**“Railplug Ignition System for Enhanced Engine Performance and
Reduced Maintenance”
Semi-Annual Technical Progress Report
Second 6 Months: April 1, 2002 - September 31, 2002**

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20 August 03**

DE-FG26-01NT41334

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ABSTRACT

During the first year of this project, three experimental subtasks and four modeling subtasks were scheduled to begin. Five of these 7 subtasks were scheduled for completion by the end of the first year. Both experimental tasks were completed on schedule. No experimental data were scheduled for the first year. The four modeling tasks are progressing well. However, two of the numerical tasks have been delayed somewhat.

A simplified plasma kinetics mechanism was developed and tested against a detailed model. The agreement was quite good. A simplified kinetics mechanism for flame propagation was also developed and validated via comparisons against an elementary kinetics mechanism. Again, the agreement was quite good. The 2D spark ignition process model was exercised to ensure stability but the 3D version was not completed. Excellent progress was made on the ignition circuit model, but it is not yet finished. The delays in these two subtasks are not expected to impact the schedule for the overall project.

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1. INTRODUCTION

The US Department of Energy established the Advanced Natural Gas Reciprocating Engine (ANGRE) program to improve large-bore stationary natural gas engines. The goals of the ANGRE program are to increase fuel efficiency to 50%, decrease emissions of the oxides of nitrogen (NO_x) by a factor of 10, and decrease maintenance costs by 10%. Achievement of the efficiency and NO_x goals of the program will require use of higher compression ratios and/or higher boost pressures and leaner air/fuel ratios. Both factors increase the demands upon the ignition system, whereas the ignition systems currently in use – for the present gas densities at ignition and mixture strengths – often fail to meet customer expectations for performance and durability. The ignition systems currently in use are derived from automotive applications and are not designed or optimized for the higher load, leaner conditions of large natural gas engines. There is, therefore, an acute need for a more robust ignition system for big natural gas engines offering longer igniter life and better ignition characteristics.

Via the ANGRE program, DOE funded a project at The University of Texas (UT) that consists of two simultaneous tasks. The experimental task is the development of a railplug and driver-electronics system designed around the unique requirements of stationary natural gas engines. Two sequential numerical tasks are also included in this project. First, we are expanding our prior model of spark ignition from a 2D transient simulation to a 3D transient version, incorporating flame chemistry for methane/air mixtures (the typical natural gas is more than 90% methane), and including the dynamics of the electronics circuit. This model will be useful as a new design tool for conventional spark plugs, optimizing the driver-electronics for spark plugs, and understanding ignition system dynamics and demands not only for current large bore natural gas engines, but also for future engines with higher boost pressures and air/fuel ratios. The second numerical task combines the improved spark plug model with a railplug model, to serve as an optimization design tool for development of railplugs for large bore natural gas engines.

The tasks and timelines that were incorporated in the proposal for this project are provided in Figure 1. The vertical dash-dot line highlights the first 12 months of the project. The beginning of each task is an open circle, the end is a filled circle, and each significant milestone is indicated by an X. Vertical arrows show subtasks that feed into other subtasks. Lines that are linked (bold) feed each other throughout the duration of both. Three subtasks from the initial 6 months were extended (Subtasks 2.1.a, b, and c). Three additional subtasks began in the second 6 months (Subtasks 1.2, 1.3, and 2.1.d), one of which was to have been completed at the end of the first year (Subtask 2.1.d). The kinetics subtask (2.1.a) that was extended from the first 6 months was completed by the end of the first year. The model validation subtask (2.1.d) that began during the second 6 months has been extended past the first year due to delays in the circuit model development. Satisfactory progress was made on Subtasks 1.2 and 1.3, which are not scheduled for completion until near the end of the project. Progress on each of the tasks is discussed in Section 3.

Figure 1. Tasks and timelines. The vertical dash-dot line highlights the first year of the project.

2. EXECUTIVE SUMMARY

During the first year of this project, three experimental subtasks and four modeling subtasks were scheduled to begin. Five of these 7 subtasks were scheduled for completion by the end of the first year.

Experimental Task 1.1, development of new railplug designs, was completed on schedule. Experimental Task 1.2, durability testing was begun but was not scheduled for completion during the first year. Experimental Task 1.3, setup of the test engine, was completed. Installation and calibration of the cylinder pressure analysis hardware, is the only item remaining before the beginning of experimental data acquisition. No experimental data were scheduled for the first year.

The four modeling tasks are progressing well. A simplified plasma kinetics mechanism was developed and tested against a detailed model. The agreement was quite good. A simplified kinetics mechanism for flame propagation was also developed and validated via comparisons against an elementary kinetics mechanism. Again, the agreement was quite good. However, two of the numerical tasks have been delayed somewhat. The 2D spark ignition process model was exercised to ensure stability but the 3D version was not completed. Excellent progress was made on the ignition circuit model, but it is not yet finished. The delays in these two subtasks are not expected to impact the schedule for the overall project.

3. EXPERIMENTAL AND NUMERICAL TASKS

Progress on each of the experimental and numerical tasks that were scheduled for the second 6 months of this project is discussed in the following two subsections.

3.A. Experimental Tasks

The experimental tasks scheduled for the second 6 months of the project were to: 1) begin durability tests and 2) set up an engine for engine tests.

The initial durability tests were focussed upon parallel railplugs. The geometric variables for parallel railplugs are illustrated in Figure 2. The values used for the railplugs that were fabricated for the initial durability tests are provided in Table 1. The durability tests consisted of firing these railplugs to failure at atmospheric pressure. These tests were not yet completed by the end of the first year.

Figure 2. Parallel railplug, illustrating the dimensions that were varied for the initial designs.

Table 1. Parallel Railplug Designs that were Fabricated for Initial Durability Testing

	electrode diameter	initiation gap	rail length	rail separation
	mm/in	mm/in	mm/in	mm/in
min.	2.36/.093	.508/.020	3.81/.015	2.54/.10
	2.54/.10	.635/.025	6.35/.25	
		1.016/.040		
max.	3.172/.125	1.54/.060	12.7/.50	2.54/.10

The second experimental task was the setup of an engine for railplug performance and durability testing. Because UT does not have a large bore stationary natural gas engine for testing, the first task was to choose the engine to use for our tests. We chose to use an engine that was designed before recent efforts to attain high combustion stability. In turn, this should provide an ignition environment for which improvements should be readily quantifiable. Therefore, we chose a 1992 GM 2.2 L SI engine. This is a 2-valve, 4-cylinder pushrod engine. The second task was to generate a means for cylinder pressure measurement. Of course, the easiest technique is to use an offset electrode spark plug, which provides room for a passage for pressure transducer mounting. However, since we are testing new igniters, this option was not feasible. Instead, we drilled a horizontal hole through the head into the combustion chamber of

cylinder #4. We relied on our contacts at GM for blueprints for location of this passage without opening into the coolant passages. The head was then reinstalled on the engine and the engine was mounted on a water brake dyno. The pressure transducer installation on the engine is illustrated in Figure 3. The completed engine installation on the dyno is illustrated in Figure 4. The only task remaining before data can be acquired is installation of cylinder pressure data acquisition and analysis hardware. We are using a DSP Redhat cylinder pressure analysis system. This system is specially designed for high-speed engine data acquisition and analysis.

Figure 3. Photo of pressure transducer mounting

Figure 4. Photo of engine installation.

3.B. Numerical Tasks

Three numerical tasks were extended from the first 6 months of this project and one numerical task was begun. Each is discussed below.

Subtask 2.1.a consists of generating the appropriate ignition kinetics. This consists of conventional methane flame chemistry and, because the gas temperature during the ignition process can exceed 6000 K, additional reactions that are important at these high temperatures. The plasma reactions that are of interest are:

Ionization reactions are not included because they are not important for gas temperatures below 10,000 K (Sher et al., 1992). Reactions 2-3d liberate chemical energy via a path other than via normal flame chemistry. That is, at extremely high temperatures, such as those found during electrical energy deposition in the spark gap, the fuel and molecular oxygen can become completely dissociated. When the plasma cools to 6000 K and lower, these atoms recombine

exothermically into stable species like CO and OH, which can then react further to form more stable species such as CO₂ and H₂O, releasing even more energy. This path is not included in any other model, but is critical. However, Reactions 3a-3d are generally incorporated in conventional flame chemistry (but the sequence leading to Reactions 3b-3d is different at the lower temperatures associated with flames). Thus, the focus of Subtask 2.1.a was to find rates for Reactions 1 and 2.

Reaction 1 is a global reaction that incorporates a series of sequential and simultaneous reactions. The elementary reaction path and rate data are provided in Table 2. The rates for Reactions 4-8 were taken from results for high temperature (6,200-11,000 K) methane pyrolysis reactions (Finck et al., 2002). Reactions 3a and 9 are normally included in conventional flame chemistry but the rate data are obtained for the temperature range that is appropriate for flames. Due to the present interest in plasma chemistry, the rates for Reactions 3a and 9, and also Reaction 2, were obtained from a study focussed upon plasmas formed during re-entry of space vehicles (Gupta et al., 1990). Similarly, the rate for Reaction 3d in the forward direction was obtained from a study of shock-heated H₂/CO/O₂ mixtures (Brown et al., 1969) and the reverse rate was obtained from Kochubei, and Moin (1969). The plasma reaction set in Table 2 includes 15 species. The GRI mechanism (GRI-Mech 3.0, Smith et al. 2002) can be used to simulate the conventional flame chemistry. It includes 52 species (not including Argon), all of which also appear in Table 2. Therefore, use of elementary kinetics for modeling the ignition and flame propagation process involves a total of 52 species.

Table 2. Elementary Plasma Reactions and Corresponding Rate Data

Reaction	A (cm, gmole, s)	m (-)	E _a (cal/gmole)	
CH ₄ = H + CH ₃	4.7*E47	-8.2	117643	(RX 4)
CH ₃ + M = CH ₂ + H + M	1.0*E16	0	90524	(RX 5)
CH ₂ + H = CH + H ₂	6.0*E12	0	-1791	(RX 6)
C + H ₂ = CH + H	4.0*E`4	0	23235	(RX 7)
CH + M = C + H + M	1.9*E14	0	66923	(RX 8)
C + O -> CO	7.253*E13	0	0	(RX 2f)
CO -> C + O	5.21*E12	3.0	256350	(RX 2b)
O ₂ + M -> 2O + M	3.61*E18	-1.0	118800	(RX 3a,f)
2O + M -> O ₂ + M	3.01*E15	-0.5	0	(RX 3a,b)
N ₂ + M -> 2N + M	1.92*E17	-0.5	226000	(RX 9f)
2N + M -> N ₂ + M	1.09*E16	-0.5	0	(RX 9b)
H + O = OH	5.0*E17	-1.0	0	(RX 3b)
H + OH -> H ₂ O	2.2*E22	-2.0	0	(RX 3c,f)
H ₂ O -> H + OH	7.42*E28	-3.0	122600	(RX 3c,b)
CO + OH -> CO ₂ + H	3.7*E11	0	699	(RX 3d,f)
CO ₂ + H -> CO + OH	1.0*E14	0	24244	(RX 3d,b)

However, because the spatial scales for these simulations are of the order of microns and the time scales are of the order of nanoseconds, simulations that involve elementary kinetics are much too consumptive of computational time. Thus, it was necessary to develop simplified chemistry for both the plasma reactions (converting Reactions 4-8 in Table 2 to the global

reaction represented by Reaction 1) and the flame propagation reactions. The results from the kinetics development tasks are discussed in the following section.

Subtask 2.1.b is conversion of our 2-dimensional spark ignition model into a 3D model. In fact, we did complete a 3D model in Fluent to examine some issues (during the first 6 months). However, to simulate the ignition process, we must use a numerical scheme called Flux Corrected Transport (FCT) to assure convergence for a reacting mixture with small time step demands. Our 2D spark ignition model was built using FCT. After completing our 3D Fluent code, we began converting our 2D FCT/Fortran code to 3D. However, this conversion was not completed by the end of the second 6-month period. Some of the results using our 2D ignition code are discussed in Section 4.

Subtask 2.1.c, development of a model for the electronics circuit, began ahead of schedule but was more time-consuming than originally expected. However, significant progress was made, and we expect this model to be complete within the near future.

4. RESULTS AND DISCUSSION

We are too early in the project to have acquired experimental results. As noted above, we did develop the appropriate chemical kinetics and also exercised our 2D model. These results are discussed below.

The simplified plasma chemistry that was developed for this project is presented in Table 3. Reaction 1 is a global representation of Reactions 4-8. A slow reverse rate was incorporated to this reaction for numerical stability. The reverse rate coefficients (RX 1b) were developed by Patrice Seers, a PhD student on this project. To assure equilibrium, Reactions 2f and 2b from Table 2 were combined into a reversible reaction for the simplified mechanism in Table 3. Coefficients A and m for this reversible reaction were altered by Seers to produce the correct reaction rates for the simplified mechanism compared to the detailed mechanism. Similarly, Reactions 3c,f and 3c,b in Table 2 were changed to a reversible reaction (RX 6') for the simplified mechanism, as shown in Table 3. Reaction 5' in Table 3 is equivalent to Reaction 3b in Table 2, but Seers modified the rate coefficients to obtain better agreement with the predictions of the detailed mechanism. Reaction 1 reduces the number of species required to form C and H in the high temperature plasma from 7 to 3.

Table 3. Simplified Plasma Reactions and Corresponding Rate Data

Reaction	A (cm, gmole, s)	m (-)	E _a (cal/gmole)		Ref.
CH ₄ -> C + 4H	8.0*E44	-7.6	131000	(RX 1f)	1
CO = C + O	4.34*E27	0	256350	(RX 2)	2
O ₂ + M -> 2O + M	3.61*E18	-1.0	118800	(RX 3'f)	1
2O + M -> O ₂ + M	3.01*E15	-0.5	0	(RX 3'b)	1
N ₂ + M -> 2N + M	1.92*E17	-0.5	226000	(RX 4'f)	1
2N + M -> N ₂ + M	1.09*E16	-0.5	0	(RX 4'b)	1
OH = O + H	2.41*E15	0	120000	(RX 5')	3
H ₂ O = H + OH	7.42*E28	-3.0	122600	(RX 6')	4
CO + OH -> CO ₂ + H	3.7*E11	0	699	(RX 7'f)	5
CO ₂ + H -> CO + OH	1.0*E14	0	24244	(RX 7'b)	5

Rate data from: (1) Gupta et al. (1990) (2) modified by P. Seers, original coefficients from Mick, et al., (1993), (3) modified by P. Seers, original coefficients from GRI-Mech 3.0, (4), GRI-Mech 3.0, (5) Brown et al., (1969).

The accuracy of the simplified mechanism is illustrated in Figures 5 and 6. Figures 5a-5d compare the predictions of the simplified plasma kinetics to those for the detailed plasma mechanism for conditions at the time typical of turbocharged large bore natural gas engines: 42 bar absolute pressure with an equivalence ratio (ϕ) of 0.6. Figures 5a and 5b are for a plasma temperature of 5000 K while Figures 5c and 5d are for 8000 K. To further illustrate the range of validity of the simplified plasma kinetics, Figures 6a-6d present similar information, but for ignition conditions that are typical for a light-duty naturally aspirated natural gas engine. Although it is difficult to see in these graphs due to the log scale, at the very earliest times, the concentrations of C and H are slightly overpredicted by the simplified mechanism. This is expected because the global fuel consumption reaction (Reaction 1 in Table 3) does not account for the C and H atoms that are bound within CH₃, CH₂, and CH. However, for all of these comparisons, the predictions of the simplified kinetics are quite close to those for the detailed

mechanism. These comparisons provide confidence that the simplified plasma mechanism is adequate for modeling the ignition process during the high temperatures that occur during electrical energy deposition.

Figure 5a. Comparison of the rates of formation of C, CO, and CO2 for $\phi = 0.6$, 42 bar, and 5000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 5b. Comparison of the rates of formation of H, O, and H₂O for $\phi = 0.6$, 42 bar, and 5000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 5c. Comparison of the rates of formation of C, CO, and CO₂ for $\phi = 0.6$, 42 bar, and 8000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 5d. Comparison of the rates of formation of H, O, and H₂O for $\phi = 0.6$, 42 bar, and 8000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 6a. Comparison of the rates of formation of C, CO, and CO₂ for $\phi = 1.0$, 6 bar, and 5000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 6b. Comparison of the rates of formation of H, O, and H₂O for $\phi = 1.0$, 6 bar, and 5000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 6c. Comparison of the rates of formation of C, CO, and CO₂ for $\phi = 1.0$, 6 bar, and 8000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Figure 6d. Comparison of the rates of formation of H, O, and H₂O for $\phi = 1.0$, 6 bar, and 8000 K plasma temperature (filled symbols: elementary plasma kinetics; open symbols: reduced plasma kinetics).

Because the temperature changes rapidly during the electrical energy deposition process, there is insufficient time for the reactions to reach equilibrium. However, additional confidence in the accuracy of the simplified plasma kinetics mechanism is obtained if the reduced plasma kinetics predict the correct values at steady state, when equilibrium occurs. Figures 7a-7d compare the equilibrium mole fractions with those predicted by the reduced plasma kinetics at long times, when the concentrations have reached constant levels. For many of the cases, there is a small discrepancy at 3000 K, when the effects of flame chemistry are also important. Also, at the higher temperatures, the predictions for CO₂ and H₂O are not strong. However, the mole fractions for these species are small at these temperatures. Thus, this discrepancy is due to the effects that small errors in predicting species with much higher concentrations have on the predictions of species with very small concentrations, like CO₂ and H₂O. However, it must be noted that the errors in predicting CO₂ and H₂O at the higher temperatures are not expected to be important for two reasons. First, because the concentrations are very small, the energy release predictions should not be significantly affected. Second, as noted previously, the plasma reactions do not have sufficient time to reach equilibrium, so rate predictions are much more important than steady state predictions.

Figure 7a. Comparisons, at 6 bar, of the equilibrium mole fractions (filled symbols) with those predicted at steady state using the reduced plasma mechanism (open symbols): the important carbonaceous species.

Figure 7b. Comparisons, at 6 bar, of the equilibrium mole fractions (filled symbols) with those predicted at steady state using the reduced plasma mechanism (open symbols): H, O, and H₂O.

Figure 7c. Comparisons, at 42 bar, of the equilibrium mole fractions (filled symbols) with those predicted at steady state using the reduced plasma mechanism (open symbols): the important carbonaceous species.

Figure 7d. Comparisons, at 42 bar, of the equilibrium mole fractions (filled symbols) with those predicted at steady state using the reduced plasma mechanism (open symbols): H, O, and H2O.

The simplified flame chemistry developed for this project is listed in Table 4. This simplified mechanism was obtained from Miyamoto and coworkers (1990) and modified by Seers to attain agreement with the detailed mechanism. For each reaction in Table 4, the reverse rate is specified independently rather than relying on the relationship between the forward rate, the reverse rate, and the equilibrium constant for the reaction. This is typical for simplified kinetics schemes, since the simplified reactions are not elementary and thus are not necessarily expected to proceed to equilibrium. The simplified flame chemistry only adds 4 species (H₂, HCO, CH₃, and CH₂O) to those that are already accounted for via the simplified plasma chemistry. Thus, the total number of species considered is only 15 for both types of reactions combined. Because computational time requirement typically scales with the square of the number of species in the kinetics mechanism (Westbrook and Dryer, 1984), the simplified plasma plus flame kinetics developed for this project should be about 12 times faster than would be possible using elementary kinetics.

Normally, predictions for simplified flame chemistry are validated via comparisons against experimental data for the unstretched laminar flame speed. However, no data were found in the literature for conditions typical of large bore natural gas engines (42 bar and 695 K at the time of spark, and higher pressures and reactant temperatures later during combustion). Therefore, the predictions using the simplified flame chemistry were validated via comparisons against the predictions using GRI-Mech 3.0. Here, it should be noted that the GRI mechanism was developed for flame temperatures from 1000-2500 K, equivalence ratios from 0.1-5.0, and pressures from 10 torr to 10 bar. For application to turbocharged natural gas engines, we are interested in higher pressures at the time of ignition and throughout combustion. However, the developers of GRI-Mech 3.0 were careful to fully account for the pressure fall-offs. Therefore, it is believed that the predictions using GRI Mech 3.0 for high pressures are reasonably accurate. Figure 8 shows the comparison between the predictions of GRI-Mech 3.0 and the simplified kinetics for 42 bar and a reactant temperature of 695 K. The predictions using the simplified kinetics are accurate within 4% for this range of equivalence ratios.

Table 4. Simplified Flame Reactions and Corresponding Rate Data

Reaction	A (cm, gmole, s)	m (-)	Ea (cal/gmole)	
CH ₄ -> CH ₃ + H	1.40*E17	0.0	88400	(RX 8'f)
CH ₃ + H -> CH ₄	2.84*E11	1.0	-19510	(RX 8'b)
CH ₃ + O ₂ -> CH ₂ O + OH	6.92*E11	0.0	4530	(RX 9'f)
CH ₂ O + OH -> CH ₃ + O ₂	7.21*E11	0.0	58050	(RX 9'b)
CH ₃ + OH -> CH ₂ O + H ₂	4.00*E12	0.0	0	(RX 10'f)
CH ₂ O + H ₂ -> CH ₃ + OH	1.20*E14	0.0	71720	(RX 10'b)
CH ₂ O + OH -> HCO + H ₂ O	5.40*E14	0.0	6300	(RX 11'f)
HCO + H ₂ O -> CH ₂ O + OH	1.87*E14	0.0	36120	(RX 11'b)
HCO + OH -> CO + H ₂ O	1.00*E14	0.0	0	(RX 12'f)
CO + H ₂ O -> HCO + OH	2.80*E15	0.0	10510	(RX 12'b)
CO + O -> CO ₂	5.90*E15	0.0	4100	(RX 13'f)
CO ₂ -> CO + O	5.50*E21	-1.0	131800	(RX 13'b)
H + O ₂ -> O + OH	2.20*E14	0.0	16790	(RX 14'f)
O + OH -> H + O ₂	1.74*E13	0.0	677	(RX 14'b)
H + OH -> H ₂ O	2.20*E22	-2.0	0	(RX 6'f)

$\text{H}_2\text{O} \rightarrow \text{H} + \text{OH}$	$7.42 \cdot \text{E}28$	-3.0	122600	(RX 6'b)
$\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}$	$3.7 \cdot \text{E}11$	0	699	(RX 7'f)
$\text{CO}_2 + \text{H} \rightarrow \text{CO} + \text{OH}$	$1.0 \cdot \text{E}14$	0	24244	(RX 7'b)
$\text{O}_2 + \text{M} \rightarrow 2\text{O} + \text{M}$	$3.61 \cdot \text{E}18$	-1.0	118800	(RX 3'f)
$2\text{O} + \text{M} \rightarrow \text{O}_2 + \text{M}$	$3.01 \cdot \text{E}15$	-0.5	0	(RX 3'b)
$\text{H} + \text{O} = \text{OH}$	$5.0 \cdot \text{E}17$	-1.0	0	(RX 5')

Figure 8. Comparison of predictions of the unstretched laminar flame speed at 42 bar, 695 K reactant temperature for two kinetics mechanisms as a function of equivalence ratio.

Some of the results using our 2D ignition code are illustrated in Figures 9a-j and 10a-j. These 2D runs did not use the appropriate electrical energy deposition schedule, which will be included once the circuit model is completed. Figure 9a-j shows the pressure profile histories beginning at 10 ns and progressing through the ignition process to 8 μs . Figure 10a-j is similar, but shows the temperature profile histories.

(9a) $t = 0.01 \mu\text{s}$

(9b) $t = 0.1 \mu\text{s}$

Figure 9a and b. Pressure profile histories for simulated spark ignition: 10 and 100 ns.

(9c) $t = 1.0 \mu s$

(9d) $t = 2.0 \mu s$

Figure 9c and d. Pressure profile histories for simulated spark ignition: 1 and 2 μs .

(9e) $t = 3.0 \mu\text{s}$

(9f) $t = 4.0 \mu\text{s}$

Figure 9e and f. Pressure profile histories for simulated spark ignition: 3 and 4 μs .

(9g) $t = 5.0 \mu\text{s}$

(9h) $t = 6.0 \mu\text{s}$

Figure 9g and h. Pressure profile histories for simulated spark ignition: 5 and 6 μs .

(9i) $t = 7.0 \mu s$

(9j) $t = 8.0 \mu s$

Figure 9i and j. Pressure profile histories for simulated spark ignition: 7 and 8 μs .

(10a) $t = 0.01 \mu s$

(10b) $t = 0.1 \mu s$

Figure 10a and b. Temperature histories for simulated spark ignition: 10 and 100 ns.

(10c) $t = 1.0 \mu s$

(10d) $t = 2.0 \mu s$

Figure 10c and d. Temperature profile histories for simulated spark ignition: 1 and 2 μs .

(10e) $t = 3.0 \mu\text{s}$

(10f) $t = 4.0 \mu\text{s}$

Figure 10e and f. Temperature profile histories for simulated spark ignition: 3 and 4 μs .

(10g) $t = 5.0 \mu\text{s}$

(10h) $t = 6.0 \mu\text{s}$

Figure 10g and h. Temperature profile histories for simulated spark ignition: 5 and 6 μs

(10i) $t = 7.0 \mu\text{s}$

(10j) $t = 8.0 \mu\text{s}$

Figure 10i and j. Temperature profile histories for simulated spark ignition: 7 and 8 μs

5. CONCLUSIONS

The test engine was completed, including mounting a pressure transducer in the cylinder head. The only task remaining before experimentation begins is installing and calibrating the cylinder pressure analysis system. It is too early in the project for experimental results.

The modeling tasks are progressing well. A simplified plasma kinetics mechanism was developed and tested against a detailed model. The agreement was quite good. A simplified kinetics mechanism for flame propagation was also developed and validated via comparisons against an elementary kinetics mechanism. Again, the agreement was quite good. The 2D spark ignition process model was exercised to ensure stability.

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