

Comparison of In-Cylinder Soot Evolution in an Optically Accessible Engine Fueled with JP-8 and ULSD

Xin Yu, Kan Zha, Radu Florea and Marcis Jansons
Wayne State University

ABSTRACT

Due to the single fuel concept implemented by the US military, the soot production of diesel engines fueled with JP-8 has important implications for military vehicle visual signature and survivability. This work compares in-cylinder soot formation and oxidation of JP-8 and ULSD in a small-bore, optical diesel engine. Experimental engine-out soot emission measurements are compared to crank-angle resolved two-color measurements of soot temperature and optical thickness, KL. A 3-D chemical kinetic-coupled CFD model with line of sight integration is employed in order to investigate the soot distribution in a 2-D projection associated with the imaging plane, as well as to aid in interpreting the third dimension along the optical depth which is not available within the experimental work. The study also examines the effect of volatility on soot emission characteristics by CFD simulation.

With the same injection pressure and timing for both fuels considered, heat release analysis shows JP-8 has more energy release than ULSD, however two color measurements indicate JP-8 produces less in-cylinder soot throughout the cycle as well as lower engine out measurements compared to ULSD. Furthermore, JP-8 is found to have a lower soot temperature and less high temperature areas than ULSD. A line of sight integration technique is applied to the CFD (Reaction Design FORTE) output to compare the simulation results with experimental high speed images. The model has good agreement with the experimental results, as does the predicted soot temperature and KL factor with the two color experimental measurements. However, interpretation of the two-color line of sight images obtained from the CFD simulation indicated that the measurement of the KL factor will be affected by the amount of radiation intensity available to a camera characterized by a finite dynamic range. Finally, the effect of fuel volatility is investigated using the CFD model by varying fuel evaporation properties. It is observed that the high volatility fuels, such as JP-8, exhibit lower engine out soot emissions due to better fuel mixing and increased local equivalence ratio homogeneity.

CITATION: Yu, X., Zha, K., Florea, R. and Jansons, M., "Comparison of In-Cylinder Soot Evolution in an Optically Accessible Engine Fueled with JP-8 and ULSD," *SAE Int. J. Fuels Lubr.* 5(2):2012, doi:10.4271/2012-01-1315.

INTRODUCTION

Soot emission is recognized as a drawback for compression ignition engines [1]. It is also an important military concern for ground vehicles and robotics [2] due to its visual signature. Various researchers have studied soot emission from diesel engines fueled with JP-8. Papagiannakis, *et al* [3] suggested that at high load and low engine speed JP-8 has less soot emissions compared to regular diesel fuel while the trend is reversed when the engine is operated at higher speed. Nargunde *et al* [4] reported that JP-8 produced less soot during the exhaust process at all injection pressures, and Fernandes *et al* observed that the soot formation was dramatically reduced when diesel fuel was replaced by JP-8 [5].

To provide a better understanding of soot formation during the combustion process, this investigation was

conducted in an optically accessible diesel engine. A fast two-color method as previously reported [6], is applied on a color CMOS camera to obtain high speed soot temperature and KL factor measurements. A similar implementation of the two color method was used by Singh [7], who studied three alternative low-temperature combustion modes. Ciatti [8] used the two color method to determine the diesel injector nozzle characteristics. However, this technique only examined the line-of-sight data, which may be significantly affected by non-uniform soot distribution along the optical axis [9]. In order to see the effect of using line-of-sight measurements, a CFD simulation-based calculation was applied. The radiation emitted by each cell is integrated along the line-of-sight, i.e. parallel to the optical axis. Additionally, previous investigations [10, 11] suggested that higher volatility of the fuel is one of the factors resulting in reduce

the engine out soot measurements. In the current work, a comparison is made between three different fuel volatilities and the impact on soot emissions predicted by the CFD simulation.

EXPERIMENTAL SETUP

ENGINE

A single-cylinder, naturally-aspirated, direct-injection optically accessible research engine (AVL Model 5402) is used to conduct this investigation. The engine specifications are provided in Table 1 and injection system specifications are given in Table 2.

Table 1. Engine specifications

Engine Type	AVL 5402, DI
Number of Cylinders	1
Cycle	4-stroke
Displacement	510 cm ³
Bore	85 mm
Stroke	90 mm
Connecting Rod Length	148 mm
Geometric Compression Ratio	15:1
Combustion Bowl Diameter	40 mm
Combustion Bowl Depth	14.5 mm
Number of Intake Valves	2
Number of Exhaust Valve	2
Intake Valve Opening/Closing	-394°/594°CA aTDC
Exhaust Valve Opening/Closing	106°/-346°CA aTDC
Injection System	Bosch Common Rail, Pmax=1350bar
Swirl Control/Ratio	AVL/2.0-4.5
Maximum Speed	3000 RPM

Table 2. Engine fuel injector specifications

Model	Bosch DSLA 142P
Design	VCO-Nozzle
Angle of Fuel-Jet Axis (inclusive)	142°
Number of Holes	5
Hole Diameter	0.18 mm

OPTICAL SETUP

Figure 1 shows the engine optical setup for this experiment work. A 20 mm-thick sapphire window mounted on the extended piston and a mirror at 45° relative to the cylinder axis at the bottom of the liner, provides a view of the 40mm diameter piston bowl during engine operation. The piston bowl is a flat surface with rectangular cross-section. There are valve pockets and valve seat chamfers in the piston bowl rim and fire deck surface, respectively. The engine is sealed by uninterrupted bronze-teflon rings, and slotted graphite rings are installed to provide oil-less lubrication. Continuous cooling is provided by compressed air directed at the underside of the flat piston window.

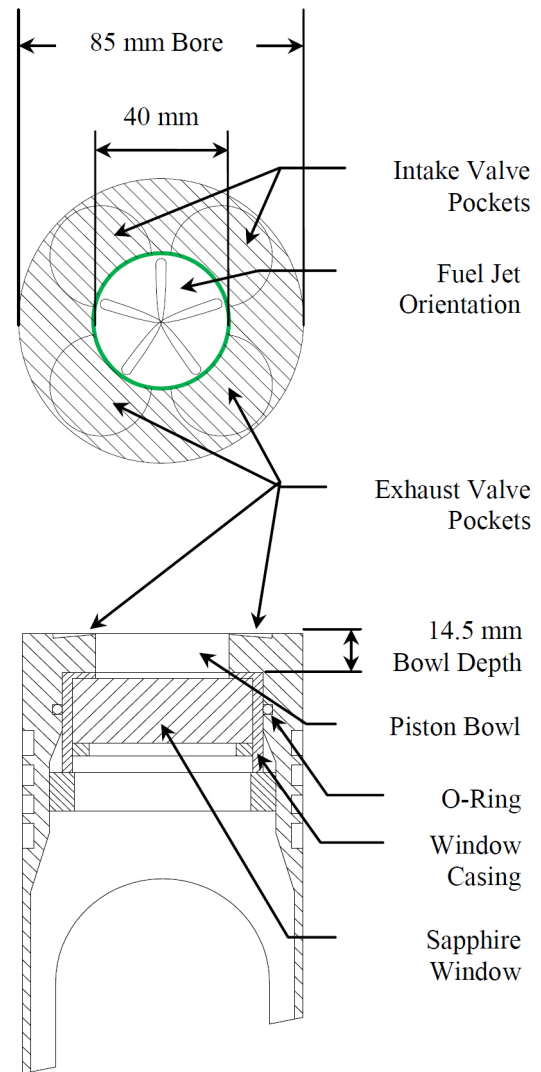


Figure 1. Extended piston and combustion bowl geometry.

ENGINE INSTRUMENTATION

The engine is equipped with an un-cooled piezo-electric pressure transducer installed through the cylinder head and mounted flush with the fire deck, a needle lift sensor in the fuel injector, and a fuel line pressure transducer located between the fuel rail and injector. Data acquisition is synchronized with and triggered every 0.1 CAD by pulses obtained by multiplying the 0.5 CAD resolution signal of an optical encoder wheel mounted to the engine crankshaft. The apparent rate of heat release (ARHR) is calculated using the analysis provided by Heywood[12], and it is normalized by the engine displacement. A detailed engine instrumentation description has been reported in an earlier publication [13, 14].

Combustion images were captured by a visible range digital color camera (Vision Research Phantom v7.3, 800×600 pixels, 14-bit image depth, and 6688 fps full

resolution up to 950,000 fps at the minimum resolution of 32×32 pixels). In this camera, the square pixel grid of the CMOS sensor is covered by a broadband color filter array arranged in a particular (Bayer) pattern, which spans the range from 400 to 700 nm. Frames were triggered at 0.5 CAD intervals and synchronized to the engine crankshaft position through a cRIO field-programmable gate array (National Instruments) and optical encoder-compatible input module (DRIVVEN). Exposure time is set to 40 μs as an optimal trade-off maximizing signal-to-noise ratio at lower source intensities, while minimizing saturation from stronger signals. The aperture ratio is set to f/11.0 to have greater depth of field and maintain focus over a wider range of crank-angles. Operating parameters of the high-speed digital color camera are shown in Table 3. The memory gate width is set to 10 msec, which is the time interval within a cycle over which imaging is conducted, and at the 1200 RPM engine speed is equivalent to 72 CAD. Images thus cover the combustion duration from SOI through late-cycle burning. Throughout this interval, the CMOS camera is storing each frame with 40 μs exposure time every 0.5 CAD. Figure 2 shows the experimental layout, the view axis of high-speed digital color camera was aligned with the axis of the extended piston through the 45° mirror. In such a configuration, the camera field of view, as represented by the green circle in Figure 1, covers the entire 40 mm combustion bowl diameter. Swirl motion is in the clockwise direction which can be found in the following soot luminosity images. A detailed description has been reported in an earlier publication [6].

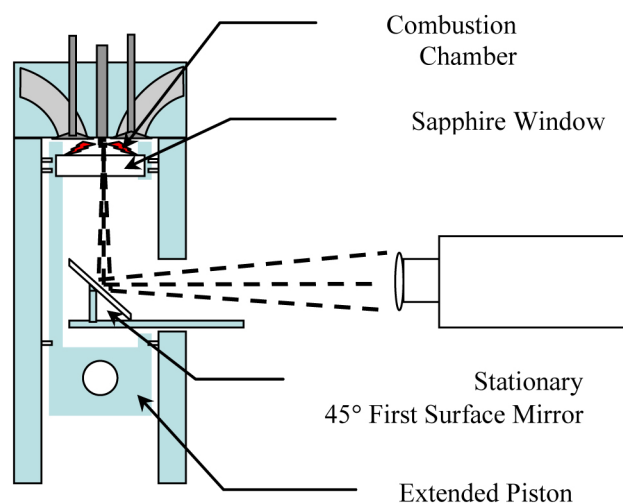


Figure 2. Experimental Setup.

Table 3. High-speed digital color camera operating parameters

Model	Phantom v7.3
Resolution (pixels)	416×400
Operating Mode	Sync with engine speed at 0.5CAD interval
Aperture Ratio	f/11.0
Exposure Time (μs)	40
Pre-trigger Start ($^\circ\text{aTDC}$)	0
Memory Gate Width (ms)	10

EMISSION INSTRUMENTATION

AVL Dilution Control Unit is continuously used to condition and dilute the exhaust gas which connects to a resonant cell in the AVL Micro Soot Sensor. Based on a photo-acoustic measurement method, dilution-corrected exhaust soot concentration data was sent to a second data acquisition unit at 100Hz.

FUELS

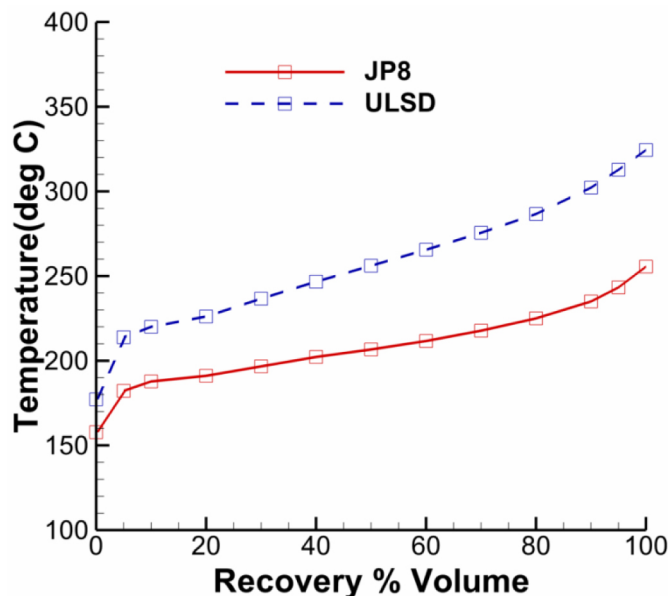
Table 4 shows the comparison of the properties for ULSD and petroleum JP-8 fuels used in the experiment. JP-8 has a relatively higher derived cetane number, much lower viscosity and slight lower density compared to ULSD. The distillation curves for both fuels are shown in Figure 3. The recovery temperature for the same volume fraction is roughly 50°C higher for ULSD than that of JP-8. The cetane number is an indication of JP-8 having a shorter ignition delay under typical diesel engine conditions. The differences of the other properties are expected to considerably affect the fuel injection, fuel evaporation, the combustion process and exhaust emissions of the two fuels.

Table 4. Fuel specifications and measured properties

Fuel	ULSD	JP-8
Derived Cetane Number	48.3	50.1
Density (@ 15°C) kg/m^3	842	798
Viscosity (@ 40°C) cSt	2.479	1.368
Bulk Modulus(@800bar) MPa	2561.8	2394.9
Aromatic Content (weight %)	27.8	16.3

Table 5. Properties of the fuel component used in the evaporation model

	n-butane	n-heptane	n-decane
Liquid Density (kg/m ³)	583	684	730
Class	n-Alkanes	n-Alkanes	n-Alkanes
Boiling Point (K)	272.7	371.5	447.3
Lower Heating Value (MJ/Kg)	45.84	44.923	44.56
Critical Temperature (K)	425.12	540.3	617.7

**Figure 3. Distillation curves for JP-8 and ULSD**

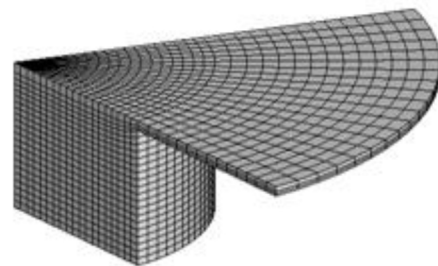
COMPUTATIONAL MODELING

A chemical kinetic-coupled CFD package (Reaction Design FORTE) is applied to simulate the in cylinder combustion process starting from IVC until EVO. The FORTE code is used to solve the system of equations describing the chemical kinetics associated with combustion, the fuel spray and gas dynamics. In this work turbulence has been modeled using the Re-Normalized Group (RNG) model, break-up by the Hybrid Kelvin-Helmholtz Rayleigh-Taylor (KH-RT) model, and their interaction by the Turbulence-Kinetics Interaction Model [11].

Figure 4 above shows the computational mesh of a 72 degree sector representing a fifth of the combustion chamber, corresponding to a five holes nozzle injector. The computational domain contains 20,000 cells near BDC and does not include a crevice region.

To capture the crevice effects, a crevice model [15] is applied to account for blow-by losses which are significant

for optical engines. The temperature and pressure conditions observed experimentally are replicated by adjusting the parameters of this crevice model. A constant temperature wall boundary condition is assumed in the model, where the bowl surface and fire deck surface are assumed to have a temperature of 400K and the cylinder liner surface is assumed to have a temperature of 350K, which is close to the coolant conditioning temperature. The engine intake valve closes at 150 °bTDC, which is the crank angle degree used to initialize the simulation. The initial pressure is based on the experimental in-cylinder pressure measurement and the temperature is assumed to be the same as the measured intake air temperature. A swirl ratio of 2.0 is assigned to the initial velocity profile, matching the setting of the calibrated swirl valve on the engine.

**Figure 4. Computational 72 degree sector mesh near TDC**

In this work the a reduced n-heptane mechanism developed at the University of Wisconsin [16], with 30 species and 65 reactions, was considered as a suitable diesel fuel surrogate. To account for the difference in cetane number between the n-heptane and the fuel used in experiments, the reaction rates are modified to match the ignition delay, as per previous work by Genzale *et al* [17]. Additionally, three kinds of n-Alkanes, n-heptane (nC7H16), n-butane (nC4H10) and n-decane (nC10H22), are separately used in the evaporation model to study the effect of the fuel volatility on the evaporation and combustion process, and the soot emission characteristics. Table 5 shows the properties of these three fuel components.

The two-step Hiroyasu soot formation model [18] and Nagle-Strickland-Constable oxidation model [19] are considered, assuming acetylene (C_2H_2) as the soot precursor.

$$\frac{dM_s}{dt} = \frac{dM_{sf}}{dt} - \frac{dM_{so}}{dt}$$

$$\frac{dM_{sf}}{dt} = K_f M_{C_2H_2}$$

$$K_f = A_{sf} p^n \exp(-E_f/RT)$$

$$\frac{dM_{so}}{dt} = \frac{6MW_c}{\rho_s D_s} M_s R_{tot}$$

Where M_s , M_{sf} , M_{so} , $M_{C_2H_2}$, is soot mass, mass for soot formation, mass for soot oxidation and mass of C_2H_2 respectively. K_f is the soot formation rate, A_{sf} is the pre-exponential factor for the soot formation reaction. E_f is the activation energy for the soot formation, MW_c is the molecular weight of the carbon, ρ_s is the soot density, D_s is the assumed soot particle diameter, R_{tot} is the Nagle and Strickland-Constable oxidation rate.

LINE-OF-SIGHT INTEGRATION

In order to aid the comparison between experimental results obtained using the two color method and CFD simulation results, an equivalent two-color method is applied to the CFD data.

Two visible wavelengths, 532nm and 655nm, have been selected for sampling the two color signals. Soot concentration, temperature and length for each cell along the line-of-sight optical axis are calculated based on the CFD simulation data. The soot emissivity is assumed to be given by the Hottel and Broughton [20] empirical model:

$$\epsilon_{soot} = 1 - \exp\left(-\frac{KL}{\lambda^\alpha}\right) \quad (1)$$

Where λ is the wavelength expressed in μm , and α is an empirical constant measured to be 1.39 in the visible spectral range[21]. The optical thickness KL can be computed as [22],

$$KL = \frac{6\pi \cdot E(m) \cdot C_m \cdot L}{\rho_p} \quad (2)$$

By obtaining the complex index of reflection, m , from

$$E(m) = \text{Im}\left(\frac{m^2 - 1}{m^2 + 2}\right) = 0.245$$

[23], $E(m)$ can be calculated as

and, C_m is the soot mass concentration, L is the optical depth, and ρ_p is the soot particle density, which is assumed as 1.86 g/cm³

Thus the emissive power for each control volume is estimated as

$$E_\lambda = \epsilon_{soot} \cdot E_{b,\lambda} \quad (3)$$

Where $E_{b,\lambda}$ is the monochromatic emissive power of a blackbody at temperature T at wavelength λ , expressed as:

$$E_{b,\lambda}(T) = \frac{C_1}{\lambda^5 (e^{\frac{C_2}{\lambda T}} - 1)} \quad (4)$$

Where C_1 is the first Planck constant

$$C_1 = 3.7418 \times 10^{-16} \text{ W} \cdot \text{m}^2 \quad (5)$$

and C_2 is the second Planck constant

$$C_2 = 1.4388 \times 10^{-2} \text{ m} \cdot \text{K} \quad (6)$$

Thus emissive power E_λ for a given wavelength λ is calculated for each cell in the combustion chamber.

Then a line of sight integration is applied to the cell-based soot emissive power. Given the discrete nature of the computational domain, each CFD cell is assumed to have a homogenous composition capable of both emitting radiation as well as absorbing incoming radiation. It is also assumed that only soot is involved in the radiation transfer process, and that the surrounding gas is completely transparent. While the radiation is characterized by a homogenous directionality, for this work, given the assumption that the detector is positioned at a sufficiently large distance from the emitter, only vertical directionality is considered. Thus any emitted radiation will travel in both directions along the line of sight. In order to evaluate the soot absorptivity, it is assumed that Kirchhoff's law applies to the soot particles, and absorptivity α is given by

$$\alpha_\lambda = \epsilon_\lambda \quad (7)$$

Additionally, neglecting reflectivity and scattering effects, the transmissivity of the cell is given by

$$\tau_\lambda = 1 - \alpha_\lambda \quad (8)$$

In order to address concerns regarding the effect of cylinder head reflectivity on the KL estimation, the line of sight integration procedure considers both possible radiation propagation directions as discussed in the previous paragraph. A diagram showing the line of sight integration procedure is shown in Figure 5 below.

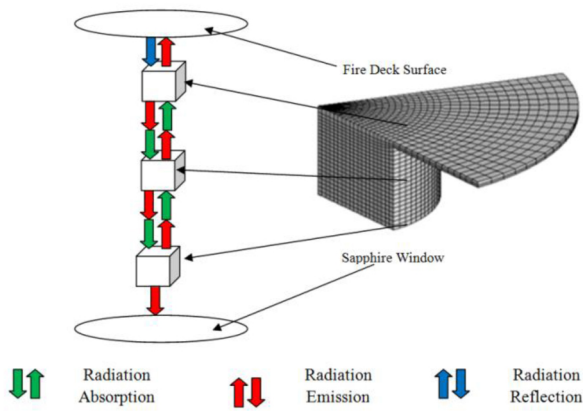
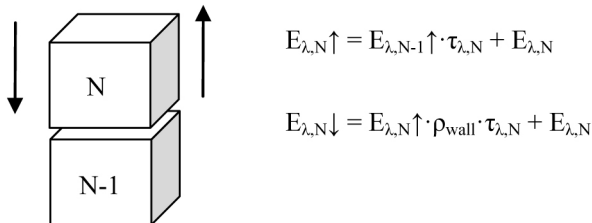


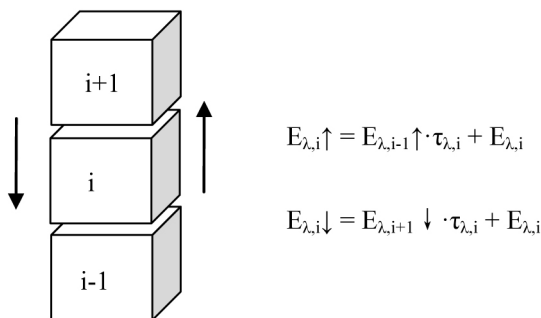
Figure 5. Schematic for line-of-sight integration

From a radiation transfer process standpoint, CFD cells along the line of sight can be grouped into three classes as follows:

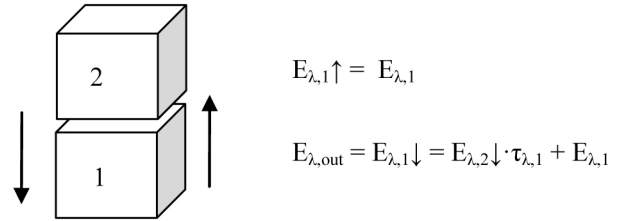
1. CFD cell adjacent to the fire deck; this cell receives radiation emitted by the cells below it, allowing part of the radiation to pass through ($E_{out} = E_{in} \cdot \tau_{\lambda}$) while absorbing the rest. It also emits additional radiation based on its own soot concentration and temperature. The total radiation is reflected by a surface (fire deck) characterized by reflectivity ρ which is further subjected to attenuation due to cell absorptivity.



2. Intermediate CFD cell; in a similar fashion, both radiation directions are considered.



3. CFD cell adjacent to the piston window; at this point radiation from the combustion chamber exits through the optical window and data is collected.



The two color method [24] is applied assuming the soot emissive power at wavelengths λ_1 and λ_2 are given by $E_{\lambda 1,out}$ and $E_{\lambda 2,out}$ described above.

RESULT AND DISSCUSSION

IN-CYLINDER PRESSURE AND HEAT RELEASE ANALYSIS

The following pressure and heat release data is reported for steady skip fired operation, where fuel was injected into the engine for 3 consecutive cycles and motored for the subsequent 9 cycles. This is necessary in order to maintain thermal stability of the optically accessible engine. Throughout this work, the injection settings were maintained constant in order to determine the effect of replacing the diesel fuel with JP-8 without changing engine controller settings. The solenoid activation time was maintained at 0.96 msec and fuel was injected at 14.8°bTDC. The two fuels investigated (ULSD and JP-8) were injected using a common rail injection pressure of 400 bar and the reported data was averaged over 150 cycles. To better match thermal conditions, the firing cycles were grouped based on firing order (1st, 2nd, and 3rd firing cycle). All plots shown below use data obtained from the 1st firing cycle.

Figure 6 is a plot of in-cylinder pressure, ARHR and needle lift signal with both fuels at an injection pressure of 400bar. From the needle lift signal, the two fuels have almost the same needle lift duration which is consistent with the constant activation time applied. However, the amplitude of the needle lift is observed to be higher for JP-8 than ULSD. This is attributed to a fairly short activation time, which results in a needle lift profile that lacks the characteristic flat zone associated with typical diesel injectors. Thus, due to the operation of the needle in its “ballistic” zone, the friction force executed on the injector needle has an important effect on its operation. When the JP-8 fuel is used, due to the reduced viscosity (almost half the viscosity of ULSD as previously shown in Table 4), the needle will experience lower friction, allowing it to travel further when subjected to the same injection pressure. In conclusion, under the conditions investigated, a higher amplitude of the needle lift is expected to result in increased volumetric flow rate when JP-8 is used. From the cumulative ARHR (IntRHR) shown in Figure 7, during the evaporation period, JP-8 is observed to consume more energy during the evaporation process. The cumulative energy release is much higher for JP-8 than it is