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# RPPR Final Report

## as of 14-Sep-2021

Agency Code: 21XD

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**Report Date:** 13-Sep-2021

Date Received: 09-Sep-2021

**Final Report** for Period Beginning 14-Sep-2018 and Ending 13-Jun-2021

**Title:** DURIP: Pre-heating Constant Volume Combustion Chamber System for Characterization of Spray

Compression-Ignition Combustion

**Begin Performance Period:** 14-Sep-2018

**End Performance Period:** 13-Jun-2021

**Report Term:** 0-Other

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**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

### STEM Degrees:

### STEM Participants:

**Major Goals:** A pre-heating constant volume combustion chamber (PHCVCC) system capable of providing compression-ignition conditions similar to the compression-stroke of diesel engines is proposed to be purchased and installed at the Spray and Engine Diagnostics Laboratory (SEDL), Department of Mechanical and Aerospace Engineering of the NC State University (NC SU). The PHCVCC system is a versatile tool to investigate fuel auto-ignition and combustion under high-pressure and high-temperature environments. The unique feature of the proposed PHCVCC system is the precise control of the gas compositions before ignition compared with other types of constant volume combustion chamber (CVCC) systems. The goal of this equipment proposal is to acquire a commercial pre-heating constant volume combustion chamber system, establishing the unprecedented capability at NCSU for extensive characterization of liquid fuel ignition and combustion under precisely controlled ambient environments.

Specifically, the proposed PHCVCC system will be featured with the following functions:

- 1). Precisely controlled high-pressure and high-temperature (HPHT) ambient conditions: the purchased PHCVCC system will be able to provide operating pressure of up to 60 bar (6.0 MPa) under ambient temperature of 900 K. The gas composition can be flexibly and precisely controlled by the gas supply system. The system will be fitted with four 100 mm fused silica windows, providing extensive optical access to the spray and combustion processes through different angles and allowing the application of various optical diagnostic techniques;
- 2). Spray and combustion characterization: another critical benefit of the optically accessible PHCVCC is to provide versatile optical measurements. These measurements will include, but not limited to, liquid spray characterization using Mie-scattering technique, fuel evaporation using Schlieren technique and laser induced exciplex fluorescence technique, chemical reaction and intermediate active species (i.e. OH radicals) characterization using laser induced fluorescence technique, gas temperature measurement using pyrometry and laser induced tracer thermometry, as well as soot volume fraction using laser induced incandescence and light extinction techniques.

In addition to the above readily available functions that can be carried out in SEDL, laser-assisted low temperature spray ignition tests can be performed by building appropriate interface. Other tests such as single droplet evaporation and combustion as well as supercritical spray combustion can also be integrated at a later time depending on the research and education needs.

**Accomplishments:** Please see this section in the attached complete final project report.

## RPPR Final Report as of 14-Sep-2021

**Training Opportunities:** Two PhD students (Wang and Nonavinakere Vinod) were trained on optical diagnostic techniques for spray and combustion experiments before the equipment's arrival. After receiving the DURIP equipment, one PhD (Nonavinakere Vinod) and one undergraduate (Kempin) students were trained to run the DURIP system to work on the fuel spray combustion under high pressure and high temperature environments. After graduated from the NC State University the undergraduate student (Kempin) continued his study as a direct PhD student in the department. Kempin and Nonavinakere Vinod are working on high pressure spray combustion using the equipment.

**Results Dissemination:** Nothing to Report

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

### **PARTICIPANTS:**

**Participant Type:** Graduate Student (research assistant)

**Participant:** Kaushik Nonavinakere Vinod

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Undergraduate Student

**Participant:** Robert Kempin

**Person Months Worked:** 6.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Graduate Student (research assistant)

**Participant:** Libing Wang

**Person Months Worked:** 6.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**RPPR Final Report**  
as of 14-Sep-2021

**Partners**

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I certify that the information in the report is complete and accurate:

Signature: Tiegang Fang

Signature Date: 9/9/21 11:03AM

**DURIP: PRE-HEATING CONSTANT VOLUME COMBUSTION CHAMBER SYSTEM FOR  
CHARACTERIZATION OF SPRAY COMPRESSION-IGNITION COMBUSTION**

**Final Report**

**Project period: 14 September 2018 – 13 June 2021**

**PI: Tiegang Fang**

**Department of Mechanical and Aerospace Engineering, NC State University**

**Grant # W911NF1810461**

**Proposal # 72041-EG-RIP**

**Foreword:**

The objective is to acquire a pre-heating constant volume combustion chamber (PHCVCC) system, establishing the unprecedented capability at NCSU for extensive characterization of liquid fuel ignition and combustion under precisely controlled ambient environments. Specifically, the proposed PHCVCC system will achieve: 1). Precisely controlled high-pressure and high-temperature (HPHT) ambient conditions: the purchased PHCVCC system will be able to provide operating pressure of up to 60 bar (6.0 MPa) under ambient temperature of 900 K. A unique advantage of the PHCVCC system is to be able to add minor species in the HPHT ambient gas before fuel ignition, making it particularly suitable for studying ignition enhancement by minor species addition; 2). Spray and combustion characterization: another critical benefit of the optically accessible PHCVCC is to provide versatile optical measurements. The applicable measurements will include, but not limited to, liquid spray characterization using Mie-scattering technique, fuel evaporation using a Schlieren technique and laser induced exciplex fluorescence technique, chemical reaction and intermediate active species characterization using laser induced fluorescence technique, gas temperature measurement using pyrometry and laser induced tracer thermometry, as well as soot volume fraction using laser induced incandescence and light extinction techniques. The interdisciplinary nature of the project presents unique learning opportunities to the undergraduate and graduate students. Three students were trained in optical diagnostics on spray combustion and/or to operate the PHCVCC system.

## **DISTRIBUTION STATEMENT**

Approved for public release; distribution is unlimited.

## **MAJOR GOALS**

A pre-heating constant volume combustion chamber (PHCVCC) system capable of providing compression-ignition conditions similar to the compression-stroke of diesel engines is proposed to be purchased and installed at the Spray and Engine Diagnostics Laboratory (SEDL), Department of Mechanical and Aerospace Engineering of the NC State University (NCSU). The PHCVCC system is a versatile tool to investigate fuel auto-ignition and combustion under high-pressure and high-temperature environments. The unique feature of the proposed PHCVCC system is the precise control of the gas compositions before ignition compared with other types of constant volume combustion chamber (CVCC) systems. The goal of this equipment proposal is *to acquire a commercial pre-heating constant volume combustion chamber system, establishing the unprecedented capability at NCSU for extensive characterization of liquid fuel ignition and combustion under precisely controlled ambient environments.*

Specifically, the proposed PHCVCC system will be featured with the following functions:

1). Precisely controlled high-pressure and high-temperature (HPHT) ambient conditions: the purchased PHCVCC system will be able to provide operating pressure of up to 60 bar (6.0 MPa) under ambient temperature of 900 K. The gas composition can be flexibly and precisely controlled by the gas supply system. The system will be fitted with four 100 mm fused silica windows, providing extensive optical access to the spray and combustion processes through different angles and allowing the application of various optical diagnostic techniques;

2). Spray and combustion characterization: another critical benefit of the optically accessible PHCVCC is to provide versatile optical measurements. These measurements will include, but not limited to, liquid spray characterization using Mie-scattering technique, fuel evaporation using Schlieren technique and laser induced exciplex fluorescence technique, chemical reaction and intermediate active species (i.e. OH radicals) characterization using laser induced fluorescence technique, gas temperature measurement using pyrometry and laser induced tracer thermometry, as well as soot volume fraction using laser induced incandescence and light extinction techniques.

In addition to the above readily available functions that can be carried out in SEDL, laser-assisted low temperature spray ignition tests can be performed by building appropriate interface. Other tests such as single droplet evaporation and combustion as well as supercritical spray combustion can also be integrated at a later time depending on the research and education needs.

## **ACCOMPLISHED**

Based the proposed requirements of the DURIP equipment, a Pre-heating Constant Volume Combustion Chamber (PHCVCC) System was identified with certain components and the system was purchased from a vendor. The entire equipment system was delivered and commissioned during the project period. Some preliminary testing and demonstration of the system operation was conducted to confirm the operation of the system. Details are briefly discussed as follows:

## 1. PHCVCC System Components

The PHCVCC system to be acquired consists of the following components: a main chamber body, a cooling system, a gas supply system, a temperature and pressure control system, a fuel supply and injection system, and a system control unit. The main chamber body includes a chamber body, an upper cover, a lower cover, an injector adapter cover, a quartz window cooler cover, quartz windows, and a mobile stand. The body is made of special forged stainless steel and it can withstand high temperature and high pressure (1000 K, 8.0 MPa) produced by heating and spray combustion. The UV grade quartz windows have wide spectral coverage specifically for laser testing. The cooling system includes a cold bath system, a temperature control module, and a water cooling jacket. The injector, quartz windows, and the exhaust system are cooled with a high-power cold bath system to ensure safe operation of the entire system. The gas supply system is used to achieve intake and exhaust of different gases such as air, oxygen, nitrogen, and other minor gases. The temperature and pressure control system includes heaters, internal insulation sets, external insulation sets, temperature measurement and control systems, pressure sensors, and a data monitor. The fuel supply and injection system includes a fuel tank, a low pressure pump, a high pressure pump, a high pressure fuel rail, high pressure tubing, a pressure gauge, and a pressure sensor, and a fuel injector. The system control unit includes the control multifunction data acquisition boards and a host computer. The control unit is able to control the fuel pressure of the fuel supply system, the fuel injection timing, the fuel injection pulse width, and number of fuel injections. The control unit provides adjustable synchronization signals to externally trigger the laser or high-speed camera.

## 2. Main System Features and Technical Specifications

The working medium is mainly composed of air, nitrogen or standard synthetic air, and added minor species. The maximum working pressure is 6.0 MPa and the maximum working temperature is 900 K. The main features and technical specifications of the chamber system are:

- Operating temperature up to 900 K with an accuracy of  $\pm 25$  K;
- Time to reach temperature of 900 K  $\leq 1$  hour;
- Maximum working pressure 6.0 MPa;
- Working time up to 0.4 second to ensure that the target temperature changes do not exceed  $\pm 2.5\%$  and the target pressure change does not exceed  $\pm 2.5\%$  during the test;
- Window diameter 120 mm with the effective optically accessible diameter 100 mm;
- Optical windows made of JGS1 high quality UV quartz material with good light transmission (UV band  $\geq 85\%$ , visible band  $\geq 95$ ) and the transmission spectrum ranges from 200 nm to 1500 nm;
- Intake system using dual control structure including a manual control valve and an electric control valve, providing flexible adjustment of the internal pressure;
- Exhaust safety valve to open automatically when the chamber is over-pressured;
- Cooled exhaust system;
- Modular fuel injector mounting adapter to achieve different installation requirements;
- High pressure fuel pump, high pressure fuel rail, injector and other core components of the common rail fuel injection system are Bosch's products and fuel injector accessories are commercially available on the market;
- Injection timing, pulse width, and number of injections can be controlled flexibly;
- Fuel injection pressure is adjustable within a range of 60-175 MPa;

- Fuel injection system can communicate with the spray combustion control system to synchronize the fuel injection, combustion, lasers, and cameras;
- Automatic control and independent adjustment of the chamber gas pressure and temperature;
- Digital display of pressure and temperature data with overheat self-protection function;
- Real time data acquisition system;
- Forced cooling for effective cooling protection of the key components;
- The bench is easy to install, disassemble, move, and fix the location.

A portion of the funds from this DURIP grant was also used to jointly purchase a high speed camera together with funds from another grant. This new high speed camera can provide much better capability in capturing transient process during fuel injection and combustion. The purchased camera model is Phantom VEO 710 from Vision research, Inc. The main features for this camera are listed below:

- 1280 x 800 CMOS sensor E.I range 6,400 to 32,000 (monochrome)
- TE cooled for lower noise and cleaner images.
- 12 Bit Pixel Bit-depth
- 20  $\mu\text{m}$  pixel size
- 20 ns timing accuracy
- Up to 7400 frames-per-second (fps) at full resolution. Maximum fps: 1.4million
- 1280 x 192 at 30,000fps
- 512 x 512 at 23,500fps
- Internal Shuttering: Hands-free/remote current session reference (CSR)
- Continuously Adjustable Resolution in 64 x 8 increments
- Image-Based Auto-Trigger
- HD video out for setup of cameras
- Memory Segmentation: Up to 64 segments
- Built-in Memory: Up to 72GB
- Optional 10GB Ethernet.
- National Instruments M- and X-Series DAQ modules with integrated support in PCC
- LabView and MatLab drivers
- Compatible with existing Phantom cameras for synchronization and 3D views.

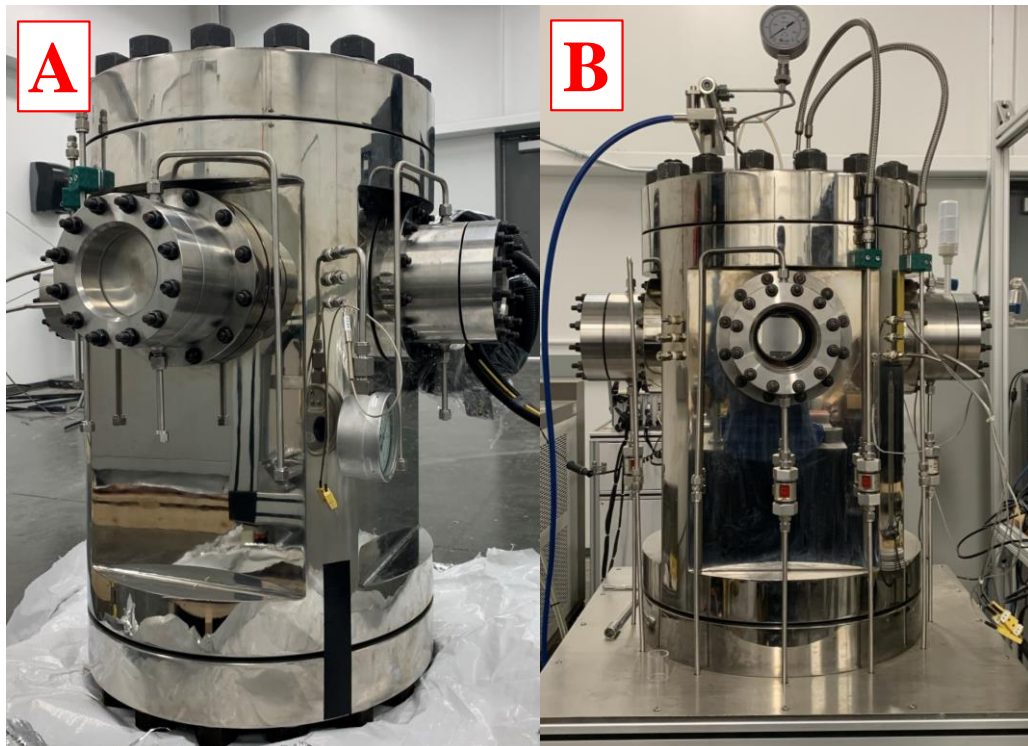
### ***3. System Setup and Preliminary Testing Results***

#### **3.1 System setup**

The experimental setup for the preheating constant volume combustion chamber consists of the following parts: 1. The combustion chamber, 2. Control system, 3. Fuel supply system, 4. Circulating cooler, and 5. Imaging system. Figure 1 shows the combustion chamber before and after final setup and all accessories attached to it including the windows. The combustion chamber is designed to have a total inner volume of 17 L including the heater. The system is also rated to heat the combustion volume up to 900 K with a max pressure of 60 bar. The combustion chamber has 4 optical window openings which are oriented perpendicularly to provide visual access from 4 directions. The openings can accept either a quartz window or a metal plug if the window is not required for that specific experiment. The chamber body also has provisions to cool the windows

with a constantly circulating coolant supply from the cooler to prevent the windows from overheating. The top of the combustion chamber has a fuel rail and an injector assembly. The bottom of the chamber has the inlet, exhaust, and the pressure transducer. The exhaust gases from the chamber goes through a heat exchanger before exiting the system to be exhausted out. Figure 2 shows the fuel rail and injector assembly (A), the inlet, exhaust assembly (B), and a view through the window of combustion volume showing the injector tip. Figure 3 shows the circulating cooler, fuel pump with motor and the control computer with the program to control the system.

The camera used for testing is the new purchased high speed video camera (Vision research Phantom VEO 710). This camera can record at a maximum frame rate of 1280x800 pixels at 7500 fps and all the way up to 1.15 million fps with a resolution of 64x8 pixels. The camera also allows multiple systems to be integrated to trigger at the same time and allows for complex triggering and recording of multiple events from recording, optimizing the memory and workflow. Figure 4 shows the camera and the lens used for the testing. The lens is a 50mm Nikon macro lens.



*Figure 1: Combustion chamber body: A). Before installation, B). Final setup with instruments and tubing attached.*

All the parts of the system were completely tested and connected to complete the pre-heating constant volume combustion chamber system. After assembling everything the system was tested to perform a few typical experiments that the system would be used for. Preliminary testing conditions are listed in Table 1.

Table 1. Parameters for preliminary testing

Parameter	Quantity
Ambient temperature	700 K to 900 K
Fuel tested	Jet-A1
Fuel injection pressure	75 MPa to 150 MPa
Ambient Gas	Air
Density inside the combustion volume	$\sim 22 \text{ kg/m}^3$

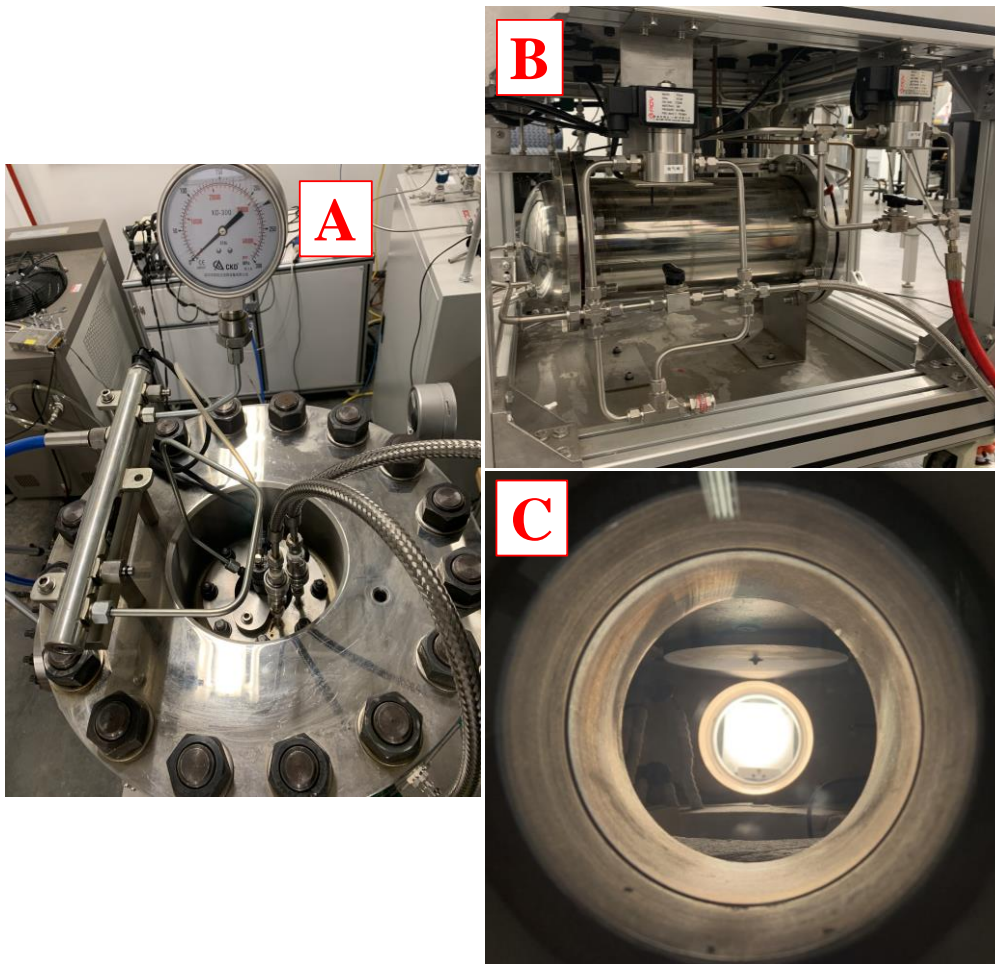


Figure 2: A). Injector and fuel rail assembly, B). Inlet, exhaust assembly, C). View through the optical windows showing the combustion volume and the injector tip.

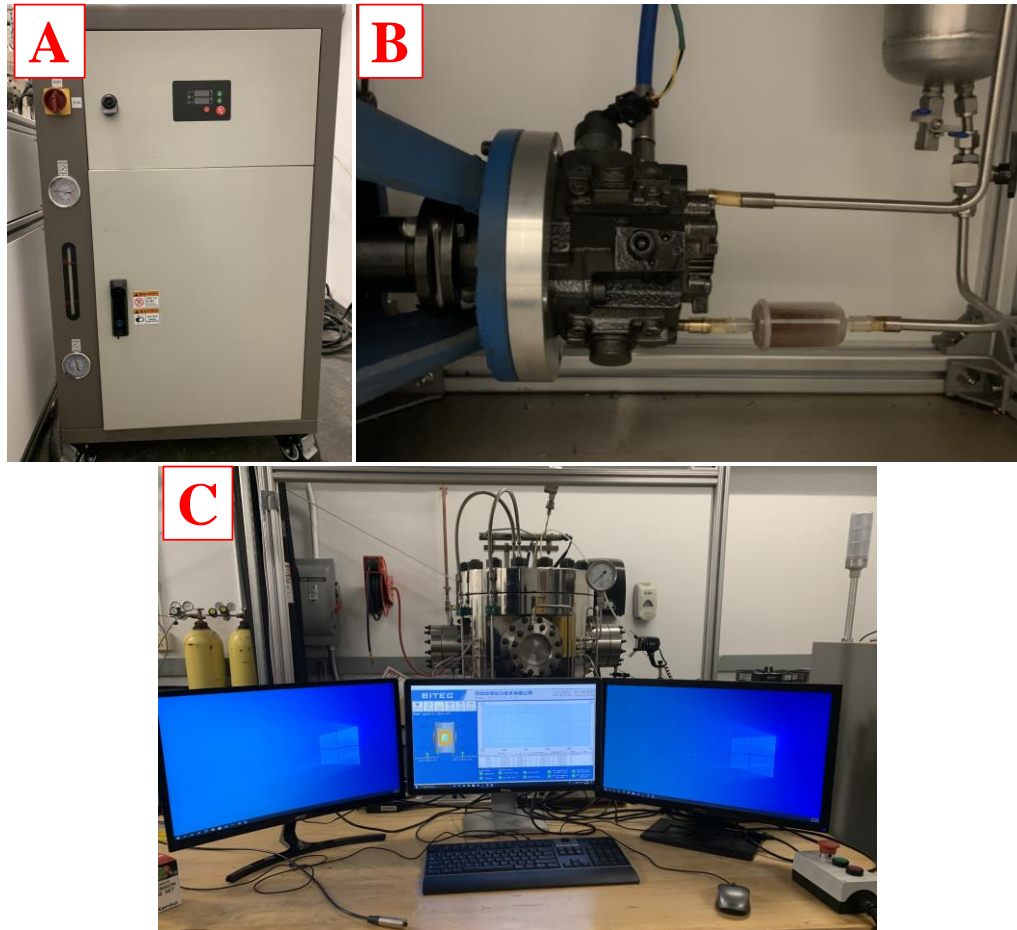


Figure 3: A). The circulating cooler, B). High pressure fuel pump assembly with fuel tank, and C). The control computer to control the system and record data.



Figure 4: Phantom VEO 710 camera used for the testing.

### 3.2. Preliminary testing results

Firstly, the fuel system was tested to visualize the spray using a backlighting imaging technique. Jet-A1 was used as the testing fuel and was tested with the combustion chamber filled with air to 30 Bar at 295 K for non-vaporizing spray testing. Figure 5 shows a sequence of images selected from the different parameters tested. For Figure 5, each row represents a different injection pressure, and each column shows the spray development at a given time after injection trigger. All images displayed were captured using the new purchased Phantom VEO 710 high speed camera at 32000 frames per second with backlighting. There is no significant change in the spray pattern for a similar back pressure under different injection pressures. But with increasing injection pressures the spray penetration increases considerably when comparing between the lowest and the highest injection pressures.

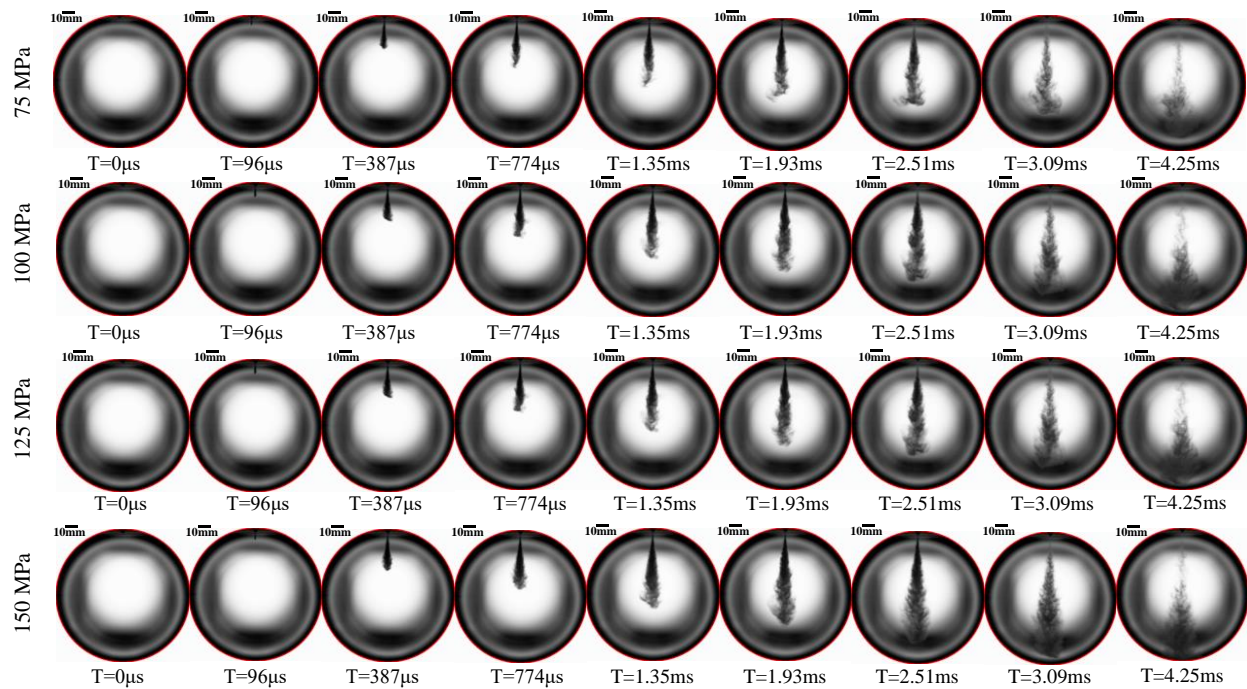


Figure 5: Sequence of images showing spray development at different injection pressures.

For combustion testing, the combustion chamber was heated up to increase the gas temperature and pressure inside the combustion chamber. The chamber was initially filled to 25 bar and then the heater was turned on to heat the inner volume slowly to raise the pressure and temperature inside the chamber. Once the chamber heats up to a given temperature the fuel system is turned on to pressurize the fuel system to the given pressure and then injected into the chamber. As the fuel is injected into the combustion chamber, the spray auto-ignites and the flame development can be captured using the high-speed camera by imaging the flame luminosity. Figure 6 shows a typical injection and combustion event as captured by the high speed camera at 24000 fps under 900 K ambient temperature and 60 bar ambient pressure with 150 MPa fuel injection pressure. The image sequence goes row by row.

Figure 7 shows a set of combustion images for 5 different ambient temperatures with the injection pressure at 150 MPa. These tests were recorded at 24000 fps using the high speed camera. Each row in Figure 7 shows a different temperature inside the combustion chamber and each

column shows the flame at different time from start of injection. T=0ms signifies the start of injection.

To visualize the flame development at greater detail we can use the higher frame rate modes of the camera by reducing the resolution of the images captured. The images shown above are all captured at a resolution of 512x512 pixels. The camera is capable of recording at 32000 fps at that resolution. But if the resolution is reduced to 64x128 the camera can record at 250000 fps. The camera can do a maximum of 1.15 million fps with a resolution of 64x8 pixels which can be useful. Figure 8 shows a sequence of selected images from a recording at 250000 fps. The full sequence covers a time of 4.89 ms from start of injection. The flame development details can be observed with the high frame rate.



Figure 6: Sequence of images for a typical injection and combustion event. This sequence shows an injection event with the chamber at 60 Bar at 900 K at an injection pressure of 150 MPa. The upper right corner shows time in millisecond after the trigger.

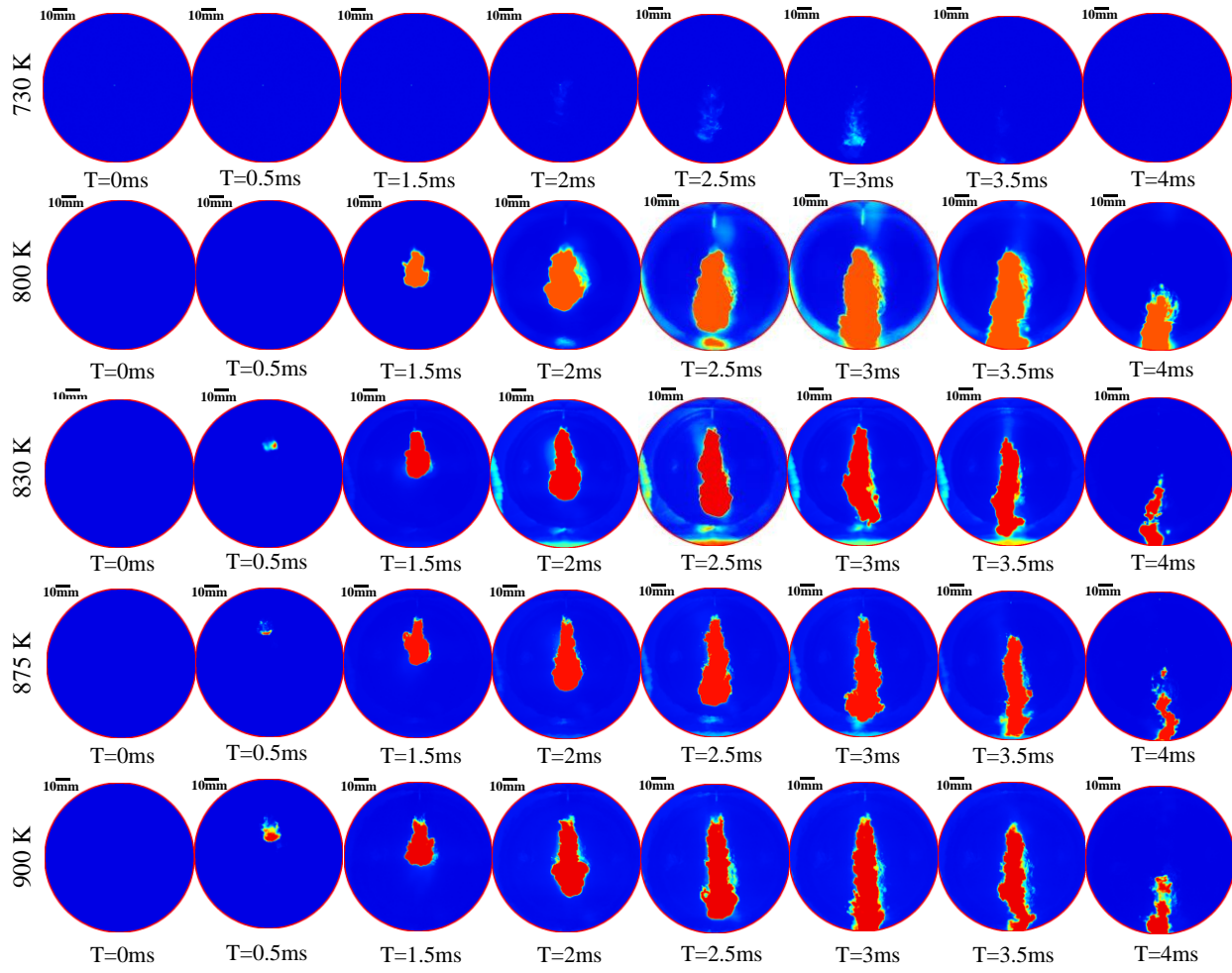


Figure 7: Sequence of images showing flame development under different temperatures.

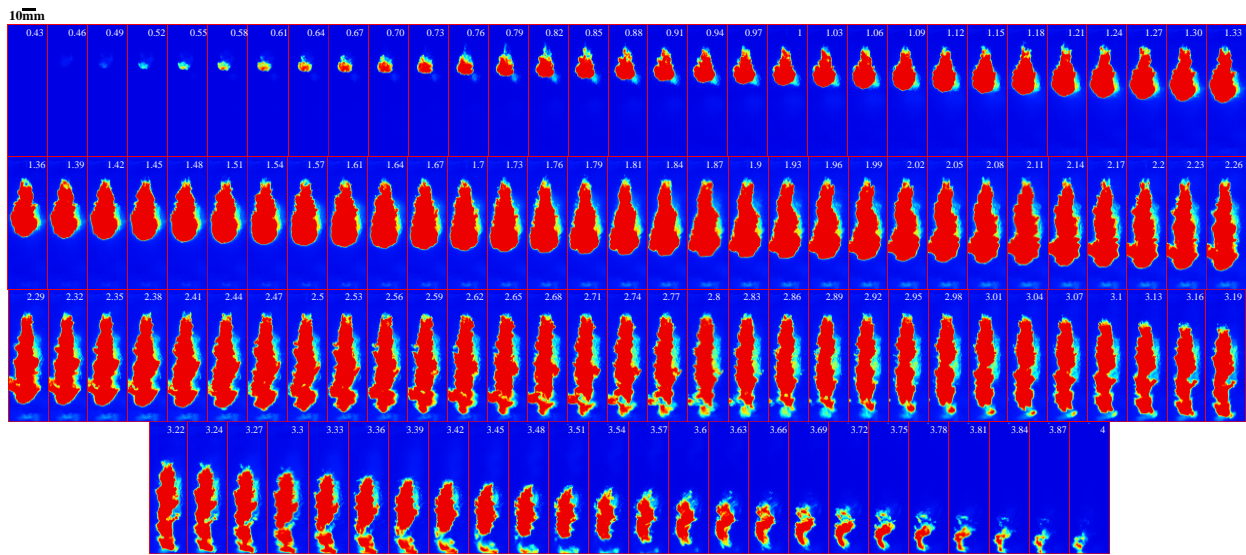


Figure 8: Sequence of images showing selected images from a recording at 250000 fps. The number at the top shows time in millisecond after the trigger.

### **3.3. Summary and future work**

The pre-heating combustion chamber was successfully set up and tested to understand its capabilities. For the next steps the system can be used as a good tool to analyze the combustion characteristics of fuels under high pressure and high temperature environments. With the ease of setup and use of the system, different imaging systems can be used to visualize the spray and flame development of the system. Schlieren is one such imaging system that can be setup with the combustion chamber to showcase the density variation inside the chamber as fuel is injected or as flame develops. Laser diagnostic techniques will also be used to measure species and temperature during combustion process.

### **TRAINING**

Two PhD students (Wang and Nonavinakere Vinod) were trained on optical diagnostic techniques for spray and combustion experiments before the equipment's arrival. After receiving the DURIP equipment, one PhD (Nonavinakere Vinod) and one undergraduate (Kempin) students were trained to run the DURIP system to work on the fuel spray combustion under high pressure and high temperature environments. After graduated from the NC State University the undergraduate student (Kempin) continued his study as a direct PhD student in the department. Kempin and Nonavinakere Vinod are working on high pressure spray combustion using the equipment.

### **DISSEMINATION**

Nothing to report

### **HONORS AND AWARDS**

Nothing to report

### **TECHNOLOGY TRANSFER**

Nothing to report

### **PARTICIPANTS**

Three students, Liging Wang (PhD student), Kaushik Nonavinakere Vinod (PhD Student), and Robert Kempin (Undergraduate student and continued as direct PhD student since fall 2021), were involved in the project and got trained on the optical techniques for spray combustion diagnostics and/or operating the DURIP equipment. Since there is no personnel fund from the DURIP grant, they didn't receive financial support as research assistants from this project.