Hydrogen as an alternative fuel for Glass Furnaces

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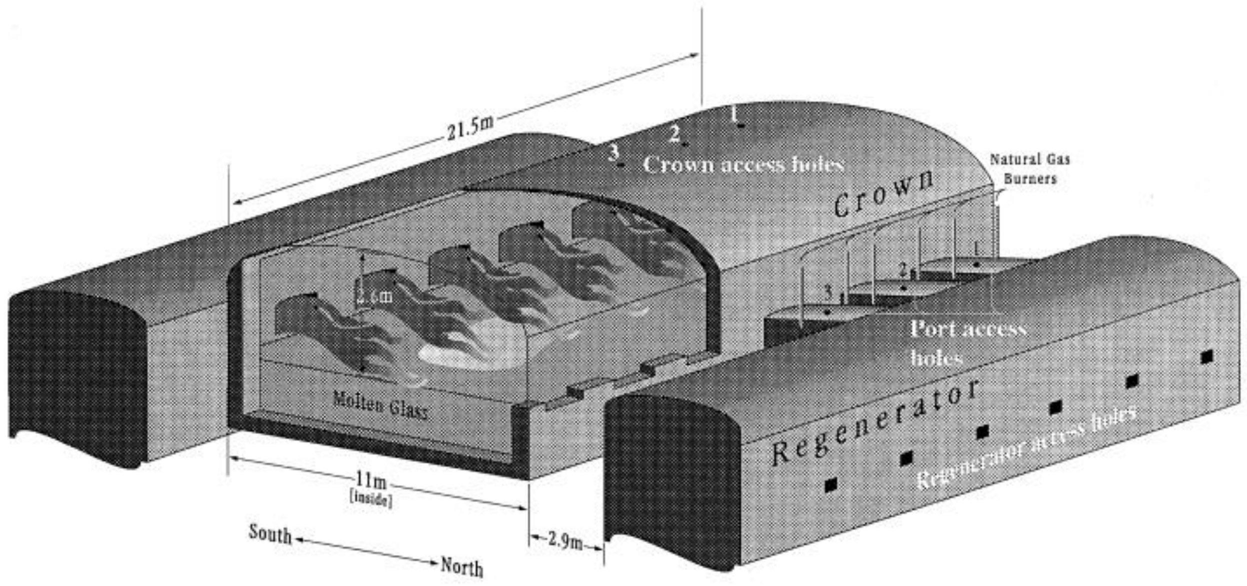
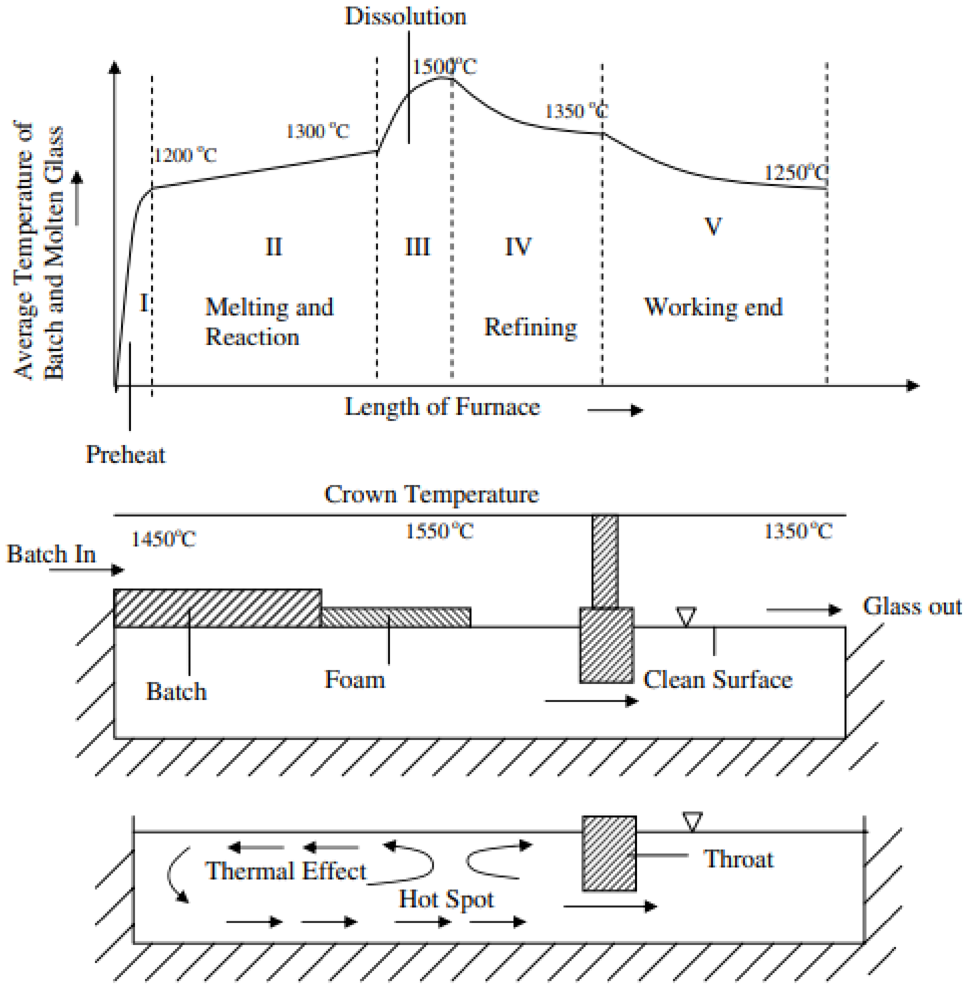
8. Micro-mixing – A possible way to reduce NOx emissions

Introduction



Schematic diagram of a cross-fired glass regenerative furnaces

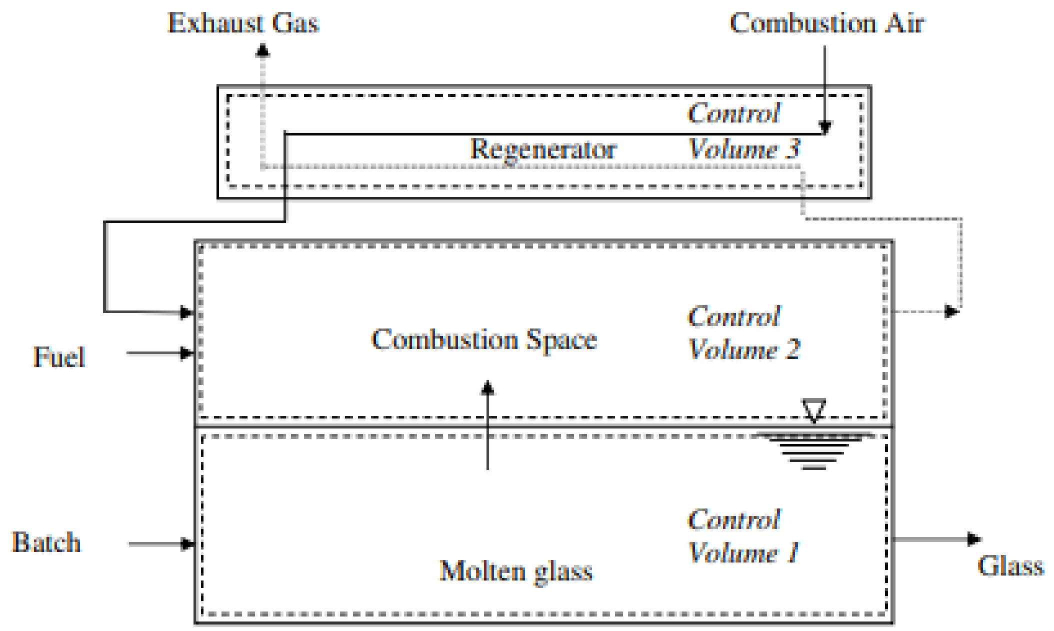
Ref[1]



Glass melting pattern and sequence

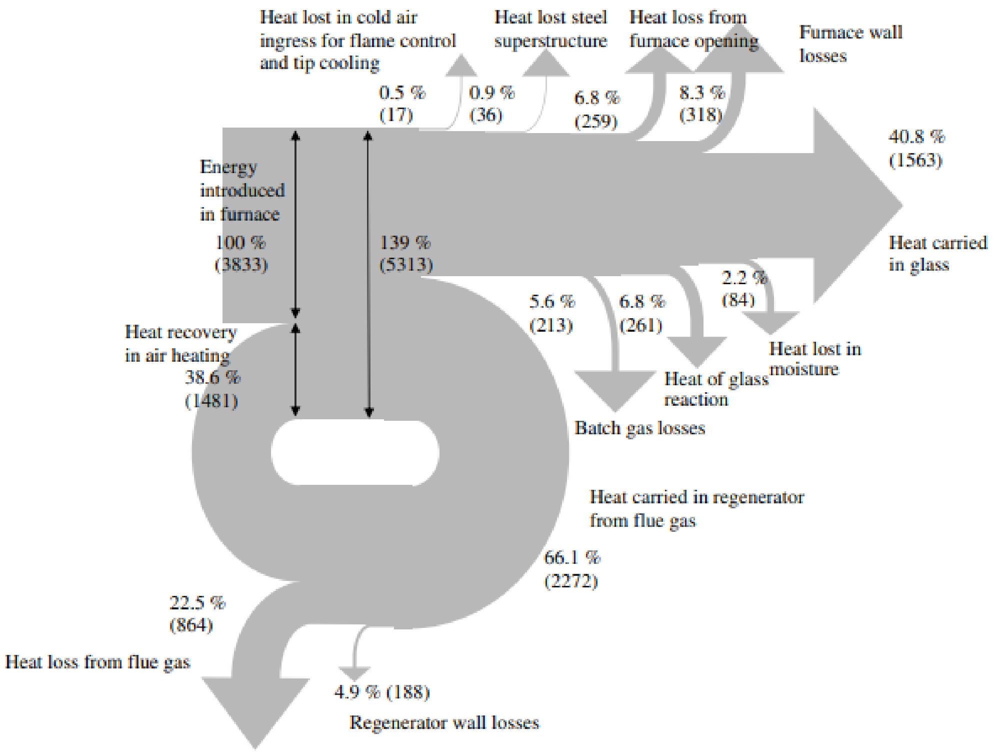
Ref [2]

Energy distribution inside a typical furnace



Various control volumes inside glass furnaces

Ref [2]



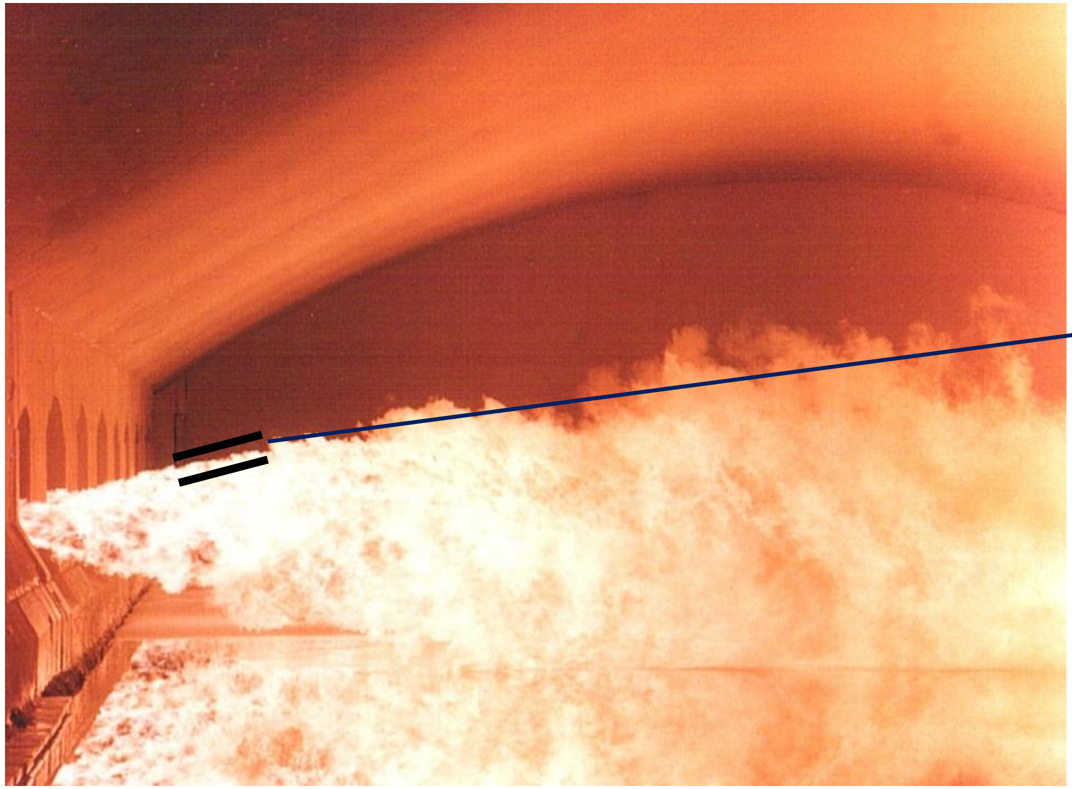
Energy distribution inside a typical glass furnace

Ref [2]

Project Objectives

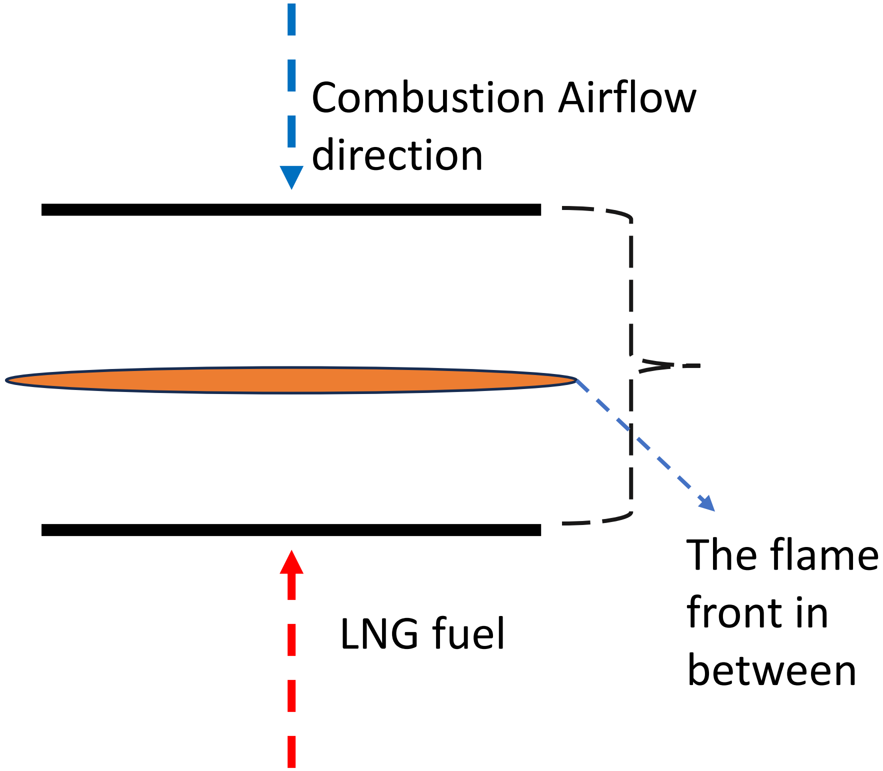
- To explore the potential of Hydrogen as an alternative fuel for glass regenerative furnaces
- Compare the flame temperatures and emissions between the conventional LNG and LNG-H2 blends.
- Perform a sensitivity analysis to reveal the predominant reactions in the reaction kinetics of both fuels.
- Explore the ways to reduce the emissions.

Methodology:



Ref:https://www.sorg.de/services/

Fig: Combustion flame in glass furnace



1D - Counter flow Non-premixed flame

Methodology:

Simulation Parameters:

- Natural gas composition (88 % CH_4, 5 % C_2H_6, 7 % N_2)
- Mass flow fuel - 325 kg/h
- Hydraulic dia fuel nozzle - 4.4 cm
- Mass flow air - 5130 kg/h (6 % extra air)
- Hydraulic dia air inlet - 1.54 m
- Fuel inlet temp - 303 K
- Air inlet temp - 1392 K
- Width of the combustion space – 20 cm

Combustion Model:

- 1-D Counter-flow non-premixed model
- Cantera for combustion modeling
- Gri3.0 mechanism (UC, Berkeley)
  - 325 reactions involving lower hydrocarbons (till C3)
  - Optimized for Natural Gas combustion
  - 53 species involved

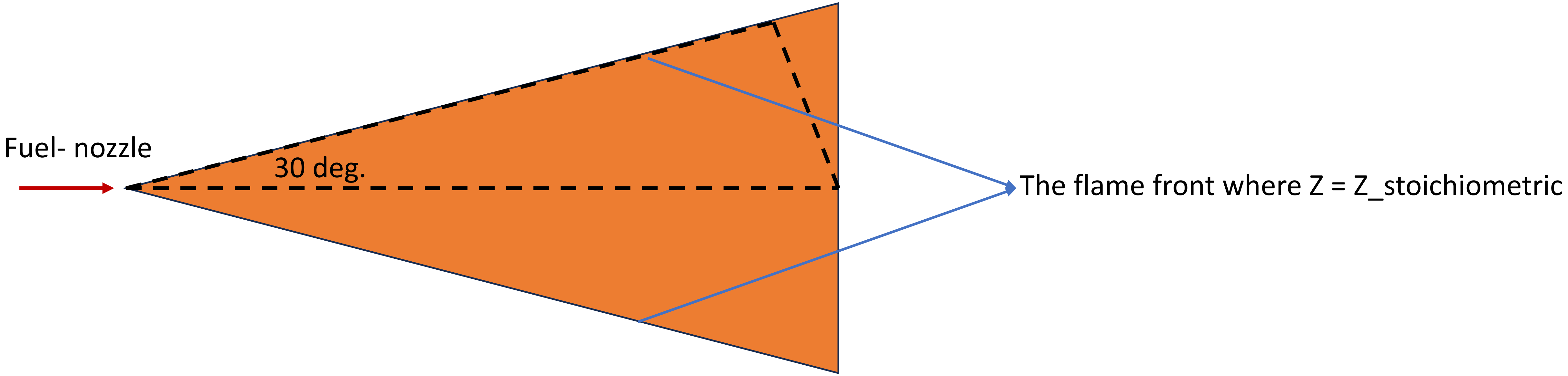
The above simulation data has been taken from: -

“McQuay, M.Q., Webb, B.W. and Huber, A.M., 2000. The effect of rebuild on the combustion performance of an industrial gas-fired flat glass furnace. Combustion science and technology, 150(1-6), pp.77-97”

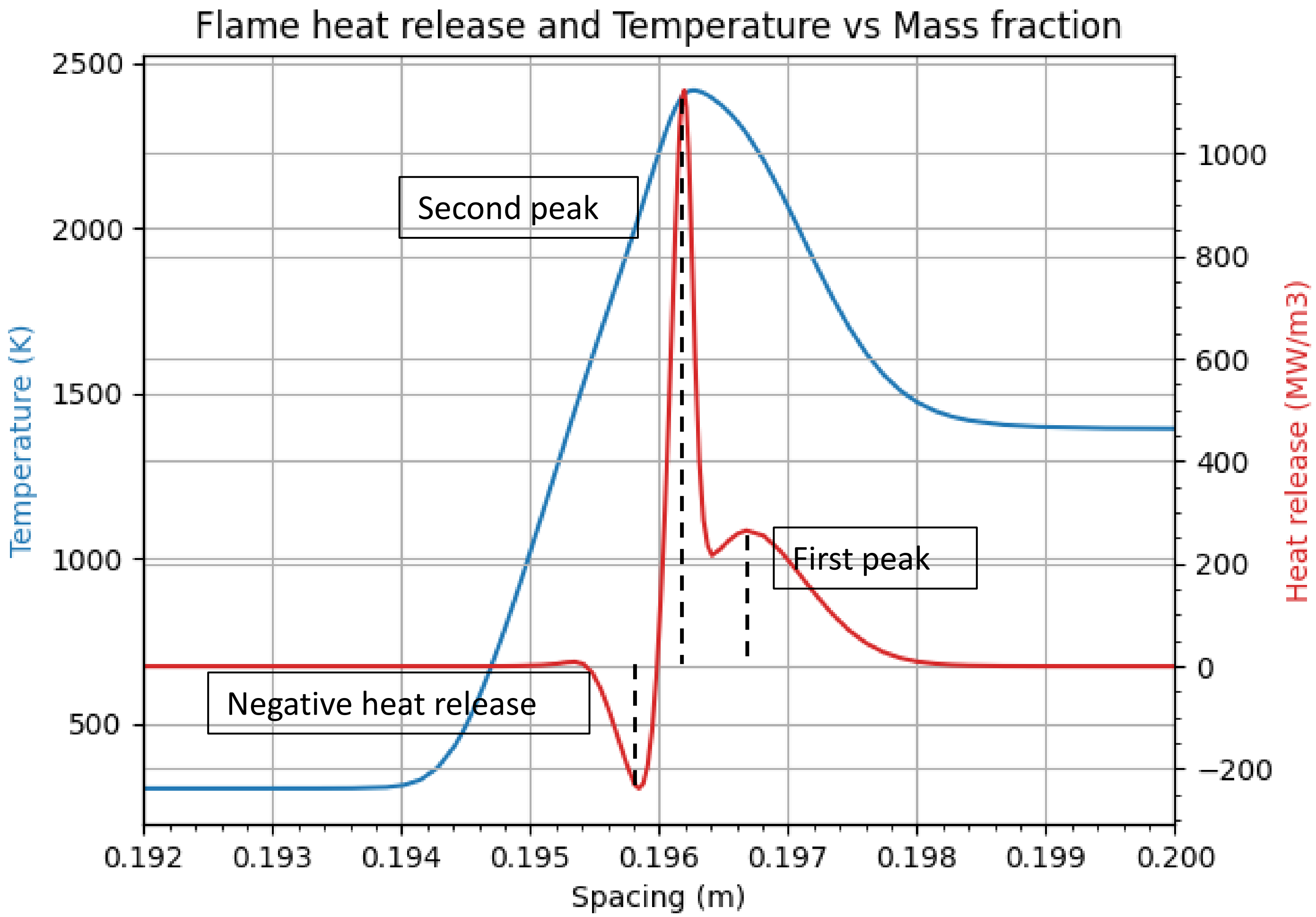
Methodology:

Assumption:

- The fuel nozzle is circular, and the flame is planar.
- The flame angle is assumed to be around 60 deg.
- With this assumption: The radial flow rate is half of the axial flow rate:
  - fuel flow - 162.5 Kg/h
  - air flow rate – 2565 Kg/h



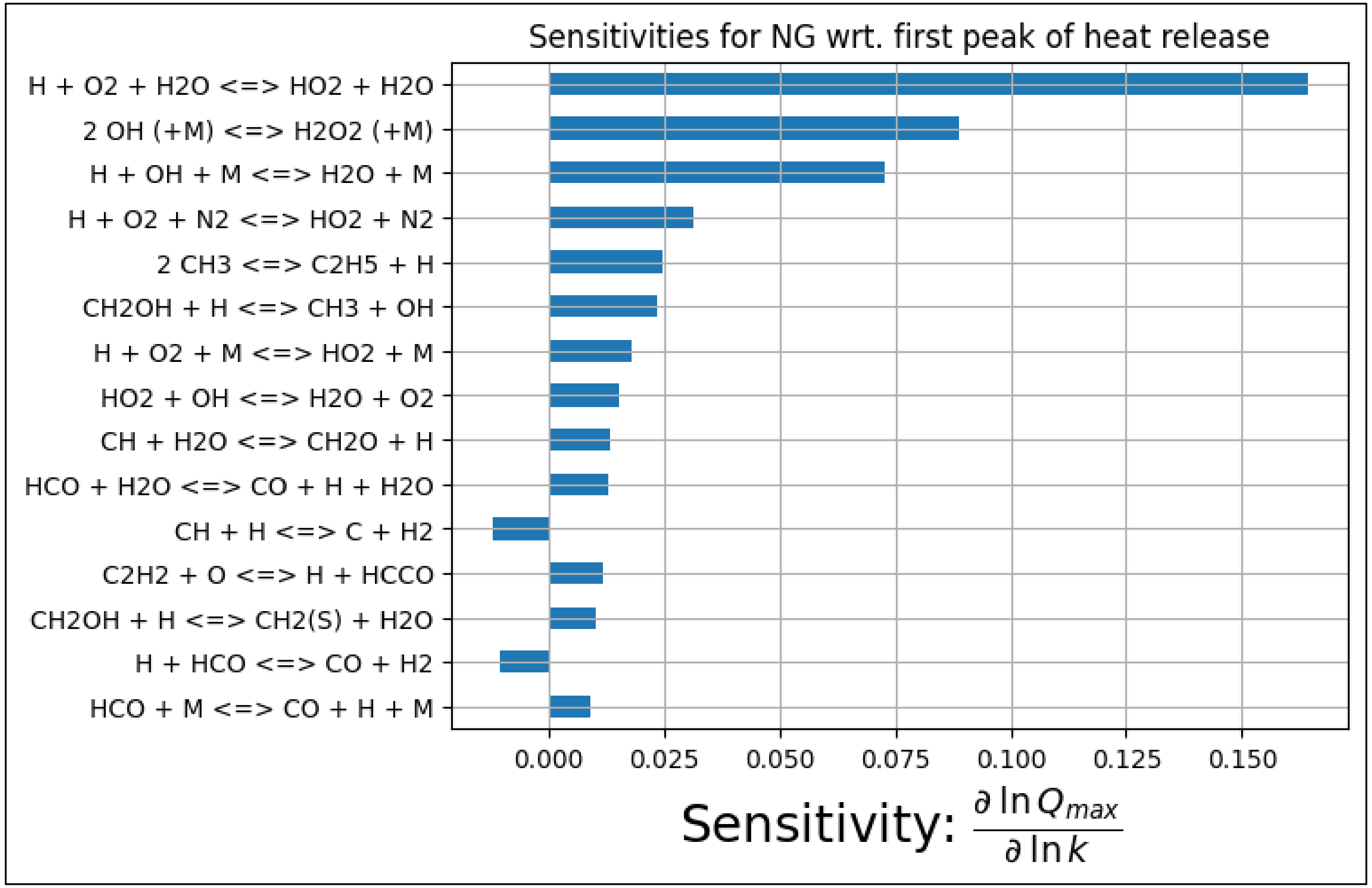
Natural Gas Combustion:



Results:

- Peak temp - 2415 K
- Peak heat release rate - 1123 MW/m3
- The first peak in the heat release curve is dominated by H radical consumption
- The second and highest peak is dominated by methane combustion
- The negative heat release area is dominated by heavy hydrocarbon radical production

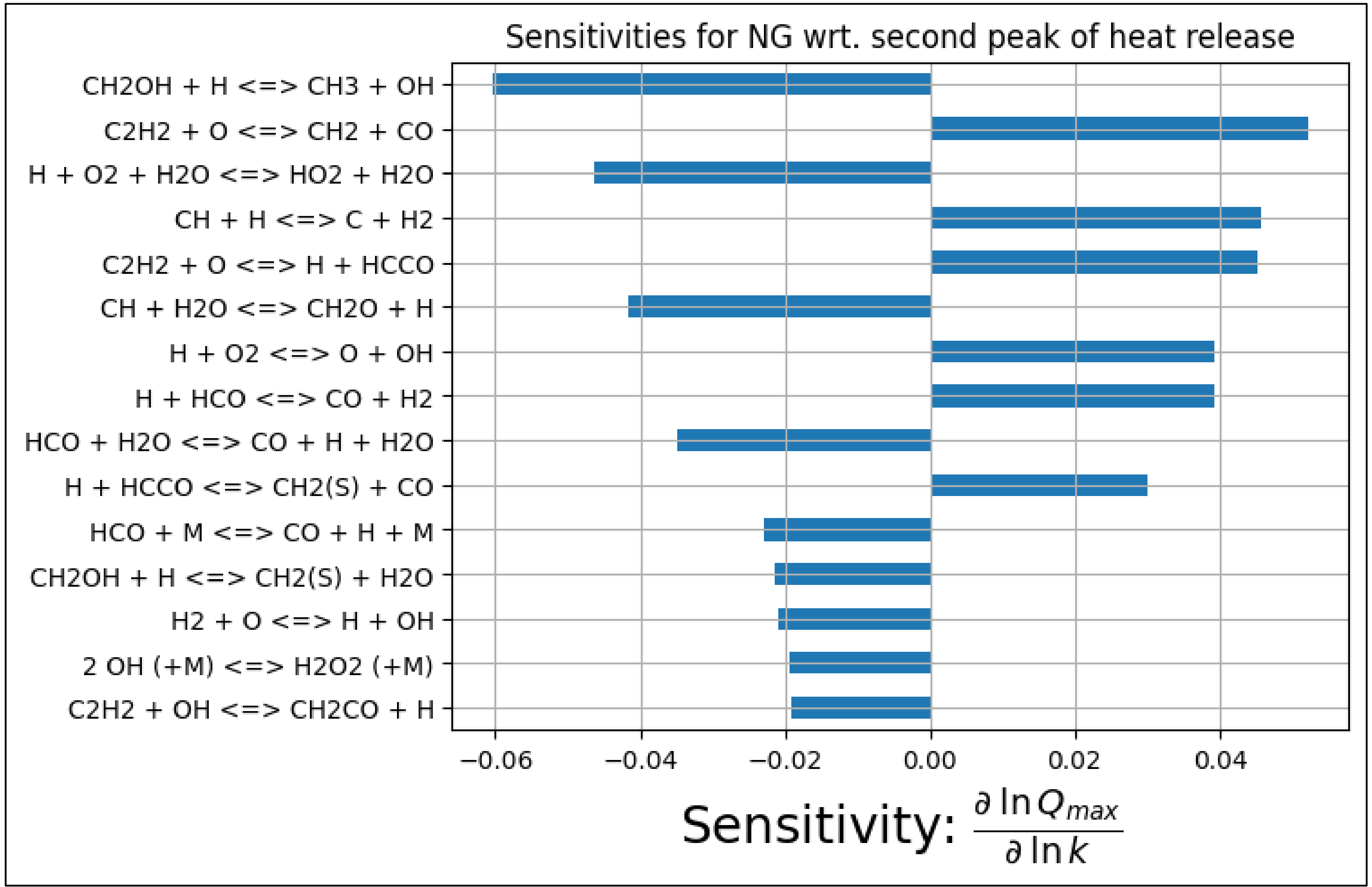
First peak dominant reactions:



Discussion:

- The first peak in the heat release rate curve is dominated by H and OH radical reactions.
- This peak is observed towards the fuel-lean side.
- H radicals being small, diffuse faster in the air and are closet to air when the combustion reactions starts.
- The main dominant reaction in this side, shows H2O in the reactant side, which means that there is already some concentration of H2O formed due to higher reactivity of H radicals with O atoms.

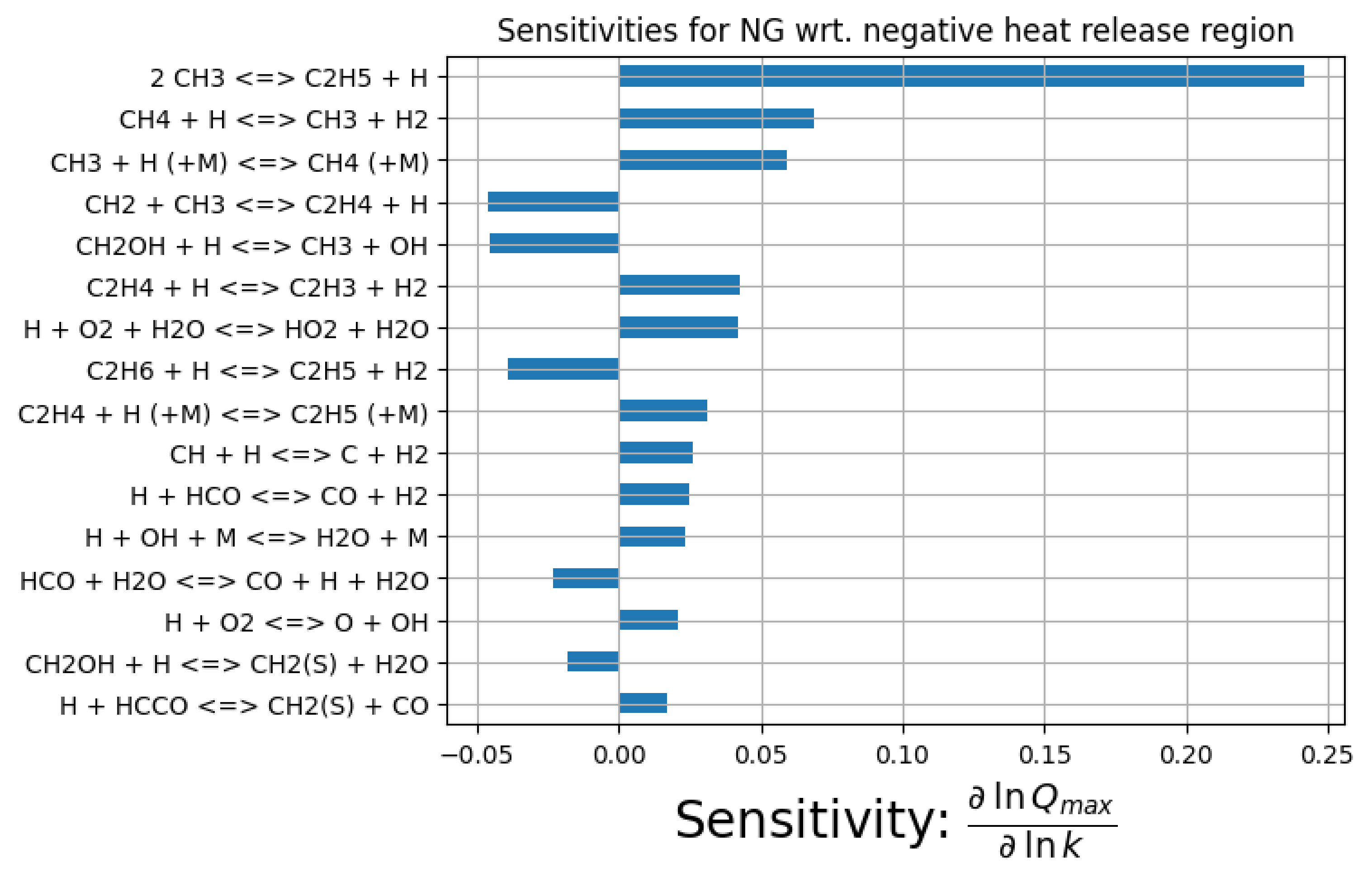
Second peak dominant reactions:



Discussion:

- The second peak in the heat release rate curve is the highest as in this region is dominated by hydrocarbon combustion.
- In the fig, negative sensitivity means that these reactions are gonna reduce the rate of combustion and vice-versa is true for reactions with +ve sensitivity.
- All the reactions associated with the NG combustion mechanism are dominant in this region.
- Reaction 10 & 12, leads to the production of CH2 in solid state.

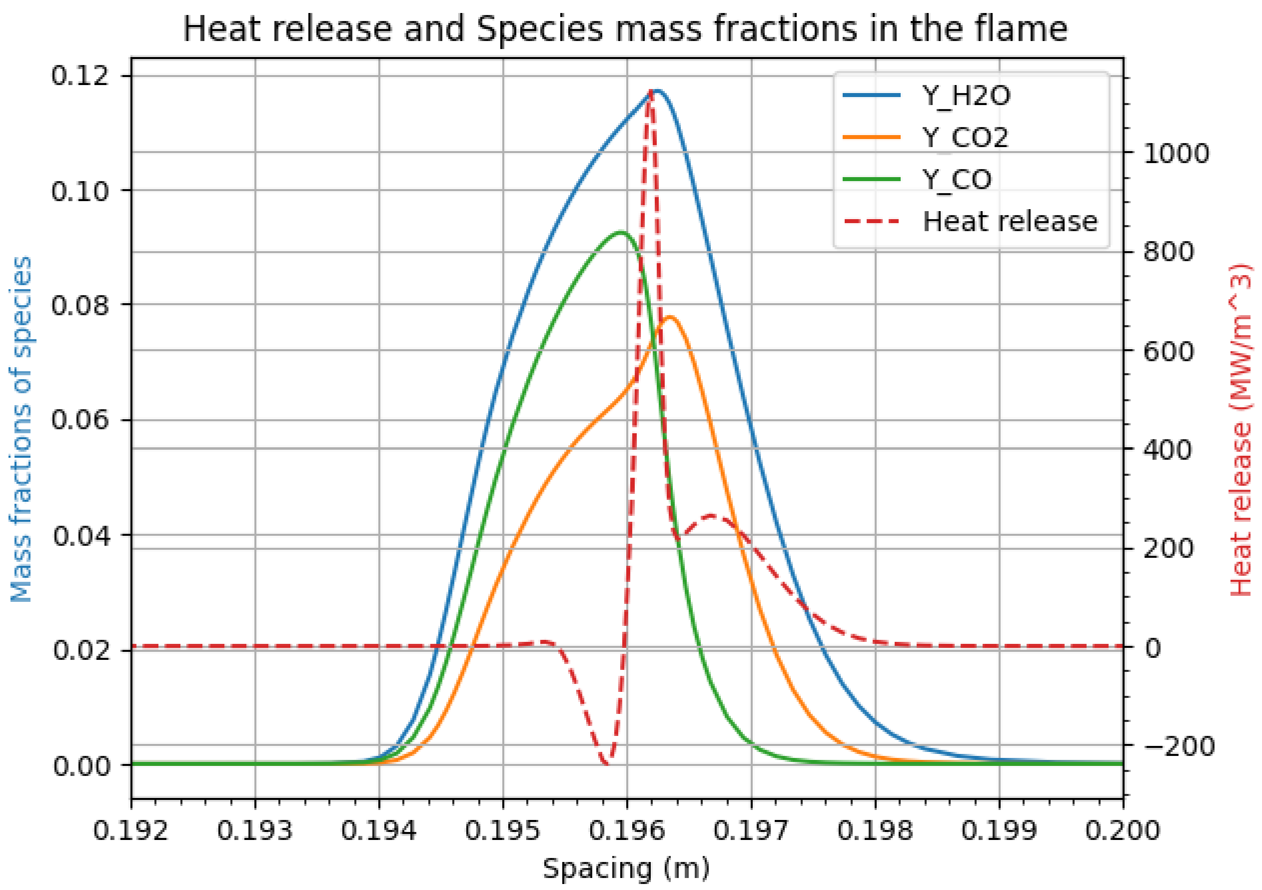
The dominant reactions in dip region:



Discussion:

- As mentioned earlier, the negative heat release rate region is dominated by lighter hydrocarbon radical consumption to produce higher hydrocarbon radicals.
- These reactions are endothermic in nature and hence consume heat.
- These reactions are dominant towards the fuel-rich side, hydrocarbon radicals being larger in size diffuse slowly compared to H and OH radicals.

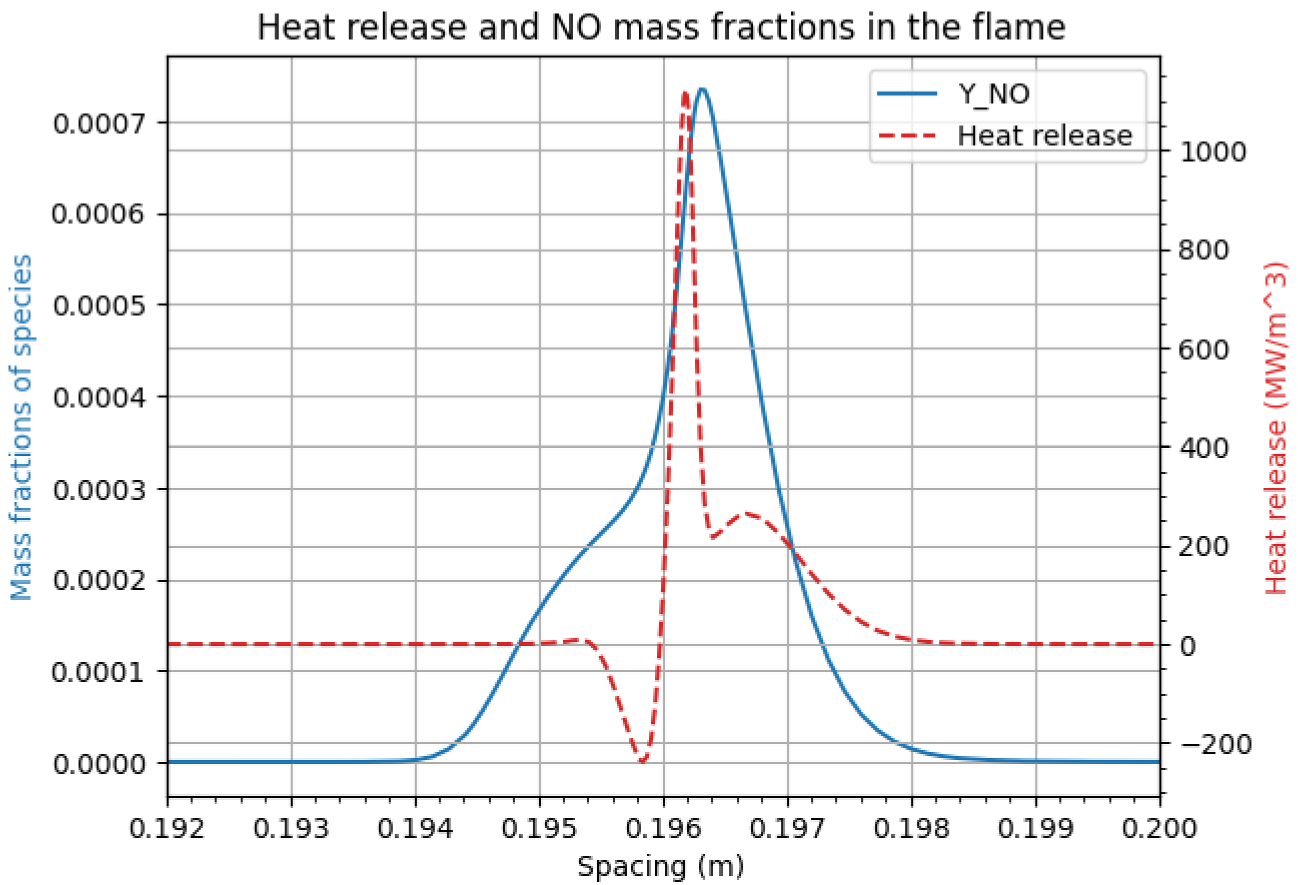
Mass fraction of species in the flame front:



Discussion:

- The fig shows the mass fraction of H2O, CO2, and CO in the flame front.
- As it can be seen, the CO mass fractions are higher towards the fuel-lean side, this is understandable as CO is an intermediate species of combustion, and as the fuel is lean, more CO is produced.
- Later on, this CO gets consumed in the production of CO2 during the complete combustion in the fuel-rich side of the flame front.
- H2O mass fraction continues to increase, from the fuel-lean side to the flame front, suggesting a complete combustion in regions near the flame front.
- On the fuel-rich side, there are chances of occurrence of water-gas shift reactions.

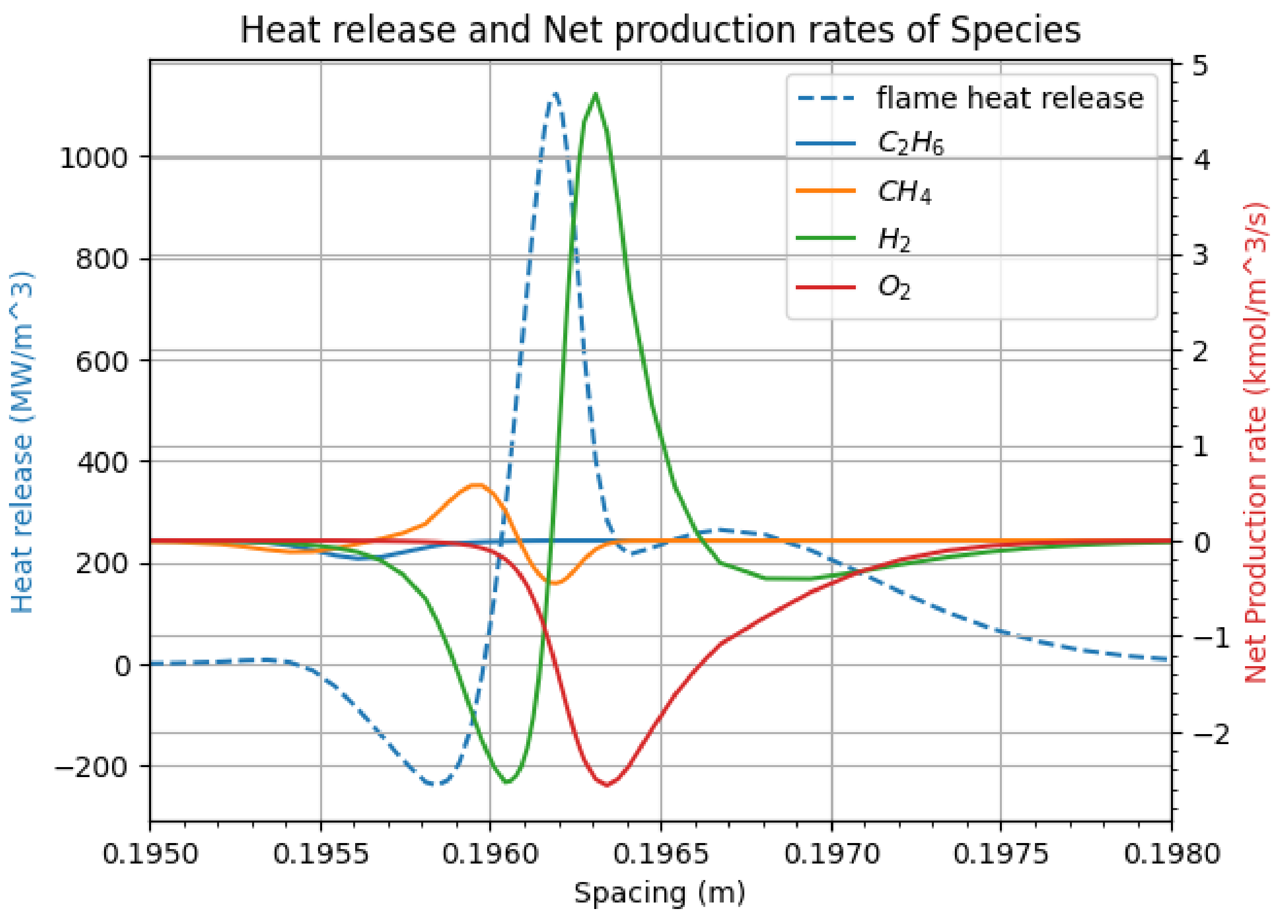
Mass fraction of NO in the flame front:



Discussion:

- The fig shows the mass fraction of NO in the flame front.
- As shown in Fig., the NO mass fractions continue to increase, from the fuel-lean side to the flame front.
- NO being the temperature-dependent species, the concentration of NO increases sharply in the flame front because of the sharp increase in the flame temperatures.

Net production rate of species:



Discussion:

- The fig. shows the net production rates of major species in the flame.
- O2 net production rate is –ve, suggesting that O2 is getting consumed in the reactions.
- For the H2, initially there is consumption, and later on the mass fraction increases. This means that initially, H2 breaks down to form H radicals supporting the combustion reaction. In the fuel-rich region, due to water gas-shift reactions, there is net +ve production of H2.
- C2H6 breaks down first into radicals, leading to an increase in CH4 mass fraction, which in regions near to flame front gets consumed in combustion reactions.

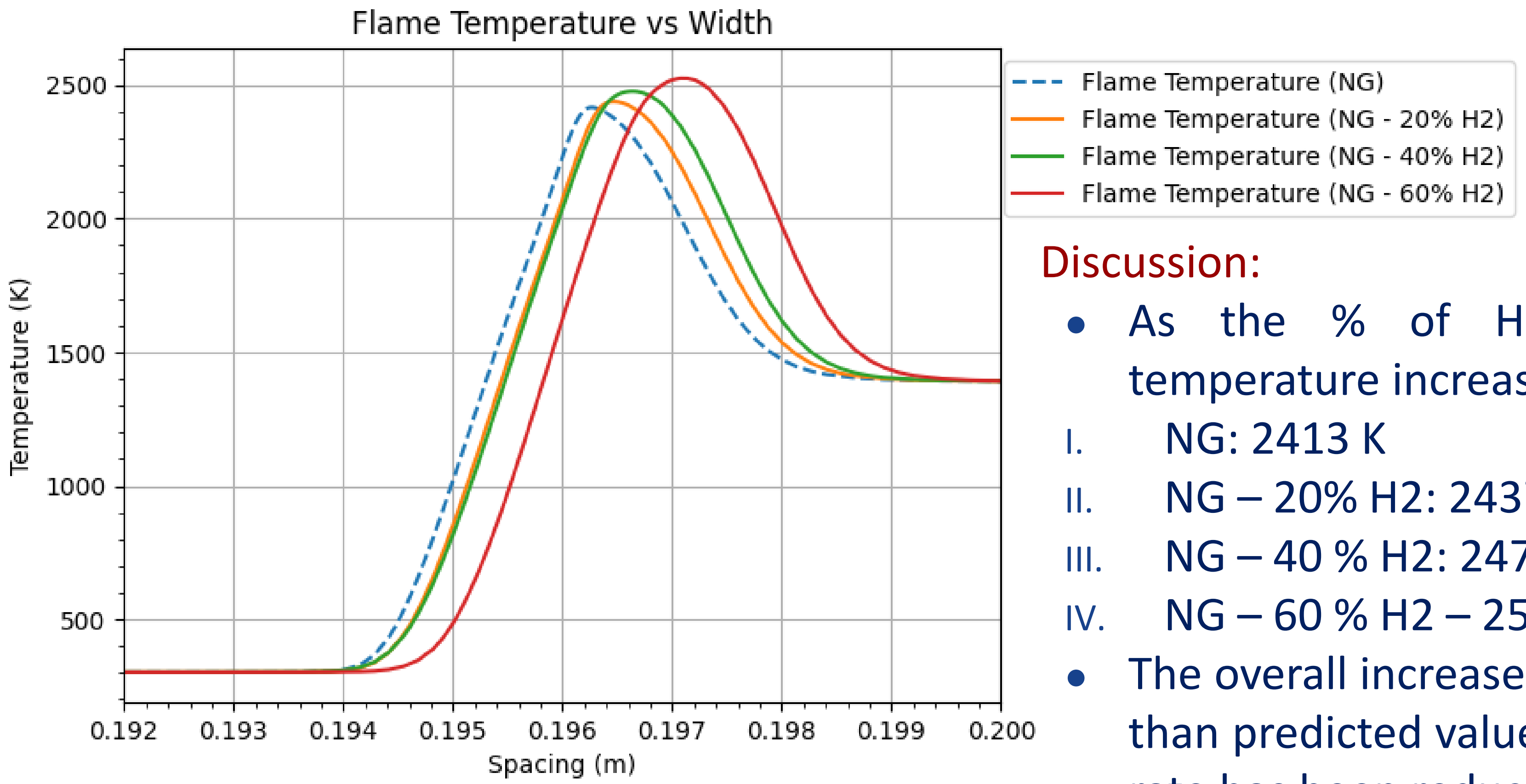
Natural Gas – H2 blend combustion:

Important points:

- Three blending percentages are considered for the simulation – 20%, 40 %, and 60%.
- The reaction kinetics for 10% H2 are mostly dominated by the NG combustion mechanism, hence not many significant differences are observed.
- As mentioned earlier in the simulation parameter slide, the radial flow rate is considered.
- As the H2 percentage is increased, the fuel velocity at the inlet increases significantly due to the lower density of H2, as a result - flame blowout happens.
- According to Cantera, in these cases - the flame is extinct.
- To counter this flame blowout effect, the flow rate of fuel is reduced by a small amount, to maintain the flame inside the chamber, Table below lists the fuel flow rate for all the cases.

Fuel Composition	Mass flow rate of fuel (Kg/m^2/s)
Natural gas	29.69
Natural gas – 20 % H2	28.27
Natural gas – 40 % H2	25.81
Natural gas – 60 % H2	24.74

Flame temperature :



Discussion:

- As the % of H2 increases, the peak flame temperature increases.

I. NG: 2413 K

II. NG – 20% H2: 2437 K

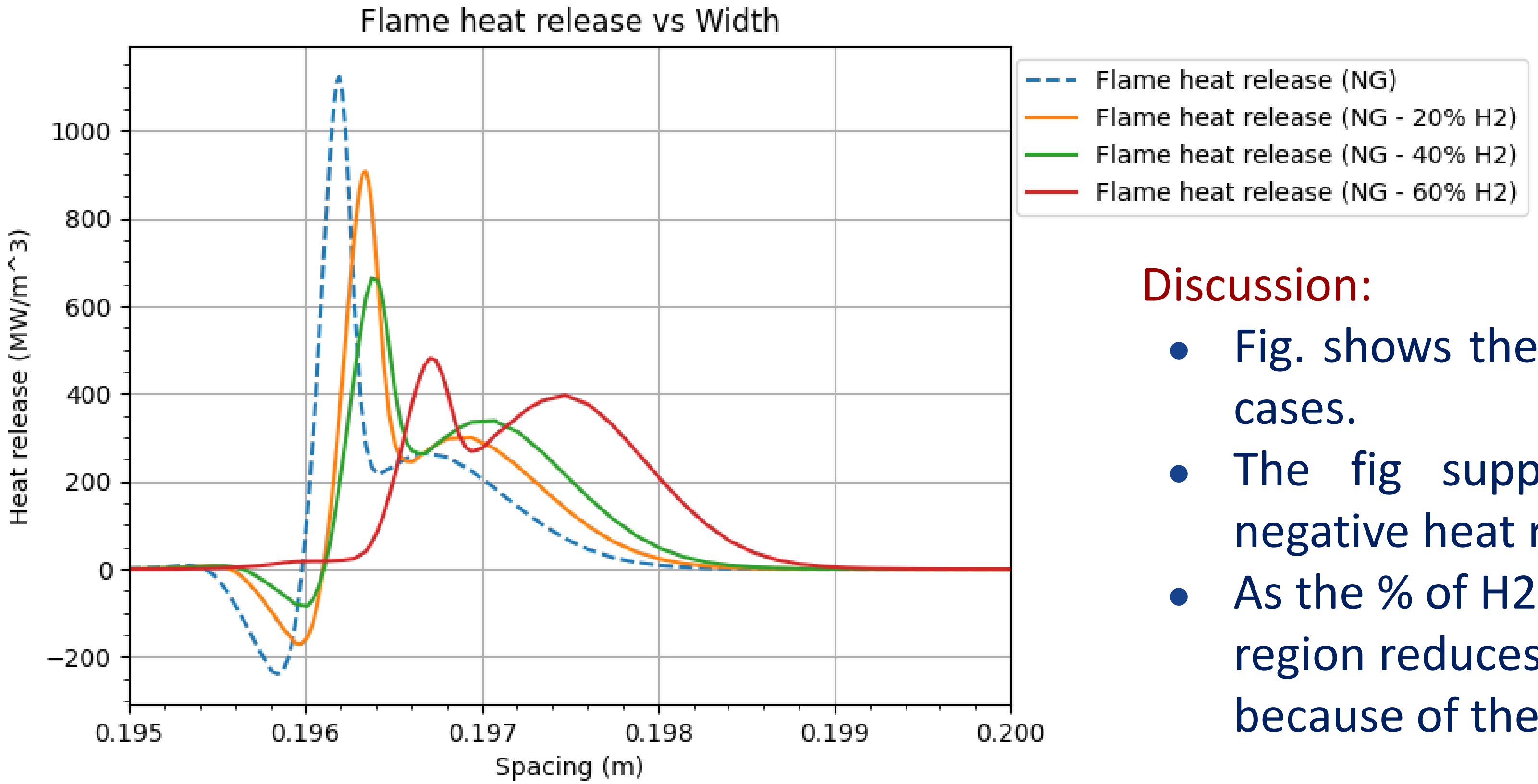
III. NG – 40 % H2: 2476 K

IV. NG – 60 % H2 – 2524 K

- The overall increase in temperature can be a bit more than predicted values, this is because the overall flow rate has been reduced with a % H2 increase.

- The peak temperature shifts towards the air-inlet side, this means that the flame front moves closer to the air-inlet.
- This signifies the higher reactivity and diffusivity of H2 gas.

Flame heat release :

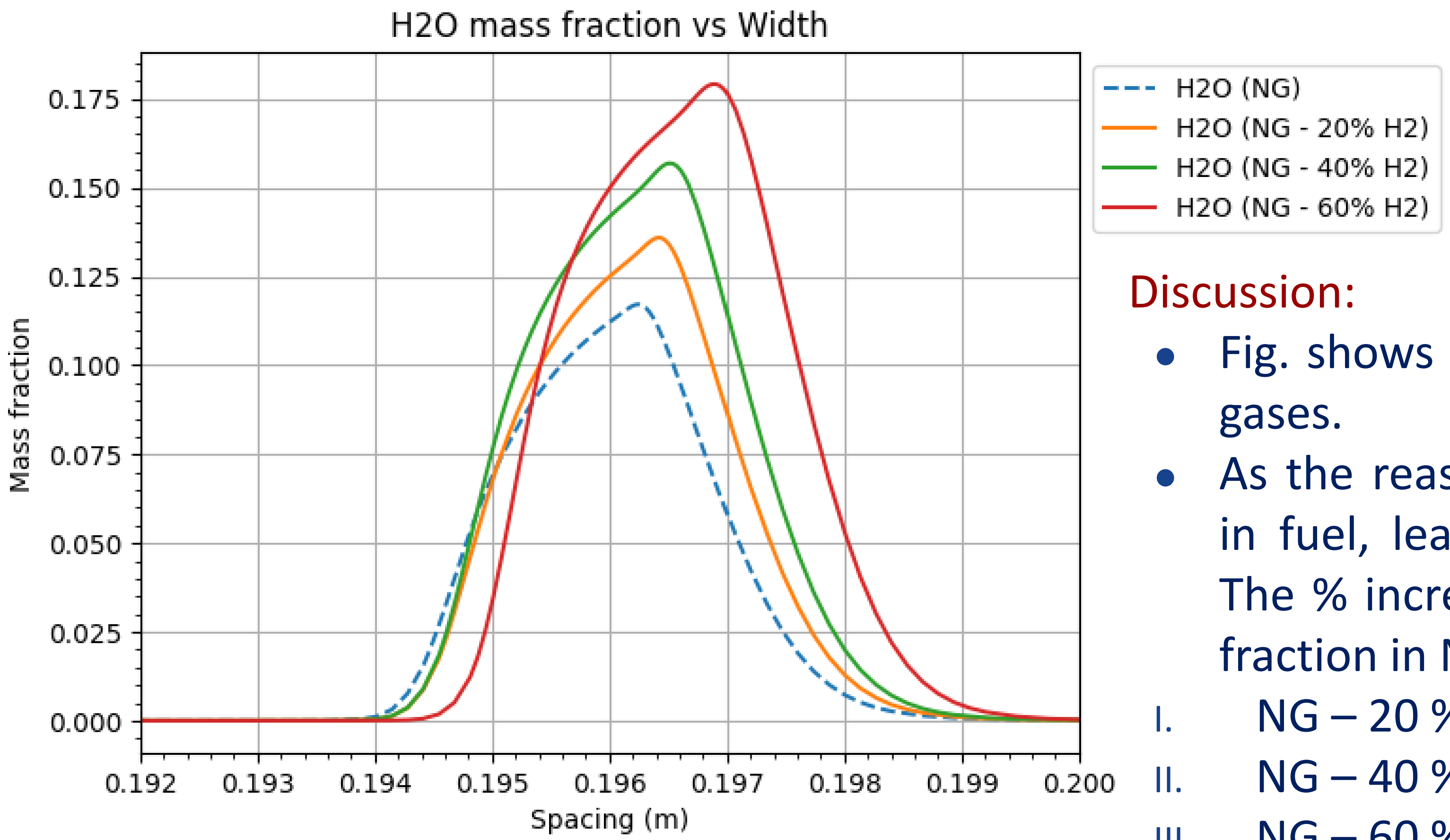


Discussion:

- Fig. shows the heat release rate curves for all the cases.
- The fig supports the earlier explanations of negative heat release, first and second peak.
- As the % of H2 increases, the negative heat release region reduces and ultimately becomes +ve. This is because of the decreased hydrocarbon %.

- For the second peak, the overall heat release decreases, as this region was dominated by NG combustion.
- The first peak increases, as this peak was dominated by H radicals. The peak shifts towards the air inlet side. The overall flame spread increases, signifying the increased flame thickness with increasing H2 %.
- Even though the peak heat release is less, the spread is more.

H_2O mass fraction in the flame:



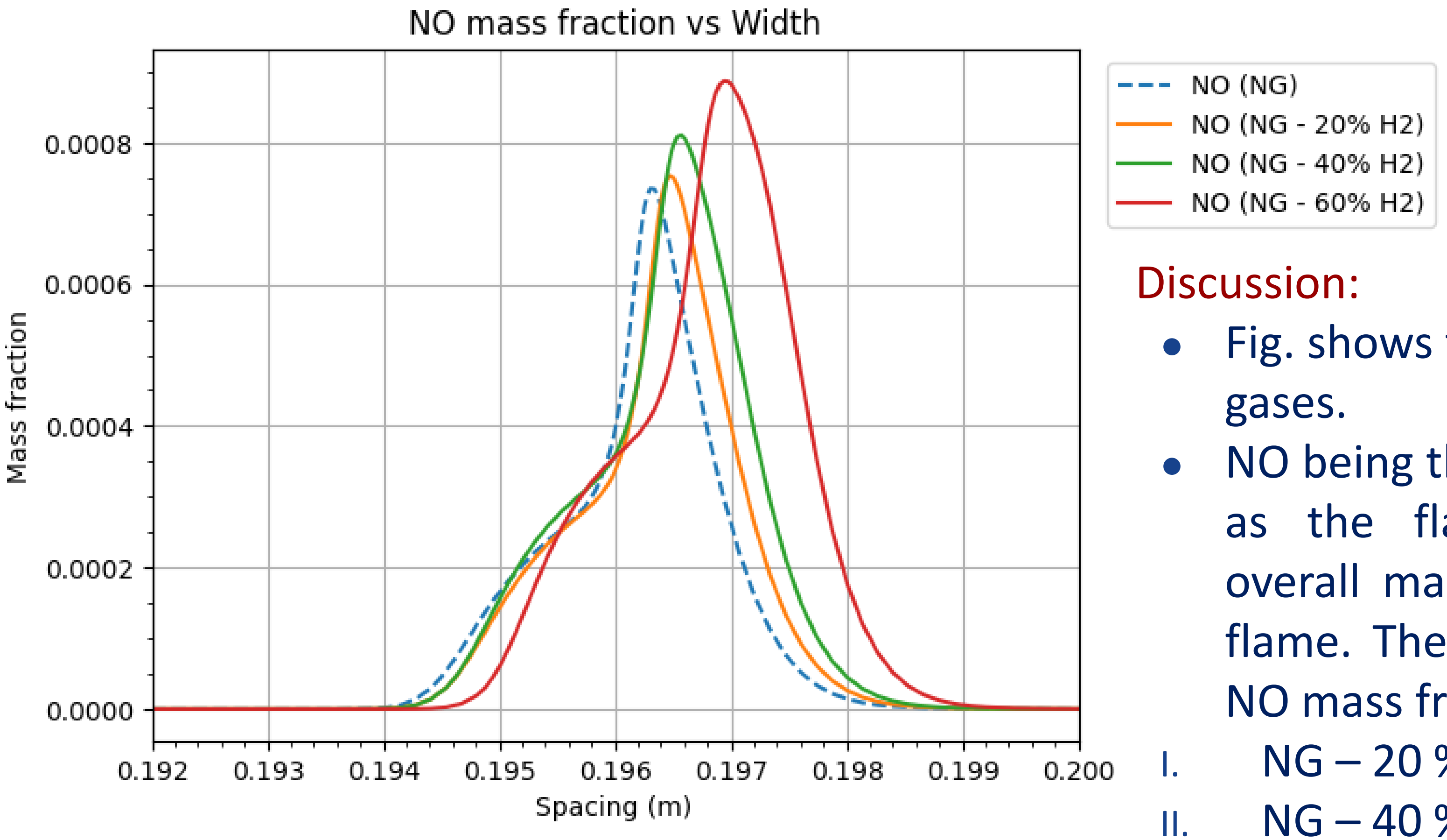
Discussion:

- Fig. shows the H_2O mass fraction in the exhaust gases.
- As the reasons are obvious, the increased % H_2 in fuel, leads to the increase in H_2O emission. The % increase is with comparison of H_2O mass fraction in NG case -

I. NG – 20 % H_2: 15.3 % increase
II. NG – 40 % H_2: 33.9 % increase
III. NG – 60 % H_2: 53 % increase

- Increased H_2O emission is indeed a problem, and needs to be addressed before H_2 as a fuel can be implemented in the furnace.

NO mass fraction in the flame:

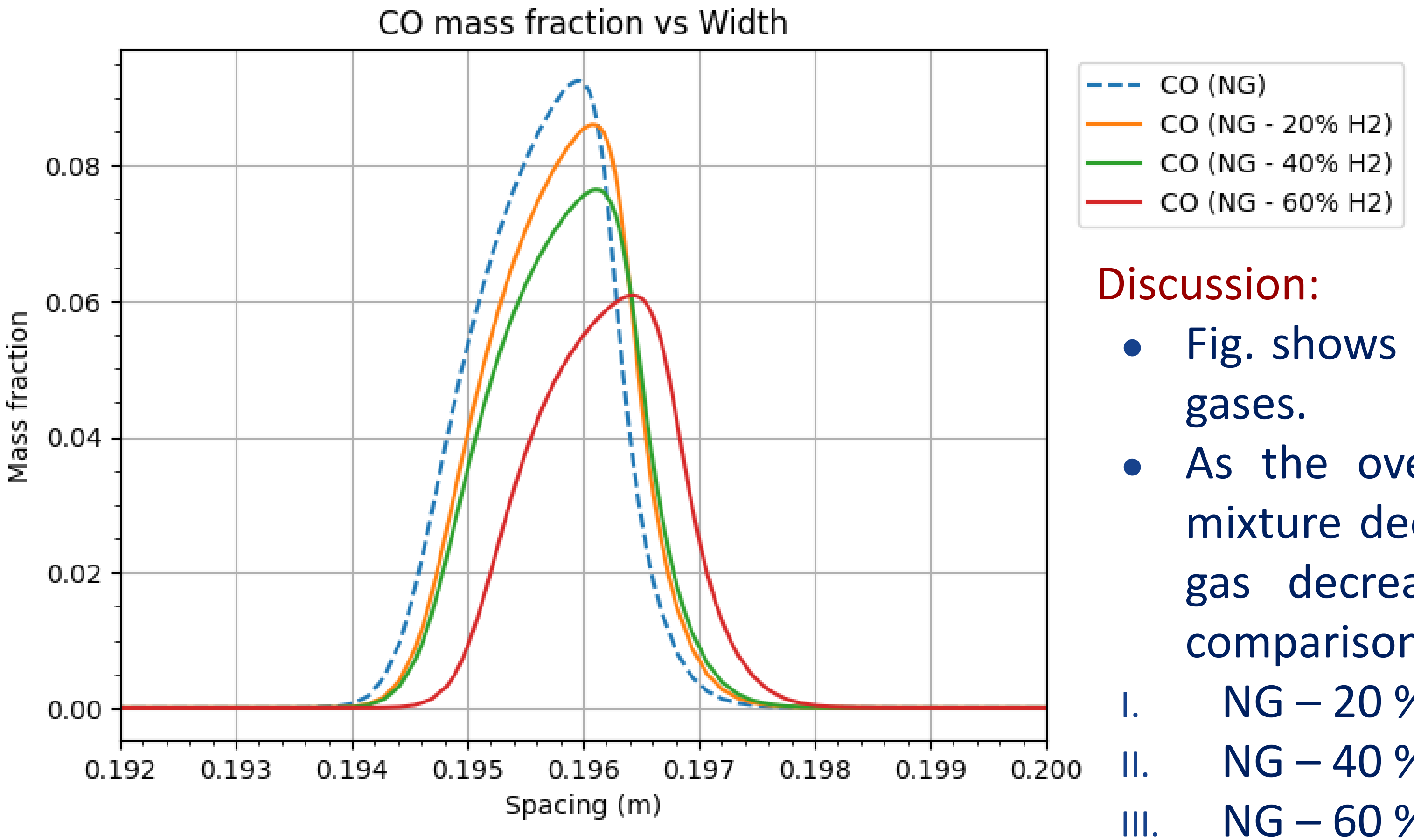


Discussion:

- Fig. shows the NO mass fraction in the exhaust gases.
- NO being the temperature-dependent species, as the flame temperature increases, the overall mass fraction of NO increases in the flame. The % increase is with comparison of NO mass fraction in NG case -

I. NG – 20 % H2: 2.7 % increase
II. NG – 40 % H2: 10.9 % increase
III. NG – 60 % H2: 20.5 % increase

CO mass fraction in the flame:



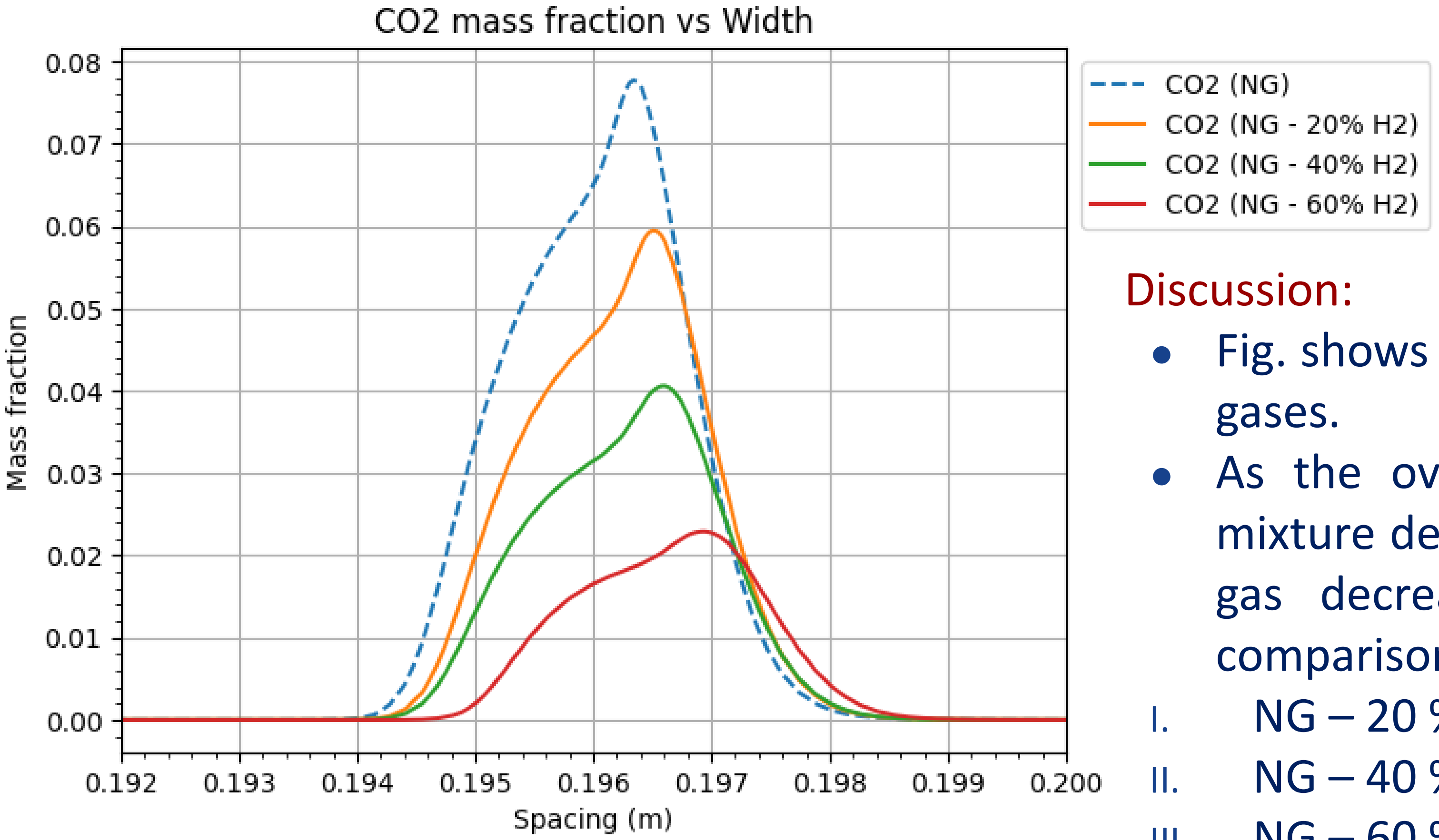
Discussion:

- Fig. shows the CO mass fraction in the exhaust gases.
- As the overall % of natural gas in the fuel mixture decreases, the % of CO in the exhaust gas decreases. The % decrease is with a comparison of CO mass fraction in NG case -

I. NG – 20 % H2: 6.9 % decrease
II. NG – 40 % H2: 17.3 % decrease
III. NG – 60 % H2: 34.2 % decrease

- CO being an intermediate species in the combustion process, achieves its peak before CO2 and later gets consumed in the production of CO2.

CO_2 mass fraction in the flame:



Discussion:

- Fig. shows the CO_2 mass fraction in the exhaust gases.
- As the overall % of natural gas in the fuel mixture decreases, the % of CO_2 in the exhaust gas decreases. The % decrease is with a comparison of CO_2 mass fraction in NG case -

I. NG – 20 % H_2: 23.4 % decrease

II. NG – 40 % H_2: 47.7 % decrease

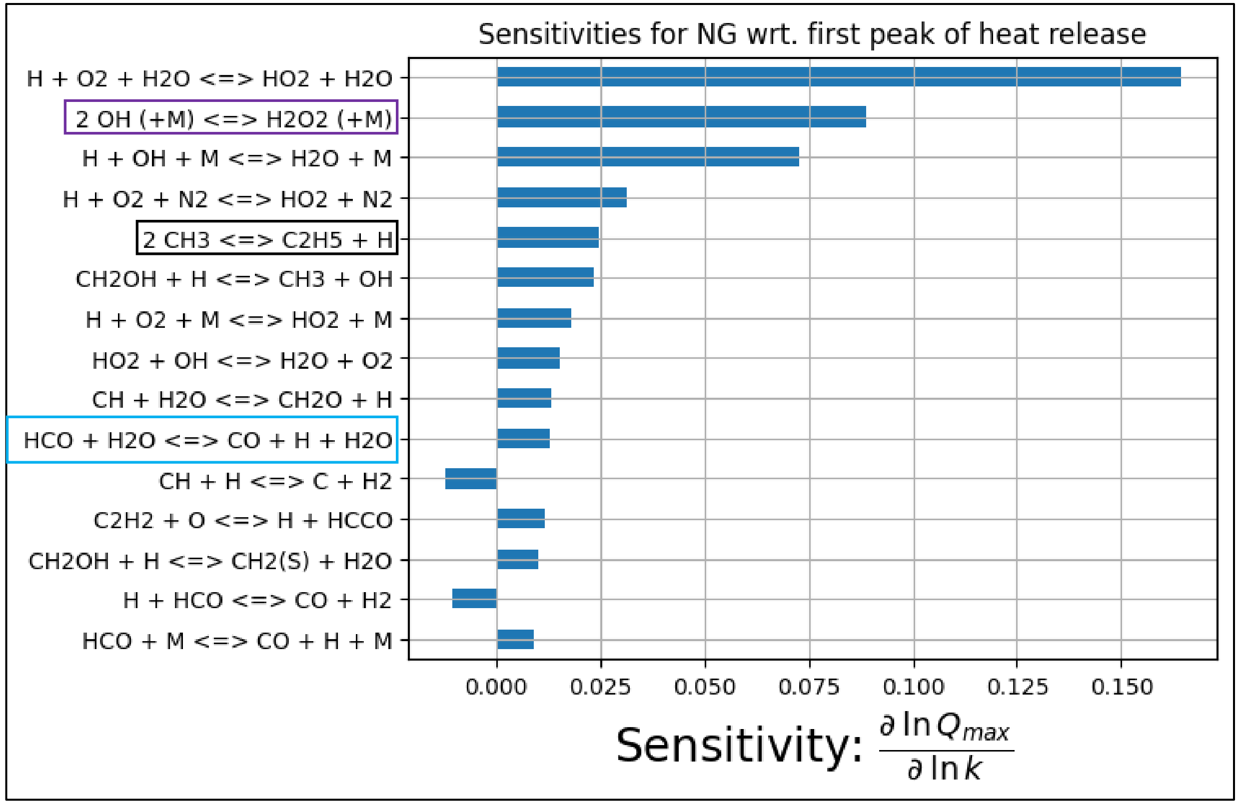
III. NG – 60 % H_2: 70.4 % decrease

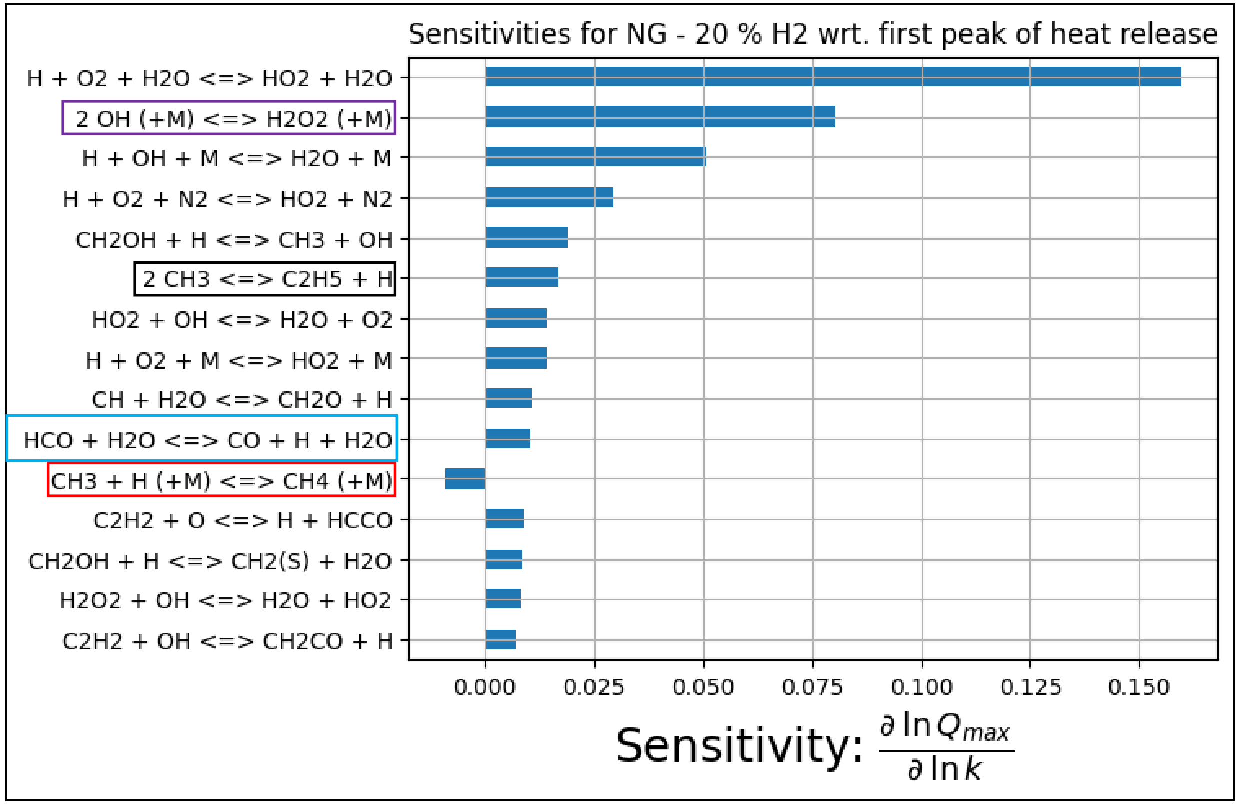
Sensitivity analysis:

Important points:

- Sensitivity analysis is performed during combustion analysis to understand how variations in different parameters can affect the combustion process and its outcomes.
- It helps to identify the key factors that influence combustion performance, efficiency, emissions, and other relevant aspects.
- In this case, the sensitivity analysis has been carried out to reveal the predominant reactions in the first and second peak heat release regions.
- The positive sensitivity of reaction means that increasing the reaction rate for those reactions will positively impact the heat release and increase the combustion rate.
- The vice-versa is true for reactions having negative sensitivity.
- In terms of magnitude of sensitivity, the higher the magnitude higher the impact on the heat release.
- In the graph, shown on the next pages: Q_{max} is the maximum heat release in the regions under study, and K is the reaction rate for a particular reaction.
- Sensitivity of a particular reaction is measured by: $\partial \ln Q_{max} / \ln K$.

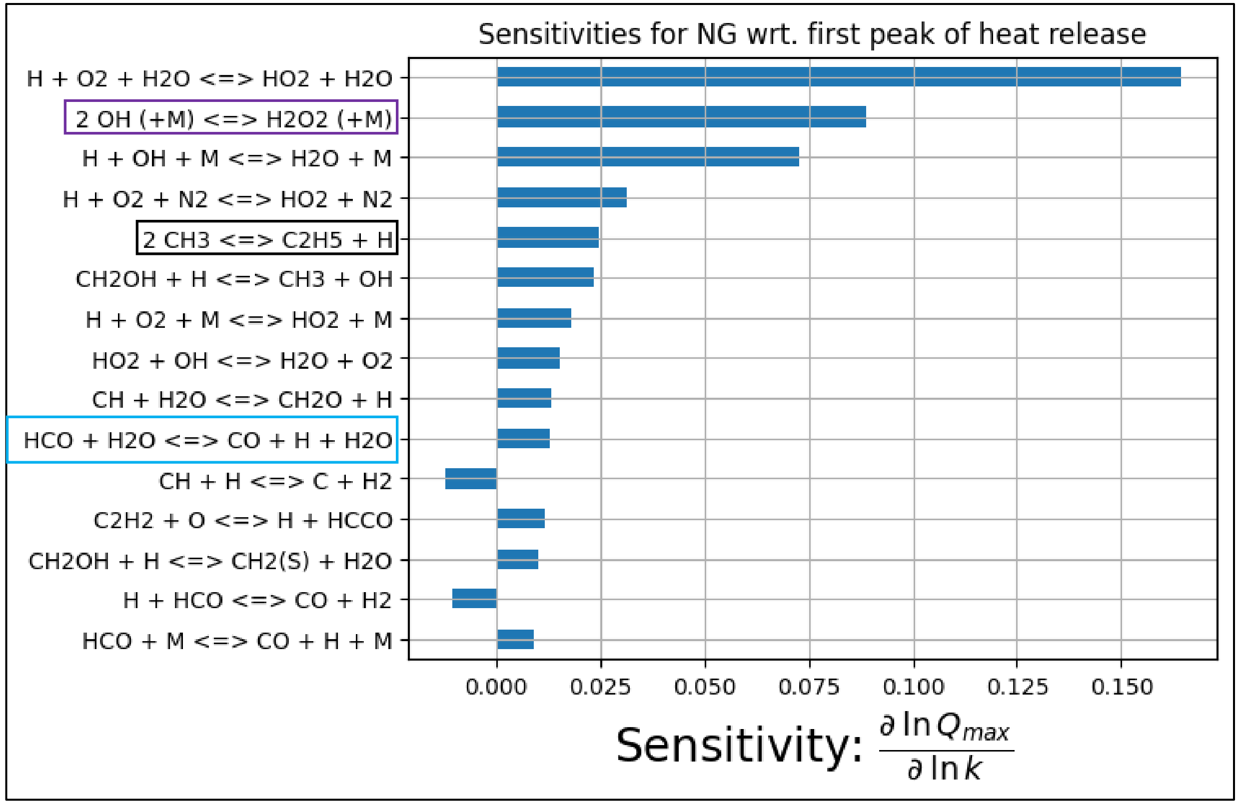
Sensitivity analysis for NG and NG- 20% H2 in the first peak region:

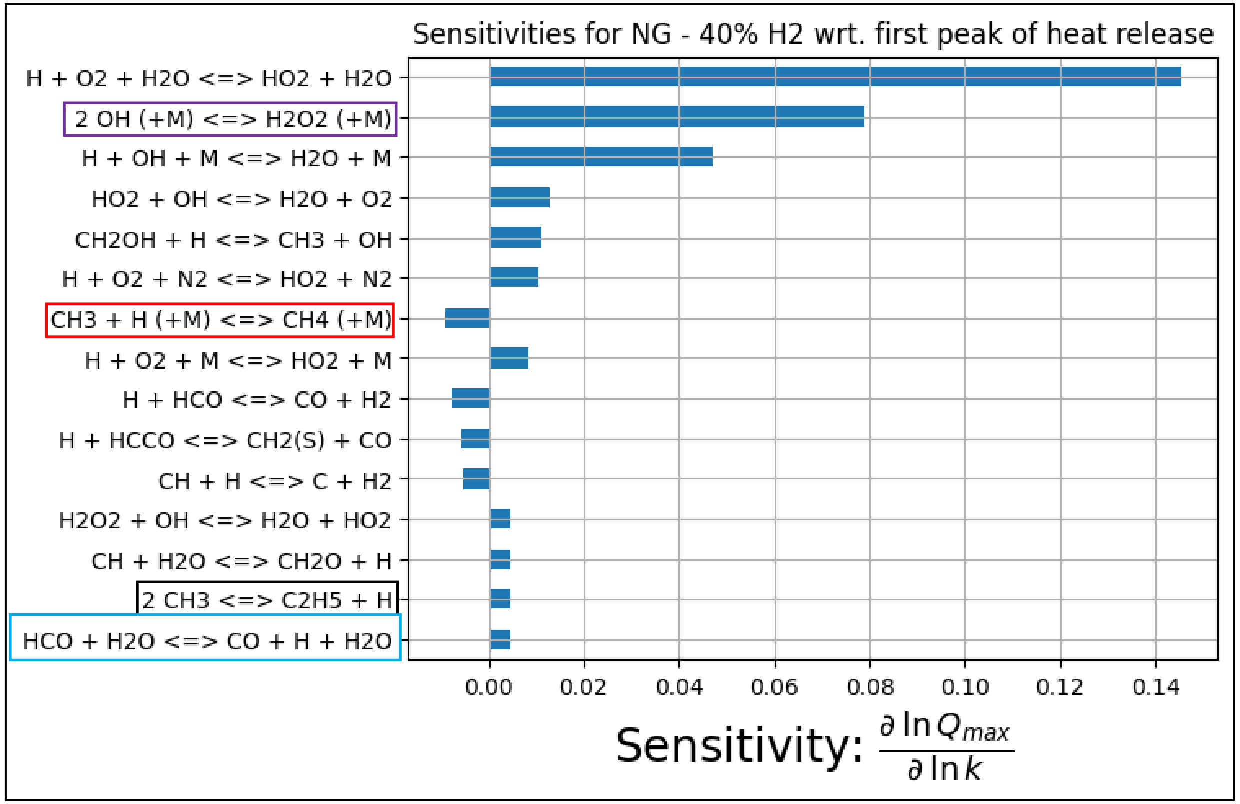




- The reasons behind all the reactions are very difficult to explain as they depend upon many parameters (A, T, Ea, and many others..) and are beyond the scope of this work. However, few inferences can be made, based on the observations.
- As discussed earlier, the first peak is dominated by the H-combustion mechanism reaction. However few reactions like, (2CH3 <=> C2H5 + H, CH3 + H (+M) <=> CH4 (+M), HCO + H2O <=> CO + H + H2O) suggest that as the % of H2 increases beyond a certain limit above 40 %, there are some adverse effects and the presence of NG combustion reactions starts increasing.

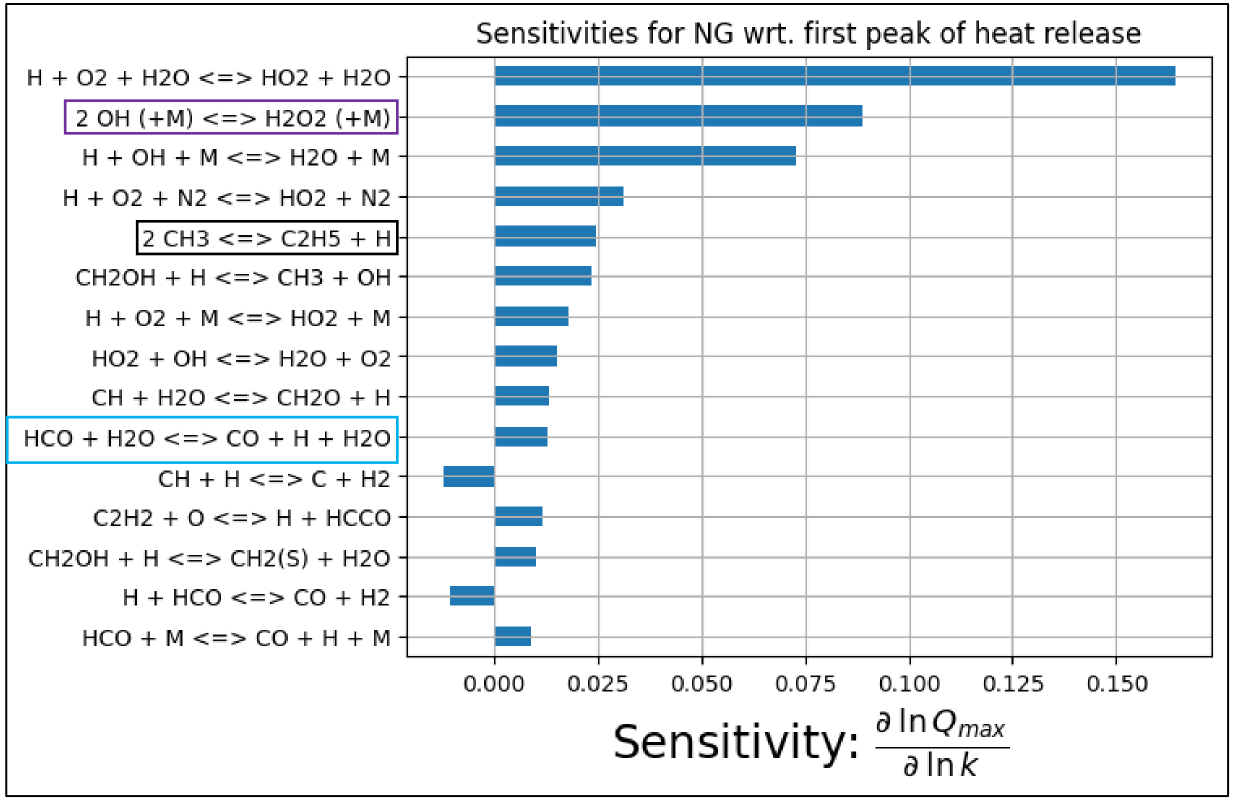
Sensitivity analysis for NG and NG- 40% H2 in the first peak region:

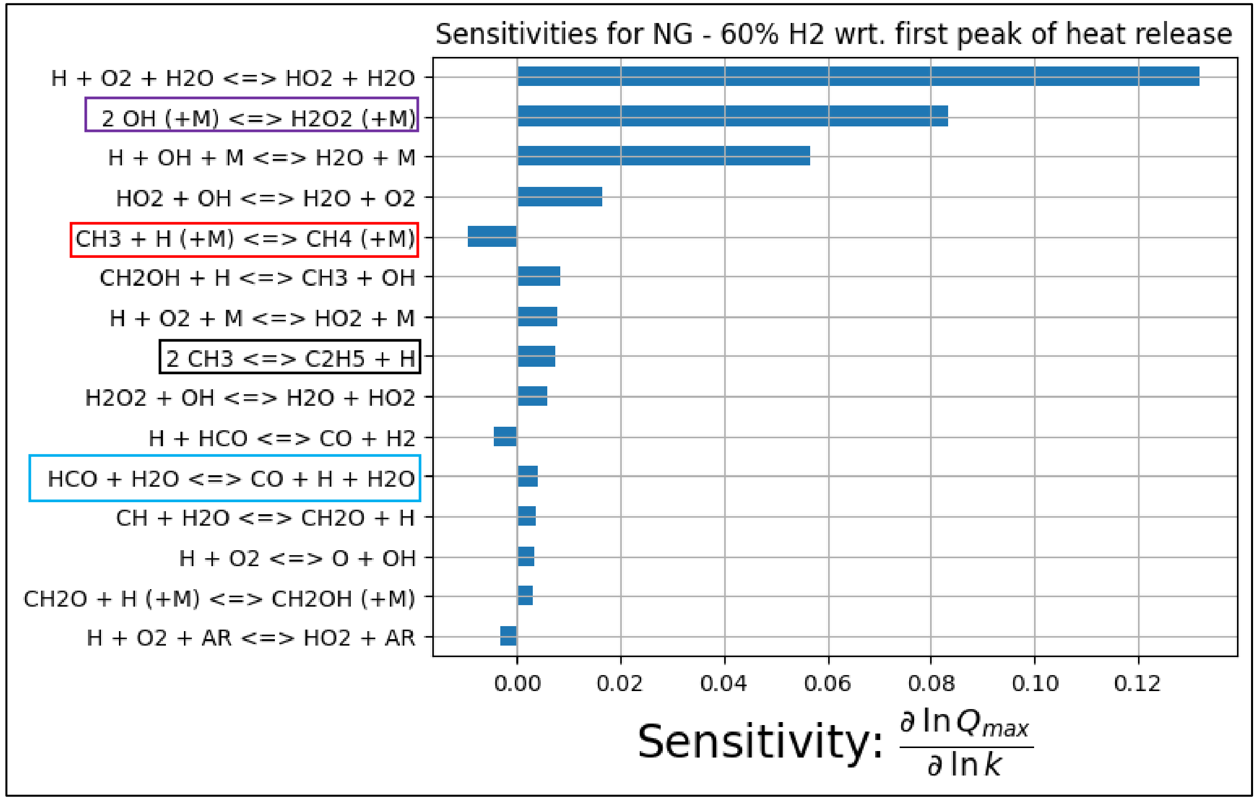




- The sensitivity for CH3 + H (+M) <=> CH4 (+M) increases in magnitude, as the percentage of H2 increases. This is because of the increased availability of H radicals in the mixture. This reaction is a chain termination reaction.
- The sensitivity for 2CH3 <=> C2H5 + H decreases in magnitude, as the percentage of H2 increases. However for 60 % H2, the sensitivity of this reaction increases a little, and the reaction moves up in the combustion mechanism.
- The similar effect is observed in HCO + H2O <=> CO + H + H2O, whose sensitivity decreases in magnitude, as the percentage of H2 increases. However for 60 % H2, the sensitivity of this reaction increases, and the reaction moves up in the combustion mechanism.

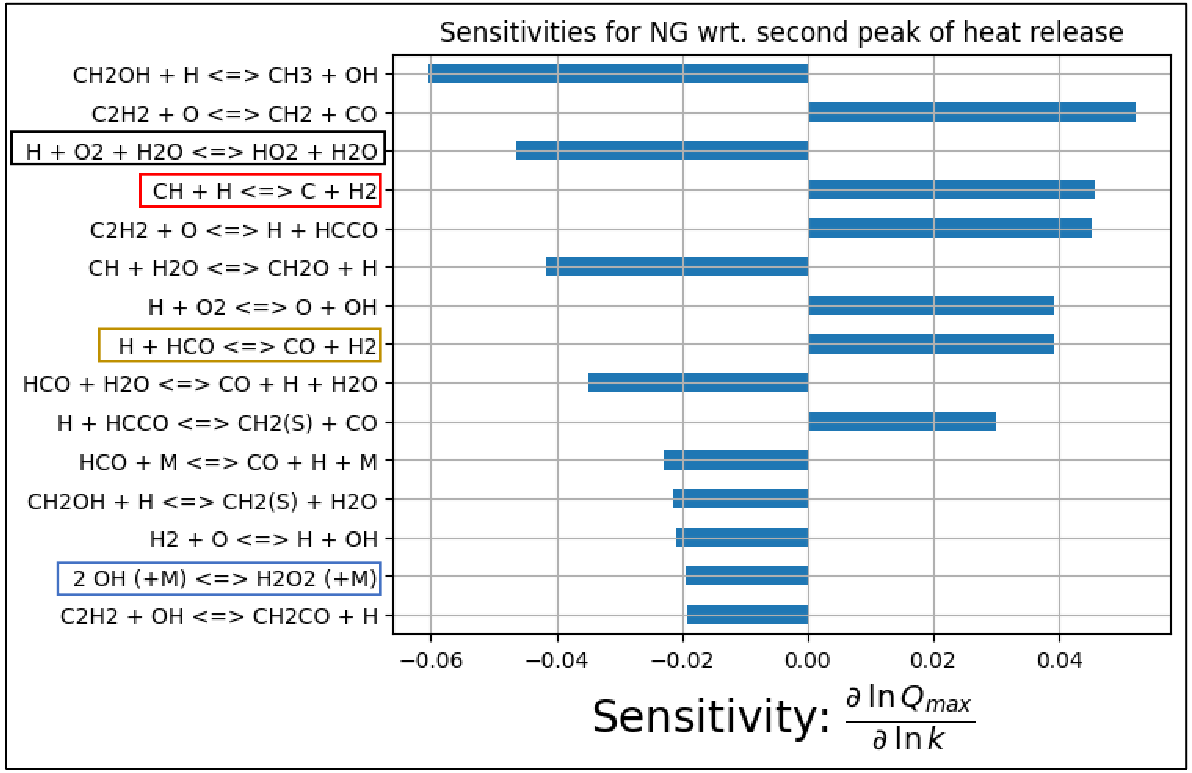
Sensitivity analysis for NG and NG- 60% H2 in the first peak region:

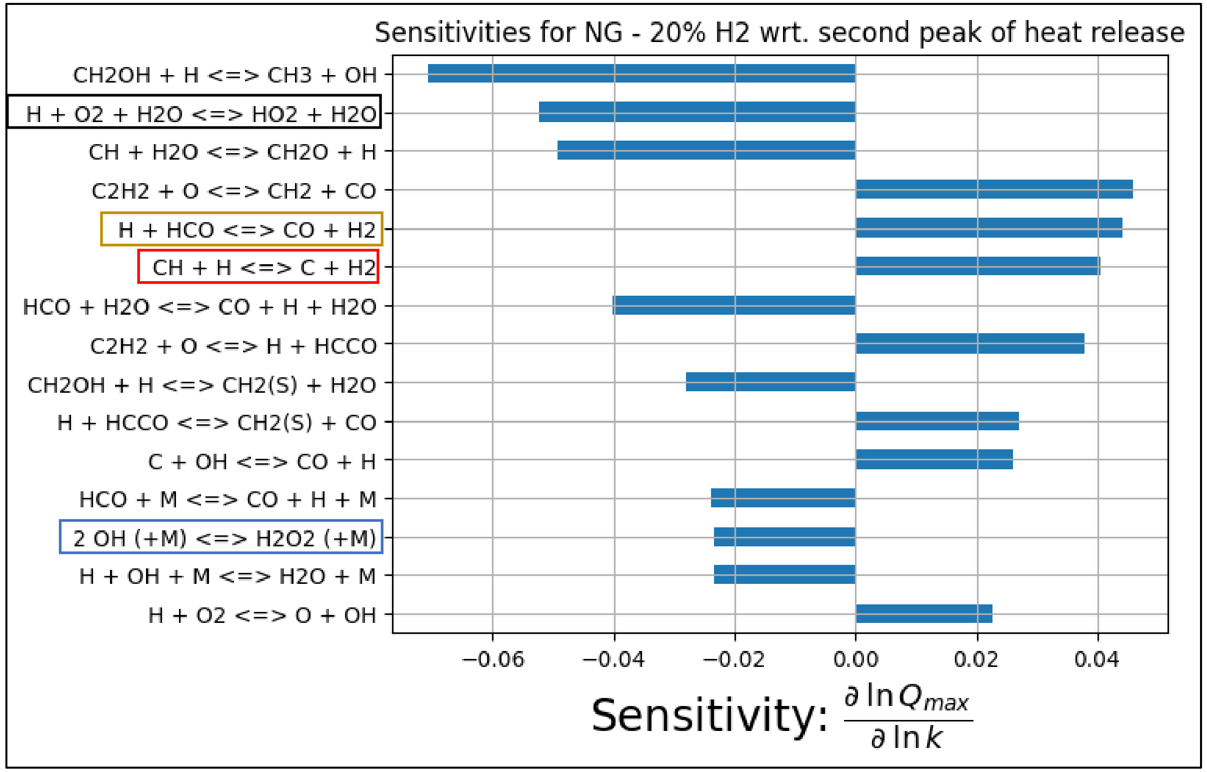




- The same effect is seen for 2OH (+M) <=> H2O2 (+M) as well.
- The heat release for 60% H2, shown on page 18, is more well-distributed as compared to the heat release curves for a lower % of H2. So, there is a possibility of some changes in the combustion mechanism which do not follow the usual pattern.
- However, this is just a hypothesis and demands further in-depth experimental research.

Sensitivity analysis for NG and NG- 20% H2 in the second peak region:

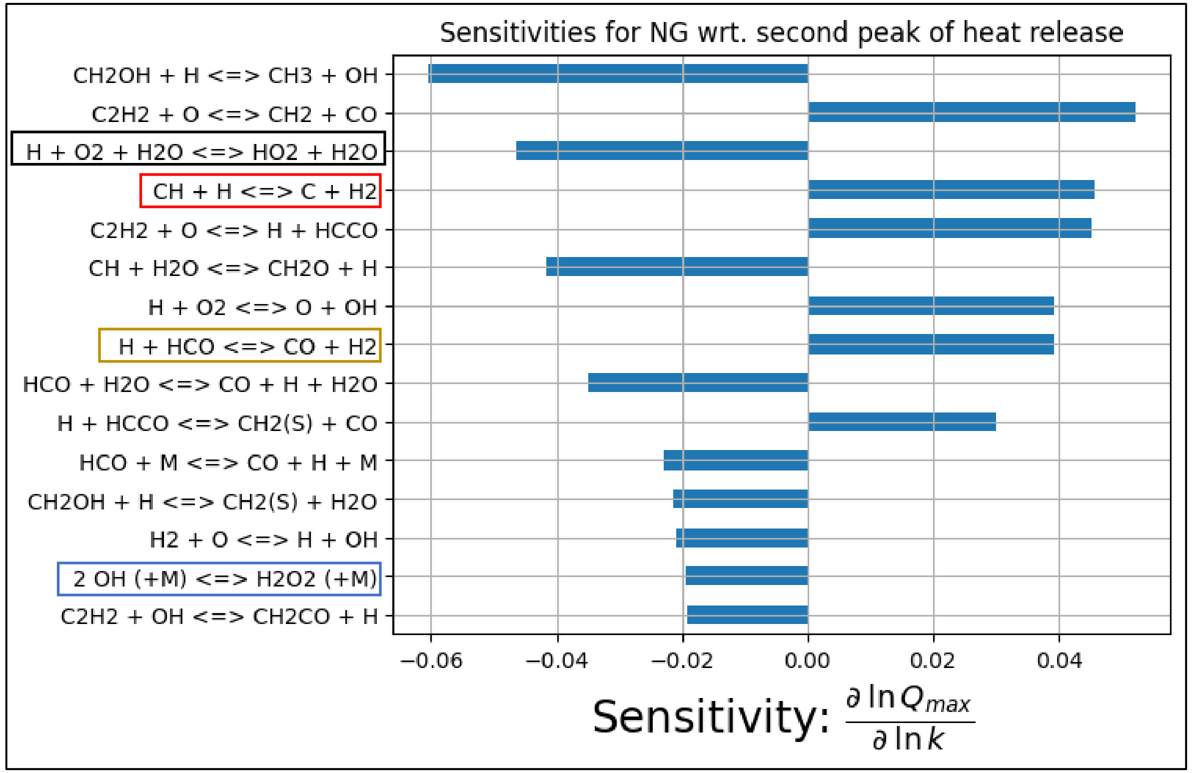


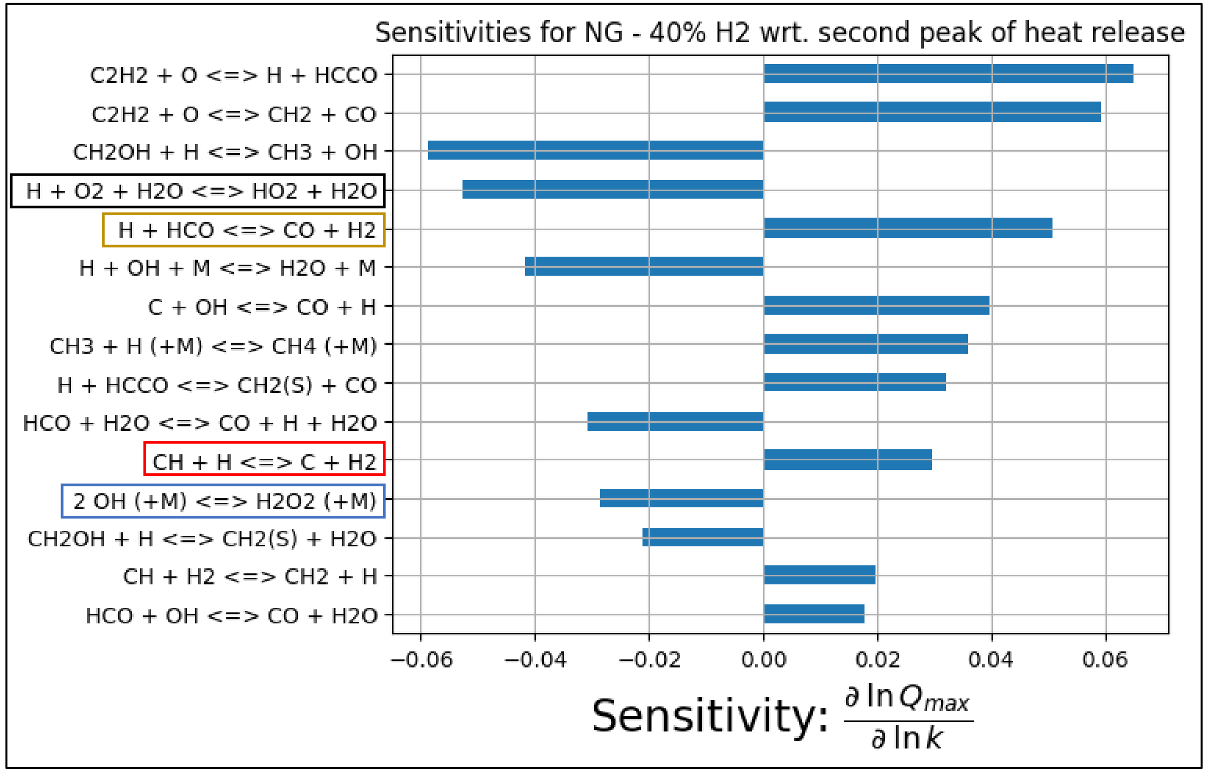


In the region of the second peak, the following inference can be made about a few reactions:

- As % of H2 increases, the sensitivity of H + O2 + H2O ⇔ HO2 + H2O becomes more negative. It is negative in the first place because it is a chain termination reaction and hence reduces the overall rate of combustion. With the increase in % of H2, more concentration of H2O in the mixture might increase the overall reaction rate.

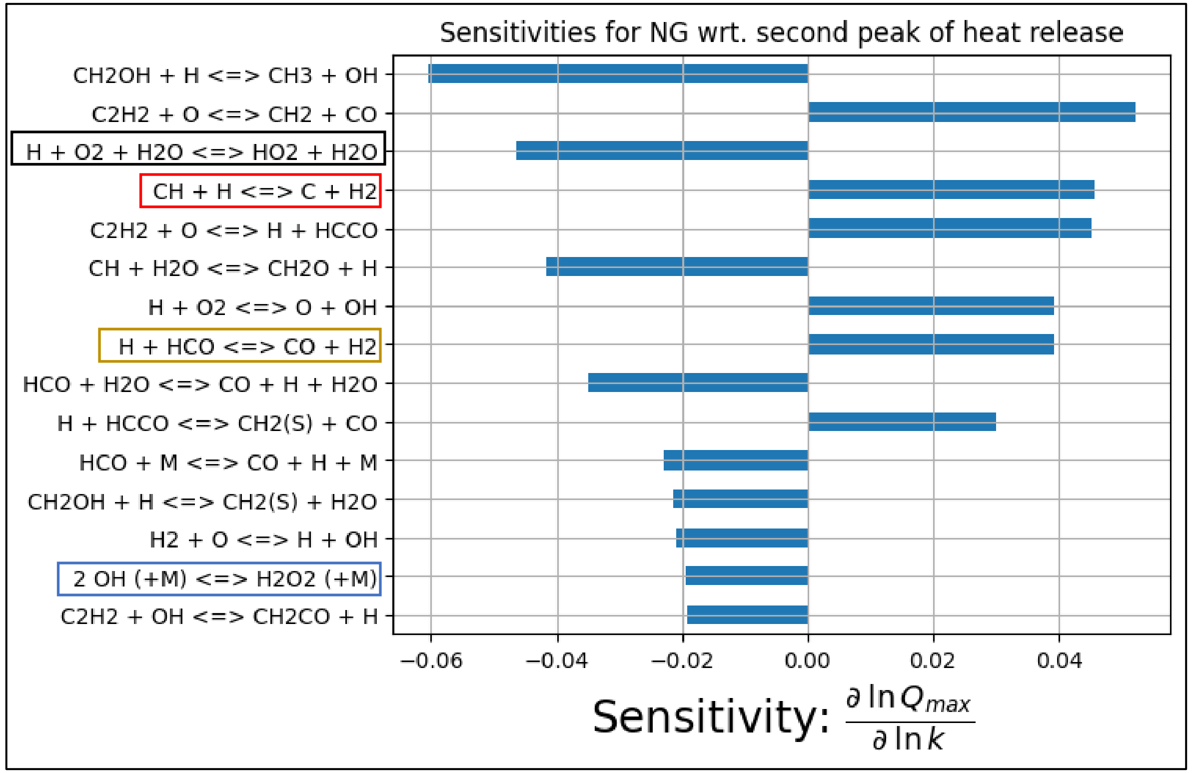
Sensitivity analysis for NG and NG- 40% H2 in the second peak region:

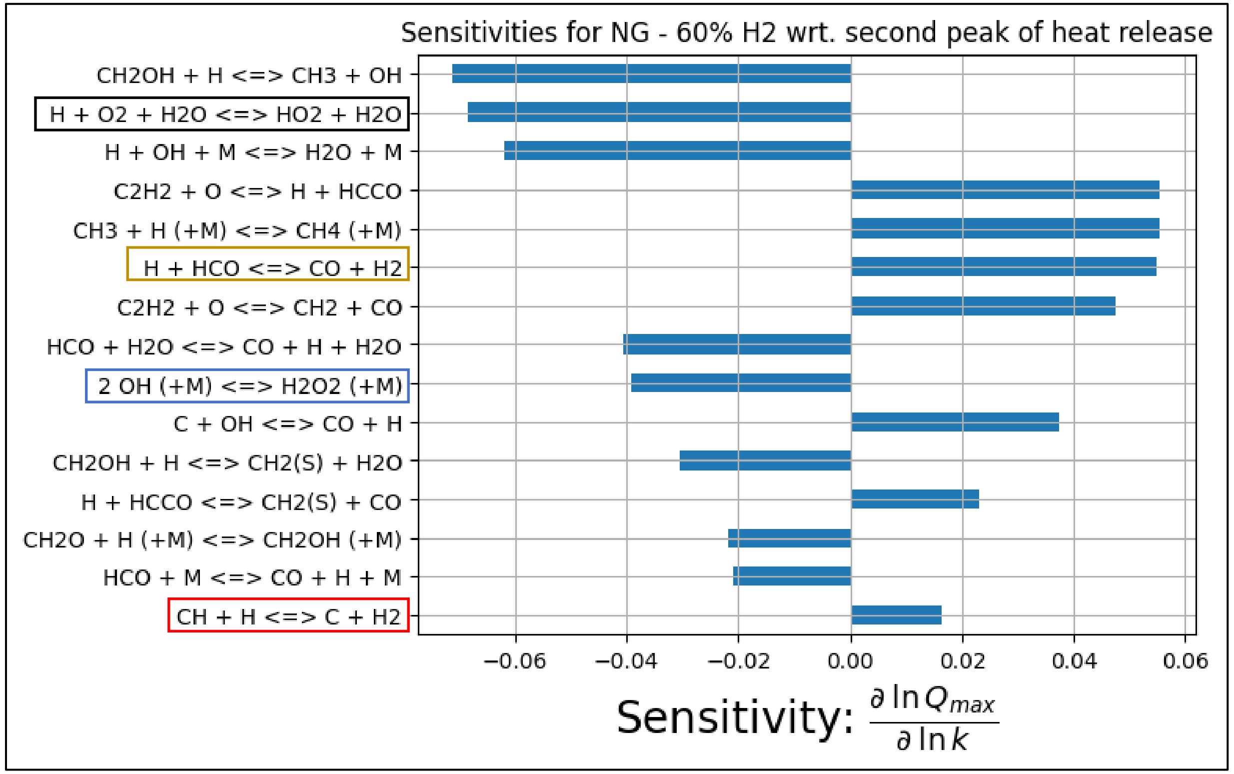




- The overall sensitivity of CH + H ⇔ C + H2 decreases as % of H2 increases. Even though with an increase in H radical concentration, the reaction should have increased and become more positive according to Le Chatlier’s principle, in this case, the trend is the opposite. This can be because the second peak is dominated by hydrocarbon reactions and hence has less effect in this region.
- As % H2 increases, the sensitivity of H + HCO ⇔ CO + H2 increases. This is because of the production of CO which will later produce CO2 as a combustion product.

Sensitivity analysis for NG and NG- 60% H2 in the second peak region:





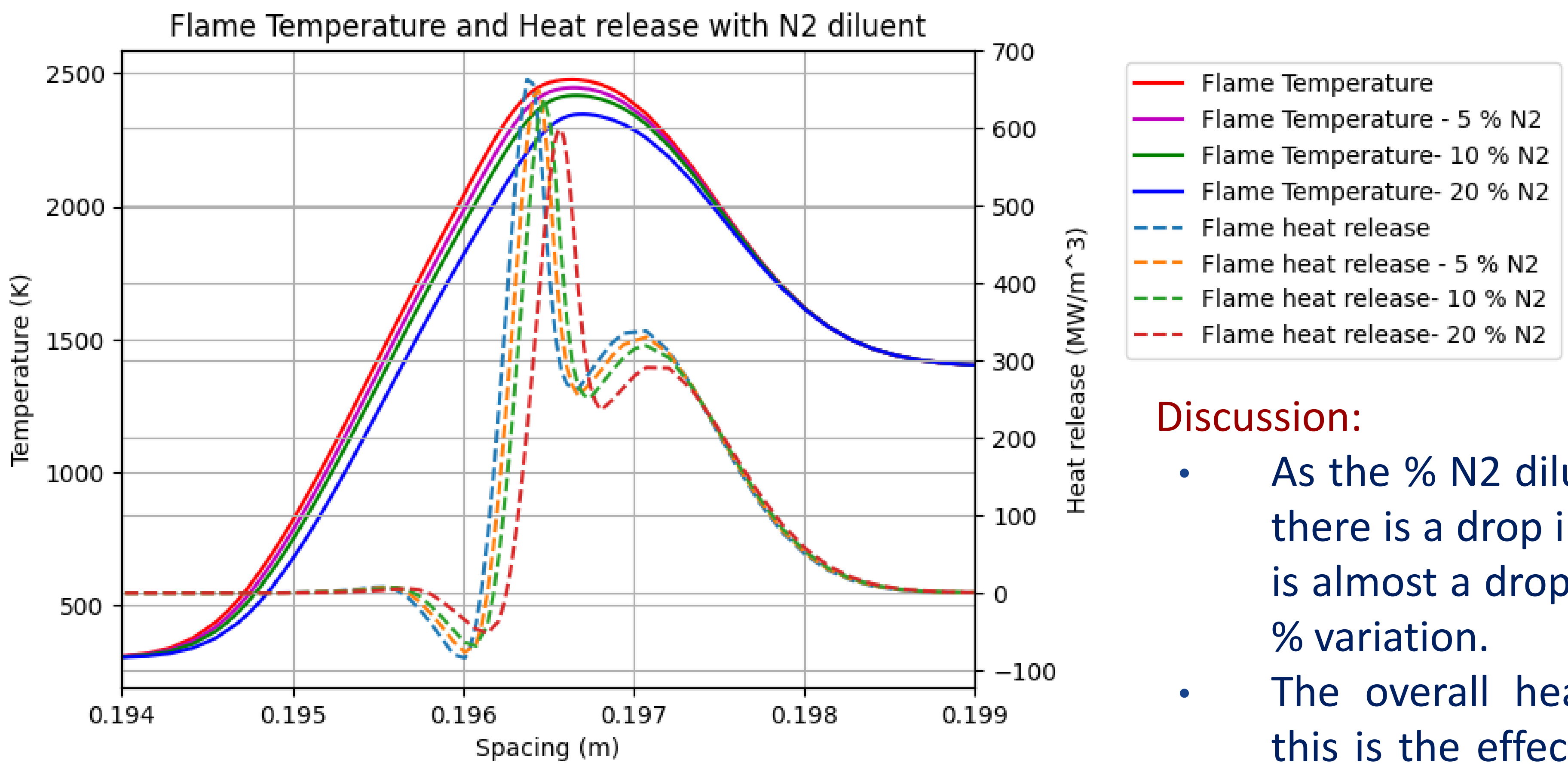
- As % H2 increases, the rank and negative sensitivity of 2 OH (+ M) ⇔ H2O2 (+M) increases. The rank of this reaction is increasing because of the increase in the concentration of OH radicals, and since this reaction is a chain termination reaction, the overall sensitivity is negative.

Emission reduction with combustion air dilution:

Important points:

- In this project, emission reduction has been carried out using the combustion air dilution with inert gases like N_2 and Ar.
- Another gas considered for dilution combustion air, is CO_2. The reason behind using this is, that grey hydrogen currently being used in industry can be converted into blue hydrogen by capturing CO_2.
- If this CO_2 can be used to dilute combustion air, and achieve emission reduction, then it can be a step towards net zero carbon emission.
- In this study, NG - 40 % H_2 blending has been used and the diluent % has been varied from 5% to 20 % by doubling the percentage in every step.

N2 dilution: Effect on flame temperature and heat release

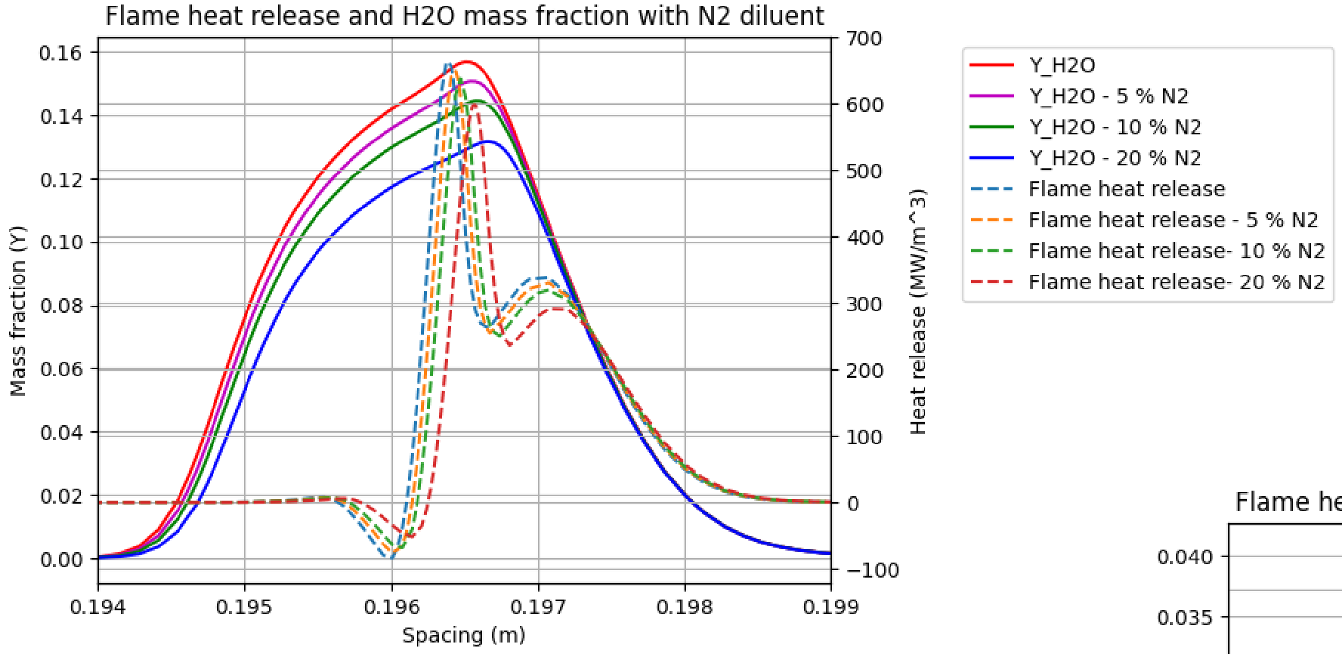


Discussion:

- As the % N2 dilution in the air increases, there is a drop in the temperature. There is almost a drop of 60 deg. with every 10 % variation.
- The overall heat release rate reduces, this is the effect of reducing air amount in the combustion.

- The flame shifts more towards the air-stream side, signifying the presence of more fuel in the combustion mixture.

N2 dilution: Effect on H2O and CO2 mass fraction



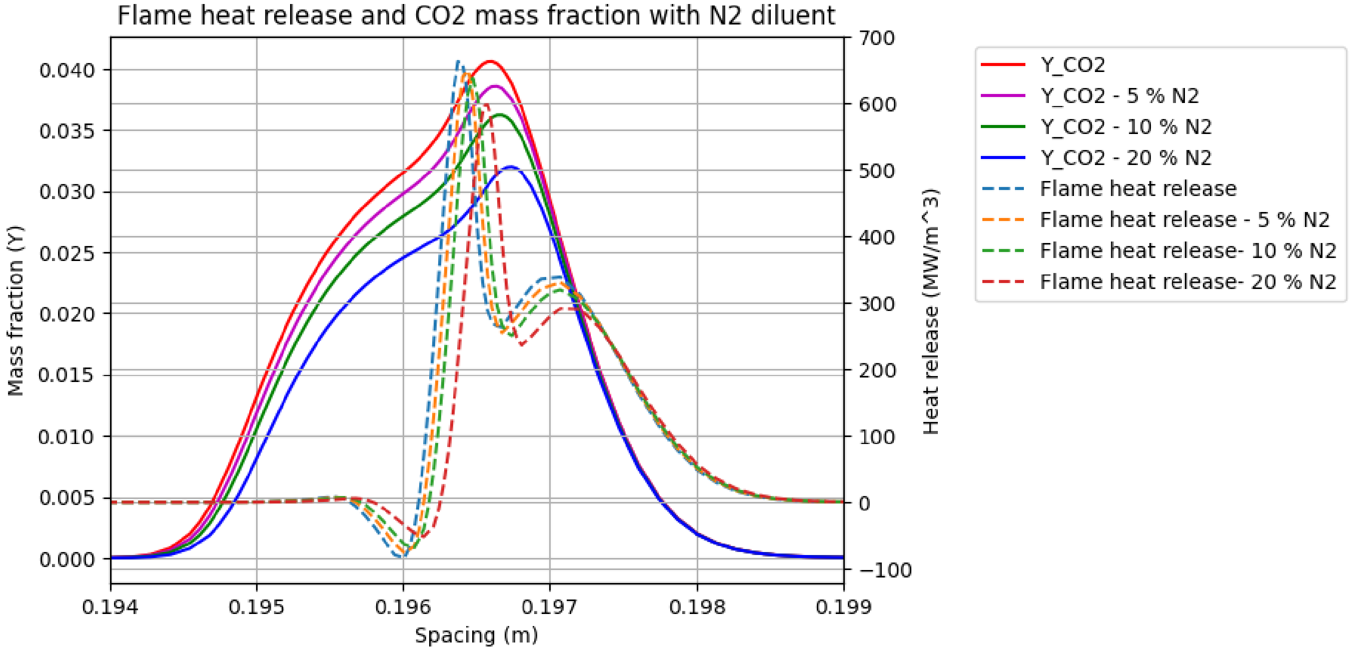
Discussion:

- As the % N2 dilution in the air increases, the % H2O in the exhaust gases drops.

I. 5 % diluent N2 : 3 % decrease

II. 10 % diluent N2 : 7 % decrease

III. 20 % diluent N2 : 16 % decrease



Discussion:

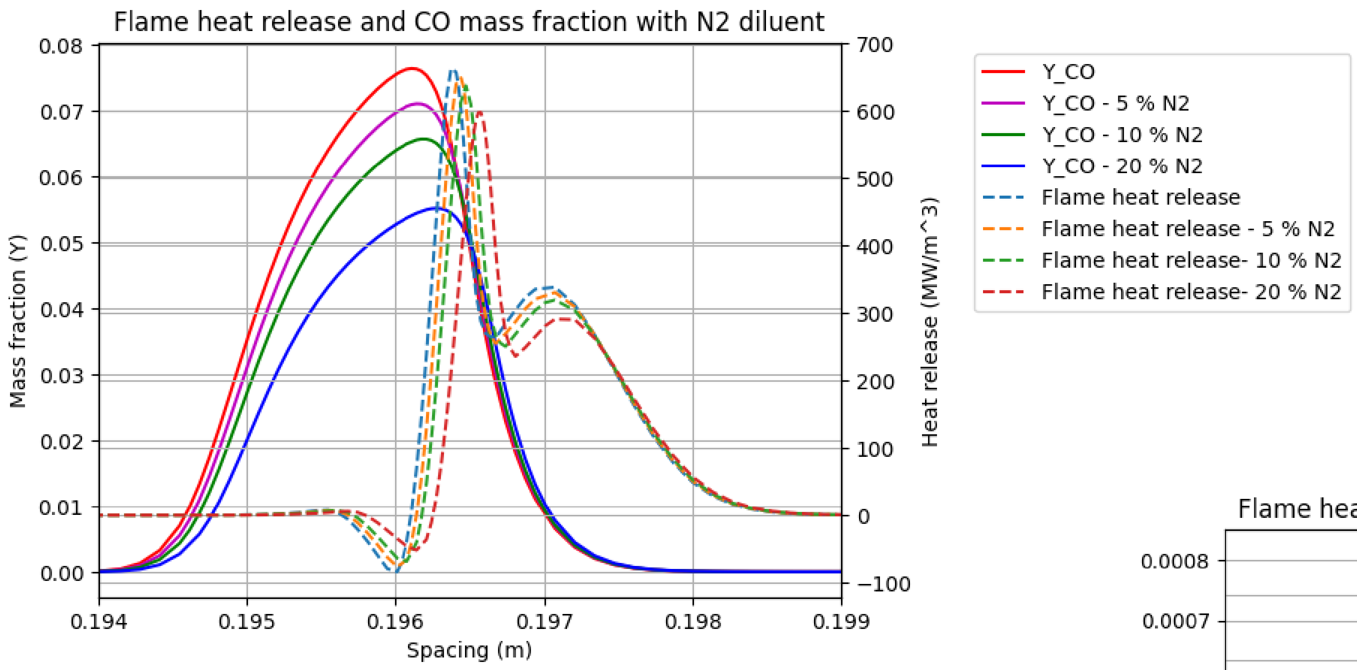
- As the % N2 dilution in the air increases, the % CO2 in the exhaust gases drops.

I. 5 % diluent N2 : 5 % decrease

II. 10 % diluent N2 : 10 % decrease

III. 20 % diluent N2 : 21 % decrease

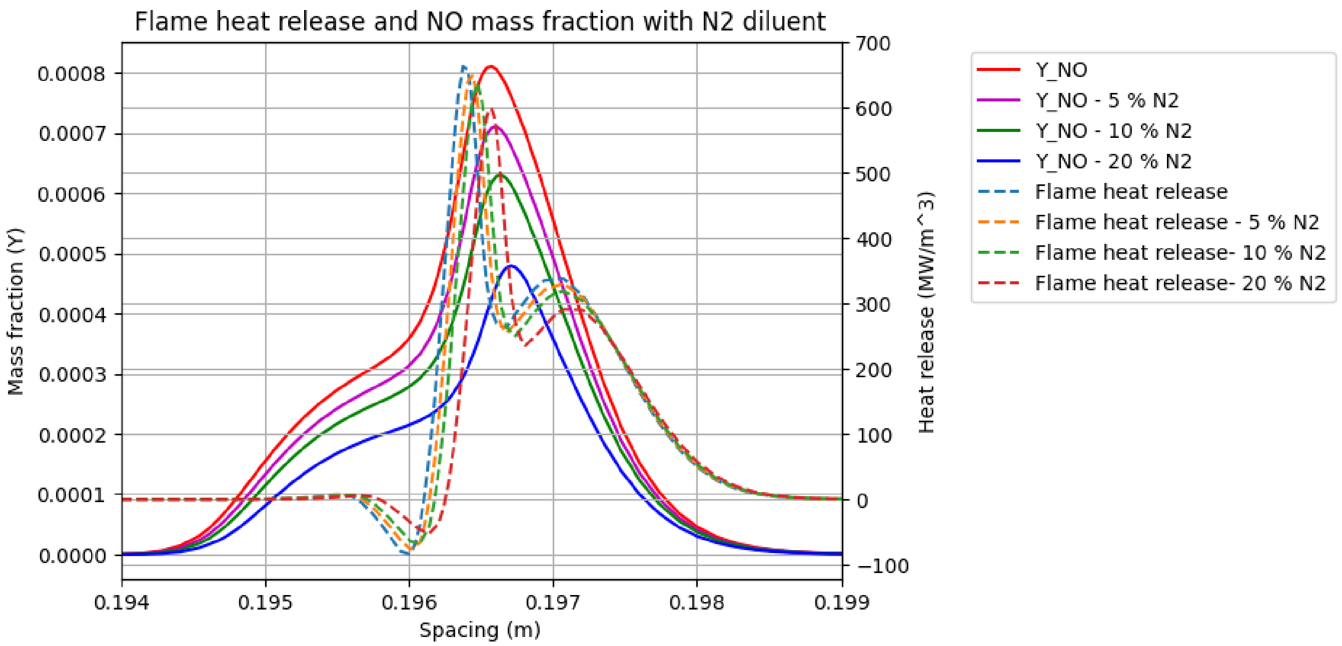
N2 dilution: Effect on CO and NO mass fraction



Discussion:

- As the % N2 dilution in the air increases, the % CO in the exhaust gases drops.

I. 5 % diluent N2 : 7 % decrease
II. 10 % diluent N2 : 14 % decrease
III. 20 % diluent N2 : 27 % decrease

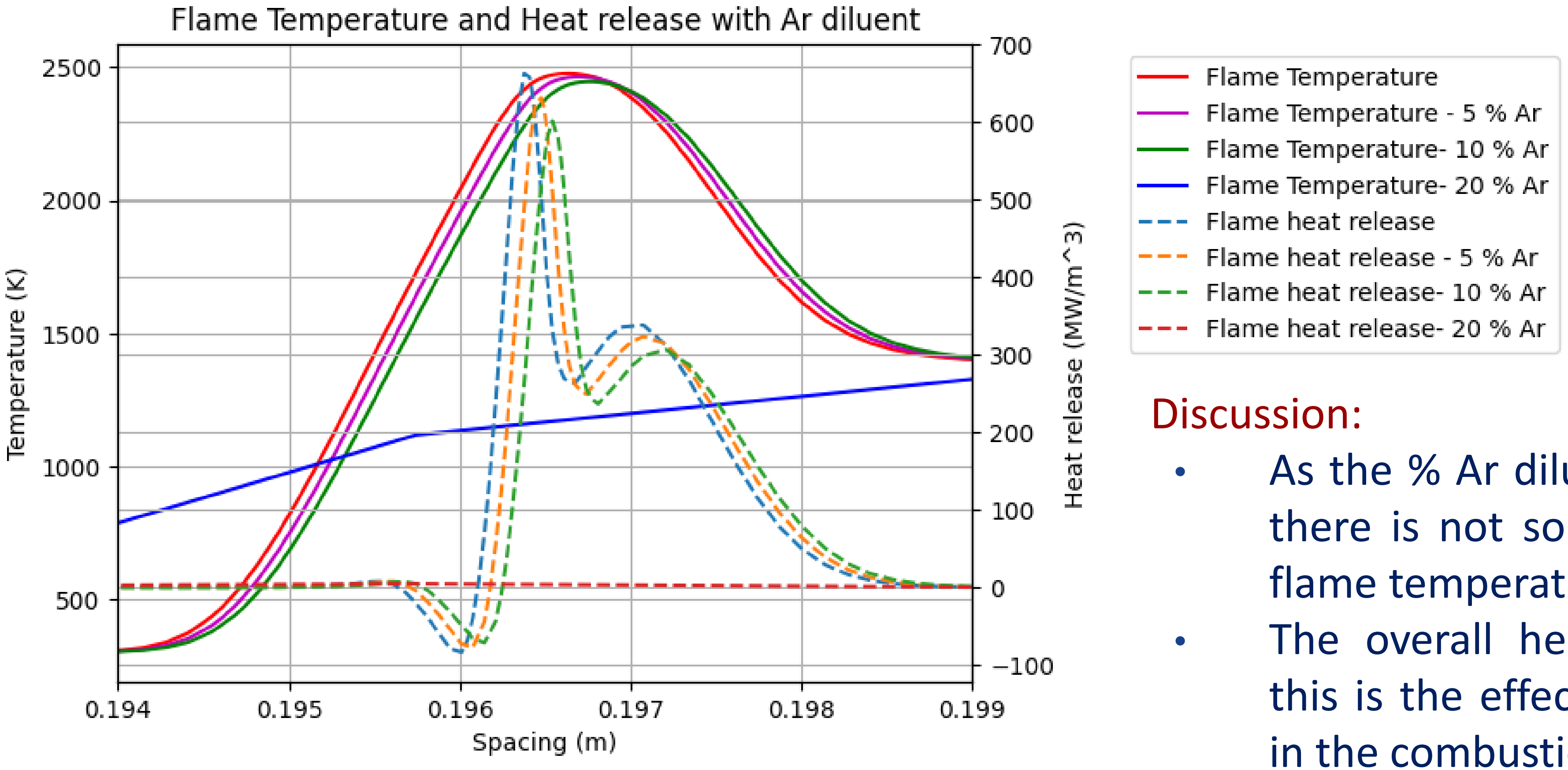


Discussion:

- As the % N2 dilution in the air increases, the % NO in the exhaust gases drops.

I. 5 % diluent N2 : 12 % decrease
II. 10 % diluent N2 : 22 % decrease
III. 20 % diluent N2 : 40 % decrease

Ar dilution: Effect on flame temperature and heat release

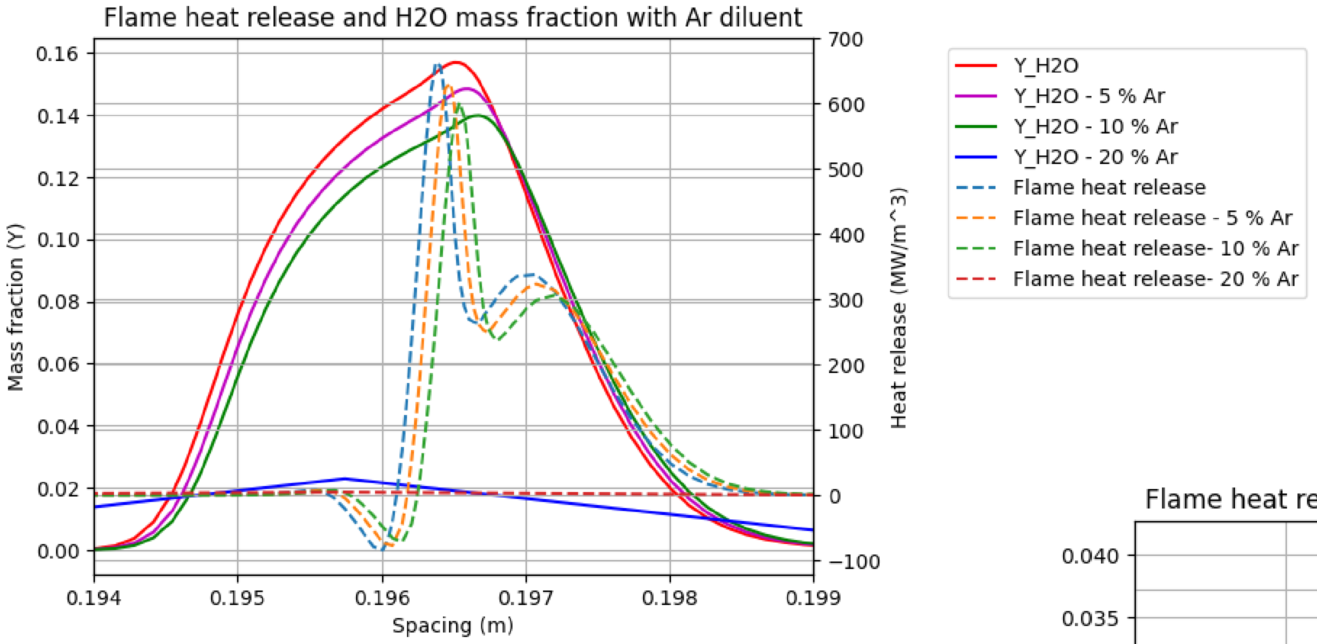


Discussion:

- As the % Ar dilution in the air increases, there is not so significant effect on the flame temperature.
- The overall heat release rate reduces, this is the effect of reducing air amount in the combustion mixture.

- No combustion is observed for 20 % of the Ar case, this is the the result of the increased amount of non-combustible gas in the combustion mixture.

Ar dilution: Effect on H2O and CO2 mass fraction



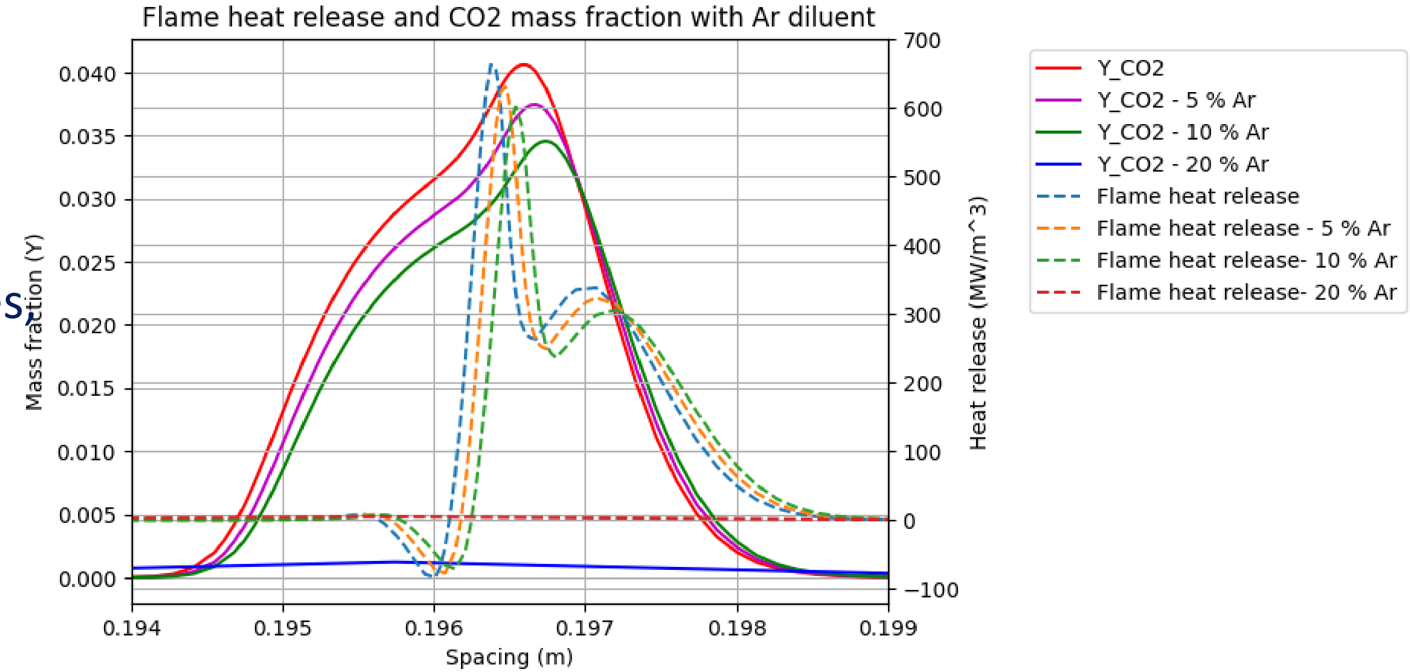
Discussion:

- As the % Ar dilution in the air increases, the % H2O in the exhaust gases drops.

I. 5 % diluent Ar : 5 % decrease

II. 10 % diluent Ar : 10 % decrease

III. 20 % diluent Ar : No combustion



Discussion:

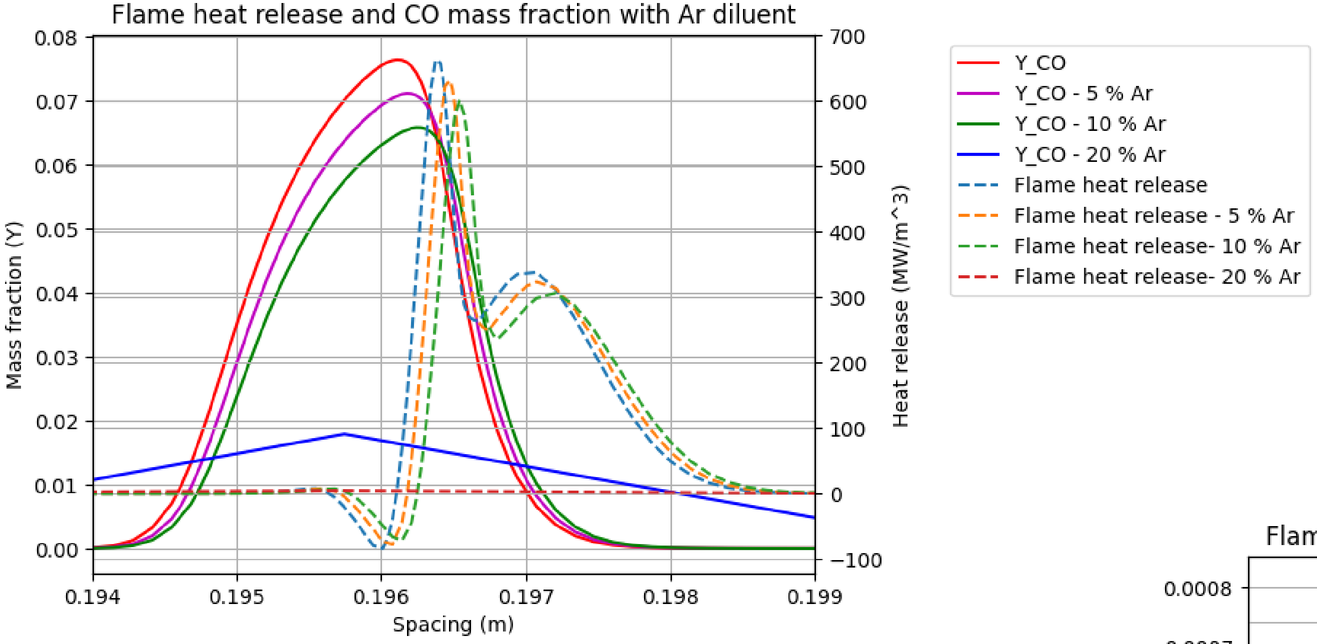
- As the % Ar dilution in the air increases, the % CO2 in the exhaust gases drops.

I. 5 % diluent Ar : 7 % decrease

II. 10 % diluent Ar : 14 % decrease

III. 20 % diluent Ar : No combustion

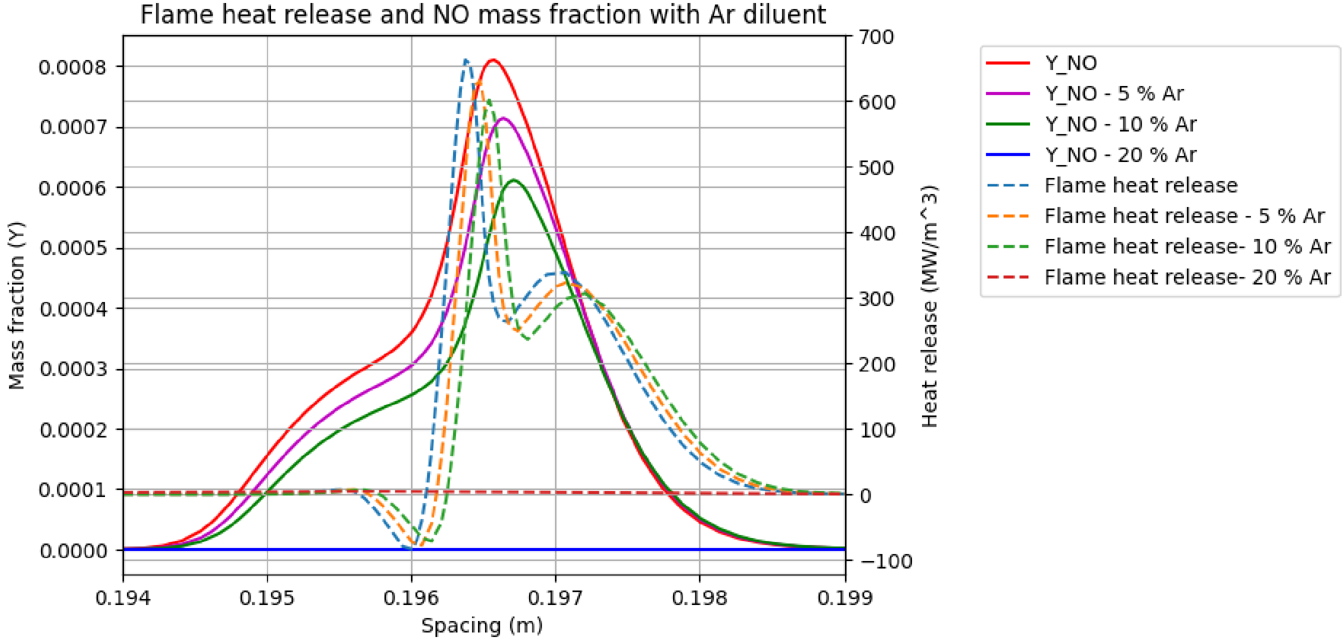
Ar dilution: Effect on CO and NO mass fraction



Discussion:

- As the % Ar dilution in the air increases, the % CO in the exhaust gases drops.

I. 5 % diluent Ar : 6 % decrease
II. 10 % diluent Ar : 13 % decrease
III. 20 % diluent Ar : No combustion

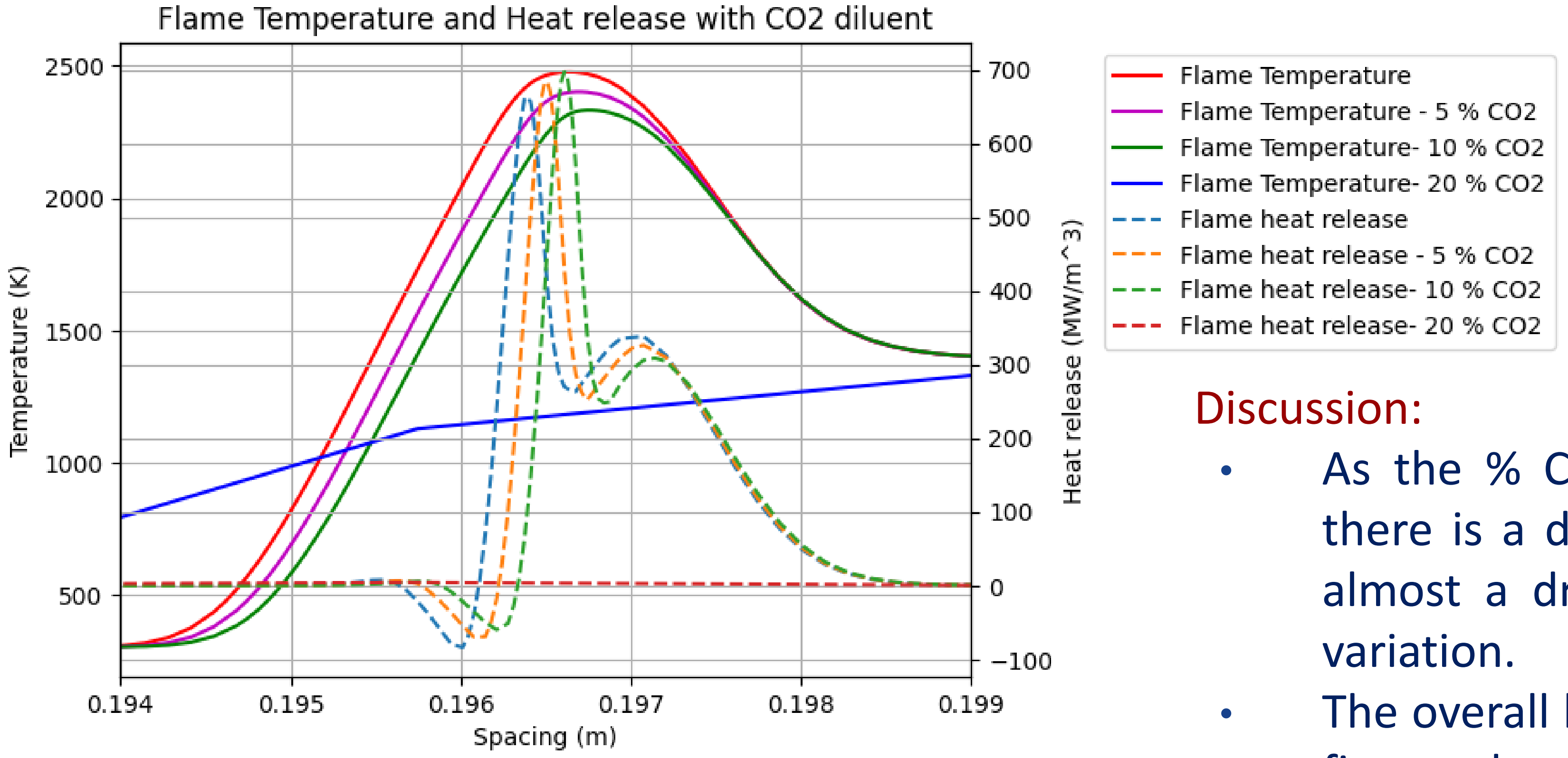


Discussion:

- As the % Ar dilution in the air increases, the % H2O in the exhaust gases drops.

I. 5 % diluent Ar : 11 % decrease
II. 10 % diluent Ar : 24 % decrease
III. 20 % diluent Ar : No combustion

CO_2 dilution: Effect on flame temperature and heat release

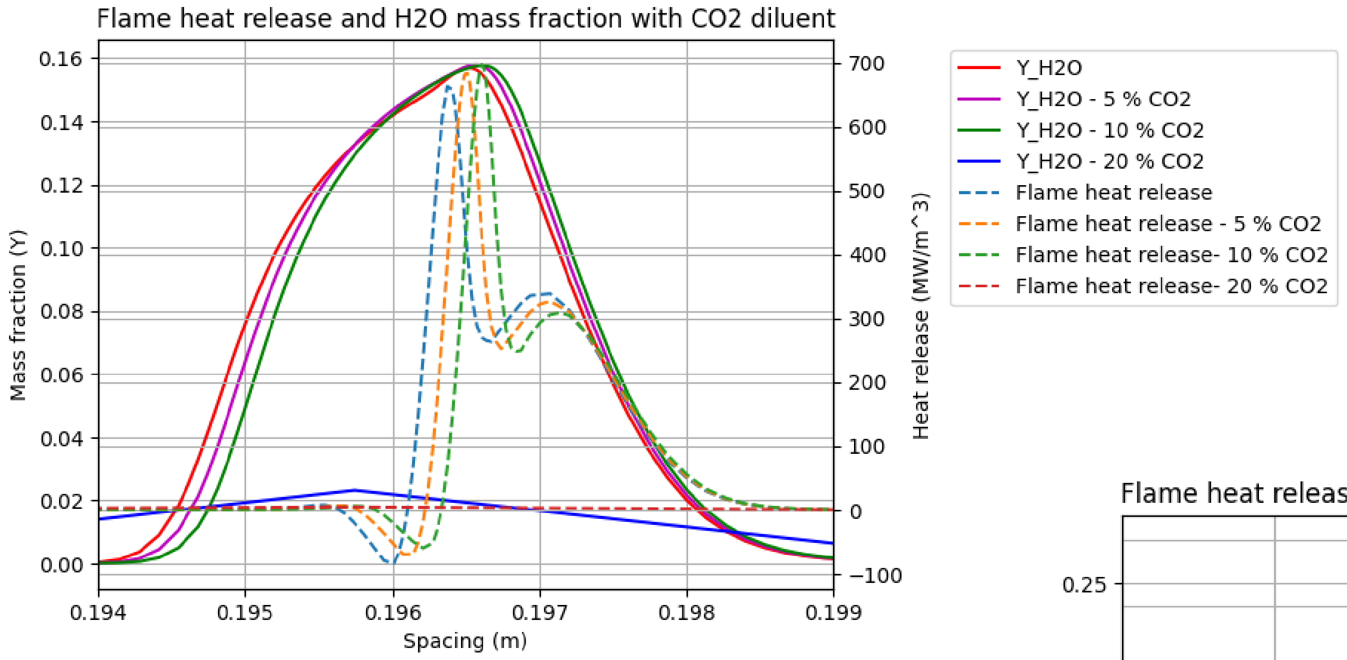


Discussion:

- As the % CO_2 dilution in the air increases, there is a drop in the temperature. There is almost a drop of 60 deg. with every 10 % variation.
- The overall heat release rate decreases in the first peak and increases in the second peak.

- This can be because the addition of CO_2 may be contributing to the hydrocarbon combustion mechanism but reducing the rate of H_2 combustion. However, the % change in heat release is not so high.
- No combustion is observed for 20 % of the CO_2 case, this is the result of the increased amount of non-combustible gas in the combustion mixture.

CO2 dilution: Effect on H2O and CO2 mass fraction



Discussion:

- As the % CO2 dilution in the air increases, there is no significant effect on the H2O emission except in the case of 20 % CO2, where there is no combustion recorded.

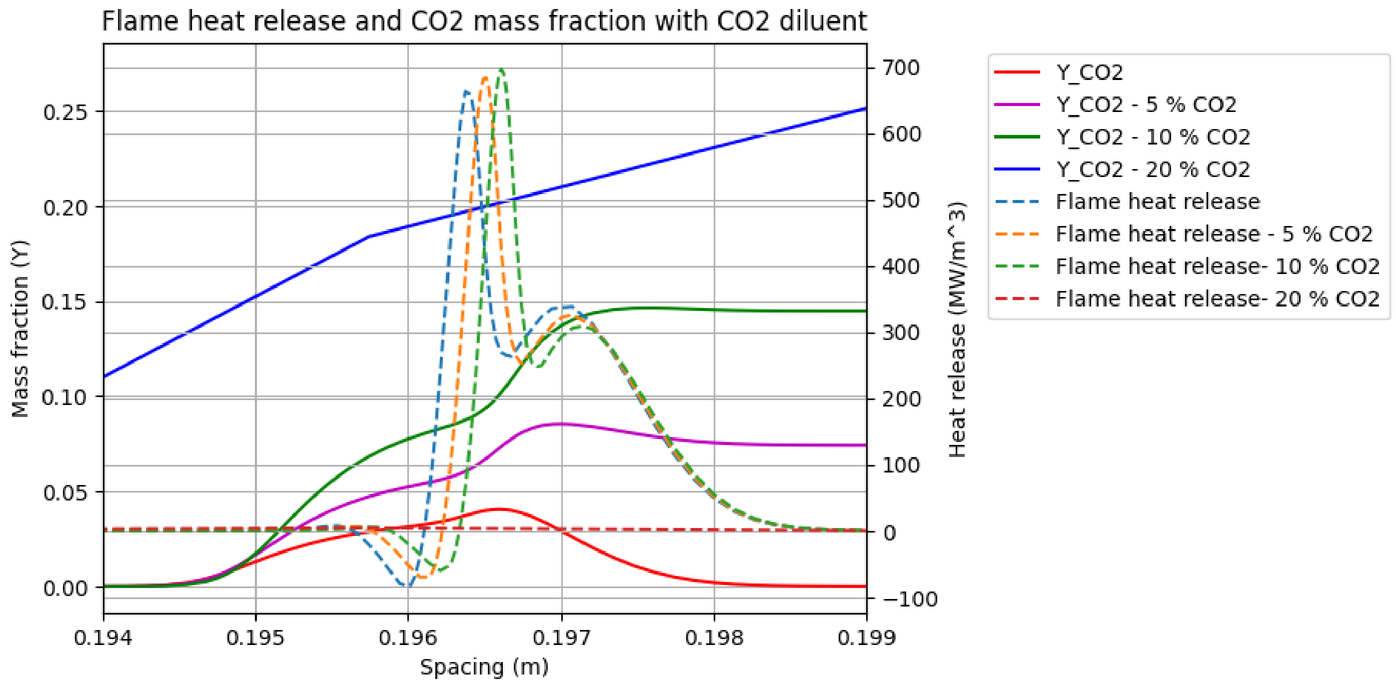
Discussion:

- As the % CO2 dilution in the air increases, the % CO2 in the exhaust gases increases.

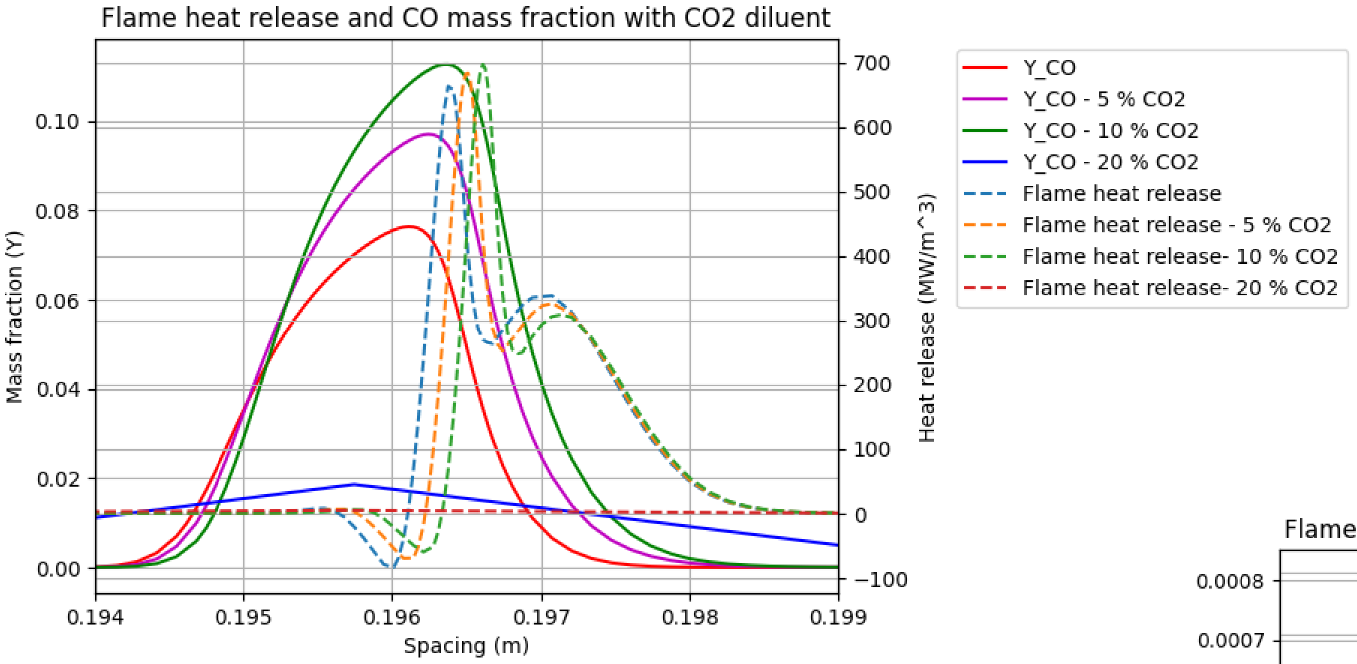
I. 5 % diluent CO2 : 110 % increase

II. 10 % diluent CO2 : 261 % increase

III. 20 % diluent CO2 : No combustion



CO2 dilution: Effect on CO and NO mass fraction



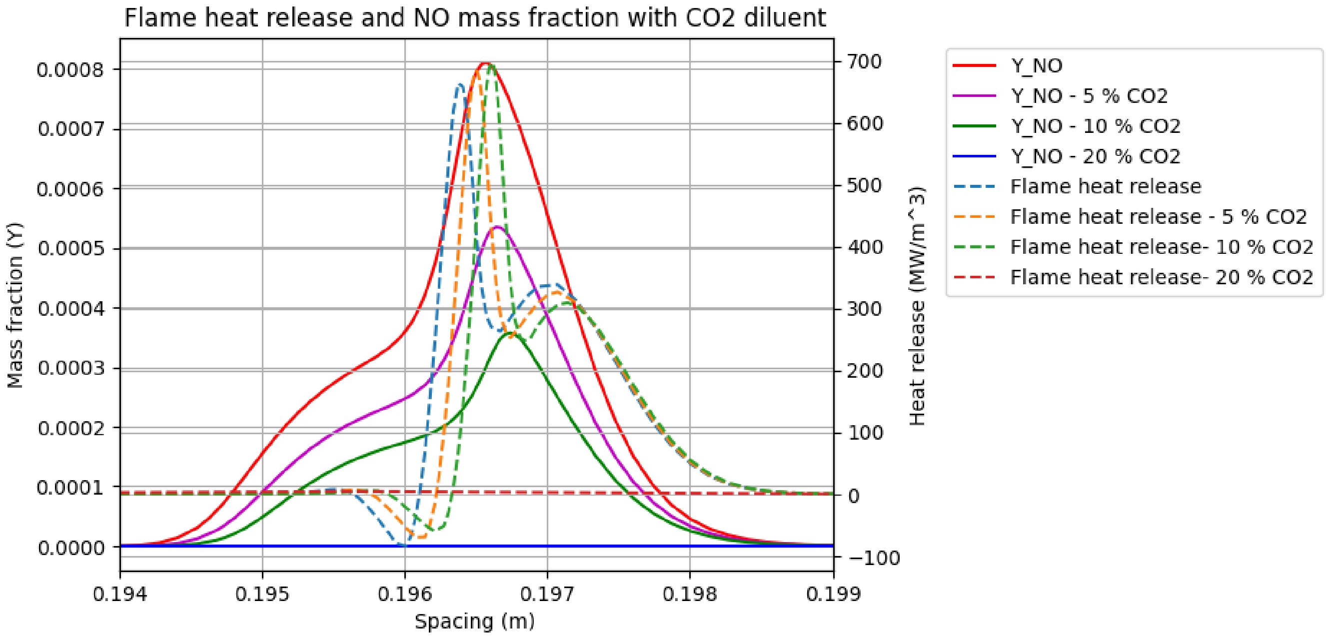
Discussion:

- As the % CO2 dilution in the air increases, the % CO in the exhaust gases increases.

I. 5 % diluent CO2 : 27 % increase

II. 10 % diluent CO2 : 47 % increase

III. 20 % diluent CO2 : No combustion



Discussion:

- As the % CO2 dilution in the air increases, the % NO in the exhaust gases drops.

I. 5 % diluent CO2 : 33 % decrease

II. 10 % diluent CO2 : 55 % decrease

III. 20 % diluent CO2 : No combustion

Micro-mixing: A possible solution for reducing NOx:

- Dependence on Natural gas as a fuel can be reduced by adapting it to burn 100% H2 or H2 blends above 20%.
- Key in applications where electrification isn't possible. ex: Melting furnaces.
- Micromix-type gas turbines take advantage of the Micromix Combustion Principle (MCP) to accommodate this H_2 and the same principle can be adopted in the case of industrial burners.

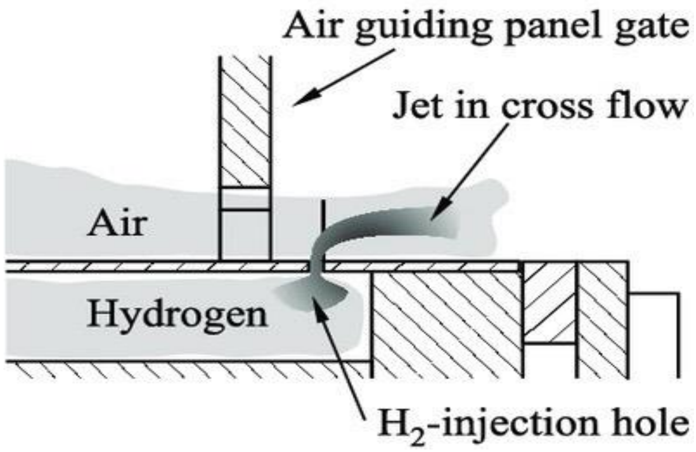
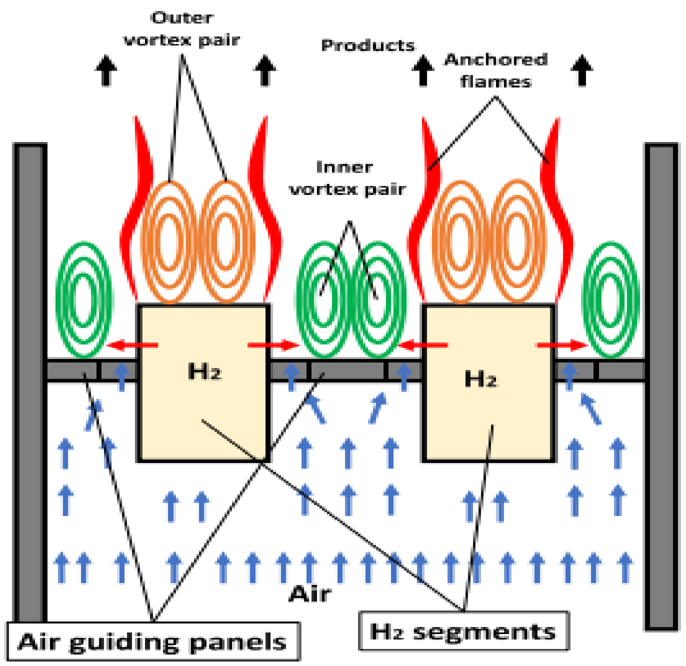


Fig: Principle of Micromixing

- Fuel flexibility of gas turbine burners at high air-fuel equivalence ratios is a subject of extensive research.
- The principle of MCP can be extrapolated to the Industrial burner case at near stoichiometric conditions.



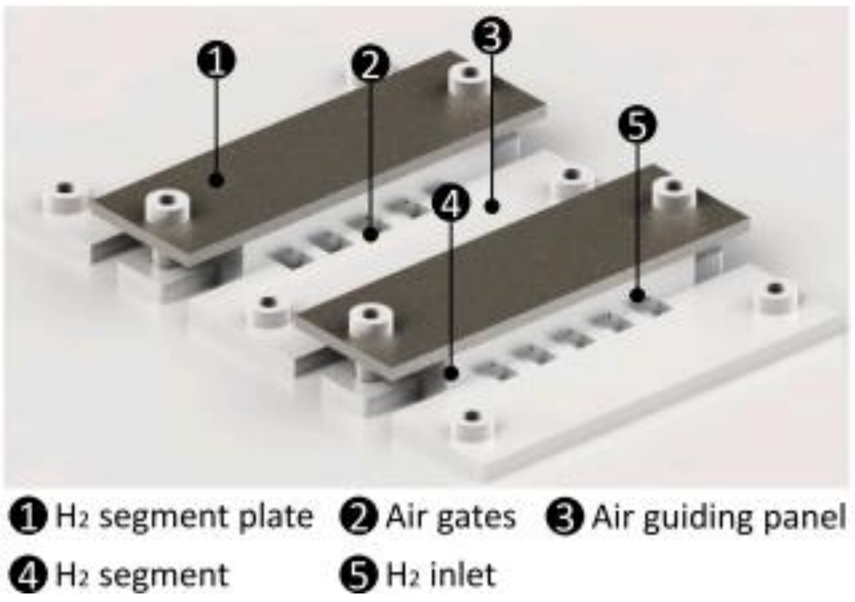


Fig: Micromix - type furnace burner working(left) and prototype(right)[10]

Fuel Index	H_2 [vol %]	Air Fuel Equivalence Ratio
A60	60	1.6
A75	75	1.6
A90	90	1.6
B60	60	1.8
B75	75	1.8
B90	90	1.8

Table: Fuel compositions used for simulations

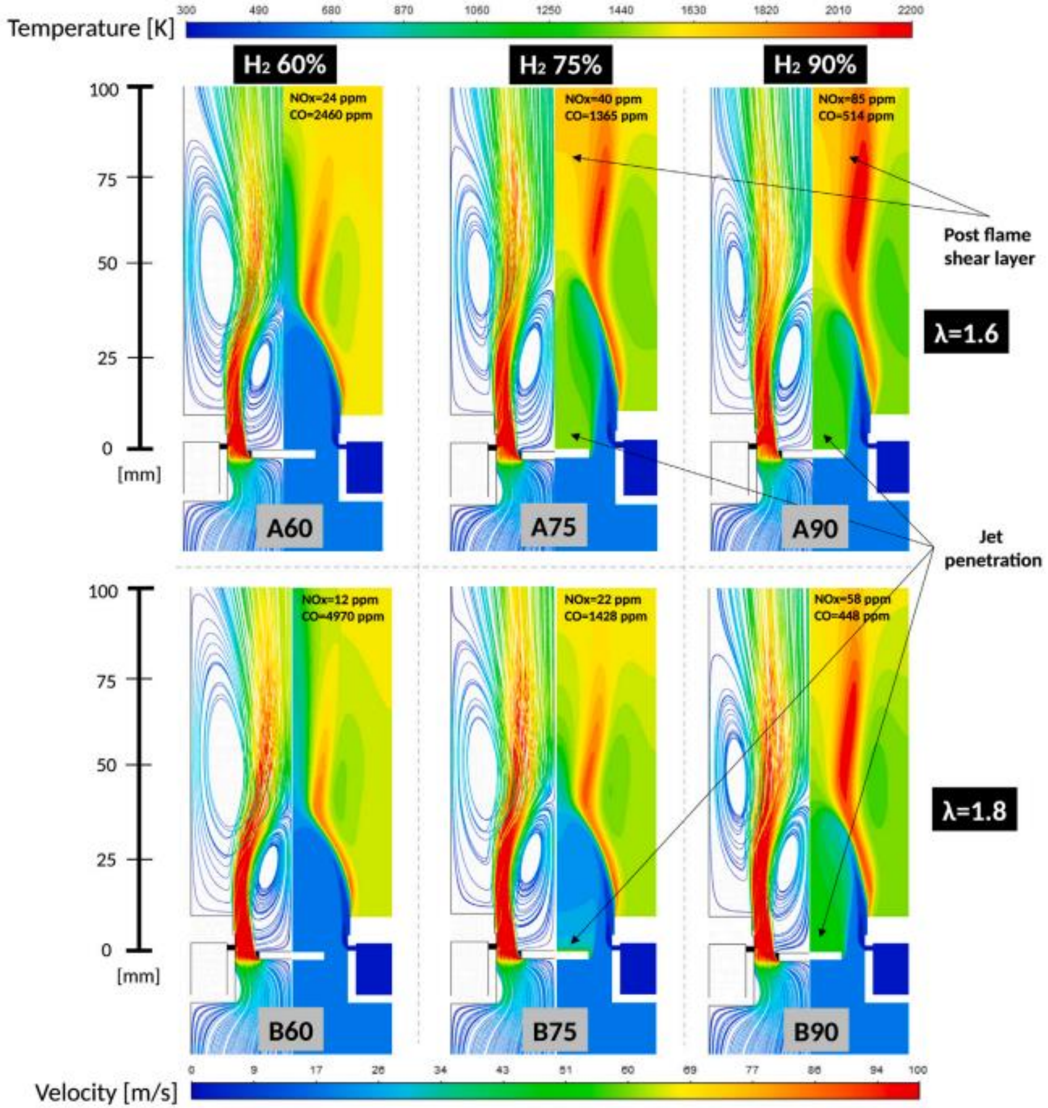


Fig: CFD results showing temperature results and Emission concentration

- Micro-mixing at an industrial scale significantly reduces the concentration of NO at H_2-60% or lower.
- Higher concentrations of H_2 promote fuel jet penetration into the oxidizer stream, which may damage the burner.
- A geometrically optimized burner design would improve the performance and make it possible for the H_2 concentration to be greater than 60%.
- This burner principle is relatively new for regenerative gas furnaces and needs further research.

Way Forward:

- For this study GRI3.0 combustion mechanism has been used. This is optimized for Natural gas combustion. This mechanism has been used based on the limitation of the scope and computational resources available for the project.
- For NG-H2 blends, the GRI3.0 predicts better the temperature-based combustion properties like flame temperature, heat release rate, and velocity, however for species concentration details, this mechanism might underpredict the values. Hence, for detailed and accurate combustion modeling, the state-of-the-art **Flamelet Generated Manifold** (FGM) combustion modeling technique with other mechanisms optimized for NG-H2 blending can be used.
- For reducing NOx production, a burner with micro-mixing has proved the best for land-based gas turbine engines burning NG-H2 blends and even 100 % H2. This technique can be explored for combustion in glass furnace burners.

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1. McQuay, M.Q., Webb, B.W. and Huber, A.M., 2000. The effect of rebuild on the combustion performance of an industrial gas-fired flat glass furnace. *Combustion science and technology*, *150*(1-6), pp.77-97.
2. Sardeshpande, V., Gaitonde, U.N. and Banerjee, R., 2007. Model based energy benchmarking for glass furnace. *Energy Conversion and Management*, *48*(10), pp.2718-2738.
3. Hayes, R.R., Brewster, S., Webb, B.W., McQuay, M.Q. and Huber, A.M., 2001. Crown incident radiant heat flux measurements in an industrial, regenerative, gas-fired, flat-glass furnace. *Experimental Thermal and Fluid Science*, *24*(1-2), pp.35-46.
4. Lopez-Ruiz, G., Alava, I. and Blanco, J.M., 2023. Impact of H2/CH4 blends on the flexibility of micromix burners applied to industrial combustion systems. *Energy*, *270*, p.126882.
5. https://github.com/Swadesh03/Project-Hydrogen-as-an-alternative-fuel-for-Glass-furnaces-