WHEN TRUST MATTERS

Hydrogen as fuel for heating processes; what are the challenges?

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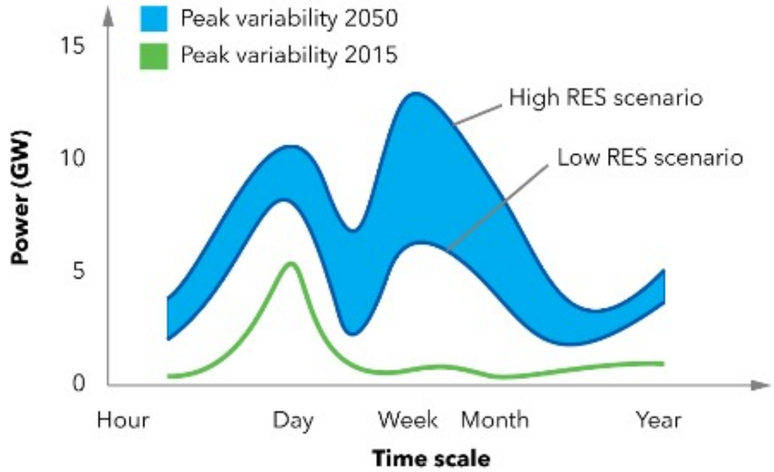
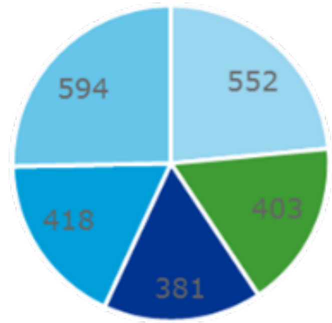
Challenges to accommodate electricity produced from solar PV and wind

- Electricity produces from solar PV and wind increases substantially
- Intermittent nature of solar and wind energy puts pressure on capacity of power grids
- Excess of renewable electricity can be converted into hydrogen (Power-To-Hydrogen)
- Injecting renewable gas in existing gas grid is an effective means to avoid large investments in new infrastructures



Renewable gas markets and opportunities



Netherlands energy consumption in PJ

- Hydrogen can be used in the mobility sector, the built environment and the industry
- Natural gas grids are already connected to the built environment and the industry
- Given the large penetration of natural gas in the total global energy mix, the increase of renewable gas in the total gas supply will result in a substantial carbon emission reduction

Industry

Mobility

Built Environment

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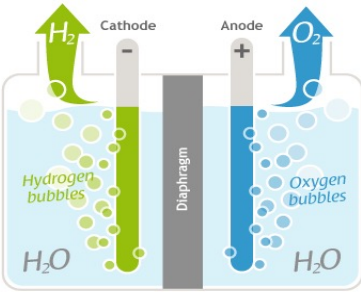
Using hydrogen as a fuel is the fastest route to making the industry more sustainable

Advantages of using hydrogen in the industry:

1. Existing processes do not have to be adjusted drastically
2. The natural gas grid is already connected to the industry and can be used to transport hydrogen
3. Individual industrial cluster(s) can be readily converted to hydrogen
4. Shortest route towards decarbonisation for the lowest investment
5. Transport of gas is much **cheaper** than transport of electricity
6. Direct use of electricity is not always suitable for direct heating processes



Case study: Hydrogen in the industry has huge impact on decarbonisation

- **Glass factory – 8 production location**
- Total energy consumption in 2020: 10 PJ
  - 6.6 PJ Natural gas
  - Total CO_2 emission: 450kton CO_2

- The annual natural gas consumption **± 200 Mln. m³** can be replaced potentially by hydrogen: equivalent to **± 600 Mln. m³** hydrogen (Economy of scale)

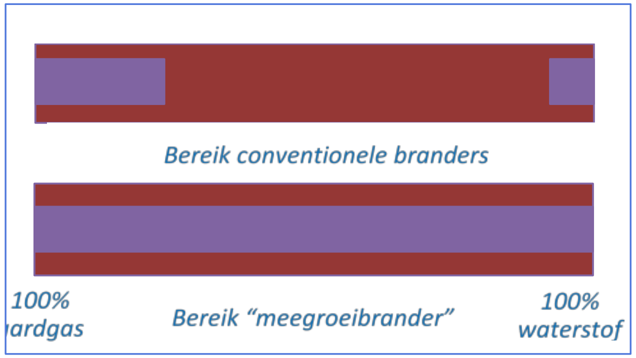
- This equals to about ca. 7500 line busses on hydrogen (the total number of line busses in the Netherlands is about 6500)

Challenges in the application of hydrogen in the heating industry

1. **Availability of hydrogen**
2. **Unchanged product quality**
   - Combustion properties
   - Changes in temperature, flue gas composition and flame radiation
3. **Simple and cost-efficient implementation**

Challenges when using hydrogen in the industry (1) - Availability

- In the initial phase of the energy transition, it is unlikely that there always will be enough hydrogen available to satisfy the entire industrial energy demand, whose processes usually run continuously (24/7) throughout the year
- Next to 100% hydrogen supply also blending natural gas with hydrogen is consider as an option
- An **attractive solution** is to apply a burner systems that can flexibly utilize the full mix of fuel compositions: 100% hydrogen, 100% natural gas and all mixtures of hydrogen and natural gas in between using a gas adaptive fuel-air ratio control system
- The major economic advantage of such a system is that it offers robust fuel flexibility with only a **limited investment**:
- **The same burner system** can be used throughout the transition, supplied initially with **varying** natural/gas hydrogen mixtures, and in the end with pure hydrogen when the supply has risen to the challenge.



Calculated Physical parameters of natural gas/hydrogen

Table 1. Physical parameters Dutch natural gas and hydrogen

	Dutch natural gas	Hydrogen
LEL, %	5.8	4.0
UEL, %	16.7	75.3
Minimum ignition energy (stoichiometric mixture)	0.274	0.017
AIT, °C	630	520
Wobbe index, MJ/m³ (25, 0)	43.75	48.35
Net calorific value, MJ/m³n	30.86	10.79
Gross calorific value , MJ/m³n	34.24	12.75
Density, kg/m³n	0.79	0.09

$$H_2 + ½O_2 => H_2O$$

$$CH_4 + 2O_2 => CO_2 + 2H_2O$$

Table 2. Changes in main components in the combustion gases at λ=1.25

	Dutch natural gas	H_2
H_2O, mole%	15.2	28.3
N_2, mole%	72.2	66.5
O_2, mole%	3.7	3.3
Ar, mole%	7.6	0.8
Other components, %	0.8	1.1
$T_{adiabatic\ flame\ temperature}$ °C	1708	1895
Water dewpoint (at 3% O_2 in flue gas)	**55.7**	**72.6**

Differences in physical and chemical properties affects:

- Safety
- Gas transport/distribution
- **Combustion behaviour (end-use)**
- Product quality (direct heating)

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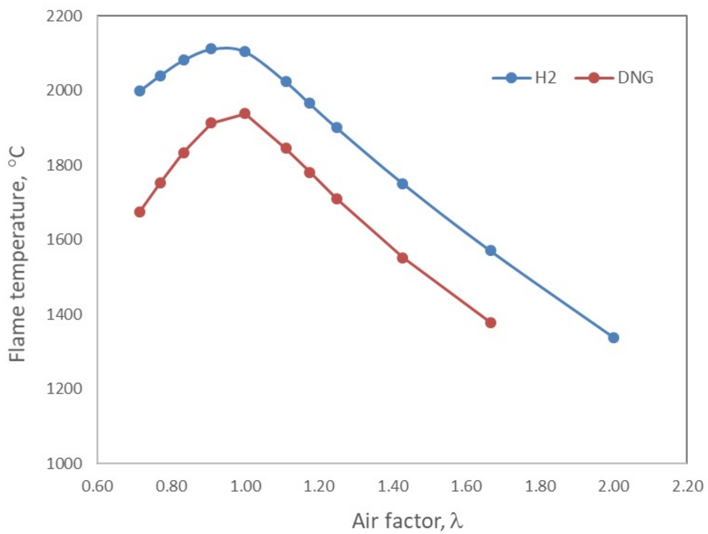
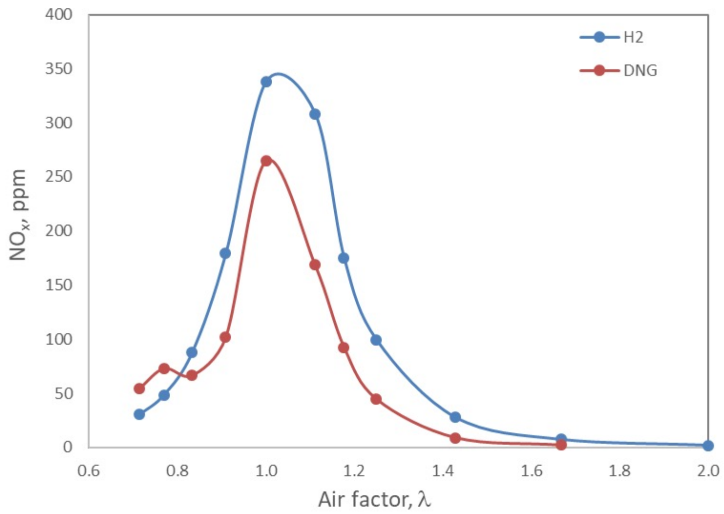
Example: Numerical calculated flame temperature and NO_x formation for a 1-D premixed natural gas and hydrogen flame (numerical laminar flame calculation)





Higher flame temperature increases the 'thermal' NO_x formation via;

$$N_2 + O \leftrightarrow N + NO$$
$$\mathrm{N} + O_2 \leftrightarrow NO + O$$
$$\mathrm{N} + OH \leftrightarrow NO + H$$

- The flame temperature of a hydrogen flame is substantially higher than a natural gas flame (~200 °C)
- The higher flame temperature results in more NO_x formation in hydrogen flames
- Note: at the conditions studied NO is formed mainly through the thermal NO_x mechanism (Zeldovich mechanism) in which nitrogen and oxygen reacts to NO molecules. To break the nitrogen bounds high temperatures are needed which makes this NO formation strongly temperature dependent.

Calculated thermal efficiency Based on higher heating value

- To get insights in the efficiency changes we calculated the thermal efficiency

$$thermal\ efficiency, \% = 100 * \frac{H_{fuel} - H_{flue\ gas}(T_{flue\ gas})}{H_{fuel} - H_{flue\ gas}(298K)}$$

- Up to about a flue gas **of 56°C no large differences** are expected between methane and hydrogen; the thermal efficiency of hydrogen is slightly better (up to ~1.5%)

- For flue gas temperatures above **73 °C (dew point hydrogen)** the efficiency of hydrogen is lower than methane; **up to about 6%** as a result of the higher water content (condensation enthalpy) in the flue gases of a hydrogen flame

- Advice: for boiler systems condensation of the flue gases is recommended to maintain efficiency (e.g. installation condenser)

- Note: these calculations are thermodynamic calculations and heat transfer from H_2 might be different from NG and, in consequence impact in a different way the thermal efficiency

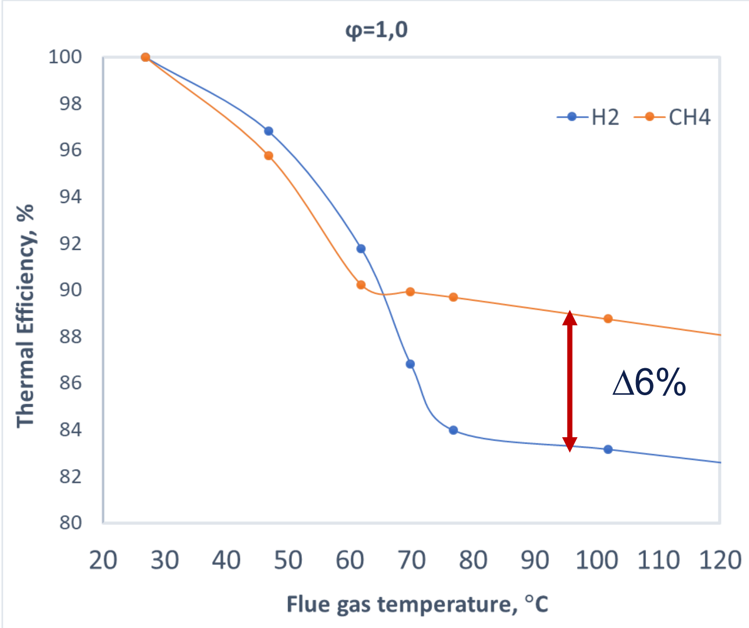


Figure: Calculated thermal efficiencies for methane and hydrogen using a thermodynamic equilibrium model

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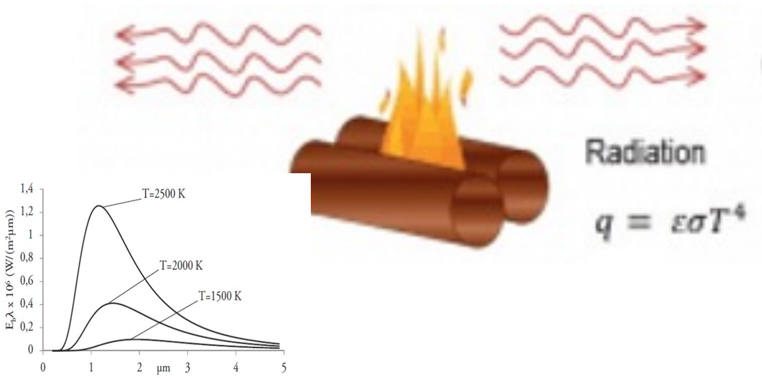
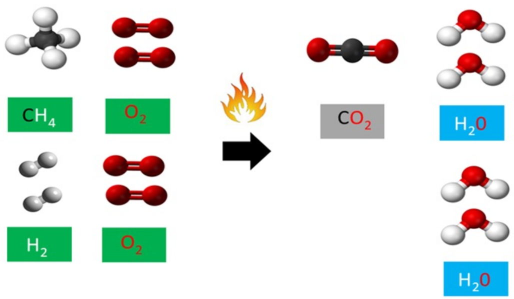
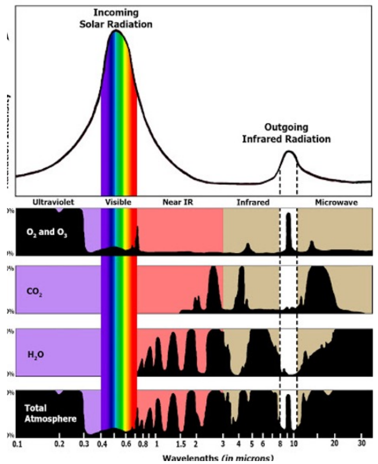
Which changes in flame radiation can we expect when adding H_2
Changes in flame radiation assume same flame geometry ?







- When adding hydrogen to natural gas the flame temperature and the combustion products will change
- As a result, the **heat radiation flux** will change accordingly;

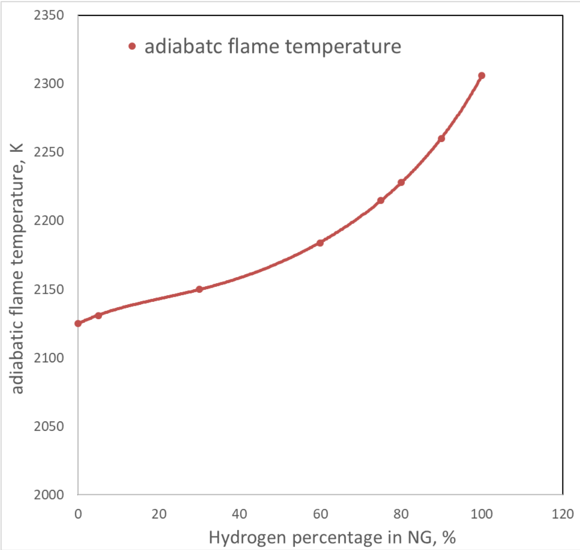
$$q_{flame\ radiation} = \varepsilon_{flame}\sigma T_{flame}^4$$

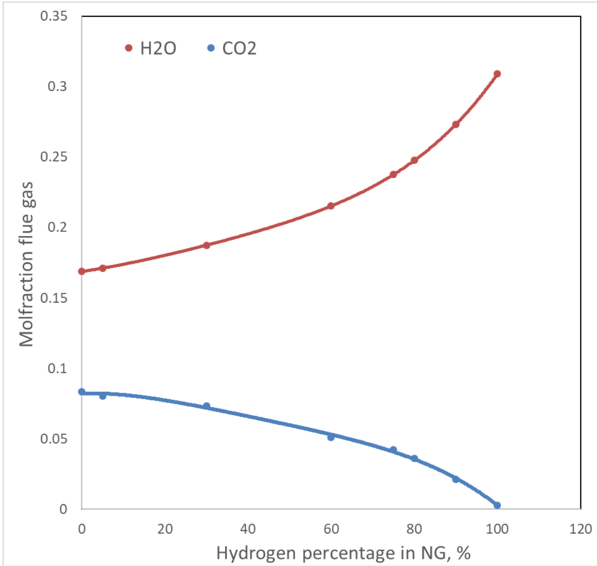
- The emission coefficient (ε) of the flame gases depends upon the partial pressures of the **gas composition**, the absorption path length, and the **temperature**.
- The gas composition and temperature is calculated via an equilibrium model and is used as input in the Leckner model that calculates the emissivity ε of the flame according to;

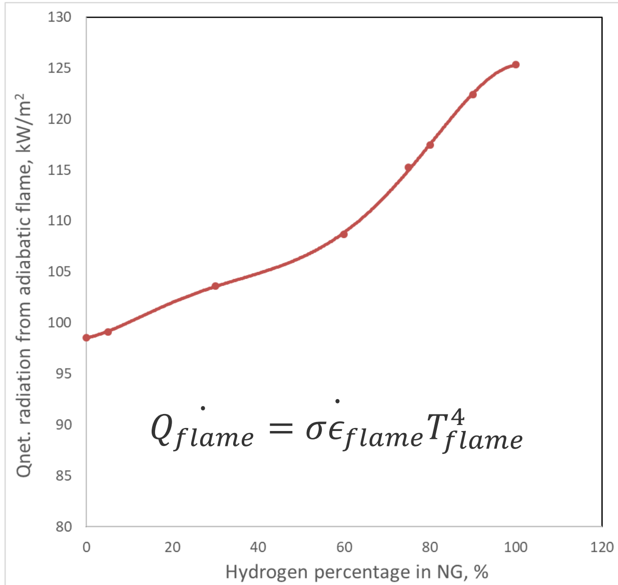
$$\varepsilon_{flame} = \varepsilon_{CO2} + \varepsilon_{H2O} - \Delta\varepsilon_{overlap}$$

- The (total) emissivity calculations, including pressure and overlap functions are derived from empirical relations derived from spectral data

Which changes in flame radiation can we expect when adding H_2
Changes in flame radiation assume same flame geometry (Leckner approach)



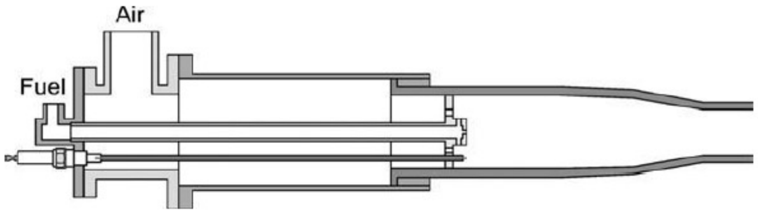




<u>Calculations show that:</u>

- The flame temperature increases with increasing hydrogen content
- The water fraction increases and CO_2 fraction in flue gas decreases with increasing hydrogen content
- As a result the estimated net radiation flux from the flame increases with increasing hydrogen content with about 25%

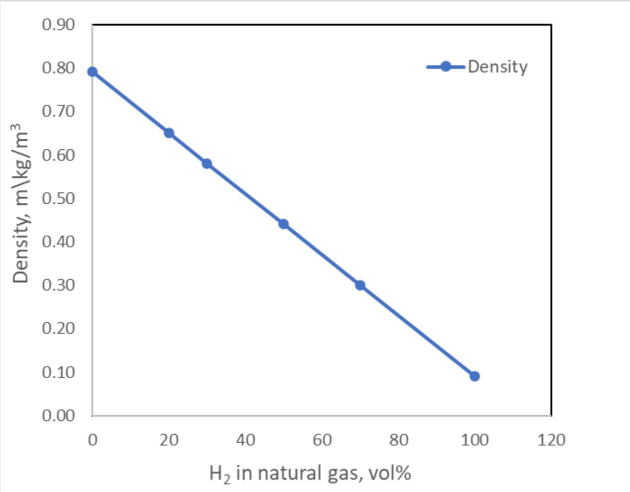
Effects hydrogen addition to methane on the thermal heat input of burners that do not use a fuel adaptive control system

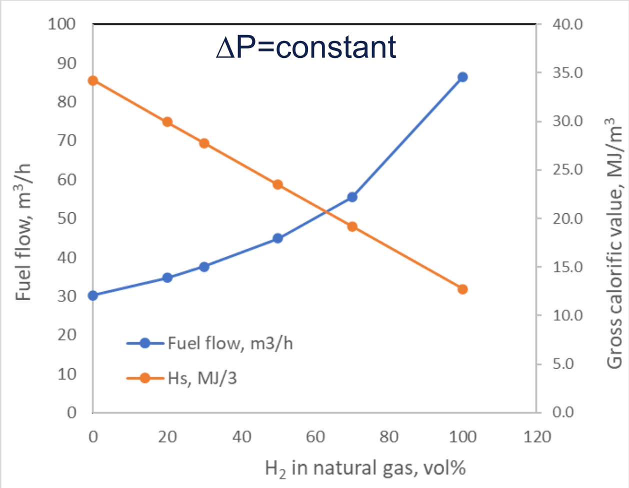


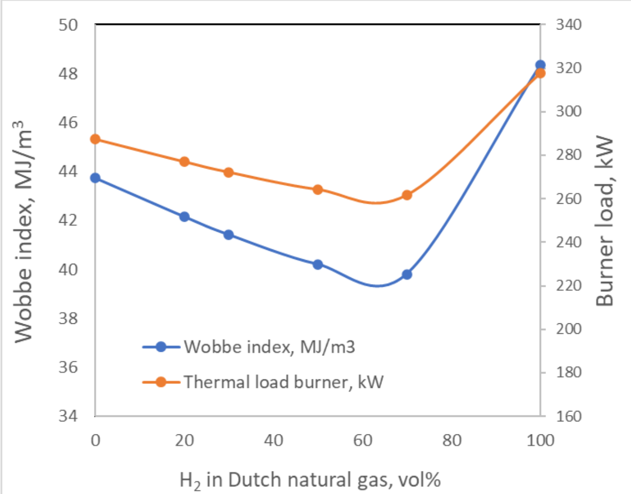
$$Q_v \approx \sqrt{\frac{2\Delta P}{\rho_{fuel}}}$$

$$Thermal\,burner\,load \approx Q_v H_s$$

Addition of H_2 to DNG results in a variation in the thermal load





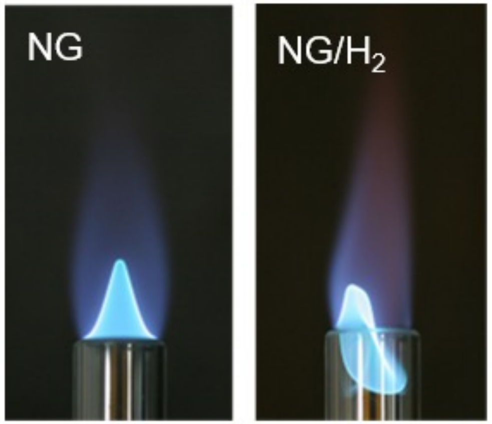


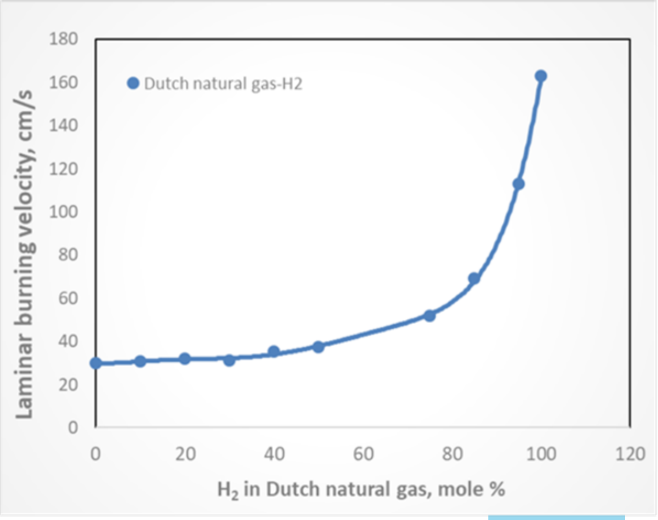
Effects hydrogen addition to methane on the burning velocity

- Hydrogen addition results in an increase in the burning velocity

- Increase in burning velocity can result in:
    - Overheating burner surface
    - Result in flame flash-back

- Important for partially and premix burner systems (domestic and industrial burners)





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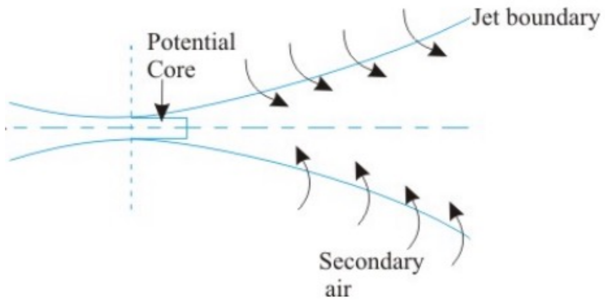
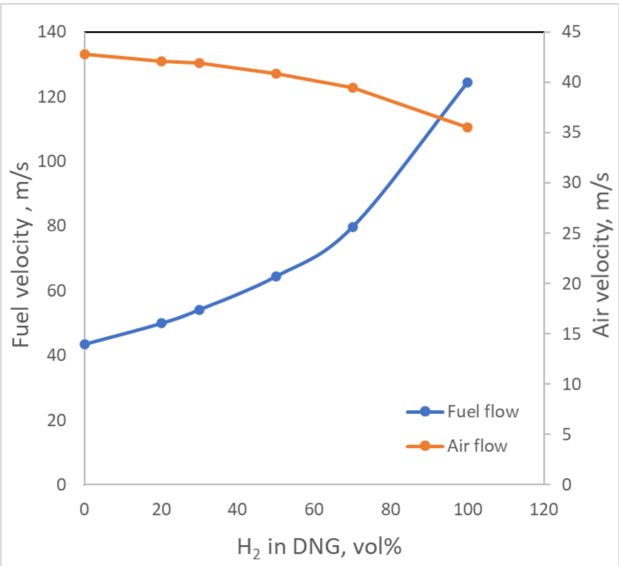
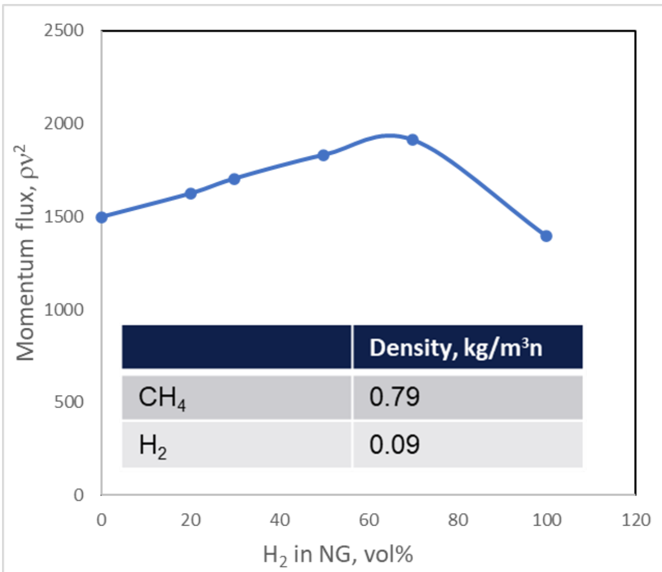
What changes to expect in the fuel and air velocity leaving the nozzles (non-premixed burners)



- Jet spreads due to difference in density jet (ρ_{jet}) and surroundings (ρ_{∞})
- The jet carries with its momentum flux. The momentum flux within the jet is

$$Momentum\ flux = density \times (velocity\ of\ the\ Jet)^2$$





	Density, kg/m³n
CH_4	0.79
H_2	0.09

- Large changes in velocity fuel jet upon H_2 addition
- Decrease in density (and air requirement) suggesting larger jet angle upon H_2 addition (hot zone closer to burner)?
- No major changes in momentum flux suggesting that flame length may not change substantially?

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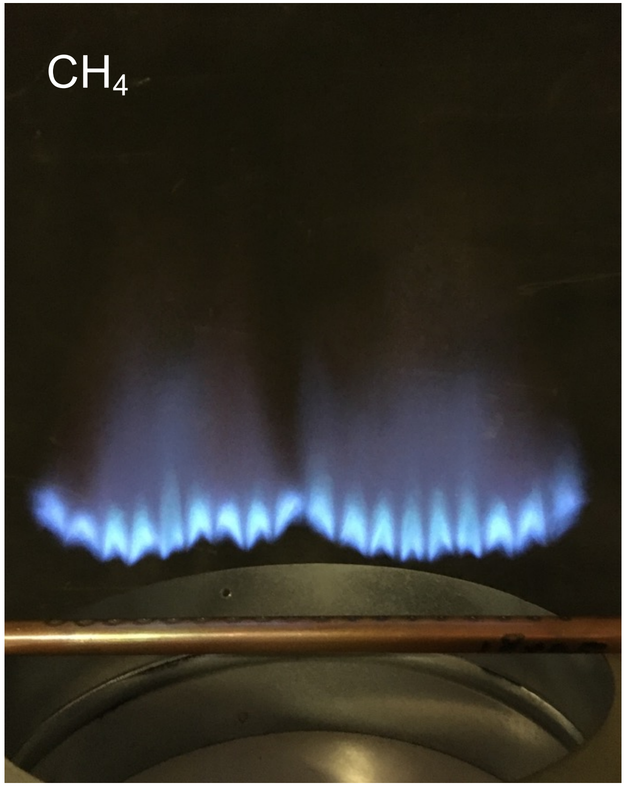
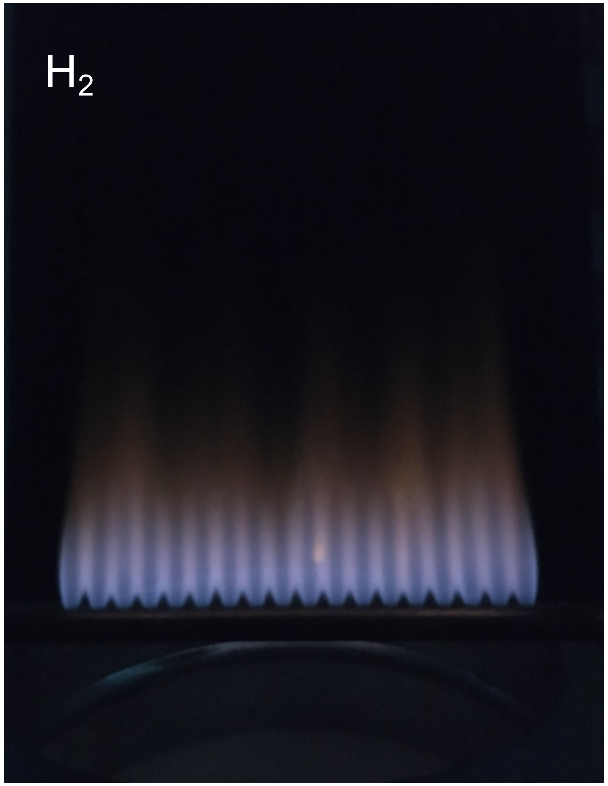
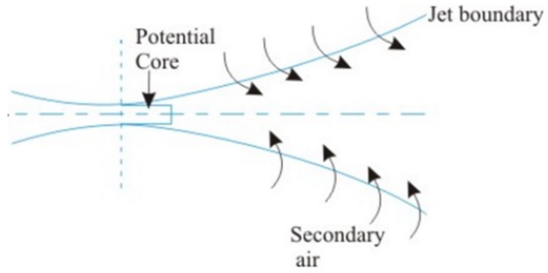
Flame zone shift closer to burner surface when switching from NG to H_2







Challenges when applying hydrogen for (industrial) burners

- Addition of hydrogen may affects burner performance for example;
  - NO_x emission
  - Changes in heat transfer (convection/radiation)
  - Can result in overheating & flash-back (premix burners)

- **Important:** burner performance changes upon hydrogen addition strongly depends upon the type of burner installed.

Ceramic industry
e.g. pipe-in-pipe burners and high speed burners

Steel industry
e.g. high speed burners, swirl burners, FLOX burners etc.

Glass industry
e.g. pipe-in-pe burners, flat flame burners, pencil burners, oxy-fuel burners etc

Food/paper etc.
e.g. Forced draught burners

Direct heating: Product quality?

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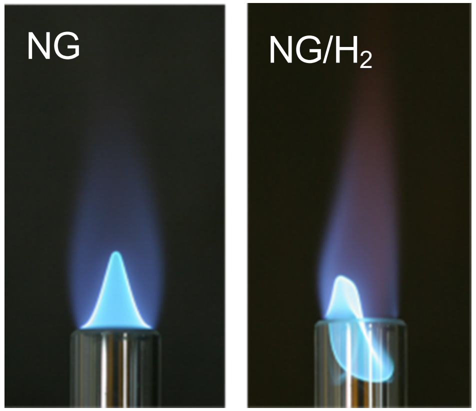
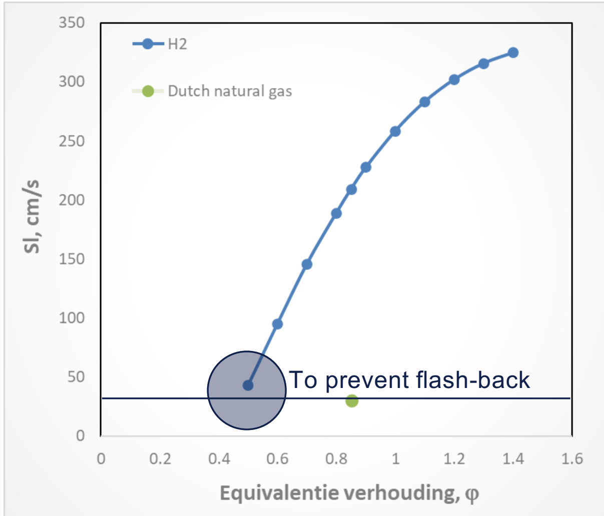
Fully premix (fuel lean) burners (domestic and industry): Flash-back





- Decreasing the equivalence ratio results in a decrease in the laminar burning velocity
- **Solution to prevent flash back**: Based only laminar burning velocity calculations lowering from φ=0.85 to φ=0.45 should prevent flash-back for H_2/air mixture
- Experiments performed in the lab show that we should go **to φ=0.3** to prevent flash-back for fully premix burners (H_2 fully premix domestic boiler at DNV)

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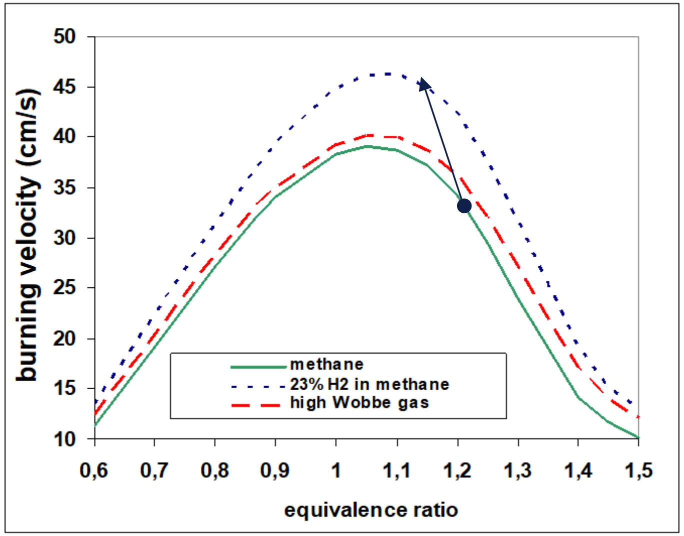
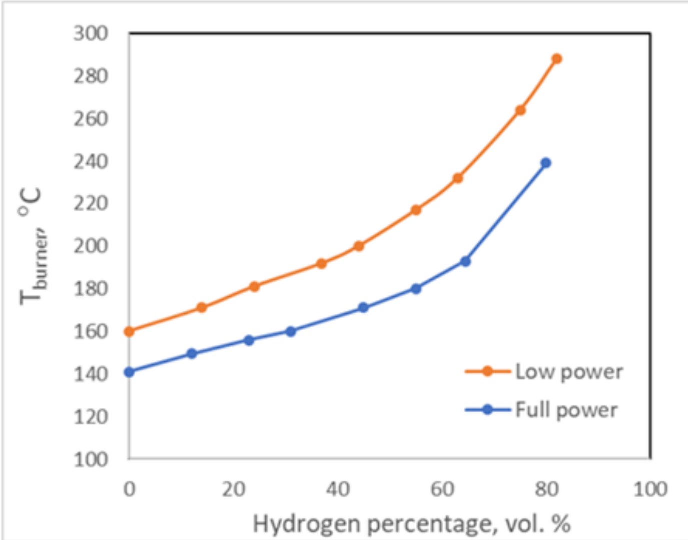
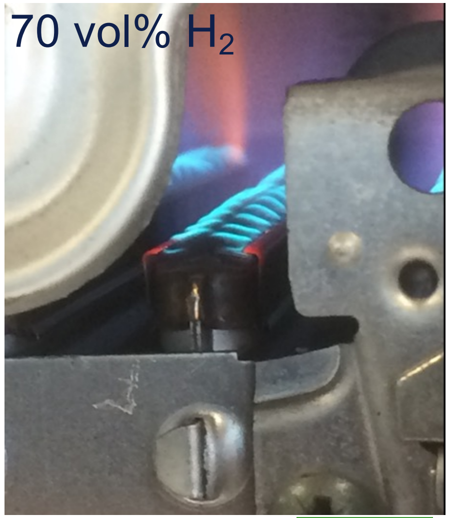
Partially (fuel rich premixed) burners (domestic and industry): burner head overheating







- For partially premix burners H_2 addition results in an increase in burning velocity resulting in:
  - Increase in flame stabilization on the burner causing high burner deck temperatures
  - At about 80 vol% H_2 flash-back occurs for this appliance
  - **Solution to prevent flash-back**: burner replacement?

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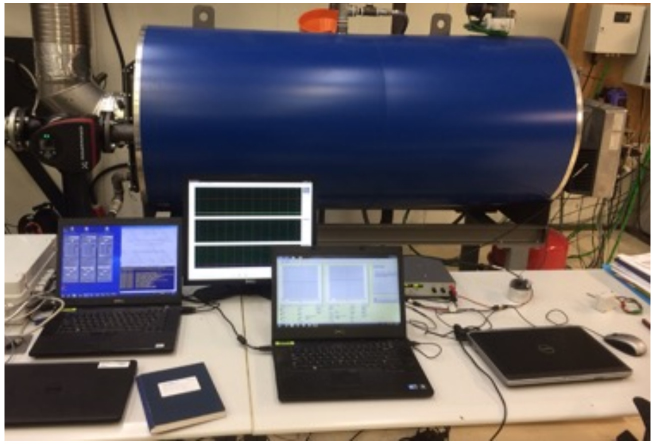
Practical examples hydrogen blending non premix burners

Example: Development of a Natural Gas/Hydrogen Boiler System for low temperature processes (SBIR project)

Goal: Development of a fuel flexible burner system for hydrogen/natural gas mixtures (0-100% H_2)

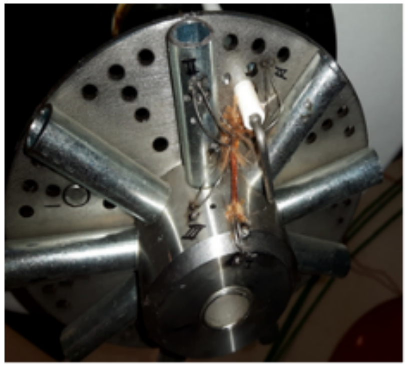
Experimental set-up contains:

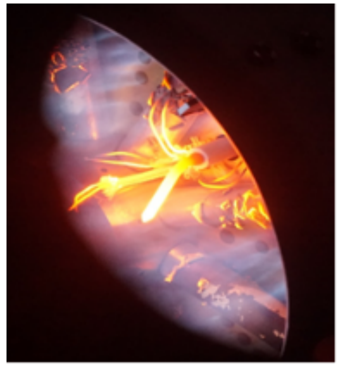
- 475 kW Novum boiler system
- Zantingh/Unigas LowNOx-forced draft burner
- Lamtec Etamatic burner management system
- UV sensor as flame guarding system
- Real time hydrogen sensor
- Natural gas sensor
- Fuel adaptive control system



475 kW boiler system

Forced draft burner



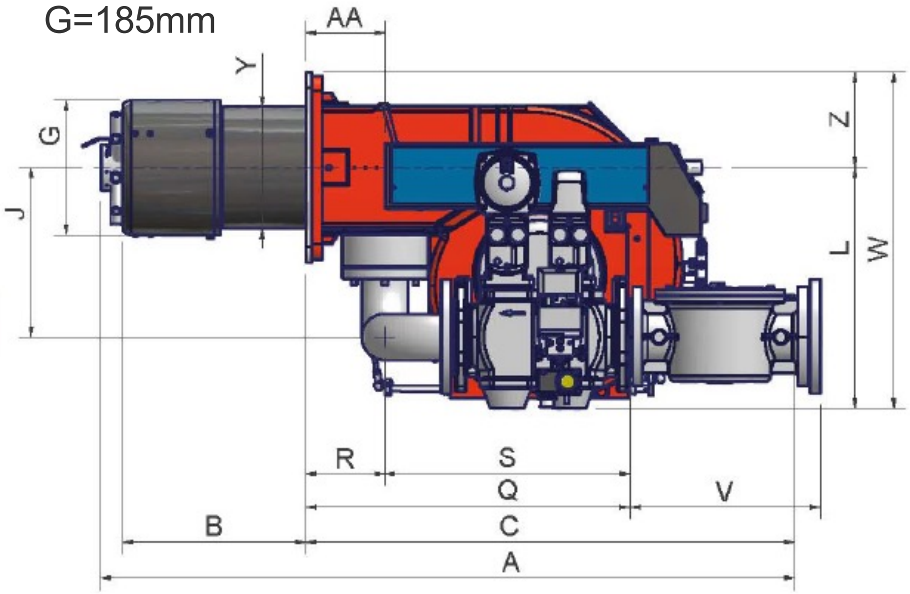


Left: 475 kW burner deck with thermocouples to monitor the temperature. Right: flame image burner

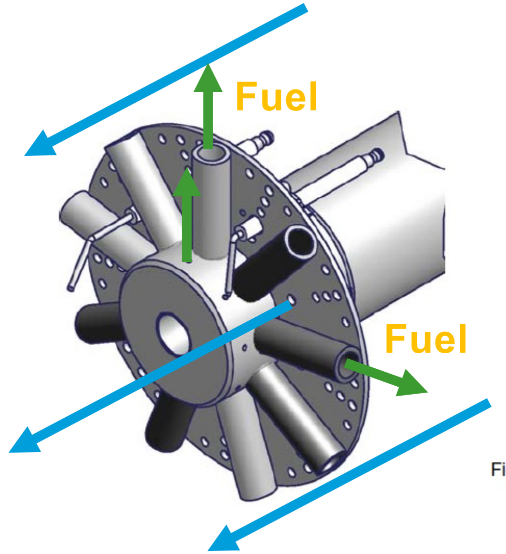
Burner details

- Burner type: Unigas LX 60 M PR S NL A 1.DN50.EA

G=185mm



Combustion air

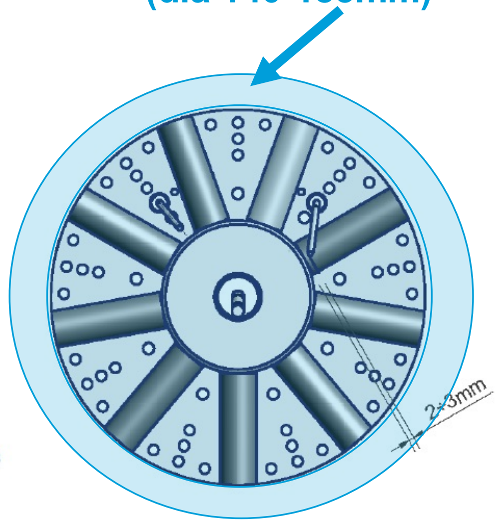


Combustion air

Fig. 33

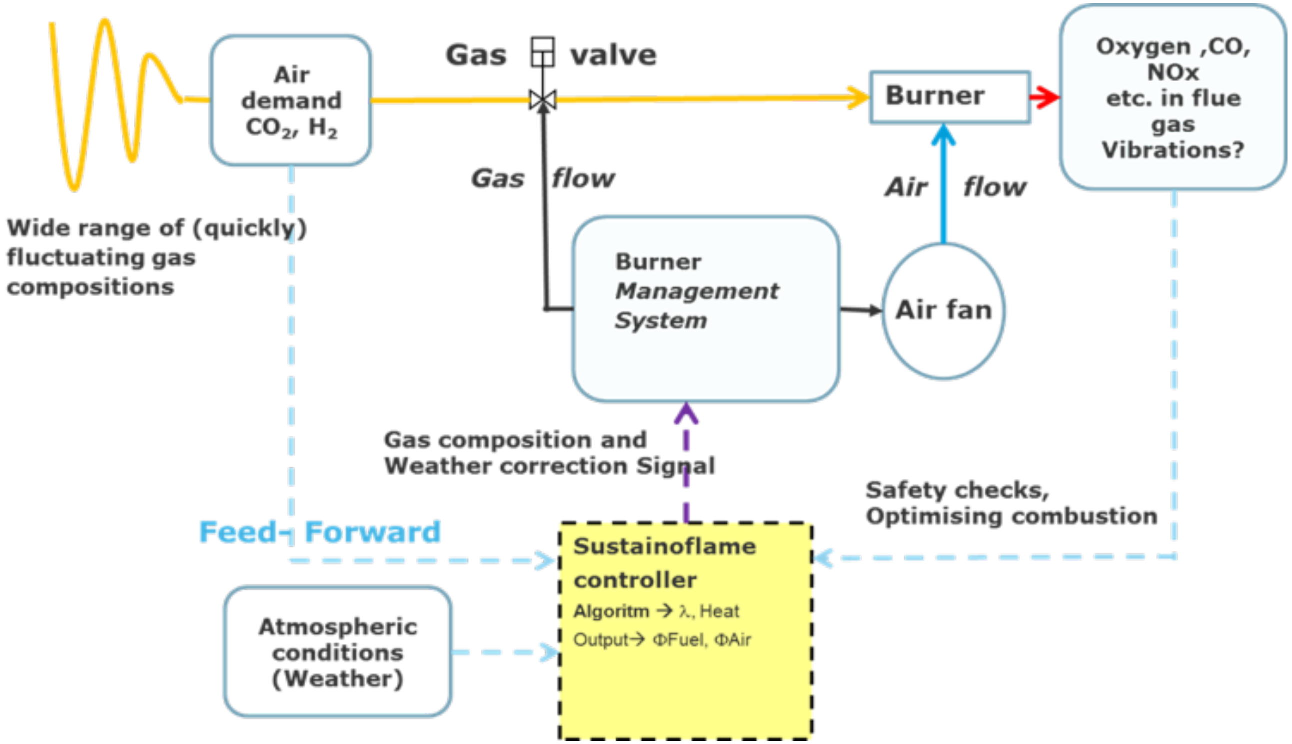
Air annulus

(dia 140-185mm)



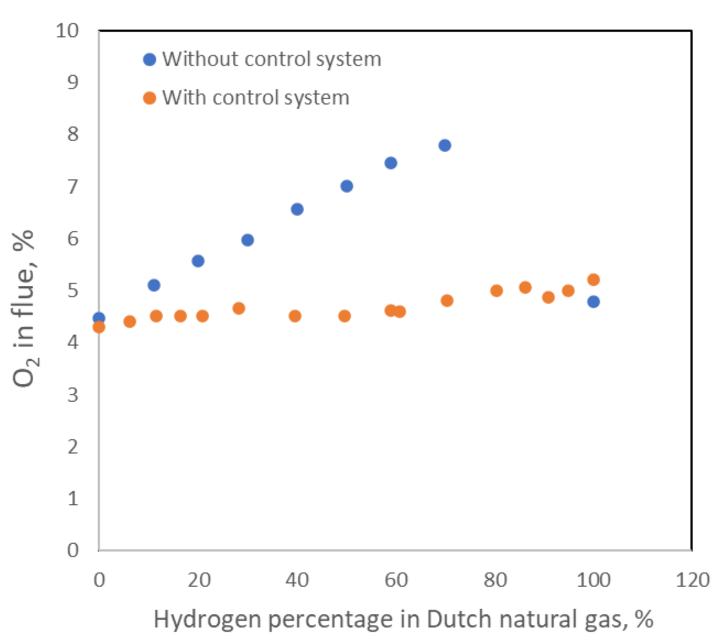
	v, ms	Momentum flux, kg/m.s2	Re
Dutch natural gas	11.9	112	8563
Hydrogen	34.0	104	3432

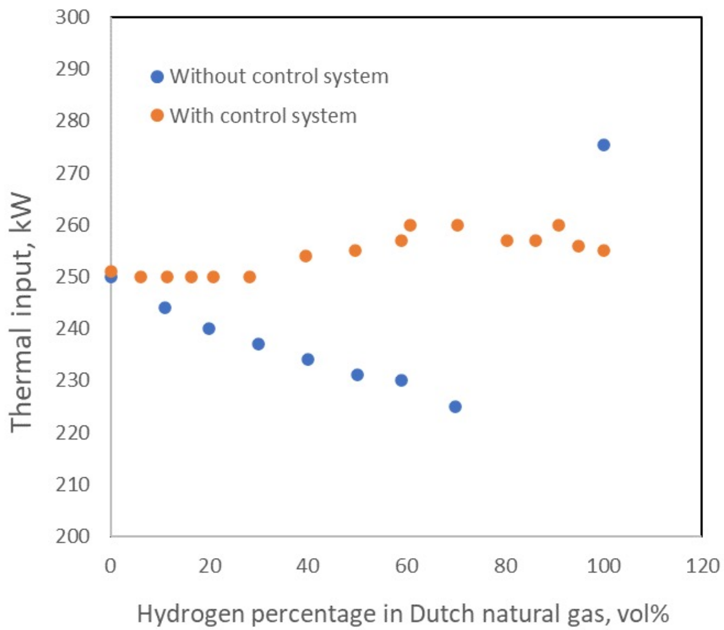
Fuel adaptive burner control system: sustainable gases and high efficiency



- **Novel Algorithms and gas analysers**
  - Combustion control algorithms based on fuel gas composition and operational conditions of installation
  - Taken into account external factors (e.g. humidity, temperature, etc)
- **Optimal equipment performance:**
  - Fuel adaptive control for a wide range of fuel compositions
  - Safe and reliable operation within a wide range of gas compositions
  - Fuel savings
  - Acceptable emission levels

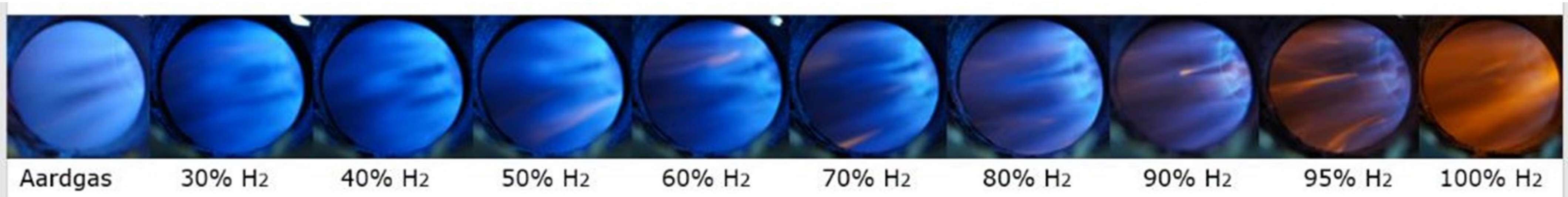
General results of industrial forced draft burner (1)



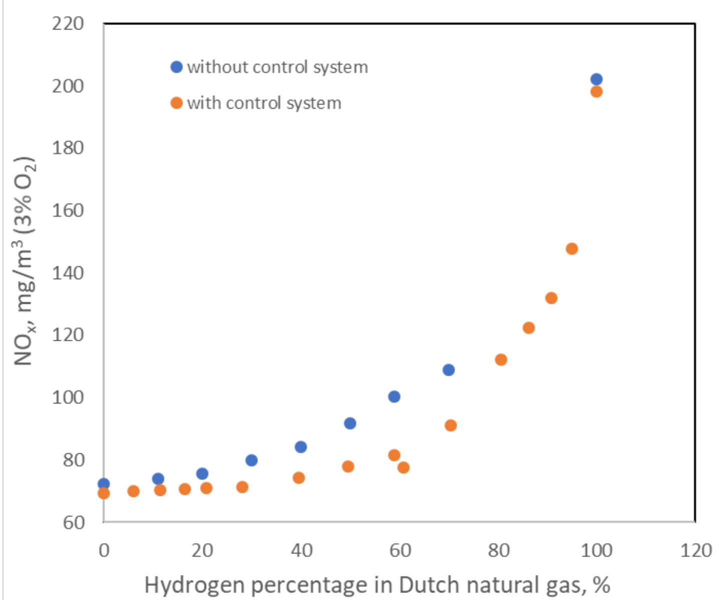


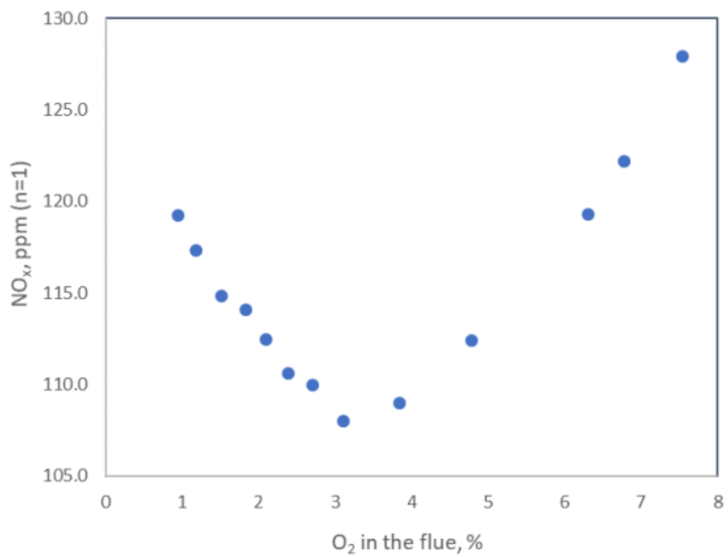
Effects H_2 addition 0-100%

- Stable combustion over the entire range observed
- **No large changes** in flame length and width
- No overheating burner observed
- Fuel adaptive control needed to keep air factor and burner power constant



General results of industrial forced draft burner (2)





- Hydrogen addition to NG results in an increase in the NO_x emission
- Changing air factor **is not** an effective NO_x mitigating strategy

NO_x emission should be decreased by applying NO_x other mitigating strategies

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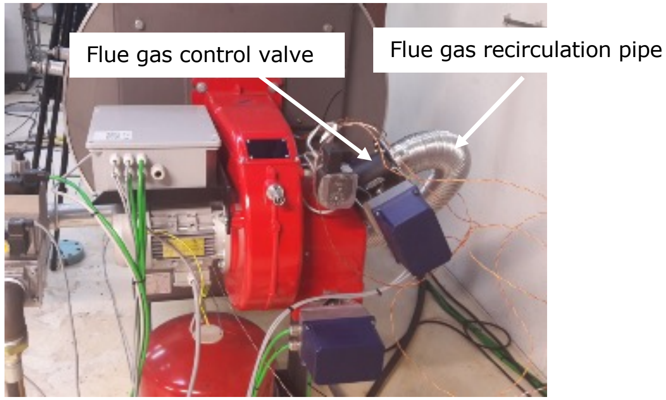
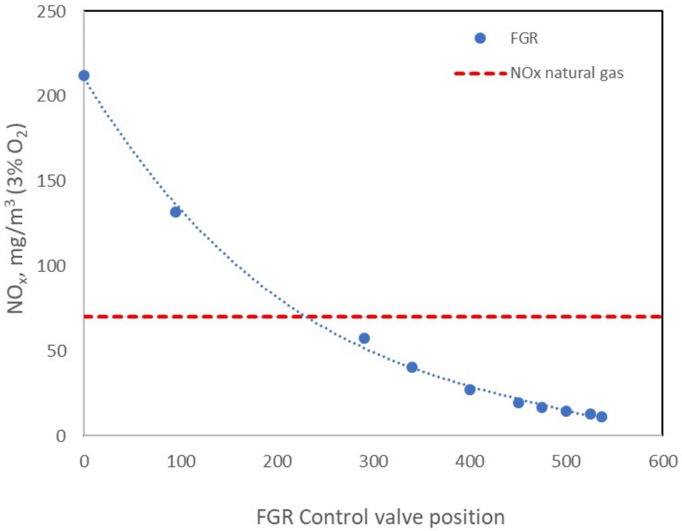
Applying Flue Gas Recirculation (FGR) as NO_X mitigating strategy (SBIR project)

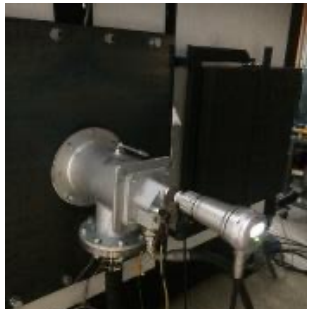
- A part of the flue gases is returned to the combustion air inlet.
- The dilution of combustion air with (inert) flue gases reduces the adiabatic flame temperature and consequently reduces the (thermal) NO_x formation.
- The preliminary results show that applying flue gas recirculation results in a reduction of the NO_x emission with more than a factor of 10.
- From this we conclude that flue gas recirculation is a very effective strategy to reduce the NO_x emission for hydrogen flames.

- **Conclusion:** The burner system developed enables the flexible introduction of hydrogen as a fuel in the natural gas grid in the energy transition period and afterwards, when natural gas is fully replaced by hydrogen





Experimental set-up for studying **high temperature** processes DNV Groningen (NL)



Burner & Flame scanner

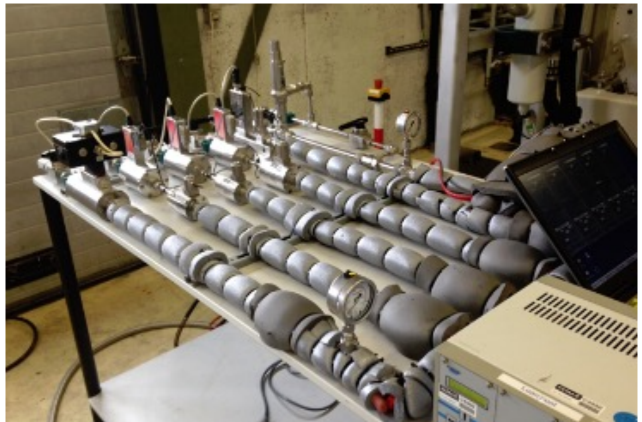
Celsian sensor (O_2, CO H_2O & T)

Flue gas analysers

500 kW air heater (up to 600 °C)

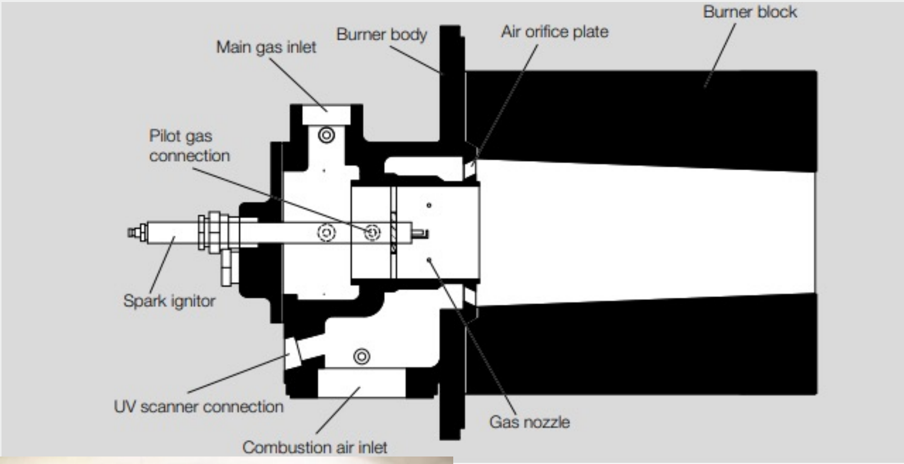
500 kw Furnace + cooling floor

Cooling infrastructure



Gas blending unit

Tests on a incinerator burner (SBIR project)



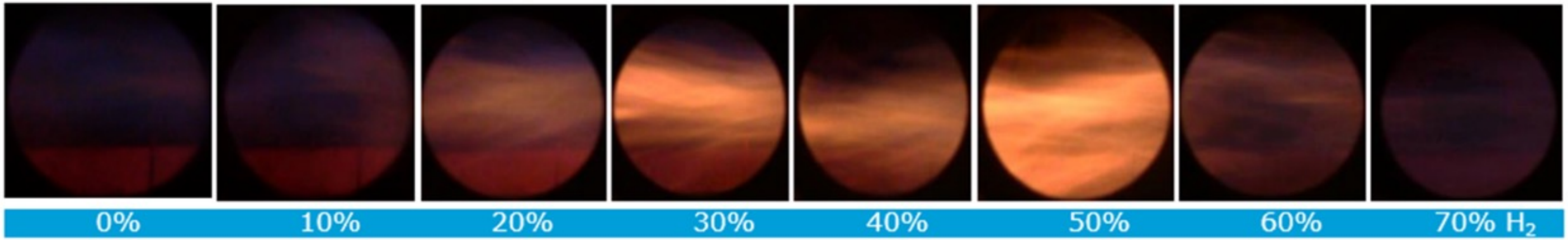
- Swirl burner
- Test at 100-200 kW
- What is the effect of hydrogen addition to natural gas on the combustion performance
  - NO_x behavior
  - Flame structure

Example combustion behaviour when adding hydrogen to swirl burners

Natural gas combustion
(F. Cozzi et al)

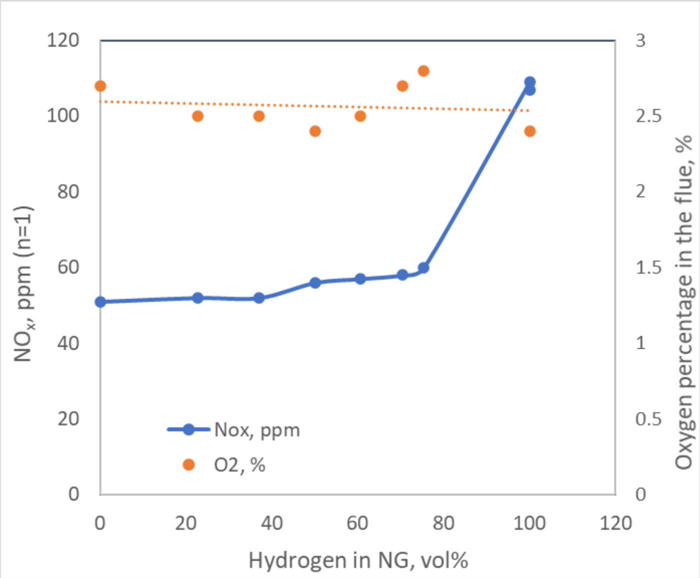
Natural gas combustion + 50% H2
(F. Cozzi et al)

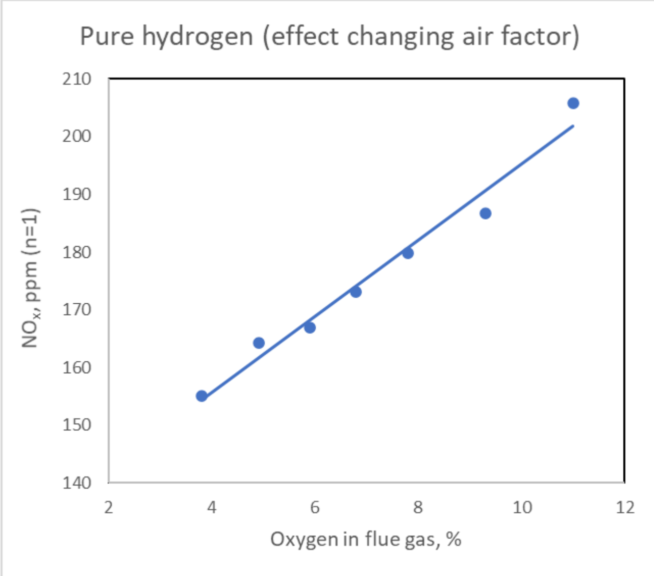
- Top: Increased soot (and radiation heat flux) formation is measured in diffusive swirl stabilized burners when 50% hydrogen is addend to natural gas
- Bottom: Increased soot (and radiation heat flux) in industrial swirl burners when between 20-50% hydrogen is present in natural gas

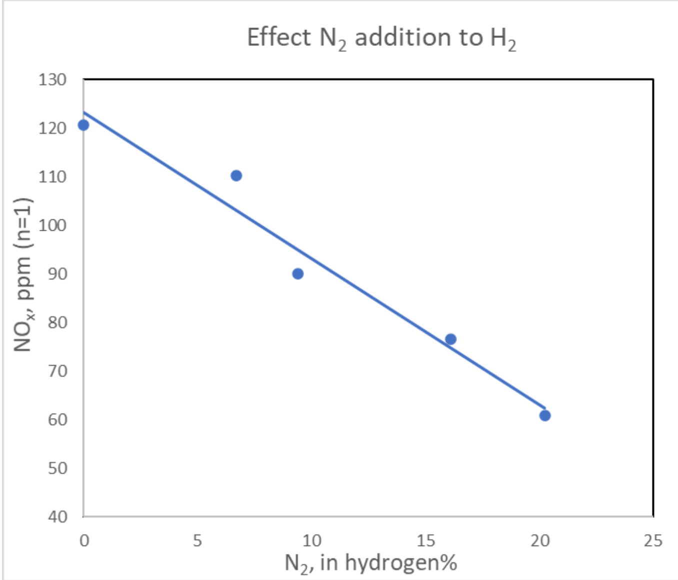


Measurements performed at DNV in a 500 kW furnace using an industrial swirl burner

NO_x emission measured (incinerator burner; SBIR project)



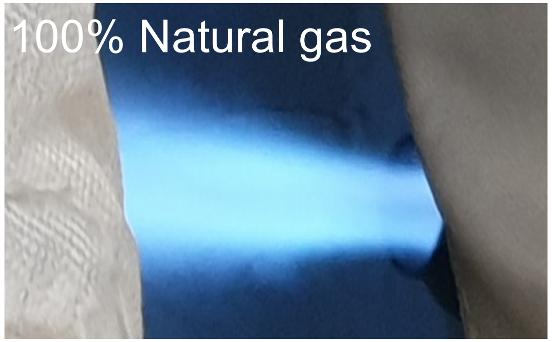


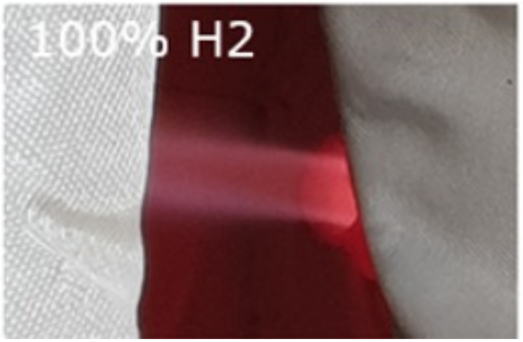


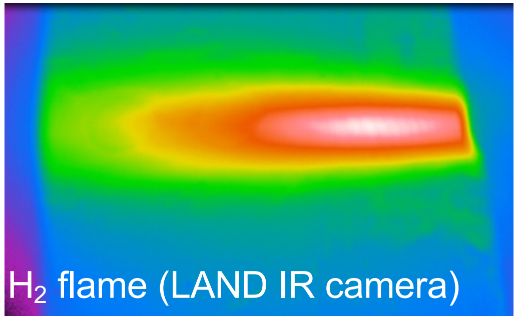
- Large increase in NO_x formation >70 vol% hydrogen
- Increasing air factor increases NO_x formation (NO_x is formed near stoichiometric conditions in the flame zone)
- Diluting hydrogen with nitrogen reduces NO_x emission substantially
- **Outlook:** development of internal flue gas recirculation for high temperature H_2 burners

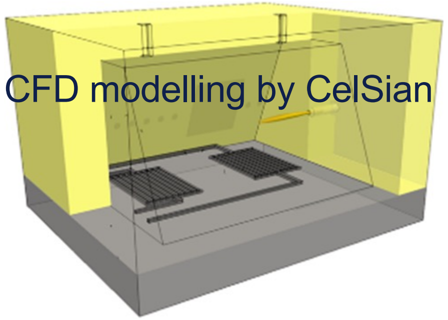
Other project examples

Joint industry project ‘hydrogen as a fuel for heating processes’ (40 partners):









Topics currently studied:

- 5 different nozzle mix burners types including oxy-fuel combustion for high temperature processes
- Development H_2/O_2 combustion concept for steam boilers (Stork Thermeq)
- Change in flame stability and **flame length**
- NO_x emission measurements and detection techniques
- Heat transfer differences (cooling floors and radiation flux sensors)
- **NO_x Mitigating measures**: applying gas adaptive control and flue gas recirculation
- Flame detection: UV flame detection and testing prototypes IR cameras to visualize H_2 flames
- CFD analyses

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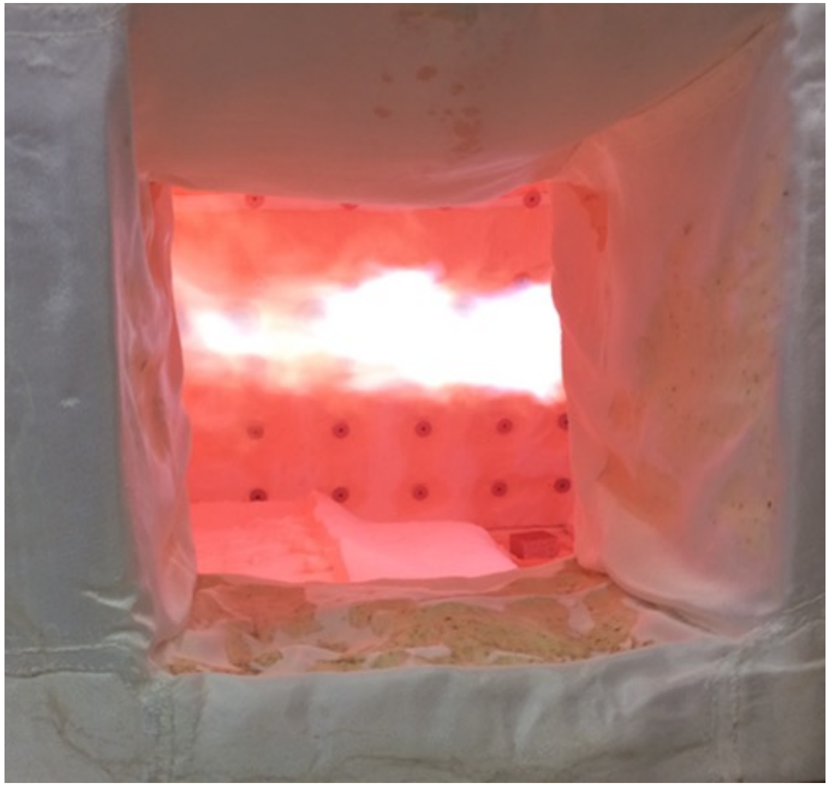
Oxyfuel combustion (H_2/O_2)

- DNV performed H_2/O_2 tests using two prototype burners from FlammaTec and Linde (Glass futures projects)
- Currently experiments with an Air Liquide burner are ongoing in the JIP Project ‘hydrogen as fuel for heating processes’
- Stable combustion observed during all experiments
- No overheating of the burner was observed

- **Advantages oxy-fuel combustion**:
- High efficiency
- Low flue gas flows and high concentrations of impurities which makes aftertreatment and CO2 capture more efficient
- Low NOx emission

- **Challenges for retrofit** air to oxyfuel combustion:
  - combustion characteristics: i.e., low flue gas flows, high flame temperatures can affect refractory lifetime and product quality

- Next step: Start pilot projects and studying product quality and refractory lifetime



Burner control strategy developed within the project is in large scale demo project

2 MW furnace to heat oil will be fuelled using NG/H_2 (0-100% H_2): planning mid-2021

Hydrogen pilot

Next Phase - to be started in cooperation with the industry

“Preparing for future use of hydrogen in the industry”

1. Further optimizing and development of high performance hydrogen burners for the industry
   - Optimization heat transfer
   - Reducing NO_x emission
   - Development of safety protocols for the industry

2. Studying impact switching from natural gas to hydrogen combustion on **product quality** and **refractory material** for specific industries:
   - Ceramic
   - Glass
   - Steel industry
   - …

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Thanks you for your attention

Questions?

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Effect of hydrogen addition on calculated laminar burning velocity of 1-D premixed flame

- To get some insights in the effect of H_2 addition to NG we performed numerical 1-D simulations of a premixed flame (CHEMKIN package, premix code, GRI 3.0 mechanism) at an air factor of λ=1.2 (similar to the overall air factor used in the burner experiments)

- Numerical burning velocity calculations (Fig. right) show an increase in the burning velocity with increasing hydrogen fractions in natural gas.
  - At H_2>60% an exponential increase in the burning velocity is calculated
  - This increase might potentially result in an increase in the burner surface temperature and therefor thermocouples have been installed on the burner surface to monitor the temperature?

- Here we note that the burner used in this study is a nozzle mix burner in which fuel and air are not premixed, but mix downstream the burner surface (at approximately an overall air factor of λ=1.2). Therefore the simplified calculations can deviate from the experimental results and only give qualitative insights

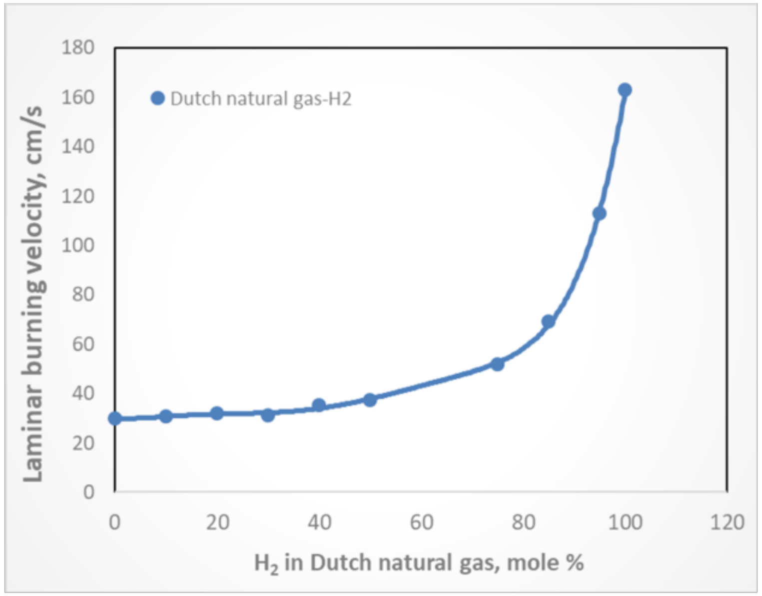


Figure: Calculated laminar burning velocity for H2/Dutch natural gas mixtures at λ=1.2 (φ=0.85), calculations in Premix using USC mech II

Effect of hydrogen addition the Wobbe index

- The **Wobbe index** is an important gas interchangeability parameter for **burners** and is a measure for the thermal load and the air demand for hydrocarbon fuel gases

$$W = \frac{Hs}{\sqrt{\rho_{rel.}}}$$

- Figure 1 shows that the Wobbe index decrease with increasing hydrogen content up to **~60% H_2** in NG, as a result:
  - the thermal load will decrease
  - the oxygen percentage in the flue will increase (reduction in efficiency)

- Figure 1 shows that the Wobbe index increases with increasing hydrogen percentages between **60-100% H_2**, as a result:
  - the thermal load will increase
  - the oxygen percentage in the flue will decrease

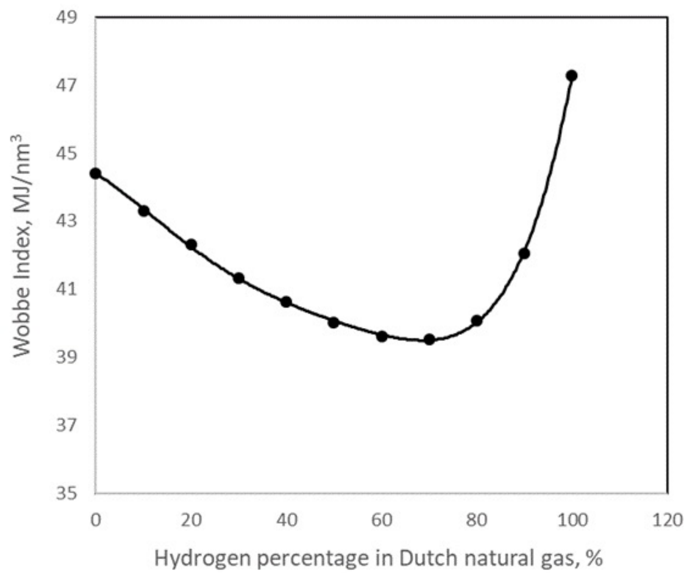
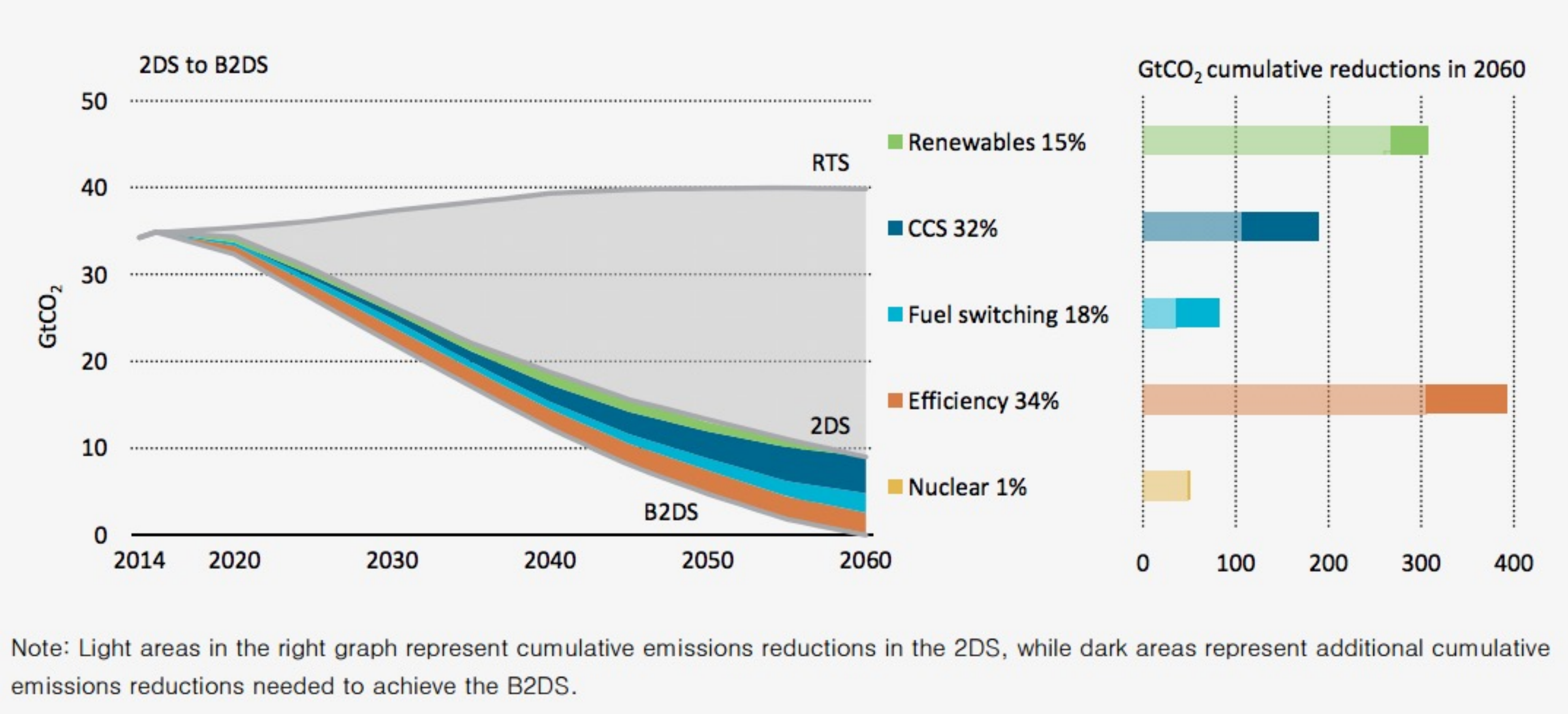


Figure 1. Effect hydrogen addition Wobbe index

The need to reduce CO_2 emissions and enhance sustainability of energy supply are major drivers towards the introduction of renewables



Bron: https://www.carbonbrief.org/iea-world-can-reach-net-zero-emissions-by-2060-meet-paris-climate-goals

source:https://www.iea.org/etp/explore/

Challenges when using hydrogen in the industry (2) - Combustion properties

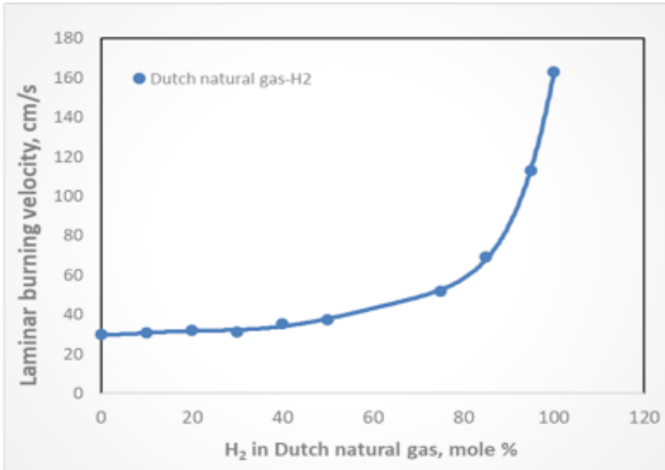
Combustion properties of hydrogen differ substantially from natural gas:

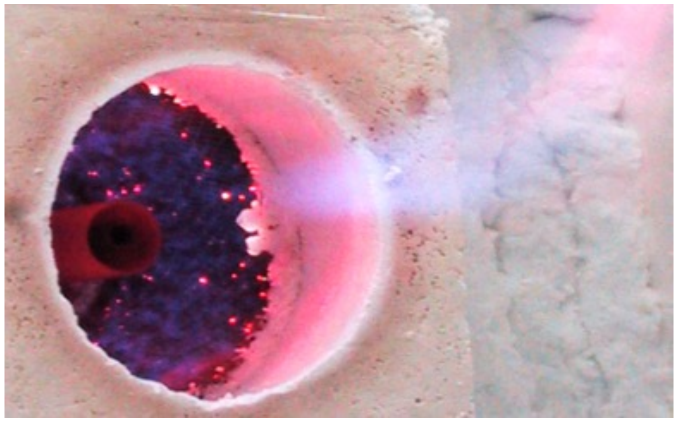
1. Higher flame temperatures
2. Burning velocity of hydrogen is about 6 times higher than natural gas
3. Calorific value of hydrogen is three times lower than natural gas
4. Factor of four difference in the air requirement between hydrogen and natural gas

$H_2 + ½O_2 => H_2O$ 11 MJ/m_n^3

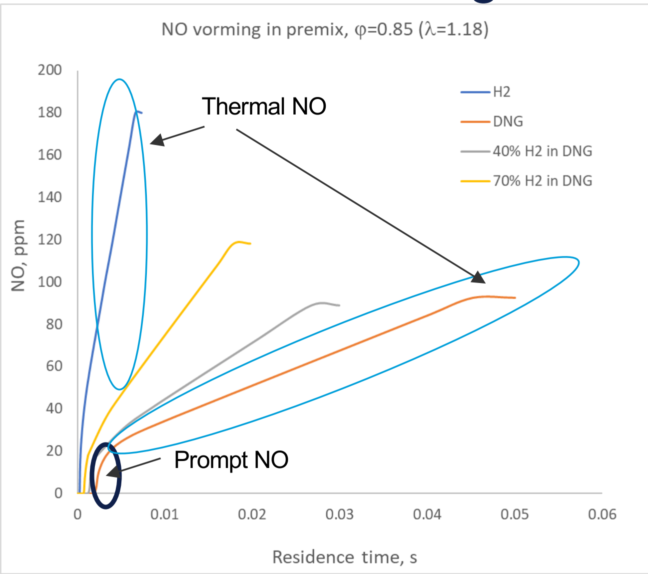
$CH_4 + 2O_2 => CO_2 + 2H_2O$ 36 MJ/m_n^3

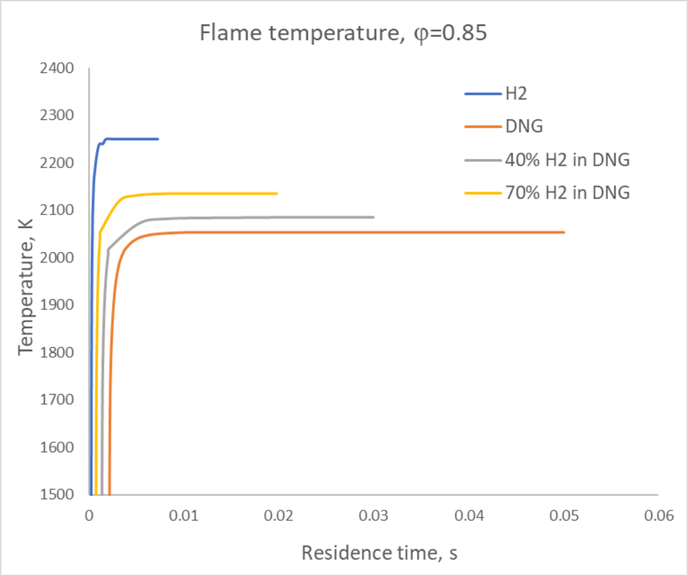
5. Potential increasing NO_x with increasing hydrogen fraction in natural gas
6. Changes in the oven atmosphere (flue gas composition)
7. Changes in the heat transfer (radiation/convection)





Theoretical calculations
1. Numerical premix flame calculations using the GRI 3.0 mechanism

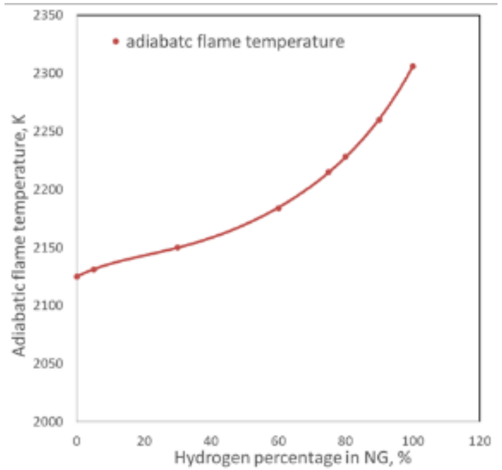




In (turbulent) non premix flames fuel and air are brought together by convection where they mix as a result of diffusion (diffusion flames) and fuel and air mix and burn in the reaction zone of the flame. The flame consist of multiple zones with different equivalence ratio's with short local residence times. Further down stream of the burner the fuel and air will mix resulting in a 'premix flame' with an overall equivalence ratio of about φ=0.8 (λ=1.2). Although it is impossible to do a qualitative analyses of the measurements (diffusion flame) with premix calculations we use the premix calculations to get a better understanding why the NOx formation increases. For the natural/hydrogen flames the NO is formed via the prompt NO mechanism and the thermal NO mechanism. The prompt NO is formed rapidly in fuel rich zones of the flame front via the reaction CH+N2. The thermal NO proceeds via the reaction with nitrogen and oxygen. High temperatures are needed to break the nitrogen bounds and therefore the thermal NO formation will exponentially increase with temperatures and continues with the production of NO after the flame front.

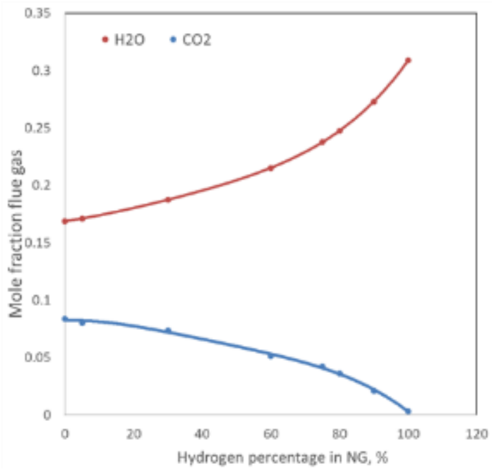
The premix calculations show that for hydrogen flames the thermal NO formation (Zeldovich mechanism) increases much faster than for natural gas flames. The NOx formation of a hydrogen flame is much higher than that of a natural gas flame due to the increase in flame temperature when switching to hydrogen as can be seen in the figure (right). Moreover, the hydrogen flame burns much faster (high burning velocity) and therefore reaches its adiabatic temperature much faster than a natural gas flame. From the Figure in the middle we can estimate that an increase in the residence time of the 'hot spots' in a hydrogen flame will result in a much higher increase of the NOx emission than for a natural gas flame which explains the increase in NOx formation when switching from high to low thermal load.

Challenges when using hydrogen in the industry (3)
Changes in temperature, flue gas composition and flame radiation

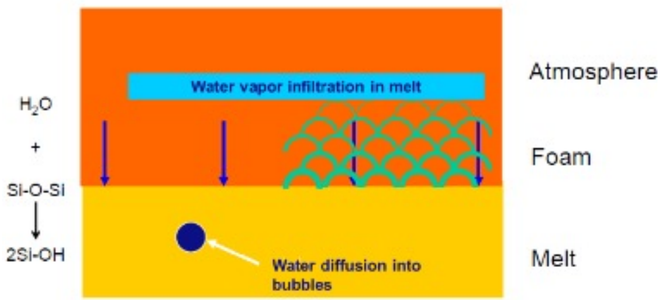


Higher flame temperature increases the 'thermal' NO_x formation via;

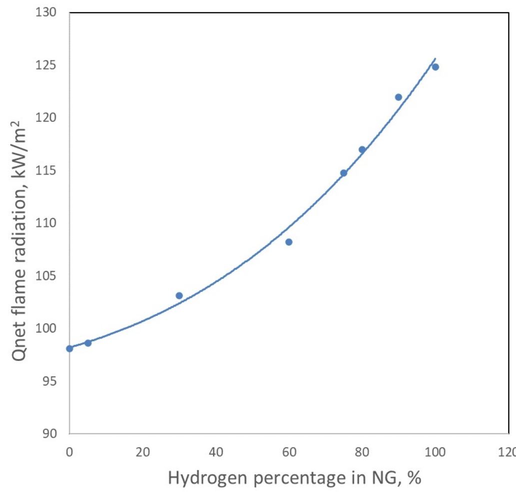
$$N_2 + O \leftrightarrow N + NO$$
$$\mathrm{N} + O_2 \leftrightarrow NO + O$$
$$\mathrm{N} + OH \leftrightarrow NO + H$$



Change in combustion atmosphere can affect production processes and product quality. For example for melting glass;



Source: Celsian



Increase in flame radiation as result of increasing temperature and change in composition impacts heat transfer and product quality

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Costs of hydrogen versus natural gas and electricity

- **Costs 1 MWhr heat:**
  - Natural gas (about 100nm^3) € 20
  - Electricity € 50
  - H_2 from NG (SMR, € 1,65/kg) € 50
  - Green hydrogen >€ 70
    (elektrolysis, >€ 2,25/kg)
  - Hydrogen produced from electricity surplus € 35