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COMBUSTION EMISSION MEASUREMENTS WITH PREHEATED JET FUEL

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ABSTRACT

Jet fuel thermal stability at high temperature is receiving increased attention recently as advanced aero engines are being pushed to high power, high pressure and temperature regimes for improved engine cycle performance and low emissions. This paper describes the rig experimental tests to assess the high fuel temperature effect on combustor emissions. A special test rig facility has been designed and set up for emission measurements with preheated fuel. The purpose of the tests is to evaluate the combustor emission characteristics under nominal and elevated fuel temperatures. The scope of the project is two fold: (1) to design, procure and establish a dedicated hot fuel deoxygenation, fuel preheat facility that can reach temperature up to 600 ^{o}F (589 K); (2) to measure combustion emissions, mainly NOx, CO and UHC, at normal and elevated fuel temperature under representative engine operating conditions. The test rig has run for extended duration and proved reliable over the whole test campaign. Measured emission results show that fuel temperature effect on NOx, CO, UHC emissions are marginal, possibly due to the low emission capability of the sector combustor that is less sensitive to fuel inlet condition changes than other combustor designs. These results indicate a manageable risk for engine development with elevated fuel temperature from the emission viewpoint.

NOMENCLATURE

CO	Carbon Monoxide
CO_2	Carbon Dioxide
EI	Emission Index
FAR	Fuel-Air-Ratio
NOx	Nitrogen Oxide
O_2	Oxygen
T_3	Combustor inlet air temperature
Tfuel	Combustion fuel inlet temperature, is relative to ISA day temperature
UHC	Unburned Hydrocarbon

INTRODUCTION

Jet fuel is often used as coolant in aircraft engines for thermal management. Advanced aero engines are being pushed to high power, high pressure and temperature regimes for improved engine cycle performance and low emissions. As a result the heat sink role of jet fuel often raises the fuel temperature above the industry best practice level. The major consequence of high fuel temperature is the deposit, mainly coke, formation. The consequences of the high fuel temperature on engine safety are severe, as fuel coking can impair the fuel system including fuel nozzles and valves and also reduce the component durability. Jet fuel thermal stability at high temperature is receiving increased attention recently due to the increased engine demand. Innovative approaches to improve fuel thermal stability, such as fuel deoxygenation techniques, will allow fuel to reach higher temperature levels that have not been envisaged so far [Ref. 1-5].

The impact of high temperature fuel on combustion performance, like emission, needs to be established. There is sparse data available on the hot fuel emission. One of the major challenges is the design, set up and operation of a dedicated fuel heating facility that can be operated reliably and safely. This paper describes the rig experimental tests to assess the high fuel temperature effect on combustor emissions. A special test rig facility has been designed and set up for emission measurements with preheated fuel. The purpose of the tests is to evaluate the combustor emission characteristics under nominal and elevated fuel temperatures. The scope of the project is two fold:

(1) to design, procure and establish a dedicated hot fuel deoxygenation, fuel preheat facility that can reach temperatures up to 600 ^{o}F (589 K);

(2) to measure combustion emissions, mainly NOx, CO and UHC, at normal and elevated fuel temperatures under representative engine operating conditions.

EXPERIMENTAL DETAILS

The high pressure emission test has been carried out at the combustion test facility (Test Cell #3) of the National Research Council Canada (NRC), located in Ottawa, Canada. This emission test is a typical high pressure combustor sector testing where four fuel injectors were used. However, the requirement for jet fuel heating made this emission test technically challenging and also meant that special equipment will be required.

De-oxygenation Equipment:

The increase of jet fuel temperature can lead to serious engine operational problems such as coking. The coking problems can significantly be reduced if the dissolved oxygen level is reduced [Ref. 1, 4]. There are a number of ways to reduce the oxygen level for rig testing. In this study, the dissolved oxygen was removed by the nitrogen sparging process.

Figure 1 shows the process and instrumentation diagram (PID) of the fuel sparging system. The nitrogen gas is bubbled through small holes evenly located on a spiral of stainless tube at the bottom of each of 1600 liter jet fuel tank at 10 psi (68,948 Pa) overpressure. After nitrogen removes the dissolved oxygen in jet fuel and fills the tank, it is eventually vented through the 2” pipe with a demister. The level of the dissolved oxygen is measured by special oxygen concentration sensors, which are located on each tank and on a small chamber before a loop pump for re-circulation to enhance fuel sparging process. The tank pressure is kept at 5 psi (34,473 Pa) above atmospheric pressure to prevent outside oxygen/air from entering back to the tank. An ultrasonic level meter is installed in each fuel tank to measure the fuel reservoir level that remains available for testing. Normally, one tank can hold enough fuel to complete tests up to eight hours.

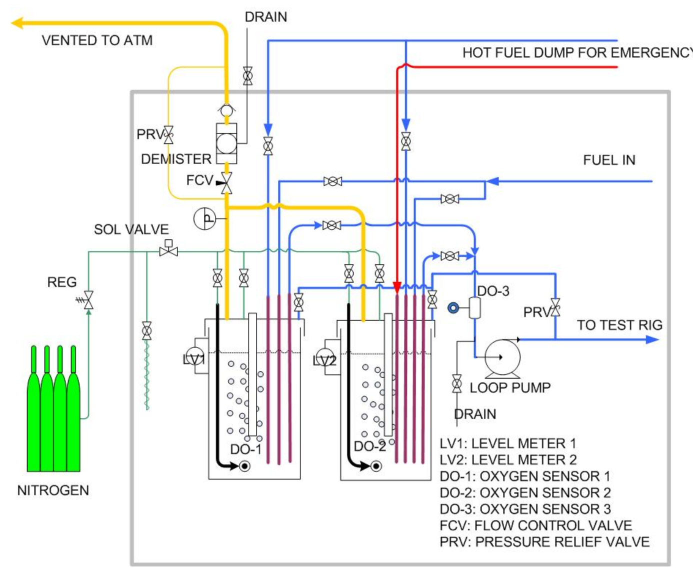


Figure 1: Process & Instrumentation Diagram of the fuel sparging system

The sparging system is housed in a fire rated fuel hut, which was specially designed and built for the test. The fuel hut also includes an explosion-proof ventilation fan, light and heating system. During the emission test, only one tank is used while the other one is used as a dump tank to which heated fuel can be immediately discharged and cooled by fuel in the tank for an emergency situation.

The dissolved oxygen concentration is about 70 ppm at fully saturated ambient condition [Ref. 4]. Figure 2 shows the gradual change of dissolved oxygen concentration in jet fuel by the sparging process. The level of dissolved oxygen drops to less than 5% of the initial value within 30 minutes after the sparging was initiated. During the test campaign, Jet A1 is usually pre-treated by sparging one day before test and re-filled again after test is completed. The actual level of dissolved oxygen in jet fuel can be confirmed through heating the fuel and check the deposit / coke accumulation in the fuel nozzle. Satisfactory results with free flowing nozzle indicated no significant coke formation and the expected achievement of deoxygenation.

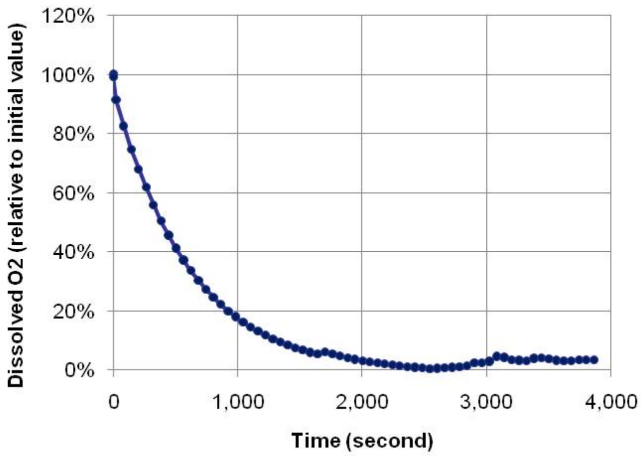


Figure 2: Change of dissolved oxygen level by the sparging process

High Temperature Fuel Supply System:

Heating jet fuel to high temperature, say 600 ^{o}F (589 K) is a technically challenging task that has a serious safety concern since the auto-ignition temperature of Jet A1 can be as low as 410 ^{o}F (483 K). As such, if there is any high temperature fuel leakage, it may lead to instant fire inside an enclosed test cell and special measures to mitigate such risks were taken. Figure 3 shows the process and instrumentation diagram of fuel heating and supply system. The pre-treated Jet A1 from the fuel hut is pressurized up to the required pressure by fuel pump and split into two fuel lines: one for primary and the other one for secondary fuel line. For the current emission test, only fuel through the secondary line was heated. Fuel is heated by one 113 kW electric heater, which is enough to Jet A1 up to 600 ^{o}F (589 K) at the maximum flow rates. Since the fuel temperature at most test points exceed the auto-ignition temperature, several provisions for safety were made. For instance, the hot fuel line is completely welded without using any fittings from the heater to the test rig. To remove the possibility of leaking of hot jet fuel from the heater flanges, the interfacing parts with the fuel pipe are completely enclosed by purge boxes to which nitrogen continuously flows (see Figure 3). After nitrogen fills purge boxes, it is vented to the outside of test cell. In addition, a gas detector is installed to measure the level of hydrocarbons in the vented nitrogen and to provide the operator with early alarm during testing. The fuel hut is also designed to be explosion proof.

In case of an emergency situation, it is important to remove hot fuel from the fuel line immediately. By closing two high temperature rated solenoid valves, fuel heater and test rigs are isolated from each other and hot fuel in the line is removed through a heat exchanger and dumped into one of the two fuel tanks in the fuel hut. Before the emission test, the heater was completely wrapped by insulation material. The electric heater was controlled by the reading of three thermocouples, two of which are installed on the heater and the third one in the fuel line after the heater, and also enclosed by the purge box.

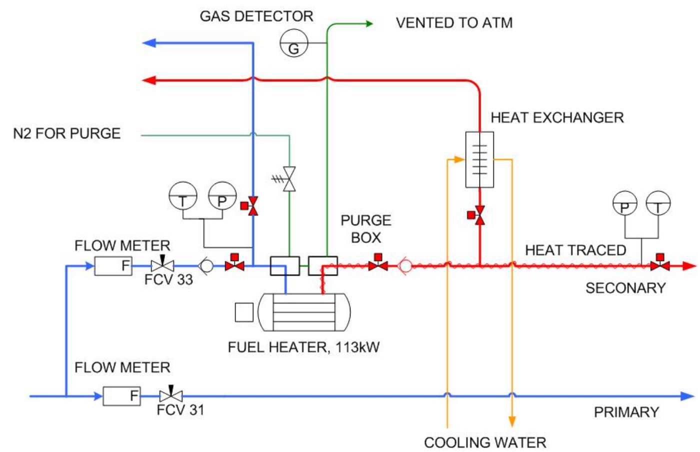


Figure 3: Process and instrumentation diagram of fuel heating & supply system.

In case of emergency, the heated fuel in the electric heater and fuel line will be immediately dumped to a dump tank on the outside of test cell. The dump tank is equipped with a pressure relief valve, pressure and temperature sensors. Before testing, the air inside the tank will be removed by a vacuum pump and nitrogen will be introduced to avoid the possibility of auto-ignition.

High Pressure Emission Test Rig Setup:

● Emission probe cooling water: the International Civil Aviation Organization (ICAO) standard requires that the temperature of emission sample gas should be maintained within 160 ±15 ^{o}C in the sampling line from the emission probes to the emission analyzers [Ref. 6]. The emission probes are cooled and protected from the hot combustion gas by cooling water through the probes. However, since the sampling emission gas can be quenched close to the emission cooling water temperature at the sampling probes, the cooling water needs to be heated. A thermocouple is installed in each emission probe to measure the cooling water temperature and determine if the emission probe is adequately cooled. The emission sampling gas taken from each emission probe is separately transported through three heated sampling lines to the emission analyzer, so that the variations from each emission probe can be assessed. Test data show that the probe to probe variation is very small, and it was decided to use one reading from all 3 probes bundled together to speed up the tests.

● Compressed Air/ Cooling Water Supply System: Figure 4 shows a process and instrumentation diagram for the high pressure emission test set-up. Compressed air is supplied from the centralized compressors through pipe line with the maximum pressure of 300 psia (20.68$\times$10^{5} Pa). Then air is split into main air line and bypass line. Air from the main air line passes through a non-vitiated gas heater to obtain the compressor discharge temperature and is fed into the combustor. Air from bypass line is used to cool the interface section between the combustor exit and the instrumentation flange in the rig. The exhaust section of test rig has water jacket cooled by water. Additionally, the combustion gas is mixed with sprayed water to lower temperature before the back pressure valve.

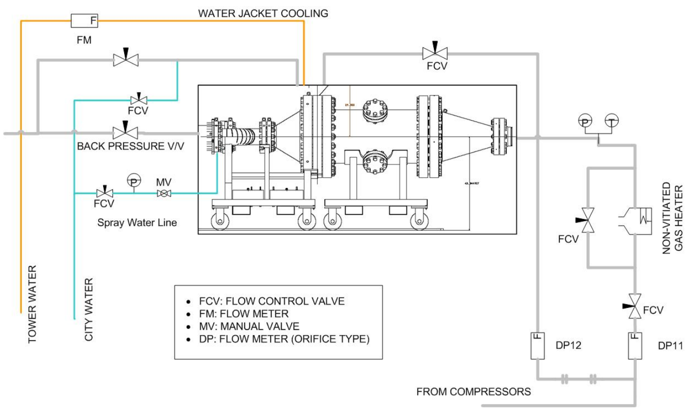


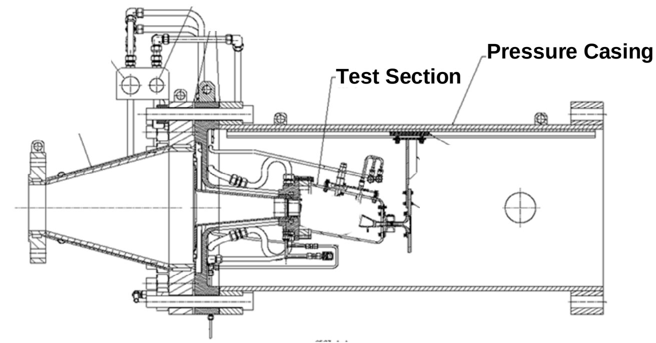
Figure 4: Experimental Setup for Emission Test

Figure 5 shows the test section and the rig set up (P&WC Proprietary Design). The combustor is a planar sector design with 4 fuel nozzles (4 sectors). The sector combustor is housed inside a pressure vessel. Emission probes are located at the exit of the combustor and emission samples are taken through heated line to the emission instrumentations. NOx, CO, UHC, CO_2 and O_2 concentrations are measured.

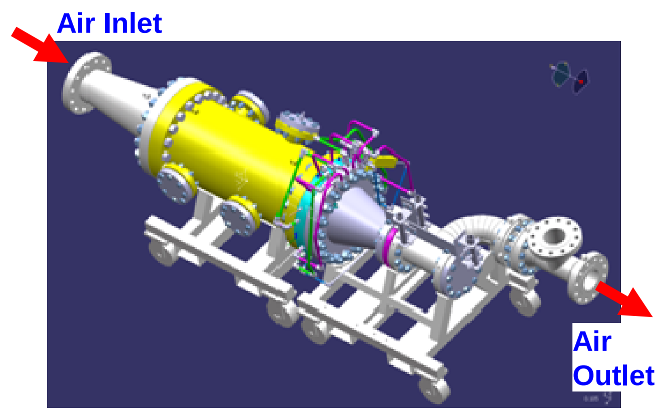
RESULTS AND DISCUSSIONS

Since this is the first time to operate the new fuel heating facility and to conduct hot fuel emission tests at NRC, it is essential to check the test rig and emission instrumentation functionality. Figure 6 shows the emission sampling efficiency, most of the data are within the ICAO limit of 100±10% for high power conditions and 100±15% for low power conditions [Ref. 6]. The sampling efficiency is considered acceptable. The sampling efficiency is a check on the agreement of air/fuel ratio as estimated from the integrated gaseous sample total carbon concentration exclusive of smoke, with the estimate based on engine air/fuel ratio.

Figure 7 shows the emission variation as the combustor inlet temperature increases. This is similar to engine power increases. The trend of NOx, CO, UHC are acceptable and it serves as quality check for the test section and the emission sampling system.



(a) Combustor Test Section



(b) Test Section Assembly

Figure 5: Schematic of Sector Combustor Test Facility (P&WC Proprietary Design)

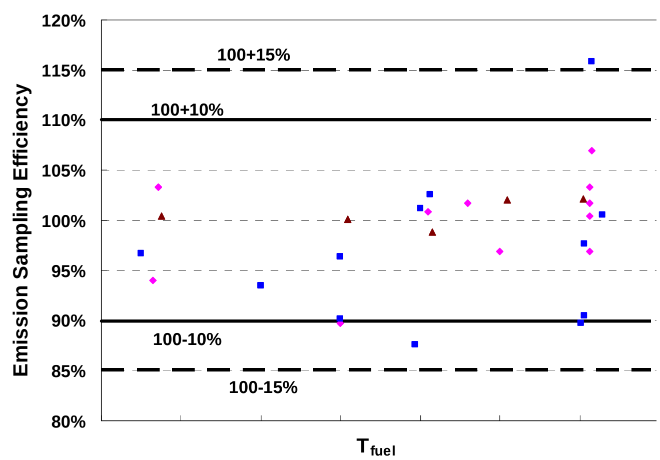


Figure 6: Emission sampling efficiency

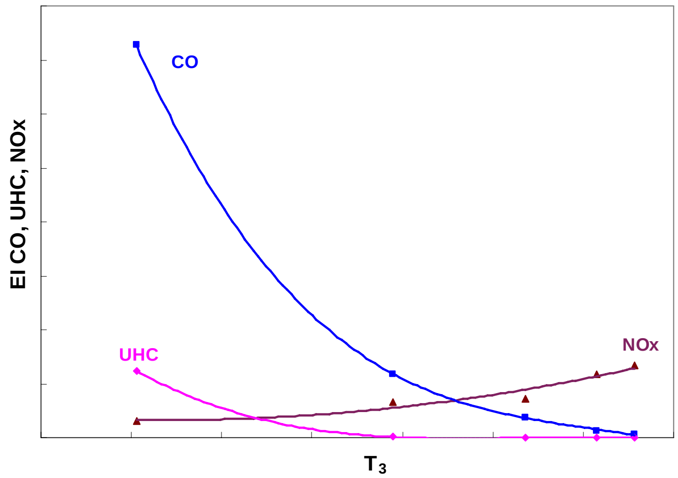


Figure 7: EI (CO, UHC, NOx) trend is reasonable

The fuel temperature effect on NOx is illustrated in Figure 8. Three flow conditions were tested, with different combustion pressure (91 to 185 psia or 6.27$\times$10^5 to 12.76$\times$10^5 Pa) and combustor exit temperature (1690 to 2312 ^{o}F or 1194 to 1540 K). At each condition, only fuel temperature was varied. The EI NOx stays fairly consistent for fuel temperatures up to 450 ^{o}F. This is presumably due to the low emission combustor design that is less sensitive to fuel temperature changes. It is reasonable to say that the NOx are mainly thermal NOx and fuel temperature change only leads to a few degree increase in flame temperature, therefore does not have significant affect on NOx formation zone, and NOx level. EI NOx is relative to high power EI NOx.

Huang et al. [Ref. 2] reported that by mixing jet fuel vapour and liquid jet fuel nitric oxides emissions remained nearly constant, suggesting that the fuel state change from liquid to vapour has little effect on the peak combustion temperature. The NOx results of the current study are in line with the conclusions of Huang et al.

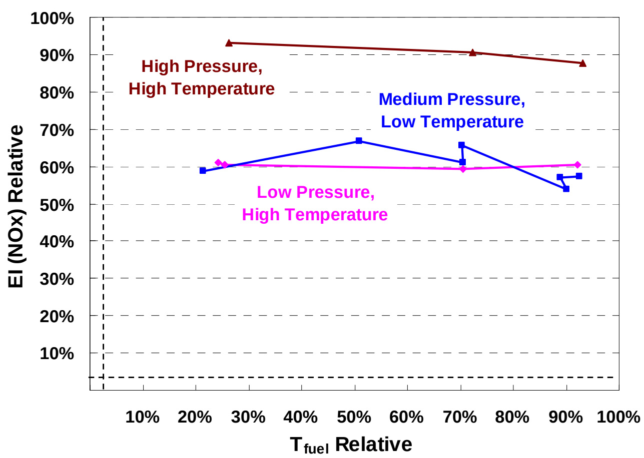


Figure 8: Fuel temperature effect on relative EI NOx

CO variation under different fuel temperature is more visible, especially at low combustion temperatures (Figure 9). The fuel temperature increase will result in lower fuel density and high injection velocity, and hence higher fuel-air momentum ratio with farther fuel penetration into the combustion regime. Such change of fuel penetration will affect the fuel-air mixing process in the burning zone, and affect the CO emission accordingly. It should be noted that the combustor, fuel nozzle, etc. are designed primarily for conventional liquid fuel application. The high temperature fuel causes deviation of the originally optimized fuel-air mixing process and leads to higher CO. This suggests that combustor system components need to be further optimized when fuel temperature is increased beyond the current commercial aviation best practice level, ~325 ^{o}F (436 K) [Ref. 2]. EI CO is relative to low power EI CO.

Unburned hydrocarbon level is very low at most conditions and variation due to fuel temperature can not be analyzed due to the low level.

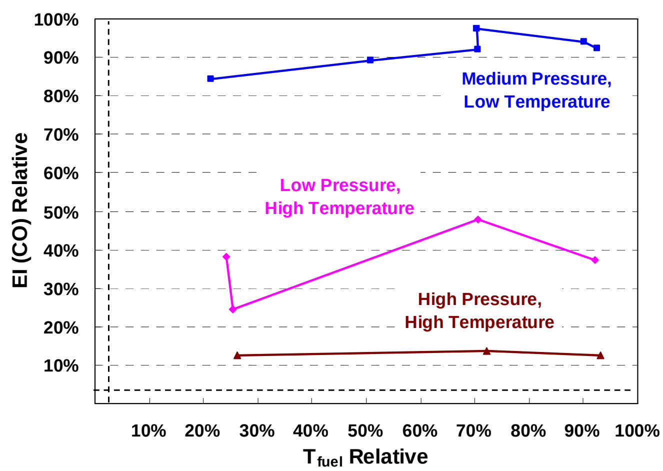


Figure 9: Fuel temperature effect on relative EI CO

High fuel temperature has impact not only on fuel thermal stability, but also on the fuel system operations. In cases where the fuel inlet pressure is below the critical pressure the heated fuel will change phase from liquid to vapour inside the fuel nozzle (vapour locking). This phase change normally leads to increase in downstream fuel back pressure and the measured nozzle flow number will show to decrease. In the extreme situation where the back pressure increase is so high it affects the flame stability and causes flame out.

To demonstrate that the vapour locking can be avoided, the existing fuel nozzle was modified to reduce the flow number to raise the fuel inlet pressure. After the modification the fuel inlet pressure is well above the critical pressures and no more flame stability issues have occurred. This indicates that to maintain reliable high fuel temperature operation the engine components need to be re-designed to accommodate the significant change in fuel property.

The test rig has run hot fuel up to 600 ^{o}F (589 K) with extended hours, the fuel nozzle are flow checked after the tests and flow number stay the same, indicating no coking and oxygen level in fuel has indeed been reduced substantially.

CONCLUSIONS

A special test rig facility has been designed and set up for emission measurements with preheated fuel. The test rig has run for extended duration and proved reliable over the whole test campaign. Measured emission results show that fuel temperature effect on NOx, CO, UHC emissions are marginal, possibly due to the low emission capability of the sector combustor that is less sensitive to fuel inlet condition changes than other combustor designs. These results indicate a manageable risk for engine development with elevated fuel temperature from the emission viewpoint.

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