

Electrorheology Leads to Efficient Combustion

R. Tao,* K. Huang, H. Tang, and D. Bell

Department of Physics, Temple University, Philadelphia, Pennsylvania 19122

Received June 20, 2008. Revised Manuscript Received August 4, 2008

Improving engine efficiency and reducing pollutant emissions are extremely important. Here, we report our fuel injection technology based on the new physics principle that proper application of electrorheology can reduce the viscosity of petroleum fuels. A small device is thus introduced just before the fuel injection for the engine, producing a strong electric field to reduce the fuel viscosity, resulting in much smaller fuel droplets in atomization. Because combustion starts at the droplet surface, smaller droplets lead to cleaner and more efficient combustion. Both laboratory tests and road tests confirm our theory and indicate that such a device improves fuel mileage significantly. The technology is expected to have broad applications, applicable to current internal combustion engines and future engines as well.

1. Introduction

It is more and more urgent and important now to improve engine efficiency and reduce pollutant emissions. While some progress in this area has been made since fuel injection technology was developed, internal combustion engines are still a long way from being clean and efficient.

Because combustion starts at the interface between fuel and air and most harmful emissions are coming from incomplete burning, reducing the size of fuel droplets would increase the total surface area to start burning, leading to a cleaner and more efficient engine. This concept has been widely accepted because the discussions about the future engine for efficient and clean combustion are focused on ultra-dilute mixtures at extremely high pressure to produce much finer mist of fuel for combustion.^{1–3} Along this direction, for example, the Delphi Company plans to develop a new fuel injector that uses a high pressure of 100 bar to reduce the size of gasoline droplets to 25 μm in diameter. Although 100 bar is not extreme pressure yet, this injector, known as the Delphi Multec 10 GDI multi-hole fuel injector,⁴ would require substantial changes of the fuel lines in vehicles, because current gasoline vehicles can only sustain a fuel pressure less than 3 bar.

Unfortunately, the new combustion technology with extreme pressure is still under development and not applicable to current engines because they cannot sustain such high pressure.

Another possible technology is electrostatic atomization, which makes all fuel droplets negatively charged.^{5–7} The droplet

size will be small if the charge density on the droplets is high, and no agglomeration would occur because the negatively charged droplets repel each other. Up to date, electrostatic atomization technology has not been employed on any fuel system, not to say any vehicles. The main reason is that electrostatic atomization technology requires special fuel injectors, which are totally different from any existing fuel injectors on vehicles. It requires a high voltage directly applied to the nozzle and the emitter cathode emitting negative charges to pass the fuel to the anode. To employ such a fuel injector on vehicles is not easy. There are also concerns that such sprays may consume high electric power.

Here, we present our technology for efficient combustion based on the new physics principle that proper application of electrorheology can reduce the viscosity of petroleum fuels. A small device is thus introduced, producing a strong electric field to reduce the viscosity of petroleum fuels just before the fuel atomization. This viscosity reduction leads to much smaller fuel droplets and cleaner and more efficient combustion. Our device could be easily applied on current engines to improve their efficiency. Both laboratory and road tests confirm our theory and indicate that such a device improves fuel mileage significantly. The technology is expected to have broad applications, to current internal combustion engines and future engines as well.

2. Theory and Experiments

2.1. Reducing Viscosity of Refinery Fuels. The principle of our device is sketched in Figure 1. The fuel flows through two metallic meshes before it reaches the fuel injector. A voltage is applied on the two meshes to produce an electric field of around 1.0 kV/mm between the two meshes. The device consumes very low electric power, lower than 0.1 W. In our setup, the field direction is opposite the flow direction, which may help to provide negative charges to the fuel droplets. However, the main function of our device is to reduce the viscosity of the fuel as it passes the electric field.^{9,10}

* To whom correspondence should be addressed. Fax: 215-204-5652. E-mail: rtao@temple.edu.

(1) Aoyagi, Y.; et al. Advanced diesel combustion using of wide range, high boosted and cooled EGR system by single cylinder engine. SAE Tech. Pap. 2006-01-0077, 2006.

(2) Hiroshi, M.; et al. The potential of lean boost combustion. FISTA World Automotive Congress, Barcelona, Spain, May 23–27, 2004.

(3) Pirault, J. A.; Klippenstein, S. J. *J. Phys. Chem. A* **2006**, *110*, 10528–10544.

(4) <http://delphi.com/manufacturers/auto/powertrain/gas/injsys/homogenous/>, 2008.

(5) Kelly, A. J. Electrostatic atomization—Questions and challenges. *Inst. Phys. Conf. Ser.* **1999**, *163*, 99–107.

(6) Kelly, A. J.; Avva, R. K. *Aerosol. Am.* **1998**, 22–23.

(7) Okuda, H.; Kelley, A. J. *Phys. Plasmas* **1996**, *3*, 2191–2196.

(8) Lehr, W.; Hiller, W. *J. Electrostat.* **1993**, *30*, 433–440.

(9) Gordon, D. G. *J. Appl. Phys.* **1959**, *30* (11), 1759–1761.

(10) Lefebvre, A. H. *Atomization and Sprays*; Taylor and Francis: Oxford, U.K., 1989; pp 27–73.

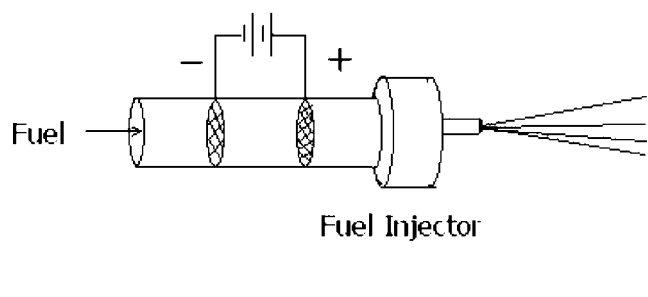


Figure 1. In the device, the fuel flows through two metallic meshes before it reaches the fuel injector. A voltage is applied on the two meshes to produce an electric field of about 1 kV/mm between the two meshes.

Proper application of electrorheology or magnetorheology can reduce the viscosity of liquid suspensions.^{11,12} According to the Krieger–Dougherty formula,^{13,14} the effective viscosity of a liquid suspension η is related to the viscosity of base liquid η_0 by

$$\eta = \eta_0(1 - \phi/\phi_m)^{-[\eta]\phi_m} \quad (1)$$

where ϕ is the volume fraction of suspended particles, ϕ_m is the maximum volume fraction to pack particles randomly, and $[\eta]$ is the intrinsic viscosity, related to the particle shape. For example, $[\eta] = 2.5$ for spherical particles.

Using the mismatch in the dielectric constant or magnetic permeability between the suspended particles and the base liquid, we can apply an electric or magnetic field to aggregate the small particles into large ones. Normally, we aggregate nanoscale or sub-micrometer particles into micrometer particles. While this change in rheology does not alter ϕ , it makes ϕ_m increased as a result of the increase of polydispersity and average particle size.^{11,12} Hence, the effective viscosity η is reduced from eq 1. The experiment with crude oil has found that this reduction can be quite significant.¹¹

Here, we extend the above physics principle to refinery fuels. In fact, refinery fuels, such as diesel fuel and gasoline, are made of many different molecules. They can be regarded as liquid suspensions if we take the large molecules as suspended particles, and the base liquid is made of small molecules. Under a strong electric field, the induced dipolar interaction makes the large molecules aggregate into small clusters. Similarly, this change reduces the effective viscosity of refinery fuels.

The above theory was verified by our experiment. As shown in Figure 2, after application of an electric field of 1 kV/mm for about 2 s, the viscosity of the diesel oil is reduced by about 9%; it was down from 4.6 to 4.18 cP. Afterward, the diesel viscosity is increasing. However, it takes quite a while for the viscosity to return to the original value. This provides the opportunity to improve fuel atomization.

2.2. Finer Mist in Fuel Atomization. Reducing the fuel viscosity improves the fuel atomization. As shown in Figure 3, the injected fuel has a pressure higher than that in the combustion chamber. The droplets are thus split, becoming smaller and smaller after they are emitted from the nozzle. If the droplets are allowed to reach the equilibrium, their radius is given by

$$a = 2\gamma/\Delta P \quad (2)$$

where γ is the surface tension of the fuel and $\Delta P = P_i - P_o$ is the pressure difference between the inside pressure P_i and the outside pressure P_o of the fuel. However, in reality, the fuel droplets can never reach equilibrium because the viscosity acts against any

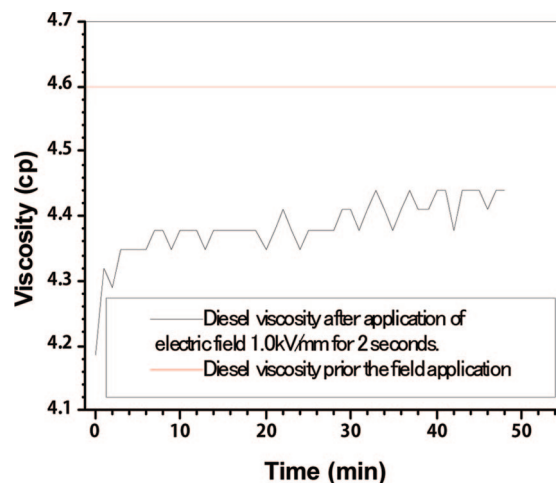


Figure 2. Diesel viscosity is reduced by 9% after application of an electric field of 1 kV/mm for 2 s, from 4.6 to 4.18 cP. Afterward, the viscosity is rising to return to the original value.

deformation of the droplets. The following fact illustrates this issue: Diesel fuel and gasoline have almost the same surface tension, about 10 dyne/cm. When $\Delta P = 2$ bar, a is about $0.1 \mu\text{m}$ for both fuels from eq 2. However, in fuel atomization, neither gasoline nor diesel fuel could have droplets as small as $0.1 \mu\text{m}$. In addition, under the same pressure, the average size of diesel fuel droplets is much bigger than the average size of gasoline droplets, because diesel fuel has much higher viscosity than gasoline. Therefore, reducing the viscosity of the fuel greatly improves the fuel atomization.

Our spray experiment further confirms the above theory. We used an Accel high impedance fuel injector to simulate fuel injection at engine chambers. When the device was on, the fuel took about 5 s to pass the electric field. The spray lasted for 4 ms. The droplets were collected by a plate, covered with a thick layer of oxidized magnesium. Once the droplets were collected, the plates were scanned by a high-resolution scanner and the droplet size distributions were then analyzed. This method was widely used in the study of droplet size distribution of fogs and clouds. Because the oxidized magnesium layer is soft and thick, there was no spreading of the droplets on the plates. In addition, our plates were placed at a distance sufficiently away from the injector to make sure no overlapping of droplets occurred. The plates were square, about 10×10 cm, which was large enough to collect all of the droplets in one spray. Shown in Figure 4 is a typical recording of collected droplets, which shows no overlapping and spreading of the droplets. While this method is much slower than the optical scattering method, which only makes sampling from a small portion of the droplets, this method collected and recorded all droplets during the injection.

The statistical results for diesel fuel are in Figure 5a, while the results for gasoline with 20% ethanol are in Figure 5b. All of them are averaged over 50 tests. The repeatability was quite good, with an error less than 5%. In both experiments with diesel fuel and gasoline, the current was less than $10 \mu\text{A}$; i.e., the electric power consumption is below 0.1 W.

For diesel fuel, the fuel pressure was 13.79 bar (200 lb./in.²) and the electric field was about 1.0 kV/mm in the experiment. As seen in Figure 5a, the electric field increased the number of droplets with a diameter of less than $40 \mu\text{m}$ dramatically. Especially, when the device was on, the number of droplets of diameter below $5 \mu\text{m}$ was increased from 5.3 to 15.3%. The effect on diesel fuel is very significant.

In the experiment with gasoline (with 20% ethanol), the fuel pressure was 7.59 bar (100 lb./in.²) and the electric field was 1.2 kV/mm. The effect on gasoline is also significant. Especially, when

(11) Tao, R.; Xu, X. *Energy Fuels* **2006**, *20*, 2046–2051.

(12) Tao, R. *Int. J. Mod. Phys. B* **2007**, *21* (28 and 29), 4767–4773.

(13) Russel, W. B.; Saville, D. A.; Schowalter, W. R. *Colloidal Dispersion*; Cambridge University Press: Cambridge, U.K., 1989; pp 456–503.

(14) Krieger, I. M.; Dougherty, T. J. *Trans. Soc. Rheol.* **1959**, *3*, 137–152.

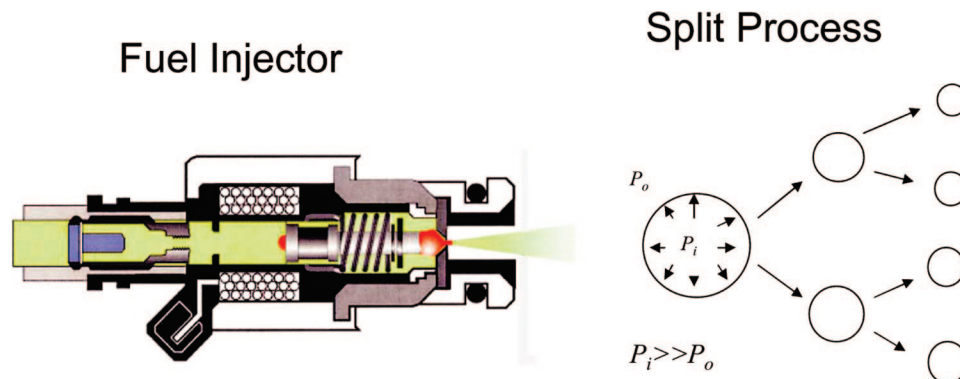


Figure 3. Emitted droplets from a fuel injector split to become smaller and smaller.

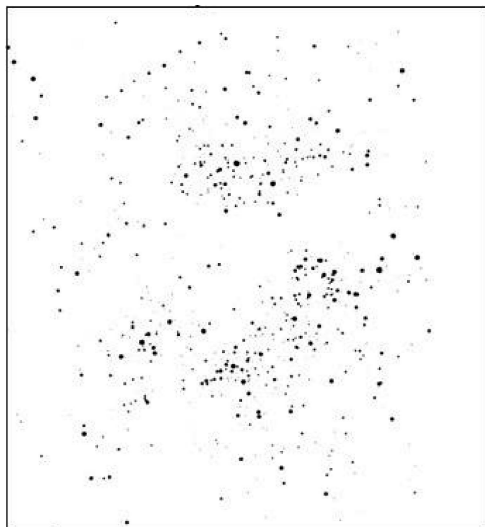


Figure 4. Typical plate with collected sprayed droplets.

the device was on, the number of droplets with a diameter around $10\ \mu\text{m}$ was increased from 17.6 to 20.7%, an increase of 18% (Figure 5b).

3. Test Results

Because the spray experiment suggests that diesel engines would significantly benefit from our device, we conducted extensive tests with our device on diesel engines. The first engine test was conducted by Cornaglia Iveco, a diesel engine manufacturer in Italy (Figure 6a). The tests measured the fuel consumption rate and the power output at a constant rpm. The results in Table 1 are averaged over measurements for 1 week, with an error bar of 2%. At 1900 rpm, the original brake-specific fuel consumption (BSFC) was $220.1\ \text{g}\ \text{kW}^{-1}\ \text{h}^{-1}$; with our device, it was reduced to $208.7\ \text{g}\ \text{kW}^{-1}\ \text{h}^{-1}$. Because diesel fuel has a heating value of $0.119\ 531\ \text{kW}\ \text{h}\ \text{g}^{-1}$, the engine efficiency was increased from 38.0 to 40.1% (a 5.5% improvement with our device). It is interesting to note that when the applied electric field direction was parallel to the fuel flow direction, the device still improved the BSFC by 4.7%, which is 0.8% lower than that in the case when the electric field direction was opposite the fuel flow direction. This could be due to some electrons attaching to the fuel droplets, which further reduced the droplet size, when the electric field direction is opposite the fuel flow direction.

The emission tests also show that our device reduces the NO_x emissions on the diesel engine. For example, at 1900 rpm, NO_x emissions were down from 570 to 550 ppm. The error of the test device is 1%.

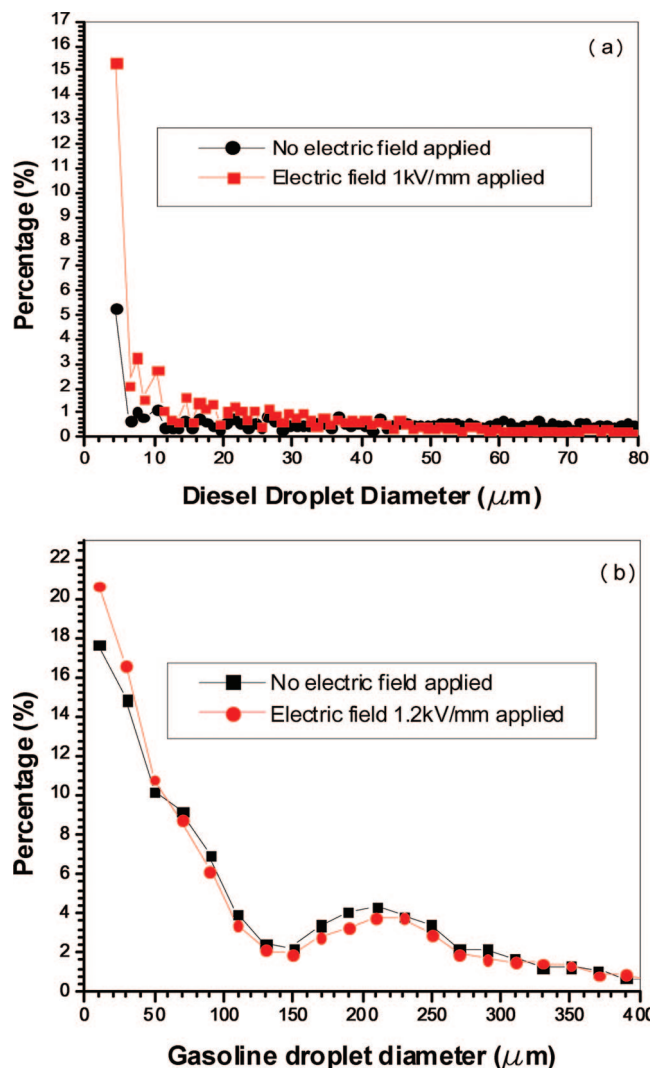
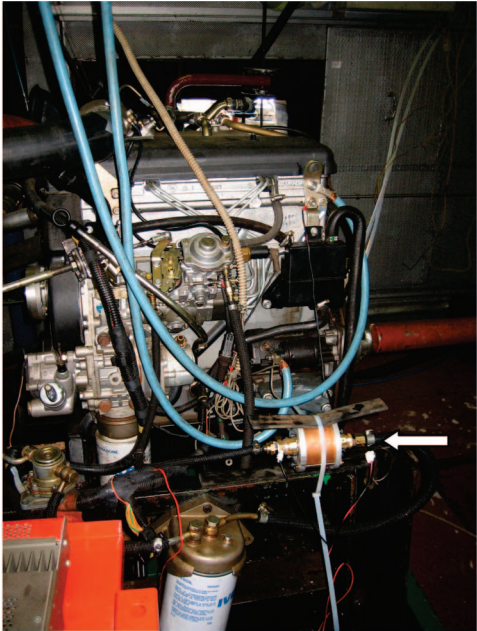


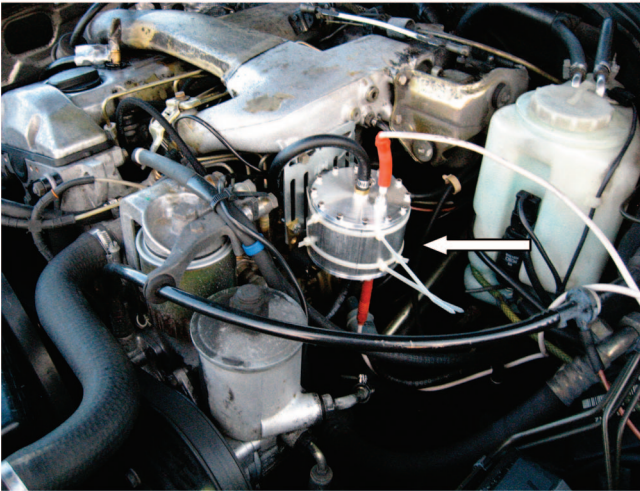
Figure 5. (a) Size distribution of diesel fuel following atomization with or without an applied electric field. (b) Size distribution of gasoline (with 20% ethanol) following atomization with or without an electric field.

The results of the Cornaglia Iveco test were not bad but below the expectation from our spray experiments. Therefore, we revised our device afterward. In the Cornaglia Iveco tests, the applied electric field was close to 1.3 kV/mm. At 1900 rpm, the diesel fuel flowed through the electric field in about 1 s. If the diesel fuel could stay inside the electric field slightly longer, the improvement can be enhanced.

Our recent tests have been performed on a Mercedes-Benz 300D, diesel sedan (Figure 6b). The device on the Mercedes-



(a)



(b)

Figure 6. (a) Installation of the device on the Cornaglia Iveco diesel engine. (b) Installation of our device on Mercedes-Benz 300D, a diesel sedan.

Table 1. Average Test Results at Cornaglia Iveco

	RPM	power (kW)	fuel consumption (kg h ⁻¹)	BAFC ^a (g kW ⁻¹ h ⁻¹)	efficiency (%)	improvement (%)
baseline	1900	54.7	12.04	220.1	38.0	
1.3 kV/ mm	1900	53.9	11.33	220.1	39.8	4.7
1.3 kV/ mm ^b	1900	54.2	11.31	208.7	40.1	5.5

^a BAFC is the brake-specific fuel consumption. In calculation of engine efficiency, the heating value of diesel fuel is 0.119 531 kW h g⁻¹. ^b The electric field direction is opposite the fuel flow direction.

Benz 300D has two mesh electrodes separated by 1 cm. The diesel fuel takes 5 s to pass through the electric field between the two electrodes. The field is about 1 kV/mm.

The typical laboratory test result of the Mercedes-Benz with a dynamometer is shown in Figure 7. At a fixed fuel consumption rate close to 500 g/h, the dynamometer measured the engine

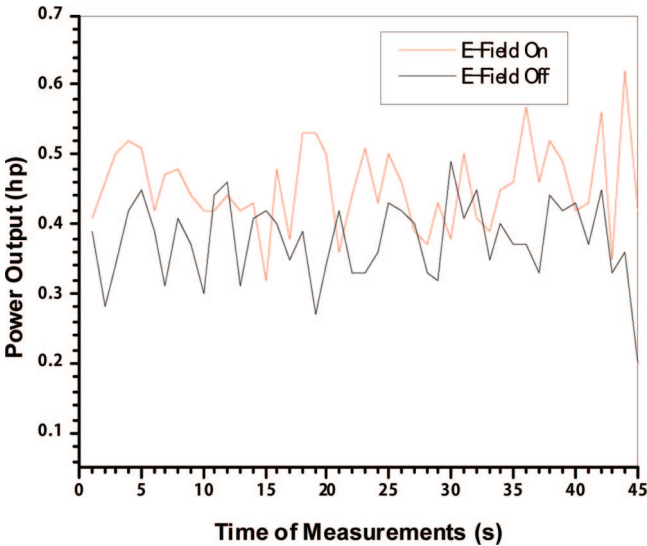


Figure 7. Laboratory test of Mercedes-Benz 300D with a dynamometer. The average power output was originally about 0.368 hp and increased to 0.443 hp after the device was turned on.

output. When the device was turned off, the average power output was 0.3677 hp. It increased to 0.4428 hp after the device was turned on. This indicates that the power output was improved by about 20.4% at the same fuel consumption rate. In other words, if the engine on the road is under the same condition as our laboratory test with the dynamometer, the fuel mileage will be increased by 20.4%. The laboratory test was repeated for 3 h and had an error within 5%.

A continuous road tests of the Mercedes-Benz 300D for 6 months showed that our device increased the fuel mileage significantly. On the highway, the device increased the fuel mileage from 32 miles per gallon (mpg) to 38 mpg. In city driving, the improvement of fuel mileage was not as good as that on the highway but was averaged at 12–15%.

4. Discussion

A comparison between the Cornaglia Iveco tests and the recent tests with the Mercedes-Benz indicates that there are optimal values for two parameters, the applied electric field strength and the time duration for the diesel fuel to pass through the electric field. The device with the Mercedes-Benz has 1 kV/mm field strength and 5 s time duration, which are better than that of 1.3 kV/mm and 1 s, used for the Cornaglia Iveco tests. There may still be some room to improve our device by adjusting these two parameters.

There are a couple of other alternatives to increase fuel efficiency, such as adding additives to the fuel to reduce the viscosity. Unfortunately, these fuel additives are quite expensive. The extremely high fuel pressure method, as mentioned before, is still under development and not applicable to current engines.

Because our technology, developed on the new physics principle, consumes very small power and improves fuel efficiency significantly, we expect it will have wide applications on all types of internal combustion engines, present ones and future ones. By adjusting the values for the electric field and time duration, we could make this technology work effectively for other fuels, such as biodiesel, kerosene, and gasoline.

Acknowledgment. This work was supported in part by RAND and STWA.

EF8004898