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Development and Application of a Surrogate Distillate Fuel

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A surrogate fuel comprised of 14 pure hydrocarbons is formulated based on the distillation curve and compound class composition of a petroleum-derived JP-4. The goal is to establish a fuel of controlled composition for modeling, and for the study of fuel property and chemical composition effects in the combustion of JP-4 fuels. Spatially resolved interferometric measurements of droplet size and droplet velocity are obtained and compared for both the petroleum and surrogate JP-4 in a nonreacting spray chamber. Measurements are also obtained for a high aromatic JP-5 of purposefully disparate properties. The performance of these three fuels is then compared in a swirl-stabilized, spray-atomized model laboratory combustor where in-flame measurements of velocity and temperature are acquired and compared. The nonreacting measurements of atomization quality establish that the atomization characteristics of the petroleum and surrogate JP-4 are identical, whereas the atomization performance of the JP-5 is significantly different. Under reacting conditions, substantial differences between the JP-4 and JP-5 are observed in both the velocity and thermal fields, whereas the surrogate, in contrast, yields an identical velocity and thermal field to that of the petroleum JP-4.

Introduction

IT is becoming increasingly clear that future jet fuels will have properties (both chemical and physical) that differ significantly from the conventional jet fuels of the past. There is now a period of transition occurring between jet fuels produced from high-quality light crudes (with a minimum of processing) and those produced from low-quality heavy crudes and alternative sources (which require sophisticated, energy-intensive refining techniques).

To assure adequate availability of jet fuel well into the next century, the relationship of fuel properties and composition to combustion hardware durability and performance must be identified more precisely. Such information is necessary if fuel specifications are to be successfully adjusted to levels that both maintain the required preformance of the combustion system (and other subsystems) and permit the desired latitude in the partitioning of hydrocarbon resources (petroleum, coal, oil shale, etc.) that can be utilized to produce aviation fuel. To this end, experimental evidence is needed to define the effects that fuel properties and composition have on the performance of gas turbine engines.

Practical jet fuels, i.e., those fuels derived from the refinery processing of crude petroleum, shale oil, etc., provide a poor model from which to gather the necessary experimental data. These fuels are chemically complex, often containing more than 300 compounds. Few individual chemical species exceed 1% in volume. Because these fuels must only meet broadly defined specifications, their composition varies not only with refinery and crude oil source, but also with season and year of production. Moreover, composition changes as the fuel ages. As a result, it is difficult to control the consistency in fuel composition required for the purposes of research.

The use of a surrogate blend, comprised of a relatively small number of high-purity hydrocarbons and blended to simulate the combustion performance of a practical fuel, has the advantage of allowing fuel composition to be accurately controlled and monitored. In addition to providing a model fuel for the study of the effect of fuel properties and chemical composition on combustor performance, the compositional control afforded by a surrogate fuel is attractive for the development and verification of computational codes for combustor design. For example, the modeling of evaporation rates would be more tractable by the availability of a data set in which the fuel composition could be exactly specified and precisely controlled.

The goal of the present paper is to establish a surrogate fuel that has the same physical and chemical properties and produces the same thermal and aerodynamic performance of a practical, petroleum-derived JP-4, and is composed of a relatively small number of pure hydrocarbons available commercially at modest cost.

The present paper reports on the formulation of a surrogate blend of 14 pure hydrocarbons prepared to simulate the distillation and compositional characteristics of a practical, petroleum-derived JP-4. Also reported are the results of in-flame measurements of velocity and temperature acquired in a swirl-stabilized, spray-fired model laboratory combustor for the surrogate and petroleum JP-4. The aerodynamic and thermal fields for each fuel are established via laser anemometry and thermocouple measurements, respectively.

In addition, nonreacting spray field characterizations of the surrogate and practical fuel are performed to assess further the ability of the surrogate to represent the petroleum JP-4. A high aromatic petroleum JP-5 fuel, which matches neither the distillation curve nor the compound class composition of the petroleum JP-4, is characterized as well to 1) support the use of distillation curves in surrogate development and 2) determine the extent to which a significant change in fuel properties affects the atomization in the nonreacting chamber and the velocity and temperature fields in the laboratory combustor.

Approach

The approach is to 1) establish a strategy for the formulation of the surrogate fuel, 2) blend the surrogate fuel from the selected components, 3) compare the physical and chemical properties of the blended surrogate and the parent, petroleum-derived JP-4, and 4) evaluate the atomization and

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combustion performance of the two fuels against each other and against other fuels of disparate properties.

Surrogate Fuel Formulation

The procedure established for the formulation of the JP-4 surrogate fuel is based on the following strategy:

1) The surrogate will be composed of 10 to 15 individual hydrocarbon species.

2) The component species will be present in the surrogate in specific concentrations that result in a strict matching of the compound class composition of the parent JP-4.

3) In addition, these component species will be chosen to produce a surrogate blend with a distillation curve that matches the distillation curve of the petroleum JP-4 being modeled.

4) The components will be of high purity ($\geq 99\%$).

5) The cost will be minimized.

The selection of 10 to 15 components allows the necessary flexibility in tailoring the specific concentrations of the individual hydrocarbons to match simultaneously the distillation curve and compound class composition of the parent JP-4, yet keeps the number of components at a manageable level. Matching the distillation curve of the parent JP-4 produces a surrogate fuel with the same overall volatility as the parent

JP-4, which should result in a nearly identical droplet evaporation rate upon atomization. Matching the compound class composition of the parent JP-4 insures a similar chemical makeup for the surrogate, providing a model fuel whose chemical composition can be selectively altered to explore the effect of fuel chemical composition on the combustion of JP-4-type aviation fuels.

Note that the process of selecting the individual hydrocarbon species is iterative and the blending and testing of the surrogate does not occur until the five elements of the formulation strategy (just detailed) are met. In the present study, the application of this strategy to the modeling of a specific petroleum-derived JP-4 results in a surrogate fuel consisting of 14 high-purity hydrocarbons. Table 1 lists the individual components of the resulting surrogate in order of increasing boiling point, along with the volume percent and chemical formula of each component.

The distillation curve of the surrogate is approximated (prior to actual blending and testing) with a cumulative boiling-point curve. The cumulative boiling-point curve represents the cumulative volume percent of all surrogate components boiling up to and including a particular temperature. As such, it is equivalent to a "perfect" distillation performed with an infinite number of theoretical plates. Figure 1 presents

Table 1 Surrogate composition

Surrogate JP-4 component	Boiling point, °C	Vol%	Chemical formula
1. <i>n</i> -Hexane	69	5.5	C ₆ H ₁₄
2. Cyclohexane	81	8.0	C ₆ H ₁₂
3. <i>n</i> -Heptane	98	8.0	C ₇ H ₁₆
4. Methylcyclohexane	101	8.0	C ₇ H ₁₄
5. Toluene	111	8.0	C ₇ H ₈
6. <i>n</i> -Octane	126	8.0	C ₈ H ₁₈
7. <i>n</i> -Nonane	151	10.0	C ₉ H ₂₀
8. Cyclo-octane	151	8.0	C ₈ H ₁₆
9. <i>n</i> -Decane	174	10.0	C ₁₀ H ₂₂
10. Decalin	190	5.0	C ₁₀ H ₁₈
11. Tetralin	207	1.0	C ₁₀ H ₁₂
12. <i>n</i> -Dodecane	216	10.0	C ₁₂ H ₂₆
13. 1-Methylnaphthalene	241	0.5	C ₁₁ H ₁₀
14. <i>n</i> -Tetradecane	253	10.0	C ₁₄ H ₃₀
		100.0%

Fig. 1 Distillation and cumulative boiling-point curves.

Table 2 Fuel composition by compound class

Compound class	Petroleum JP-4 vol%	Surrogate JP-4 vol%	Surrogate components
Paraffins	61.2	61.5	<i>n</i> -Hexane <i>n</i> -Heptane <i>n</i> -Octane <i>n</i> -Nonane <i>n</i> -Decane <i>n</i> -Dodecane <i>n</i> -Tetradecane
Monocycloparaffins	24.2	24.0	Cyclohexane Methylcyclohexane Cyclo-octane
Dicycloparaffins	4.9	5.0	Decalin
Alkylbenzenes	8.2	8.0	Toluene
Indans and tetralins	1.1	1.0	Tetralin
Indenes and dihydronaphthalenes	0.0	0.0	—
Naphthalenes	0.4	0.5	1-Methylnaphthalene
Total paraffins	90.3	90.5	
Total aromatics	9.7	9.5	
	100.0%	100.0%	

distillation curves (ASTM method D86) for both the petroleum JP-4 and its surrogate, as well as the cumulative boiling-point curve for the surrogate. Although the surrogate was formulated to produce a cumulative boiling-point curve that closely matched the D86 distillation curve of the petroleum JP-4, the actual D86 distillation curve for the surrogate shows it to begin boiling approximately 25°C higher than the petroleum JP-4. (Note that the surrogate distillation curve quickly aligns with the petroleum JP-4 distillation curve and matches it closely to the final boiling point.) The slight

delay in the initial boiling point of the surrogate relative to the petroleum JP-4 indicates that a strict matching of the cumulative boiling-point curve of the surrogate to the D86 distillation curve of the petroleum JP-4 leads to a slight underestimation of the concentration of the most volatile (lowest boiling-point) fraction of the surrogate. For the D86 distillation curves to strictly coincide, the concentration of the lowest boiling components of the surrogate must be increased to displace the low temperature end of the cumulative boiling-point curve toward lower temperatures by approximately 25°C relative to the distillation curve of the petroleum JP-4.

A summary of compound class composition for both fuels and a breakdown of the individual chemical components of the surrogate by compound class is presented in Table 2. (Note that the class composition of the surrogate matches that of the petroleum JP-4 to within less than 0.5% for each class.) Gas chromatograms are presented for both the petroleum JP-4 (Fig. 2a) and the surrogate JP-4 (Fig. 2b) to show the inherent chemical complexity of the petroleum JP-4 relative to the surrogate. The paraffins, which comprise over 60 vol% of the petroleum JP-4, are represented in the surrogate by normal paraffins from hexane to tetradecane. Whereas the gas chromatographic analysis reveals that the individual normal paraffins in the petroleum JP-4 increase in concentration from C₆ to C₈ and then decrease with increasing molecular weight, the normal paraffins in the surrogate are chosen to increase in concentration to C₉ and stay constant at 10 vol% from C₉ to C₁₄, this allows the surrogate to match both the distillation curve and the paraffin class volume percent of the petroleum JP-4. Note that the surrogate gas chromatogram shows the decalin (chosen to model the dicyclopentadiene class) to be comprised of an approximately equimolar mixture of *cis*- and *trans*-decalin, (whose boiling points differ by 9°C), resulting in a chromatogram with 15 individual peaks.

The monocyclopentadiene class of the surrogate is composed of equal volume percent fractions of C₆, C₇, and C₈ monocyclic compounds. These were selected both to match the distillation curve of the petroleum JP-4 and to keep fuel costs at a reasonable level. Monocyclic compounds with higher carbon numbers were found to be prohibitively expensive.

Fig. 2 Gas chromatograms: a) petroleum JP-4, b) surrogate JP-4.

Table 3 Physical and chemical fuel properties

	Petroleum JP-4	Surrogate JP-4	Iso-octane	High aromatic JP-5
Equivalent chemical formula	Not determined	C _{8.35} H _{16.8} ^c	C ₈ H ₁₈	C _{11.6} H _{21.1} ^e
Equivalent molecular weight, g/mole	Not determined	117.2 ^c	114.22	161 ^h
Vol% aromatics	9.7 ^a	9.5 ^c	0.0 ^e	22.7 ^f
Specific gravity (at 20°C)	0.757 ^g	0.761 ^g	0.692 ⁱ	0.823 ^f
Viscosity (at 38°C), cS	0.786 ^a 0.789 ^b	0.894 ^b	0.608 ⁱ	1.50 ^f
Surface tension, dynes/cm	25.7 ^c	26.4 ^c	18.3 ^j	Not determined
Hydrogen wt%	14.5 ^a	14.4 ^c	15.9 ^c	13.5 ^f
Smoke point, mm	25.0 ^a 24.3 ^d	46.0 ^d	43.2 ^d	21.0 ^f
Heat of combustion, MJ/kg	43.6 ^a	43.9 ^c	44.65 ^j	42.9 ^f

^aLetter from William Harrison, Fuels Branch, Fuels and Lubrication Division, Air Force Wright Aeronautical Lab., Wright-Patterson AFB, OH, Aug. 13, 1981.

^bASTM Method D445, UNOCAL Center Analysis.

^cASTM Method D971, UNOCAL Center Analysis.

^dASTM Method D1322, UCICL Analysis.

^eCalculated.

^fLetter from Anthony Klarman, Naval Air Propulsion Ctr., Trenton, NJ, May 17, 1985.

^gASTM Method D1298, UNOCAL Research Center Analysis.

^hPrivate communication from Dennis Hardy, Naval Research Lab., Washington, DC, March 1987.

ⁱDreisbach, R. R., "Physical Properties of Chemical Compounds-II," *Advances in Chemistry Series*, Vol. 22, American Chemical Society, Washington, DC, 1959, p. 47.

The remaining compound classes are represented in the surrogate fuel by a single compound in each class, chosen as representative of that class, with the exception of the indene/dihydronaphthalene class, for which no compounds were detected in the petroleum JP-4.

The physical and chemical properties of the resulting surrogate fuel, as well as those of the petroleum JP-4 fuel, are listed in Table 3. The properties of the surrogate and petroleum JP-4 compare favorably with the exception of the smoke point. The higher smoke point of the surrogate indicates that the surrogate does not have the same propensity to produce soot in practical combustion systems relative to the petroleum JP-4.

In addition to the JP-4 and its surrogate, a high aromatic petroleum JP-5 was chosen for parallel comparison. The fuel properties of the JP-5 are also included in Table 3. The extent to which the surrogate formulation protocol produces a surrogate fuel that effectively reproduces the performance characteristics of the parent can be demonstrated by comparing these fuels to a fuel of purposefully disparate chemical and physical properties. For example, compared to the surrogate and petroleum JP-4, the JP-5 has 1) a distillation curve of much higher initial boiling point and much narrower boiling-point range (see Fig. 1), 2) a much higher aromatic content (22.7 vol% vs 9.5 vol%), 3) a significantly lower hydrogen content (13.5 wt% vs 14.5 wt%), and 4) a higher specific gravity and viscosity.

Experiment

Nonreacting Flow

Chamber

The spray facility is designed to characterize a liquid fuel atomizer under nonreacting conditions.¹ The chamber consists of a 30.5 cm i.d. $\times$ 152 cm long, clear cast acrylic resin tube positioned vertically at the center of an optical platform. The chamber is mounted on a precision platform, permitting movement with one degree of freedom in the horizontal plane for radial traverses of the spray.

The nozzle is centrally positioned within the chamber in a fixture that permits vertical movement for axial traverses. The nozzle is assembled in the end of a 19 mm o.d. fuel-delivery tube, identical to the one used for the reacting flow measurements in the model laboratory combustor, and is plumbed to accept fuel and atomizing air.

Nozzle

The nozzle used in this evaluation is an air-assist atomizer^{1,2} designed to provide a high degree of atomization in a model laboratory combustor. For the present study, the same nozzle was operated in both the nonreacting spray chamber and the combustor at a fuel mass flow rate of 3.3 kg/h and an atomizing air mass flow rate of 9.9 kg/h (i.e., 4.9 standard ft³/min), for a resulting air-to-fuel mass ratio of 3.0.

Diagnostics

An interferometric technique is employed to determine atomization quality. Interferometric measurements are made with a single-component phase Doppler instrument³ to obtain spatially resolved measurements of both droplet diameter and droplet velocity. Verification of phase Doppler via comparisons with diffraction and other interferometric techniques are described elsewhere.^{4,5}

Reacting Flow

Combustor

The combustor employed is a model, axisymmetric can combustor (ASCC) described in detail in Ref. 6. The configuration is presented in Fig. 3. The ASCC features an aerodynamically controlled, swirl-stabilized recirculation zone to simulate important features of practical combustors (e.g., swirl and highly turbulent recirculation).

Fig. 3 Axisymmetric can combustor.⁶

Fig. 4 Laser anemometry system.

For the results reported here, the fuels are burned at an overall equivalence ratio of 0.3, corresponding to a primary zone equivalence ratio of approximately 0.8 with the current combustor geometry. The combustor is operated at atmospheric pressure and a bulk reference velocity of 7.5 m/s. The ratio of swirl air to dilution air is 1.5 by mass. Prior to introduction into the combustor, both swirl and dilution air are heated to 100°C.

Laser Anemometer

A laser anemometer (LA) system is employed to characterize the axial component of the velocity (Fig. 4). The green (514.5 nm) beam from an argon-ion laser is isolated with a dispersion prism and is focused onto a radial diffraction grating where it is split into ordered pairs. The first-order pair is subsequently collimated, focused, and crossed to form the probe volume. Frequency shifting is provided by rotating the diffraction grating to allow the distinction between negative and positive velocities. A precision motor-speed control provides shift frequencies to 8 MHz. Note that the beams are crossed in a horizontal plane to measure the axial component of velocity.

The Doppler bursts are collected 20 deg off the forward scatter direction by a photodetector. Pedestal and high-frequency noise removal and data processing are performed by a Macrodyne Series 2000 laser velocimeter electronic processor. Data reduction is performed by a Digital Equipment Corporation PDP 11/23 minicomputer.

The LA technique requires particles to scatter light while passing through the probe volume. Alumina seed is introduced for the velocity measurements following the procedure outlined in Ref. 7. Discrimination between Doppler bursts from small droplets and alumina in the spray region of the combustor are not made. Hence, the velocity reported in the spray region includes measurements of both phases.

Thermocouple Probe

The temperature probe consists of a type R (platinum-13% rhodium vs platinum) exposed-junction thermocouple. The

Fig. 5 Isothermal comparison: a) petroleum JP-4 and surrogate JP-4, b) petroleum JP-4 and petroleum JP-5.

thermocouple is supported by a 1.6 mm (0.063 in.) o.d. inconel tube, 38 mm (1.5 in.) in length, which in turn is mounted to a 6.4 mm (0.25 in.) o.d. inconel support to give structural rigidity. Water cooling is provided in the larger inconel tubing to assure the structural integrity of a probe bend necessary to clear the exhaust stream, but only to within 41 cm (16 in.) of the thermocouple bead so as to minimize conduction losses down the length of the probe. The thermocouple probe is mounted on a three-axis positioning traverse consisting of three orthogonally oriented screw motion assemblies. The data presented are uncorrected for radiation loss.

Results

Comparison in Nonreacting Spray Chamber

The mean droplet velocity and flux sensitive Sauter mean diameter (flux-SMD) profiles are presented in Fig. 5. The SMD, or $\bar{D}_{32}$, is defined as $\sum_i D_i^3 / \sum_i D_i^2$, where D is the

Fig. 6 Mean axial velocity fields: a) petroleum JP-4, b) surrogate JP-4, c) petroleum JP-5, d) iso-octane.

measured diameter of each droplet traversing the optical probe volume. The flux-SMD is the SMD of droplets passing through a sampling zone during a given time interval, wherein individual droplets are continuously counted and sized. The data are presented for one axial station, 9 cm from the nozzle. This location was selected to facilitate the interferometric-based measurement, since the nozzle operating conditions selected for this study result in a dense spray field that limits this measurement technique to locations well separated from the nozzle exit.

A comparison of droplet size provided by phase Doppler interferometry is shown in Fig. 5a for both the petroleum and surrogate JP-4. The flux-SMD profiles indicate that both fuels maintain very similar SMD values at all points in the spray field. Also presented are the mean velocity profiles for both the petroleum and surrogate JP-4, which are shown to be the same as well.

A comparison of droplet size for the petroleum JP-4 and JP-5 is presented in Fig. 5b. The flux-SMD profiles again indicate a well mixed spray field for both fuels. Although the air-assist nozzle used in the present study is relatively insensitive to fuel-property variations in the range evaluated,⁸ the values of SMD for the JP-5 are consistently larger than for the petroleum JP-4 by approximately 30%.

The mean velocity profiles, shown also in Fig. 5b for both the petroleum JP-4 and JP-5, are again the same. Note that the asymmetry present in Fig. 5a is not evident. The nozzle is rotated in this case, with the result that the nozzle generates a slightly different velocity profile than that of Fig. 5a.

Comparison in Model Combustor

Results are presented first for the aerodynamic fields, followed by the thermal fields.

Aerodynamic Fields

The mean axial velocity fields for the petroleum JP-4, surrogate JP-4, and JP-5 are presented in Fig. 6. Also presented in Fig. 6 is the aerodynamic field for iso-octane, a high-purity compound of relatively high volatility (boiling point = 99.2°C). Iso-octane is included here for comparison to assess the effects of fuel volatility. The fuel properties of iso-octane relative to the other fuels are included in Table 3.

With the exception of the axial station at $x/R = 1.00$, the mean axial velocity profiles for all four fuels are remarkably similar. The velocity field for each fuel clearly shows the presence of an off-axis, toroidal recirculation zone at $x/R = 0.30$, positioned directly downstream of the swirl vanes. At $x/R = 1.75$ and axial locations further downstream, the mean velocity profiles are again remarkably similar among the four fuels. Note that at the axial station $x/R = 0.30$, data are not presented at the core radial locations due to the very high spray densities that precluded LA measurements.

At $x/R = 1.00$, the mean axial velocity profiles show significant differences among the iso-octane, petroleum JP-4, and

Fig. 7 Mean axial velocity profiles at $x/R = 1.00$: a) iso-octane, petroleum JP-4, and petroleum JP-5; b) petroleum JP-4 and surrogate JP-4.

Fig. 8 Thermal fields: a) petroleum JP-4, b) surrogate JP-4, c) petroleum JP-5.

JP-5 fuels (Fig. 7a). A dramatic increase in mean axial velocity just off the centerline becomes evident as fuel volatility decreases from iso-octane to petroleum JP-4 to JP-5. Whereas the iso-octane profile shows clear evidence of the negative velocities associated with the aerodynamic recirculation zone, the JP-5 profile shows positive mean axial velocities in excess of 60 m/s, with the petroleum JP-4 profile falling between. This trend is interpreted as showing the influence of high-velocity spray droplets as fuel volatility is decreased. The visual observations of laser beam brightness at these radial locations correlate as well with fuel volatility. Since the processing instrumentation used on the LA system does not distinguish between alumina seeding and fuel droplets, the measured mean velocity profiles can be significantly influenced by the presence of high-velocity droplets, as is the case here for the petroleum JP-4 and JP-5. It should be noted that the shoulder on the petroleum JP-4 profile at $x/R = 1.00$ (the location of spray droplet influence) was a persistent result that was consistently measured in six different experiments.

The mean axial velocity profiles of petroleum JP-4 and surrogate JP-4 at $x/R = 1.00$ are plotted in Fig. 7b for comparison. It is immediately clear that the mean axial velocity profile of the surrogate is an excellent match for the petroleum JP-4 profile and is significantly different from that of either the iso-octane or JP-5.

Thermal Fields

The thermal fields for the petroleum JP-4, surrogate JP-4, and JP-5 are presented in Fig. 8. Inspection of the thermal field for petroleum JP-4 (Fig. 8a) confirms the location and size of the off-axis, toroidal recirculation zone. Also revealed is a uniform, high-temperature core downstream, with a steeply decreasing radial gradient to a relatively cool outer flow. Figure 8b shows the surrogate temperature field within the combustor to be virtually identical to that of the petroleum JP-4.

The thermal field for the fuel with disparate properties, the high aromatic JP-5 (Fig. 8c), is distinct from those for both the petroleum and surrogate JP-4. First, the region near the nozzle exit depicts a more pronounced hollow cone structure, which indicates maintenance of the spray cone at distances further from the nozzle than with either the petroleum or surrogate JP-4. This is consistent with the higher number densities of droplets encountered during measurements of velocity at $x/R = 1.00$. Second, the overall temperature is higher in the core region of the combustor for the JP-5.

Summary and Conclusions

The present paper assesses the suitability of utilizing a surrogate multicomponent blend of pure hydrocarbons to simulate the combustion performance of a practical jet fuel.

A formulation strategy and procedure are described for blending pure hydrocarbons in such a way as to produce a fuel surrogate that matches the distillation curve and compound class composition atomization of a practical, petroleum-derived JP-4. Specific hydrocarbon compounds are selected whose cumulative boiling-point curve closely matches the ASTM method D86 distillation curve of the petroleum-derived JP-4.

In-flame measurements of the velocity and temperature fields for the surrogate JP-4, acquired in a swirl-stabilized, spray-fired, model laboratory combustor, closely match those of the petroleum JP-4, yet they are easily distinguished from those associated with a JP-5, a fuel of disparate properties. Nonreacting measurements of atomization quality show similar correspondence between the surrogate and parent fuels. In contrast, the atomization quality of the JP-5 is significantly different. Hence, the surrogate provides an attractive baseline fuel of controlled composition and manageable complexity from which to explore fuel property and chemical composition effects upon gas turbine combustion.

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