Study of the various factors influencing deposit formation and operation of gasoline engine injection systems

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Abstract. Generally, ethanol fuel emits less pollutants than gasoline, it is completely renewable product and has the potential to reduce greenhouse gases emission but, at the same time can present a multitude of technical challenges to engine operation conditions including creation of very adverse engine deposits. These deposits increasing fuel consumption and cause higher exhaust emissions as well as poor performance in drivability. This paper describes results of research and determination the various factors influencing injector deposits build-up of ethanol-gasoline blends operated engine. The relationship between ethanol-gasoline fuel blends composition, their treatment, engine construction as well as its operation conditions and fuel injectors deposit formation has been investigated. Simulation studies of the deposit formation endanger proper functioning of fuel injection system were carried out at dynamometer engine testing. As a result various, important factors influencing the deposit creation process and speed formation were determined. The ability to control of injector deposits by multifunctional detergent-dispersant additives package fit for ethanol-gasoline blends requirements was also investigated.

1. Introduction

Emission control and energy conservation policies are the main drivers for change in engine and fuel technology. Modern spark ignition engines are designed to use high octane fuel as for example ethanol-gasoline fuels for optimal fuel efficiency. Moreover, ethanol heat of evaporation is about 280% higher versus gasoline and effective evaporative cooling of air-fuel mixture allows the compression ratio to be raised, providing a higher level of thermodynamic efficiency. Ethanol fuel emits less pollutants than gasoline, it is completely renewable product, allows to increase economic and energy independence state and has the potential to reduce greenhouse gases (GHG) emission. However ethanol-gasoline blends can present a multitude of technical challenges to engine operation including creation of very adverse deposits. It is well known that harmful deposits would build up inside an engine (intake ports, intake valves, combustion chambers) and inside as well as outside fuel injectors if commercial gasoline or the most alternative fuels (as for example ethanol fuels) – Fig. 1, did not contain effective deposit control additives [1-5]. Deposits in the fuel intake system can have detrimental influence on preparation of air-fuel charge leading to suboptimal engine performance. The challenge for modern additives is not only to keep vital engine and fuel systems parts clean, but they should also remove existing deposits [1, 2, 6 - 8]. Fuel injectors are highly sensitive even to small deposits in the regions where fuel is metered and atomized. A period of hot soak when engine is fully warmed up and next switched off when the injector tip temperature has been measured to reach about

100 °C is essential for PFI (Port Fuel Injection) deposit formation [9 - 11]. During the hot soak period, the lighter hydrocarbons, from small amount of fuel left at the injector tip, evaporate, leaving a thin film rich in heavy hydrocarbons on the orifice surfaces. These hydrocarbons oxidize to form gums and resins, and this sticky varnish can bake into hard deposit given sufficient time [9 - 14]. These deposits, mostly from chemical (incompatible additives with base fuel) or thermal degraded fuel (high temperature pyrolysis) and its poor stability can restrict fuel flow and alter the spray pattern, which can deteriorate drive ability, decrease power and fuel economy as well increase exhaust emissions [1, 12 - 18]. Therefore if a fuel injector becomes clogged due to gasoline deposits, the injector will not be able to supply the proper amount of fuel to air ratio, leading to a sluggish, inefficient motor.

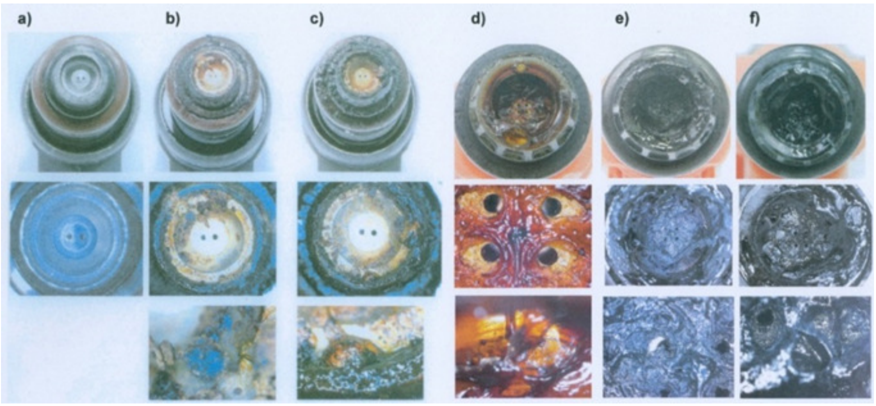


Figure 1. Injector appearance of Mercedes M111 PFI system (a – clean injector), deposits after 60 hours test with unadditized E10 fuel (b, c) and FORD 1.8L Duratec-HE PFI FFV injector deposits after 100 hours tests of various unadditized E85 fuel (d, e, f).

The most serious consequences of injector fouling, especially in case of direct injection, are pre-ignition, and engine misfiring and malfunction [14 - 16].

Furthermore, deposits in spark ignited engines are formed not only by the fuel influence but also by engine lubricating oil flow and especially its high consumption quantity, blow-by gases (positive crankcase ventilation - PCV) and combustion gases (exhaust gas recirculation – EGR). Particulates such as airborne dirt and solids from combustion products brought into the intake system by EGR and PCV systems may have also considerably affect on deposit formation. A great significance for deposit formation have also engine operation conditions in connection with fuel composition [1, 8, 9].

Regardless of factors causing both engines as well injectors harmful deposits it appears that fuel treatment with efficient detergent additives compatible and fitted for fuel composition are the most effective method in controlling and counteracting deposit formation.

The objective of this paper is presentation of study results evaluating the influence of various causative factors of deposit formation and operation of gasoline engine PFI system. Dynamometer engine simulation tests were crucial for deposit reproducing and special test bench including fully adjustable actual engine fuel injection system was used for assessment of generated injector deposits on this injection system operation.

2. Materials and methods

2.1. Test fuels

The E20 and E85 fuels used in dynamometer engine tests were splash blends consisting of fuel grade ethanol and base (unadditized) E0, RON 98 unleaded gasoline – Table 1. In one test, conventional gasoline - RON 95 complying with EN 228, from the gasoline station, was used to the preparation of the E85 fuel. This fuel was composed of the 15 % v/v commercial RON 95 gasoline blended with 85

%v/v fuel grade ethanol. In addition in one test E85 base fuel was treated with developed in Oil and Gas Institute – National Research Institute detergent-dispersant additive dedicated for high ethanol-gasoline blends. The additive containing a detergent-dispersant DEM1 of N-alkylated benzoxazine derivative structure, possessing hydrogenated heterocyclic ring and aromatic ring substituted by an alkyl and a synthetic carrier oil of oxyalkylated alkyl phenol structure and an aromatic solvent.

Table 1. Physicochemical properties of the E0, E20 and E85 fuels

Properties	Base Gasoline E0	Fuel E20	Fuel E85	Test Methods
Research Octane Number	98,1	100,3	108,2	PN-EN ISO 5164
Motor Octane Number	89,5	90,8	93,7	PN-EN ISO 5163
Lead, mg/l	<2,5	-	-	PN-EN 237
Density in 15^{0}C, kg/m^3	725,6	748,0	784,0	PN-EN ISO 12185
Sulphur, mg/kg	<3	<2	<0,5	PN-EN 20846
Copper, mg/kg	-	-	<0,05	EN 15837
Phosphorus, mg/l	-	-	<0,15	EN 15487
Induction period, min.	>480	>360	>360	PN-ISO 7536
Gums content, mg/100ml:				PN-EN ISO 6246
- unwashed		5,4		
- washed	<1	0,3	1,0	
Copper corrosion	1A	1A	1A	PN-EN ISO 2160
Benzene, %(*V/V*)	0,25	-	-	PN-EN 238
Oxygen, %(*m/m*)	0,0	7,4	-	PN-EN 1601
Ethanol, %(*V/V*)	<0,1	20	70,5	PN-EN 1601
Methanol, %(*V/V*)	-	-	0,3	EN 1601
Inorganic chloride mg/kg	-	-	<4,0	EN 15492
Vapor pressure (DVPE), kPa	57,8	67,0	45,2	ASTM D 4953
Distillation characteristics:				PN-EN ISO 3405
IBP, °C	33,4	35,7	-	
- up to 70^{0}C distilled volume, %(*V/V*)	21,1	48,2	-	
- up to 100^{0}C distilled volume, %(*V/V*)	52,5	71,2	-	
- up to 150^{0}C distilled volume, %(*V/V*)	93,1	91,2	-	
- end of distillation, ^{0}C	181,9	184,6	-	
- residues, %(*V/V*)	1,0	1,0	-	

2.2. Test benches and procedures

A special engine test bed and in-house test procedure were developed to study the effect of fuel composition, fuel additives, engine systems design, engine operating parameters and quantity of lubricating oil consumption on PFI system injector deposits. As a test engine on the test bench was used FORD 1.8L Duratec-HE PFI FFV (125PS) – Table 2.

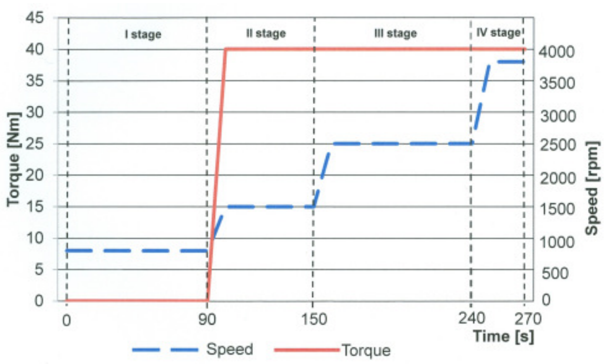
The engine was operated on the engine test bench according one of the two newly (in-house) established 100 hours tests cycles which were prone to build up injector deposits. Both tests cycles included 4 stages differ in engine speed, load and time of duration. The test was automatically performed up to total cycles time of 100 hours. The first quasi static operation pattern test assumed

mild operation condition, and the second one more severe operation conditions by more dynamic pattern, higher engine load and speed. The speed / load profiles for both test cycles are shown graphically in Fig. 2.
In order impact assessment of injector deposits formation on injector operation, directly after engine simulation test, not only visual rating of the external injector tips coking deposit was performed but also checking and assessment fuel injectors flow and spray pattern degradation on the special in-house flow bench. The main part of the flow bench was complete PFI system of FORD 1.8L Duratec-HE PFI FFV (125PS) engine connected to the control block allowing for variable test fluid (instead gasoline) pressure adjustment range (from 0 to 0,6 MPa) as well provides constant control over fuel injection variables such as injector pulse width (from 0,02 ms to 50 ms), injector frequency opening (from 15 Hz to 150 Hz) and operating time (from 1 s to 3 h) per test – Fig. 3.

Table 2. Specification of the test engine FORD 1.8L Duratec-HE PFI FFV (125PS)

Engine operating cycle	Four-stroke, spark ignition engine
Fuel delivery	Indirect fuel injection
Configuration	Straight 4
Aspiration	Naturally aspirated
Firing order	1-3-4-2
Valvetrain	DOHC (chain driven) /4 VPC
Cylinder bore	83,0 mm
Piston stroke	83,1 mm
Displacement	1798 cm^3
Power	125 bhp (92 kW) @ 6000 rpm
Torque	165 Nm @ 4000 rpm
Compression ratio	10,8 : 1
Medium fuel consumption (E85)	10,5 l/100 km
Tappet clearance	Hydraulically adjustment
Oil capacity with filter	4,3 dm^3
Engine emission level	Euro IV

a)



b)

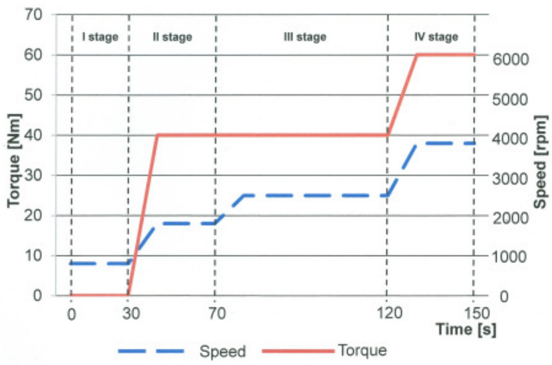


Figure 2. Engine test cycles. a) mild operation conditions, b) more severe operation conditions.

3. Tests results

Within the frame of the project a research study of various factors influencing injectors deposit formation and their operation in a PFI gasoline FFV engine were carried out. Since high ethanol-gasoline fuel blends are viewed as a potential alternative fuels to decrease fossil CO2 emissions and dependence on crude oil, such fuels formed the basis of the study. As in the case of fossil fuels, FFV fueled by ethanol-gasoline fuels deliver optimal performance when the sensitive areas in the intake system and in the fuel injectors are kept clean that is free of deposits. No standard test is available to assess the tendency of ethanol-gasoline blends to form intake system and injector deposits. So, a proprietary engine test bench and devised in-house test method in two versions was used to provoke by various factors and next to evaluate tendency of deposits formation in and on the fuel injectors. Directly, after engine test, measurements of fuel quantity delivery by particular injectors for various parameters of their operation, and evaluation spray pattern degradation were performed.

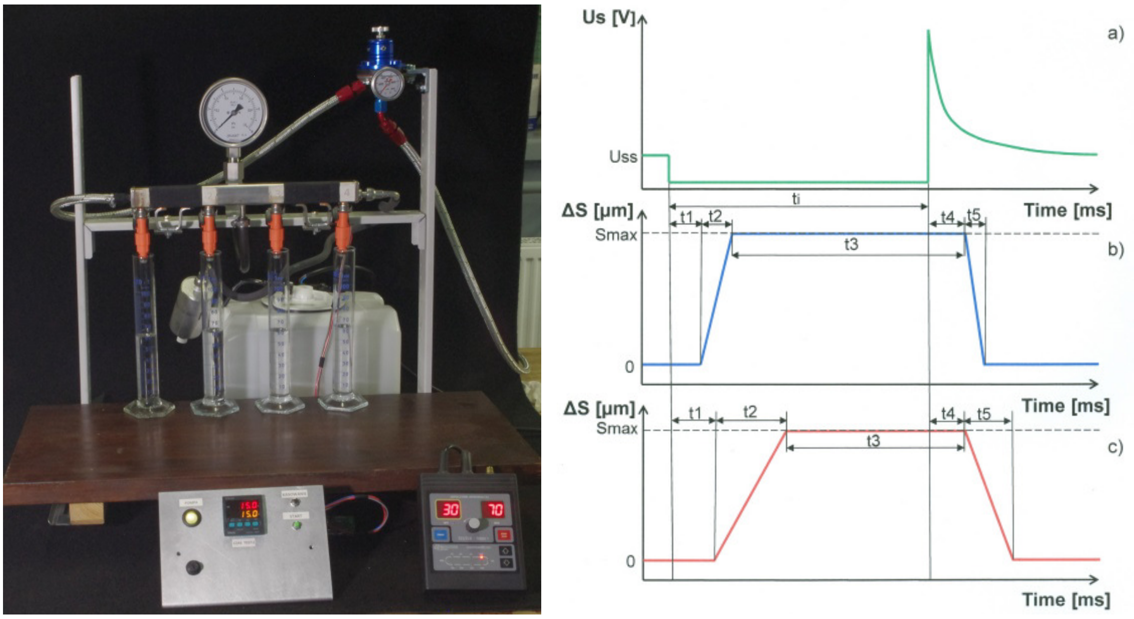


Figure 3. Flow bench for assessment of injectors operation and electronic pulse oscillation of injector control (a), correct course of raising and lowering injector metering needle (b), delayed by internal deposits course of raising and lowering injector metering needle (c)

- Evaluation of base (unadditized) E85 fuel impact for injector deposit formation of PFI FFV engine without EGR and blow-by in mild operation conditions (Fig. 2a) – Fig. 4a.

Port fuel injector deposits form especially during the hot soak period after an engine has been turned off. Fuel trapped in an injector tips is exposed to a higher temperature for a longer time than fuel that flowed through the injector when the engine was running, and forms both external coking deposits as well internal deposits especially in the absence of efficient deposit control additive. Therefore injector flow assessments were performed 24 h after engine bench test. Since injectors are designed for pulsed operation they were tested by pulsing. It is well known that engine and fuel injector deposits are formed not only by the fuel and its treatment but also by engine lubricating oil, blow-by gases (positive crankcase ventilation – PCV) and EGR. Therefore in the first test was used base E85 fuel and engine without EGR and PCV.

After the test was observed negligible external injector deposits, and asymmetrical control liquid spray pattern for injector No. 4. In this case droplets settling on the surfaces of intake manifolds is possible and as a result deterioration HC emissions due to increased wall wetting and worse air-fuel mixing. There is also evidence injector-to-injector diversification of fuel quantity delivery for rail pressure 0,38 MPa – Fig 4a.

- Evaluation of base (unadditized) E85 fuel impact for injector deposit formation of PFI FFV engine without EGR and blow-by in more severe operation conditions (Fig. 2b) – Fig. 4b.

The only difference between first and the second test are more severe engine operation conditions. This change led to a spray pattern degradation in the case second and fourth fuel injectors. Taking into

account lack of external injector deposits, the reason of observed spray pattern degradation is probably due to internal injector fuel channels deposits. This increase possibilities of droplets setting on the surfaces of intake manifolds and early described negative results.
The diversification of fuel quantity delivery by particular injectors are smaller, but it should be remembered that new set of fuel injectors usually flowing within 2 – 3% of one another. However following injector deposit formation, the flow rate varies increasingly from injector to injector and the ECU continually correcting fuel rate up to about 10% by adjusting individual injector pulse width to balance fuel delivery. If the flow rate varies by too much from injector to injector, the engine will cause drive-ability problems.

a) b)

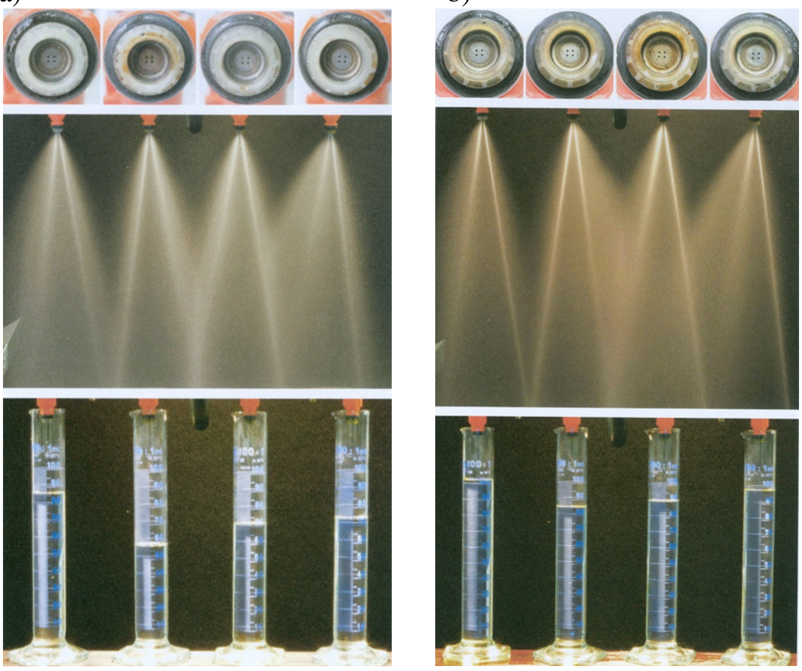


Figure 4. View of injector tips deposits, spray patterns and quantity of delivered fuel by injectors after bench test of PFI FFV engine
a) without EGR and blow-by run with base E85 fuel in mild operation conditions
b) without EGR and blow-by run with base E85 fuel in more severe operation conditions

- Evaluation of base (unadditized) E85 fuel impact for injector deposit formation of PFI FFV engine with EGR and blow-by in mild operation conditions (Fig. 2a) – Fig. 5a.

The results in Fig. 5a confirm that EGR and blow-by gases which are directed into intake system with E85 base fuel injected by PFI system, as a result each other interaction, to form significant injector deposits. Spray pattern degradation due to external injector deposits in combination with diversification in spray penetration resulting in poorer engine performance and increased HC emission. It is clear also significant injector-to-injector difference of fuel quantity delivery for rail pressure 0,38 MPa, but also for lower pressure - 0,12 MPa, Table 3.

- Evaluation of base (unadditized) E20 fuel impact for injector deposit formation of PFI FFV engine with EGR and blow-by in mild operation conditions (Fig. 2a) – Fig. 5b.

Reduction of ethanol content in the fuel to 20%v/v (E20) resulted in significantly less injectors tips deposits for comparison to E85 fuel – Fig. 5a and 5b. But despite that offset spray pattern especially third injector indicate the possibility of droplets setting on the surface of intake manifolds and increasing HC emission. Moreover poor injector-to-injector metering consistency has been observed probably as a result of deposit build-up inside internal injector flow holes and channels – Fig. 5b.

- Evaluation of base (unadditized) E85 fuel (including 15%v/v commercial standard gasoline) impact for injector deposit formation of PFI FFV engine without EGR and blow-by in mild operation conditions (Fig. 2a) – Fig. 6a.

Detergent additives for EN 228 gasoline application are compatible with an ethanol content up to 10%v/v but not always for higher ethanol content because of poor solubility of some conventional additives in ethanol. So, higher additive treat rates or different detergent-dispersant additive chemistry may be necessary for optimal detergent performance of ethanol-gasoline fuel.

a) b)

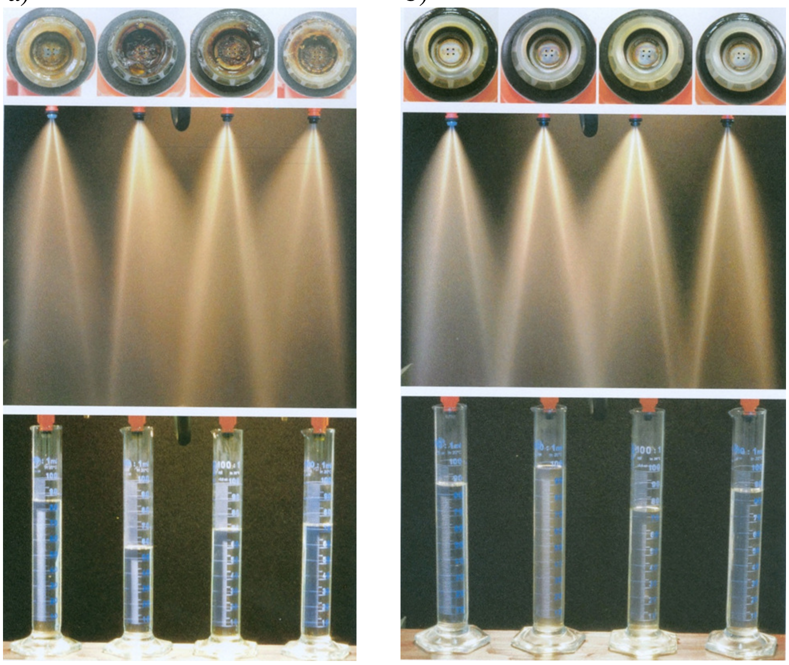


Figure 5. View of injector tips deposits, spray patterns and quantity of delivered fuel by injectors after bench test of PFI FFV engine

a) with EGR and blow-by run with base E85 fuel in mild operation conditions

b) with EGR and blow-by run with base E20 fuel in mild operation conditions

Presented results of the test – Fig. 6a, represent example where traditional detergent additives used to treatment of commercial gasoline, constituting 15%v/v tested E85 fuel, have solubility problem in the high ethanol fuel and through the incompatibility leading to external and internal injector deposit formation. Significant injector deposits caused considerable diversification in spray pattern and cone angle between injectors. This leads to deterioration HC emissions due to increased wall wetting and worse air-fuel mixing – Fig. 6a.

Injectors flow measurements both for rail pressure 0,38 MPa as well as for 0,12 MPa showed very poor injector-to-injector metering consistency and very significant differences of fuel delivery between injectors – Fig. 6a, Table 3. Increasing rail pressure to 0,5 MPa for injector pulse width 0,1 ms led to switch off two injectors operation (No. 2 and 3) through injector internal deposits build up. Internal deposits can slow the injector response for control electric signal and change dynamic response characteristics resulting in a loss of control of injection event timing and/or amount of fuel delivered. Injector deposits, both external-coking as well as internal will increase engine-out emissions and deteriorate engine performance.

- Evaluation of base (unadditized) E85 fuel impact for injector deposit formation of PFI FFV engine with EGR and blow-by and increased engine lubricating oil consumption in mild operation conditions (Fig. 2a) – Fig. 6b.

Increased engine lubricating oil consumption was achieved through application of used intake valves stem seals. Lubricating oil consumption was at the level 0,8 liter per 100 h of engine operation in mild conditions. 24 h after engine bench test (injector soaking period) has been stated that a few injectors fuel holes are blocked by heavy, black, sticky deposits. This had an impact on diversification in spray patterns and fuel atomization quality injector-to- injector. Reduced test fluid flow by fouled injectors holes has resulted in significant diversification of fuel quantity delivery – Fig. 6b especially for rail pressure 0,38 MPa – Table. 3.

- Evaluation of treated E85 fuel impact for injector deposit formation of PFI FFV engine with EGR and blow-by in mild operation conditions (Fig. 2a) – Fig. 6c.

E85 base fuel was treated with developed in Oil and Gas Institute – National Research Institute detergent-dispersant efficient additive specifically designed and optimized for high ethanol-gasoline blends. The results of a research test proved that specifically developed for high ethanol-gasoline blends detergent-dispersant additives can be effective in preventing formation of internal and external injector deposits (keep clean) and remove already formed deposits (clean up) – Fig. 6c.

After engine test on the injectors tips have not been found any deposits formation, and diversification of spray pattern was very small. Very good injector-to-injector metering consistency has been ascertained both for rail pressure 0,38 MPa as well as for 0,12 MPa – Fig. 6c. This contributes to the notion that deposit control additives provide means to effectively and efficiently modify fuel properties counteracting injector deposit formation.

Considering fuel injector design, improved injector deposit resistance can be achieved due to laser drilling and smoother surface in flow holes.

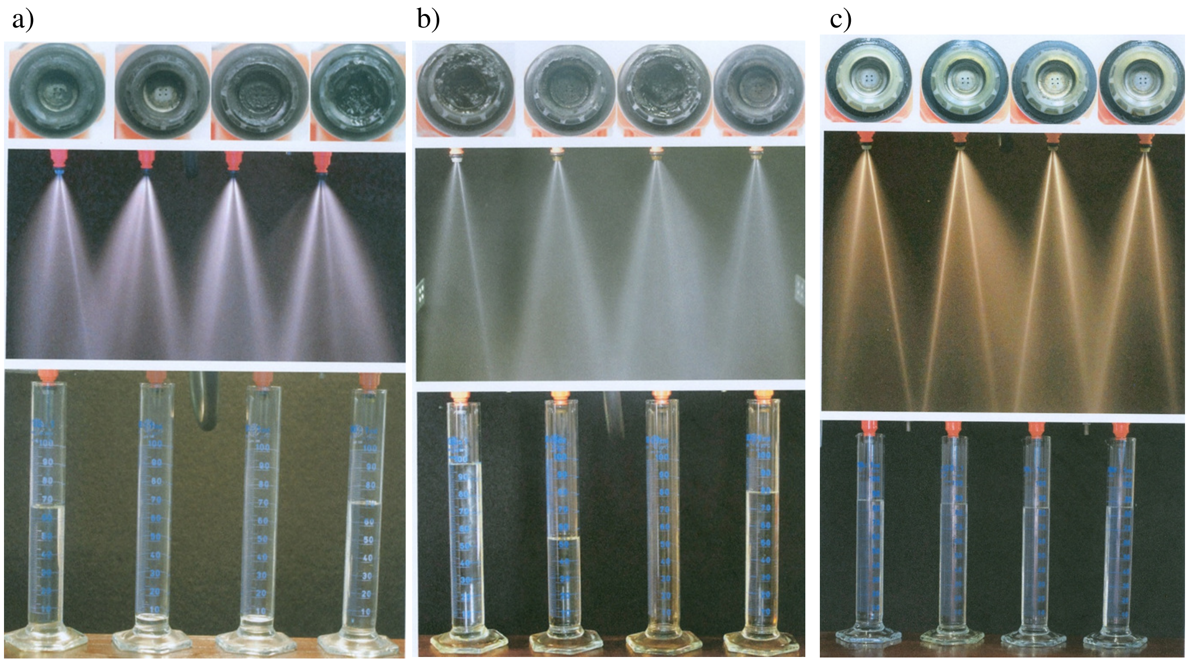


Figure 6. View of injector tips deposits, spray patterns and quantity of delivered fuel by injectors after bench test of PFI FFV engine: a) without EGR and blow-by run with base E85 fuel (including 15%v/v commercial standard gasoline) in mild operation conditions, b) with EGR and blow-by and increased engine lubricating oil consumption run with base E85 fuel in mild operation conditions, c) with EGR and blow-by run with treated E85 fuel in mild operation conditions.

All tests and results have been summarized in Table 3 below.

Table 3. Breakdown of all carried out tests and obtained results.

Fuel and assessing conditions	Figure No.	Quantity of injected fuel [ml]		External injector tips deposits	Quality of fuel atomization
		Rail pressure 0,12 [MPa]	Rail pressure 0,38 [MPa]		
Unadditized E85 without EGR and blow-by – low engine load	5	68 52 60 63	87 58 71 74	Negligible deposits	For injector No 4, asymmetrical control liquid spray pattern, too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds.
Unadditized E85 without EGR and blow-by – higher engine load	6	80 71 74 82	103 85 90 98	Negligible deposits	For injector No 2 and 4, asymmetrical control liquid spray pattern. For injector No. 4 spray too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds.
Unadditized E85 with EGR and blow-by – low engine load	7	68 52 60 63	87 58 71 74	Significant resin and lacquered deposits especially on the injectors of the second and fourth cylinder	For injector No 2 and 4, asymmetrical control liquid spray pattern, too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds.
Unadditized E20 with EGR and blow-by – low engine load	8	71 81 66 70	88 99 76 87	Negligible deposits	For injector No 3, asymmetrical control liquid spray pattern, too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds.
Unadditized E85 including 15% commercial standard gasoline, without EGR and blow-by – low engine load	9	67 64 50 69	67 7 6 71	Heavy, black, sticky deposits especially on the injectors of the third and fourth cylinder	For injector No 2 and 4, asymmetrical control liquid spray pattern. For injector No. 2 and 4 spray too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds.
Unadditized E85 with EGR and blow-by – low engine load (increased engine lubricating oil consumption)	10	77 61 59 71	100 54 0 76	Heavy, black, sticky deposits especially on the injectors of the first and third cylinder	For injector No 3, asymmetrical control liquid spray pattern, too broad on its bottom. Possibility of droplets settling on the surfaces of intake manifolds. Quality of the control liquid spray atomization varies between the injectors.
Treated by additive dedicated for E85 with EGR and blow-by – low engine load	11	72 70 71 71	88 87 86 87	Clean injectors	The correct shape of the control liquid spray pattern, and good quality of spray atomization in the injectors.

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4. Conclusions

- Evolving engine construction and fuel technology defines additive requirements including cleanliness challenge for counteract fuel injector external and internal deposits
- Reduced injector deposit build-up improves performance over entire injector lifetime
- Injector deposits, both external – coking as internal will increase engine-out emissions and deteriorate engine performance
- Properly designed fuel additives required to control injector deposits
- Detergent-dispersant additive system will be critical in controlling deposit forming tendencies
- Fuel deposit control additives enable the safe and efficient utilization of fuel
- Regardless of the reasons injector deposits build-up and their location the most effective means to prevent these harmful phenomenon are fit for fuel composition detergent-dispersant additives

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