Experimental and numerical analysis of hydrogen combustion in a high-pressure Oxygen-CO2 environment. Design and performance of a combustion chamber

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HERMES
Highly Efficient super critical zeRo eMission Energy System

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General agenda

- Introduction – general concept of installation?
- Experimental test rig
- Experimental results
- Numerical results
- Conclusions

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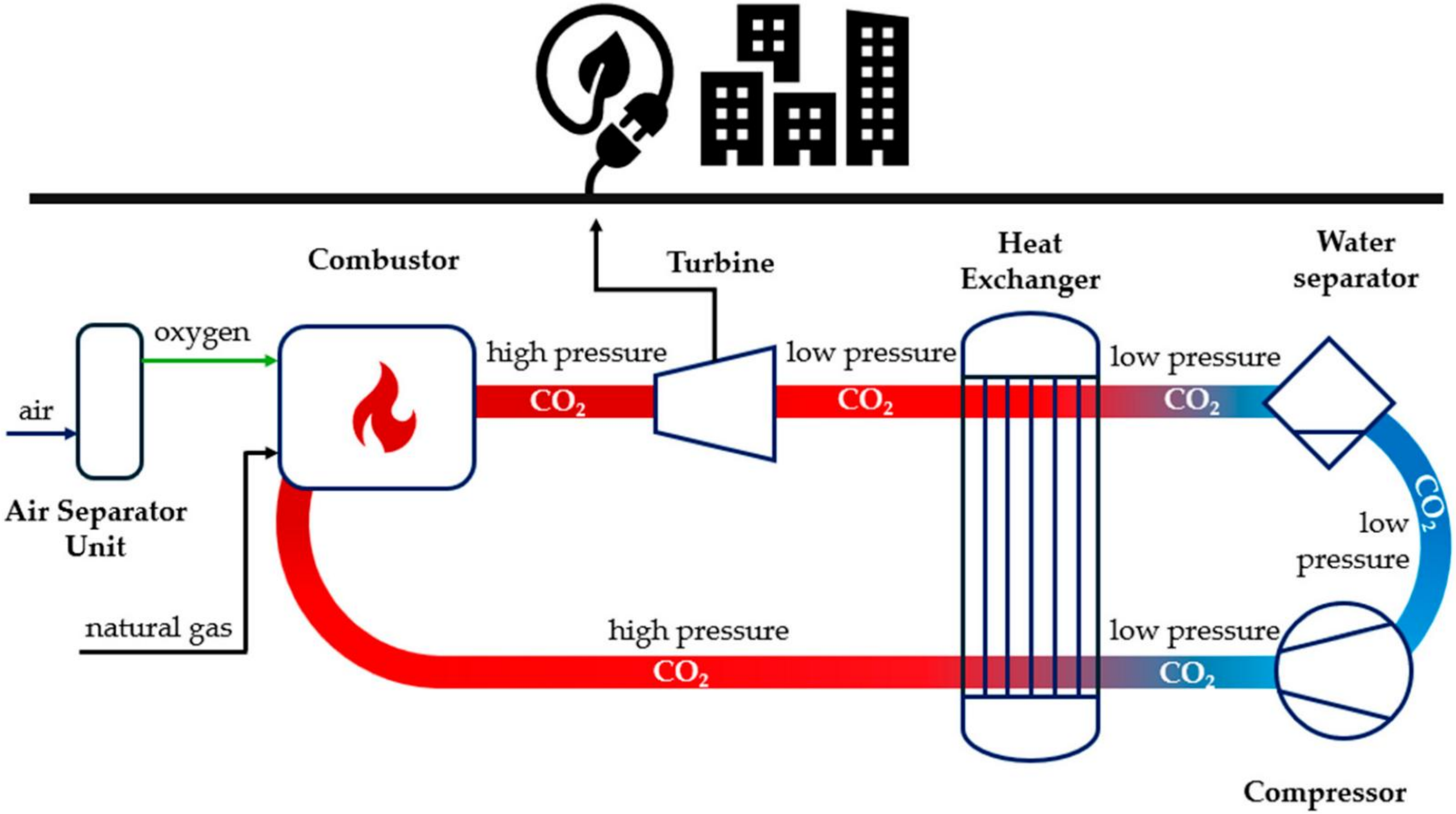
General motivation



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The oxy combustion of direct fired H2 in high concentration of CO2 at high Pressure close supercritical conditions– (The Allam cycle concept)

Design and Modeling of high pressure OxyCombustor for Direct Fired Supercritical SCO2 cycle

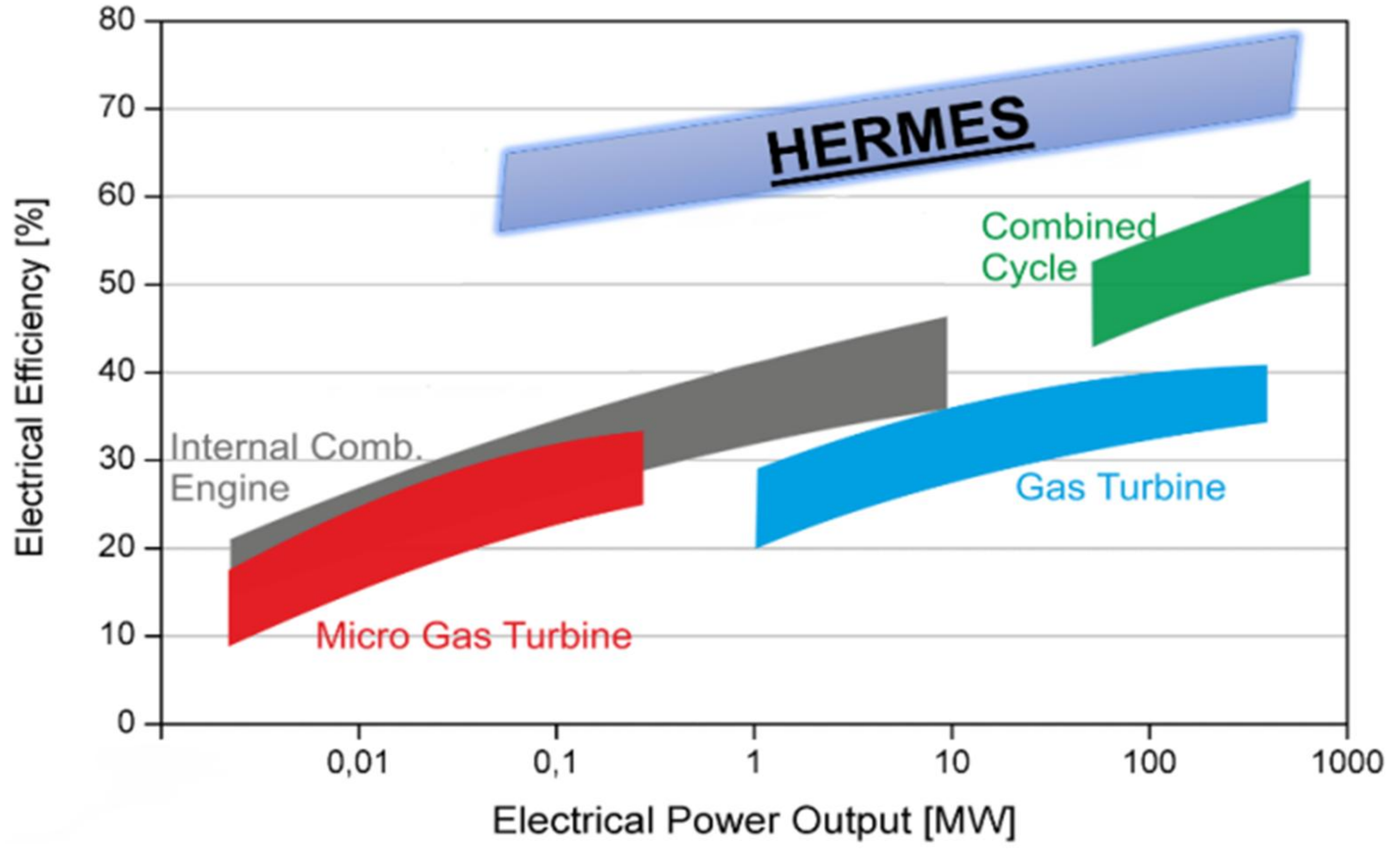

Fig. 2.1. Estimated efficiency development of supercritical GT in comparison with other power systems

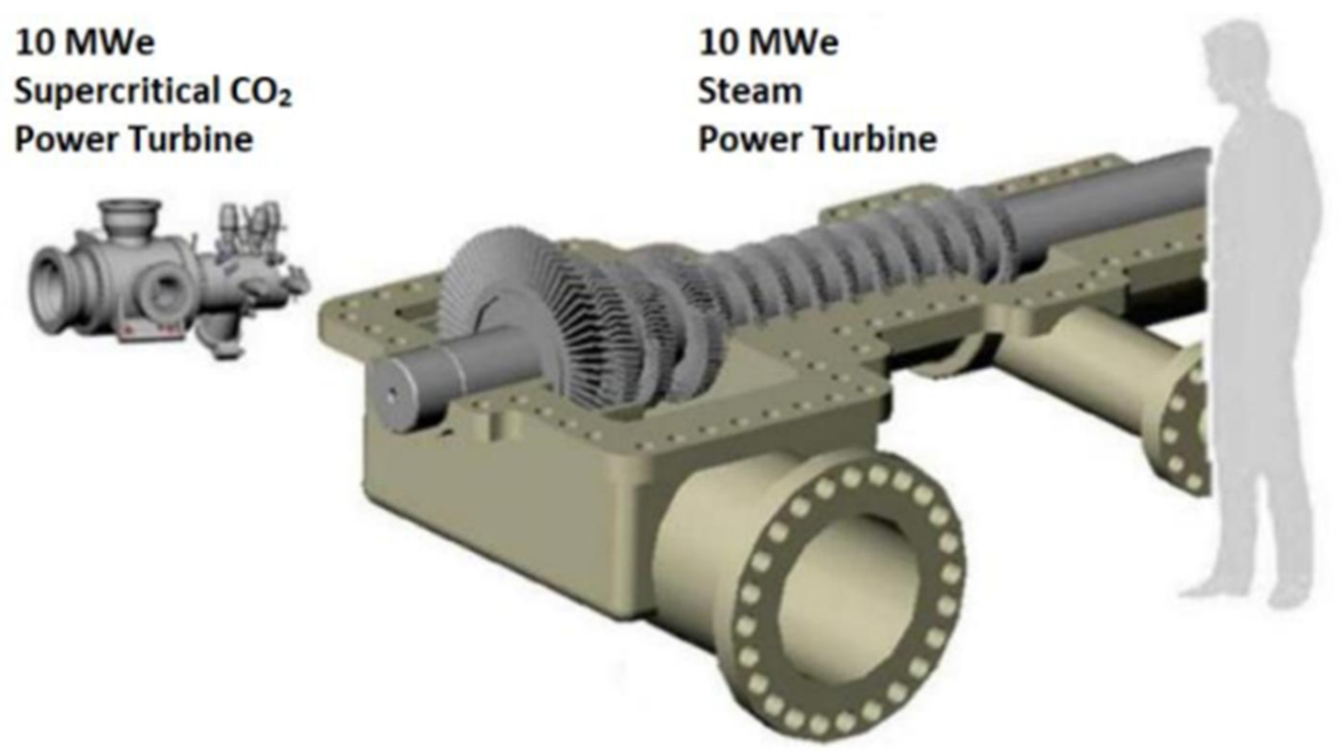

Fig.2.2 Comparison of sizing the supercritical technology with conventional system[49]

Fig. 2.1. Indicates the advantages of the supercritical HERMES system in terms of efficiency (>65%) for power outputs above 1MW, that are typical for decentralized electricity and heat production at neighborhood level (contributing to Net Zero Energy Communities, large building complexes, critical infrastructures like hospitals power generation, and energy intensive industries).

The idea of oxy combustor for direct fired H2 in supercritical CO2 – (The Allam cycle concept)

- **Introduction**

Our work presents experimental and numerical simulation studies of hydrogen combustion in an atmosphere highly diluted with carbon dioxide and at various pressures ranging from 10 to 50 bar. A special combustion chamber with a multi-hole burner was designed for this problem to determine the effect of pressure and CO_2 concentration on flame stability and flammability limits. The problem required the use of a special fuel and oxidizer injection system due to the significant differences in the density and heat capacity of hydrogen and carbon dioxide.

Developing a cooling system for the chamber material was a challenge.

Temperature distribution studies were conducted to verify the results of the numerical calculations.

General concept of installation

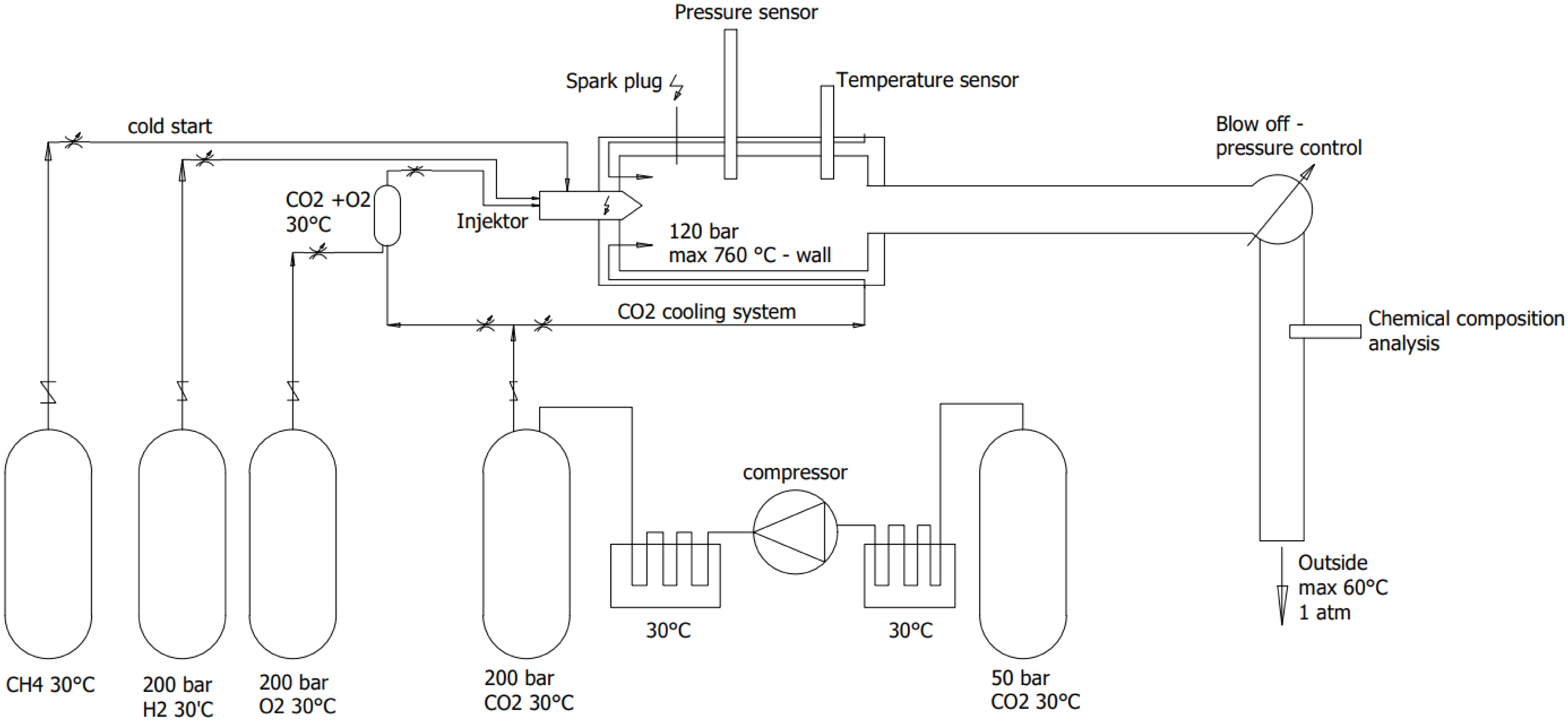

Fig. 1 General concept of installation

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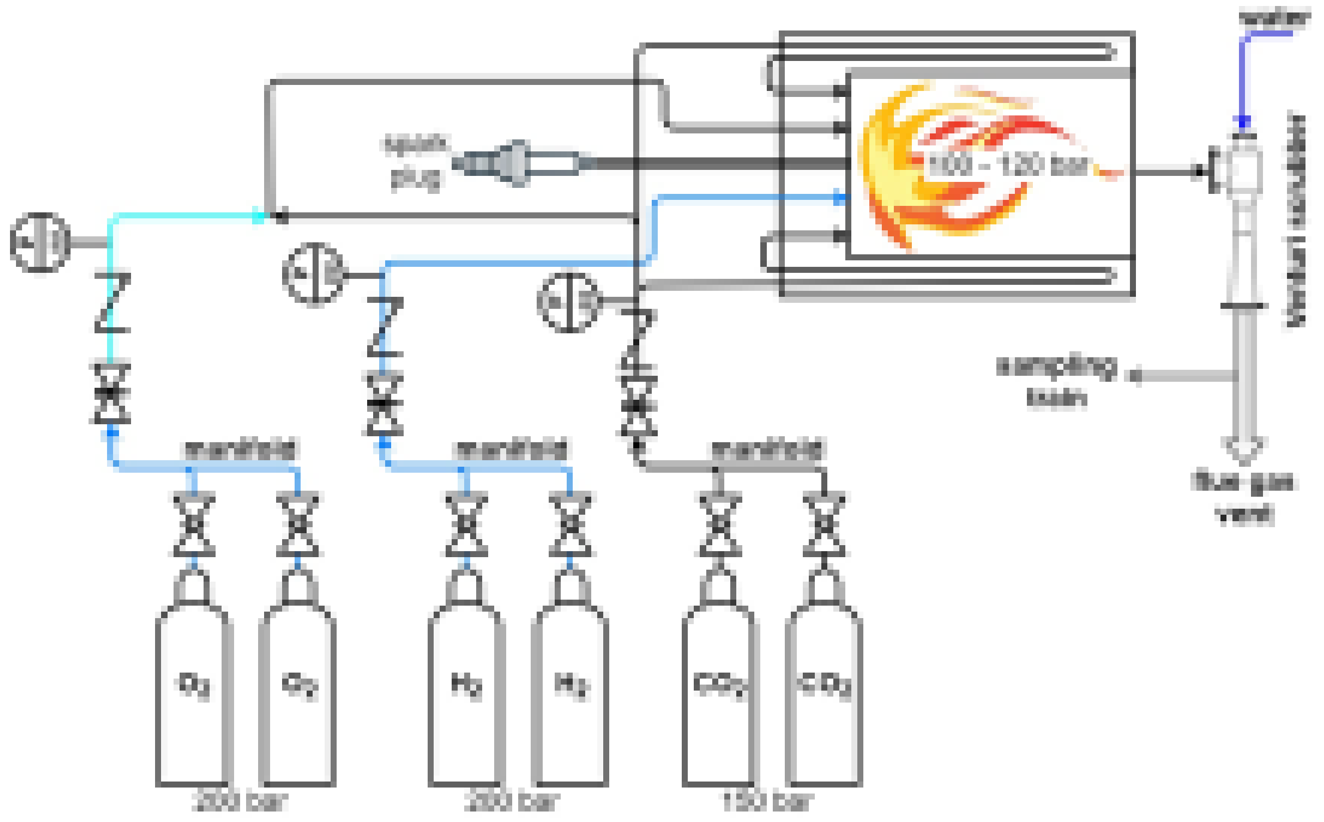
General concept of installation –for oxy combustion H2



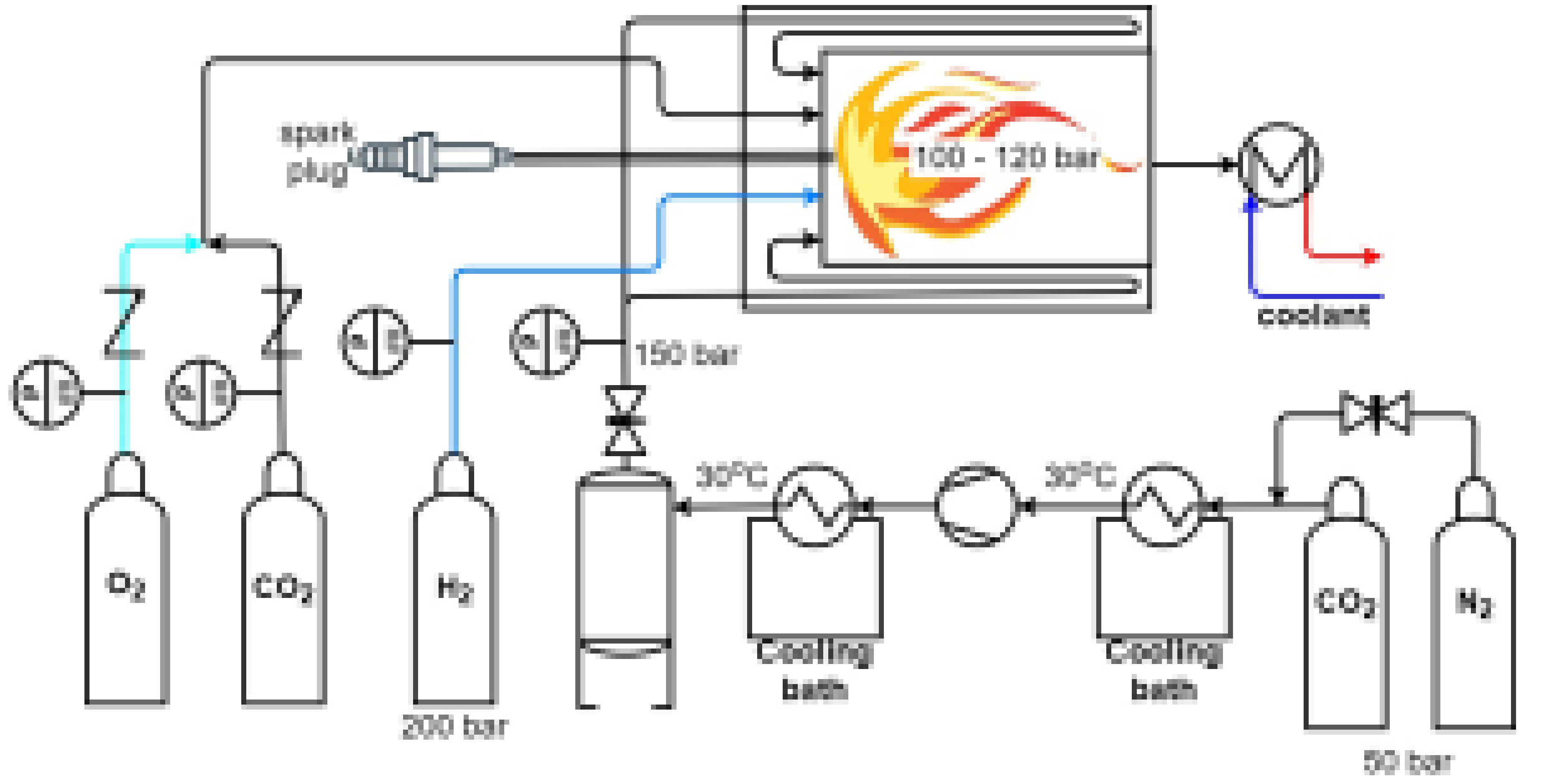


Fig. 2 Two alternatives. CO2 and H2 filling of installation. Left: Without compressor. Right: With compressors

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Design of a test rig

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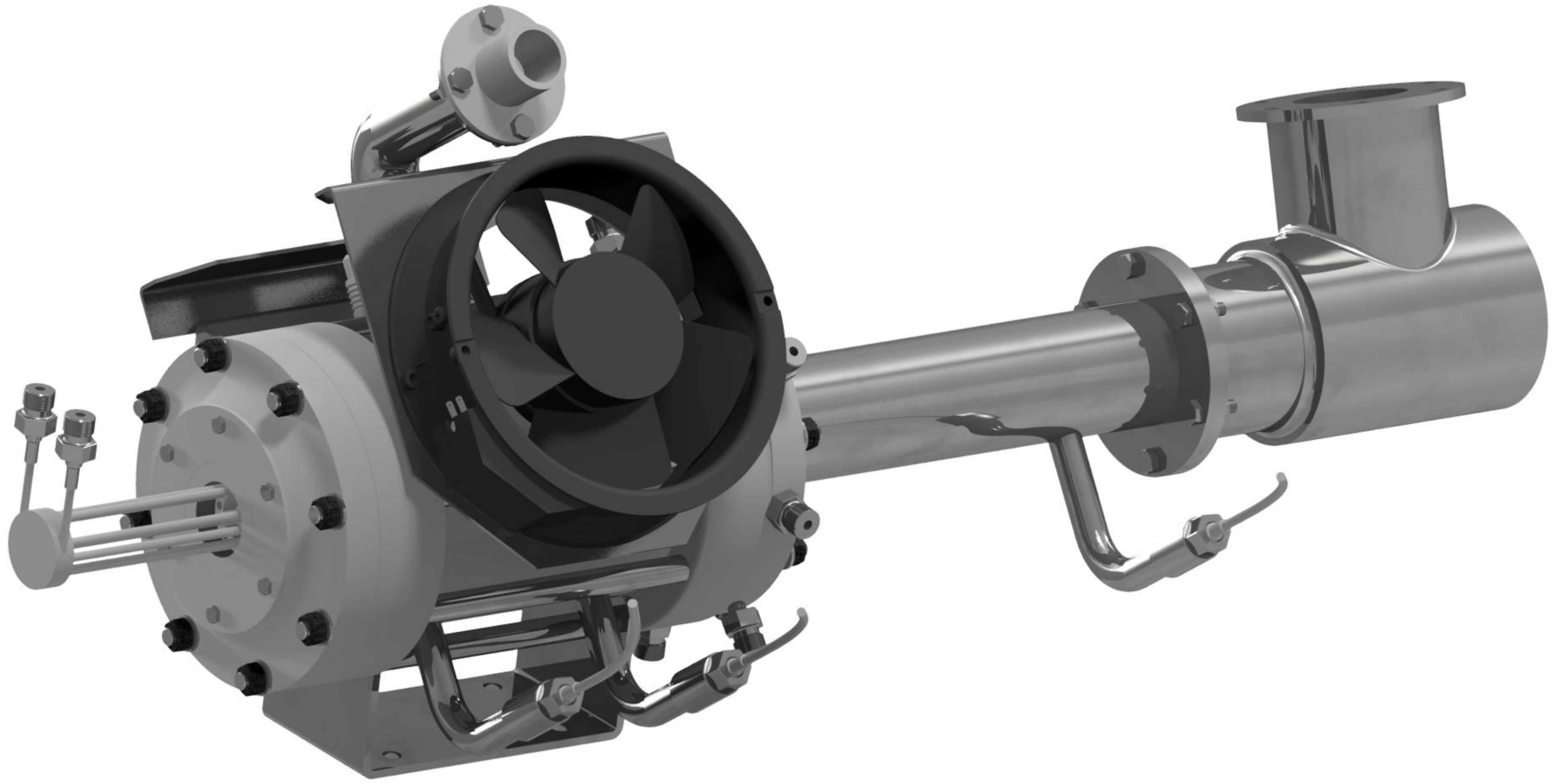
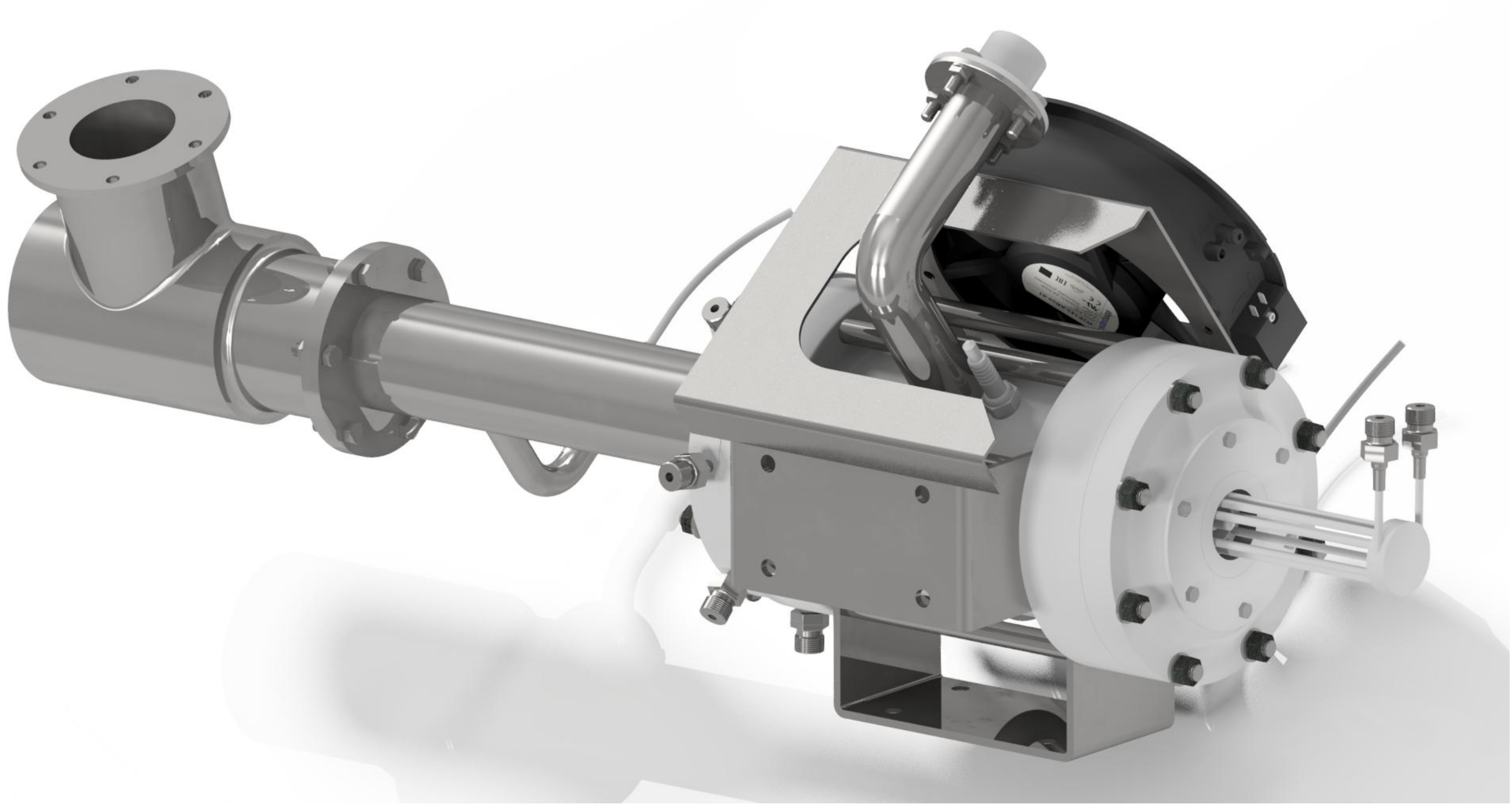
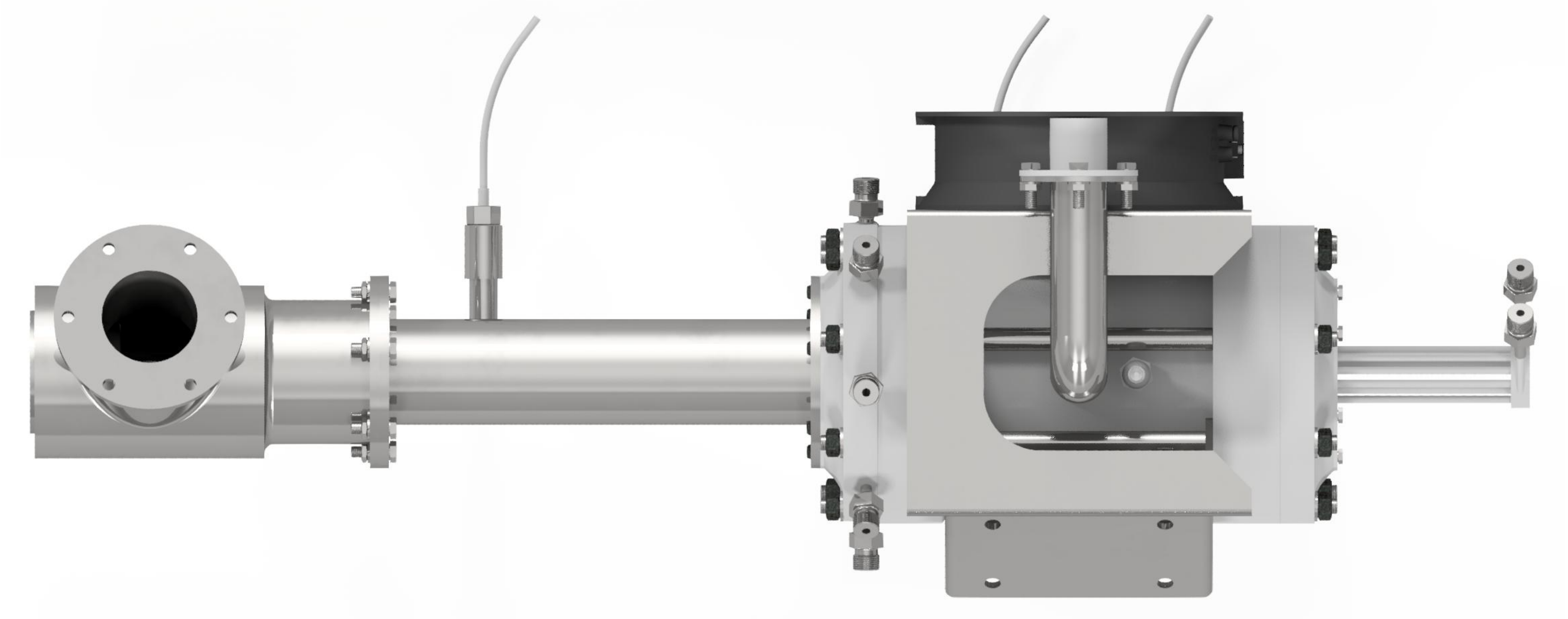
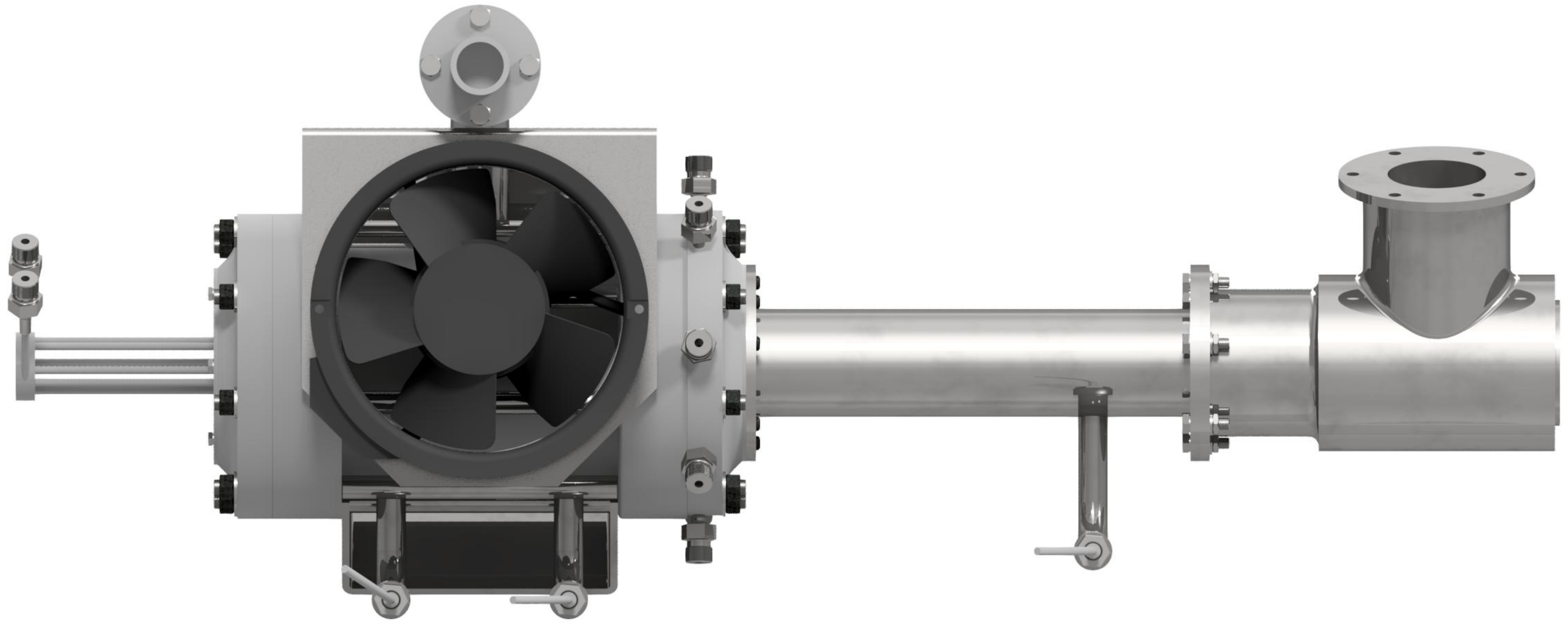
Current version of combustion chamber









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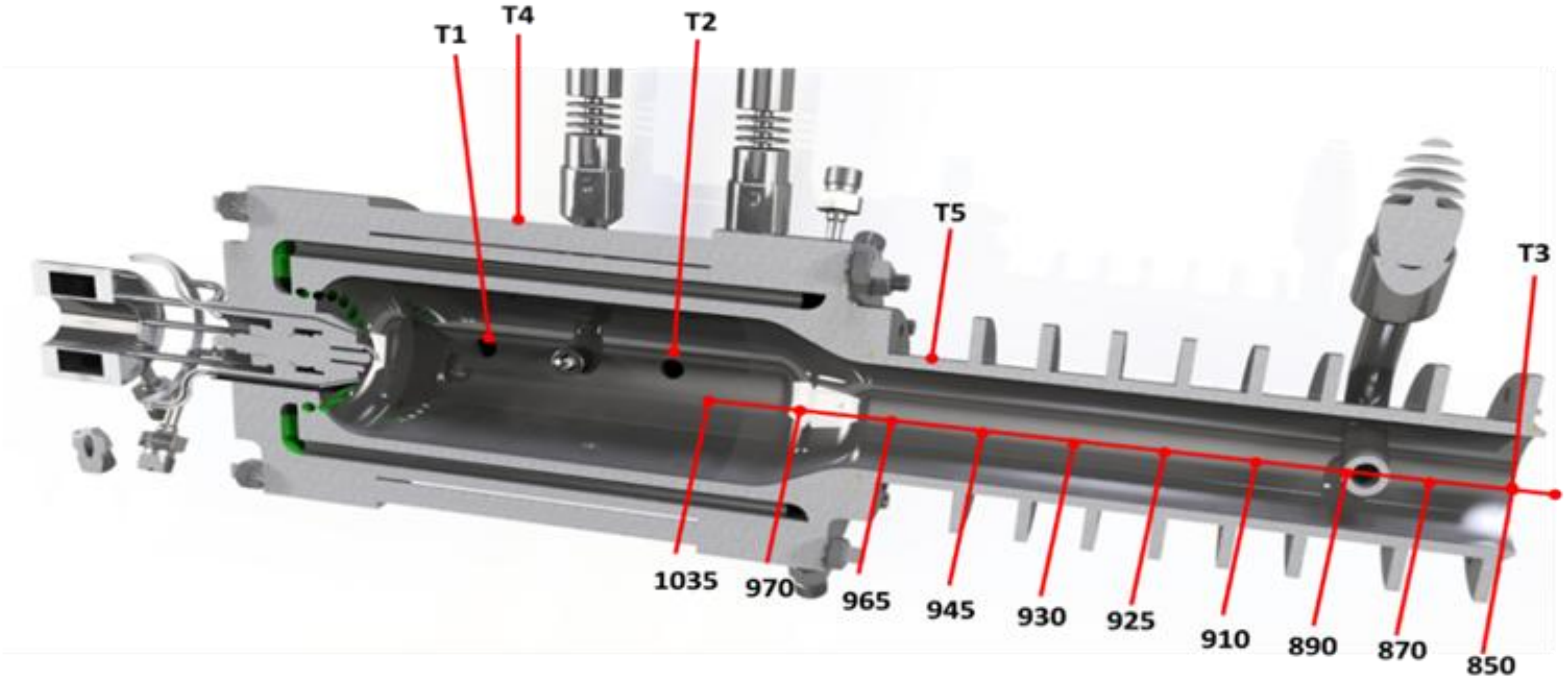
Current version of combustion chamber – Under the ventillator (air cooling) – pins that stiffen the whole construction and properly compress it. It is also possible to fix it to the table. Stainless steel 17TH(316)

Current version of combustion chamber



Current version of combustion chamber – cross-section

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Experimental research

Preliminary tests of oxy combustion of H2 at various excess oxygen at pressure 10 20 30 40 50 bar , and respectively high concentration of carbon dioxide were performed.

The temperature distribution in the chamber was measured for stable combustion conditions, which were consistent with the values obtained from numerical calculations.
See next slide
The effect of pressure is insignificant on flame length at a constant equivalence ratio, while carbon dioxide concentration has a significant effect on both flame length and flammability limits.

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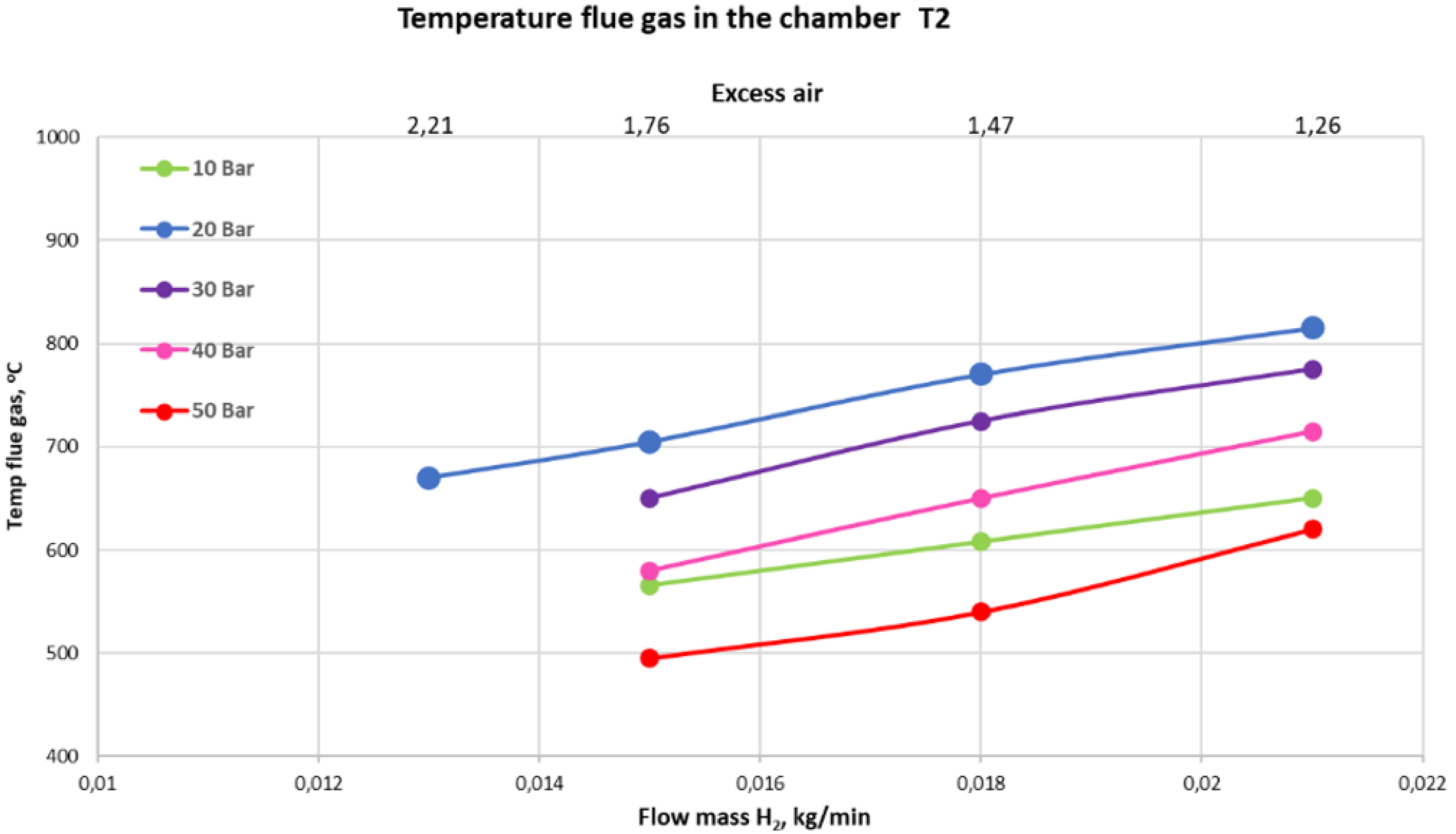
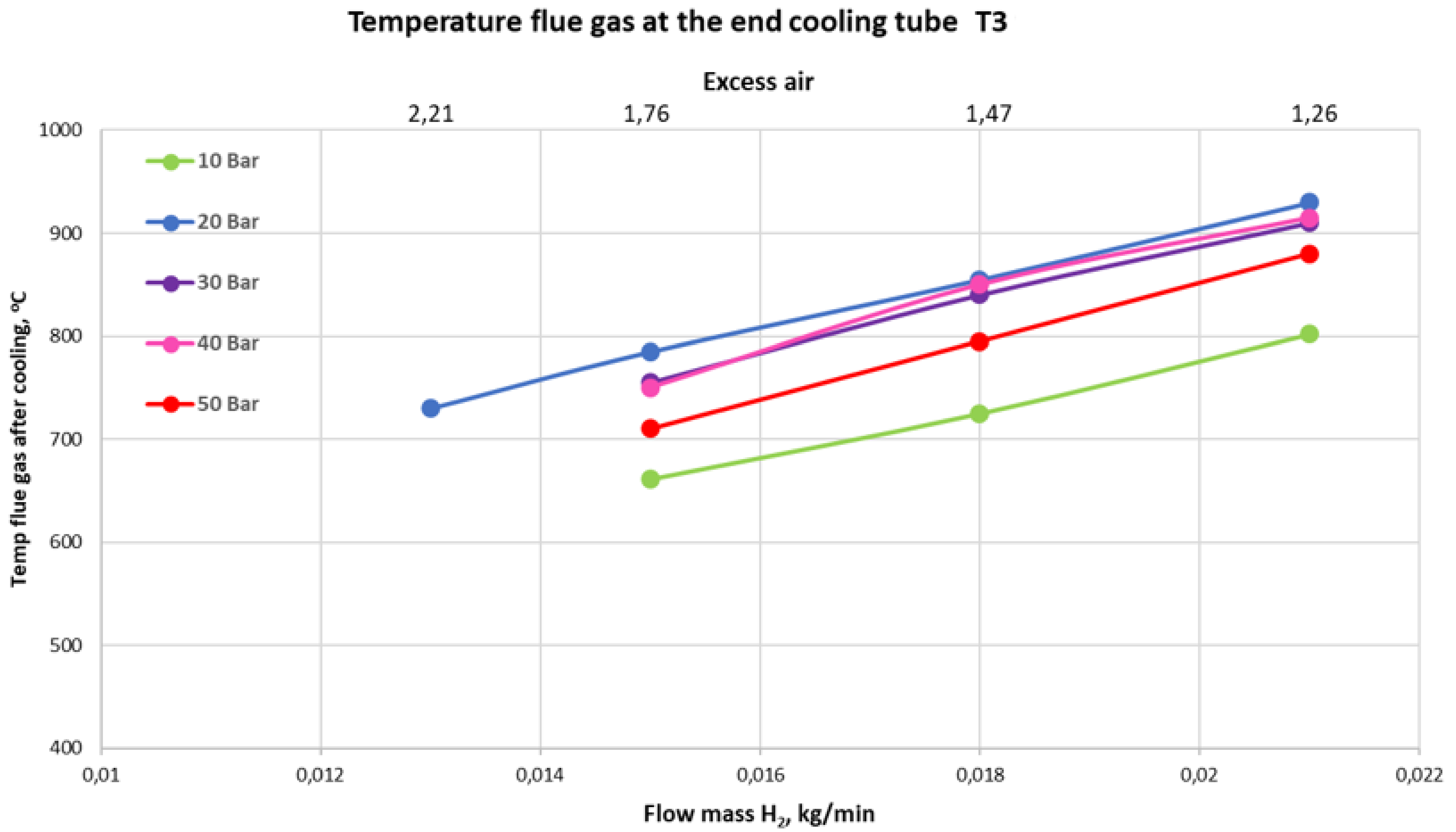
Combustion chamber: flow parameters

H_2 mass flow rate: 0.02 kg/minute. Pressure 10-50 bars. Different Excess oxygen ratios.
Cooling CO_2 mass flow rate: 1.7 kg/minute
Oxidant (O_2 with CO_2) mass flow rate: O2: 0.21 kg/min, CO2: 0.7kg/min





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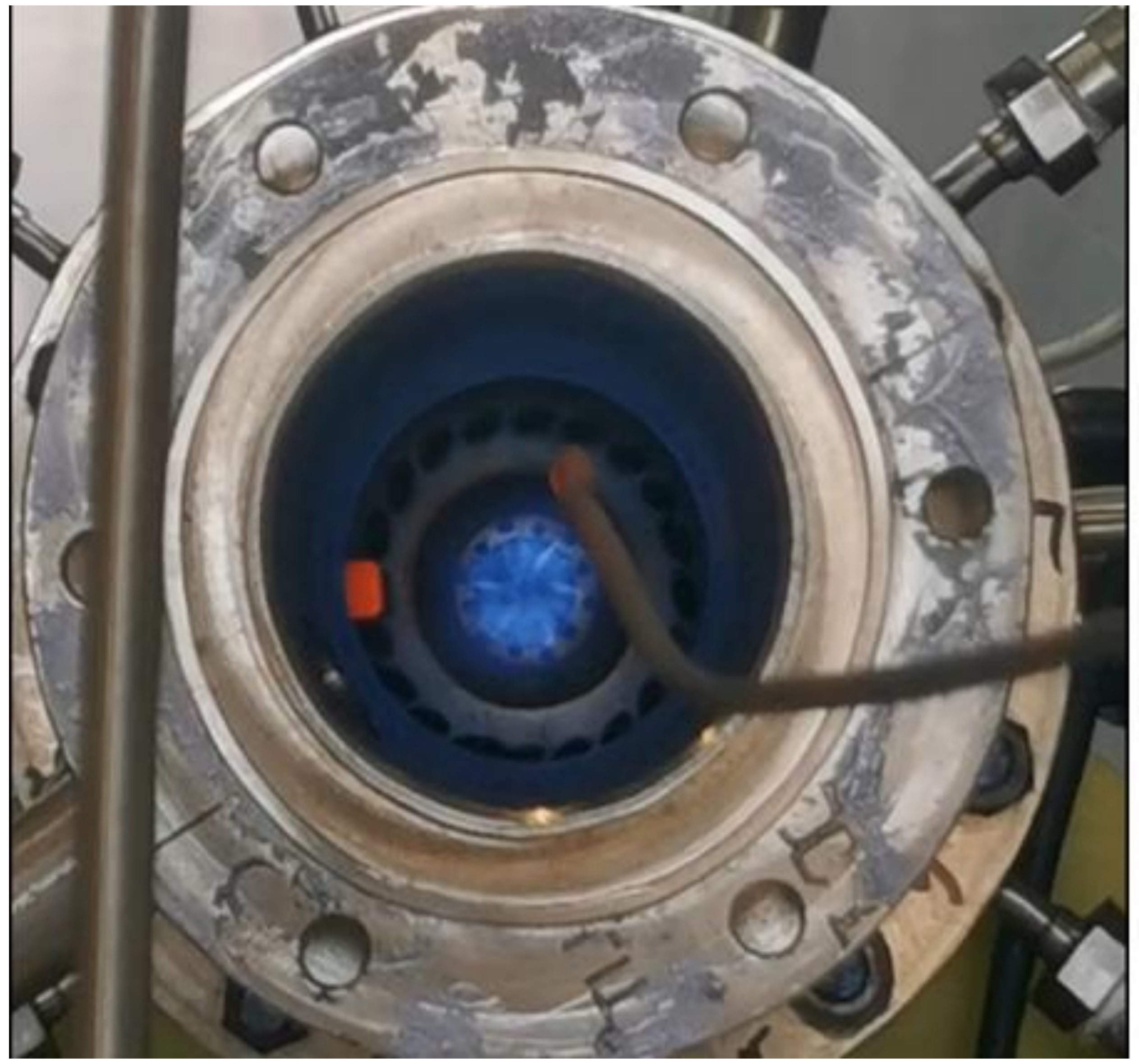
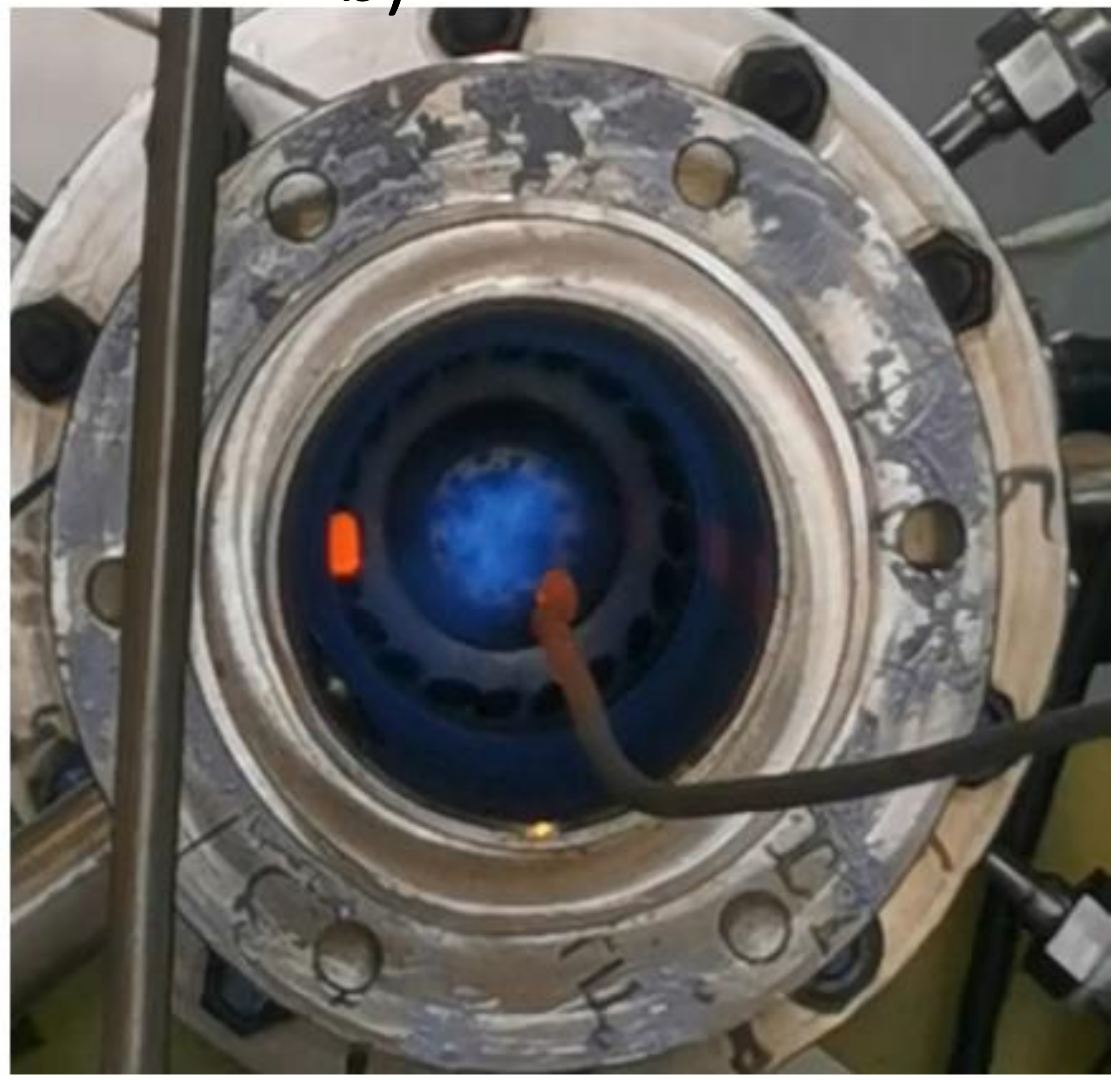
Combustion

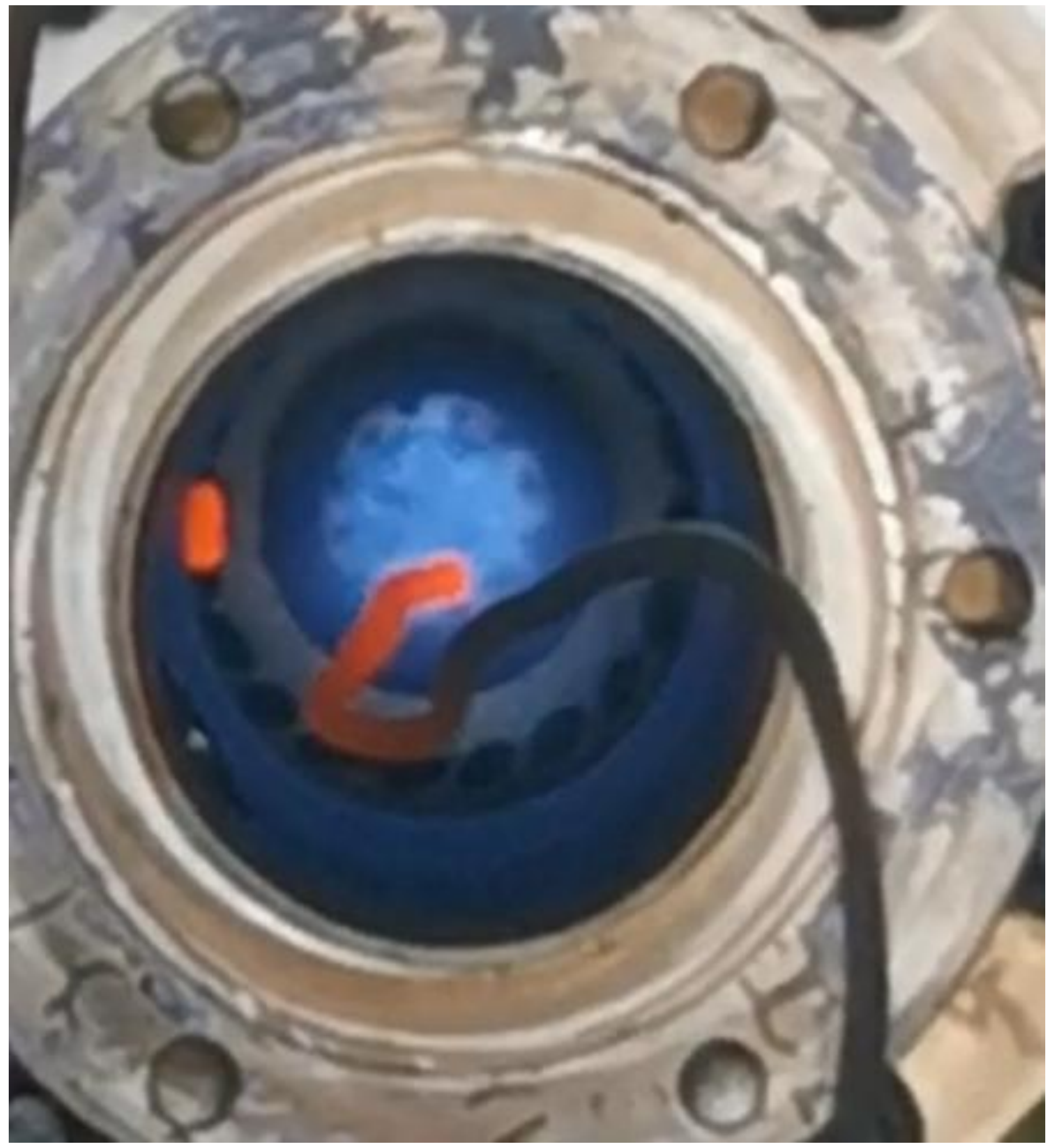
a)



b)



e)



View of: a)10bar, b) 20bar, c) 30bar, d) 40bar, e)50bar hydrogen flame of the front on the combustor

c)

d)

10 bar (a): Flame is visibly larger and fills more of the chamber volume. It looks more extended and less compact, confirming the “long flame” trend.

50 bar (e): The most compact flame. It’s pulled close to the injector region, with reduced visible length compared to low-pressure cases.

Numerical modeling

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Combustion chamber: flow parameters

H_2 mass flow rate: 0.02 kg/minute. Pressure 10-50 bars
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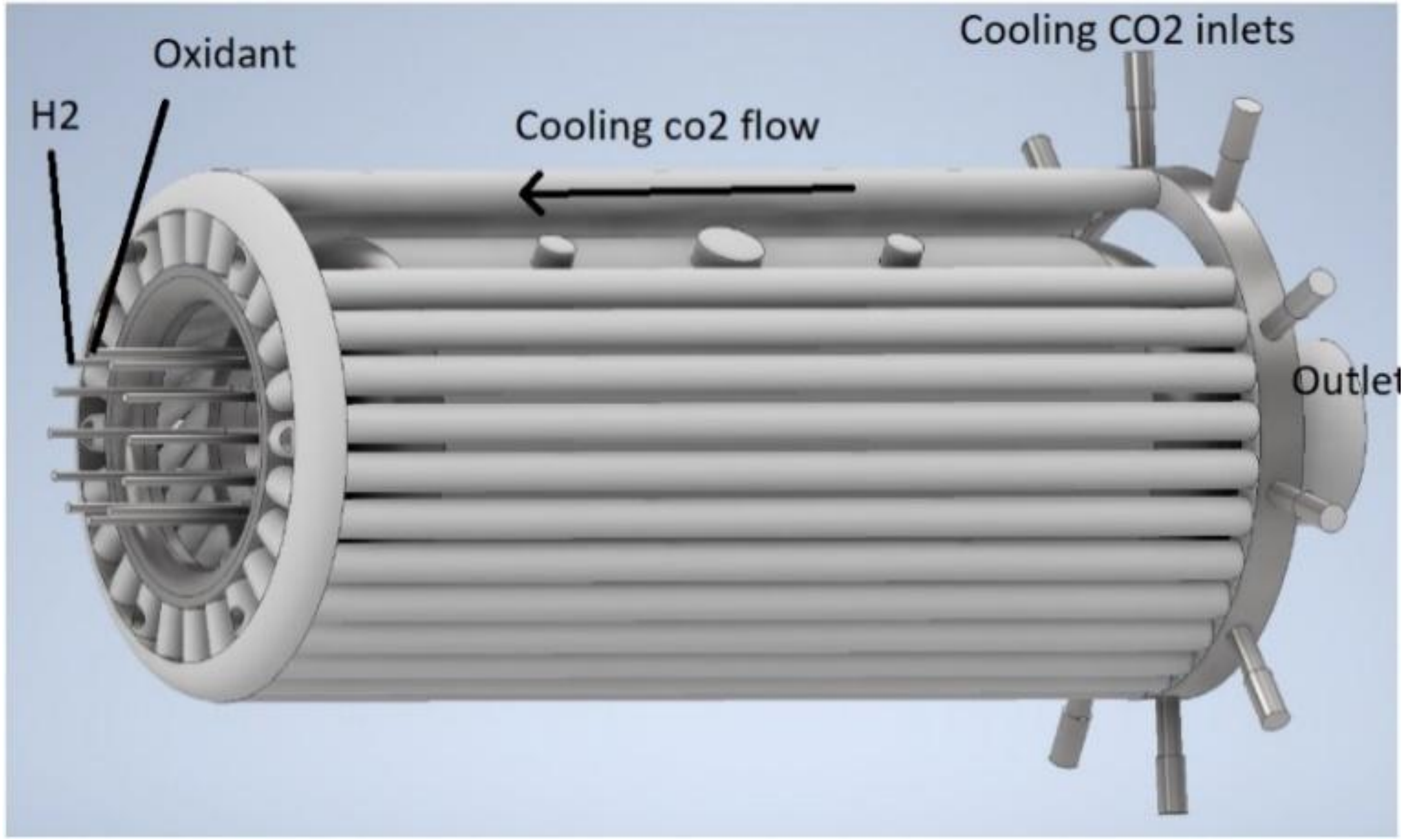

Modeling approach:

1. Global reaction Mechanism – Eddy Dissipation Model
   Density: Redlich Kwong Model (real gas assumption)

- $H_2 + 0.5O_2 \rightarrow H_2O$
- $H_2O \rightarrow H_2 + 0.5O_2$
- $CO + 0.5O_2 \rightarrow CO_2$
- $CO_2 \rightarrow CO + 0.5O_2$

Radiation: Discrete Ordinate Method

Turbulence: Realizable k-ε approach

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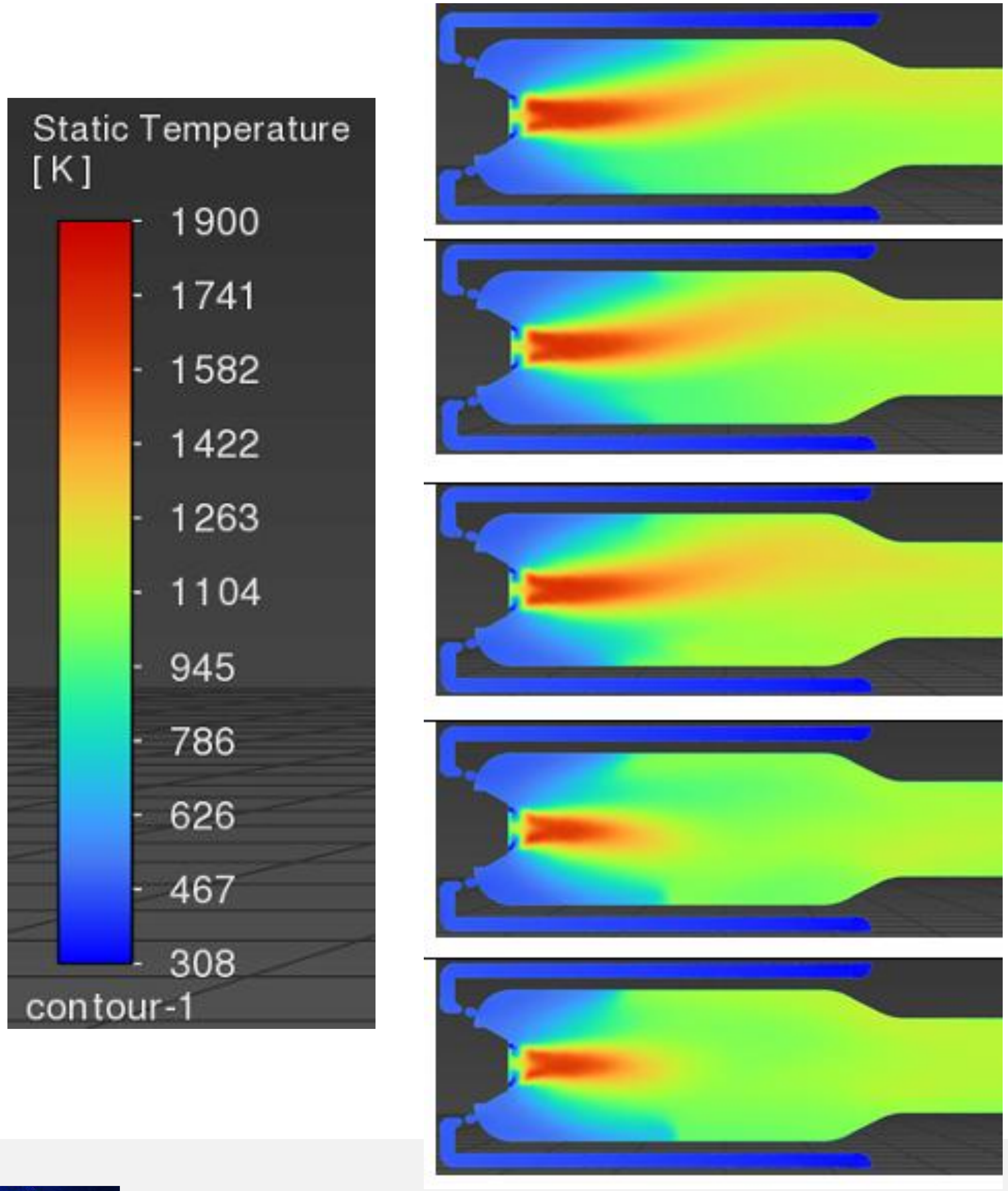
Temperature, H2O mole fraction



At 10 bar (top image):
The flame is long, stretching downstream. Mixing is relatively efficient, and combustion continues farther along the tube, giving that extended red/yellow core.

At 50 bar (bottom image):
The flame is compact and “short.” Higher density at 50 bar suppresses turbulence length scales, so mixing is slower and more localized. Heat loss to the walls is also stronger. Result: the hot zone near the inlet is quenched more quickly, and the flame doesn’t extend downstream

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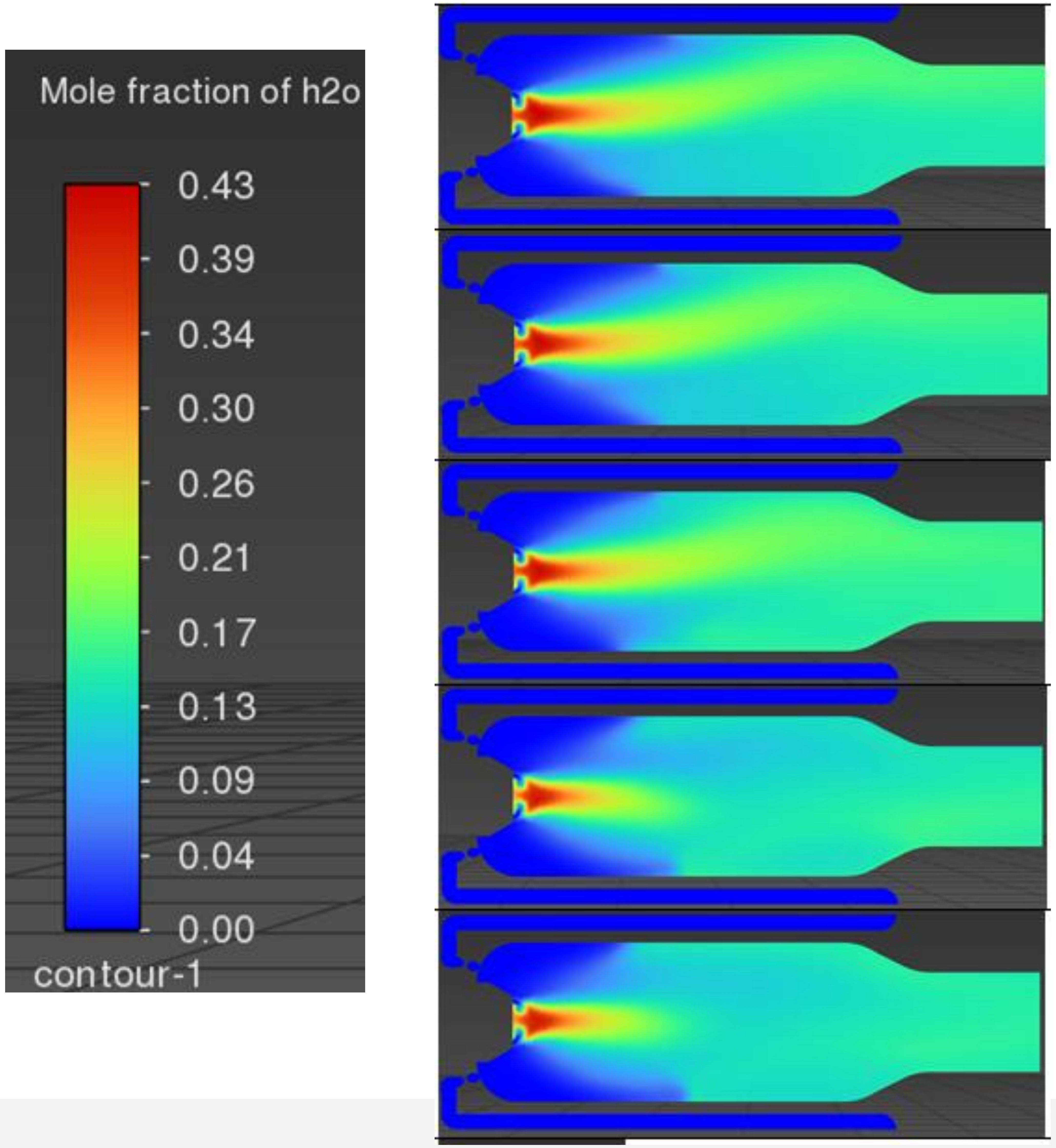
Temperature, H2O mole fraction

10 bar (top): The H_2O-rich region is long and extends far downstream, similar to the long flame. Combustion is stretched out in space.

50 bar (bottom): The flame is the shortest. H_2O is produced intensely near the inlet but doesn't extend downstream as far. The distribution is more localized and indicates incomplete mixing — water production is concentrated but not spread along the tube.



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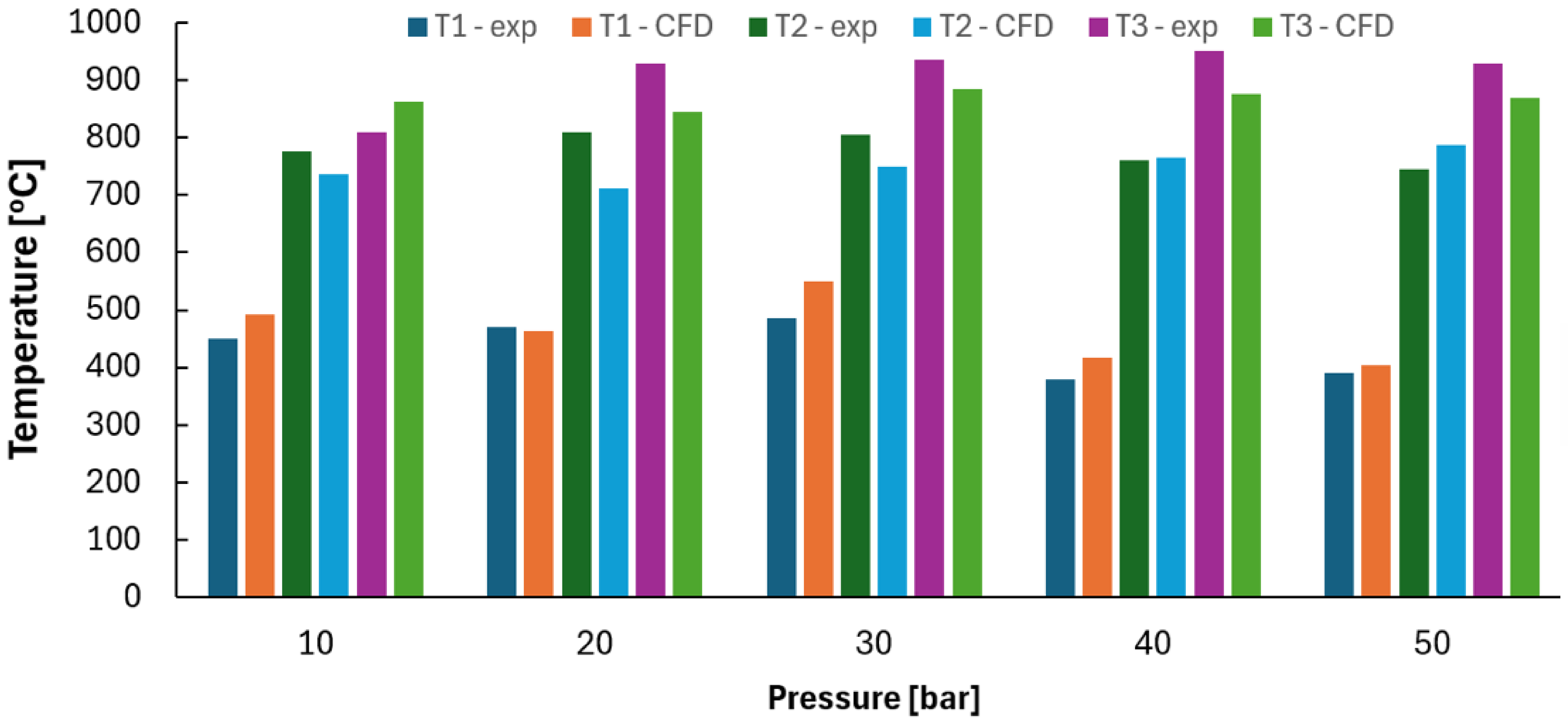
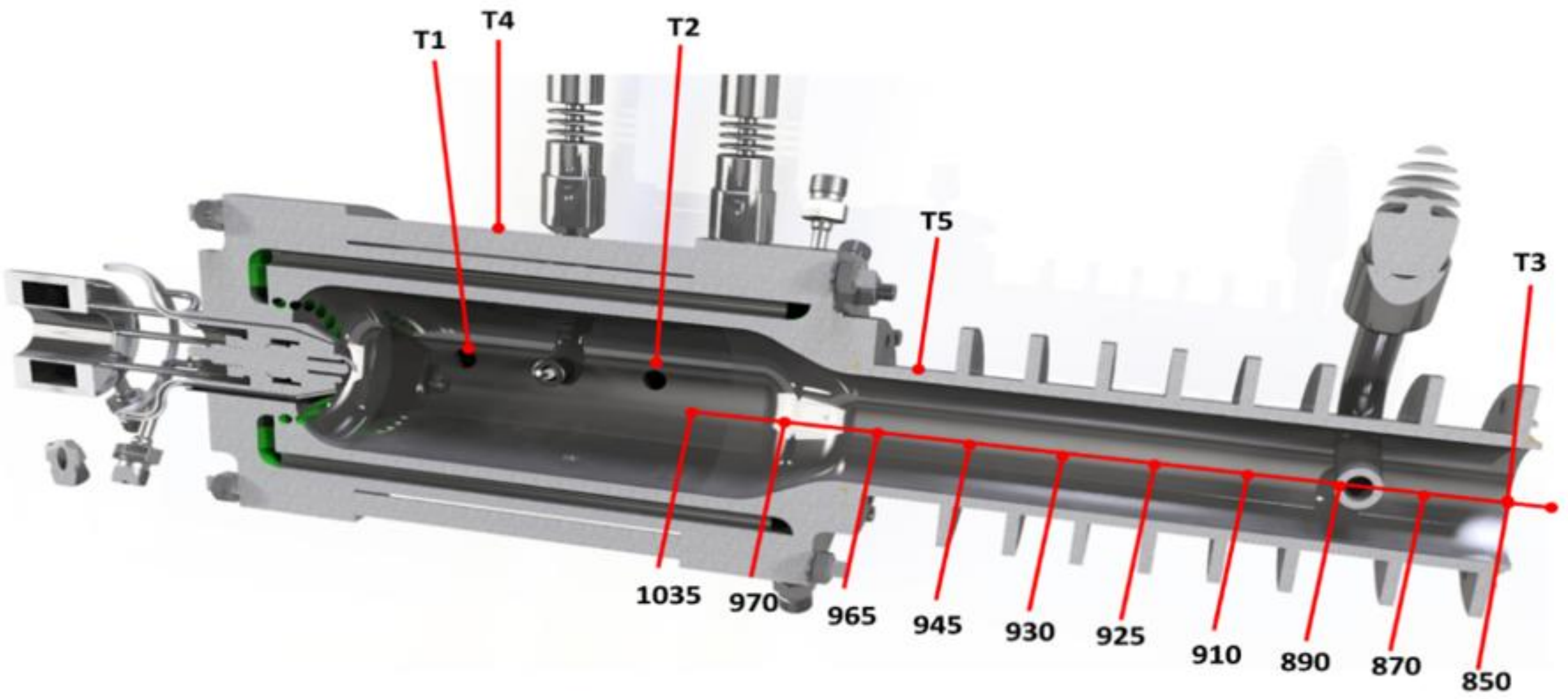
Temperature results: Exp vs CFD





T_1, T_2, T_3

Overall trends:

With increasing pressure:

- **T1 decreases**
- **T2 remains relatively stable**
- **T3 increases**

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Conclusions based on experiments and numerical research

- The study demonstrates stable hydrogen flame propagation in an environment with over 70% CO_2 dilution and pressures up to 50 bar
- Flame length decreases with pressure. The H_2O distribution confirms what the temperature plots already showed: higher pressure produces a more compact, quenched flame.
- Maximum H_2O concentration (~0.4) is roughly constant across all pressures, so the total combustion chemistry isn't suppressed — only the flame shape changes.
- With increasing pressure, T1 decreases and T2 is roughly constant, while T3 increases (outlet heating). Lower local temperatures near the inlet are consistent with stronger quenching/mixing constraints at 50 bar, even as exhaust temperature T3 rises.
- Because T3 rises with pressure, the downstream components face higher gas temperatures; combined with reduced convective effectiveness at elevated density/viscosity conditions, this implies higher wall thermal loads and potential durability concerns.
- The temperature along the cooling tube decreases steadily with distance from the burner, confirming the effectiveness of CO_2 cooling.
- The numerical simulations closely match experimental results, validating the computational models used

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World Map

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