

Comparison of Diesel Spray Combustion in Different High-Temperature, High-Pressure Facilities

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ABSTRACT

Diesel spray experimentation at controlled high-temperature and high-pressure conditions is intended to provide a more fundamental understanding of diesel combustion than can be achieved in engine experiments. This level of understanding is needed to develop the high-fidelity multi-scale CFD models that will be used to optimize future engine designs. Several spray chamber facilities capable of high-temperature, high-pressure conditions typical of engine combustion have been developed, but because of the uniqueness of each facility, there are uncertainties about their operation. For this paper, we describe results from comparative studies using constant-volume vessels at Sandia National Laboratories and IFP. Targeting the same ambient gas conditions (900 K, 60 bar, 22.8 kg/m³, 15% oxygen) and using the same injector specifications (common rail, 1500 bar, KS 1.5/86 nozzle, 0.090 mm orifice diameter, n-dodecane, 363 K), we describe detailed measurements of the temperature and pressure boundary conditions at each facility, followed by observations of spray penetration, ignition, and combustion using high-speed imaging. The spray diagnostics show reasonable similarity despite the challenges of providing matched boundary conditions at these unique facilities. Performing experiments at the same high-temperature, high-pressure operating conditions is an objective of the Engine Combustion Network (<http://www.ca.sandia.gov/ECN/>), which seeks to leverage the research capabilities and advanced diagnostics of all participants in the ECN. Thus, in

addition to the presentation of a comparative study, this paper demonstrates steps that are needed for other interested groups to participate in ECN spray research. We expect that this collaborative effort will generate a high-quality dataset to be used for advanced computational model development at engine conditions.

INTRODUCTION

The Engine Combustion Network (ECN) is an experimental and modeling collaboration dedicated to the improvement of engine CFD modeling. The ECN contains an internet data archive library (<http://www.ca.sandia.gov/ECN/>) with well-documented diesel spray experiments at engine conditions. Quantitative comparisons of spray evaporation and mixing at high-temperature, high-pressure conditions are now possible, providing new opportunities for CFD model improvement at realistic engine conditions. The dataset also currently includes reacting and non-reacting data such as the liquid and vapor penetration versus time, liquid length, ignition delay and pressure-rise rate, lift-off length, quantitative soot volume fraction, and various high-speed movies of combustion. Several research groups have used the dataset for model validation (e.g. [1, 2, 3, 4, 5, 6, 7, 8]).

Until recently, the ECN data archive was derived from a single spray chamber facility at Sandia National Laboratories. However, many ECN users responded favorably to this initiative and are now working collaboratively to create future datasets of interest, utilizing multiple facilities throughout the

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world. In particular, IFP is now an active participant and is working together with Sandia National Laboratories to structure and initiate the international collaboration. This collaboration has led to an ECN working group on spray combustion. The working group has identified a few experimental conditions that could become the focus of those who wish to voluntarily participate in the ECN. The experimental collaboration is made possible by the donation of “identical” injection systems by Robert Bosch, LLC. The ECN group has agreed to experiment at the same injector and ambient conditions, thereby leveraging the expertise of each participant, and enabling direct comparison between different facilities. Significant effort is being made to verify the boundary conditions at each facility, as well as to measure the rate of fuel delivery and internal movement of the injector. In the end, all participants will benefit by sharing information at the same operating conditions. This is the same vision guiding the Turbulent Non-premixed Flame (TNF) workshop [9], where years of quantitative experimental effort on a particular flame (e.g. “Flame D”) have created a standard library for computational comparison. The ECN seeks to generate a similar database at engine conditions. We expect that the dataset developed will become a serious focal point for model validation and further advanced diagnostics.

Following the tradition of the TNF workshop, the ECN group has chosen to name the first target condition “Spray A” [10]. Specifications for the injector and ambient operating conditions for this condition are given in [Table 1](#). Spray A is a low-temperature combustion condition relevant to engines that use moderate EGR and have minimal NO_x emissions. The injector specifications pertain to modern advanced injection systems with high pressure capability. Bosch donated 10 different injectors for the initiative, including 5 single-hole injectors with an orifice on the axis of the nozzle, as well as 5 three-hole injectors with the same orifice size and an 145° included angle. Single, axial-hole injectors will be used for Spray A, while the multi-, side-hole injectors will be used at the same “Spray A” conditions, but with a “Spray B” designation. A comparison between single and multi-, side-hole injectors is therefore the objective of Spray A/Spray B experiments. Using the same injector body, the common rail and injector tube length are also specified to ensure consistent hydraulic effects on injection. A single-component fuel, n-dodecane, is chosen to enable a complete specification of the chemical and physical properties of the fuel. Detailed chemical kinetic mechanisms exist for n-dodecane [11, 12], allowing full treatment of the combustion chemistry. Although the boiling point temperatures of n-dodecane are lower than that of diesel fuel, n-dodecane has boiling point temperatures that are sufficiently high to emphasize spray mixing processes, n-dodecane is also compatible with production fuel pumping systems.

Spray data of the caliber needed for detailed model development and validation requires extensive

characterization of all of the boundary conditions that will be used as model inputs. Two types of controlled spray chambers that are capable of operation at high-temperature, high-pressure conditions typical of engine combustion have been developed: (1) heated flow chambers and (2) constant-volume chambers that employ a preburn and cool down to the desired pressure and temperature. These facilities were recently reviewed by [13]. Although there are a growing number of these facilities throughout the world, uncertainties about their operation exist because of the uniqueness of each facility. To our knowledge, there has never been a direct comparison of spray combustion at two different facilities of this type.

The objective for this paper is to present concurrent measurements of Spray A boundary conditions and spray penetration and combustion data from combustion vessels at IFP and at Sandia National Laboratories. This work represents a collaborative effort to facilitate research at Spray A conditions, and other conditions that will be chosen as part of the ECN. ECN participants are expected to measure the boundary conditions (e.g., the parameters specified in [Table 1](#)) for the ambient and injector, and to state uncertainties associated with the boundary conditions and other data. However, some uncertainties are not recognized until there is repeat and duplicate experimentation. Our approach to better understand each facility, and to minimize uncertainties, is to directly compare results at these standardized experimental conditions. Once these boundary conditions are better understood, variation in parameters beyond those of Spray A can proceed with higher confidence. Accordingly, this paper demonstrates steps that are needed for other interested groups to participate in ECN spray research.

As opposed to a traditional paper, we have grouped the experimental setup and results together into individual sections that correspond to various phases of the research. These sections include (1) combustion vessel operation, (2) ambient gas characterization, (3) injector characterization, (4) spray liquid and vapor penetration, and (5) combustion characterization.

COMBUSTION VESSEL OPERATION

IFP and Sandia use a preburn-type combustion vessel to generate high-temperature, high-pressure gases. The ambient pressure, temperature and species at the time of injection are varied by igniting a premixed combustible-gas mixture that burns to completion. Following the spark-ignited, premixed combustion, the combustion products cool over a relatively long time due to heat transfer to the vessel walls and the vessel pressure slowly decreases. When the desired pressure and temperature is reached, the diesel fuel injector is triggered and fuel injection occurs. A detailed description of this type of facility is found in [10].

Table 1. Spray A Operating Conditions.

Ambient gas temperature	900 K
Ambient gas pressure [§]	near 6.0 MPa
Ambient gas density [§]	22.8 kg/m ³
Ambient gas oxygen (by volume)	15% O ₂ (reacting); 0% O ₂ (non-reacting)
Ambient gas velocity	Near-quiescent, less than 1 m/s
Common rail fuel injector	Bosch solenoid-activated, generation 2.2
Fuel injector nominal nozzle outlet diameter	0.090 mm
Nozzle K factor	$K = (d_{\text{inlet}} - d_{\text{outlet}})/10$ [use μm] = 1.5
Nozzle shaping	Hydro-eroded
Mini-sac volume	0.2 mm ³
Discharge coefficient	$C_d = 0.86$, using 10 MPa pressure drop and diesel fuel
Spray full included angle	0° (single axial hole)
Fuel injection pressure	150 MPa
Fuel	n-dodecane
Fuel temperature at nozzle	363 K (90°C)
Common rail volume/length	22 cm ³ / 28 cm (Use GM rail model 97303659)
Distance from injector inlet to common rail	24 cm
Fuel pressure measurement	7 cm from injector inlet / 24 cm from nozzle
Injection duration	1.5 ms
Injection mass	~3.5 mg
Approximate injector driver current	18 A for 0.45 ms ramp, 12 A for 0.345 ms hold

§This exact combination of ambient pressure and density corresponds to a particular set of gases for a 0%-O₂ condition with 89.71% N₂, 6.52% CO₂, and 3.77% H₂O by volume and a compressibility factor, $Z = 1.01$. When different gases are used, the pressure must vary to maintain the same density.

Photographs of each facility are given in Fig. 1. Each vessel has full optical access for line-of-sight or orthogonal diagnostics. The vessels are cube-shaped, measuring greater than 100 mm on each side, and allowing extensive visualization of the spray prior to wall impingement. Vessel dimensions and other characteristics are given in Table 2. The vessels are heated to mimic engine surface temperatures and to prevent condensation of combustion products onto windows. Multiple spark plugs are utilized to provide consistent ignition of fuel-lean mixtures. A mixing fan stirs the gases during intake filling and afterwards in order to prevent mixture and temperature non-uniformities. Corner ports of the vessel are used for the mixing fans, intake and exhaust valves, high-speed pressure transducers, or other instrumentation.

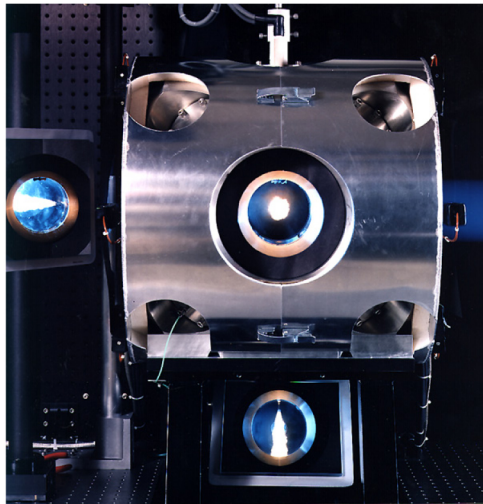
Since a preburn-method is used to generate high-temperature, high-pressure conditions, the composition of the initial fill reactants determines the combustion product mixture that exists at the time of injection. Product mixtures may be made inert (0% O₂), to simulate air (21% O₂), or to simulate air-EGR mixtures as is the case for Spray A (15% O₂). While only the target oxygen mole fraction is listed for the Spray A condition, the reactant mixture that is used will also affect the concentration of other combustion products, which in turn

affects the molecular weight and other thermodynamic properties. IFP and Sandia traditionally use different reactant gases. The composition of the reactant and product mixtures that simulate Spray A conditions are given in Table 3 for 0% O₂ and 15% O₂ conditions. Product compositions are calculated based on the stoichiometry of the reactant mixture and the assumption of complete combustion. Other experimental conditions for the reactants and combustion products at the time of injection are also given in the table. These quantities will be explained and referred to throughout the paper.

The reactant mixtures differ between the two facilities in several ways. First, IFP used ethylene C₂H₄ as the hydrocarbon reactant as opposed to acetylene C₂H₂ at Sandia. In addition, IFP used a significantly higher percentage of hydrogen compared to Sandia. As a result, the molecular weight of the reactants and products is lower for IFP compared to Sandia, accompanied by a higher H₂O concentration and lower CO₂ concentration in the products. Because of the differing molecular weights (as much as 8%), the ambient gas pressure and density varies slightly between facilities, or between inert (0% O₂) and reacting (15% O₂) experiments. IFP chose to operate with an ambient gas

density 2% lower than Sandia in order to maintain ambient pressure near 6.0 MPa. Although operating with different ambient density, IFP and Sandia chose to keep the ambient gas density constant between inert and reacting experiments at their own facilities, thereby attempting to minimize differences in mixing and momentum exchange for the reacting and non-reacting experiments. Since other facilities plan to operate with pure nitrogen (inert) or nitrogen-diluted air (reacting), producing yet another ambient gas composition, we sought to understand how the different ambient gas composition might affect results in these preburn-type environments.

Sandia Combustion Vessel



IFP Combustion Vessel

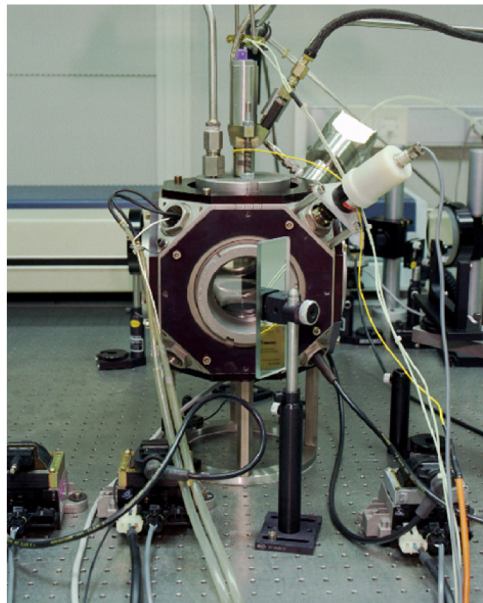


Figure 1. Constant-volume spray chambers at Sandia (top) and IFP (bottom).

Table 2. Combustion vessel characteristics for Spray A experiments.

	IFP	Sandia
width of cube	125 mm	108 mm
window aperture	80 mm	100 mm
chamber volume	1400 cm ³	1150 cm ³
injector mounting	center side window	center side window
injector tip protrusion from wall	3 mm	14.4 mm
injector serial #	210676	210677
mixing fan location	upper corner, near injector	upper corner, opposite injector
fan speed	3140 rpm	1000 rpm
# of spark plugs	4	2
spark plug position	lower corners	top window
body temperature	473 K	461K
combustible gas fill	sequential	premixed

Table 3. Reactant (at the time of spark) and product (at the time of injection) gas composition and properties.

	0% O ₂ conditions		15% O ₂ conditions	
	IFP	Sandia	IFP	Sandia
Reactant / Conditions at Spark				
%vol C ₂ H ₄	0.780	-	0.816	-
%vol C ₂ H ₂	-	3.20	-	3.06
%vol H ₂	9.20	0.50	9.39	0.50
%vol N ₂	83.00	88.05	68.36	73.82
%vol O ₂	7.00	8.25	21.43	22.63
Mol. Weight MW	25.88	28.14	26.42	28.71
Compress. Fac. Z	1.00	1.010	1.00	1.009
Pressure [MPa]	3.42	3.30	3.35	3.23
Temperature [K]	453	445	453	445
Bulk density [kg/m ³]	23.50	24.79	23.5	24.85
T _{ad, equil.} [K]	1762	2008	1772	1925
P _{ad, equil.} [MPa]	12.44	13.97	12.45	13.78
Product / Conditions at Injection				
%vol O ₂	0.00	0.00	15.00	15.00
%vol CO ₂	1.68	6.52	1.71	6.20
%vol N ₂	87.01	89.71	71.73	75.10
%vol H ₂ O	11.32	3.77	11.56	3.60
Mol. Weight MW	27.14	28.68	27.72	29.25
Compress. Fac. Z	1.010	1.016	1.010	1.015
Set pressure [MPa]	6.14	6.04	6.02	5.92
Act. pressure [MPa]	6.12	5.96	6.01	5.91
Set T _{bulk} [K]	853	826	853	826
Act. T _{core} [K]	897	873	900	888
Set ρ _{core} [kg/m ³]	22.06	22.80	22.06	22.8
Act. ρ _{core} [kg/m ³]	22.05	23.15	22.05	23.06

AMBIENT GAS CHARACTERIZATION

An accurate understanding of the ambient gas properties at the time of injection requires knowledge and control of the gas properties inducted into the chamber prior to spark-ignition, as well as during the premixed flame and combustion product cool down periods. The properties of these gases affect every aspect of spray combustion, including penetration, mixing, vaporization, ignition, and so

forth. In this section, we discuss measurement techniques and methods to produce consistent ambient gas distribution in the region of the vessel in front of the injector.

To provide an overview of the premixed burn and cool down processes, we performed high-speed imaging of the vessel gases during these time periods. [Figure 2](#) shows schlieren and luminosity imaging for Spray A conditions in the vessel at Sandia. The optical setup is discussed in more detail below in [Fig. 14](#). Briefly, the schlieren images were taken through the side of the vessel while, simultaneously, unfiltered luminosity was collected by a second high-speed camera from below. Schlieren imaging provides a measurement of density (or temperature) gradients, while luminosity imaging will show line-of-sight chemiluminescence or thermal emission. The images show premixed flames propagating from a pair of spark plugs at the top of the vessel. The injector tip is located in the cone-shaped feature at the left, and the mixing fan is at the top right in both the side and bottom views. The flames propagate down through the chamber, reaching the chamber walls and merging together as they move through the charge towards the bottom of the vessel. The flame nearest the mixing fan propagates more quickly. At 200 ms, the flame envelope is midway through the combustion chamber, and transparent zones are found on the top and the bottom of the schlieren images. The bottom transparent zone is fresh reactants that have yet to burn. The top zone (about -10 to -40 mm) contains combustion products that are no longer burning across the entire span of the chamber. Lacking strong gradients in temperature that are characteristic of a premixed flame (the flame has passed), the top zone also appears transparent, at least at first. With increasing time, however, schlieren disturbances appear at the top and move throughout the chamber. These schlieren effects are caused by heat transfer to the cooler vessel walls, which forms temperature gradients in boundary layers near the walls [25].

The schlieren images show complete combustion by approximately 400 ms after the time of spark, at which time the bright luminosity completely saturates the luminosity-imaging camera. As gases cool down after the premixed burn, luminosity from hot gases decreases but thermal radiation from hot metal surfaces is notable. The mixing fan glows red hot at the upper right, a bare-wire thermocouple radiates at the bottom right, and spark plug ground straps are visible near the middle. In the next sections, we discuss measurements of gas temperature and pressure corresponding to these image sequences.

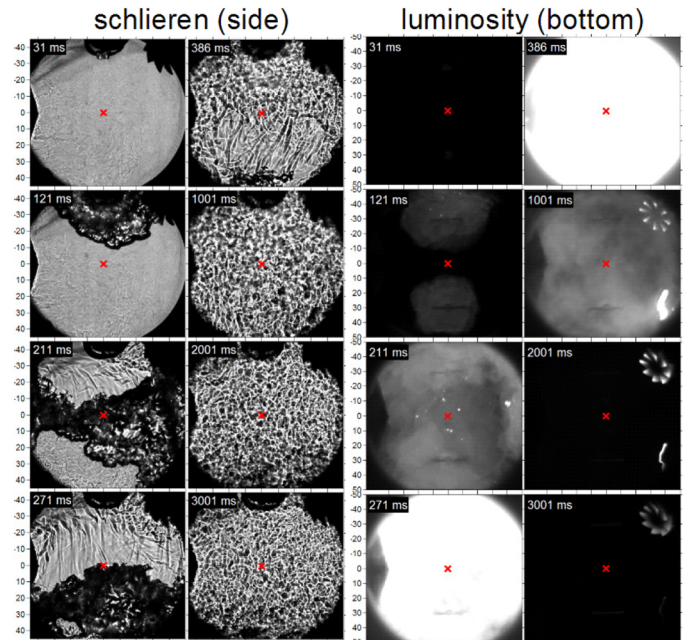


Figure 2. Schlieren (left) and luminosity (right) imaging of preburn and cool down for Spray A conditions. Flame begins at two spark plugs at the top. Injector is at left, distances are relative to injector in mm. Red x's are the position of a thermocouple measurement that will be discussed. Sandia vessel.

GAS TEMPERATURE

Gas temperature measurements were performed during the preburn and cool down to understand the temperature distribution of gases that will mix with the spray upon injection. Fine-wire thermocouples were used at both IFP and Sandia, consisting of two different setups as discussed below.

Platinum (type-R) thermocouple probe

A schematic of an adjustable probe with fine wire (50- μ m diameter) platinum/platinum-rhodium (type-R) thermocouples is shown in [Fig. 3](#). Five thermocouple probes are mounted on a rotational and traversable shaft, allowing for spatially-resolved temperature measurements within the volume in front of the injector. The dimensions of the thermocouple were chosen to minimize several sources of error, while also surviving repeated premixed burn and cool down periods in the combustion vessel. Small diameter wires are needed to minimize errors caused by thermal inertia, radiation, and conduction [15-16]. As is common for thin-wire thermocouples [17], the thermocouple is supported by larger wires of the same material, in this case 250- μ m wires that extend approximately 10 mm from an insulated sheath. The thin-wire thermocouple is suspended between the two prongs, separated by approximately 8 mm.

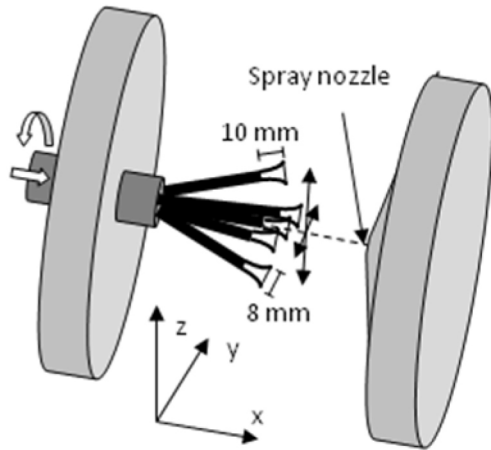


Figure 3. Schematic of adjustable probe with five fine-wire, type-R thermocouples.

Investigations (see e.g. [15, 16, 18]) show that the errors due to conduction heat exchange between wire and prongs can be neglected when the prong separation length, l , is,

$$l > 10 \cdot \sqrt{\alpha \tau} \quad (1)$$

In Eq. (1), α is the thermal diffusivity, and the time constant is

$$\tau = \frac{\rho_t c_t d_t}{4h} \quad (2)$$

using the thermocouple density ρ_t , specific heat c_t , diameter d_t , and the convective heat transfer coefficient h . Evaluation of these properties gives a value of 7 mm for right-hand-side term in Eq. (1), which is shorter than the prong separation distance. Therefore, conduction errors can be neglected for this thermocouple design.

Performing an energy balance at the location of the thermocouple junction it can be shown [15] that the actual temperature of the gas T_g is related to the junction temperature T_j in the following way:

$$T_g = T_j + \tau \frac{dT_j}{dt} + \frac{\varepsilon \sigma}{h} (T_j^4 - T_{sur}^4) \quad (3)$$

The second term is the convective heat transfer contribution and the third term is the radiation heat transfer contribution, including temperature-dependent emissivity ε . Note that the radiation correction will always be positive when the surroundings temperature T_{sur} (in this case, the vessel wall temperature) is lower than the junction temperature, as will

be the case during the entire cool down period. Since the convective term strongly depends on the gradient of the junction temperature trace, the measured temperature is filtered to lower frequencies to avoid amplification of noise. The signals were low pass filtered to 100 Hz, which is more than 15 times greater than the -3 dB cutoff frequency of the thermocouple ($1/2\pi\tau \approx 7$ Hz) [15]. Smoothing prior to calculation of the derivative therefore has negligible effects on the frequency response of the system.

The R-type adjustable probe design was implemented in experiments at both Sandia and IFP. The experiments were successful at Sandia. However, IFP encountered difficulties that prevented use of the probe in their combustion vessel. During the filling of premixed combustible gases, IFP found that the mixture ignited when pure oxygen was being inducted into the chamber. The cause of the pre-ignition is almost certainly a catalytic response induced by the platinum thermocouple wires. In one event, uncontrolled ignition destroyed (melted) the thermocouple wires. We believe that the different outcomes at Sandia and IFP are related to the gas fill sequences at each institution. As shown in Table 2, IFP fills combustible gases sequentially into their chamber, which exposed high oxygen concentrations at elevated temperature and pressure to the platinum probe. However, Sandia fills its chamber with combustible gases that are already premixed. Although there is still potential for ignition, the diluted mixture of fuel and oxidizer was inducted without catalytic ignition. We recommend that caution be exercised when using catalytic thermocouple material for these types of heated, pre-burn combustion vessels.

Type-K thermocouple probe

As an alternative to the platinum thermocouple probe, IFP used a type-K thermocouple to measure gas temperatures. Unlike the type-R probe, the type-K probe consisted of only one thermocouple junction in a single location as shown in Fig. 4. The probe is a prototype designed by Thermo Est, which consists of progressively reduced diameter wire, terminating with a 25 μ m diameter thermocouple to ensure fast response and minimum radiation and conduction error as discussed above.

Due to the limited temperature range of type-K thermocouples compared to the peak pre-combustion temperature, however, the thermocouples were operated at the limits of their design, causing failure and limiting the number of measurements carried out during the experimental campaign. Failed runs were removed from the dataset and the thermocouple probes were frequently replaced by new probes.

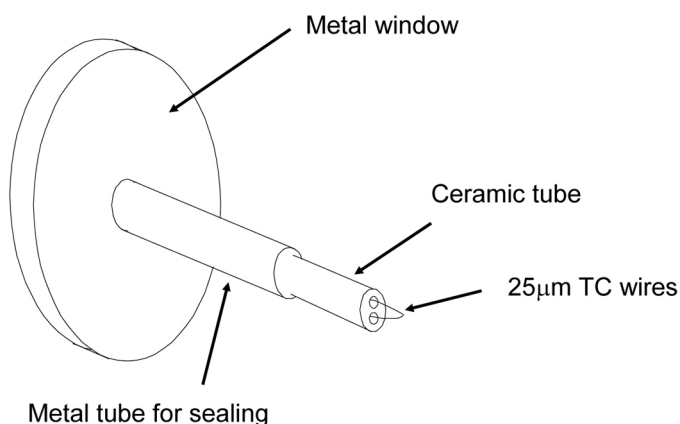


Figure 4. Schematic of thin-wire thermocouple. Type-K setup at IFP.

Gas temperature results

Figure 5 shows a sample measurement of gas temperature in the Sandia vessel from a single thermocouple 40 mm in front of the injector for 0%-O₂ conditions.

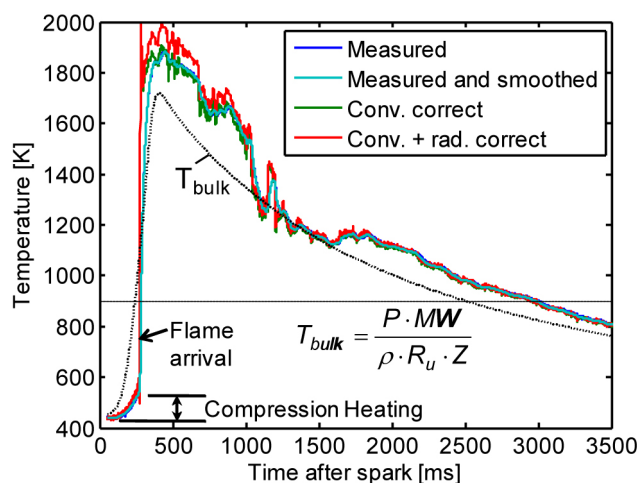


Figure 5. Measured gas temperature during the premixed burn and cool-down period. Sandia vessel. Type-R TC position is 40 mm directly in front of injector ($x=40$ mm, $y=0$ mm, $z=0$ mm). 0% O₂ combustion products and 24.8 kg/m³ bulk density.

For reference, this position is also indicated by a red marker in the images shown in Fig. 2. The measured temperature is corrected for radiation and heat transfer transients after low-pass filtering as described above.

The bulk temperature (T_{bulk}) is also shown, as determined from the real-gas equation of state using the measured pressure and initial mass-averaged bulk density as indicated in the figure. Since the total mass within the chamber is constant, the bulk density is constant for an experiment and

T_{bulk} depends only on the measured pressure. For calibration purposes, T_{bulk} can be related to the actual temperature of the gases that will mix with the spray, which is called the core gas temperature (T_{core}).

The gas temperature measurements show an initial rise caused by compression heating of unburned mixtures ahead of the flame. The flame arrives at the thermocouple at approximately 250 ms, whereupon there is a rapid increase in temperature. The corrected temperature appears to track the transient of the flame, rising quickly as would be expected for a premixed flame front. The temperature continues to rise due to compression heating as the vessel pressure (or bulk temperature) increases, reaching a peak temperature slightly lower than the adiabatic, constant-volume temperature given for 0%-O₂ conditions in Table 3. After the time of peak pressure, the gases slowly cool by heat transfer with the surrounding walls. The images in Fig. 2 exhibit evidence of this heat transfer as the schlieren disturbances grow along the windows and exposed surfaces (like the fan blades) begin to glow. Significant fluctuations in gas temperatures occur for temperatures higher than approximately 1200 K and time less than 1 s, with dips that even approach the bulk temperature. These early fluctuations are repeatable, and location-specific, indicating that they are most likely caused by large-scale movement of the product gases. The large-scale convection does tend to settle with increasing time. Note, for example, the overall similarity in the schlieren images at 2 s and 3 s with a darker zone near the bottom of the vessel, compared to that at 1 s. The gas temperature eventually cools to the Spray A temperature (900 K) at approximately 3 s. During most of the cool down, the measured temperature in the core zone right in front of the injector is higher than the bulk temperature because cooler, higher density gases exist in boundary layers and in the bottom of the vessel. Temperature gradients in these locations appear in the schlieren visualization.

Heat transfer corrections for convective response and radiation are shown to be significant during the early, high-temperature period of the cool down. However, the corrections are small, producing only a 2 K mean decrease, when the temperature decreases to 900 K. This is partly because of offsetting corrections during the cool down. Addressing the time period when gas temperatures are near 900 K, the convective heat transfer corrections lower the temperature by 5 K, but radiation corrections raise the temperature by 3 K. The heat transfer corrections do show more fluctuation in temperature, as would be expected because the corrections attempt to account for the thermal inertia of the thermocouple. An accurate measurement of the fluctuation in temperature, as well as the mean value, will be important as one tries to describe the initial boundary conditions as completely as possible. The average often different cool-down events is shown in Fig. 6. In this case, we

show measurements taken at both IFP and Sandia at the same position, 40 mm in front of the injector. IFP's measurements were made using the type-K setup, while the Sandia measurements were from the type-R probe, as above. IFP's data are also corrected for heat transfer as discussed above, but similar to the Sandia data, the correction is minimal. The bulk temperature history for each facility is also shown for comparison with the measured temperatures.

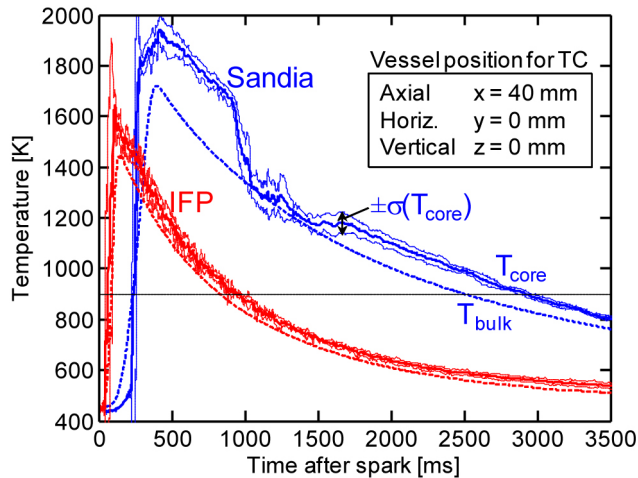


Figure 6. Average core gas temperature 40 mm directly in front of injector ($x = 40$ mm, $y = 0$ mm, $z = 0$ mm) for IFP and Sandia vessels. 0% O_2 combustion products and 25 kg/m^3 bulk density.

An obvious difference between IFP and Sandia is the faster premixed flame and cool down at IFP. This difference is related to the operation of the mixing fan. The fan speed is higher at IFP (see [table 2](#)), causing higher velocities and a higher rate of heat transfer. Increasing or decreasing the fan speed at either facility permits adjustment of the cool down rate to be faster or slower than either curve given in [Fig. 6](#). In this case Sandia purposefully slowed the fan speed in order to make the environment more suitable for schlieren visualization of the vaporizing spray, as will be shown.

Another difference between IFP and Sandia data is the lower peak temperature measured at IFP. A lower peak temperature is actually expected, based on the initial reactants used at IFP. [Table 3](#) shows that the adiabatic temperature at these conditions is only 1762 K at IFP, compared to 2008 K at Sandia. A faster rate of heat transfer during the premixed combustion event at IFP is also a likely contributing factor.

Gas temperature measurements at both institutions show higher core gas temperatures compared to the bulk temperature. However, the ratio of $T_{\text{core}}/T_{\text{bulk}}$ is higher at Sandia, approaching ratios of 1.08 at the Spray A temperature. Our experience shows that this finding is once again related to the slower gas velocities, which leaves large

zones of cool fluid at the bottom of the vessel. Increasing the fan speed tends to lower $T_{\text{core}}/T_{\text{bulk}}$. For example, an 8000 rpm fan speed produces $T_{\text{core}}/T_{\text{bulk}}$ values of only 1.03 in the Sandia vessel [[10](#)].

The particular relationship between $T_{\text{core}}/T_{\text{bulk}}$ is not important, as long as the temperature distribution is consistent from run to run. To indicate the variance in temperature, we show thin dotted lines at $\pm$ one standard deviation during the cool down period surrounding the mean. The variance in temperature tends to decrease during the cool down, and at the target temperature of 900 K, is ± 10 K for the IFP measurements and ± 10 K for the Sandia measurements at the target time of injection. Considering the resolution of the experiment, and the need to make corrections for heat transfer, these variances are similar to the expected uncertainty in gas temperature. Analysis of the temperature histograms shows that the temperature fluctuations are normally distributed, implying that 70% of the temperature fluctuations fall within these limits. The variance statistics do not improve when collapsing the data to $T_{\text{core}}/T_{\text{bulk}}$ which one might suppose would account for different cool down timings because of variation in wall temperature, for example. Since the experimental method requires heat transfer to cool combustion product gases, temperature fluctuations are natural and expected. The local temperature fluctuations are one likely explanation for any variation in system performance from injection to injection.

Spatial variation in temperature was addressed by movement of the thermocouple probe to different positions within the chamber at Sandia. [Figure 7](#) shows the average gas temperature at various positions in this “core” region of the vessel, relative to predictions based on a single relationship between T_{core} and T_{bulk} (i.e., using only the measured pressure to predict T_{core}). Along the axis of the spray, the gas temperature is uniform within 1%, except for a measurement point in the boundary layer only 1 mm in front of the injector tip. This spatial variation in mean temperature is similar to the instantaneous fluctuation shown above. Temperature is also uniform along the same horizontal plane ($z = 0$, $y = \pm 15$ mm) outside of the spray. The most significant variation is in the vertical direction ($z = \pm 15$ mm, $y = 0$) where the temperature varies by $\pm 4\%$ for a vertical change of ± 15 mm. This vertical stratification is obviously caused by buoyancy effects. Despite the vertical variations in temperature, systematic combustion asymmetries in the vertical direction (i.e., ignition site, or liftoff length) have not been found, as will be shown later.