Università di Foggia

Scienze Agrarie, Alimenti, Risorse Naturali e Ingegneria

HR EXCELLENCE IN RESEARCH

Technical Specification for the Development of a Prototype for the Analysis of the Combustion of Zero-Carbon Alternative Fuels

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Brief Description of the Prototype

The prototype consists of a Constant Volume Combustion Chamber (CVCC) designed to measure the laminar flame speed of low- or zero-carbon fuels and their mixtures. The primary fuels to be investigated include hydrogen, ammonia, and their combinations.

The initial conditions of the air/fuel mixture must be fully controllable and adjustable. The system shall ensure reliable measurements with high acquisition frequency, compatible with the dynamics of the phenomena under investigation.

The measurements will include:

- Physical parameters of the mixture: temperature and pressure, both in the unburnt phase, during combustion, and downstream of the process.
- Visual acquisition of the flame front position through high-speed imaging systems, for all the fuel types considered.

This prototype will serve as an advanced tool for the study of the combustion behaviour of innovative fuels, contributing to the development of technologies with reduced environmental impact.

Supply Details

Prototype for the Analysis of the Combustion of Zero-Carbon Alternative Fuels

1. General Description

The supplier shall develop a spherical Constant Volume Combustion Chamber (CVCC) intended for the study of the combustion of mixtures of hydrogen, ammonia, and their combinations. The system must enable the measurement of laminar flame speed, with data acquisition concerning the physical parameters of the mixture, as well as high-speed imaging of the flame front.

2. Technical Requirements

2.1 Combustion Chamber

- **Structure**: High-strength stainless steel suitable for operation under high-pressure and high-temperature conditions considering the ammonia.
- **Internal diameter**: 400 mm.
- **Shape**: spherical.
- **Volume**: Dimensioned to allow flame expansion without interaction with the chamber walls.
- **Initial pressure range of the mixture**: Up to 10 bar for the unburnt mixture.
- **Initial temperature range of the mixture**: Up to 400°C for the unburnt mixture. Materials must be compatible with the presence of ammonia at high temperatures.
- **Optical access**: Quartz windows or equivalent materials resistant to the operating conditions. Four diametrically opposed optical ports are required, with a minimum window diameter of 120 mm.

2.2 Air/Fuel Mixture Control

2.2.1 ***Dosing and Mixing System***

- **Configuration**:
  - Mixing system with electronically controlled proportional valves to ensure precise composition of the mixture.
  - Capability to adjust the volumetric ratios of the gases (hydrogen, ammonia, and air) with a tolerance of < ±1%.
  - Static or dynamic mixer to ensure proper homogenisation prior to entering the combustion chamber.

- **Main components**:
  1. **Coriolis Mass Flow Controllers (MFCs)**:
     - **Flow range**:
       Hydrogen: 0 - 5 SLPM (Standard Litres Per Minute)
       Ammonia: 0 - 5 SLPM
       Methane: 0 - 5 SLPM
       Air: 0-10 SLPM
     - **Accuracy**: ±0.5% Full Scale
     - **Resolution**: 0.1% of the set value
  2. **Safety mixer** equipped with non-return valves to prevent accidental backflow between gases.

2.2.2 ***Sensors for Mixture Measurement and Regulation***

- **Pressure sensors**:
  - Measurement range: 0 - 100 bar.
  - Accuracy: ± 0.25% Full Scale.
  - Transducers with 4 - 20 mA or digital output (Modbus, Profibus) for integration with the control system.
  - Monitoring and saving of chamber pressure curves for each test case.

- **Temperature regulation**:
  - External band heaters, installed on the combustion bomb vessel and three K-type thermocouples, are required in a PID hardware control system to regulate the chamber temperature up to 500 K:
    - Larger bands will be used to heat the bulk of the CVCB.
    - Smaller heaters to avoid cold-spot formation on the viewing windows.
  - Two separate operating circuits are required to monitor the temperature system with an accuracy of ±1.0K.
  - Real-time display of system temperature curves and data storage for each test case.
  - A set point alarm is required to control the maximum temperature of the vessel.
  - Operating range: –20°C to 500°C (to accommodate extreme operating conditions).

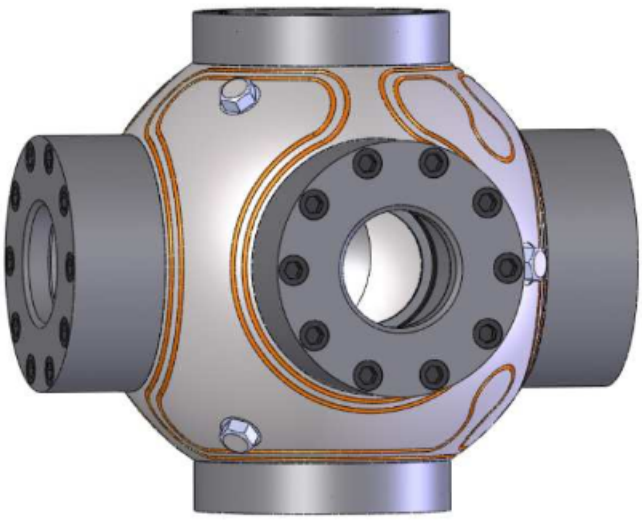

Figure 1: Sketch of the spherical combustion vessel with heater bands.

2.2.3 *Safety Valves and Controlled Exhaust System*

- **Overpressure safety valves**:

1. Relief valves with adjustable set points (e.g. controlled venting to atmosphere).

2. Non-return valves to prevent backflow of unwanted gases into the supply system.
3. Emergency solenoid valves to immediately shut off gas supply in case of malfunction.

- **Controlled exhaust system**:
  1. A dry scroll vacuum pump is installed on the evacuation line to extract exhaust gases from the combustion chamber. The dry scroll mechanism prevents potential contamination by eliminating the risk of oil vapor migration into the evacuated chamber. The nominal evacuation rate must be sufficiently high to ensure rapid and effective flushing of the combustion chamber ($15m^3/h$).
  2. Discharge routed to a designated safe area, with monitoring of combustible gas concentrations to prevent accumulation hazards.
  3. Gas leak detector for continuous monitoring and automatic shut-off in the event of detection of dangerous concentrations.

2.2.4 *Fuel, Oxidizer, and Inert Gas Supply Systems*

Dedicated storage tanks and supply lines for ammonia (NH_3), hydrogen (H_2), methane (CH_4) and inert gases (nitrogen N_2, helium He, oxygen O_2 or others as specified).

2.2.5 *Mixture Homogenisation*

- **Uniformity of composition**:
  - Fuel and oxidizer must be supplied independently introduced into the chamber by means of a needle valve, which allows fine adjustment of the internal partial pressures to the resolution of the pressure gauge (0.1 mbar).
  - A manifold with 1/4-inch stainless steel tubes is required for the independent distribution of the gas in the combustion chamber and has been connected to all specified cylinders.
  - The fuel manifold must be connected to a nitrogen supply to purge the system when necessary.
  - The air/fuel mixture must be homogeneous in the combustion chamber to avoid concentration and temperature gradients that could affect flame propagation results.
  - This is particularly important for fuels such as hydrogen and ammonia, which differ in density and diffusivity compared to hydrocarbons.

- **Uniform temperature distribution**:
  - Prevents thermal stratification that could influence ignition delay and combustion speed.

- **Enhanced experimental repeatability**

- Ensures more reliable data and reduces dispersion in test results.

- **Implementation**:
  - **Method**: Mechanical stirring using six black identical internal fans positioned close to the container's inner wall in an octahedral configuration. Each fan has four blades that channel air towards the centre of the sphere.
  - **Materials**: Stainless steel suitable for high-pressure and high-temperature operation.
  - **Control**: Adjustable stirring speed, with stirring halted prior to ignition. The fans are directly coupled to six brushless electric motors equipped with independent speed controllers. Each fan can be independently controlled up to a maximum speed of 15000 rpm.

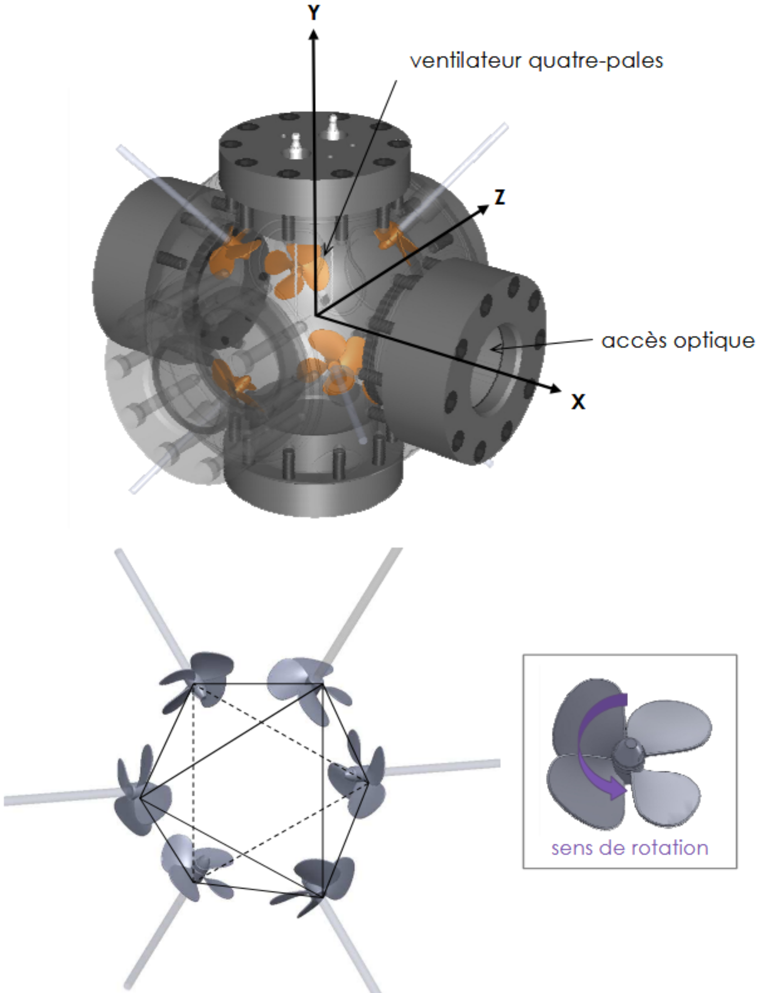

Figure 2: sketch of the combustion bomb vessel with the position of the fans.

2.2.6 Additional Considerations

- **Integration with ignition system**: Fuel dosing and ignition should only be enabled once the combustion chamber is sealed and ready.
- **Control interface**:
- PLC or dedicated software for real-time management of mixture parameters.
- Graphical user interface for remote monitoring and adjustment.
    1. Fuel and air dosing and mixing system for hydrogen, ammonia, and air.
    2. Sensors for real-time measurement and regulation of mixture flow rate, pressure, and temperature.
    3. Safety valves and controlled exhaust system to ensure safe operation.

2.3 Ignition System

2.3.1 ***Spark Plug Ignition***

- **Power Supply and Control**:
    - Capacitor discharge ignition equipped with a variable voltage supply and auto-ignition coil.
    - Tungsten or stainless electrodes electrodes. Fine diameter (diameter of 1.5 mm) of electrodes to have minimal influence on flame propagation. Possibility of varying the gap between electrodes.
    - Discharge voltage: 35 kV.
    - Spark energy: > 50 mJ, to ensure reliable ignition even for lean mixtures.
    - Timing control capability to optimise ignition timing.
    - In addition, the electrodes must be rotatable to allow positioning at 0°, 45°, 90°, and 135° relative to the measurement plane of the Schlieren imaging system.
    - The pulse generator must also be connected to the high-speed camera and recording systems, so that video and data acquisition are sequenced to the point of ignition.
    - Variable electrode gap to provide a stable discharge with hydrogen and ammonia, which exhibit different ionisation characteristics compared to conventional hydrocarbons.
    - Operating pressure: suitable for the maximum combustion chamber pressure.

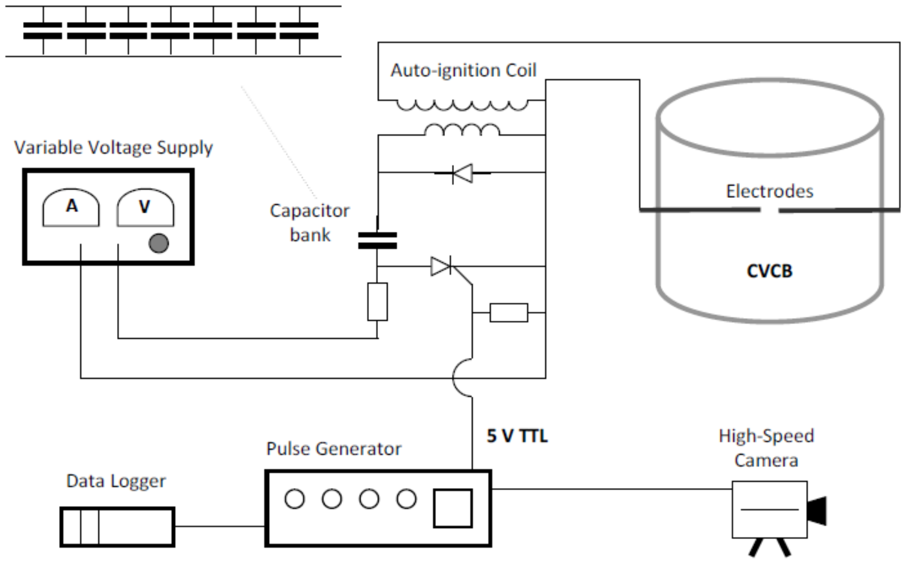

Figure 3: Schematic of the ignition system required.

- **Fast Response Time**
  - Discharge delivery system optimized to minimize the delay between the ignition trigger and actual flame initiation.
  - Ignition system response time < 1 ms to ensure uniform combustion onset.
  - Discharge monitoring to confirm ignition and generate fault signals in the event of ignition failure.

2.3.2 ***Safety and Control Systems***

- Flame detection sensors to verify the success of ignition.
- Interruption of the fuel-air mixture supply in the event of ignition failure after a predefined number of attempts.
- Electrical isolation and electromagnetic interference protection to prevent disturbances to the data acquisition system.

2.4 Measurement Instrumentation

- High-frequency pressure sensors to monitor the combustion process at ≥ 40 kHz.
- High-precision thermocouples for measuring the mixture temperature.
- High-speed data acquisition system, with a frequency compatible with combustion analysis.

2.5 Image Acquisition System

2.5.1 ***Schlieren Z-type System for Flame Front Visualization***

- Configuration: Classic double-mirror Schlieren system to maximise sensitivity to density gradients.
  - Concave mirrors:
    - Diameter: ≥ 150 mm
    - Focal length: 1000 - 1500 mm
  - Light source: High-intensity white LED or solid-state laser, preferably with collimated optics to ensure uniform illumination.
  - Cutting pinhole screen: Adjustable blade with micrometer to optimise image contrast.
  - Alignment: Fine mounting system for optical axis adjustment.

2.5.2 ***High-Speed Camera***

- Resolution: ≥ 1024 × 1024 pixels to ensure good flame definition.
- Minimum frame rate 16.000 fps.
  - Exposure time: ≤ 1 µs to avoid motion blur.
  - Sensitivity: Sensor with high sensitivity (ISO 10,000 or higher) to operate under low light conditions.
  - Acquisition interface: GigE, CoaXPress, or USB 3.0 for high data transfer speeds.
  - Triggering: Synchronisation with the ignition system to capture the initial moments of flame propagation.
  - Memory capacity up to 128 GB

2.5.3 ***Dedicated Illumination***

- Light source: High-power white LED or pulsed laser to enhance contrast in the Schlieren images.
- Adjustable power: Variable light intensity to adapt to different tests.
- Optical filter: To reduce potential light interference and optimise image contrast.

3. Software and Hardware

The software for managing the Constant Volume Combustion Chamber (CVCC) must be highly flexible and modifiable, allowing adaptation to new experimental configurations and different types of fuels. It must ensure reliable system control, high-frequency data acquisition, and easy integration with new measurement instruments or analysis algorithms.

3.1. Modularity and Adaptability

- Modular software architecture, allowing the updating or replacement of individual components without impacting the entire system.
- Possibility of customizing test sequences, with interfaces for defining new experimental protocols.
- Support for scripts and custom configurations, with the ability to add specific modules without rewriting the core code.

3.2. Control and Regulation

- Flexible management of the initial conditions of the mixture (temperature, pressure, composition).
- Configurable interface for controlling sensors and actuators, enabling the integration of new devices with minimal programming.
- Possibility of automatic or manual calibration to adapt to new experimental needs.

3.3. Data Acquisition and Processing

- High-frequency data sampling, with management of multiple sensors and the ability to select variables to monitor.
- Compatibility with various imaging systems, to adapt to high-speed cameras from different manufacturers and models.
- Customizable data analysis, with the ability to add new filtering, processing, and visualization functions without modifying the core software.

3.4. User Interface and Integration

- Dynamic and configurable dashboard, allowing interface customization based on user requirements.
- Compatibility with standard protocols (Modbus, OPC UA, TCP/IP) for integration with other measurement and control instruments.
- Remote control capability, with a web-based interface or client software for remote access.

3.5. Maintainability and Scalability

- Well-documented code and open framework to facilitate expansion and maintenance over time.
- Support for incremental updates, enabling continuous improvement of functionalities without interruptions.

- Open structure for the integration of advanced algorithms, including CFD models or AI for combustion analysis.

3.6. Hardware

The hardware of the Constant Volume Combustion Chamber (CCVC) system must ensure high precision, reliability, and compatibility with the management and data acquisition software.

3.6.1. *Computing and Control Unit*

- Industrial PC or Workstation with high-performance multi-core CPU, adequate RAM, and a dedicated graphics card for image processing.
- Operating system Windows/Linux, with support for compatible development environments (Python, MATLAB, LabVIEW, or proprietary software).
- Dedicated data acquisition (DAQ) boards, with high-resolution analog and digital interfaces for sensor and actuator management.
- PLC or microcontrollers for real-time control, if required for fine-tuning experimental parameters.

3.6.2. *User Interface*

- Touchscreen monitor or dedicated graphical interface for direct management of the system in the laboratory.
- Remote control capability, via web-based interface or client-server software.
- Customizable dashboard, with options for visualizing acquired data, configuring tests, and performing real-time analysis.

3.6.3. *Communication Systems and Connectivity*

- USB, Ethernet, or Wi-Fi interface for data transfer and integration with other measurement systems.
- Standard communication protocols (Modbus, OPC UA, RS232, TCP/IP) to ensure compatibility with existing and future instrumentation.

4. *Safety Requirements*

- Structure resistant to accidental overpressures.
- Safety systems for the management of reactive mixtures:
    - **Safety Regulations**: Ensure that all components comply with local and international regulations for the storage and handling of hazardous gases.

- **Leak Detection Systems**: Integrate leak detection sensors for hydrogen and ammonia, with visual and acoustic alarms.
- **Adequate Ventilation**: Ensure that the installation area is well-ventilated to prevent gas accumulation.

- **Relief Valves and Emergency Shutdown Systems**.
- **Remote Control** for operation management.

5. Requested Services

- Design and construction of the prototype.
- Transport, installation and testing at the designated laboratory or facility.
- Staff training for the use of the equipment.
- Maintenance and support for a minimum period of 12 months.

6. Delivery Times

- **Design**: Within 1 month from the contract signing.
- **Construction and Testing**: Within 4 months.
- **Delivery**: By September 2025.
- **Operational Tests**: By October 2025.

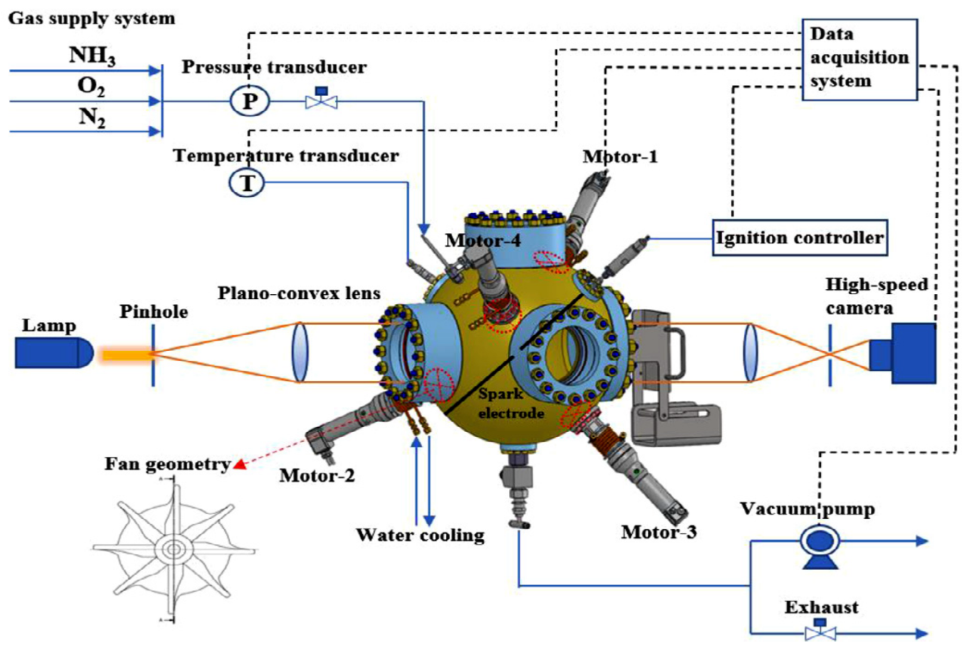

Figura 1. Esempio di configurazione di una camera di combustione a volume costante.