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TEMPERATURE MEASUREMENTS OF n-HEPTANE INJECTION AND COMBUSTION IN THE IGNITION QUALITY TESTER (IQT^TM^)

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Abstract**—** An experimental work has been conducted to investigate the ignition of n-heptane in the ignition quality tester (IQT^{TM}) by using fine gage thermocouples. A set of eight butt-welded exposed junction thermocouples (TCs) were inserted inside the chamber of IQT^{TM} at different preselected locations to get the temperature variation spatially and temporally in the period prior to the fuel injection up to the mixture ignition. The data were recorded by using a high frequency data acquisition system with a sampling rate of 10 kHz per channel. The experimental data were characterized at set point temperature 584 ^{o}C and pressure 21.3 bar. For reproducibility purposes, 32 injections have been averaged and presented. A drop in temperature due to fuel spray cooling effects has been recorded by TCs at the chamber centerline whereas TCs near the chamber walls did not show a significant drop in temperature. Thus, there was no evidence that the fuel spray reached the chamber walls. The measurements showed that the combustion occurs in the main part of the chamber and the region near the fuel injector nozzle did not show a significant rise in temperature.

Keywords- heptane; combustion; injection; pressure; spray; thermocouple; temperature.

I. INTRODUCTION

Diesel engines are more economical than gasoline engines but generate different toxic emissions (particulate matter, PM, in addition to elevated NOx, as well as CO, and hydrocarbons) in their exhaust gases, which present major risks on public health and environment. Extensive work has been conducted on combustion of diesel fuel and its influence on the performance of compression ignition engines [1]. Most studies discuss the measurement of the time interval between the start of fuel injection until the start of combustion which is called ignition delay (ID) period.

The ignition quality of diesel-like fuels is rated through their cetane number (CN) which is inversely proportional to the ID period. The Cooperative Fuel Research (CFR) test engine under designation number ASMT D613 [2] is commonly used to determine the CN of diesel fuels. Techniques which use constant volume combustion chambers to analyze diesel ignition have been developed and the results have shown an excellent agreement with engines [3]. Therefore, three standard test methods [4] using constant volume combustion chambers have been developed to test diesel fuels and obtain their Ignition Delay (ID) or Derived Cetane Number (DCN). The Ignition Quality Tester (IQT^{TM}), the most precise device used to rate diesel fuels in the present [5], is one of these standards with designation number ASTM D6890.

Most of the experimental data involving the IQT^{TM} are related to pressure measurements. There seems to be a void in temperature measurements, although temperature distributions inside the IQT^{TM} during operation conditions have been obtained numerically [6,7]. The present work aims to analyze n-heptane spray behavior and combustion in the IQT^{TM} through temperature measurements by using multiple fine gage thermocouples located throughout the combustion chamber. These measurements have the potential to identify the regions within the chamber where fuel vaporization takes place and combustion is initiated.

II. EXPERIMENTAL SETUP

A. Ignition Quality Tester (IQT^{TM}) Overview and Setting

The IQT^{TM} has been developed and automated by Advanced Engine Technology Ltd. (AET) [8] to make it a precise and accurate system for oil industry, research and regulatory applications [9, 10]. It is a bench-scale device which is mainly utilized to determine the ignition quality of diesel and alternative diesel fuels. It is comprised of a constant volume combustion chamber with intake/exhaust systems, a fuel injection system, temperature/pressure sensors and a data-acquisition system. Detailed information on the IQT^{TM} can be found in [4].

There are six ports and holes on the walls of the IQT^{TM} chamber as shown in Figure 1: nozzle body port on one end of the chamber, pressure transducer port on the other end, air inlet valve, exhaust outlet valve, and front & back thermocouple

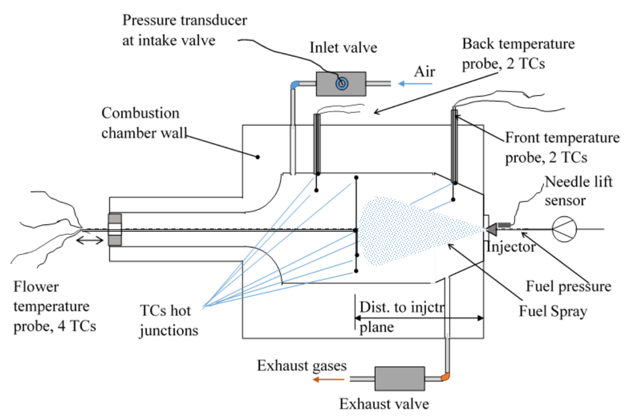

Figure 1: Thermocouple settings inside IQT chamber

holes. Nine electrical heaters of cartridge-type are embedded in the chamber walls and are used to heat chamber walls up to approximately 600 ^{o}C. The combustion chamber is a cavity of cylindrical and conical shapes with total volume of 0.213±0.002 liters. The charge-air gains the heat from the hot walls of the chamber. Both ends of the IQT^{TM} chamber are maintained at a lower temperature compared to the temperature of main portion of the chamber to protect sensors located at the extremities.

The fuel is injected into the chamber as a hollow spray cone from an inward opening single-hole pintle-type nozzle. The spray characteristics from this nozzle design and others are well studied [11]. The nozzle needle starts to lift and the fuel is injected when the pressure of the liquid fuel line behind the nozzle reaches 17.92 MPa. The main injection duration lasts for approximately 2 ms [12].

B. *Temperature Measurement Settings*

Only three out of the six ports on chamber wall could be used to install temperature probes that would protrude into the chamber: front and back TC ports and pressure transducer port. An 1/8 inch probe with two TCs could be used with either front or back TC ports because those ports are already fitted for 1/8 inch temperature probes and they did not require any modifications.

Slight modifications have been made on the IQT^{TM} chamber to allow adjustment of the axial temperature probe. The port of the pressure transducer was used to insert a probe with 4 TCs, which was named "flower" temperature probe (FTP). The coolant adapter of the pressure sensor was modified to accommodate 3/16 inch diameter probe. The pressure sensor was moved with its housing and fitted to the intake valve port. The data from the pressure sensor at the new location was verified against the standard location, showing adequate fidelity. Thus, a total of 8 TCs (2 at the front port, 2 at the back port, and 4 through the pressure transducer port) were fitted inside and near the wall of the combustion chamber as shown in Figure 1.

C. *Thermocouple Selection and Temperature Probe Fabrication.*

A robust temperature probe was required in order to withstand the harsh combustion environment presented by the high temperature, pressure and turbulence, and to track and record the instantaneous temperature variation. Thermocouples (TC) were selected for the present measurements due to their relative robustness, response time, and wide temperature range of operation [13, 14] compared to other temperature sensors.

Thermocouple of type K has been selected to be used in all experiments due to its high sensitivity (41 µV/C) and availability [13].

Three sizes of TC wires (0.003", 0.005", and 0.010" of a butt welded hot junction end) were tested to achieve a compromise between response and durability. Although they exhibited good transient response, the 0.003" and 0.005" TCs did not withstand the harsh environment. They were damaged during warming-up time of the combustion chamber or at mid combustion. The 0.010'' TC had a very good transient response to the temperature variations especially at discriminatory points (Start Of Injection (SOI) and Start Of Combustion (SOC)). Thus, 0.010'' butt welded TC wires of type K from Omega were adopted for temperature measurements.

Based on the dimensions of the front and back TC ports and pressure transducer port, two sizes (1/8'' and 3/16'') of stainless steel sheath tubes were used to encase the temperature probes. An alumina ceramic insulator rod was used around the TCs before insertion of the probe into the sheath tubes [15]. The 1/8'' probe contains two thermocouples and the 3/16'' probe contains four thermocouples. Each thermocouple required two holes in the ceramic insulator rod. A maximum of 4 holes (2 TCs) and 8 holes could be created on the face of a 2.5 mm and 3.2 mm diameter ceramic rods, respectively.

D. *Connections and Data logging*

Tests were conducted in the laboratory at the AET facilities. All sensors were fitted to the chamber and connected to the data logger before the test as shown in Figure 2. Two temperature probes with 2 TCs each were fitted in the front and back TC ports. The flower temperature probe (FTP) with 4 TCs was inserted into the chamber from the pressure transducer port through a bored coolant adapter. All the TC wires of the hot junction side of the FTP were kept straight in the axial direction at first. Then, they were bent inside the chamber by 90^{o} to be distributed radially (see Figure 1). TCs wires were bent manually by getting access to them from the injector nozzle side. For sealing purposes, a reusable Teflon ferrule was used with the stainless steel compression fittings to allow the FTP to be traversed inside the chamber.

All the sensors are connected to a laptop through a data acquisition system from Omega of model OMB-DAQ-3005. DAQ software (Daq view) settings are adjusted to synchronize the feedback from the sensors. The data were collected for the period beginning 10 ms before needle lift until the end of combustion, with a sampling interval of 0.1ms. The recorded

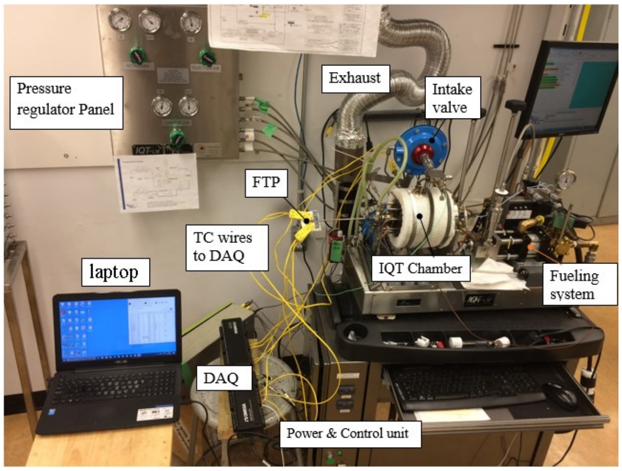

Figure 2: Experimental connections of sensors on IQT to the DAQ

data sets for all injections were saved automatically into the pre-selected file names. A Matlab code was created to analyze and present the collected data. The data of 32 test injections were low-pass filtered first and then the mean values were calculated for temperatures, pressure and needle lift as shown in the following figures below.

E. Points of Temperatre Measurements

Temperature variations were captured at 20 different locations inside the IQT^{TM} chamber as shown in Figure 3. The front or back TCs locations are: first TC was at the wall chamber plane, and the second TC was 8 mm from the wall in a radial direction. The 4 TCs of the FTP were distributed radially as follows: the first TC was at chamber centerline (r=0mm), the second TC was 12 mm from center, the third was 18mm from center, and the fourth was 25mm from the center which is almost on the wall.

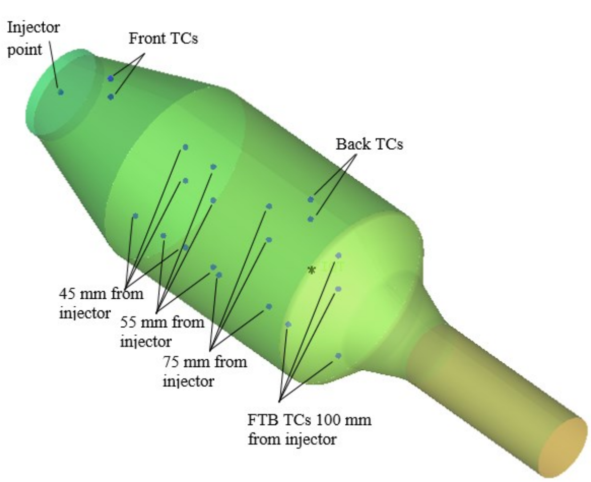

Figure 3: Temperature measurement locations in the IQT chamber

III. RESULTS AND DISCUSSION

The IQT^{TM} was calibrated first and the test conditions were 584 ^{o}C for set point, 310 psi (21.3 bar) for charge air pressure and 0.8231 grams per 10 injections of heptane. Four runs on heptane were conducted at four different axial locations of the FTP, where the distances from the probe plane to the injector were 100, 75, 55, and 45 mm as shown in Figure 3. The three main parameters: nozzle needle position, combustion chamber pressure and spatial gas temperature are collected from needle lift sensor, pressure transducer (mounted in a new position) and TC probes, respectively.

A. Needle lift and Chamber Pressure

The nozzle needle lift position and the chamber pressure traces for 32 individual injections, along with their mean value trace (thick line) are presented in Figures 4 & 5, respectively. The ignition delay period begins when the needle lift signal begins to rise. All injections have the same starting point and the peak of needle lift is around 0.6mm. The main injection duration lasts in about 2 ms.

The chamber pressure (Figure 5) initially drops slightly due to cooling effects of evaporating spray. The required time for atomization, vaporization, mixing and heating of the injected fuel is called physical ignition delay period. During this period, the pressure and temperature inside the chamber decrease. This period is followed by a sudden increase in pressure and temperature due to heat released from the chemical reaction.

B. Temperature measurement results

The temperature variation at two locations were selected to be presented in this section: chamber centerline at a plane 55 mm from injector, and back port at chamber wall.

The time history of the gas temperature measured by FTP for 32 injections is given in Figure 6. The temperature drops initially due to the evaporation of the spray (as mentioned earlier), then the combustion will take place. The maximum temperature measured by FTP was around 1300 ºC. Notice the strong scatter of the temperature measurements from 25 to 500 ms, indicating significantly different combustion processes for each injection during this interval. Nevertheless, the onset of

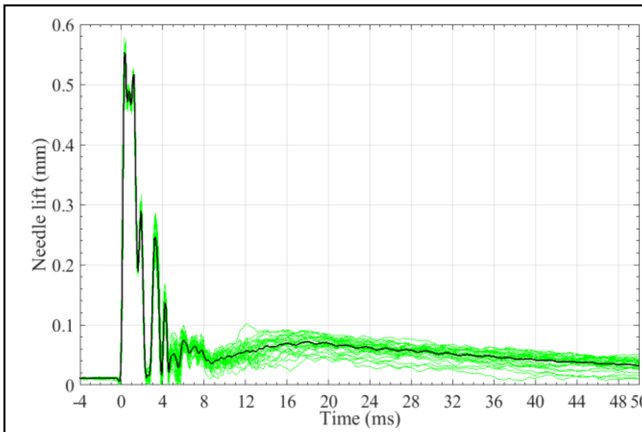

Figure 4: Needle lift trace of 32 injections with mean

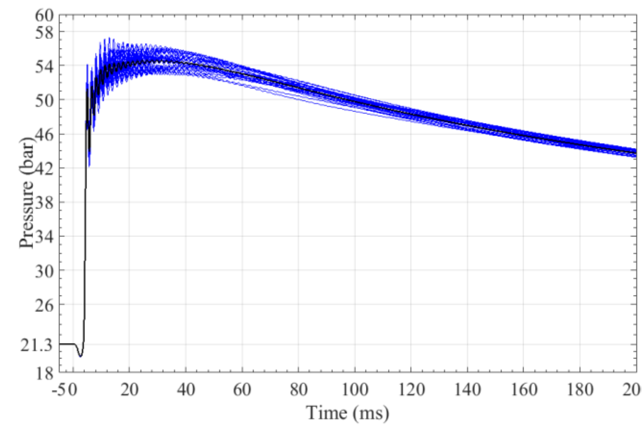

Figure 5: Chamber pressure trace of 32 injections with mean

combustion (the region of interest from 0 to 5 ms) shows high reproducibility.

Temperature profiles at back port of chamber (Figure 7) are slightly different to that at the main part of the chamber (Figure 6). There was no drop in temperature recorded after fuel injection and before the sudden increase in temperature. In this case, a maximum temperature around 850 °C was recorded. The peak temperature at chamber wall, (Figure 7) continues for a very short period of time and then drops.

C. Mean Temperature, Pressure and Needle lift Results at ID Period

To observe clearly temperature variation with pressure during the ID period, the mean values of 32 low pass filtered test injections are presented for the time prior to the fuel injection up to the fuel's IOC as shown in Figures 8 and 9. Three parameters (temperature, pressure and needle lift) are shown on the each figure.

Figure 8 gives temperature variations in four locations along the chamber centerline. The temperature of pressurized air prior to the fuel injection at locations 3 and 4 is higher than that at locations 1 and 2 by almost 10 °C and it drops when the released

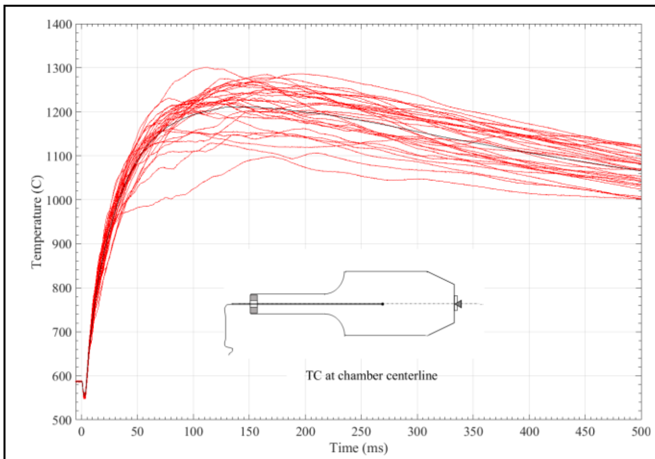

Figure 6: Temperature variation of 32 test injections with mean value from FTP

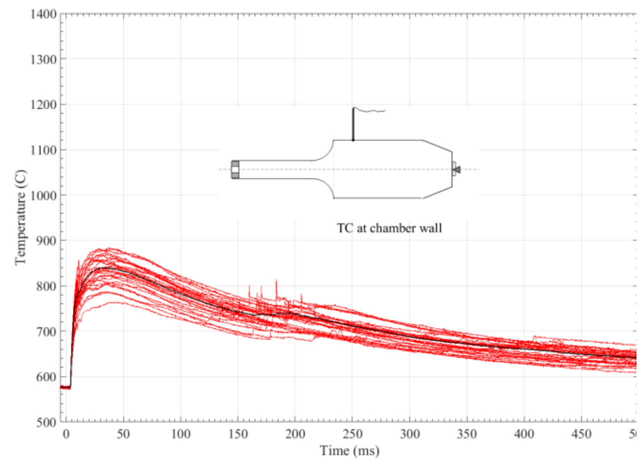

Figure 7: Temperature variation of 32 test injections with mean value at chamber wall, back port

spray from injector nozzle reaches the thermocouples. All four curves have shown a drop in temperature for various periods and are followed by that a sudden increase in temperature. The drop in temperature was due to the high vaporization rate of the fuel, which absorbs heat during that time. The starting point of that drop in temperature depends on the location of the thermocouple. Thus, the closest TC (line 4) to the injector nozzle sensed the spray first after SOI by 0.5ms whereas the farthest one (line 1) sensed the spray after almost 1.25 ms from SOI. The lowest temperature was measured at location 2. The rate of change in temperature (dT/dt) in the rear part of the chamber (locations 1 and 2) was close to zero (temperature does not change with time) and remains at lowest point for a while (0.5 – 0.8 ms) before the sharp rapid increase which gives an indication of the IOC at that location. After that, the rate of increase in dT/dt is almost the same for all locations.

The results from the standard front and back TC locations of the IQT™ (at the wall and 8 mm from the wall) are presented

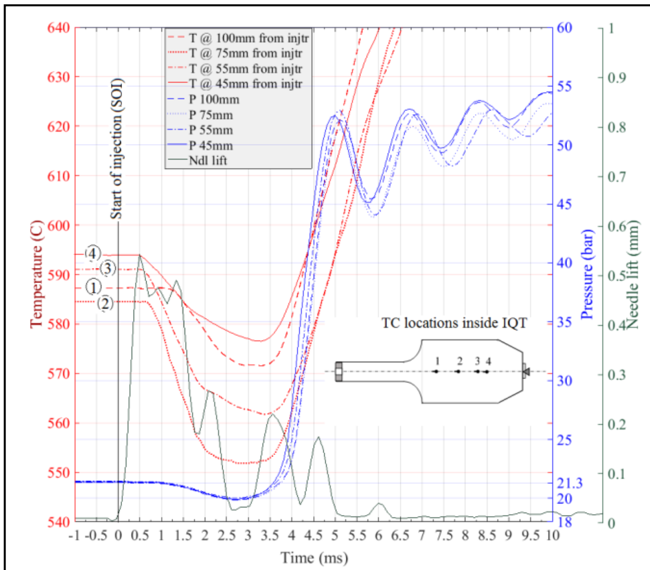

Figure 8: Temperature variation with time at chamber centerline with different locations from injector plane

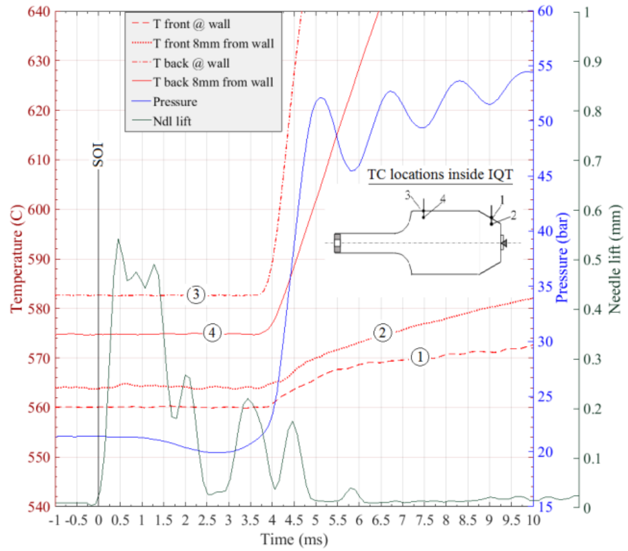

Figure 9: Temperature variation with time at front and back ports

in the Figure 9. None of these TC locations recorded a drop in temperature during the period between SOI and SOC. The temperatures at the front TC location showed only a minor increase after IOC whereas a sudden increase in temperature was measured from front port TCs. For the sake of conciseness, additional data at different locations are not shown here.

IV. CONCLUSIONS

Fine gage, exposed junction thermocouples were successfully used to trace temperature variations at twenty different locations in the combustion chamber of an ignition quality tester. The significant drop (about 30 ^{o}C) in temperature due to an evaporative cooling effect of the fuel spray was recorded at the region of chamber centerline. On the other hand, no evidence of cooling by fuel spray droplets was observed in measurements at and near the chamber walls, where only sudden rise in temperature (due to combustion) was recorded. These results indicate that fuel spray vaporization in the IQT^{TM} takes place in the compressed, heated air within the combustion chamber rather than through contact with the hot chamber walls.

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