potential impacts or risks which shall be qualitatively explained in the following. It is generally assumed in these considerations that appliances designed and manufactured for the use with natural gas are exposed to a hydrogen / natural gas (H2NG) mixture, without any adjustments being made.

Due to the low density of hydrogen and its lower energy density per volume (i.e. its calorific value), H2 'dilutes' natural gas when being admixed[3] to some extent. As a result, appliances that operate at constant fuel gas inlet pressure - basically all residential appliances - will show a **reduced heat output**. This effect may simply be compensated in typical domestic or commercial boilers by increasing the operation time accordingly to achieve the set temperatures of the warm water circuit or storage without any loss of comfort. For instantaneous appliances however, the reduction of the maximum heat output may lead to reduced comfort in cases where the nominal system output was tightly dimensioned already for the combustion of natural gas.

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[3] This change in gas quality is amongst other characteristics expressed by a reduction of the 'Wobbe Index' for the case of H2NG mixtures as compared to natural gas. The Wobbe Index equals the heating value divided by the square-root of the relative gas density [LSCA20]. It is an important and useful measure for the interchangeability of fuel gases, even if in the case of gas mixtures, the Wobbe Index alone is not sufficient as an interchangeability indicator.

The combustion characteristics of H2NG mixtures [LSCA20] physically differ from those of natural gas, for which today's appliances were designed. As a result, the use of H2NG mixtures may lead to **thermoacoustic effects** in terms of notable noise emissions which may result in a loss of comfort – depending on the hydrogen admixture level, the specific appliance design and the acoustic characteristics of the installation site.

Hydrogen admixture into natural gas may also have an impact on the **position of the flame**. There are two competing physical effects to consider in this context. In an uncontrolled system or an appliance whose combustion control is unable to adequately respond to $H_2$ admixture, the stoichiometry of the combustion process will change to higher air excess ratios due to **reduced minimal air requirement**. At high air excess ratios flame lift can potentially occur. However, at the same time, hydrogen admixture also leads to **increased laminar combustion velocities** leading to the opposite effect, i.e. moving the flame closer to the burner. This over-compensates the increase in volume flow and leads to increased risk of local overheating or even light-back. For this reason, today the limit gas G222 from EN 437 [Cent03] with 23% hydrogen is used for flashback tests.

This is particularly relevant for systems where the air excess ratio is maintained (almost) constant (i.e. combustion controlled appliances) as increasing air excess ratios counteract the rise in laminar combustion velocities due to the presence of $H_2$ in the fuel [LSCA20].

In the past it was common to use a **pilot flame** as ignition system that was including the so called Oxy-pilot safety, a device that was detecting the $CO_2$ increase in the ambient air via a thermocouple very sensitive to the flame shape. A small reduction of $O_2$ in the primary air would have shut off the fuel gas valve. $H_2$ admixture to natural gas could have comparable impacts on the flame length.

If the appliance is equipped with an ionisation current sensor, the hydrogen admixture also affects the **ionisation current signal** measured near the burner. H2NG combustion leads to a reduced formation of free charge carriers that can be used for the ionisation current measurement. For high $H_2$ contents also a change in the position of the flame may further deteriorate the reliability of the signal, impacting the suitability of the combustion control strategy[4].

Under special circumstances, and highly depending on design details, material temperatures, partial load settings and operation dynamics of the specific appliances, **flash back** may occur. Especially when reducing the load (reduced flow rates and reduced cooling by the fuel gas mixture, while materials are still overheated), ignition may occur upstream of a burner nozzle. It is for example possible that overheating of materials due to changes in the position of the flame (see above) happens and the hot material leads to ignition of an ignitable mixture upstream of the burner nozzle.

After long-term exposure of the burner materials to hydrogen a degradation e. g. of the burner surface due to higher temperatures / overheating may be witnessed. **Material degradation** may lead to reduced lifetime and permanent damage to the appliances. Details on the impact of hydrogen on materials with a focus on hydrogen embrittlement can be found in the public THyGA report D2.4 [BlBr20] as well as the respective webinar slides available on the THyGA website[5].

[4] For more details see section 3.2.1.

[5] https://thyga-project.eu

### 2.1.2 Room-sealed boiler

In contrast to the open flued appliance designs discussed above (2.1.1), a completely different flue gas handling is implemented for room-sealed boilers. Appliances with room-sealed designs operate independently from the ambient air of the room they are installed in, but instead they draw in the combustion air via a separate air intake. The air supply is carried out according to the conditions at the installation site. The air may for example be provided by a second available chimney or through the outer wall of the building or using a pipe within the chimney. Since the operation of room-sealed appliances does not rely on air from the installation site within a building, no specific outdoor/indoor air vents are needed for the installation room. The combustion circuit consisting of (1) drawing of combustion air, (2) fuel/air mixing (3) combustion chamber, (4) heat exchanger and (5) discharge of products of combustion is entirely sealed off from the room in which the appliance itself is installed, leading to advantages in terms of safety and comfort (lower noise level, no indoor/outdoor room vent needed).

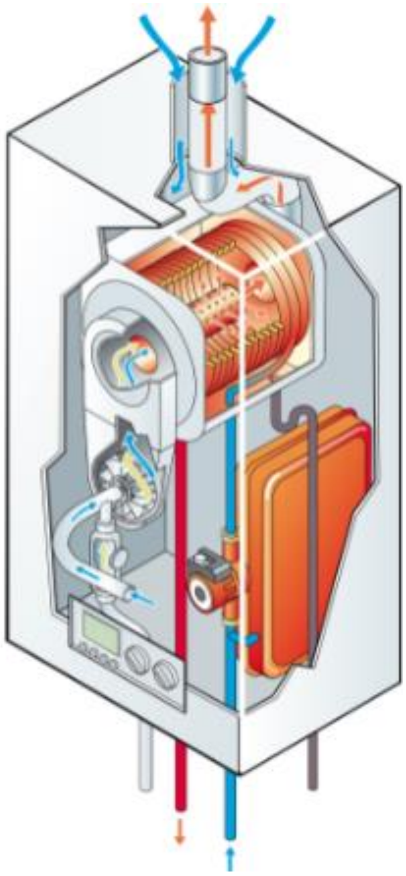

*Figure 2-5 Illustration of a room-sealed boiler [GRDF/CEGIBAT].*

## ➢ Impact of hydrogen admixture

The expectable impacts of hydrogen admixture to natural gas concerning room-sealed boilers are in general equivalent to the situation described above for the case of open flued boilers (see 2.1.1).

## 2.1.3 Condensing boiler

Condensing boilers are the boiler design that can be considered the state-of-the-art technology for heating and warm water supply purposes in domestic contexts today, even if they do not dominate the domestic boiler market [FSCB20].

Condensing boilers always exhibit room-sealed designs (as in 2.1.2) where external air is provided for the combustion process, many times realised via a specific pipe, that may be retrofitted to existing buildings, e. g. within an existing, sufficiently dimensioned chimney.

The key characteristic of a condensing boiler is that the appliance takes advantage of the amount of energy that is contained as latent heat in the water vapour in the flue gas, which cannot be utilised in older, non-condensing heating systems. The flue gas is cooled by a heat exchanger to temperature levels below the saturation temperature of water in the flue gas. The latent heat of water vapour is released during the phase change and can be used. When extracting heat, water molecules from the flue gas stream condense at the walls of the pipes and the resulting amounts of liquid water accumulate and need to be removed. Due to the occurring phase change, higher overall efficiencies are achieved. Typically, efficiencies exceed 100 % (calculated based on the net calorific value (NCV)). On average, by replacing non-condensing boilers with condensing boilers, the appliance thermal efficiency increases by about 10 % even without exploiting the full condensing potential [HoKE19]. Figure 2-6 shows theoretical efficiencies calculated for pure methane combustion with and without condensation for various air excess ratios. The non-condensing mode with high flue gas temperatures as well as the high-efficiency condensing mode, separated by the dew point, can be clearly distinguished.

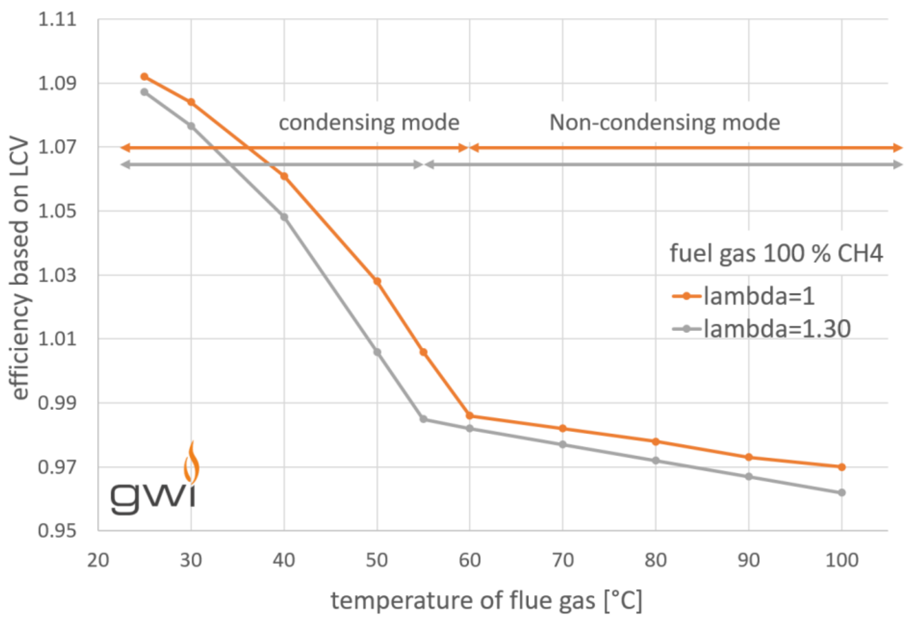


*Figure 2-6 Theoretical efficiency gain by using the condensing boiler technology in heating appliances for the case of pure methane combustion. Calculations by GWI.*

### ➢ Impact of hydrogen admixture

Partially premixed condensing boilers are impacted by hydrogen admixture as the fully premixed appliances described previously. In general, the risk must be considered, that appliances in the field may be adjusted to settings in presence of an H2NG blend, while at a later point in time the distributed gas changes to natural gas without hydrogen admixture. Potentially, if no interval of expectable hydrogen admixture is defined in a given distribution grid, any change between 0% $H_2$ to the locally defined maximum level needs to be considered. Adjustments of installations by technicians need to be organised accordingly to prevent critical situations e.g. for cases, where the adjustments are made with a natural gas from the lower Wobbe index range and hydrogen admixture, while at a later point in time potentially higher Wobbe index range gas without hydrogen admixture might be distributed.

One additional operational matter needs to be noted. When hydrogen is admixed to natural gas more condensate will be produced which has to be handled accordingly. Depending on the actual installation situation of an appliance, the accumulating water may be drained off via a floor drain or similar solution. In some cases, a pump is needed to pump the water to the next available drain as soon as a collecting tank is filled. In case of hydrogen admixture, the running times of such an on-demand water pump increase accordingly.

In theory, the hydrogen admixture would lead to an overall improvement of the appliance efficiency as more latent heat can be recovered from water vapour for a given flue gas temperature. To what degree this theoretical efficiency gain can be translated into real-life applications, is, however, highly dependent on the actual appliance. For example, it makes a significant difference if there is a combustion control system installed which can adequately handle higher and fluctuating levels of hydrogen in the flue gas, as variations in the air excess ratio affect both combustion efficiency and the flue gas composition (and hence the saturation temperatures to make use of the latent heat of the water vapour). Different effects, like changes in the air excess ratio, increased production of condensate water or changes in water temperatures can either counteract or amplify each other.

### 2.1.4 Forced-draught burners / jet burners

Similar to other fan-assisted burners, forced-draught jet burners are supplied with the necessary air by means of a fan which conveys ambient air into the combustion chamber. The main difference to other fan-assisted burner systems in the residential sector is the shape of the flame. While most burners for small-scale boiler applications utilize large burner cross sections with a multitude of small laminar premixed flames (a "flame carpet", cf. Figure 2-1) to produce a short compact flame, the fuel-air mixture (or fuel and air separately, in the case of non-premixed burners) in forced-draught jet burners is injected into the combustion chamber using distinct nozzles, forming jet flows. These flames are longer and generally turbulent, but with a much smaller cross-section, similar to flames of industrial burner systems. Also, like the majority of industrial burners, these burner systems are generally non-premixed (segment 3.1 in the segmentation of the GasQual project), although premixed systems exist as well (GasQual segment 3.2).

This burner type is disappearing from the market for residential and commercial gas appliances [VhBr19], with one of the major disadvantages being the high noise emissions of a turbulent flame.

They are still very common, however, in larger applications in the commercial sector and even in industry, with firing rates up to the double-digit MW range [Hube00]. Figure 2-7 shows an industrial forced-draught burner installed at a burner test rig. Two industrial standards are relevant for these systems: EN 303 [Cent17] describes heating boilers with forced-draught burners, while EN 676 [Cent20] describes forced-draught burners themselves.

*Figure 2-7 Industrial forced-draught burner installed at a burner test rig in the GWI laboratory [Hube00].*

## ➢ Impact of hydrogen admixture

Given that most forced-draught burners are non-premixed combustion systems, many of the findings from the theoretical considerations on these combustion processes apply here as well. One recent study [Hube00] investigated the impact of hydrogen admixture (up to 100 vol.-% $H_2$) on a larger forced-draught burner system (firing rates up to 600 kW) in a semi-industrial burner test rig. While this burner is certainly too large for use in the residential sector, the burner technology is very similar to those found in smaller domestic appliances, so some conclusions can be drawn.

It was found that hydrogen admixture generally results in higher NOx emissions due to the increased local flame temperatures in this non-premixed burner system. The overall NOx increase also becomes much more dependent on the firing rate of the burner. When switching from natural gas to a blend of natural gas with 70 vol.-% $H_2$, $NO_x$ concentrations in the flue gas doubled at minimum load, but increased "only" by 50 % at maximum firing rate, compared to operation with natural gas only. It was also shown that flue gas recirculation can be used to significantly mitigate $NO_x$ emissions, although this technology is usually reserved for larger burner systems.

As the flame structure changes and it also moves closer to the burner, the burner was subjected to higher thermal loads. This would result in increased component deterioration when operating over longer periods of time and at partial load.

The investigated burner system was equipped with a sensor to detect ionization currents as a safety feature to monitor the flame. It was found that at lower levels of H2 admixture, the signal actually increased due to the shrinking flame and the corresponding higher thermal load of the electrode. At hydrogen levels close to 100 %, the signal strength dropped rapidly, however.

The authors point out that fluctuations of hydrogen concentrations will require additional effort in terms of a fail-safe combustion control and optimization due to the strong changes in the minimum air requirement of the fuel to ensure safe, efficient and environmentally friendly operation. The expected increased component deterioration due to local overheating will have to be addressed by other materials (in new burner systems) and adjusted maintenance intervals.

## 2.2 Combined heat and power (CHP) appliances

In recent years, small-scale combined heat and power appliances have been entering the markets in larger quantities. This technology class combines the decentralised generation of electricity, e. g. in a household, with the supply of heat for room heating and warm water by making use of the excess heat of the electricity generation. The electricity can either be used in the building where the CHP unit is installed, or it may be fed into the local electricity distribution grid. Heat is stored in a hot water storage and utilised by the building heating and warm water system. In combination of both energy vectors high efficiencies become possible.

The three most prominent CHP technologies for small scale decentralised applications are 1) reciprocating engines, as known from Otto engine cars, 2) micro gas turbines and 3) fuel cells.

### 2.2.1 Reciprocating gas engines

In many residential or commercial CHP systems, reciprocating gas engines serve as prime movers (see Figure 2-8). These engines are very similar to four-stroke spark-ignited engines (Otto engines, see Figure 2-9) in vehicles, but adapted to use natural gas as fuel. In contrast to other residential gas appliances, combustion in such systems is intermittent and cyclical, i.e. it only takes place during the third stroke of the Otto cycle, the so-called power stroke. Most other residential gas-fired applications use continuous combustion processes.

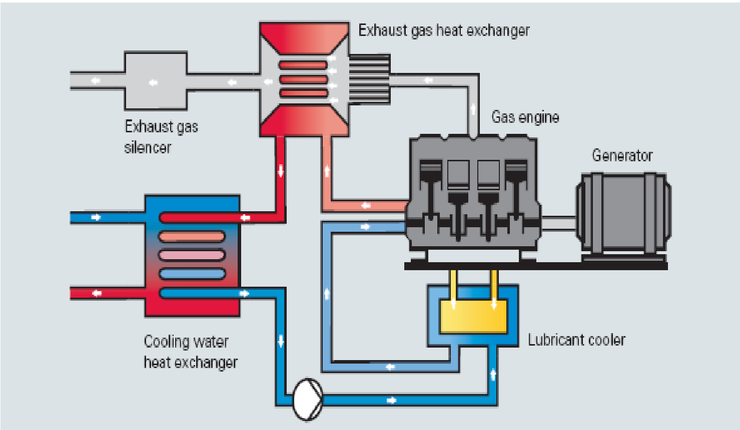


*Figure 2-8 Schematic of a gas engine CHP system [Roga11].*

In a gas engine, the heat that is released by combustion in the power stroke of the Otto cycle (red arrow in Figure 2-9) is converted to kinetic energy. The kinetic energy drives a generator connected to the shaft, producing electricity. In a residential micro-CHP system, the hot flue gas is conveyed to an exhaust gas heat exchanger where heat is transferred to the water cycle that is used for room heating and warm water supply. The lubricant cooler is also connected to water cycle. An exhaust gas silencer included in the flue gas system reduces noise emissions before the flue gas reaches the chimney (see Figure 2-8). The combined generation of both power and heat results in very high total efficiencies of CHP systems.

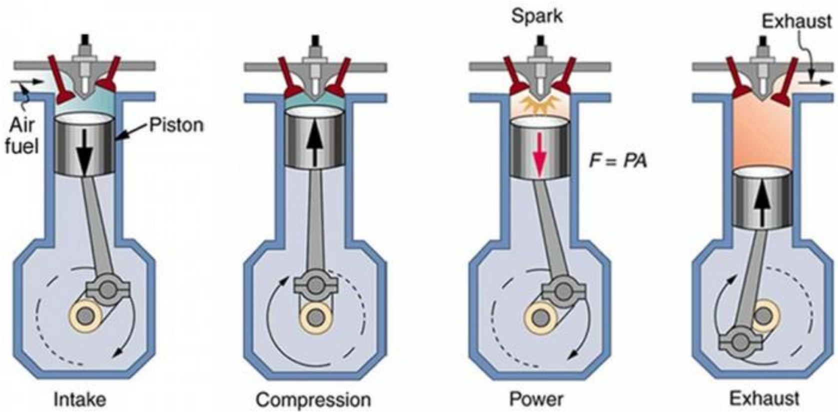


*Figure 2-9 Working principle of the Otto cycle [UrHi12]*

Given the working principle of an Otto-cycle engine, where an ignitable fuel-air mixture is compressed and then ignited in a controlled manner by a spark plug, a premature, uncontrolled ignition is a major concern for the operation of such an engine. This premature ignition is called “knocking” and can cause uneven operation, reduced engine efficiency, higher pollutant emissions and even damage to the engine. Knocking is a complex phenomenon whose underlying mechanisms are not yet entirely understood, but it is known that the fuel composition plays a major role. Higher hydrocarbons such as ethane or propane promote knocking, while some inert species (e.g. $CO_2$) reduce the knocking propensity of a fuel gas [LSCA20].

## ➢ Impact of hydrogen admixture

The knocking propensity of a gaseous fuel is commonly described by the so-called Methane Number (MN), an empirical gas quality criterion which is determined using a well-defined test engine operated in certain conditions. Methane, which is very knock-resistant, is set to have a Methane Number of 100, while hydrogen, which is very likely to knock, is set to have a Methane Number of 0. A fuel gas with a MN of 80 then will show the same knocking behaviour in the test engine as a blend of 80 vol.-% methane and 20 vol.-% hydrogen. This empirical approach is similar to the Octane Number used to quantify knocking propensity in gasoline engines.

The definition of the Methane Number already shows the main challenge of hydrogen admixture into natural gas for gas engines, be they installed in vehicles for propulsion or stationary as primary movers for (micro-) CHP units. Blending hydrogen into natural gas will significantly increase the overall knocking propensity of the fuel gas, making such engines more likely to experience reduced power output and efficiency, higher pollutant emissions or even physical damage.

The European natural gas quality regulation EN 16726 [En1619] prescribes a minimum Methane Number in natural gas of 65, while gas engine manufacturers usually demand MN of 80 or higher for optimum performance. Considering that natural gas does not have a specified composition but can contain significant amounts of higher alkanes such as ethane, propane or butane (e. g. in North Sea H gas and some LNG), the amount of hydrogen that can actually be injected into natural gas without violating the minimum MN requirement is dependent on the actual natural gas composition.

Larger, stationary gas engines for power generation are sometimes equipped with sensors to detect the onset of knocking. They can then be down-rated, i.e. their power output is temporarily reduced, to prevent damage to the engine. Also, in the case of small-scale CHP appliances suitable measures are taken by the manufacturers (or could be taken in the future) to cope with challenge of knocking.

### 2.2.2 Micro gas turbines

An alternative prime mover for a residential or commercial CHP system is the micro gas turbine. The general setup of such a system is similar to a CHP system with a gas engine, but instead of the intermittent combustion in a reciprocating engine, a continuous, pressurized combustion process in the combustion chamber of a micro gas turbine is used to convert the chemical energy of the fuel into kinetic and thermal energy, finally generating heat and power.

Micro gas turbines are technologically very different from their much larger counterparts in gas-fired power plants. Pressure levels in the combustion chamber usually are at less than 5 bars, and often, non-premixed burners are used. The turbines themselves generally are radial turbines because of their compact size suitable for domestic or commercial contexts.

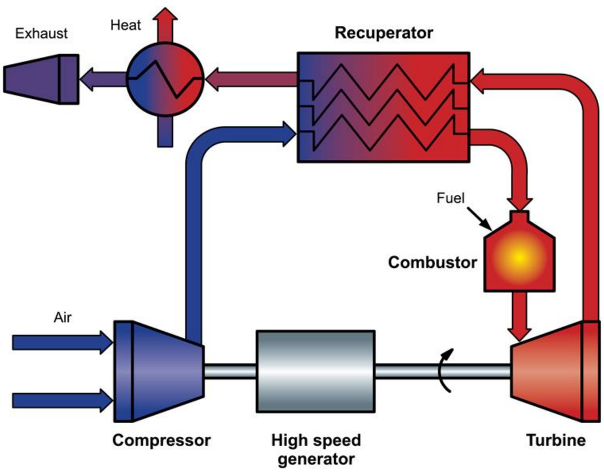


*Figure 2-10 Flow chart of a micro turbine combined heat and power appliance [Mttm00]*

The working principle is explained in Figure 2-10. First, ambient air is pressurized in the compressor. The compressed air is pre-heated in the recuperator. In the combustion chamber, more heat is added by fuel combustion. The hot pressurised gas expands in the turbine, providing mechanical power for both the compressor and the generator. An 'inverter' converts the power supplied by the generator to the voltage and frequency of the electricity grid (230V / 50Hz). The expanded flue gas heats the incoming air in the recuperator. The residual heat still present in the recuperator outlet gas is transferred to water in the heat exchanger, before the flue gas finally reaches the exhaust. The hot water can be used for central heating and/or as tap water. [Mttm00]

A schematic drawing of a micro gas turbine can be seen in Figure 2-11, showing a typical arrangement of the system components presented in in the flow chart Figure 2-10.

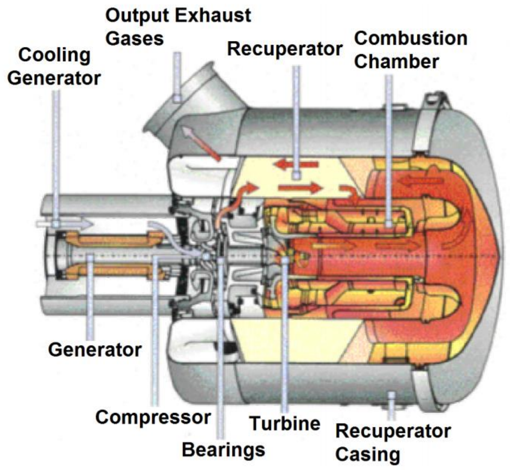


*Figure 2-11 Schematic drawing of a micro turbine [Rosa13]*

There are not many products on the market today for the application in domestic or small commercial contexts. The topic of micro gas turbines is currently the subject of research and development [Clea20].

## ➢ Impact of hydrogen admixture

From a combustion point of view, the aspects previously discussed for non-premixed burner systems can directly be transferred to micro gas turbines. Hydrogen admixture is likely to lead to higher $NO_x$ emissions as the main combustion reactions (and hence local maximum temperature) will take place at stoichiometric conditions. The flame may also move closer to the burner mouth and shrink in size, potentially causing local overheating, but this is very much dependent on the actual burner design and whether combustion control systems are used or not.

Whether the actual turbine inlet temperature (TIT, a main design criterion for any kind of gas turbine) also increases, depends on the presence of a combustion control system. If some kind of combustion control maintains a constant air excess ratio, then TIT will increase as well. If not, the previously discussed stoichiometry shift will cause lower turbine inlet temperatures (and hence reduce combustion efficiency).

Another aspect to consider is the change in flue gas mass flows and how it may affect the performance of the turbine itself. While micro gas turbines are usually more benign in partial load operation than the heavy-duty axial gas turbines found in power plants, the changing flows in the turbine may also effect turbine efficiency and thus power output.

### 2.2.3 Fuel cells

The fuel cell performs electrochemical conversion of fuel into electricity and heat, without combustion. Natural gas needs first to be converted to Hydrogen by a reforming process.

- The reaction happens inside elementary cells made of 2 electrodes separated by an electrolyte.
- The main difference from a combustion process is that hydrogen and oxygen cannot meet directly and remain separated by the electrolyte. As a matter of fact, hydrogen dissociates in protons and electrons, the latter using an external path to go across the window and meet oxygen molecules thus creating current.
- The protons can go through the window and meet oxygen and electrons to form water. The reaction is exothermic and heat is released.

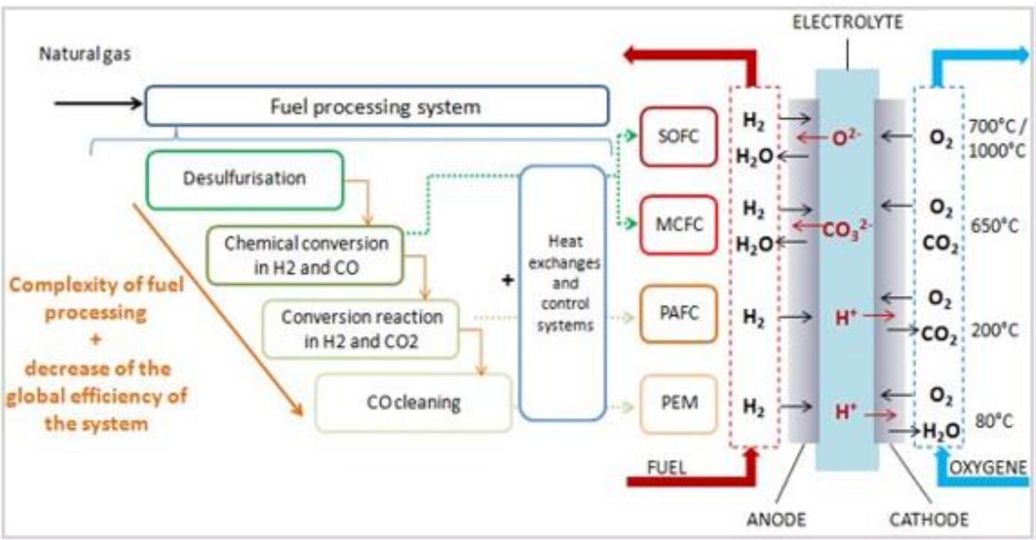


*Figure 2-12 Fuel processing for the various fuel cell technologies. Source: ENGIE.*

Generally, the conversion efficiency from fuel to electricity is high in a fuel cell and the technology is scalable without loss of efficiency. There are different kinds of fuel cells, characterized by criteria such as:

- fuel purity,
- electrolyte,
- temperature range,
- type of ions exchanged through the electrolyte
- The temperature range corresponds to the temperature at which the electrolyte allows the ion to go through (end thus the electrochemical reaction)

Figure 2-12 shows the processes to transform natural gas into a suitable hydrogen (containing more or less sulphur or carbon monoxide) to be used in a fuel cell application.

There are two main technologies on the market today for the residential and commercial sectors: PEM and SOFC. MCFC and PAFC are less suited because these technologies involve very strict installation rules (dangerous products are involved in the electrolyte). Figure 2-13 shows the working principle of PEM and SOFC.

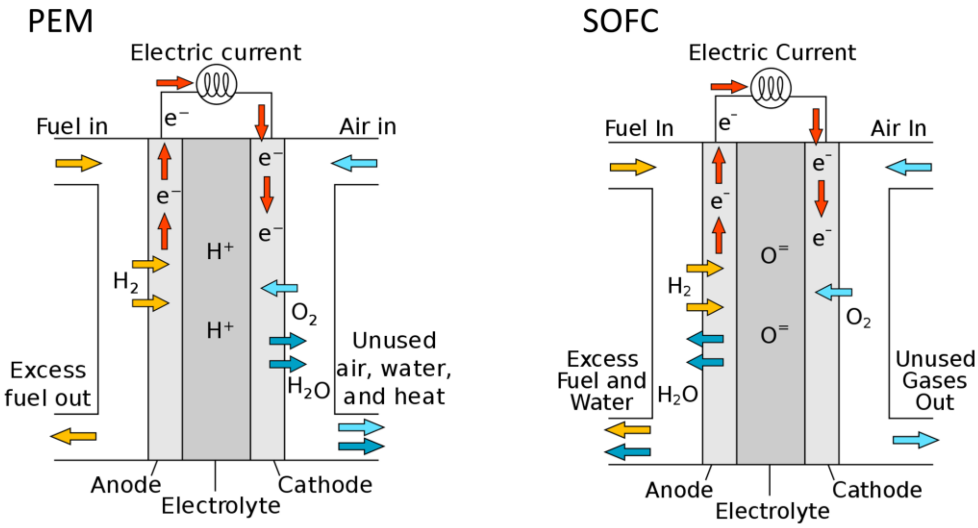


*Figure 2-13 Working principle of the Proton exchange membrane (PEM) fuel cell and the solid oxide fuel cell (SOFC)*

**Proton exchange membrane (PEM)**

For PEM fuel cells, the H2 purity expectation is high: Two successive chemical steps are necessary to remove all the carbon monoxide coming from the reforming step and increase the hydrogen content

Both electrodes (anode and cathode) are generally made from carbon in which channels allow for gas diffusion. Platinum is dispersed on the electrodes to catalyze reactions. A wet polymer membrane is placed between both electrodes: only protons can go through.

The PEM fuel cell operates at low temperatures (< 120°C) the advantages being a quick start-up. PEM catalysts are sensitive to fuel impurities (odorant needs to be removed, influence of the natural gas quality fluctuations and its nitrogen content).

**Solid oxide fuel cells (SOFC)**

SOFC operate at very high temperatures, generally between 700 and 900°C, they can allow a simple reforming of natural gas. Anodes are nickel-based alloys and cathodes are built from a ceramic based on lanthane, strontium, cobalt and iron. The electrolyte is a ceramic generally built from zirconium and yttrium. At high temperatures, it allows exclusive conduction of ions $O_{2-}$ from the cathode to the anode. The catalysts are not based on noble (and expensive) materials (unlike PEMFC).

Because of the high temperature operation, they are subject to long start-up time and suffer from start/stop cycles (thermal stress on the stack), strong attention is to be paid to the installation environment.

### ➢ Impact of hydrogen admixture

For fuel cell CHP systems designed for natural gas use, hydrogen tolerance remains unknown so far and strongly depends on the type of technology implemented (PEM or SOFC) as well as the internal methane reformer. The reforming step may be problematic in case of hydrogen admixture, as potential issues correlate with the precise temperature control needed. Hydrogen admixture could disturb the material temperatures foreseen by design and lead to material damage. Preventing such impacts, strict maximum $H_2$ levels in the base gas defined by the manufacturers may apply.

The potential presence of impurities such as sulphur, CO and other components may lead to damage of the fuel cell stacks. Existing and currently debated requirements on hydrogen purity for injection in the grids need to protect the sensitive technologies.

## 2.3 Gas heat pumps

Over the last years, the electric heat pump has gained a lot of attention with rising numbers of installations in the new building sector as well as in energy renovated buildings. In 2018 more than 37.2 million heat pumps [OTRF19] were in operation in European Union[6]. The advantages of the technology lie in the high efficiency with which it provides space heat by exploiting environmental warmth and lifting this available temperature to the use heat level needed. Due to its thermodynamical operation principle, typically only 1/4 to 1/3 of the building heat demand needs to be covered by electricity, underlining the high efficiency of the heat pump. The annual average utilisation rate however depends strongly on the heat insulation level of the specific building envelope. In order to reach high levels of efficiency in existing buildings, electric heat pump installation should go hand in hand with substantial energy renovation measures. However, heat pumps – especially gas heat pumps – can also be installed in older existing buildings.

[6] w/o installations in Italy, France and Portugal

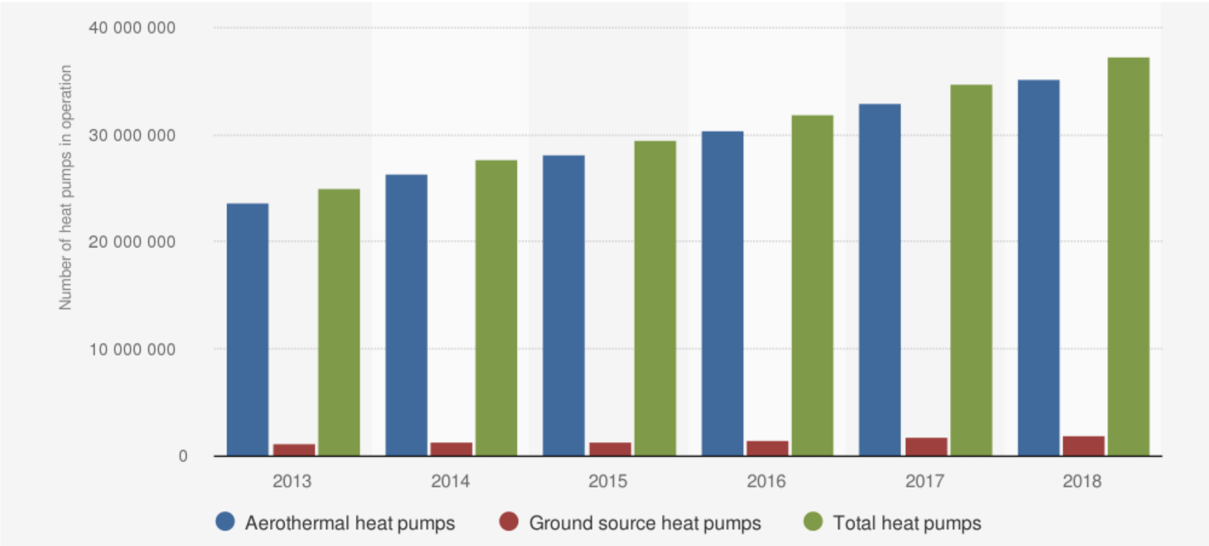


*Figure 2-14 Annual volume of heat pumps in operation in the European Union from 2013 to 2018 (w/o installations in Italy, France and Portugal) [Euro20]*

Besides the more popular electric heat pump, **gas heat pumps (GHP)** also exist, though publicly widely unknown. Thanks to their high range of power, gas heat pumps are particularly suited for commercial applications. They usually come with an auxiliary boiler [EGGI20].

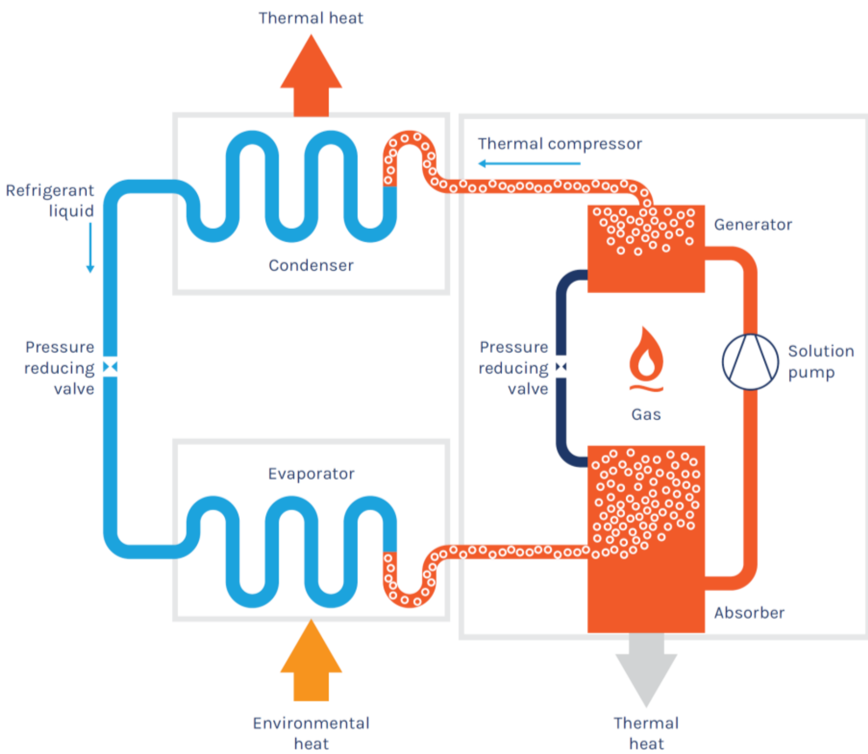


*Figure 2-15 The working principle of a heat pump consists of the four process steps compression, condensation, expansion and evaporation [EGGI20].*

Their operation principles will briefly be described in the following.

Figure 2-15 shows the basic principle of heat pumps. A refrigerant is compressed and heated. It flows through the condenser, transferring heat to the heating cycle of the appliance. During this process the refrigerant condensates. The pressure is then reduced in an expansion valve. In the evaporator the refrigerant absorbs heat from the surroundings and is evaporated in the process. Some heat pumps can also reverse the cycle and serve as an air conditioning system to provide local space cooling. Primary and secondary circuit change roles in that case.

There are two different technical implementations for gas heat pumps:

1) **Gas sorption heat pumps** also called “thermally driven heat pumps” with two technologies: **adsorption and absorption**. In contrast to an electric heat pump or gas engine driven heat pump, no compressor is needed. Adsorption systems are not able to produce cold (‘inverter mode’). However, absorption gas heat pumps can have this feature. The cold production power is however limited to around 50% of its heating power.
2) **Gas engine driven heat pumps** mainly used in commercial application. Production of cold and heat is possible.

**Gas absorption heat pumps**: In the basic absorption process, ammonia is evaporated by the free energy (e.g. outside air) and flows to an absorber, where it forms a solution with water. The heat is transferred from the absorber to the heating system. The ammonia-water solution is pumped at increased pressure to the generator where heat from a gas burner (**typically produced with a full premix burner)** is added. The ammonia vapour formed in the generator flows to the condenser, where it is condensed, and energy is transferred to the heating system. A lean ammonia-water solution recirculates from the generator to the absorber. Liquid ammonia flows after a pressure reduction from the condenser to the evaporator where it is vaporized again. The use of other refrigerants is possible for the absorption process, but typically ammonia-water is used in heat pumps for space heating.

**Gas adsorption heat pumps**: In **adsorption** processes, the water, which is mainly used as the refrigerant, evaporates, and in this process it absorbs ambient heat. The water vapour is adsorbed on the surface of a solid substance, such as active charcoal, silica gel (glass-like silicates) or zeolite (such as the Viessmann and Vaillant appliances). Thus, heat is released at a higher temperature. Once the zeolite is saturated, the water is driven out of the zeolite again in the desorption phase. Heat from a gas burner is used for this purpose. The adsorption heat pump process is a non-continuous regenerative and periodic process.

Alternative choices of materials, e.g. solid-sorption systems such as solid-ammonia, salt-ammonia, LiCl-$H_2O$ are also used [GCEK10].

A **gas engine heat pump** uses the same heat pump process as the electric heat pump, but the compressor is operated by a gas engine instead of an electric motor. Heat is also recovered from the engine cooling and the flue gases. In principle, any gas can be used in the gas engine (natural gas, biogas or upgraded biogas, LPG or hydrogen).

- In heat production mode, it is possible to recover energy from the engine to preheat hot water if the temperature of external air is not too low (>4°C). Below that temperature, the recovered energy is used in the thermodynamic cycle.
- In cooling mode, this recovery to preheat hot water is possible independently from the external temperature.

For details concerning gas engines, please also see section 2.2.1

#### ➢ Impact of hydrogen admixture

Thermally driven heat pumps use premix burners such as condensing boilers as heat supply. Therefore, the impact of hydrogen is expected to be similar to the impacts discussed for premix burner boilers.

Gas engine based heat pump appliances are expected to react to hydrogen the same way as the gas engine technology itself (see section 2.2.1).

## 2.4 Water heaters

Gas Instantaneous Water Heater (GIWH), also called tankless water heaters and Gas Storage Water Heaters (GSWH) are widely installed technologies in Europe even if they suffer a continuous decline in stock of appliances on the residential market (2004-2014, GIWH stock decreased from 19.1M to 17.2M installed appliances and GSWH from 3.8M to 3.6M installed appliances).

Technologically, the base product for the commercial sector is practically same as residential water heaters but figures on stocks are not available. As a reference, in 2016, 1.2M GIWH and 0.025M GSWH (including 0.012M condensing appliances) were sold [KeEl19a].

Technologies are generally segmented in the following ways

- Burner type: non-premixed, partially premixed and fully premixed
- Flue type: open flued and room sealed (with or without fan)

A gas water heater is fundamentally similar to a boiler, therefore, the principles are basically the same as what was described in chapter 2.1 on gas boilers.

### 2.4.1 Gas Instantaneous Water Heater

The appliances of this category are covered are regulated under EN 26 [Cent15a] (capacity not exceeding 70kW), the scope of the standard includes non-premixed and partially premixed burners.

The operation of the gas instantaneous water heater (GIWH) starts when an end-user draws water. A sensor detects the flow and the gas burner is started so that Domestic Hot Water (DHW) is warmed through the heat exchanger (generally serpentine). A temperature sensor controls the water temperature where the DHW exits the appliance.

Most GIWHs are open flued meaning that the combustion air comes from the room and the flue gases are evacuated outside through an exhaust duct (thermal draught or under pressure according the GIWH technology). Nowadays, most appliances introduced into the market are room sealed.

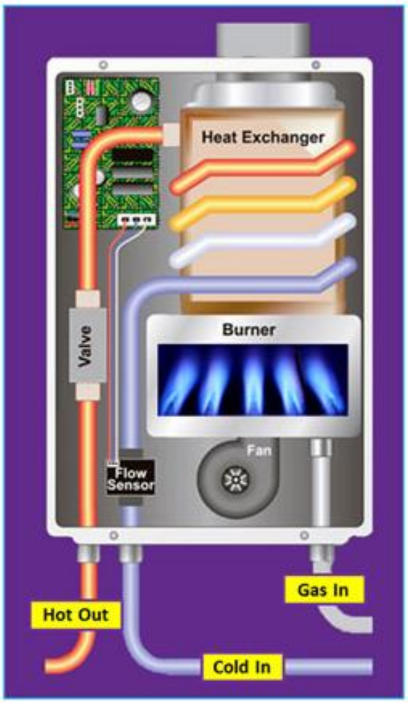


*Figure 2-16: Schematic drawing of an Instantaneous Water Heater system [Hahn20]*

Condensing GIWH generally use a secondary heat exchanger to make the exhaust fumes condense (higher efficiency) while pre-heating the cold DHW.

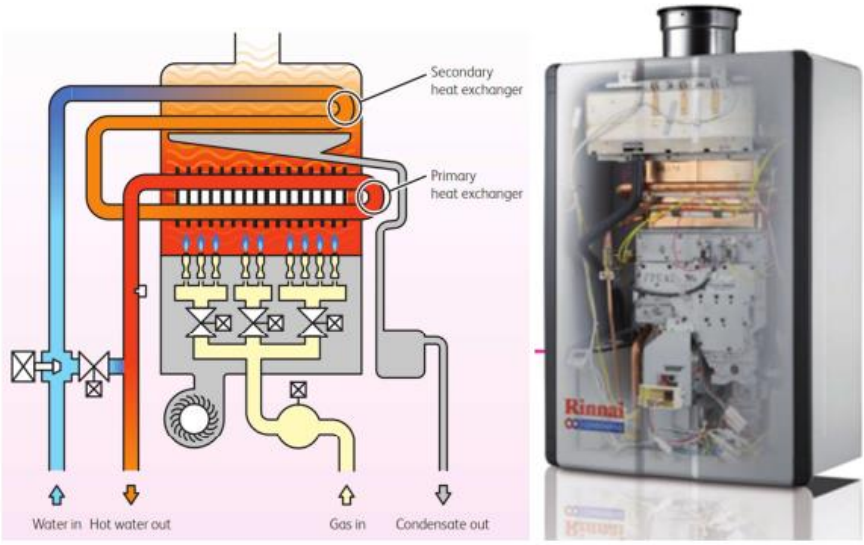


*Figure 2-17: Rinnai Infinity K26i, 'continuous flow' condensing tankless water heater, 48.3 kW max [KeEl19b]*

Older models also emit flue gases to the room (type A according to EN 1749) but are now largely forbidden for safety reasons. Small GIWHs still use pilot lights, the stock is relatively low (countries in Southern Europe) and new GIWH appliances with pilot flame are rare.

Similarly to GIWH,

- Most existing GIWHs are open-flued while more recent appliances are room-sealed.
- Condensing technologies are more and more frequent, especially in the commercial sector.

### 2.4.2 Gas Storage Water Heater

The appliances of this category are covered are regulated under EN 89 [Cent15b] (capacity not exceeding 150 kW), the scope of the standard includes non-premixed and partially premixed burners.

A GSWH uses a water tank filled by heated water, it is stored and used when a tapping is generated by the customer. Hot water is drawn from the top of the tank and replaced by cold water coming from the bottom of the tank. When one or several sensors detect a temperature below the set-point, the burner is ignited and provides thermal energy until come back to the set point.

#### ➢ Impact of hydrogen admixture

The conclusions are similar to the hints about boilers since the combustion processes are implemented similarly.

However, special attention should be taken to GIWH with pilot lights, since the blending natural gas with hydrogen will provoke a change in the flame characteristics (temperature, velocity) which could prove harmful for the appliance.

## 2.5 Cooking appliances

### 2.5.1 Gas hobs

Gas hobs have one or more gas burners with four being the most common number in domestic appliances. Usually hobs are made with burners of two or more different size and heating power to accommodate different size of cooking vessels.

In order to have more heating power and/or a greater heating power range, the most powerful burners can have two or three rings, but the technology behind is the same as for single ring burners.

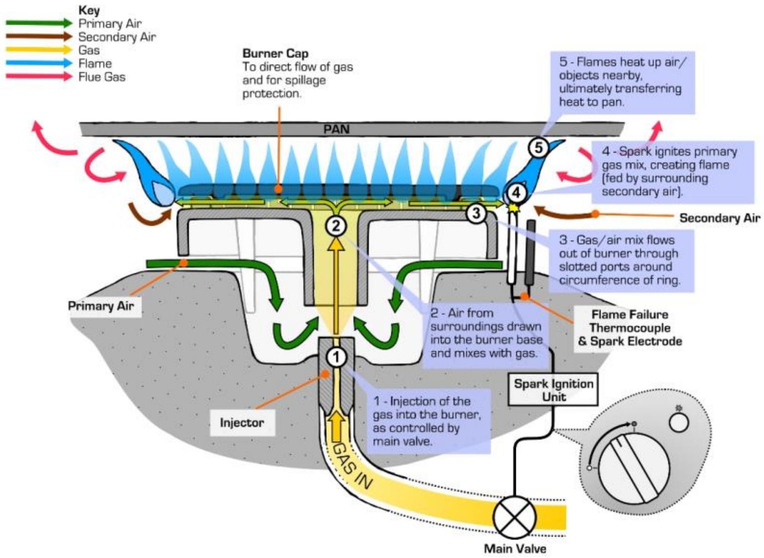


*Figure 2-18 Schematic drawing of a domestic burner [Fraz18]*

A typical burner design is shown on Figure 2-18. After leaving the control valve, the fuel gas flows through a calibrated injector (1) whose internal orifice geometry (along with the gas pressure and Wobbe Index) determines the heating power of the burner. The gas is then mixed with the primary air. The mixing process is realised taking advantage of the momentum of the gas jet and through the Venturi effect provided by the geometry of the gas burner. Only 40% to 60% of the total combustion air is mixed with the gas as this stage. For highly aerated burners such as horizontal Venturi type this value can be higher than 80%.

This partially premixed air/gas mixture goes through the flame ports into the flame where, in a first stage, it is partially oxidized. The final stage of the combustion occurs when secondary air mixes with the flame and completes the oxidation of the fuel gas to $CO_2$ and $H_2O$.

Most of the time, flame supervision is performed by a thermocouple which shuts down a safety valve when it is no longer heated by the flame.

### ➢ Impact of hydrogen admixture

Partially premixed burners, which are most widely used in domestic cookers, are more sensitive to flashback/lightback than fully premixed burners. The flashback phenomenon appears when the flame enters the burner when flame velocity is higher than the gas/air mixture velocity at the flame port. For partially premixed burners, the flame velocity increase is also enhanced by an increase of the primary air/fuel ratio [LSCA20]. This phenomenon was, for example, observed by Zhao *et al.* at a hydrogen admixture level as low as 20% [ZhMS19a].

As flame speed increases due to the presence of hydrogen, the flame will move closer to the burner, causing an increase of its surface temperature. This can be a problem with some aluminium alloys, as they could partially melt (blistering) if the flame gets too close and causes overheating.

A third impact of hydrogen addition is the decrease of the Wobbe Index (Ws). As the heating power of domestic burners is proportional to Ws, the maximum heat output will decrease (concretely, time to make water boil will increase).

The higher reactivity of hydrogen could lead to a decrease of the ignition time. This change was measured by Zhao & al. [ZhMS19a] on a domestic cooktop.

No tendency can be predicted for CO and NOx emissions as hydrogen has several effects which can increase or decrease the production of these molecules (flame temperature, air/fuel ratio, position of the flame, etc…).

Hydrogen admixture affects the ionisation current signal measured near the burner. H2NG combustion leads to a reduced formation of free charge carriers that are used for the ionisation current measurement. For high $H_2$ contents also a change in the position of the flame may further deteriorate the reliability of the signal, impacting the suitability of the combustion control strategy.

### 2.5.2 Ovens

A gas oven is an appliance which incorporates one or more cavities heated by gas in which food is prepared. Most of them are built with atmospheric burners such as shown on Figure 2-19. The fuel gas flows through the injector and entrains some surrounding air (primary air) through the aeration port. Then the mixture passes through the burner (Venturi effect). Secondary air is provided through specific air inlets to the combustion chamber. A metal plate separates the flame from the oven cavity. Oven burners are mostly constituted by a perforated stainless steel tube with an injector located at one end (see examples on Figure 2-20).

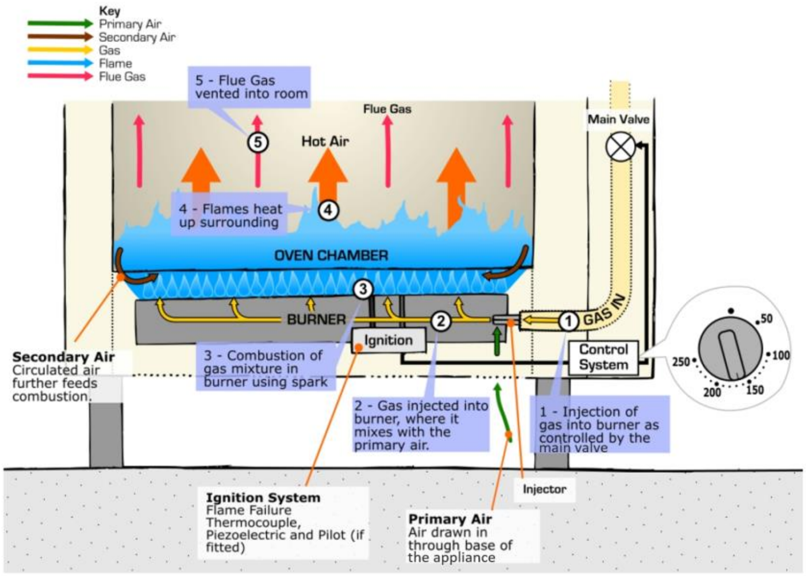


*Figure 2-19 : Schematic drawing of a domestic oven; based on [Fraz18]*

The combustion products are directly vented into the room. Freestanding appliances vent the exhaust gases at the back of the appliance, while built-in appliances are vented in the front.

By entraining the secondary air in the oven cavity, the burner ensures a constant flow of air inside the oven in order to redistribute the heat uniformly.

Many gas ovens are also equipped with grills which are located on the top of the cavity. One example is presented on Figure 2-19 (on the right-hand side). As for the main cavity burners, combustion is partially premixed. Other designs can be based on natural draught radiant burner with an enlarged burner head that forms the complete area of the grilling surface.

The flame supervision sensor could be either a thermoelectric sensor or an ionization sensor. The heating power of the oven is typically controlled by a thermostat.

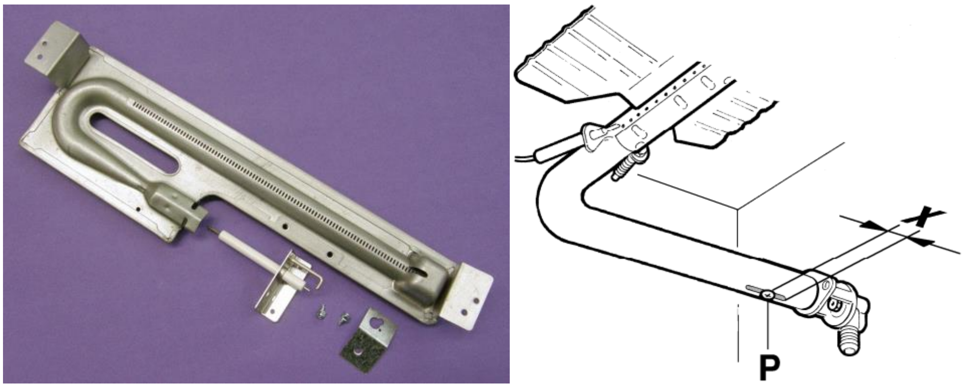


*Figure 2-20: Example of gas oven burners (left: bottom burner, right: grill burner) [Elec00, Germ00]*

## ➢ Impact of hydrogen admixture

Oven burners are partially premixed burners. As described for hob burners, oven burners are also sensitive to flashback due to the combined effect of laminar flame velocity increase and increase of the primary air excess.

As for cooktop burners, flame speed will increase with hydrogen proportion and the flame base will get closer to the burner, causing an increase of its surface temperature. This phenomenon was observed by Zhao *et al.* [ZhMS19b] even at very low hydrogen concentrations (less than 20%). They also observed a decrease of ignition time.

In many cases the decrease of the heating power with increasing proportion of $H_2$ should not impact the cooking temperatures, as modern ovens are usually fitted with a thermostat. However, at maximum inlet pressure (thermostat fully open) the power output of the burner is defined by the gas type, pressure and injector size. In that case – with or without thermostat – the heating power is reduced. Lower Ws could result in a lower maximum temperature in the cavity at the thermal equilibrium between heat rate input and dispersion.

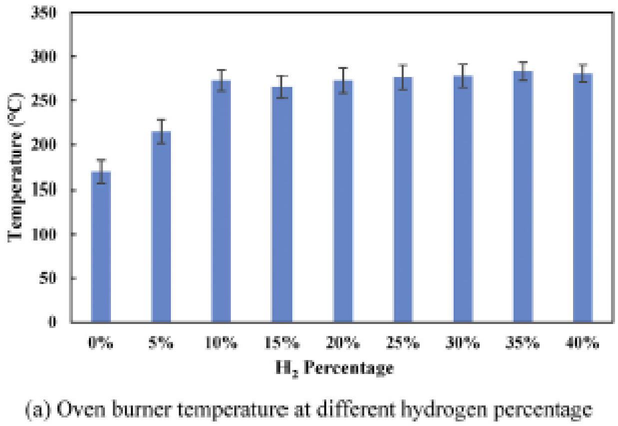


*Figure 2-21: Impact of hydrogen on oven burner surface temperature [ZhMS19b]*

No tendency can be predicted for CO and $NO_x$ emissions as hydrogen has several effects which can increase or decrease the production of these species (flame temperature, air/fuel ratio, position of the flame).

Both, thermocouple and ionisation sensors can be implemented in ovens. The ionisation probe exhibits faster reaction times and is therefore preferably applied in high power appliances. Hydrogen admixture affects the ionisation current signal measured near the burner. H2NG combustion leads to a reduced formation of free charge carriers that are used for the ionisation current measurement. For high $H_2$ contents also a change in the position of the flame may further deteriorate the reliability of the signal, impacting the suitability of the combustion control strategy.

## 2.6 Catering appliances

The "catering appliances" category gathers a lot of different appliances that can be found in commercial kitchens. Open burners, grills, solid tops, boiling pans, frying pans, rotisseries, salamanders, ovens, steam ovens, pancake cookers, etc., which are used to fry, sear, simmer, boil, steam cook, etc. Moreover, the catering equipment market segment covers appliances designed for different sizes of kitchens and thus, shows a variety of scales and heating power with no comparison to domestic appliances.

Therefore, due to this great diversity, it will not be possible to describe all appliances and all the associated technologies in detail here.

One of the most critical aspect of catering equipment technology regarding the admixture of hydrogen to natural gas is the choice and design of the burner itself. Examples are shown in Figure 2-22. Most burners are atmospheric and partially premixed burners, but some appliances are equipped with force draught burners or fully premixed atmospheric burners.

*Figure 2-22: Examples of burners used in catering equipment (source: Brûleurs AEM).*

### ➢ Impact of hydrogen admixture

General remarks concerning the hydrogen impact on natural gas catering equipment are summarised in subchapter 2.6.9.

## 2.6.1 Open burners

The principles governing the air/gas mixing and combustion of catering burner are the same as for domestic appliances. The main differences between a domestic and a catering burner are the heating power, ranging from 3 kW to 15 kW with catering equipment representing the higher thermal powers. In addition, the nature of the materials differs, as brass is also often used for manufacturing catering equipment.

### 2.6.2 Ovens

Gas heated commercial oven are designed to cook food on several levels at the same time. As a consequence, their heating power can rise as high as 60 kW, and above sometimes. They use a wider variety of burner designs compared to domestic ones. Some of them, mostly combi-streamer ovens, are built with premixed burners.

Combi ovens allow cooking in hot air mode, in steam mode or in a combined cycle (hot air plus steam). They are used interchangeably to cook meats, vegetables, pastries, reheat dishes, which makes them indispensable in most kitchens. Some ovens allow low temperature cooking (around 60°C). Air convection can be forced by one or more turbines, which makes it possible to obtain a good distribution of heat in the oven. These ovens are equipped with advanced electronic management, ignition, flame safety, door opening safety, overheating safety, temperature control, and programming of cooking cycles.

**Forced convection ovens**

In these ovens, the heat exchange is dynamic hot air used for cooking is set into motion by means of a mixing fan. The advantage of this principle is a very high temperature homogeneity. Cooking results are regular and almost identical at each position within the oven. In addition, forced convection makes it possible to quickly change the heating regime to obtain the required temperature. These ovens are typically equipped with atmospheric burners. An example appliance is shown in Figure 2-23.

*Figure 2-23: Example of catering oven (Bonnet).*

### 2.6.3 Boiling pans

The pot of the boiling pan is used to heat or cook a large volume of liquid food products or solid food in a liquid for which several techniques are used:

- direct-heating pot is the most widely used technique, the burner heats the bottom of the pan/tank directly,
- the bain-marie pot has a double jacket containing water. This technique allows to distribute evenly the heat transmitted by the burner up to 100 ° C,
- double-walled pots use a heat transfer fluid (oil or more generally water vapor). They allow the temperature of 100 ° C to be exceeded, always with perfect temperature uniformity on the walls of the tank. In this case, the heating body (burner and exchanger) can be placed next to the tank.

The typical heating power ranges from 10 to 50 kW. All tank shapes are possible. An exemplary appliance model is shown in Figure 2-24.

The burners mounted under the pots can be circular with blue flames or multiamp with blue or radiant flames. The main burner is usually ignited by a pilot burner. In all cases, the pots are equipped with a flame control device, mainly by thermocouple. For better controlled, more economical and more autonomous cooking, they can be equipped with a regulation of the temperature.

*Figure 2-24 Boiling pan (CAPIC)*

### 2.6.4 Fryers

This appliance, intended for frying, is a material which has undergone major technical developments in recent years: productivity, compactness, automation, cleanability.

The heat exchange between the burner and the oil takes place through tubes located in the tank or directly by the walls, which allows easier cleanability.

Some fryers have a tank equipped with a cold zone in the lower part. Located under the burner, this zone is at a temperature lower than the regulation temperature. Cooking residues fall in the cold zone where they are trapped, which preserves the quality and durability of cooking oil.

The burners used on the fryers are circular, torch, or single or multiple ramps. Radiant burners are used, sometimes as well as the use of forced-air burners.

The fryers are equipped with a flame safety device and an overheating limiter which prevents the oil from reaching the temperature self-ignition. The typical heating power ranges from 5 to 30 kW.

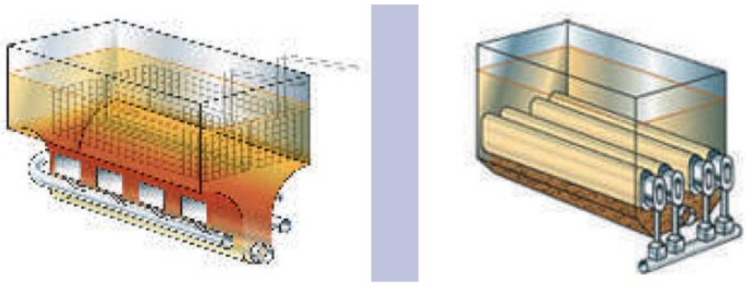

*Figure 2-25 Typical burner positions for gas fryers (source: ENODIS)*

### 2.6.5 Rotisseries

Whereas in most catering appliances heating is performed by conduction or convection, in rotisseries, cooking is done mainly by radiation on food products, convection intervening to a lesser extent.

The most widespread heating technique uses radiant burners: in this case, the burner emits the necessary radiation during cooking. The other technique is to use a blue flame rail burner that heats cast iron plates fitted with pins. These are the elements that provide the radiation for cooking.

Rotisseries exist in various sizes and heating power. Typically, their heating power can range from 5 kW to 60 kW, which enables to prepare 4 to 80 chickens at a time.

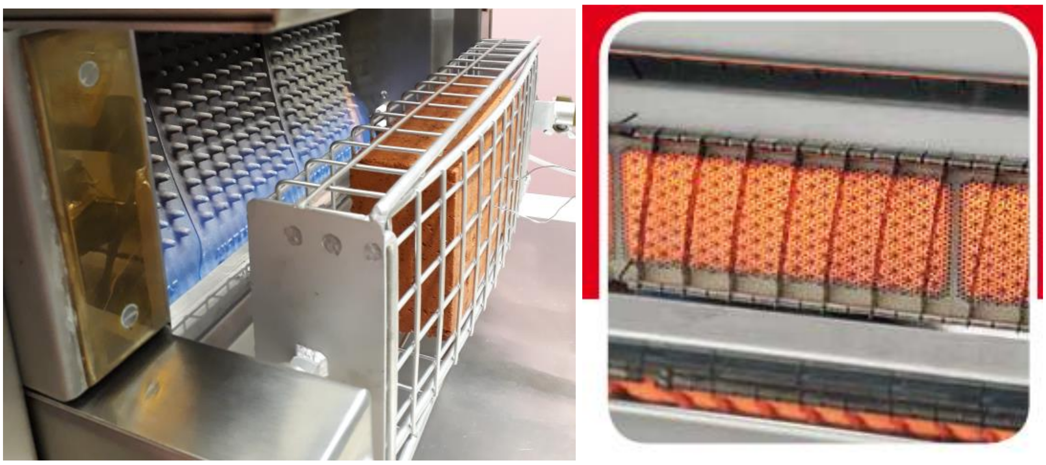

*Figure 2-26: Two kinds of burners used in a rotisserie. Left: blue flame (photo taken during tests at CRIGEN, ENGIE). Right: radiant burner (source: SOFINOR, commercial documentation).*

### 2.6.6 Salamanders

This appliance is intended for cooking, gratinating or keeping dishes hot below the grill. Heat exchange is obtained by radiation downwards, the food is placed under the radiant zone. The radiation is produced directly by one or more radiant burners.

Heating intensity can be adjusted by varying the distance between the food and the radiant zone; depending on the case, the burners or the dish holder can move.

Typical heating power ranges from 5 to 15 kW.

*Figure 2-27: Radiative gas burner salamander (source: CHARVET)*

### 2.6.7 Brat pans

The brat pan is mainly used to sear or braise meats, fish or vegetables over low heat and protected from air. It can also be used for cooking dishes in sauce.

The brat pan, with low edges and rectangular in shape, can be fixed or tilting. The heat exchange takes place through the bottom of the tank by means of ramp burners. The homogeneity of the temperatures at the bottom of the tank is obtained thanks to the multiplicity of burners. They are attached to the frame of the device or integral with the tank.

Ignition is usually automatic. The temperature regulation is controlled either by a thermostatic regulation, or by a sequential control.

Typical heating power ranges from 15 to 60 kW.

Figure 2-28 Brat pan (left) and brat pan burner (right). Source: CAPIC.

### 2.6.8 Covered burners (grills, solid tops, pancake cookers)

**Grills**

The principle of the grill is to cook by contact with a hot plate. The plate is heated by a blue flame burner. The power of the fire associated with the thermal properties of pre-heated plates allow immediate seizure of products, as needed e.g. in the lunchtime rush in gastronomic environments. Adding meat and fish does not significantly lower the temperature of the (brass) grill plates if the material is thick enough.

The traditional ribbed plate is very effective for meat and fish. Plane plates requires a slight addition of fat to cook. It has the advantage of easy cleaning.

Some grills can have a homogeneous surface temperature to maximize cooking surface or a specific temperature gradient with a hot zone for cooking and a warm zone to keep food warm. Typical heating power ranges from 5 to 30 kW.

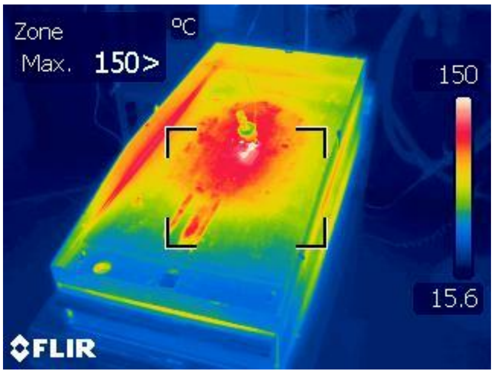


Figure 2-29 Example of a grill with temperature gradient with a cooking zone at the centre and warm zone on the borders (Source: CRIGEN)

**Solid tops**

While grills are used to put food directly on the heated plate, solid tops are used to heat pans and pots.

A solid top is a cast iron plate heated by a high power gas burner (≈5kW). Thanks to the cast iron which accumulates and retains heat evenly over its entire surface, it is possible to sear, simmer or keep warm dishes.

By ensuring a regular temperature gradient, it allows cooking or simmering temperatures to be adjusted accurately by moving the pans or pots on its surface. The large surface area allows to use several pots and pans at the same time for cooking and keeping warm. By removing the central plate cover, the burner can be used as a traditional fire.

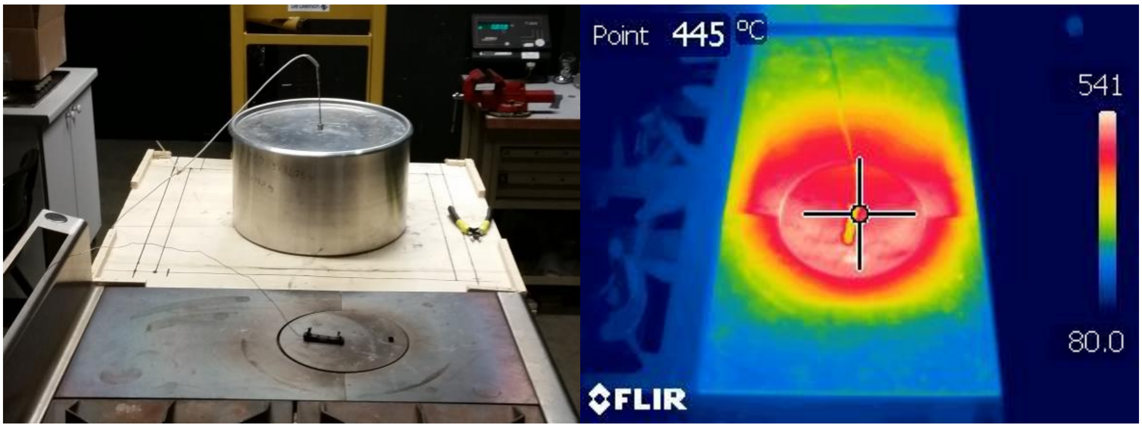


*Figure 2-30: Left: Example of small solid top. Right: Temperature distribution on the surface of a solid top. (Source: CRIGEN).*

**Pancake cookers**

A pancake cooker is a cooking device used to prepare dishes like crêpes, galettes, pancakes, blinis or tortillas. It is usually composed of a 40 cm circular cast iron plate with a heating element underneath.

Burners used for this kind of appliance are usually radial ramp burners in order to provide a homogeneous heating of the plate.

*Figure 2-31: Left: Gas pancake cooker. Right: Pancake cooker burner (source: Krampouz)*

### 2.6.9 Impact of hydrogen admixture on catering equipment

Hydrogen addition to the gas grid can have several impacts on natural gas-fired catering equipment. Besides effects already described for domestic cooktop burners the expectable impacts of higher hydrogen admixtures to natural gas concerning open burners from the catering sector are in general reduction of power output, safety issues such as flashback or unstable / incomplete combustion, especially for radiant burners.

Low hydrogen admixture levels (e.g. below 10%) of $H_2$ are expected to be tolerated by catering appliances safely with minor, almost negligible reduction of the maximum possible heat output and may lead to a gradual reduction of pollutant emissions.

**Flashback**

In catering equipment, the probability of having flashback is enhanced because most burners are partially premixed. This phenomenon was already discussed in THyGA report D2.2 [LSCA20] However, other appliance characteristics may also contribute to the appearance of flashback:

- Covered burners are enclosed in a cavity where temperature is higher than for open burners. The higher burner temperature may facilitate the flame propagation through the flame ports and, thus, flashback may appear at lower hydrogen concentrations.
- In tubular slot burners, the pressure gradient between the gas inlet and the final slot may enhance flashback where pressure is low.
- Radiant burners are known to be sensitive to changes in laminar flame velocity as there must be an equilibrium between burner temperature, flame velocity and the pre-heating of fresh gases by the burner.

**Heating power**

Gas catering equipment will be affected differently by the addition of hydrogen to the grid gas. All appliances will suffer from a decrease of the heating power due to the decrease of the Wobbe index of gas when hydrogen is added. Thus, it will take a little bit more time for appliances to heat up until they reach their operational temperature.

During the cooking phase, appliances with a thermostat that controls cavity or surface temperature won't be much affected by the change of gas (ovens, fryers, for example), as well as appliances that rely on boiling water to cook food (pasta cookers, some boiling pas).

Appliances that only rely on a manual gas valve to control heating power may need to be adjusted by the cook to reach the right operational temperature (some grills, rotisseries).

**Pilot flame characteristics**

Catering appliances that are equipped with a pilot flame including flame detection devices could be affected in their performance by changing characteristics of the pilot flame (e.g. length with relation to the sensor position) when admixing hydrogen to natural gas.

**Efficiency and pollutants**

Addition of hydrogen to grid gas has two major effects: the first one is to increase the primary air excess and the second one is to reduce the heating power. Depending of the appliance and the air/fuel ratio, these effects may have different impacts.

Decrease of heating power generally lead to an increase of efficiency because heat exchangers become oversized. Increase of air excess and higher reactivity of hydrogen can lead to a decrease of CO and NOx emissions.

However, all these general tendencies have to be confirmed appliance by appliance type by measurements. That is what will be done in work package 3 of the THyGA project.

## 2.7 Space heaters

This chapter only concerns fixed residential space heaters. It does not include

- mobile space heaters that are generally not designed for use with natural gas, but with LPG;
- non-residential space heaters like infrared radiant heaters (considered in the following chapter) and air heaters, which are a technologically very different application.

Space heaters (Figure 2-32) provide direct local heat to rooms but are often valued for their decorative appearances too (sometimes more than their ability to provide heat). Originally designed for solid fuels (e.g. wood, coal, etc.), electric, gas, liquid fuel and fuel gel (ethanol) local space heaters also exist.

Fixed residential gas space heaters generate heat by combustion of natural gas by means of a partially premixed non-fan-assisted burner (i.e. so-called atmospheric burner). That burner can have different shapes adapted to its purpose of heating only (e.g. gas convectors) or a combination of heating and decorative function (by creating cosiness). In the latter case the burner is often covered with some decorative material like imitations of wood logs or stones. The flame tubes of gas fireplaces may even be built into a fireproof imitation of these wood logs, so that it visually simulates a real wood fire. Ignition can be realised by a pilot or electronic ignition system. Apart from the gas convectors (Figure 2-34) these appliances typically have big combustion chambers to give space to longer, decorative and often yellow flames. The combustion chamber can be open or closed fronted. For appliances with a decorative fuel-effect function flame shape and colour are considered very important. The heat produced is distributed by both radiation and natural convection or by forced convection (i.e. fan-assisted).

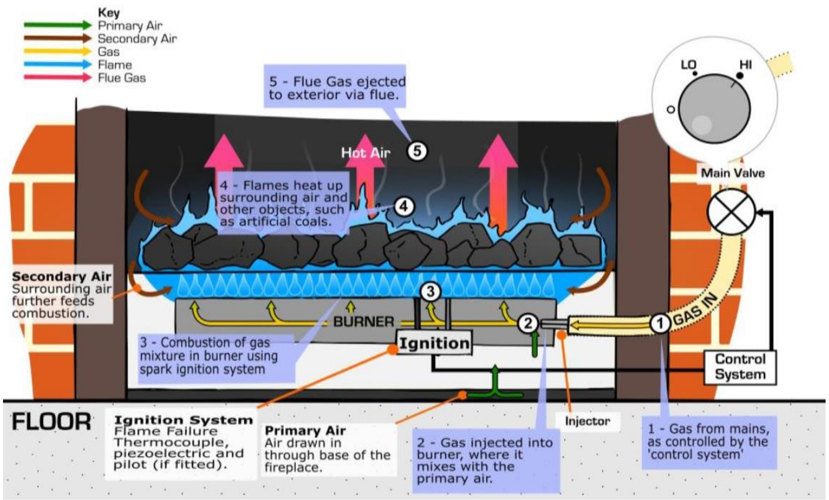


*Figure 2-32* Cross-section showing the principle of an independent gas-fired space heater *[Fraz18]*

Finally, the combustion products are either evacuated directly in the room (i.e. flueless space heaters also known as 'type A') or outside of the building via a flue system (i.e. flued space heaters).

Fixed flueless gas space heaters only represent a very small market share as they cannot be used in most countries due to the installation regulation in force not allowing to evacuate combustion products directly into the room.

Flued space heaters can still be subdivided in

- open flued (also known as 'type B'), taking the air needed for combustion directly from the room they are installed in and in which case they often are equipped with some kind of draught diverter to reduce influence of the draught conditions;
- balanced flued (also known as 'type C'), in which case the combustion air is drawn in from outside the building.

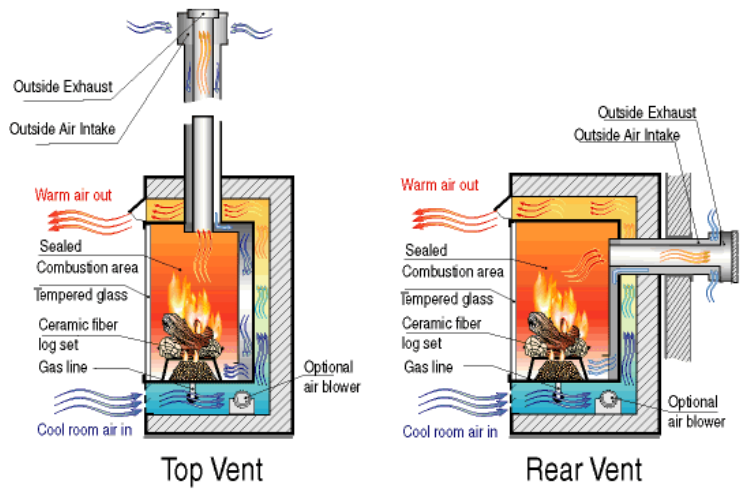


*Figure 2-33* Cross-section of a type C independent space heater (source: thefiresidegroup.com)

Fixed residential space heaters are available as wall-mounted (Figure 2-34), free-standing (Figure 2-35) or built-in (Figure 2-36) devices.

A specific case of local space heaters are gas convectors consisting of a closed floor-standing or wall-mounted box without visible flames and a heat transfer mainly based on convection (Figure 2-34).

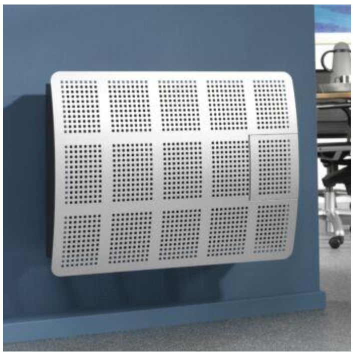

*Figure 2-34* Wall-hung gas convector (Dru – www.dru.nl)

*Figure 2-35 Free standing closed glass fronted space heater (source: www.wellstraler.be)*

*Figure 2-36 Built-in closed glass fronted fireplace (source: www.kalfire.com)*

The market segmentation used in the THyGA project is based on the related EN product standards as developed by CEN/TC62:

**Independent convection space heaters** (EN 613, [Tech04])

These products are independent convection space heaters:

- of type B or type C → in the THyGA project they have been divided into a different market segment as some risks are specific to the type;
- that are wall mounted, free-standing or built-in;

- that have a nominal heat input not exceeding 20 kW (NCV);
- that are or are not live fuel effect appliances.

**Open fronted independent space heaters** (EN 13278, [Cent13])

These products are open fronted independent space heaters:

- of type B;
- that have a nominal heat input not exceeding 20 kW (NCV);
- that are delivered with the gas carrying components, burner(s), combustion chamber and heat exchanger fully assembled;
- that are or are not live fuel effect appliances.

**Decorative fuel-effect appliances** (EN 509, [Cent99])

These products are decorative fuel-effect appliances

- of type B and more specifically type $B_{AS}$ which are appliances equipped with an oxygen depletion device;
- that have a nominal heat input not exceeding 20 kW (NCV);
- that are designed to simulate a solid fuel fire;
- that are designed for decorative purposes only and not for heating;
- that are designed to be installed within a non-combustible builder's opening or a non-combustible fireplace recess.

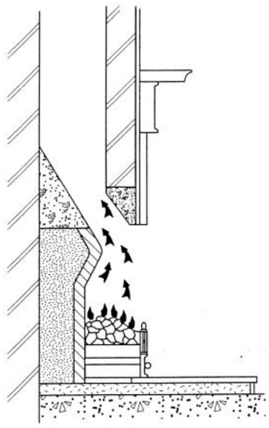

*Figure 2-37* Decorative fuel-effect gas appliance (source: EN 509, *[Cent99]*)

**Independent flueless space heater** (EN 14829, [Plng08])

These products are independent flueless space heaters of 'type $A_{AS}$'. In contrast to 'type A' flueless appliances, 'type $A_{AS}$' concerns flueless appliances equipped with a safety device which will shut-off the gas supply in case of insufficient oxygen in the room in which it is installed. The safety device is more specifically called an oxygen depletion device. The scope of the EN 14829 is specifically limited to 'type $A_{AS}$' appliances [Plng08].

## ➢ Impact of hydrogen admixture

**Flashback**

In local space heaters, the probability of flashback to occur is enhanced because most burners are partially premixed. This phenomenon was already discussed in THyGA report D2.2 [LSCA20].

**Heating power**

All local space heaters will suffer from a decrease of the heating power due to the decrease of the Wobbe index of the gas when hydrogen is added. For appliances with mainly a decorative function this will obviously not create space heating issues, but the flame shape and colour may be affected. For appliances with an essential space heating function a lower heating power may obviously affect its fitness for purpose.

**Efficiency and pollutants**

Addition of hydrogen to grid gas has two major effects on space heaters: the first one is to increase the primary air excess and the second one is to reduce the heating power. Depending on the appliance and the air/fuel ratio, these effects may have different impacts.

Decrease of heating power generally lead to an increase of efficiency because heat exchangers become oversized. Increase of air excess and higher reactivity of hydrogen can lead to a decrease of CO and $NO_x$ emissions, but also to a lower efficiency.

However, all these general tendencies will have to be confirmed appliance by appliance type by measurements. That is what will be done in work package 3 of the THyGA project.

**Other**

Besides similar impacts as on other partially premixed non-fan-assisted burners (see above) attention needs to be paid to some specific risks of this kind of appliances:

- the large volume of the combustion chamber (except open fires of course) and the lack of a fan in the combustion circuit increases the **risk of unburnt gas accumulation**; the closed front fireplaces are often equipped with a pressure-relief system to avoid the glass window to be projected into the room;
- the presence of hydrogen will also affect the **shape and colour of the flames** which may harm the decorative function which e.g. imitates a wood fire. To the best of the authors' knowledge, there is no way how flame colours can be predicted by combustion theory in a satisfactory manner. Few fundamental research studies (e.g. [Sche09], [Elgh10]) on the impact of hydrogen on flame colours were found, however, it has yet to be evaluated to what extent these findings can be transferred to residential gas fired appliances. Most of these experiments were conducted using very different burner designs compared to typical technology used for residential appliances.

## 2.8 Radiant heaters

Infrared radiant heaters are a heating technology class which is used to provide space heat in large buildings, such as production halls or similar non-domestic contexts.

The general principle is heating up a material by burning natural gas with the aim to transfer heat by both convection and infrared radiation to the body which is intended to get heated. There are two different main technologies of gas-fired radiant heaters:

- **Tube heaters** (metal tube used as radiative body, Figure 2-38)
  At the one end of the heater a flame burns inside a metal tube, which heats up the outer surface of the metallic tube. The hot metal surface then emits infrared radiation which transfers heat to the surrounding.
- **Luminous heaters** (ceramic surface used as heat exchanger, Figure 2-39)
  The gas burns in the ceramic structure and near the surface. Infrared radiation heats up the surrounding.

The typical power range is 3 to 70 kW. Due to the individual design of the applications, the energy efficiency needs to be analysed as well from a system perspective. The efficiency measurements are based on the radiometric method (Test method B of EN 416-2 [Dine00]) for determining the radiant efficiency of gas fired overhead luminous and radiant tube heaters.

The main European standards used for certification are based on the Gas Appliance Regulation (GAR) (EU/2016/426) [RaBZ16], EN 419 for luminous radiant heaters [Cent19a] and EN 416 [Cent19b] for t radiant tube heaters.

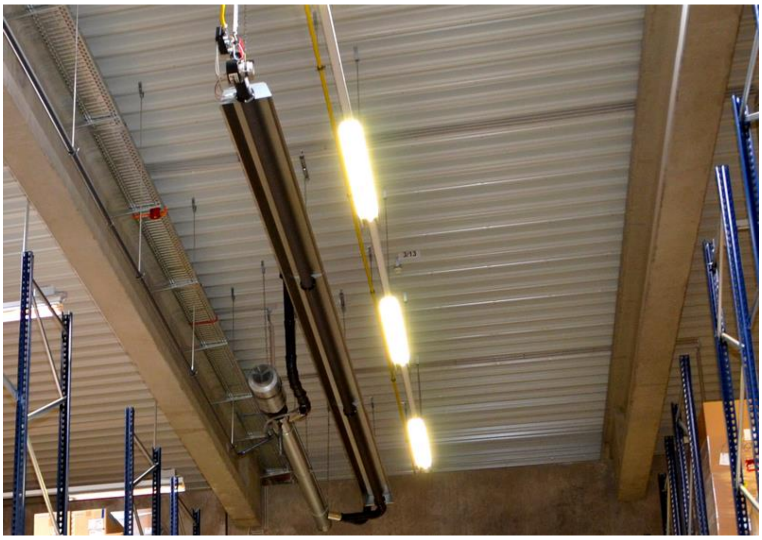

*Figure 2-38 Example for radiant tube heater [source: GoGaS Goch GmbH & Co. KG, Zum Ihnedieck 18, 44265 Dortmund]*

*Figure 2-39 Example for radiant luminous heater [source: GoGaS Goch GmbH & Co. KG, Zum Ihnedieck 18, 44265 Dortmund]*

### ➢ Impact of hydrogen admixture

Radiant heaters are using premixed burners like e.g. condensing boilers. Therefore, the impact of hydrogen is expected to be similar as what will happen for premix burner boilers, at least for tube heaters. However, for luminous heater the burning inside the holes or pores of the ceramic body can be influenced a lot, due to the fact that the flame speed varies, depending on the amount of hydrogen. The sizes of such holes might be adjustable for a certain range of hydrogen but maybe very limited.

# 3 Systematic literature review on the impact of hydrogen admixture on natural gas fired appliances

In addition to the general explanations on the impact of hydrogen on gas-fired appliances, an extensive literature meta-analysis was performed at GWI, to generate an overview of the knowledge that is already present in literature.

## 3.1 Method

### 3.1.1 Study design

Considering the broad collection of literature available from the authors and project partners on the topic of interest, a **two-fold approach** for the literature study was used. The study design combines 1) a systematic exploitation of online-available literature databases with 2) relevant documents from the THyGA partners' literature collections. The rationale for this approach is that the two sources of information were found to be not congruent, but complementary. While the systematic database searches identified studies published in peer-reviewed journals, the document collection of the THyGA laboratories also contained document types such as conference papers that were not to be found in the systematic database search.

### 3.1.2 Keywords

The literature search was performed by using the *Katalog+* [Rub00] of the *Ruhr-University Bochum*, Germany. The online tool performs parallel searches in 96 databases for all thematic areas. The most relevant out of the 96 accessed databases for this work turned out to be *Scopus* and *ScienceDirect* [Scie00, Scop00]. The identification of relevant studies was based on the use of keywords. Figure 3-1 shows an overview of the search process.

A first challenge was to cope with the disambiguation of technical terms. As there is no universally established term for the addition of hydrogen to natural gas (admixture, blending, etc.), several options and combinations have been used as inputs for the search engine. In the international literature 'hydrogen-enriched natural gas' as well as the respective abbreviation 'HENG' are the most used terms. However, 'hydrogen addition' and 'hydrogen admixture' are also regularly used.

In total, first level keywords (Figure 3-1) generated over 400,000 hits. This number contains an unknown amount of double and multiple hits as most studies exhibit several keywords. Because such a huge amount of studies could not be reviewed the number of search results had to be narrowed down. Therefore, each first level keyword was combined with different second level keywords. If the number of hits of any combination resulted in less than 100 hits those studies were saved for rough manual screening. However, in most cases the number of studies was still too high, adding up to a total of 10,144 studies after the use of first level and second level keywords. Thus, third level keywords were used to further focus the results and reduce the number of hits.

Once an acceptable number was reached the results were screened based on the title and abstract and relevant studies were selected. Only at this point could multiple hits be eliminated. The criteria applied for integration or exclusion of studies are described in the following section. After the rough screening of 1,821 studies, the preliminary literature collection contained 110 results, which were selected for a subsequent detailed screening phase. In this final phase, the papers were read in detail to understand which technologies were studied at which scale and numbers, what kinds of experiments or simulations were done etc. to evaluate for each publication whether the content was in the scope of the THyGA project. A final set of 36 studies is the result of this final selection step (see Figure 3-1). The list of included studies can be found in the appendix of this report.

| Keywords | first level | second level | third level | Manual screening of titles and abstracts | Final set of included studies |
|---|---|---|---|---|---|
| | hydrogen tolerance | natural gas | premixed | | |
| | hydrogen admixture | energy | non-premixed | | |
| | hydrogen sensitivity | boiler | atmospheric | | |
| | hydrogen acceptance | water heater | heat | | |
| | hydrogen enriched | chp | $NO_x$ | | |
| | hydrogen injection | burner | CO | | |
| | hydrogen blend | domestic | $CO_2$ | | |
| | hydrogen mixture | residential | ignition | | |
| | hydrogen addition | safety | flashback | | |
| | H2NG | emission | leak | | |
| | HENG | combustion | reliability | | |
| Hits | 41,4115 | 10,144 | 1,821 | 110 | 36 |

*Figure 3-1 Process of keyword search with a selection of keywords*

## 3.1.3 Inclusion and exclusion criteria

The systematic literature search was done in **English language**. One study in German language was included as well. No other publishing languages were included in this work. The choice of languages is one of the main limitations of the study, since it can be assumed that a broad variety of further knowledge exists that has been published worldwide in other languages. The use of the English language results in a location focus on Europe and the United States of America, while non-English publications e.g. from Asian authors are neglected by this approach. An implicit location focus also exists for the literature collections by the THyGA partners, who collected publications predominantly from European and English language authors as well.

In general, reports on the behaviour of appliances **below 150 kW nominal heat output** were studied. This criterion has been chosen to meet the scope of the THyGA project, which is to investigate the impact of hydrogen admixture on representative domestic and commercial appliances, which typically exhibit clearly below 150 kW nominal power output. With this criterion any larger scale industrial appliances are implicitly excluded from the literature study.

Studies that give hints on the impact of hydrogen admixture on gas-fired appliances solely on a **qualitative level**, were **excluded**, since a clear reference to a specific burner type was defined as a minimum requirement for the clear assignment of literature statements to the appliance technologies as listed in the THyGA segments [FSCB20].

In addition, theoretical studies were excluded. However, in some cases, **numerical studies** were **included** when the simulations referred to a **specific appliance technology** that was found to be within the scope of the THyGA project.

Studies that reported on hydrogen contents in fuel gas but investigated other parameters, technologies or **results outside of the scope of the THyGA project** (such as oxy-fuel applications) were **excluded** from the analysis in course of the manual literature screening.

**Syngas** experiments that included hydrogen in the fuel gas mixture but did not focus on natural gas / hydrogen blends were **excluded** as well.

In a small number of cases, studies reported on the same experimental results as published earlier by the same authors. In these cases, the more complete publication was chosen for inclusion into this work and **results published twice were excluded** during the manual screening phase.

### 3.1.4 Final literature collection

After the exclusion of studies following the criteria described in 3.1.3, the final literature collection was identified. The total number of screened studies has been reduced to 36 studies selected for deeper analysis. A complete list of the included studies can be found in Table 6-1 in appendix 6.1. All detailed bibliographic information are given in the references (chapter 7).

Figure 3-2 shows in which countries hydrogen admixture has been investigated.

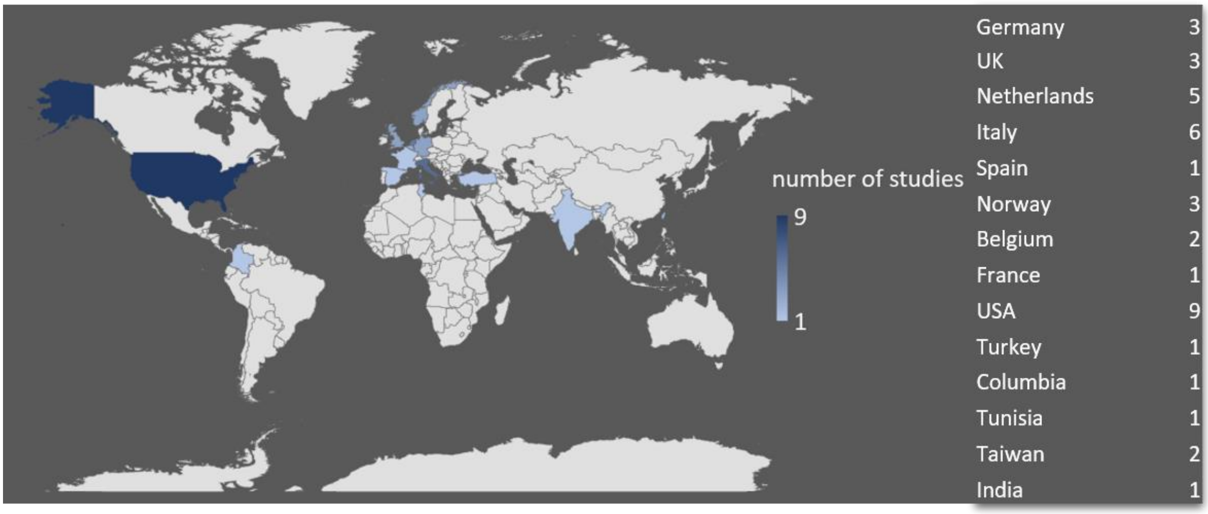


*Figure 3-2 Investigation of hydrogen admixture worldwide by number of studies included in this work.*

As can be seen on the map of the included studies, hydrogen admixture to natural gas and the impact on end-user appliances is a topic that is relevant around the world. Most studies were made in the USA and Europe with a quarter of the reported literature being published by US american authors. In Europe research groups from several countries nvestigated the impact of hydrogen admixture. The highest number of reported studies originates from Italy.

In recent years, scientific and societal discussions as well as political actions on fighting climate change has motivated an increasing number of studies on hydrogen admixture as a potential for decreasing carbon emissions.

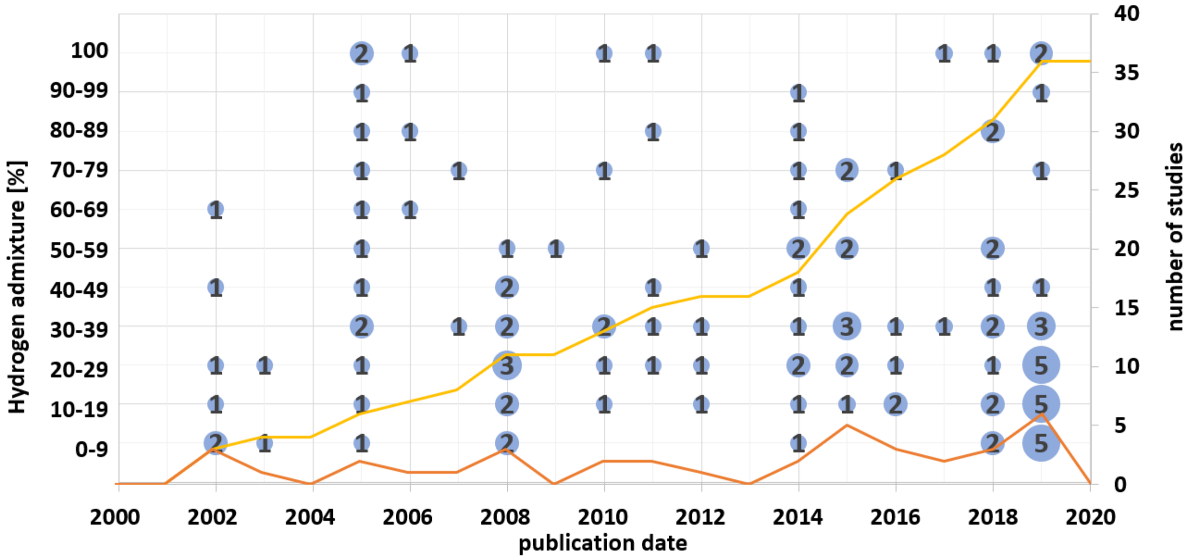


*Figure 3-3 Hydrogen admixture covered in collected literature over the past 20 years (as of July 2020). The number of studies is shown cumulatively (yellow) and per year (red). Furthermore, the distribution of investigated hydrogen admixture rates is shown.*

Figure 3-3 shows the annual (red) and cumulative (yellow) number of studies for the last 20 years. As this literature collecting was finished in July 2020, the number for 2020 is not meaningful. The bubbles show how often each hydrogen admixture rate was investigated in every year. Most investigations end with 30% or less hydrogen admixture rate and there was very little research found for higher amounts.

Before the analysis, several categories have been defined. The reported literature was screened for investigations into these categories.

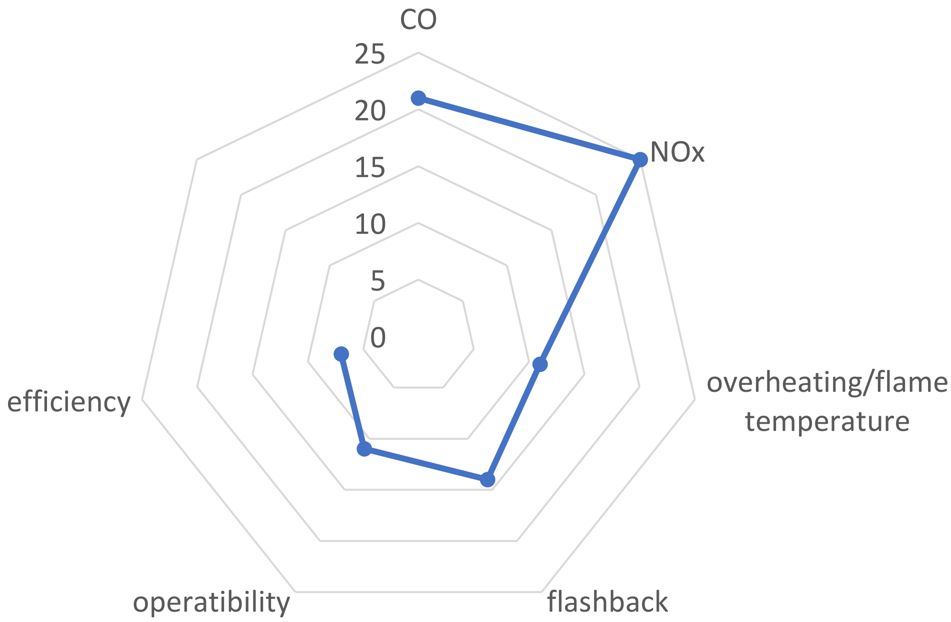


*Figure 3-4 Categories defined before the analysis with the number of studies covering these aspects*

Figure 3-4 shows the categories and the number of studies that examined the respective topics. A majority of included studies covered analyses of CO and $NO_x$ emissions, while all other categories are addressed in fewer studies. Possible leakage of hydrogen was not investigated at all in the set of selected studies[7]. Operational issues like flame stability and reliability were combined in one category. Eleven studies investigated at least one of the topics. Flashback was investigated fourteen times and flame temperature eleven times.

The results of the reported literature are presented and discussed in the following chapter.

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[7] The topic of hydrogen leakage has been addressed in task 2.4 of the THyGA project. The deliverable D2.4 "Non-combustion related impact of hydrogen admixture – material compatibility" [BlBr20] can be downloaded from the website https://thyga-project.eu. Experiments will be conducted within work package 3 of the project.

## 3.2 Results and Discussion

### 3.2.1 General findings from the literature review

In this chapter, the results of the literature analysis are shown. Figure 3-5 summarises statements from the categories "operation/stability/lifetime," "efficiency" and "flame temperature". The diagramme indicates how many studies agree or disagree with the given statements.

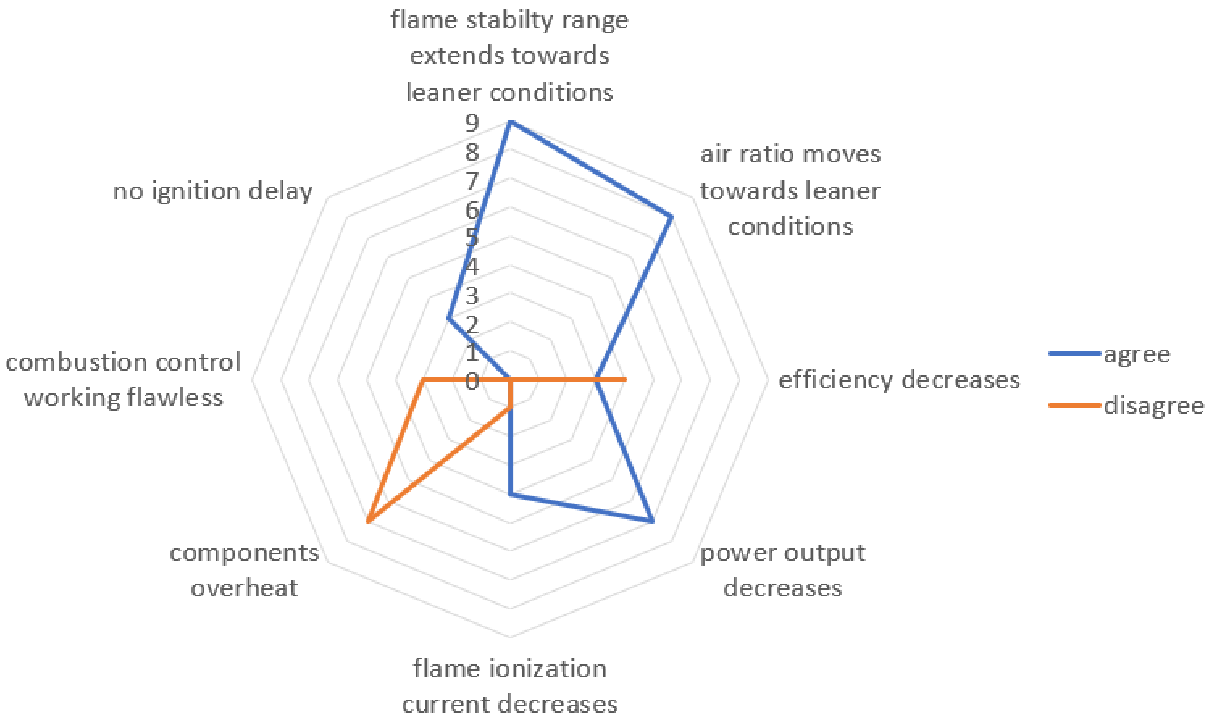


*Figure 3-5 Collection of statements on operational issues when admixing hydrogen to various types of natural gas fired burners*

Seven studies investigated the effect of hydrogen admixture on the **efficiency** of appliances. The results show that three studies found a decrease in efficiency when testing unmodified appliances that were designed for natural gas [LNAC17, NiWe12, SaPL20] while three studies found no effect [PGRS12, PoDC03, SLBD20] and one even an efficiency increase [LSAN15]. However, the differences in comparison to natural gas are small in all cases. The biggest difference was reported by [NiWe12] with a decrease of 2 % in electrical efficiency for a Stirling engine micro CHP unit at 30 % hydrogen admixture. For the condensing boilers tested in [NiWe12] the efficiency losses were smaller than 2 %.

**Flame ionisation detectors** are installed in many appliances as a safety device. If there is no flame present the gas valve is closed. Some appliances also use the ionization current for combustion control. The principle of operation of ionisation flame monitoring is that the gas molecules which are dissociated by the high temperature during the combustion reaction become ionized and serve as electrical charge carriers that produce an observable current. To exploit this effect, an electric circuit is interrupted at the flame, so that in operating condition the circuit is closed by the conductivity of the ions available in the burning gas-air mixture. The ionisation current signal provides information on the current air excess ratio (λ) at the individual position of the sensor within the combustion chamber. The combustion of hydrogen creates less free electrons compared to methane combustion which can lead to a decrease of the ionisation current [CeLe16, PoDC03].

The flame ionisation current for H2NG mixtures was experimentally investigated in [Isaa19, KDHO11, KrDr16, NiWe12, PoDC03]. The authors of [Isaa19, KDHO11, Kiwa00, NiWe12] found a decrease of the ionisation current when increasing the hydrogen content of the fuel gas with a maximum hydrogen percentage of 30%. However, [KrDr16] found the ionisation signal to be equal at 0% and 30% hydrogen. The decrease of the ionisation signal did not reach a critical level in either study to imply a safety risk. However, while the safety is ensured as long as the minimum current does not fall below a certain level, the actual value is more important for combustion control. In [KrDr16] and [NiWe12] the control system using flame ionisation signals failed to correct the air excess ratio while [Isaa19] only noted a difference in behaviour. The behaviour of appliances from the market (designed for natural gas combustion) will differ from case to case due to combustion chamber designs, sensor position, control logic etc. Therefore, the suitability of typical flame ionisation measurement sensors should be further investigated.

In systems without combustion control, the air excess ratios increase because less air is necessary for combustion. Simultaneously, the stability range extends towards leaner conditions [CoCo06, CoMc18, GaBa15, Isaa19, Jone18, KDHO11, Sche03, ScWA02, VrLM17, YiIl08]. This is due to the fact that hydrogen admixture leads to an extension of the ignitable mixtures towards the super-stoichiometric regions.

Hydrogen admixture increases the **adiabatic combustion temperature**, which is the theoretical maximum temperature that can be achieved in a combustion process [LSCA20]. This indicates a potential increase in the actual combustion temperature which could lead to overheating of components and increased NOx emissions.

While some studies found an actual increase in **flame temperature** [KiAG09, KrDr16, RBHM17, YiIl08], other measured lower or equal temperatures [SEML08, SLBD20]. The studies [KrDr16, YiIl08] additionally measured the flue gas temperature which did not increase. A possible explanation is, that hydrogen admixture increases the temperature in the flame, but due to the increased air excess ratio the flue gas is cooled down, thus compensating the effect. [KrDr16, PoDC03, ZhMS20] investigated hydrogen concentrations up to 30% and found that the temperature close to the opening of the burner increases with hydrogen admixture. This can be explained with the increased flame temperature. The studies did not find components overheating or damage to the burner at the hydrogen admixture levels tested. There have not been any long term investigations though.

It is important that the burner establishes a flame without a **delay upon ignition**. Otherwise unburned fuel could leak out of the burner. The addition of hydrogen does not delay the ignition of the burner as reported in [CoMc18, NBML15, ZhMS20], where hydrogen admixture up to 30% was tested. Hydrogen with its extremely high diffusion velocity and reactivity compared to methane leads to enhanced flammability of H2NG mixtures.

In Figure 3-6 the relative **thermal power output** (for boilers typically referring to the energy input into the water cycle) of appliances that witness hydrogen admixture compared to pure natural gas is shown for different studies. The results vary slightly between the appliances. The overall trend suggests a power decrease of around 10% is to be expected at 30% hydrogen admixture. In theory, the power reduction should tendentially follow the Wobbe Index, however, as it can be seen in Figure 3-6 in most appliances the decrease is stronger. This observation can be assigned to heat losses caused by specific appliance designs that are not made for hydrogen admixture and do not transport the usable heat into the warm water cycle in an optimal way.

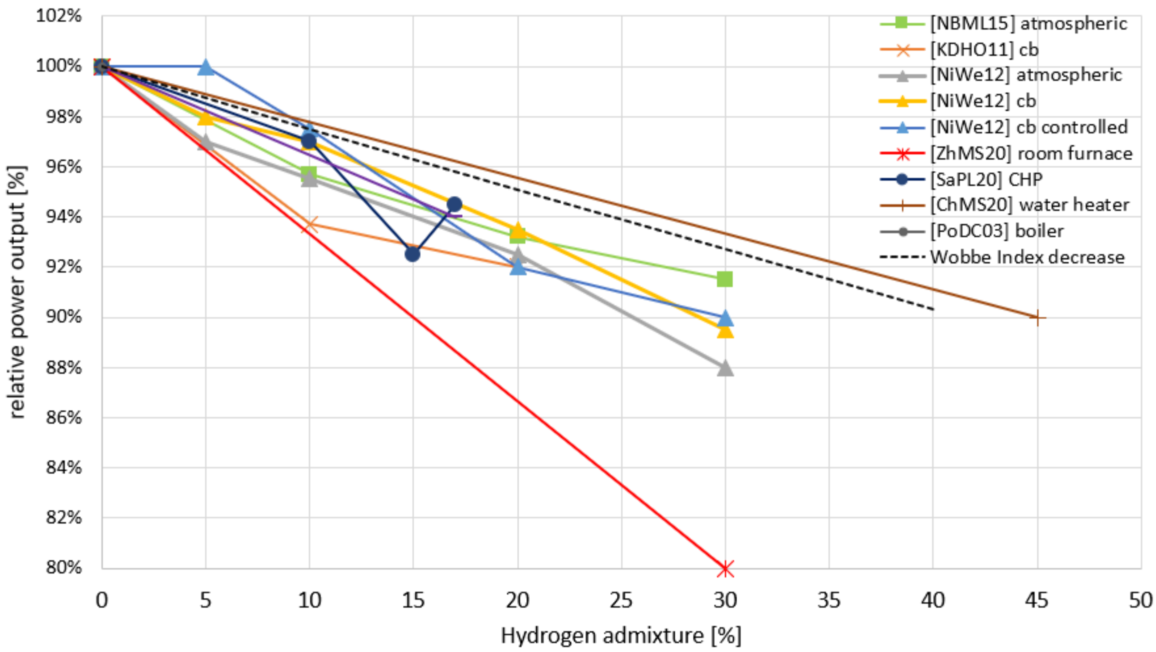


*Figure 3-6 Power output of different appliances with increasing hydrogen admixture reported in literature. For comparison, the dotted line indicates the theoretical relative reduction of power output as calculated from the Wobbe index of the gas mixture.*

## 3.2.2 CO emissions

**Carbon monoxide** (CO) is a toxic pollutant that is a result of the incomplete combustion of hydrocarbon fuels and as such, closely related to the air excess ratio λ. The addition of hydrogen to natural will shift the stoichiometry of a combustion process towards higher λ values, unless a constant air excess ratio is maintained by some kind of control system. This means that carbon monoxide emissions are less likely to occur.

Figure 3-7 shows the qualitative results of 21 studies that investigated CO emissions. In total three studies [ChMS20, NiWe12, ShLi14] found an increase in CO emissions while twelve found a decrease and six comparable results. The hydrogen admixture rate does not have a clear impact on the experimental results from literature. The results indicate that CO emission can be expected to be lower compared to natural gas. However, hydrogen admixture is not the only factor that impacts CO emissions. The emissions closely relate to the air excess ratio. As explained before, the air excess ratio shifts with hydrogen admixture in an uncontrolled combustion process. If the shift leads to unstable combustion condition it will increase the emissions significantly e.g. near the blowout limit, there will be a peak in CO emissions [CoMc18, RZSF02]. However, the flame stability range is also extended which could prevent burners from reaching the blowout limit. Unusual operating modes could be potentially problematic for appliance operation. Some studies found increasing CO emission in steady-state partial load operation [NBML15, NiWe12].

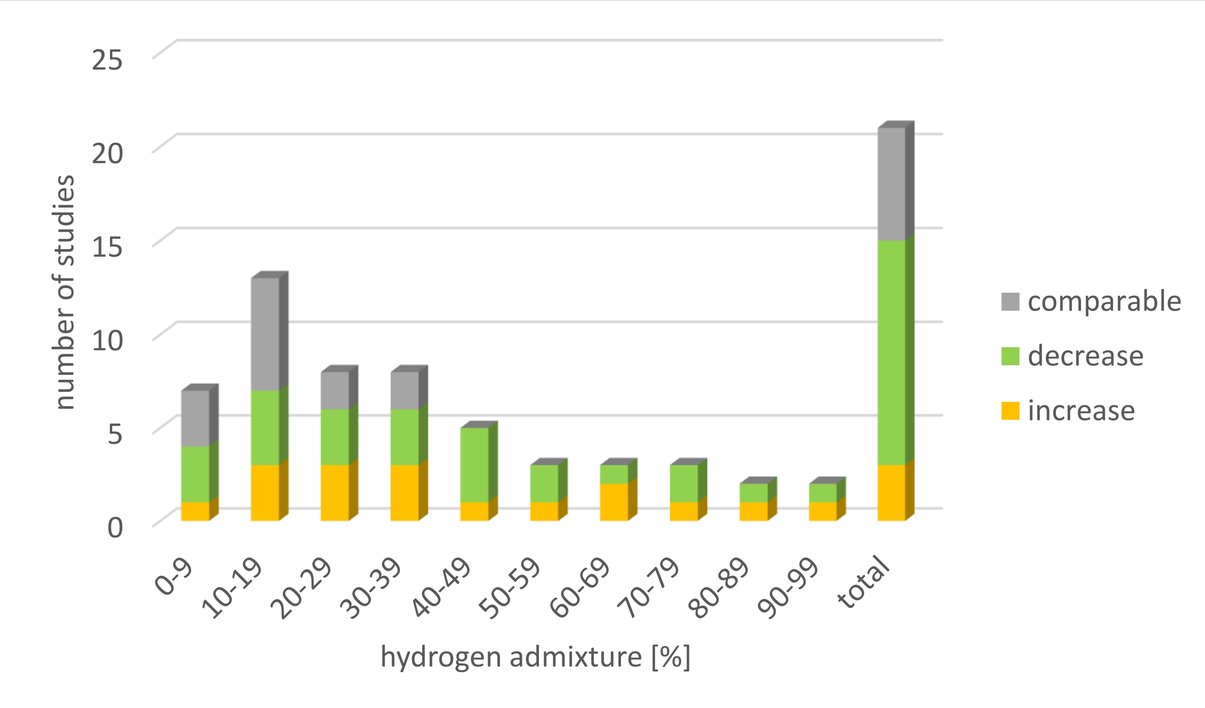


*Figure 3-7 Overview of CO emission results in reported literature*

The qualitative results give an overview of how different types of appliances might react. To spot differences between different studies, it is necessary to compare similar appliances. However, because of the low number of overall tested appliances there are only few similar devices to compare. Furthermore, there is no uniform measurement procedure. While some studies use the energy input as reference (mg/kWh) others use the volumetric reference (mg/m3 or ppm). For the volumetric reference it is important to relate to a specific oxygen concentration in the exhaust gas as the same amount of pollutants delivers lower concentrations with more air in the combustion process. Some studies did not report the air excess ratio or correct diagrams by referring to a uniform $O_2$ concentration. Further systematic measurements are needed to obtain comprehensive results.

Figure 3-8 shows the results of three studies with the emissions corrected to 0 % oxygen in the flue gases. The tested appliances are condensing boilers both with and without combustion control [KrDr16, NiWe12] as well as a conventional boiler [NBML15]. All appliances are fully premixed.

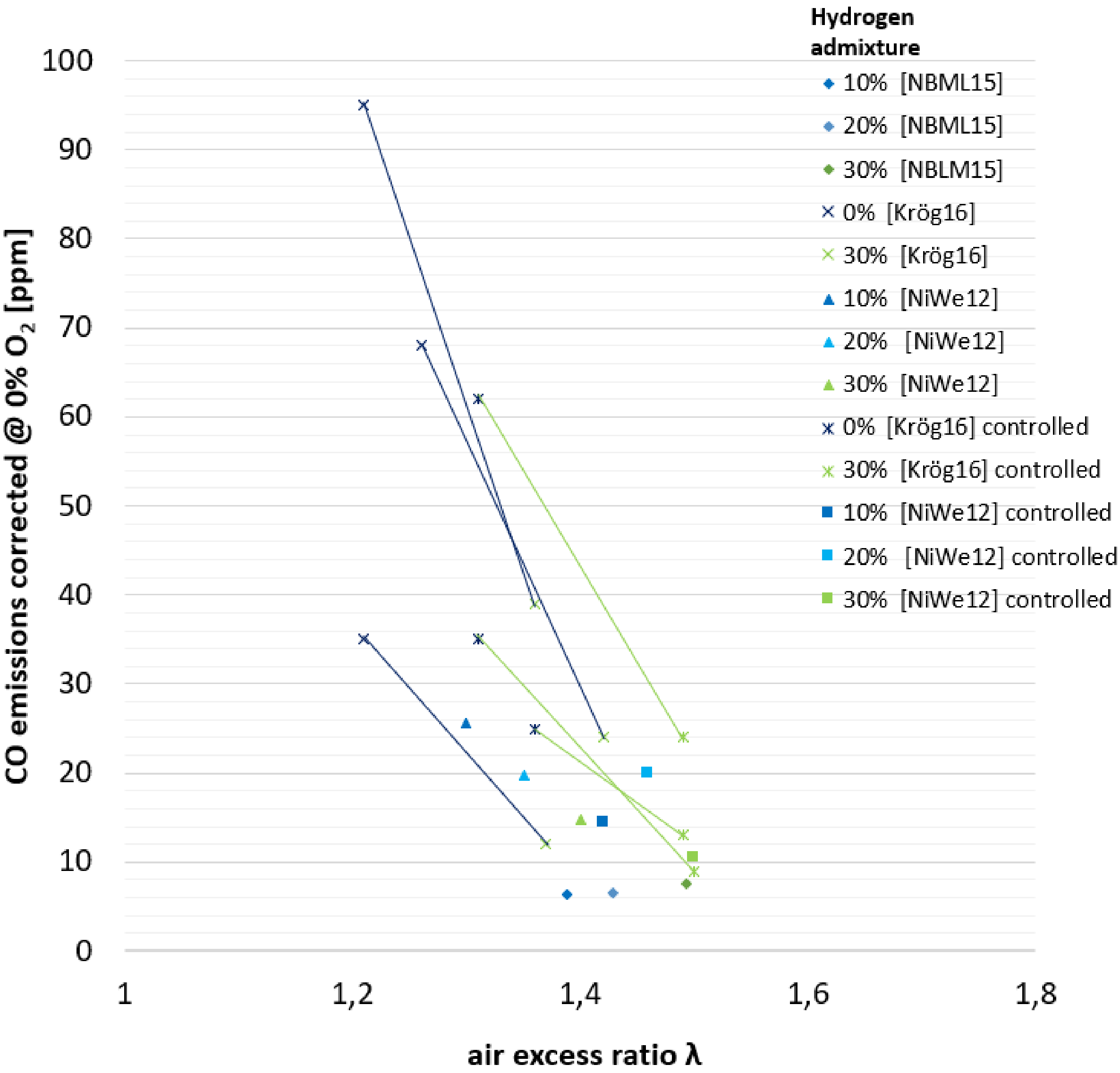


*Figure 3-8 CO emissions of different premixed burner systems reported in literature. Data points from the same appliance are connected with a line.*

As can be seen, the CO emissions decrease in most cases while showing a slight increase in [NBML15]. The CO reduction can be explained with two different influences. Hydrogen causes an increase of **OH radicals** which in turn **promote the reduction of CO to $CO_2$** [ZhMS19b]. Additionally, with less methane in the fuel there is **less carbon in the fuel**. All appliances show a stable flame because otherwise peaking CO emissions would be observed. The results shown in Figure 3-8 were measured under full load operation.

The shift to higher air excess ratios also happened for the case of the combustion-controlled boilers. In the case of CO emissions this has no negative impact as the emissions decrease with increasing lambda.

The quantitative results only show a very limited number of appliances and only measurements for a maximum of 30% hydrogen admixture. For future investigations and the experiments in the THyGA project it is important to test a wider range of appliances under various operating conditions.

### 3.2.3 NOx emissions

The term NOx combines the **emissions of NO and $NO_2$**. Once in the atmosphere, nitrogen oxides react with water to form nitric acid ($HNO_3$) which are one of the main causes for acid rain. Furthermore, nitrogen oxides can irritate and damage the respiratory organs and are therefore a health issue.

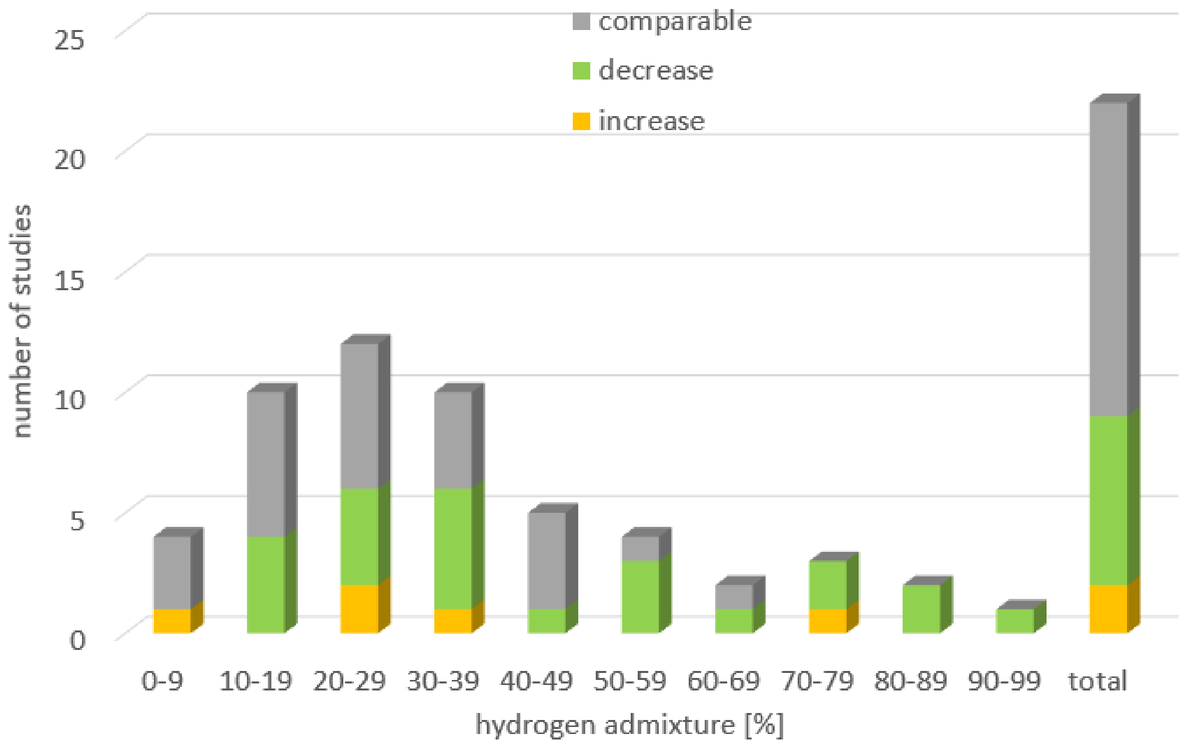


*Figure 3-9 Overview of $NO_x$ emission results in the reported literature*

Figure 3-9 shows the qualitative results of 23 studies investigating $NO_x$ emissions. Just two studies report on an increase in $NO_x$ emissions [DuDL15, SaPL20], seven report a decrease and thirteen found comparable emission levels.

$NO_x$ formation in the reaction zone mainly depends on flame temperature and the local availability of oxygen. As shown before, flame temperatures can increase with hydrogen addition but the higher air excess ratios occurring in premixed or partially premixed gas appliances without combustion control can also lead to lower local temperatures. Which effect is dominant depends on the actual appliance and the type of combustion process that is being used. In the studies with similar $NO_x$ emission levels compared to natural gas, it can be assumed that both effects compensate each other to some extent (see combustion theory report D2.2 for details [LSCA20]).

Detailed experimental data on this topic are shown in Figure 3-10.

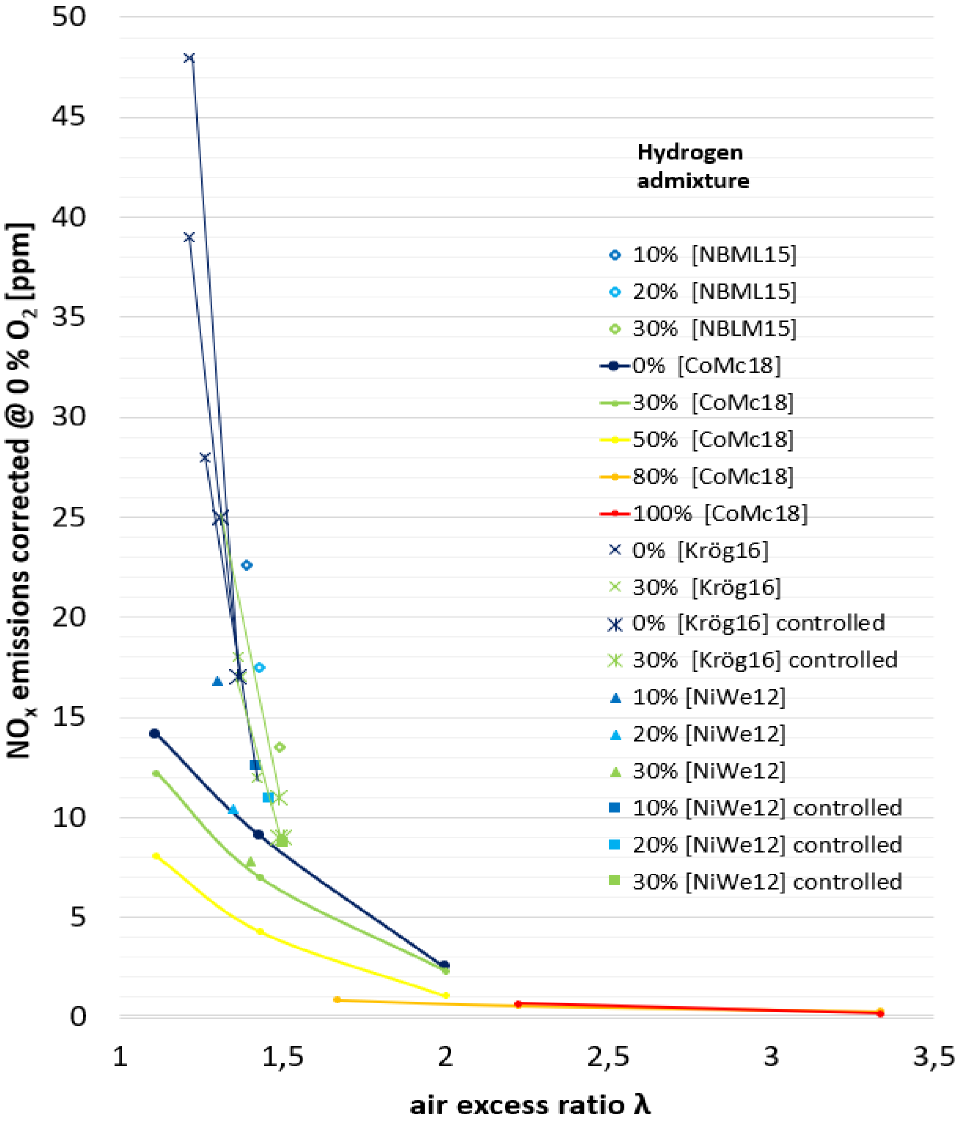


*Figure 3-10 $NO_x$ emissions of different premixed burner systems reported in literature. Data points from the same appliance are connected with a line.*

Figure 3-10 shows the $NO_x$ emissions of several premixed appliances. The emissions vary between different appliances but also show some similarities. With increasing hydrogen admixtures, the $NO_x$ emissions decrease. This could be expected because at the same time the air excess ratio increases. $NO_x$ formation largely depends on the temperature. Higher air excess ratios, which can also be seen in Figure 3-10, lead to a decrease in temperature and therefore $NO_x$ emissions. It is noteworthy that this also applies to the appliances with integrated combustion control. The implemented combustion control mechanisms seem to be unable to correct the air excess ratio for the H2NG mixtures which leads to a similar behavior in regard to the $NO_x$ emissions.

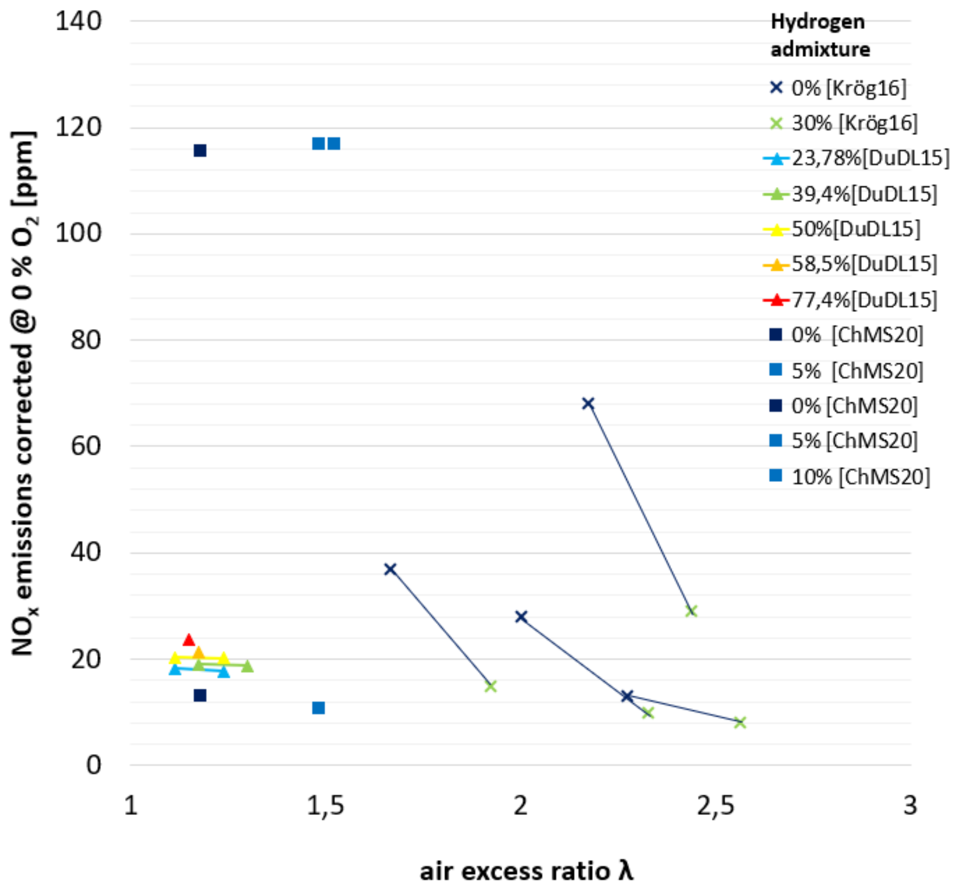


*Figure 3-11 $NO_x$-emissions of partially premixed burners reported in literature. Data points from the same appliance are connected with a line.*

Figure 3-11 shows the emissions of partially premixed appliances. While the results in [KrDr16] are similar to the premixed devices with a decrease in emissions and an increase in air excess ratio, [ChMS20] found an increase in air excess ratio but no decrease in $NO_x$ emissions. [DuDL15] showed that the $NO_x$ emissions increase at higher hydrogen admixture levels if the air excess ratio is kept constant but also show a decrease if the stoichiometry shift towards higher air ratios is allowed to happen.

### 3.2.4 Flashback

A safe combustion process is dependent on a stable flame. The **flame stability** in turn is dependent on the laminar combustion velocity in a residential appliance. The vast majority of technical combustion processes are turbulent and the respective turbulent combustion velocity is relevant here. In the case of residential combustion technology, laminar combustion plays an important role with advantages e.g. in noise emissions of the combustion process. **The addition of hydrogen increases the combustion velocity**. If the combustion velocity is larger than the flow velocity the flame moves closer towards the burner. A **flashback** occurs when the flame propagates upstream through the nozzle. This can seriously damage the burner as upstream components are not designed to withstand high temperatures.

*Table 3-1 Flashback occurrence vs. hydrogen enrichment reported in literature*

| study | type of study | Hydrogen admixture [%] 0-9 | 10-19 | 20-29 | 30-39 | 40-49 | 50-59 | 60-69 | 70-79 | 80-89 | 90-99 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [GaBa15] | exp. | | | | | | | | | | | |
| [VrLM17] | num. | | | fuel rich | | | | | | | | |
| [PoDC03] | exp. | | | | | | | | | | | |
| [KDHO11] | exp. | | | | | | | | | | | |
| [SAGO12] | exp. | | | | | | | | | | | |
| [Krög16] | exp. | | | | | | | | | | | |
| [NiWe12] | exp. | | | | | | | | | | | |
| [NBML15] | exp. | | | | ignition | | | | | | | |
| [VrFT00] | num. | | | fuel rich | | | | | | | | |
| [ZhMS20] | exp. | | | ignition | | | steady state | | | | | |
| [Jone18] | num. | | | | extinction | | ignition | | | | | |
| [NZST06] | exp. | | | | | | | | | | | |
| [CoMc18] | exp. | | | | | | | | | | | |
| [Isaa19] | exp. | | | | | | | | | | | |

| | | | |
|---|---|---|---|
| not tested | no flashback | possible flashback | flashback |

While hydrogen admixture increases the combustion velocity it also increases the local air excess ratio in a premixed combustion process which in turn decreases the combustion velocity unless a constant air excess ratio is maintained with some kind of combustion control. In the case of super-stoichiometric combustion ($\lambda > 1$, common for heating systems), these effects will then to a certain degree cancel out each other.

In the case of a sub-stoichiometric system ($\lambda < 1$), however, the effects of the shift in stoichiometry and higher hydrogen content will stack, leading to a significant increase of the laminar combustion velocity [LSCA20]. This aspect is relevant for partially premixed devices, e. g. cooking hobs, where the primary reaction zone often is sub-stoichiometric.

This is also shown in numerical investigations in the reported literature [VrFT00, VrLM17], as flashback occurrence is critical with 20% hydrogen admixture for the fuel rich case. Fuel rich compositions are common in partially premixed burners which only reach super stoichiometric combustion with the addition of secondary air. In [ZhMS20], flashback occurred during ignition of a partially premixed burner at 20% hydrogen admixture. However, if ignited successfully, flashback did not happen until 40% hydrogen admixture. Meanwhile, [Jone18] found that turning off the burner was the critical situation when flashbacks occurred at 35% hydrogen admixture and ignition was successful until 50% hydrogen. In [NBML15], multiple appliances including partially premixed boilers were tested for a cold start at 30% hydrogen admixture and no flashback was noted. These differences could be explained with different burner geometries, especially different diameters of the burner ports.

For fully premixed burners, flashback can be expected to happen only with higher hydrogen admixture levels. **For hydrogen admixture below 30% none of the analysed studies on household boilers found a severe flashback risk** at laboratory conditions within the testing time.

At 30% hydrogen a possible flashback risk is shown in [CoMc18]. However, the air excess ratios were varied strongly in these specific experiments in order to provoke flashback which does not represent the domestic use case. In [NZST06], flashback happened with more than 50% hydrogen admixture while [Isaa19] found flashback only at 80% hydrogen.

The results from the literature study underline that more laboratory tests must be conducted through all phases of burner operation. The future experimental findings of the THyGA project should be helpful to fill the existing knowledge gaps and may be compared to the results from literature summarised here in the future.

# 4 Summary and outlook

This report gave a structured overview of the various natural gas-fired appliance types installed in the field across the European Union and assigned the corresponding potential impacts of hydrogen enrichment in natural gas to each appliance category. The report includes appliance technologies from the heating sector, such as various boiler types, as well as combined heat and power appliances, water heaters, gas heat pumps, cooking appliances, various types of catering equipment, local space heaters, and radiant heaters.

**First aspects and expectations on the impacts of hydrogen admixture** on the combustion processes were described within chapter 2, based on the authors' experiences and knowledge as of 2020, i.e. before the experimental campaign of the THyGA project, aiming to test up to 100 appliances, started.

Additional insight was gained by performing a **systematic literature review** which was presented in chapter 3. For this review, 110 publications were filtered out of 414,115 initial sources using keywords to focus on the subject of the study. One by one screening of the 110 publications applying selection criteria led to a subset of 36 studies that were included in this work. As a result, concurring quantitative as well as qualitative statements were identified, assessed and discussed. Amongst other, available knowledge on CO and $NO_x$ formation, overheating, flame temperature, flashback, $H_2$ leakage, operational implications and efficiency of appliances supplied with H2NG blends was presented.

**Summary**

Given the significant differences between the physical and chemical properties of natural gas and hydrogen, switching from natural gas to natural gas/hydrogen blends or even pure hydrogen can affect combustion processes in residential and commercial appliances in terms of performance, but also and most importantly in terms of safety. It is obvious that the consequences will become more pronounced with higher levels of hydrogen in the fuel gas. However, the response of a combustion process to higher hydrogen levels is not only dependent on the change in the fuel properties, but to a large extent also on the technological implementation. For example, a premixed combustion process will react differently than a non-premixed system, and the presence of a combustion control system plays an important role as well.

The focus of the analysed literature was found to be on hydrogen admixture levels below 30 vol.-%. The included literature was analysed regarding CO and $NO_x$ emissions, flame temperature, flashback, operability and efficiency. A decrease of power output up to 12 % at 30 vol.-% hydrogen admixture compared to the operation with natural gas was reported. Furthermore, increasing risk of flashback was noted. The first occurrence of flashback was found at an admixture ratio of 20 %. The risk depends on the type of appliance and is particularly pronounced for partially premixed appliances, a common technology for domestic and commercial cooking appliances. Efficiency changes were found to be below two percent. However, the analysis also revealed existing knowledge gaps. Testing procedures in different studies proved to be inconsistent. This led to contradicting statements especially concerning CO and $NO_x$ emissions as well as flame temperature. Flashback testing was also inconsistent and did not cover all operating points. Combustion control systems were found to be affected but the specific extents of the impacts remain largely unknown. Leakage of hydrogen is also considered problematic, but there are not enough research results publicly available to assess its influence on domestic and commercial technologies investigated here.

Overall, it can be concluded, that for many common situations found in residential and small commercial appliances, different effects of hydrogen admixture compensate each other to a certain degree. For example, in uncontrolled residential combustion systems (which comprise a large proportion of the residential appliance population in the EU), hydrogen admixture will result in a shift of the air excess ratio towards higher values which will largely counteract the increase of the laminar combustion velocity and combustion temperatures due to the presence of hydrogen.

**Outlook**

In general, the distribution of hydrogen-natural gas blends is a viable option to partially decarbonise the combustion processes in the technologically very heterogeneous heat sector. The theoretical background presented in the previous report [LSCA20] must be taken into account when developing suitable equipment technology as well as the necessary rules and standards for hydrogen / natural gas blends. Typical technologies installed in the field may be used up to certain hydrogen admixture levels without causing safety risks, while some technologies, especially at high hydrogen additions, will have to be replaced. Detailed insight into the experimental findings on specific appliance technologies will be given in the future reports from the THyGA project[8]. The partners of the THyGA project plan to test up to 100 domestic and commercial appliances following uniform test procedures with the aim to fill some of the existing knowledge gaps on the suitability of today's portfolio of end-use appliances for hydrogen admixture.

[8] Please visit https://thyga-project.eu/

# 5 Acknowledgments

The authors gratefully acknowledge the valuable input, discussions and feedback provided by all partners of the THyGA consortium when preparing this report. Special thanks to Patrick Milin, ENGIE, for the smooth coordination of the overall project as well as Manfred Lange, GWI, for feedback on the report.

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# 6 Appendix

## 6.1 Table of studies included in the literature review

*Table 6-1 Studies included in the literature review*

| Title | Author(s) | Year | Reference |
|---|---|---|---|
| Energy-environmental experimental campaign on a commercial CHP fueled with h2ng blends and oxygen enriched air hailing from on-site electrolysis | Livio de Santoli, Romano Paiolo, Gianluigi Lo Basso | 2019 | [SaPL20] |
| A comparison of low-NOx burners for combustion of methane and hydrogen mixtures | Geir J. Rørtveit, Klaus Zepter, Øyvind Skreiberg, Morten Fossum and Johan E. Hustad | 2002 | [RZSF02] |
| An experimental study on hydrogen–methane mixtured fuels | Ilker Yilmaz, Mustafa Ilbas | 2007 | [YiIl08] |
| Application of a central composite design for the study of NOx emission performance of a low NOx burner | Marcin Dutka, Mario Ditaranto and Terese Løvås | 2015 | [DuDL15] |
| Combustion of hydrogen-enriched methane in a lean premixed swirl-stabilized burner | R. W. Schefer,D. M. Wicksall and A. K. Agrawal | 2002 | [ScWA02] |
| Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas | Chiny Choudhury, Vincent G. Mcdonell, Scott Samuelsen | 2019 | [ChMS20] |
| Combustion with mixed enrichment of oxygen and hydrogen in lean regime | Zouhaier Riahi, Hamdi Bounaouara, Ibtissem Hraiech, Mohamed Ali Mergheni, Jean-Charles Sautet, Sassi Ben Nasrallah | 2016 | [RBHM17] |
| Effects of hydrogen addition to methane on the flame structure and co emissions in atmospheric burners | Hugo J. Burbano, Andre´S A. Amell, Jorge M. Garcıa | 2008 | [BuAG08] |
| Behavior of hydrogen-enriched non-premixed swirled natural gas flames | F. Cozzi, A. Coghe | 2005 | [CoCo06] |
| Direct emissions of nitrous oxide from combustion of gaseous fuels | Andres Colorado, Vincent Mcdonell, Scott Samuelsen | 2016 | [CoMS17] |
| Effects of hydrogen enrichment on adiabatic burning velocity and NO formation in methane + air flames | F.H.V. Coppens, J. De Ruyck, A.A. Konnov | 2005 | [CoDK07] |
| Emission characteristics of a novel low NOx burner fueled by hydrogen-rich mixtures with methane | Marcin Dutka, Mario Ditarantob , Terese Løvås | 2015 | [DuDL16] |
| Experimental analysis of the effects of hydrogen addition on methane combustion | Mustafa Ilbas and Ilker Yılmaz | 2010 | [İlYı12] |
| Experimental and numerical investigation of a micro-CHP flameless unit | A. Parente, C. Galletti, J. Riccardi, M. Schiavetti, L. Tognotti | 2011 | [PGRS12] |
| Hydrogen-enriched natural gas as a domestic fuel: an analysis based on flash-back and blow-off limits for domestic natural gas appliances within the UK | Jones, D., Al-Masry, W. & Dunnill, C | 2018 | [Jone18] |

| | | | |
|---|---|---|---|
| Operational issues in premixed combustion of hydrogen-enriched and syngas fuels | Tatiana Garcıa-Armingol, Javier Ballester | 2014 | [GaBa15] |
| Seasonal energy and environmental characterization of a micro gas turbine fueled with h2ng blends | Livio de Santoli, Gianluigi Lo Basso, Shahrokh Barati, Stefano D'ambra, Cristina Fasolilli | 2019 | [SLBD20] |
| Surface stabilized combustion technology: an experimental evaluation of the extent of its fuel-flexibility and pollutant emissions using low and high calorific value fuels | A. Colorado, V. Mcdonell | 2018 | [CoMc18] |
| Syngas mixture composition effects upon flashback and blowout | David R. Noble, Qingguo Zhang, Akbar Shareef, Jeremiah Tootle, Andrew Meyers, Tim Lieuwen | 2006 | [NZST06] |
| The effect of hydrogen containing fuel blends upon flashback in swirl burners | Nicholas Syred, Mohammed Abdulsada, Anthony Griffiths, Tim O'doherty, Phil Bowen | 2010 | [SAGO12] |
| The effects of hydrogen addition on fenimore NO formation in low-pressure, fuel-rich-premixed, burner-stabilized CH4/O2/N2 flames | A.V. Sepmana, V.M. Van Essena, A.V. Mokhova, H.B. Levinsky | 2008 | [SEML08] |
| The impact of natural gas/hydrogen mixtures on the performance of end-use equipment: interchangeability analysis for domestic appliances | Harmen De Vries, Anatoli V. Mokhov, Howard B. Levinsky | 2017 | [VrLM17] |
| Untersuchungen zur Einspeisung von Wasserstoff in ein Erdgasnetz | Dr. Holger Dörr, Kerstin Kröger, Dr. Frank Graf, Wolfgang Köppe | 2016 | [KrDr16] |
| Effect of hydrogen addition on combustion and emission characteristics of methane fuelled upward swirl can combustor | Parag Rajpara, Rupesh Shah, Jyotirmay Banerjee | 2018 | [RaSB18] |
| Flame characteristics of hydrogen-enriched methane–air premixed swirling flames | Han S. Kim, Vaibhav K. Arghode, Ashwani K. Gupta | 2008 | [KiAG09] |
| Hydrogen enrichment for improved lean flame stability | R.W. Schefer | 2003 | [Sche03] |
| Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen | Yan Zhao, Vincent McdonelL, Scott Samuelsen | 2019 | [ZhMS19b] |
| Impact of hydrogen admixture on installed gas appliances | Petra Nitschke-Kowsky | 2012 | [NiWe12] |
| Assessment of the combustion performance of a room furnace operating on pipeline natural gas mixed with simulated biogas or hydrogen | Yan Zhao, Vince Mcdonell, Scott Samuelsen | 2019 | [ZhMS20] |
| H2NG (hydrogen-natural gas mixtures) effects on energy performances of a condensing micro-CHP (combined heat and power) for residential applications: an expeditious assessment of water condensation and experimental analysis | Gianluigi Lo Basso A, Livio De Santoli, Angelo Albo, Benedetto Nastasi | 2015 | [LSAN15] |
| A computational study on the combustion of hydrogen/methane blended fuels for a micro gas turbine | Hsin-Yi Shih, Chi-Rong Liu | 2014 | [ShLi14] |
| How to handle the hydrogen enriched natural gas blends in combustion efficiency | Gianluigi Lo Basso, Benedetto Nastasi, Davide Astiaso Garcia, Fabrizio Cumo | 2017 | [LNAC17] |

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|---|---|---|---|
| measurement procedure of conventional and condensing boilers | | | |
| Effects of hydrogen addition on methane combustion in a porous medium burner | Chung-Jen Tseng | 2002 | [Tsen02] |
| Behaviour of domestic appliances using hydrogen enriched natural gas | Dr. Petra Nitschke-Kowsky | 2015 | [NBML15] |
| DGC82 Kiwa paper cofiring h2 - ng | Kiwa Technology B.V. | - | [PoDC03] |
| Hydeploy: the UK's first hydrogen blending deployment project | Tommy Isaac | 2019 | [Isaa19] |
| Hydrogen injection in natural gas on island of Ameland in the Netherlands | M.J. Kippers, J.C. De Laat, R.J.M. Hermkens | 2011 | [KDHO11] |
| Safe operation of natural gas appliances fueled with hydrogen/natural gas mixtures (progress obtained in the Naturalhy-project) | De Vries, H., Florisson, O. and Tiekstra, G.C. | - | [VrFT00] |

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[Cent03] CEN/TC 238: *EN 437 Test gases - Test pressures - Appliance categories*, 2003

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