

# NEW CONCEPTS IN OCTANE BOOSTING OF FUELS FOR INTERNAL COMBUSTION ENGINES

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## ABSTRACT

The holy grail of the combustion of fuels in internal combustion engines is the perfect mixture of fuel and air. This ideal state will allow complete combustion at a uniform rate, delivering optimal power with no harmful emissions under all operating conditions. A primary objective of engine builders is to achieve engine designs that will produce a uniform distribution of very-small-diameter fuel droplets, said to be crucial to forming a mixture approaching perfection. When high molecular weight polymers are added to hydrocarbon fuels at low ppm levels, the viscoelasticity manifested during the stress of carburetion or injection precludes the formation of large numbers of fine droplets. The average droplet size of such fuels, aerosolized in air, is measurably larger than the droplets sprayed with neat fuels, and the size distribution is narrowed. Moreover, the number of droplets below the upper threshold for explosive combustion is greatly reduced. Such polymer-fortified fuels burn at substantially lower average temperatures, thereby increasing the octane rating of the fuel, the efficiency of combustion, and the power delivered to the crankshaft.

## INTRODUCTION

The combustion of hydrocarbon (HC) fuel in internal combustion (IC) engines is an extremely complex event, encompassing many variables, and far from being completely understood. It is a phenomenon which is readily characterized by the adage, "The less known about a scientific or engineering process, the more measurements required to define it." In support of this view, a partial listing of topics on the combustion of gasoline in IC engines, which appeared in publications of the Society of Automotive Engineers over the last decade, includes: the properties of spray from an injector, the location and focusing of injectors, the time of injection relative to intake valve position, the flow of the air/fuel mixture in the induction channel, the liquid fuel films on the walls of the induction channel and the intake valve, the vaporization of droplets in the induction channel, the vaporization of the wall film in the induction channel, the atomization of the wall film from the induction channel caused by air flow, the fuel species which comprise the wall film of the induction channel, the effects of viscosity and surface tension on the air-stripping of fuel from the wall film of the induction channel, the fuel from one injection remaining in the induction channel through multiple cycles, the condition of the air/fuel mixture in the cylinders, the liquid fuel film on the walls of the cylinders, the spatial distribution of the fuel species in the gas in the cylinders, the effects of swirl and tumble motions in the cylinders, the presence of liquid fuel at the end of compression, the stratification of the fuel/air charge, the air/fuel ratio at the spark plug, the condition of the air/fuel mixture at ignition, the carryover of unburned fuel in the cylinders from the previous exhaust stroke, and the charge temperature. Many of these factors have been investigated over a range of operating conditions and then related to ignition, inflammation, rate of heat release, burning time, mean effective pressure, cycle variability, end-gas temperature, knock, emissions and volumetric efficiency.

The segment of the combustion process addressed in this paper is the air/fuel mixture preparation, a critical component of the overall process, which affects virtually all of the variables listed above. The air/fuel mixture preparation involves the introduction of the gasoline into the induction system from a carburetor or an injector, the mixing of the air and fuel in the induction channel, the transport of the air/fuel mixture into the cylinder during the intake stroke, the compression of the mixture, and the condition of the mixture at the time of ignition.

It is the physical properties of the gasoline which constitute the greatest single barrier to providing an optimal air/fuel charge at the spark plug at the time of ignition. A description is given here, and a model is proposed, for the manner in which polymers alter the physical properties of gasoline droplets. Polymers improve the combustion process, and lead to increases in fuel octane rating, power production and volumetric efficiency, as well as substantial emissions reductions. Analogous benefits have been found with low ppm concentrations of polymers in diesel fuel, burned in both large and small diesel engines, where the release of black particulates is greatly diminished. The most dramatic improvements have been recorded with the

polymer-fortified fuels used in two-cycle engines, where the usual raw-gas emissions are significantly curtailed and noise is abated.

## EXPERIMENTAL

### VISCOELASTICITY

When elastomers of molecular weight, sufficient to impart a viscoelasticity at low concentrations, are added to gasoline, a hydrodynamic control is conferred upon the fuel. A quiescent viscoelastic fluid acts as an ordinary liquid. Under sudden stress, the liquid exhibits greatly increased viscosity and solid-like elastic properties. The effect of viscoelasticity on the aerosolization of fuels is shown in Figure 1, where an antimisting function,  $P/(P - R)$  is plotted against both the molecular weight and the concentration of polyisobutylene in diesel fuel at 20° C (●).  $P$  is the quantity per minute of liquid pumped through a paint sprayer;  $R$  is the quantity of liquid recovered in a line-of-sight vessel, positioned two meters from the sprayer (1). In a correlative experiment, the function,  $h/c$ , is plotted against the molecular weight of polyisobutylene in toluene at 20° C (○). The term,  $h$ , is the height to which a thin stream of viscoelastic solution may be stretched before separation occurs, and  $c$  is the concentration (2).

Polyisobutylene, of molecular weight 7.2 Md, was used in all of the measurements reported here.

### TEMPERATURE

Table 1 contains measurements recorded at the D.A.M. engine lab in Dutchess County, NY, on a four-cycle, single-cylinder Briggs & Stratton gasoline engine. The fuel contained 10 ppm of polymer. The data are representative of the temperature decreases observed in both gasoline and diesel engines using polymer-fortified fuels. A relation developed between the temperature of the unburned gas in a gasoline engine and the octane requirement, measured on a 2.2 liter, 4-cylinder, Chrysler production engine, is that for each 7° K increase in unburned gas temperature, the octane requirement of the fuel increases by a single unit (3). If a substance decreases the operating temperature of an engine, this is tantamount to increasing the octane rating of the fuel-in-use. Such a substance would not necessarily exhibit an octane increase when tested at constant temperature.

### POWER

In Figure 2 are presented test data recorded on a 1990 turbodiesel Toyota Landcruiser with a 400,000 km odometer reading, in Perth, Australia. The dynamometer measurement of horsepower (BHP) was first determined without polymer in the fuel. The peak BHP was 95.7. Polymer was added to achieve a concentration of 10 ppm, and the vehicle was returned four days later for testing. The 107.2 BHP recorded represents a 12 % increase in power attributable to the polymer [in order to save space the neat fuel value was traced into Figure 2 from the DYNO DYNAMICS dynamometer graph].

### EMISSIONS

As a consequence of the overall decrease in operating temperatures, and the control of the droplet size and size distribution, the emissions of the routinely-monitored pollutants from gasoline engines are reduced substantially by the addition of 10 ppm of polymer to the gasoline. The first three entries in Table 2 were measured by engineers from SNAP-ON TOOL INC., in Richmond, VA; the last two were determined at an official State of Virginia testing facility in Fairfax County, VA.

### TRANSIENTS

The values given in Figure 3 were measured by engineers from EG&G AUTOMOTIVE RESEARCH, INC., in San Antonio, TX, on a 1985 Nissan 300 ZX, with a gasoline engine and an odometer reading of 180,000 miles. The dark bars show the mass of neat fuel required to attain a given MPH; the light bars, the mass of fuel containing the polymer at 10 ppm required to reach comparable speeds. The polymer has a profound effect on the efficiency of combustion during accelerations, where engines are least efficient, and the emissions of pollutant species are greatest---the conditions frequently met in urban driving.

### PARTICLE SIZE AND DENSITY

Figure 4 shows photographs of aerosols, produced by a paint sprayer, taken at the University of Dayton, Dayton, OH. The probing technique used was laser light scattering. In order to avoid a possible explosion from the mist, which would be produced with raw gasoline, water and an aqueous solution of high molecular weight polyethylene oxide were sprayed. The solution was identical in viscoelastic properties to a solution of polyisobutylene in gasoline at 10 ppm, measured with the ductless siphon (2). The dark region depicts water, with its high density of minute droplets; the light region shows the droplets from the polymer solution. The marker is a 50-micron copper wire.

## DISCUSSION

Gasoline contains species which vaporize at different rates, at a given temperature. In neat fuel, the "light" ends vaporize more rapidly, and concentrate near the spark plug at ignition. The "heavy" ends dominate the liquid films in the induction channel, and on the cylinder walls, and remain further from the spark plug at ignition. The "light" paraffin molecules burn more rapidly than the "heavy" aromatic molecules. The ignition of the "light" molecules causes an early

temperature spike which dissociates Nitrogen molecules and generates  $\text{NO}_x$ . The predominance of the “heavy” ends in the unburned fuel causes a relatively slow flame-front advance, and these ends may persist beyond exhaust valve opening. This model leads to: knock, poor effective pressure, unburned HC, CO, partially oxidized HC,  $\text{NO}_x$  and particulates.

The viscoelastic effect displayed in Figure 1 demonstrates that, at sufficiently high molecular weight, the polymer is a strong deterrent to mist formation. Very little fuel is lost at the higher concentrations sprayed. In usable fuels, the concentration is two orders of magnitude lower, so the polymer can permit appropriate droplet formation. The polymer is able to achieve the beneficial results reported here by limiting the population of very-small-diameter droplets (Figure 4). In addition, the droplets formed possess a certain toughness. The larger size, and inelastic structure, provide the momentum for further penetration of the fuel droplets into the faster moving air mass, thereby producing an air/fuel mixture closer to the ideal. Moreover, under stress, the polymer conveys to the droplets a surface viscoelasticity which increases the surface tension, and limits the vaporization of the “light” ends from the droplets throughout the stress, and until such time as the polymer molecules relax. The composition of the fuel droplets should remain relatively uniform during the relaxation. As the droplets are heated, at the point of relaxation, the vaporization of all species, through the surface film, is likely to be spontaneous, leading to a more uniform distribution of the various gaseous species in the air/fuel mixture.

The polymer-containing fuels reduce the temperature, as reported in Table 1, and result in antiknock activity and an octane increase. This suggests that a more homogeneous blend exists at ignition, and that the high temperature spike, which causes knock, is moderated, and this implies an improved air/fuel mixture preparation. Moreover, exhaust temperatures are lower with polymer-fortified fuels. High exhaust temperatures are produced by fuels burning late into the expansion stroke. A more uniform blend of “light” and “heavy” species in the unburned gas, ahead of the flame front, results in faster flame advance, and lower exhaust temperatures. The exhaust temperature differentials, entered in Table 1, indicate better air/fuel mixture preparation. Likewise, the power increase, displayed in Figure 2, can develop only with an increase in the octane (cetane here) rating of the fuel, suggesting a more homogeneous air/fuel mixture preparation. The reduction of the pollutants HC and CO, reported in Table 2, reflects a more complete combustion, and the decrease in  $\text{NO}_x$  relates to the paucity of fine fuel droplets. These environmental improvements, together, imply an air/fuel mixture preparation nearer to the ideal. As revealed in Figure 3, the fortified fuel is particularly effective in overcoming inefficiencies during transients. The cause of transient hesitations is the build-up of the liquid-fuel film in the induction channel. The consensus is that it is the inability of this film to vaporize rapidly enough to be readily transported into the cylinder, when the intake valve opens, that is the cause of the lean mixture and the hesitation. It is counterintuitive to believe that a substance which limits vaporization from the droplets in the cylinders, as suggested here, could improve engine performance during transients, when limited vaporization from the liquid-fuel film in the induction channel is the cause of the hesitation. The results from the EG&G tests, however, are quite convincing. A reconsideration of the problem is instructive. The paradigm proposed here is: 1) the transient hesitations arise because, with neat fuels, there is insufficient fuel, either in the liquid or vapor phase, imported into the cylinder; 2) the inelastic droplets of fortified fuels, which exist before the polymer reaches complete relaxation, rebound from the induction channel walls in sufficient numbers to reduce the portion of liquid film on the walls, and increase the concentration of liquid droplets in the air/fuel mixture; 3) the polymer limits vaporization from the fuel droplets in the air/fuel mixture flowing in the induction channel, and these fuel-dense droplets are available for transport into the cylinder when the intake valve opens. This model is satisfactory for understanding the improvement of engine performance during transients and in steady-state combustion as well.

## CONCLUSIONS

High molecular weight polymers confer significant benefits when present in fuels burned in IC engines. The overall operating temperatures are decreased, imputing an octane or cetane rating increase to the fuel-in-use. The power output is increased. Fuel consumption is reduced and, while not reported explicitly here, mileage gains are substantial, particularly with diesel and two-cycle, engine-powered vehicles (4). The pollutants, HC, CO and  $\text{NO}_x$  are reduced.

## ACKNOWLEDGEMENT

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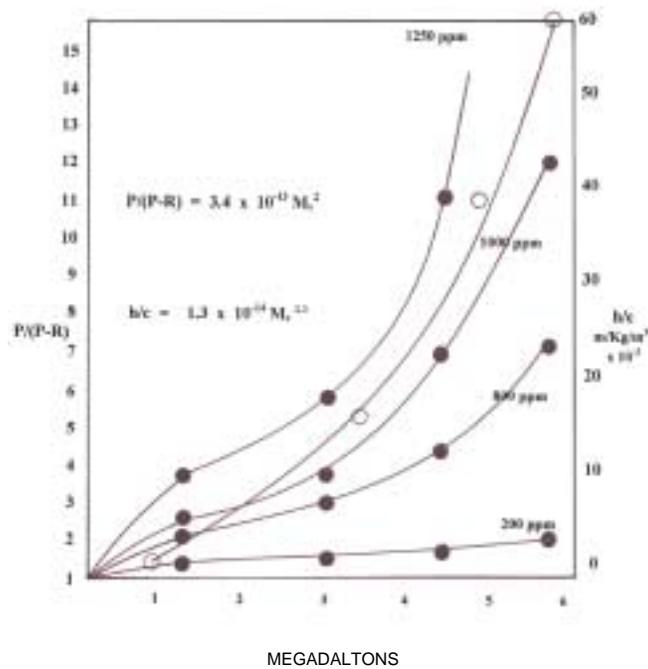


Figure 1. Anti-misting function,  $P/(P-R)$  and ductless siphon function,  $h/c$  vs. molecular weight of polymer at 20°C (● in diesel fuel, ○ in toluene).

**TABLE 1. ENGINE TEMPERATURES OF A 4-CYCLE, SINGLE-CYLINDER GASOLINE ENGINE**

FUEL	CYLINDER HEAD EXHAUST		DIFFERENCE
	RANGE	AVERAGE	
No polymer	290-300°F	295°F	
With polymer	260-270°F	265°F	-30°F
	EXHAUST MANIFOLD		DIFFERENCE
	RANGE	AVERAGE	
No polymer	1280-1360°F	1320°F	
With polymer	1208-1248°F	1228°F	-92°F
	TAILPIPE		DIFFERENCE
	RANGE	AVERAGE	
No polymer	980-1110°F	1045°F	
With polymer	798-862°F	830°F	-215°F

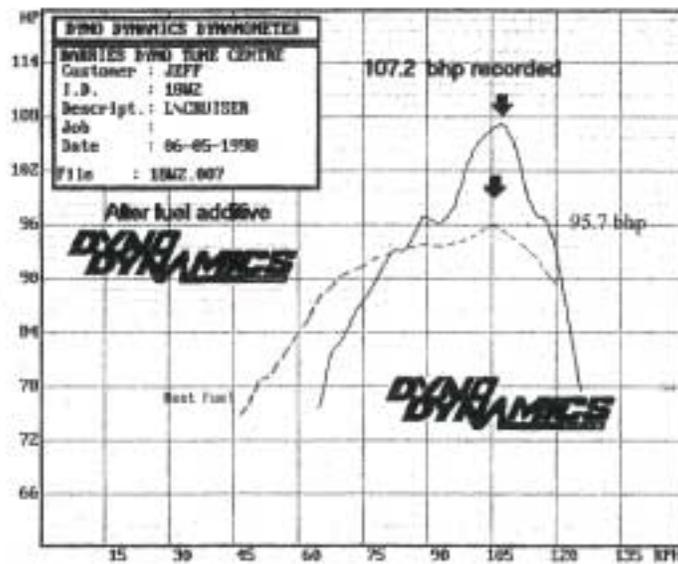


Figure 2. Brake horsepower (BHP) of a 1990 turbodiesel Toyota Landcruiser with polymer (solid line) and without polymer (broken line).

TABLE 2. VEHICLE EMISSIONS TEST RESULTS

Vehicle	Test	HC			CO			NOx		
		BEFORE	AFTER	LOS	BEFORE	AFTER	LOS	BEFORE	AFTER	LOS
		(PPM)	(PPM)	%	%	%	%	(PPM)	(PPM)	%
'97 Jeep Wrangler	Sun Dyno	22	6	72	0.02	0.0	100	34	0.0	100
'95 Nissan Pathfinder	"	92	8	91	0.10	0.0	100	162	0.0	100
'88 Chevy Suburban	"	139	54	61	0.32	0.05	84	370	151	59
'90 Ford Bronco	Bear Static	135	0.0	100	0.90	0.0	100	not measured		
'87 Toyota Pickup	"	280	40	86	1.50	0.0	100	not measured		

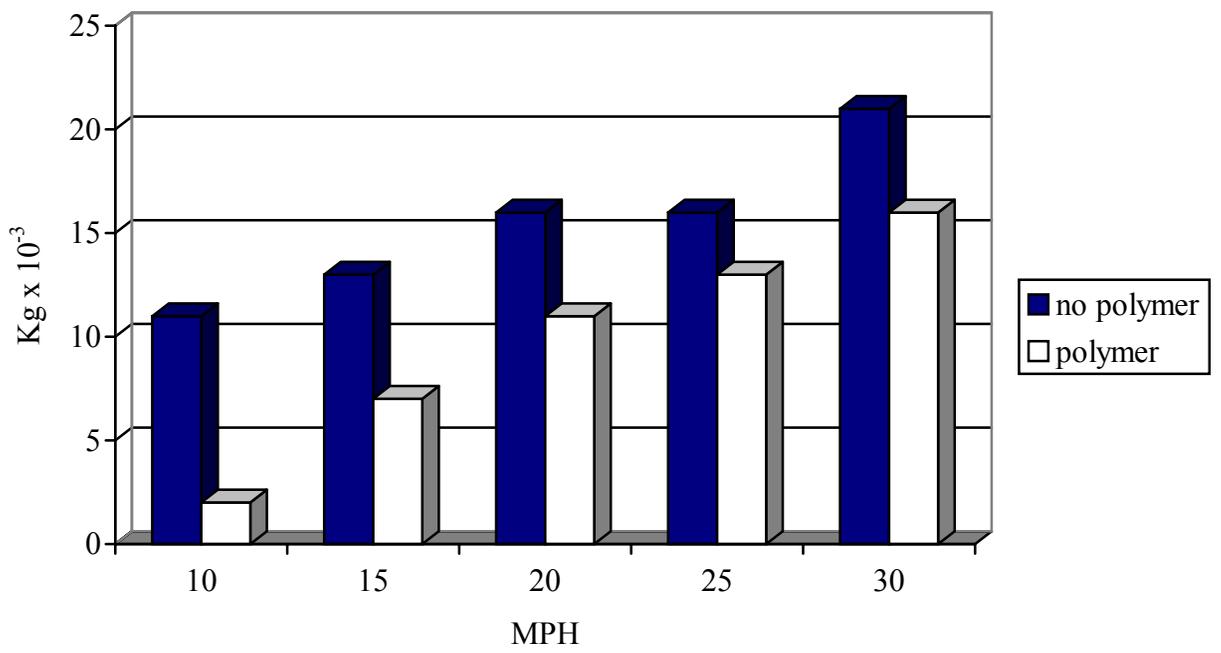


Figure 3. Acceleration tests on a 1987 gasoline-powered Nissan 300 ZX.



Figure 4. Laser light scattering images of droplets of an aqueous solution of polyethylene oxide (low density) and water (high density)