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DIESEL EMISSION REDUCTION BY ON-BOARD FUEL REFORMULATION

FINAL REPORT

For Period: September 4, 1999 to March 4, 2000

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March 1, 2000

Prepared for

THE U.S. DEPARTMENT OF ENERGY
Under Award No. DE-FG02-99ER82923

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SUMMARY

In this PHASE I proposal, four tasks were investigated:

- Plasma reforming in the mode of energy neutral reforming
- Testing in a diesel engine with hydrogen injection (port-injection)
- Analysis of the data
- System analysis

It was demonstrated that it is feasible using a compact microplasmatron fuel converter to obtain near energy neutral reforming! Heat efficiencies of diesel fuel reforming as high as 95% can be achieved in compact plasmatron devices. This means that reforming of diesel fuel does not result in a significant loss of efficiency of the system, and opens the possibility for their application in diesel-powered automobiles, trucks and buses.

Experiments were carried out on a diesel engine in a test stand. **Hydrogen addition was used in a compression ignition engine and a factor of 10 decrease in the particulate size concentration and mass was achieved.** The potential benefits of onboard reforming of diesel for particulate control were therefore demonstrated. Two points of operation were tested, with different levels of hydrogen addition.

The potential advantages of the use of advanced microplasmatron fuel converters for improved plasmatron operation were investigated in the system analysis. Additional improvements in engine operation by varying the start-of-injection timing of the "pilot" diesel (i.e., changing the timing of the ignition of the fuel) have produced even more dramatic decreases in the emissions from diesel engines.

Experiments with a diesel engine using EGR, exploring more completely the variation of ignition timing and exploring the possibility of homogeneous charging with a combination of fuel and hydrogen rich gas will be tested in PHASE II experiments.

A. Introduction

Hydrogen rich gas can be produced from diesel fuel by different reactions. Some of them include:

partial oxidation

steam or CO₂ reforming

pyrolysis

(It is assumed that the formula for diesel fuel can be written as $C_{15}H_{25}$).

Reaction (1) is endothermic while reactions (2-4) are exothermic. Thus it is possible to have autothermal or energy neutral process by combining reaction (1) with reaction (2) or (3). Such processes are currently being used for the conversion of hydrocarbons to syngas [1]. The use of syngas as an additive to fuel in commercial engines is very attractive because autothermal processes can be used to minimizing thermal energy losses during the reaction.

If combustion in engine occurs under air excess higher than one, the exhaust gas contains water vapor and carbon dioxide as well as oxygen. The ratio between the oxygen and combustion products depends on the air excess during combustion. It can be controlled. Combustion in lean fuel-air mixtures is very attractive as a way of reducing NO_x emission.

It has been shown [2,3] that the use of a plasma generator for hydrocarbon conversion provides the following advantages. It is:

- economically attractive for small scale hydrogen production,
- compact and low weight (due to high power density),
- rapidly responding (fraction of a second),
- inexpensive,
- highly efficient,
- used for producing higher concentrations of hydrogen because less air is required during production.

In this program, a plasma generator was used to convert diesel fuel in exhaust gas to provide a hydrogen rich gas without any loss in heating value.

The PHASE I program involved:

- a thermodynamic simulation of the reaction between diesel fuel and exhaust gas to determine an acceptable region of operation using an equilibrium approach,
- experimental measurements of diesel conversion by exhaust gas in plasma-catalyzed reactor.

These tasks will be briefly summarized.

a) Thermodynamic simulation of the reaction between diesel fuel and exhaust gas

The overall reaction of diesel fuel, $C_{15}H_{25}$, combustion in air under various air excess conditions k ($k \geq 1$) can be written as

The overall reaction of diesel fuel conversion by combustion products (exhaust gas) at an element ratio of C/O=1 can be written as

The heating value of reformed fuel (as a fraction of initial diesel fuel heating value) as a function of air excess k in the exhaust gas is shown in figure 1.

Fig.1. Heating value of reformed fuel (as a fraction of initial diesel fuel heating value) as a function of air excess k in the exhaust gas.

The composition of the reformat, under a ratio of $C/O=1$, is independent of the composition of exhaust gas (EG) used in accordance with reaction (6). The reformat produced under a ratio of $C/O=1$ contains:

$$H_2 - 22.5 \text{ vol.}, \quad CO - 26.9 \%, \quad N_2 - 50.6 \%$$

As Fig. 1 suggests, there is no loss in heat efficiency if the exhaust gas produced under $k=2$ is used as the oxidizer in the diesel fuel conversion.

Thus, the thermodynamic simulation were carried out for this value of k as well as for $k=4$.

The computer program ASTRA.4 [4] was used to calculate the equilibrium composition of the diesel/exhaust gas mixture. The calculations were carried out for an isoenthalpic-isobaric process at a total pressure of 0.1 MPa. It was assumed that the initial exhaust gases were heated to operational temperature in the range of 800 K to 1400 K. The diesel fuel was assumed to be a liquid at a constant temperature of 298 K.

The ratio EG/diesel was varied so that the corresponding range of element ratio O/C was from 1 to 1.3.

A set of calculations was also performed for an element ratio O/C between 0.9 to 1.0 using a quasi-equilibrium approach. In that case, condensed carbon formation is forbidden in the system.

As a result of these calculations, the equilibrium composition and temperature were determined. The equilibrium composition was used to calculate the heating value of the reaction products as well as the heating efficiency of the diesel fuel. The following conversion eff was defined:

$$eff = \frac{(\Delta H_{c_i} * m_i)}{\Delta H_{c_d} * m_d}, \quad (7)$$

where ΔH_{c_i} - heating value of component i ,

ΔH_{c_d} - heating value of diesel fuel,

m_i - number of moles of each component in the reaction product,

m_d - number of moles of diesel fuel.

It was found that there were some restrictions placed on the operating regimes because of carbon formation. An acceptable region of operation using an EG with $k=2$ is shown in Fig. 2. The maximum heating efficiency (higher than 95 %) can be reached only at a ratio C/O lower than 1.2. In that case, the EG should be heated up to a temperature higher than 1100 - 1300 K producing an adiabatic reaction temperature higher than 1050 K (Fig. 3). The calculations showed that the initial temperature of the EG had only a slight influence on the reformat combustion efficiency but had a significant effect on the reaction temperature (Fig. 3). It is clear that the initial temperature will have a strong effect on the reaction kinetics.

Fig. 2. Heating efficiency of the reformat produced under $k=2$ conditions.

Fig. 3. The adiabatic temperature of reaction under $k = 2$ conditions.

In the region where the ratio of $C/O =$ was 0.9 to 1, carbon was present in the equilibrium composition under all initial conditions that were considered.. The heating efficiency of reformat was close to 95-100 % as can be seen in Figure 4.

Fig. 4. Heating efficiency of the reformat produced under quasi-equilibrium conditions using EG with $k = 2$.

If the exhaust gas is generated at $k = 4$, the heating efficiency of the reformat is lower than 90 % as can be seen in Figure 5.

The thermodynamic simulations show that the production of hydrogen rich gas by the reaction of diesel fuel with EG will provide a high heating efficiency of reformat if the following happens:

- the exhaust gas is produced at air excess close to 2 ($k \approx 2$),
- the ratio of O/C is less than 1.2,
- and the initial temperature of the EG is higher than 1100 K.

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Fig. 5. Heating efficiency of the reformat produced under $k = 4$.

B. Experimental Results

a) Equipment

Fig. 6 and 7 show a schematic of the experimental setup that was used in this program. Air or its mixture with argon was heated in a DC plasma generator (1) to an enthalpy value of 6 – 19 MJ/kg. Additional air or its mixture with steam and carbon dioxide as well as atomized diesel fuel were injected into the plasma jet in the mixing unit (2). The diesel fuel atomization was produced using air in one or two pneumatic atomizers. All the initial components were further mixed just before the entrance to the catalyst bed. The heat insulated stainless steel reactor which was filled with the catalyst, was equipped with thermocouples at different distances from the reactor entrance. Thermojunctions were placed on the reactor vertical axis. A stationary gas probe was placed at the exit of the reactor.

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Additional gas or its mixture with water and carbon dioxide (exhaust gas) was preheated by hot reaction products in the heat exchanger (4).

Fig. 6. Schematic of the experimental setup.

Fig.7 Experimental Plasma Reactor Design

b) GC analysis

Gas samples were analyzed using gas chromatographs for H_2 , O_2 , N_2 , CO , CH_4 , C_2H_4 , C_3H_6 and CO_2 . The gas chromatograph was equipped with thermal-conductivity detectors. The error bars of the GC analyses were estimated as ± 2.5 relative % for all the components except C_3H_6 .

c) Materials

1. Fuel. Commercial diesel was used as the fuel. The fuel composition of the elements C and H were analyzed with a chemical analyzer.
2. Exhaust gas. The exhaust gas simulant was produced by adding water and carbon dioxide to air. This technique provided the ratios of CO_2/O_2 and H_2O/O_2 corresponding to the ratios found in diesel combustion products under any air excess conditions. The reduced concentration of N content in such a mixture compared with a real exhaust gas was of no importance because nitrogen is a non-reactive component in oxidative treatment of the fuel.
3. Catalysts. The experimental reactor was packed with a commercial nickel catalyst ICI 57-4. The amount of catalyst contained in the reactor was 400 – 500 g. Before an experiment was conducted, the catalyst was pre-heated *in situ* using hot reducing gases at 800 – 1000 C for 30 – 40 min.

C. Results and discussion

The basic parameters of interest in these reactions include the heating value of the reaction product after the conversion of the diesel fuel. The heating value depends on the reaction product flow rate as well as on its composition. It has been found during the performance of the experiments that a noticeable difference may exist between the total carbon flow rate at the entrance and at the exit of the reactor. The ratio of these flow rates ($C_{final} / C_{initial}$) is shown in Fig.8 as a function of the initial element ratio O/C.

Fig. 8. Total carbon content as a function of the ratio O/C.

It can be seen from Fig. 8 that carbon content increases if the ratio O/C decreases. Diesel is a multicomponent fuel containing a large number of organic compounds. The oxidative treatment of the diesel fuel in the reactor may be accompanied by the pyrolysis of diesel compounds. The pyrolysis of diesel compounds may lead to the formation of a wide range of hydrocarbons with at a low concentration in the reaction products. There are significant difficulties in the proper sampling and analysis of such reaction products. The difference between the diesel heating value and the heating value of diesel conversion products does not exceed about 15 % as can be seen from the above simulations of diesel fuel conversion with EG. Thus, if the carbon content is comparable to this value, it is impossible to determine the difference in heating value.

Two limiting estimates were used in this program to determine the heating value of the reaction products taking into account the carbon content.

The upper limit on the heating efficiency is calculated as follows:

$$eff_{upper} = \frac{G_i * \Delta H_{ci} + \frac{\Delta G_{c total}}{G_{cin}} * \Delta H_{cdiesel}}{G_{diesel}^o * \Delta H_{cdiesel}}, \quad (8)$$

where G_i - mass flow rate of component i in reaction product,
 $\Delta G_{c total}$ - total carbon mass flow rate,
 G_{cin} - carbon mass flow rate in initial reagents,
 G_{diesel}^o - initial mass flow rate of diesel,
 ΔH_{ci} - heating value of component i,
 $\Delta H_{cdiesel}$ - heating value of diesel.

In this limit, it was assumed that the carbon content was determined by the presence of diesel hydrocarbons in the reaction products. It should be noted that heavy hydrocarbons in the reaction products are different from those in the initial diesel fuel as a result of the pyrolysis reactions in the reactor. Therefore, the use of the diesel combustion value for the heavy hydrocarbons is in turn a lower estimate.

The lower estimate of heating efficiency was calculated from the following formula:

$$eff_{lower} = \frac{G_i * \Delta H_{ci}}{G_{diesel}^o * \frac{G_{c out}}{G_{cin}} * \Delta H_{cdiesel}} \quad (9)$$

where $G_{c out}$ - carbon mass flow rate in the reaction products.

All the experimental tests were run at atmospheric pressure a small fraction of the air (less than 10 % of total gases flow) preheated in the plasma generator. In the majority of the experiments the average air enthalpy at the exit of plasma generator ranged approximately from 6 to 19 MJ/kg corresponding to a mean air plasma temperature in the range of 3500 to 6500 K. Under such conditions, the thermal equilibrium dissociation of oxygen molecules may run between 40 to 100 %. This provides the initiation of hydrocarbon oxidation because of thermal energy input as well as the presence of highly active oxygen atoms. The presence of active particles at initial stage of the process may lead to a change in the reaction mechanism.

a) Oxidative conversion of diesel by air

Despite the fact that it is impossible to provide high heating efficiency under partial oxidation of diesel by air under equilibrium conditions, some experiments were carried out using air as the oxidizer. In principle, the combination of partial oxidation reactions with pyrolysis reactions may also produce a product gas with a high heating value.

Experiments were carried out varying diesel hourly mass flow velocity (DHMV), net power input and ratios of O/C. The range of parameters is shown below:

diesel flow rate	0.115 - 0.35	g/s,
net power input	0.7 - 1.6	kW,
DHMV	1 - 2.5	g diesel / g catalyst hour
ratio O/C	0.9 - 1.8	
catalyst	ICI 57-4	

It was found that the maximum concentration of H₂ was produced at an O/C ratio that was in the neighborhood of 1.2. This is shown in Fig. 8. The Hydrogen yield is equal to 65 % under such conditions. Oxidative diesel conversion by air must be accompanied by ethylene formation if

the O/C ratio drops below 1.2. The concentration of methane is approximately three times lower the concentration of ethylene. This is shown in Fig. 9.

Fig. 9. The concentration of H₂ and CO in the reaction products as a function of the ratio O/C

Fig. 10. The concentration of C₂H₄ and CH₄ in the reaction products as a function of the ratio O/C.

The calculation of the reaction products heating efficiency shows that its value gradually increases if the ratio O/C decreases. The maximum value of heating efficiency does not exceed 85 % even though there is considerable C₂H₄ formation and the ratio of O/C is at the minimum value

of 0.92. This is shown in Fig.11. We believe that at a lower ratio O/C ratio a high heating efficiency may be achieved but there may be a serious problem with free carbon formation under when the O/C ratio is less than 1.2-1.3. An increased pressure drop in the catalyst bed has been observed in experiments under these conditions. This is the result of carbon formation in the reactor.

Fig. 11. Heating efficiency of the reaction products as a function of the O/C ratio.

A decrease in the ratio $2O_2/mCmHn$ leads to the formation of light hydrocarbons with a low ignition point. The presence of these compounds in the product gas can produce pre-ignition and knocking during engine operation.

b) Oxidative conversion of diesel by exhaust gas

Oxidative conversion of diesel by exhaust gas (EG) was performed using mixtures of air, steam and carbon dioxide. The mole ratios CO_2/O_2 and H_2O/CO_2 in the experiments approached the theoretical values for combustion reactions with air excess equal to 2 (corresponding to 0.705 and 0.588 respectively).

The experiments were performed using different diesel hourly mass velocity (DHMV), net power input and O/C ratio. The range of the parameters is shown below:

diesel flow rate	0.1	- 0.39	g/s,
net power input	0.4	- 2.2	kW,
DHMV	0,8	- 3.1	g diesel / g catalyst hour
total ratio O/C	1.1	- 2.0	

It was found that diesel conversion by EG occurs in the plasma-catalytic reactor without carbon formation at a ratio of $2 \cdot O_2 / mC_mH_n > 0.9$.

The results of these experiments demonstrate that diesel treatment by EG results in the production gas with a H_2 content up to 19 vol. % and CO up to 22.6 vol. %. The Hydrogen yield is equal to 83 % and carbon monoxide yield is close to 100 % under such conditions. These results of diesel conversion were obtained at a ratio of $2 \cdot O_2 / mC_mH_n = 1.16$. Under such conditions, diesel oxidation occurs mainly because of partial oxidation by oxygen (1) therefore the heating efficiency of the final gas is low (80 %). It should be noted that a good balance of input and output carbon is achieved in this case. It indicates that complete oxidation of diesel compounds to carbon monoxide and carbon dioxide can be achieved and that there are no heavy hydrocarbons in the reaction products.

A change to lower a value of the ratio of $2 \cdot O_2 / mC_mH_n$ leads to a decrease in the production of H_2 and CO and to an increase in the production of hydrocarbons. A small amount of C_2H_4 (up to 3 vol.%) may present in the final gas especially at O/C ratios of less than 0.8, but in all cases the CH_4 concentration does not exceed 0.5 %.

It is known that hydrocarbon conversion by $O_2 - H_2O - CO_2$ mixtures may be considered as a sequence of hydrocarbon combustion and hydrocarbon reforming by H_2O and CO_2 . The final yield of H_2 and CO in real reactors depends on the reaction macrokinetics involving processes of heat and mass transfer in a catalyst bed as well as reactor heat losses. It is necessary to emphasize that reforming reactions are highly endothermic and therefore the reacting gas mixture should be overheated to balance the reactor heat losses and heat consumption by the reforming reactions.

It is clear that an increase in power input will lead to an increase of the initial temperature of the reaction. In our tests, the power input was provided by a plasma generator as well as by the preheating of the H_2O , CO_2 and a portion of air stream. A relatively small part of the experimental reactor is responsible for a large part of the heat losses in the overall heat balance of the reactor. Thus an increase in reactor efficiency leads to a decrease of the relative heat losses in the reactor energy balance.

The influence of the various process parameters on the composition of the reaction products and its heat efficiency is shown in Fig.12-14.

Fig. 12. Concentration of H₂ and CO, heating efficiency in the reaction products as a function of the ratio $2 \cdot O_2 / mC_mH_n$ under various diesel flow rates and preheating temperatures.

Measurements of the axial temperature profile in the reactor demonstrated that higher H₂ and CO concentrations correspond to higher temperatures along the reactor under increased diesel flow rates. This is shown in Fig.15.

Tests show that H₂ and CO concentrations in the reaction products depend on total net power input very significantly as can be seen in Fig.14. The total net input power involves the net power of plasma generator as well as the power of preheated gas. In the experimental results shown in Fig.15, the contribution of the preheating power to the total net power is 27 % at 1.6 kW. The preheating temperature in this case was equal to 340 C. By increasing this temperature to 600 C it is possible to extend the preheating power to 50% thus decreasing the electric power consumption about a factor of two.

It follows from the experiments that the heating efficiency of the reaction product increases with increasing power input and could be as high as 92%. The maximum value of CO₂ production reaches 10 %. At the same time an increase of the catalytic bed temperature by power from the plasmatron may cause the catalyst bed to overheat resulting in a degradation of its performance.

Fig. 13. Concentration of CH_4 and C_2H_4 in the reaction products as a function of the ratio $2 \cdot O_2 / mC_mH_n$ under various diesel flow rates and preheating temperatures.

Fig. 14. Concentration of H_2 , CO , C_2H_4 in the reaction products as a function of the total net power input (plasma generator + gas preheating).

In this program, a nonstationary reagent was used to provide the necessary heating to lower the catalyst bed temperature. Initial catalyst heating was carried out under higher ratio $2 \cdot O_2 / mC_mH_n$. The value of this ratio was chosen to provide the required temperature distribution along the reactor. This value was close to 1.8-2.0. This parameter was controlled by

varying the diesel flow rate while keeping the flow rate of the other reagents constant. When stationary temperature profile was achieved, the diesel flow rate was rapidly increased to the required ratio of $2 \cdot \text{O}_2 / \text{mC}_m\text{H}_n$. The time required for diesel conversion was approximately 15-20 s this provides a small temperature decrease. Under such conditions, the heat required for endothermic reforming was stored in the catalyst bed. This technique provides a significant increase in the temperature of the "reforming" region of the catalyst bed compared with the stationary conditions as can be seen in Fig.17.

Fig.15. Axial temperature profiles in the reactor at various process parameters.

Fig. 16. Dependence of heating efficiency and CO₂ conversion on energy consumption

—□— O/C=1,56 —△— 1,45 —○— 1,34 —◇— 1,45 ▲ 1,45 stat.

Fig.17. Axial temperature profiles in the reactor under various total ratio of O/C in nonstationary regimes.

It was found that an initial heating of the catalyst significantly improves the conversion of diesel by EG. Hydrogen concentration in the product gas increased up to 21-23 vol.% as can be seen in Fig.18, and the hydrogen yield reached 85 – 87 % as can be seen in Fig.19.

Improved heat transfer in the reactor resulted in an increase of CO₂ conversion up to 50 %. As a result, the heating efficiency of the reaction products increased to 90 – 98 % as shown in Fig.20.

Fig.18. H₂ and CO content in the reaction products as a function of the ratio O/C (total) in nonstationary regimes.

Fig.19. H2 and CO yield as a function of the ratio O/C (total) in nonstationary regimes.

Fig.20. Heating efficiency of the reaction products as a function of the ratio O/C (total) in nonstationary regimes.

The nonstationary regime of diesel conversion by EG may be useable only in a research environment. A temperature increase in the lower catalytic bed under stationary conditions may be realized with the use of various modifications to the reactor design.

For example, heat insulation of the reactor should be improved. The use of advanced heat insulation with the lowest heat conductivity such as refractory ultra fine powder (zirconia, alumina) need be tested in association with reactor heating by high temperature reaction products.

Using a metal carrier for the catalyst could increase the heat flux through catalyst bed from the upper combustion zone to the lower reforming zone. Honeycombs made out of metal catalysts having small cell dimensions, as well as porous, permeable metals need to be tested.

Electrical heating of a metal honeycomb with a catalytic deposit could be attractive as well. Such a catalytic reactor has been developed and it may be used effectively in combination with an initial heating of a reagent by the plasma generator.

D. Engine experiments with hydrogen additives

A set of experiments to demonstrate the technology using a Ricardo diesel engine was carried out. The Ricardo is a single cylinder engine, with many diagnostics (NO_x, CO, particulates by particulate mobility sizer).

The engine does not allow the ignition timing to be changed. This is because the injection system is mechanical rather than electrical. In order to change the timing, it is necessary to "slip" the timing chain. It is important to vary the timing because hydrogen has very high flame propagation speeds. Leaving the timing constant results in total combustion of the fuel prior to top-dead-center.

Researchers of MIT Sloan Automotive Lab with coaxing and participation of HMT engineers carried out a limited number of experiments. The technical characteristics and operating conditions are shown in Table 1

Table 1

Engine description

- -Direct injection
- -Single cylinder
- -Two valves
- -Bore: 80.3 mm
- -Stroke: 88.9 mm
- -Displacement: 0.45 liters
- -Compression ratio: 19.8:1
- -Naturally aspirated

Operating Conditions

- -Steady state test
- -2400 rpm (mid-speed)
- -imep: 5.6 bar & 2.4 bar
- -SOI (start of injection) :6.12 CA BTC

The experiments were carried out by port injection of hydrogen, by a capillary tube that released the hydrogen continuously next to the inlet valve. Hydrogen is therefore homogeneously mixed with the incoming air. The engine did not EGR.

We decided to utilize port injection instead of direct injection into the high pressure cylinder because of the great burning properties of hydrogen. Hydrogen has a very high self-ignition temperature, and therefore can be compressed to very high compression ratios without preignition.

Ignition was achieved by the injection of diesel fuel. In the experiments, even in the highest hydrogen cases, substantial energy is still delivered by diesel injection. Therefore, the diesel injection sets the timing of the ignition. The timing was not changed for the cases that were ran, and it was set to start of injection (SOI) at 6 degrees before top-dead-center.

The experimental results shown on Figures 21 and 22 indicate increases in the cylinder pressure with increase of hydrogen in the air-diesel mixture especially at high power. This increase accompanied with increase of the rate of heat release (Fig.23). Hydrogen has a very high flame front propagation velocity, and therefore it is expected that the rate of heat release is larger than in the case of just diesel. In addition, the peak pressure increases, due to the faster heat release rate, at constant thermal power. Delaying the ignition time thus may have a positive effect on the engine efficiency.

These figures and the following ones show for comparison the results for the case of several types of diesel fuels (curves labeled D-377 and DG20).

In the case of operation at 2.4 bar with heavy hydrogen injection, the diesel injection amount was small, and stability of the injection was degraded (too little fuel was being injected). However, it can still be seen that the injection of hydrogen starts faster, but then slows down. It is presumed that not enough diesel is being injected to start the burn, since once the burn starts it is expected that the hydrogen will burn very quickly.

The distribution of particulates for both loads are shown in Figure 24 and 25. These measurements were carried out with the mobility particle sizer MPS from TSI Inc. The particle size distribution from this diesel engine peak at around a hydrodynamic diameter of 120 nm, and closely resembles a normal distribution. Injecting hydrogen decrease the concentration of particulates. For large hydrogen fraction injection (in the case of 2.4 imep) the distribution changes substantially from normal. It is the view of experts in the field (Dr. John Storey, Advanced Propulsion Technology Center of the Oak Ridge National Laboratory who participated in this effort) that the smallest particles in the case of large hydrogen injection are actually water droplets.

Large decreases in the concentration of particulates occur at high injection of hydrogen. Therefore, it seems that the decrease in the particle concentration is mainly a displacement effect, that is, the concentration is proportional to the diesel fuel fraction, and as the diesel fuel fraction decreases, so does the concentration.

Figure 26 and 27 show the corresponding mass distribution as a function of the aerodynamical diameter. This is assuming that the density of particulates is constant (both small and large particulates have similar mass concentration). The decrease of mass occurs throughout the range of particles.

Finally, Figure 28 shows the total mass reduction and volume reduction as a function of the hydrogen addition for the case of 5.6 bar imep. The case with imep 2.4 bar indicates a factor of 10 reduction for 80% hydrogen addition.

The total number and total volume of particulates decreases to a first approximation linearly with hydrogen addition (Fig.24-28). Large amounts of hydrogen correspond to larger decreases in the number of particulates (about 1 order of magnitude for 85% of fuel as hydrogen). This effect is being attributed to the displacement of carbonaceous fuel by hydrogen.

Therefore, it was demonstrated that both the mass and the concentration of particulates decrease. It decreased by an order of magnitude in the case of large hydrogen addition, even in the absence of changes in timing.

In the next section, the effects that are expected in the case of changes in timing demonstrate that even larger decrements of particulate concentration can be achieved!

Figure 21. In-cylinder pressure as a function of crank angle for diesel and different amounts of hydrogen addition, for imep 5.6 bar.

Figure 22. Same as 21, but for imep 2.4 bar.

Figure 23. Rate of Heat Release (ROHR) as a function of crank angle for diesel and different amounts of hydrogen addition (corresponding to Figure 21)

Figure 24. Particulate size distribution, for the case in Figure 21, as a function of aerodynamic diameter, for the case of Figure 21

Figure 25. Particulate size distribution, for the case in Figure 22, as a function of aerodynamic diameter, for the case of Figure 22

Figure 26. Volume concentration distribution for the case of Figure 24

Figure 27. Volume concentration distribution for the case of Figure 25

Figure 28. Total mass and total volume reductions as a function of hydrogen addition, for imep 5.6 bar

E. Advanced method of operation with hydrogen gas addition

The engine tests carried out in the section described above were performed with constant injection timing. The possibility of changing the injection timing, and the greatly improved performance made possible by changing the timing, are briefly described in this section. The one difficulty of this approach, namely operation at high load and rpm is difficult, can be substantially decreased with hydrogen addition. The use of homogeneous charge injection, where both hydrogen and diesel are injected in the engine, are described in this section. Hydrogen in this case may be used only as an additive, to improve the combustion of diesel under conditions of high power and high rpm.

A new combustion concept that simultaneously reduces NO_x and smoke levels in diesel exhaust by combining low-temperature combustion with premixed combustion has been previously developed. [Kimura]

The low-temperature combustion is accomplished in this concept by applying heavy exhaust gas recirculation (EGR) to reduce the oxygen concentration. In order to decrease a high smoke level usually accompanied reduced oxygen concentration the low-temperature combustion was combined with premixed combustion.

Sufficient mixing time is secured by prolonging the ignition delay, which was accomplished by a retardation of the fuel injection timing. Additionally, a higher swirl ratio is generated to suppress the formation of unburned HC and to reduce cooling losses.

The tests conducted with a multi-cylinder engine verified that MK combustion could be achieved in the low-load region. In the high-load region where the EGR gas temperature rises, MK combustion cannot be accomplished because the ignition delay is shortened.

In trying to apply MK combustion to the high-load region, it is predicted that two problems will have to be resolved. The first problem is that ignition delay is shortened by the higher temperature of the EGR gas. The second problem is that the injection duration is prolonged by the greater quantity of fuel injected. The multiplied effects of these two problems make it impossible to complete the injection of all fuel prior to ignition, which is one of the necessary conditions for accomplishing premixed combustion.

Hydrogen injection may solve this problem. This mode of operation is desirable because both particulate and NO_x emissions are decreased by about one order of magnitude. This mode of operation with diesel fuel and hydrogen injection will be tested in PHASE II with heavy EGR.

F. System optimization

Since the proposal was written, substantial decreases in the required electrical power requirements for the plasmatron fuel converters have been obtained, by using a low power, low current plasmatron. This device has been shown to operate equally well with diesel as with gasoline and natural gas.

Operation with the low power plasmatron decreases the needs for converting exhaust heat into electricity. This is because the electrical power is so low that it constitutes only a very small parasitic load on the system.

To minimize the required exothermicity of the reaction an efficient heat exchanger needs to be utilized. In the experiments, a poor man's heat exchanger was used to preheat the gas. The efficiency of the heat exchanger (change in enthalpy of the air/EGR gas divided by thermal power out from the plasmatron fuel converter) was on the order of 7-10%. Much higher efficiencies can be obtained by using novel and larger heat exchangers.

In the following section, the impact of the use of a heat exchanger on the required electrical power is described. The analysis is carried out for the case of partial oxidation.

Partial Oxidation with heat recovery

With the use of a heat exchanger, the thermal enthalpy of the reformat can be used to preheat the air, diesel fuel or their mixture prior to injection into the plasmatron. In this way net external heating requirements from the plasmatron can be reduced. Thus the parasitic losses of the system can be considerably decreased.

The net effect is that of reducing the required electrical energy in the reforming process. For a fixed reactor temperature of 1500K, Figure 29 shows the value of R as a function of the temperature of the feedstock, T_{initial} . R is the ratio between the chemical energy leaving the plasma reformer and the thermal energy externally added to the reforming reaction in the plasmatron. At about 900 K the value of R is about doubled, corresponding to a reduction of about a factor 2 in the energy required from the plasmatron.

The overall system efficiency, for a reactor temperature of 1500 K increases with the initial temperature of the feedstock. The increase in the efficiency is approximately linear with the temperature. The maximum amount of regeneration from the reformat of the plasmatron in a heat exchanger occurs when the temperature primary and secondary are comparable. Since the flows are comparable, if the entire products are used to preheat the entire feedstock, then the maximum temperature of the feedstock is about 900 K.

Figure 29 R as a function of the initial feedstock temperature, for a final reformat temperature of 1500 K.

This analysis assumes that the entire feedstock mixture was raised in temperature. This may have the problem that the hot feedstock may react prior to the reactor. Therefore, it would be preferable to heat exclusively the air, with the hydrocarbon injected separately at lower temperatures.

G. Commercialization issues

In a parallel effort to its technical research, HMT is developing a plan to commercialize the plasma fuel converter (PFC) system. The Company has drafted a comprehensive business plan, and has initiated contact with potential investors. HMT has also initiated discussions with potential strategic partners with expertise in diesel engine management. HMT plans on securing an arrangement with a strategic partner by December 2000. The Company would then work closely with the partner to conduct extensive testing and to optimize the PFC in the overall fuel management system for diesel engines. This process could be completed by December 2001 and fully optimized systems could be available at this point. In one scenario, HMT would license its PFC technology to the strategic partner and would provide extensive technical consulting services. Alternatively, the Company would explore opportunities to outsource production of the PFC systems to a capable auto parts supplier and would sell directly to the major diesel engine and truck manufacturers. With an aggressive schedule, the PFC could be a standard component on MY 2003 diesel trucks.

HMT remains optimistic about the commercial potential of the technology. At this time, diesel engine manufacturers in the U.S. are under significant pressure to develop new engine systems with significantly lower emissions. One reason for this pressure is a lawsuit which was settled in 1998. In October 1998, the Department of Justice and the EPA announced a settlement with seven major diesel manufacturers, which allegedly circumvented regulations aimed at limiting emissions from diesel engines. Under the settlement, the manufacturers will pay \$83.4 million in civil penalties, the largest civil penalty ever for an environmental violation. The manufacturers will also spend more than \$850 million to produce significantly cleaner engines. Engine emissions will be reduced by 50 percent by January 1999 and by 80 percent on October 2002. Finally, the manufacturers will spend \$109.5 million for additional environmental projects like development of new emission control technologies.

A second force driving the need for new anti pollution technologies is a set of strict new regulations recently announced by the EPA. In October 1999, the EPA unveiled plans to reduce diesel emissions in a two-step process. By 2004, the combined emissions of hydrocarbon and NOx of all diesel engines weighing over 8500 pounds must be reduced by 50 percent. According to EPA estimates, the resulting increase in engine costs would be about \$700 per class 8 engine and \$600 for a medium duty engine. By 2007, the EPA plans to reduce NOx emissions by 75 to 90 percent compared to 2004 levels.

These new emission standards have created a very attractive market for new diesel exhaust after-treatment technologies. Diesel engine manufacturers have been able to reduce emissions through new engine designs and other incremental improvements. However, there is a limit to the emissions reductions that can be derived from these improvements. The aggressive new standards cannot be met without incorporating new anti-pollution innovations in diesel systems.

The attractive market for new technologies may extend to the millions of diesel vehicles sold annually in Europe and Japan. Diesel engine manufacturers in Japan are under enormous pressure from strong public opposition. In fact, the governor of Tokyo recently initiated a campaign to "Say No! to Diesel Vehicles". Tokyo is calling on the central government to speed development of emission control devices and mandate their use in diesel vehicles. The city is also calling for an acceleration of the scheduled to implement new diesel exhaust emission standards.