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Durability Study of a High-Pressure Common Rail Fuel Injection System Using Lubricity Additive-Dosed Gasoline-Like Fuel—Improved Endurance with Upgraded Hardware

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Abstract

Gasoline compression ignition (GCI) is a promising combustion technology that can help the commercial transportation sector achieve operational flexibility and meet upcoming criteria pollutant regulations. However, high-pressure fuel injection systems (>1000 bar) are needed to enable GCI and fully realize its benefits compared to conventional diesel combustion. This work is a continuation of previous durability studies that identified three key technical risks after running gasoline-like fuel through a heavy-duty, common rail injection system: (i) cavitation damage to the inlet check valve of the high-pressure pump, (ii) loss of injector fueling capacity, (iii) cavitation erosion of the injector nozzle holes. Upgraded hardware solutions were tested on a consistent 400- to 800-hour NATO durability cycle with the same gasoline-like fuel as previous studies. The upgraded pump showed no signs of abnormal wear or cavitation damage to the inlet check valve. In contrast to previous studies, there were no signs of pump performance degradation observed after 400 hours of testing. Material selection and design upgrades were also made to the injector which, only showed a 6.5% loss in fueling capacity after 800 hours of durability testing compared to 49.3% previously. Finally, geometric nozzle hole features such as higher inlet radius of curvature and higher K-factor were found to correlate with reduced cavitation erosion. However, mitigation of eccentric radial needle motion (i.e., wobble) is likely needed to further suppress cavitation. In general, the results from this study indicate there are viable hardware-based solutions for improving the endurance of high-pressure systems when running with gasoline-like fuel.

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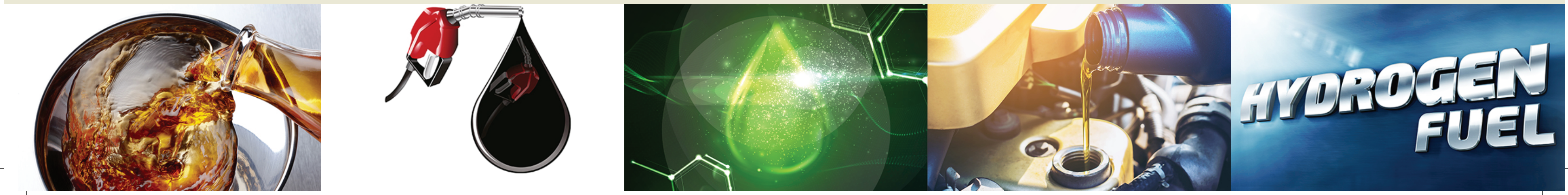


1. Introduction

Liquid petroleum fuels are projected to remain a major part of the transportation energy mix over the next 30 years [1, 2]. This is due to their high energy density and established distribution network. The demand for middle distillates such as diesel and kerosene is expected to continue rising within the commercial transport sector. These fuels are needed to support the increased economic activity associated with developing countries. Concurrently, demand for light distillates such as gasoline is expected to decrease due to efficiency gains in the passenger vehicle sector. These will take the form of hybridization, electrification, and other powertrain advancements. This scenario will ultimately create a demand disparity, which could negatively impact the economics of commercial freight operations that rely solely on medium distillates [3]. Furthermore, the carbon and criteria pollutant emissions regulations for the on-road commercial transport sector are becoming increasingly stringent and difficult to meet with conventional diesel engines [4].

Gasoline compression ignition (GCI) is one promising technology that could help mitigate the impacts of a demand shift by enabling the use of light distillates in the heavy-duty transportation sector. Recent research has shown that compared to diesel combustion, GCI can drastically reduce soot emissions while achieving relatively low engine-out NOx [5, 6]. This is due to the higher volatility, lower viscosity, longer ignition delay, and better fuel–air mixing achieved with gasoline-like fuels. The improved soot–NOx tradeoff could also help alleviate the tremendous operational and durability demands placed on modern lean aftertreatment systems to meet upcoming emissions regulations [4, 7, 8]. However, relatively high injection pressures (>1000 bar) are needed to simultaneously manage soot emissions and heat release rates over the entire operating range of the engine, especially at high loads. Modern gasoline direct injection (GDI) systems have only reached pressures of 700 bar in production applications [9]. Understanding and developing the use of high-pressure common rail injection systems for gasoline-like fuels is thus a necessary step toward enabling GCI as a viable engine technology.

The current work is a continuation of prior studies, which identified the key technical risks of running gasoline-like fuels in high-pressure common rail injection systems [10, 11]. For heavy-duty applications, the fuel system must be extremely robust and is typically rated for 30,000 hours of operation, or approximately 1.25 billion cycles. Comparing the properties of light distillates to that of diesel immediately reveals some potential risks associated with hardware endurance. The lower viscosity, lower lubricity, and higher volatility make gasoline-like fuels prone to increased wear rates and cavitation-induced erosion [12, 13]. In prior work, it was found that dosing gasoline with an appropriate lubricity-improving additive can effectively bring its wear scar diameter (WSD) below the range recommended for protecting high-pressure hardware (i.e., <380 microns at 25°C) [14, 15]. Subsequent durability evaluations were performed with the additive-dosed fuel on a fully instrumented test rig containing an entire Cummins XPI fuel system and using an aggressive test cycle intended to accelerate potential failure mechanisms [11]. Results from this study indicated that fuel-wetted components exposed to sliding friction, such as the high-pressure pump plunger and injector needle, did not show any abnormal signs of wear after 800 hours of operation.

However, the high-pressure pump experienced severe cavitation-induced erosion after only 400 hours of operation on gasoline-like fuel, especially around the pumping chamber inlet bore and inlet check valve (ICV) [10, 11]. Damage to the ICV compromised its ability to passively seal against fuel flow and led to an unacceptable buildup of rail pressure (i.e., “runaway”) under motoring conditions. The injector nozzle holes also showed significant cavitation erosion after only 400 hours [11]. At the 800-hour mark, the level of damage observed was expected to eventually cause poor flow and spray performance, lower combustion stability, increase engine emissions, and potentially, lead to mechanical failure of the nozzle tip. Finally, a substantial loss in fueling capacity was observed for some of the injectors after 800 hours of exposure to light distillate operation [11]. Teardown of the malfunctioning injectors revealed that this was caused by a material compatibility issue that severely inhibited the pilot valve stroke.

The first objective of the current study was to modify existing hardware or select new fuel system configurations that could mitigate the major durability concerns when operating high-pressure components with light distillates. The second objective was to test the upgraded hardware under the same conditions as the original studies and determine if any improvements in robustness were achieved. The three key risks can be summarized as follows:

1. Inlet side cavitation damage to the high-pressure pump, specifically the ICV
2. Loss of fuel metering capacity for the injectors due to pilot valve material incompatibility
3. Cavitation-induced erosion damage to the injector nozzle holes

The way in which each of these issues were addressed using specific design considerations will be briefly discussed. Performance and teardown results after running the upgraded hardware on a consistent durability test cycle to prior work will then be presented. Finally, a summary of key design guidelines for enabling high-pressure gasoline fuel systems will be provided.

This work is the culmination of controlled durability studies focused on heavy-duty, high-pressure injection systems run with gasoline-like fuel [10, 11]. Unlike other similar prior studies [16], this work builds on the thorough identification of key hardware endurance issues by proposing, implementing, testing, and validating solutions to mitigate the operational risks. Additionally, the ranges in viscosity, lubricity, and volatility are far more aggressive than middle distillates or kerosene-like fuels that are typically investigated with this type of hardware and could help inform the design of more robust systems for other volatile fuels. Readers are strongly encouraged to consult [10, 11, 15], which will significantly help to place the current work in context.

2. Materials and Methods

2.1. Fuel Properties

Table 1 compares the fuel properties of diesel to RON60 and market gasoline containing 10% ethanol by volume (E10). RON60 gasoline is named as such because it has a research octane number (RON) of 60. This fuel was retained as the hydraulic test fluid to be consistent with prior durability control studies [10, 11]. RON60 and E10 have similar density, viscosity, and volatility characteristics (i.e., vapor pressure and distillation curve). This makes RON60 a viable candidate for evaluating the impact of light distillates on fuel system hardware. Compared to diesel, the low viscosity means that lubricating film thicknesses will be lower and could contribute to accelerated wear [12, 14]. In addition, flow velocities through orifices or clearance gaps will be higher, thereby increasing the propensity to form regions of low local static pressure. Coupled with the higher vapor pressure of gasoline, this leads to an increased risk of cavitation and material erosion [17, 18]. The relatively low WSD of RON60 was achieved by dosing it with 200 ppm of lubricity-improving additive [15]. A value even lower than the recommended maximum (i.e., 380 microns) is typically targeted to compensate for the impact of low viscosity on wear [14]. The neat WSD of gasoline-like fuel typically falls within the range of 700–1000 microns [19], as evidenced by the E10, which contained no lubricity-improving additives. An additional concern for fuels with ethanol is corrosion [20]. However, prior durability testing on a light-duty common rail injection system using E10 gasoline did not reveal any signs of corrosion damage after 500 hours of operation [21]. The severity of corrosion to fuel-wetted components could potentially be mitigated by controlling the level of acid, chloride, sulfide, sulfate, and ethyl acetate impurities in the fuel, or by dosing it with corrosion-inhibiting additives.

2.2. Upgraded Fuel System Hardware

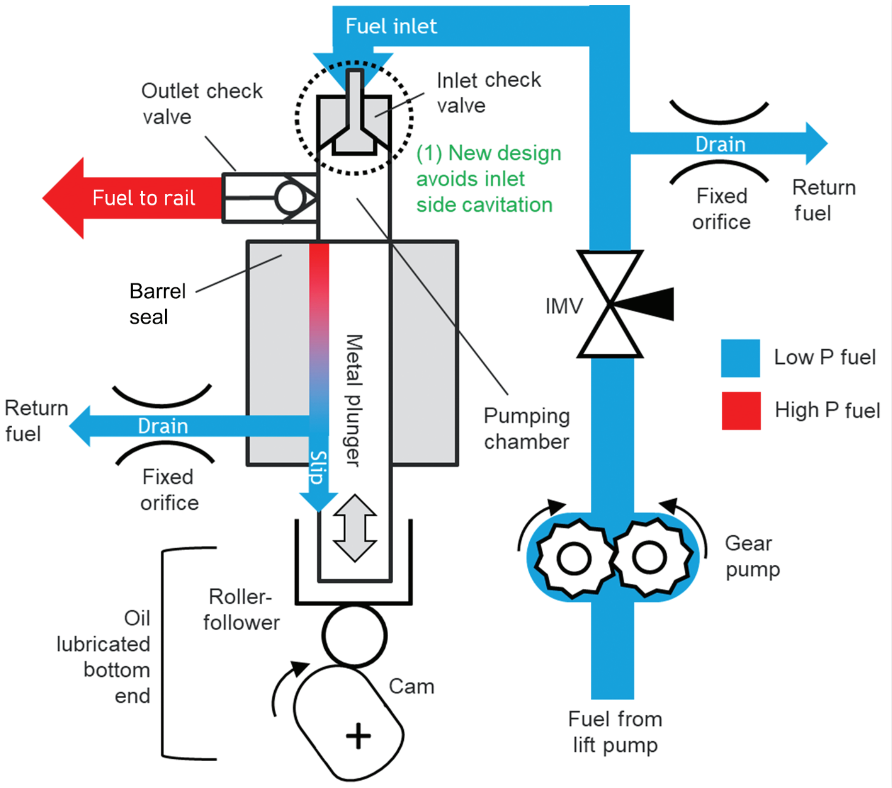
Figure 1 shows a schematic of the upgraded high-pressure pump architecture. It is clear from the schematic that if ICV sealing is compromised, fuel can continuously leak into the pumping chamber and cause a condition of runaway pressure buildup in the rail. This situation is most concerning under motored conditions when the inlet metering valve (IMV) is fully closed, excess fuel is intended to leak through the drain orifice back to the return, and there is no other means of cutting off fuel supply to the rail other than the passive seal provided by the ICV. An advantage of the upgraded pump design compared to the original Cummins XPI hardware is larger fuel inlet drillings, which increase effective area and

TABLE 1 Fuel properties.

Property	Units	Method	ULSD	RON60 gasoline	E10 gasoline
Density	kg/m^3	ASTM D4052	848.0	706.8	744.6
Viscosity[1]	cSt	ASTM D445	2.6	0.576	0.629
IBP	°C	ASTM D86	173.3	35.9	36.7
T10	°C	ASTM D86	214.4	61.3	54.3
T50	°C	ASTM D86	267.8	95.9	92.1
T90	°C	ASTM D86	315.0	125.2	158.4
FBP	°C	ASTM D86	346.7	141.2	197.2
RVP	kPa	ASTM D5191	—	51.4	63.5
WSD[2]	µm	ASTM D6079	570	280	770
Saturates	% Vol	ASTM D1319	71.0	91.8	64.5
Olefins	% Vol	ASTM D1319	1.0	0.5	4.8
Aromatics	% Vol	ASTM D1319	28.0	7.7	20.9
Carbon	% Wt	ASTM D5291	86.80	84.76	82.61
Hydrogen	% Wt	ASTM D5291	13.20	15.24	13.72
Oxygen	% Wt	ASTM D5622	—	<0.05	3.67
Sulfur	ppm (m)	ASTM D5453	8	9.2	9.9
LHV	MJ/kg	ASTM D240	42.83	44.17	41.83
RON	—	ASTM D2699	n/a	60.0	91.8
MON	—	ASTM D2700	—	57.3	84.0
(D)CN[3]	—	ASTM D6890	44.2	34.5	19.9

Notes: (1) Measured at 40°C for diesel, 20°C for gasoline, (2) measured at 60°C for diesel, 25°C for gasoline, (3) measured with ASTM D613 for diesel, derived cetane number (DCN) reported for gasoline using an ignition quality tester (IQT).

FIGURE 1 Upgraded high-pressure pumping system architecture.



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decrease flow velocity. In addition, the new ICV is designed with less contact area over its sealing surfaces, which reduces throttling losses and pressure drop. Both features help to maintain relatively high local static pressures on the inlet side of the pump and avoid conditions that lead to cavitation. The overall architecture of this high-pressure pump design is like the one presented in prior light-duty work, which showed good performance and durability after 500 hours of operation with E10 gasoline [21].

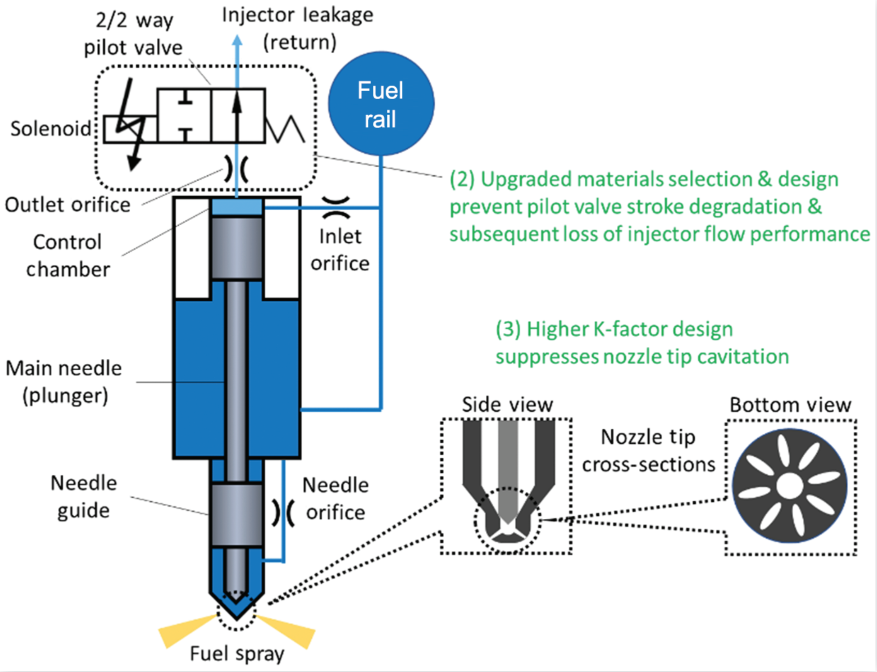
Figure 2 provides the hydraulic schematic of a standard Cummins XPI common rail injector. The gasoline incompatibility issue that led to reduced flow loss with the original hardware was isolated to the pilot valve and addressed by adjusting materials selection and design. These proprietary upgrades were used to mitigate degradation of the pilot valve stroke, which was previously determined as the cause of injector fueling rate loss after 600–800 hours of operation with gasoline [11]. If the pilot valve stroke becomes inhibited, flow through the control chamber orifices is reduced, the force imbalance driving main needle lift is lowered, and the development of pressure in the nozzle sac becomes compromised, ultimately lowering the rate of fuel injection over a given duration.

Figure 2 also indicates that changes to the nozzle tip design were made as part of the injector upgrade package. Previous internal nozzle flow simulation studies based on the same heavy-duty injector used in this and prior durability assessments found that increasing inlet hole ellipticity, radius of curvature (i.e., edge rounding), and hole channel K-factor (i.e., converging taper) could all be used to help suppress cavitation [22]. When the vapor bubbles formed by cavitation condense onto a surface, they can release enough energy to exceed the yield strength of a material and cause erosion. The geometric design features mentioned earlier increase flow area, reduce velocity magnitude, and avoid regions where fluid streamlines are forced to accelerate around a sharp corner. All these techniques demote the formation of recirculation zones and accompanying regions of low static pressure, which act as the inception points for cavitation. Although the original injector hardware used all these design features to some extent, the upgraded nozzle tip was fabricated with a larger K-factor to further suppress cavitation for light distillate fuels. Note that the term "original" pertains to the stock or production XPI fuel system hardware used on a model year 2014 Cummins ISX15 engine. Figure 3 summarizes the key failure mechanisms and proposed solutions that were tested in the current work.

2.3. X-Ray Imaging

High-resolution imaging of the injector nozzle tips was performed using the 7-BM beam line of the Advanced Photon Source (APS) at Argonne National Lab. X-ray computed tomography was employed to measure the geometry of various nozzle designs with a resolution of 1.17 microns. Achieving

FIGURE 2 Hydraulic schematic of upgraded high-pressure common rail injector.



this level of spatial fidelity was only possible because the experimental facility had been optimized for imaging with the highly attenuating materials found in injector nozzle tips [23]. In prior durability assessments, the X-ray images were used to make qualitative statements about the location and extent of cavitation-induced nozzle hole erosion [11]. In the current study, nozzle hole erosion was also evaluated quantitatively using the metrics of total cross-sectional area, "bounded-box" height (BBH) and bounded-box width (BBW), all along the entire axial length of the orifice channel. Figure 4 shows how these metrics were defined and that the axial reference point of zero distance was set at the nozzle hole exit plane. Given the three-dimensional nature of an orifice channel, the determination of K-factor can be defined in various ways. Figure 4 shows that a separate K-factor determination was made along the BBH and BBW dimensions due to the elliptical nature of the hole. Furthermore, the K-factor calculation was performed between axial distances of 50 and 1000 microns from the nozzle hole exit plane.

2.4. Test Bench and Durability Cycle

The test bench used to run the durability cycle has been thoroughly described in previous publications leading up to this work [10, 11]. No changes were made in configuration or instrumentation to maintain consistency. An entire Cummins XPI fuel system including the high-pressure pump and all six injectors was installed on the bench and driven with an external electric motor. Use of a flexible control module allowed pump speed, rail pressure, and injection duration (i.e., total fuel flow rate) to be prescribed. The only major difference in how the fuel system was operated compared to the real engine application was the lack of combustion. Instead of burning, injected fuel was recirculated back to the tank and exchanged with a fresh batch every 50 hours. Previous studies showed that the lubricity of gasoline did not change over the course of this exchange interval and remained representative of the initial fuel quality [10, 11, 21]. Standard 15W-40 lubricating oil was also supplied to the bottom end (i.e., cam and roller-followers) of the high-pressure pump as in previous work and was exchanged every 200 hours.

Rate of injection (ROI) measurements were also conducted to understand the impact of gasoline-like fuels on injector performance. A commercial device from IAV was used, which relies on the principle of a Bosch rate tube [24, 25]. The device was installed on the durability test rig to directly measure the ROI of a single injector while the remaining fuel system components operated as intended. This ensured that measured ROI profiles represented the real application as closely as possible. For these experiments, the pump speed was set to 1400 revolutions per minute (RPM) and the counterpressure to 50 bar, the same as previous studies. Individual ROI profiles were generated from an average of 500 individual injection events, while injected mass quantity versus electronic duration curves were generated using single shot sweeps of duration and integration of the profile.

Table 2 provides details of the NATO cycle used to operate the hardware with RON60 gasoline. This relatively aggressive cycle has been used in previous heavy-duty fuel system durability studies to help accelerate failure mechanisms and identify key technical risks within a reasonable runtime [16]. Once again, the same cycle used in preceding work was

FIGURE 3 Summary of main failure mechanisms and proposed solutions being evaluated.

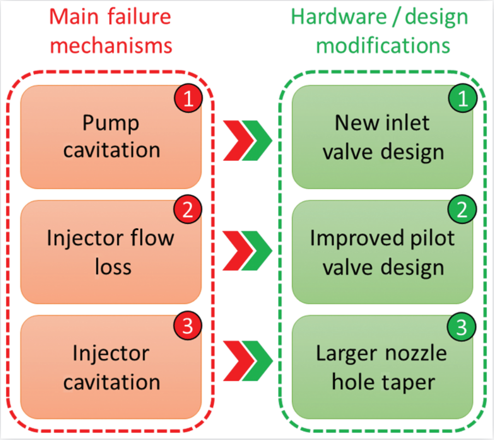


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TABLE 2 NATO durability test cycle specification.

Time (hours)[1]	Pump speed (RPM)	Injection duration (ms)[2]	Rail pressure (bar)	Fueling rate (kg/h)[3]
0.5	600	0.44	700	0.87
2.0	1800	1.82	2500	75.1
0.5	2130	0.44	700	0.87
1.0	1350	2.21	2200	64.3
2.0	600-1800	0.44-1.82	700-2500	0.87-76.6
0.5	1080	2.50	1850	53.0
0.5	600	0.44	700	0.87
0.5	1900	1.64	1975	63.6
2.0	1100	2.50	1850	53.0
0.5	1080	0.98	1400	15.6

Notes: (1) The complete 10-hour cycle is repeated to accumulate the desired runtime, (2) electronic injection command, (3) injected fuel flow from all six injectors installed on the test bench.

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employed here to maintain consistency. Additional details about the test bench, ROI measurement technique, and NATO test cycle can be found elsewhere [10, 11, 16].

3. Results and Discussion

3.1. Upgraded High-Pressure Pump

Figure 5(a) shows that after 400 hours of operation with RON60 gasoline on the original pump, it was not possible to properly control rail pressure near the motored (i.e., zero fueling rate) condition [10]. As testing time progresses and the injection duration is decreased, fuel flow to the common rail should drop to zero, thereby stabilizing the demanded pressure level. However, the used pump exhibited a type of rail pressure "runaway," even when the IMV attempted to compensate by closing off completely (i.e., 100% duty cycle). Figure 5(b) shows the upgraded pump's performance after 400 hours of runtime with RON60 under the same test conditions. Compared to Figure 5(a), stable rail pressure control was achieved for the new pump design and the IMV duty cycle remained within acceptable operating limits. Therefore, the upgraded pump showed no signs of performance degradation after equivalent exposure to gasoline.

The photos in Figure 6(a) clearly show cavitation-induced pitting of the original ICV sealing surfaces, which normally prevent fuel from leaking into the pumping chamber [11]. The mating surfaces on both the ICV plunger and stop were severely damaged after running with gasoline. However, the upgraded pump features larger fuel inlet drillings and a cone-shaped ICV pintle/seat with reduced sealing surface contact area. These features help to reduce the high flow velocities and throttling losses, which lead to regions of low local static pressure and cavitation. Photos of the new pump's ICV pintle and seat are shown in Figure 6(b). No signs of cavitation-induced pitting or erosion were detected after running with gasoline for 400 hours. There were also no abnormal signs of impact or friction wear indicating that these components were properly lubricated by the additive-dosed gasoline. The excellent condition of the new ICV at the end of testing means that it was able to maintain its seal integrity and prevent any

FIGURE 4 Bounded-box and K-factor definitions for nozzle hole geometry measurements (production injector shown).

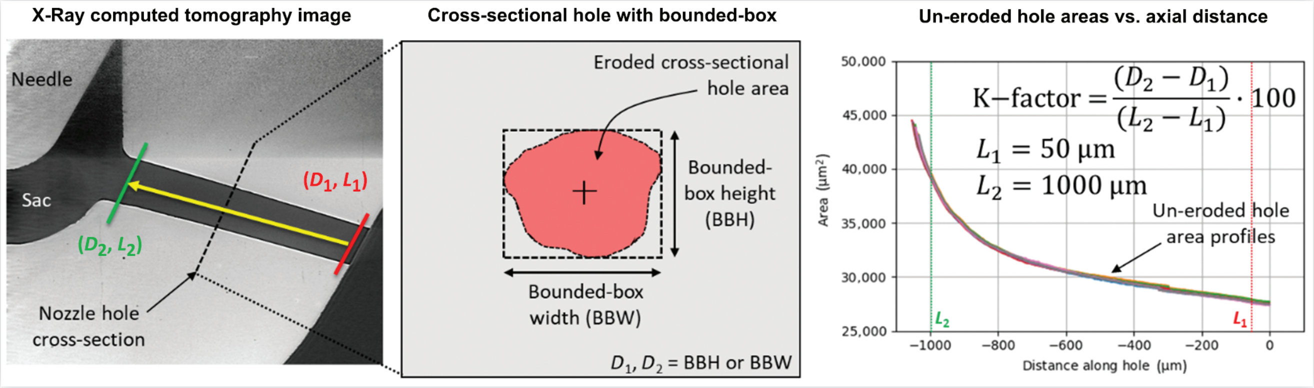

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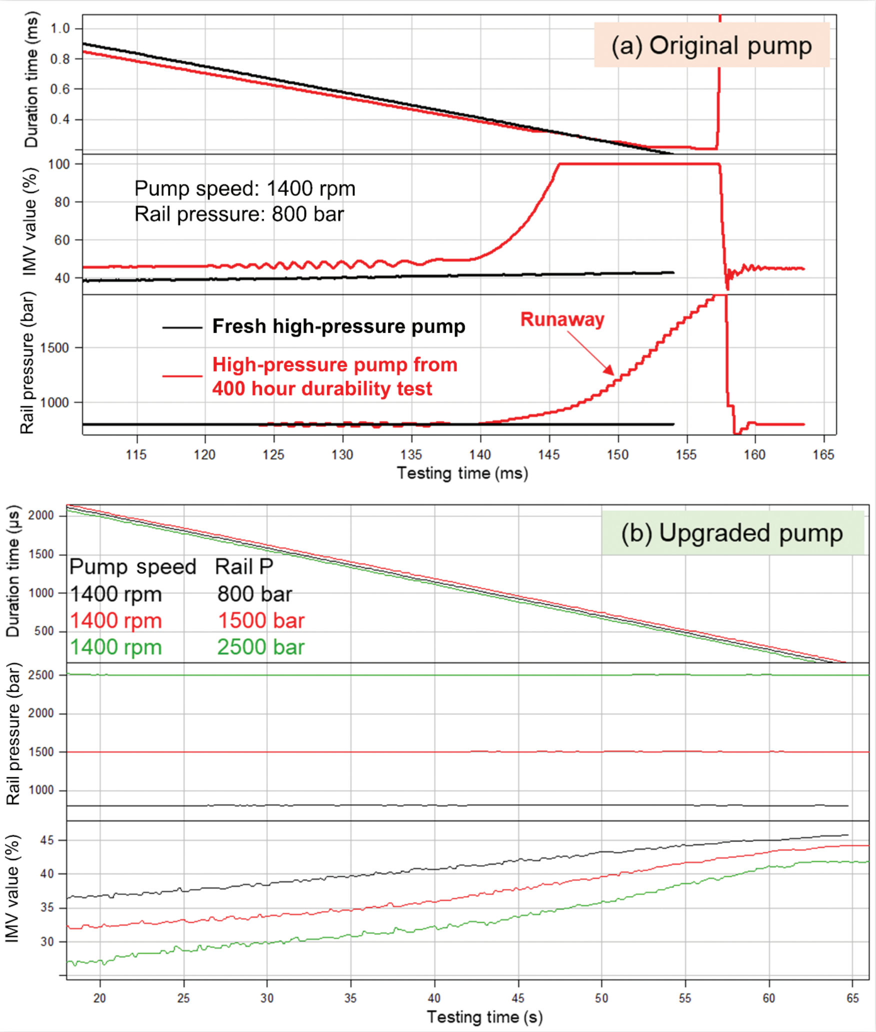
FIGURE 5 Pump performance after 400 hours of operation with RON60 gasoline: (a) original pump design and (b) upgraded pump design.



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unintended fuel leakage into the pumping chamber. This design shows drastically improved gasoline robustness and aligns with a prior light-duty endurance study run with similar hardware and E10 [21].

3.2. Upgraded Injector Pilot Valve

Figure 7 shows the fueling curves of original injectors exposed to different runtimes on RON60 gasoline [11]. Although fueling capacity was maintained after 600 hours of operation, a significant degradation was observed after 800 hours on the NATO durability cycle. Teardown analysis was performed on the malfunctioning injector and revealed that the flow loss was due to a material compatibility issue in the pilot valve. The low fueling performance was caused by a 30% reduction in the nominal pilot valve stroke. Proper operation of the pilot valve is essential for ensuring that hydraulic performance of the injector is maintained throughout its useful life. As indicated by the inset to Figure 7, the condition labeled as "Rate of Injection—Point 1" (P1) shows a longer hydraulic delay, slower opening ramp, lower peak fueling rate, and reduced hydraulic duration at the 800-hour mark. The malfunction also seems to be pressure dependent with the largest deviations occurring between 1700 and 2500 bar.

The injector fueling loss issue was resolved by making proprietary upgrades to the materials and design of the pilot valve mechanism. Although the details of these modifications will not be discussed here, results using the upgraded hardware indicate that significantly improved robustness against gasoline-like fuel was achieved. Figure 8 compares the fueling curves of a fresh upgraded injector with its performance after running 800 hours on the durability cycle with RON60 gasoline. There is some observable flow loss as indicated by the lower injected quantities after 800 hours. Compared to the results from Figure 7, however, degradation of the upgraded injector was far less severe at the highest injection

FIGURE 6 Teardown photos of the inlet check valve (ICV) after 400 hours of operation with RON60 gasoline: (a) original pump design—(i) plunger and (ii) stop, (b) upgraded pump design—(iii) pintle and (iv) seat.

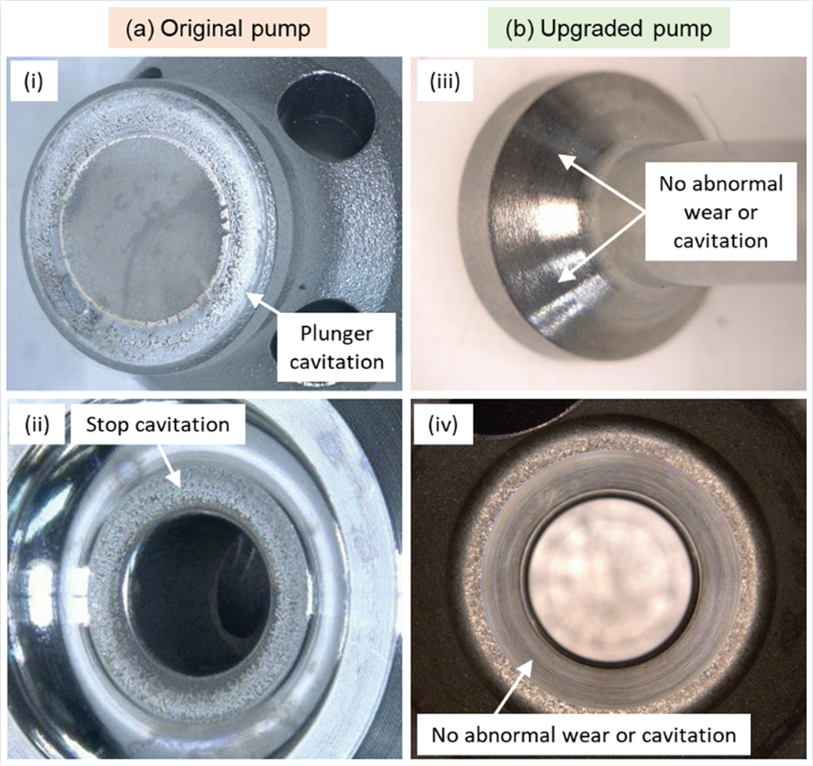

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FIGURE 7 Injected quantity vs. electronic duration curves for original injectors taken at different durability cycle runtimes; Inset—ROI profile at an injection pressure of 2500 bar and electronic duration of 1.56 ms.

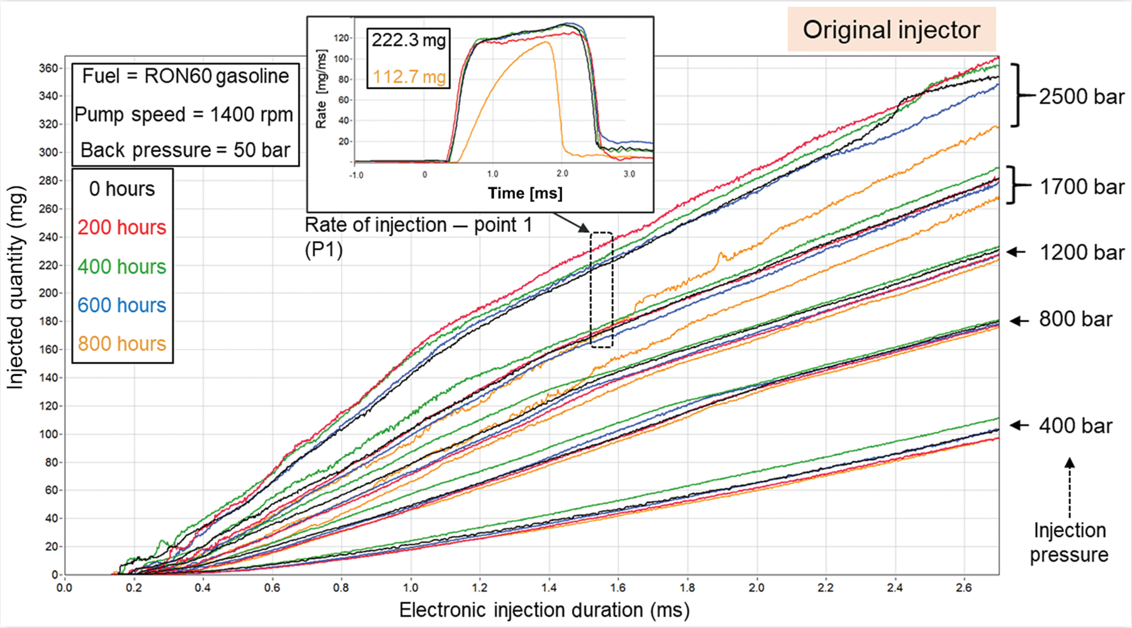

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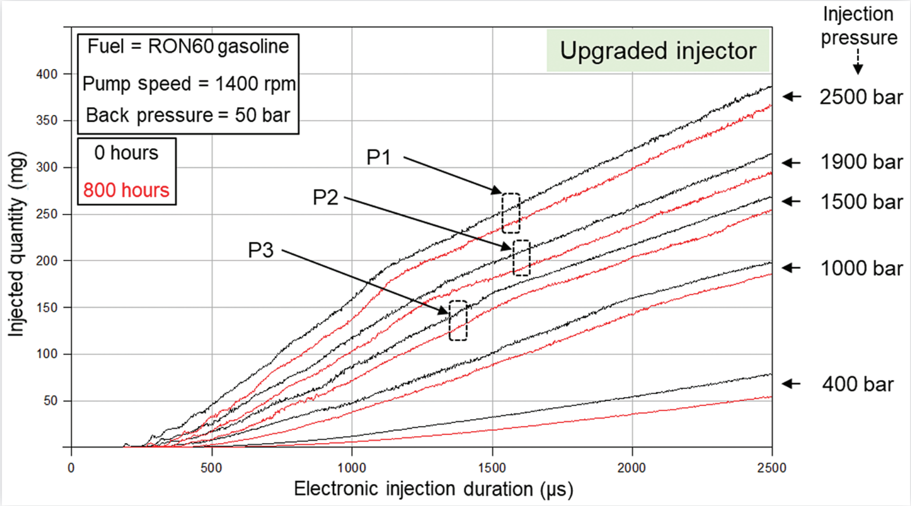
FIGURE 8 Injected quantity vs. electronic duration curves for the upgraded injector comparing fresh and 800-hour performance.



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pressure of 2500 bar. Additionally, there did not seem to be any pressure dependance of the flow loss with a similar decrease observed across all injection pressures. This suggests that the mechanism of fueling loss for the upgraded injector may have been due to a different phenomenon, such as hardware break-in. Figure 8 also identifies three specific operating points where high-fidelity ROI profiles were measured before and after running the durability test cycle. The conditions for P1, P2, and P3 are summarized in Table 3.

The ROI profiles for the test points listed in Table 3 are plotted in Figure 9. Compared to the inset of Figure 7 for the original injector, the upgraded hardware shows much more consistent behavior for P1 after 800 hours of durability testing. The same level of consistency was also observed at all the other test conditions. For the original hardware, there was a decrease of 109.6 mg (49.3%) in total injected quantity at P1 after 800 hours of operation with RON60 gasoline. In contrast, the upgraded injector only lost 8.1–11.2 mg (3.6-6.5%) of total fueling capacity after 800 hours and across all three test points. The data in Table 4 shows that this degradation did not exceed the fresh part-to-part variability among three upgraded injectors (i.e., a range in the maximum difference of injected quantity from 13.3 to 16.4 mg). Therefore, the 800-hour fueling performance of the upgraded injector remained within acceptable limits at the end of durability testing.

TABLE 3 Rate of injection test point specifications.

Test point	Injection duration (ms)	Rail pressure (bar)
P1	1.56	2500
P2	1.59	1900
P3	1.36	1500

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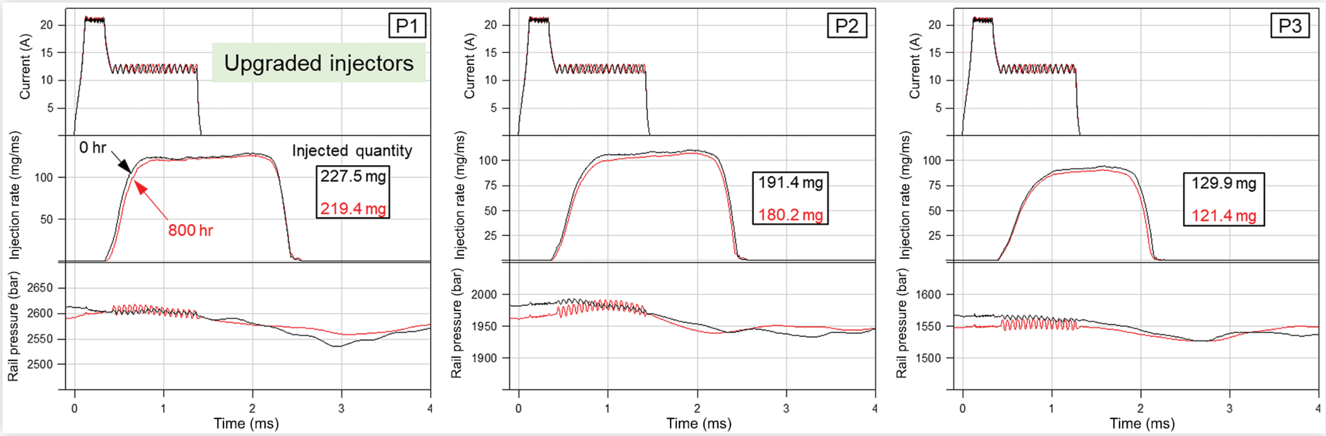
3.3. Upgraded Injector Nozzle Tip

Figure 10 compares the hole-averaged K-factor (Kf) determinations of various injector nozzle tips. This data was extracted from corresponding X-ray computed tomography images along the bounded-box height (BBH) and width (BBW) dimensions (i.e., Kf-BBH and Kf-BBW, respectively). Several key points can be discerned from the results. First, the hole-to-hole variability in K-factor determined for a used injector when excluding eroded orifices closely matches that of a fresh, unused injector where all the holes are considered. This tight tolerance in geometric repeatability for a given injector can also be seen in the overlapping hole area curves presented in Figure 4. Therefore, the K-factors of used injectors can be accurately determined even when excluding eroded holes from the calculation. This helps to avoid erroneous K-factor determinations when orifice damage extends to locations along the orifice where diameters need to be evaluated. Second, Figure 10 indicates that when accounting for hole-to-hole variability, there was no large, statistically significant difference in Kf-BBH or K-factor along the vertical bounded-box direction. Therefore, the propensity for cavitation erosion along this dimension was not expected to vary much across injectors. Third, there was a large, statistically significant difference between Kf-BBH and Kf-BBW for all the injectors. This means that different levels of cavitation erosion were expected along the height and width dimensions of the nozzle holes. Finally, one of the injectors showed a higher Kf-BBW than the others. This is labeled as the "high K-factor injector" and was expected to exhibit suppressed cavitation damage compared to the original geometry, specifically along the width dimension.

Figure 11 compares the nozzle hole BBH and BBW profiles of the original versus upgraded injectors after 400 hours of

FIGURE 9 Current, rate of injection, and rail pressure profiles before and after 800 hours of durability cycle runtime on RON60 gasoline for the upgraded injector and test points listed in Table 3.



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durability testing with RON60 gasoline. Any increases in these metrics along the orifice channel represent deviations from the nominal profile and indicate cavitation damage due to erosion. One clear observation is that the erosion was much less pronounced along the BBW dimension for both injectors. This correlates well with expectations given that Kf-BBW is larger than Kf-BBH in both cases. However, it is difficult to deconvolute the impact of K-factor from the inlet hole radius of curvature (R_{in}), which has also been found to reduce cavitation. Both parameters increase when comparing the width versus height dimensions. Furthermore, previous internal nozzle flow simulation studies have found that hole ellipticity (i.e., larger diameter along the width versus height dimension) has a substantial, independent effect on cavitation suppression in addition to K-factor and R_{in} [22]. Therefore, with these points in mind, it is only reasonable to conclude that a more gradual inlet hole profile and larger channel taper help to reduce cavitation erosion. The main evidence supporting this finding is given by the geometric feature and erosion pattern trends between the BBH and BBW profiles.

Even with the quantitative assessment of erosion shown in Figure 11, it is somewhat difficult to determine which injector experienced more severe nozzle hole damage. Although there was perhaps a slightly higher Kf-BBH for the upgraded injector, it had a very similar peak magnitude of pitting damage compared to the original injector at a location closest to the nozzle hole inlet. This does not suggest a strong correlation between cavitation avoidance and K-factor. However, the secondary erosion peaks closer to the nozzle hole exit were higher for the original, slightly lower Kf-BBH injector, as were the number of holes that started to show signs of damage at the primary upstream pitting location. This does suggest a positive correlation. Finally, although the extent of damage along the BBW dimension for the upgraded injector was quite localized, the peak magnitude of pitting was like that of the original injector with lower Kf-BBW. These somewhat conflicting results suggest that perhaps another competing factor besides geometry was likely influencing the mechanism of cavitation.

TABLE 4 Variability in fresh (0-hour) injected quantity performance for three upgraded injectors.

Test point	Injector-1 (mg)	Injector-2 (mg)	Injector-3 (mg)	Maximum difference (mg)
P1	227.5	227.4	240.7	13.3
P2	191.4	187.7	202.0	14.3
P3	129.9	124.2	140.6	16.4

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Previous needle lift measurements and internal nozzle flow simulation studies for the same baseline Cummins XPI injector have shown that eccentric radial needle motion (i.e., wobble) is likely a significant driver of cavitation phenomena within the injector tip [26, 27]. It was found that unique flow fields in the sac region were caused by repeatable needle wobble motion and strongly correlated with the preferential cavitation-induced erosion patterns observed in used injector nozzles run with light distillate fuels. Measured needle wobble was superimposed on the real, high-resolution geometry of the nozzle tip to simulate the flow patterns of RON60 gasoline during an injection event [22]. Figure 12 shows that eccentric needle motion creates preferential flow along the seat closest to Orifice 7, which then cuts across the sac and exits through Orifice 3. A very low-pressure region is created at the entrance of Orifice 3 resulting in the formation of a corresponding vapor envelope. The location of cavitation zone collapse coincides with where pitting was observed on the injector after durability testing with gasoline. This finding helps to explain why different holes showed more cavitation damage than others, even though their geometric features suggest otherwise.

The data in Table 5 further elaborates on this point by demonstrating that the most severely eroded holes from the upgraded injector (i.e., #1 and #2) do not correspond to those with the lowest K-factor along the BBH or BBW dimensions. In fact, the holes with the highest K-factor exhibited the most severe erosion. A similar analysis was not performed on the original injector because the erosion damage extended to the nozzle exit plane, which would influence the calculation of

FIGURE 10 Hole-averaged injector K-factor determinations based on X-ray computed tomography images using bounded-box height (BBH) and bounded-box width (BBW) definitions.

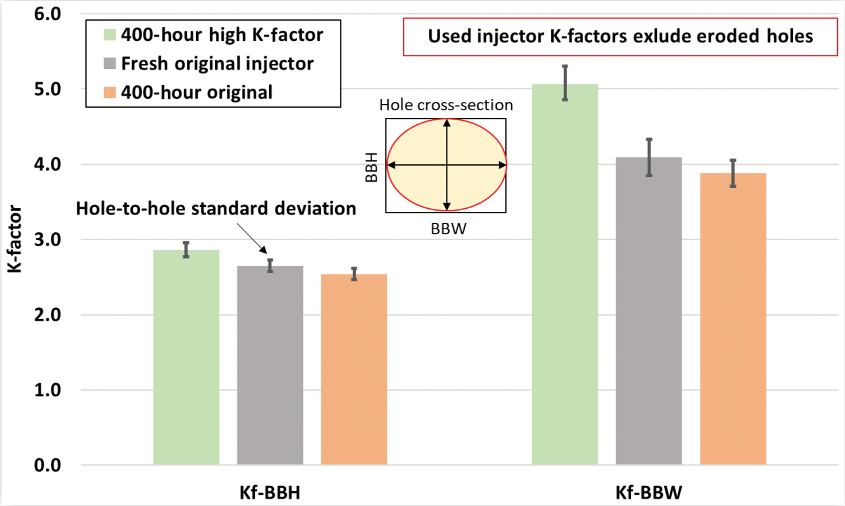

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FIGURE 11 Nozzle hole bounded-box height and bounded-box width profiles for (a) the original nozzle tip design and (b) the upgraded nozzle tip design, both after 400 hours of durability cycle testing with RON60 gasoline.

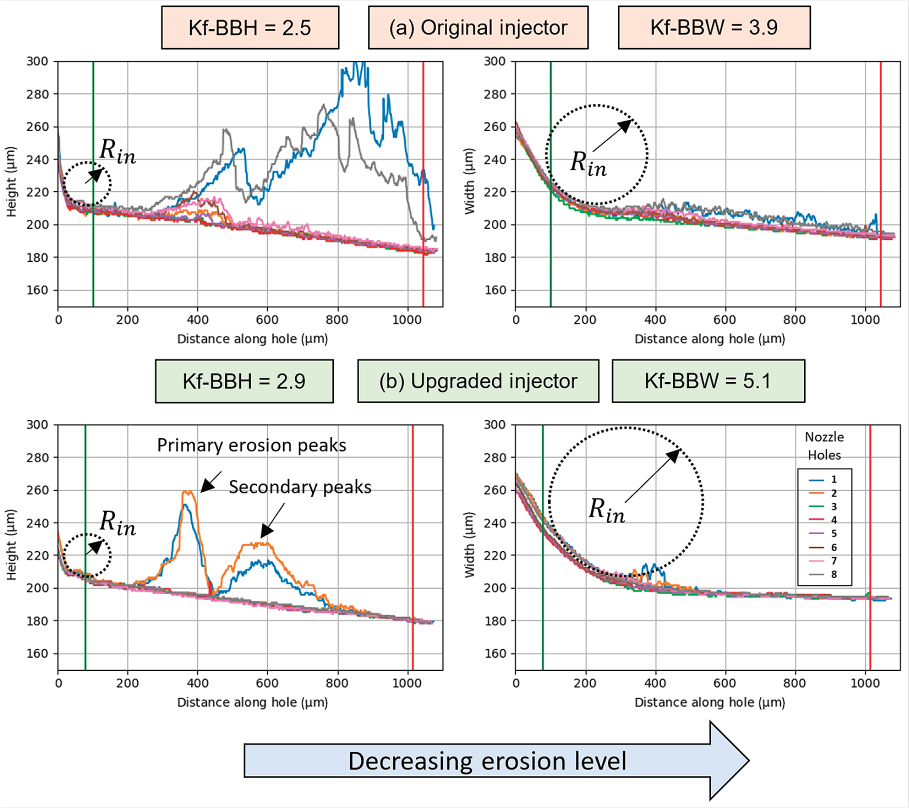

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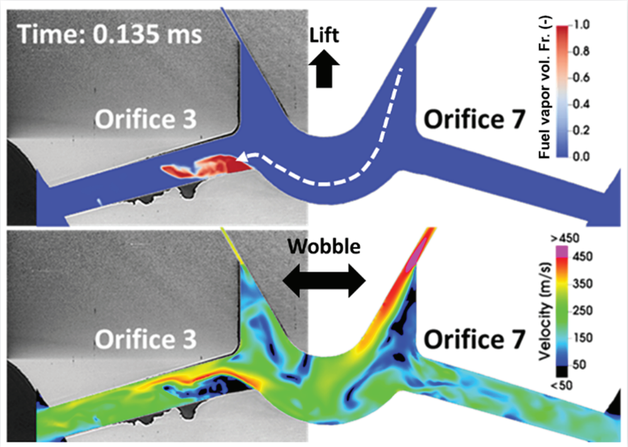
FIGURE 12 Internal nozzle flow simulation results overlaid with X-ray computed tomography scans of an injector tip after 800 hours of durability cycle runtime with RON60 gasoline.



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K-factor. In summary, there seems to be a competition between which mechanism drives cavitation-induced erosion differences with injector-to-injector variation in eccentric needle motion likely dominating over geometric factors.

Figure 13 compares the individual hole erosion patterns of the original versus upgraded injectors using side-view X-ray computed tomography images (see Figure 2 for viewpoint definitions). The original injector shows the most severe cavitation damage in holes 1 and 8, while the upgraded hardware shows erosion only in holes 1 and 2. The pattern of an initial or primary erosion zone followed by a cascade of one or more subsequent pitting locations is somewhat repeated with both injectors. The hole area profiles in Figure 14 clearly show these primary and secondary zones of cavitation-induced damage as well. One possible explanation for these patterns is that once a primary pitting location has been established at the original location of vapor envelope/bubble collapse, another one appears downstream due to the flow patterns induced by the first, and so on. According to the hole numbering convention shown for the bottom-view images shown in Figure 15, the most severely eroded holes also consistently appear near or alongside one another. As previously described, this grouping and preferential hole pitting can be explained by the influence of radial needle motion on internal nozzle flow. Therefore, in addition to mitigating cavitation with nozzle tip geometric features such as high K-factor, R_{in}, and ellipticity, reducing the extent of needle wobble motion is also strongly recommended.

TABLE 5 Hole-by-hole K-factors and erosion levels along the bounded-box height and width dimensions for the upgraded injector.

Hole #	Kf-BBH	Kf-BBW	Comment
1	2.96	5.56	Severely eroded
2	2.96	5.56	Severely eroded
3	2.96	5.31	No damage
4	2.84	4.94	No damage
5	2.96	4.69	No damage
6	2.59	4.82	No damage
7	2.84	5.19	No damage
8	2.96	5.43	No damage

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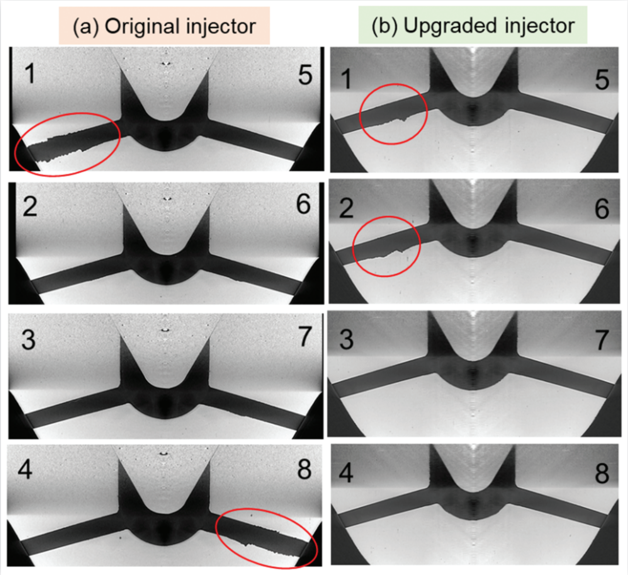
FIGURE 13 Side-view X-ray computed tomography images of the (a) original vs. (b) upgraded injector nozzle tips after 400 hours of durability cycle runtime with RON60 gasoline.



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4. Conclusions

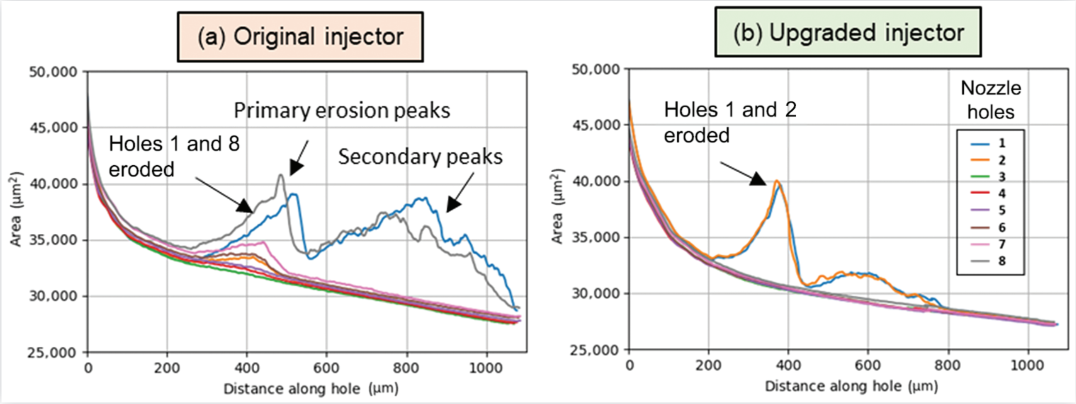
Previous durability studies were conducted using a heavy-duty common rail injection system with gasoline-like fuel and identified the following key technical risks for high-pressure applications:

1. Inlet side cavitation damage to the high-pressure pump, specifically the ICV
2. Loss of fuel metering capacity for the injectors due to pilot valve material incompatibility
3. Cavitation-induced erosion damage to the injector nozzle holes

The purpose of the current work was to address these concerns by upgrading the hardware, running a consistent 400- to 800-hour NATO test cycle with the same light distillate fuel, and demonstrating that the proposed solutions could extend the endurance of fuel system components for high-pressure gasoline applications. The main findings from this investigation are as follows:

- An upgraded high-pressure pump with larger fuel inlet drillings and lower ICV sealing surface contact was tested. These features helped to suppress cavitation on the inlet side of the pump. As a result, the cone-on-cone ICV pintle/seat design showed no abnormal signs of

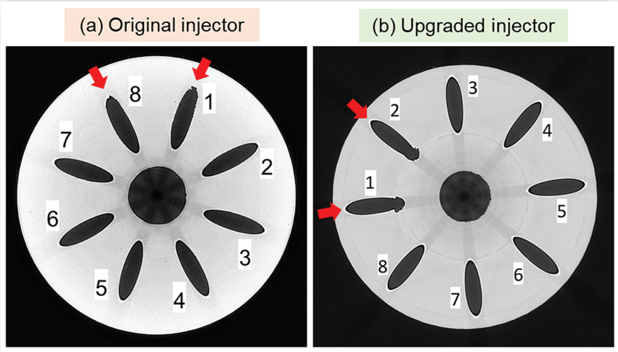
FIGURE 14 Nozzle hole area profiles of the (a) original vs. (b) upgraded nozzle tips after 400 hours of durability cycle runtime with RON60 gasoline.



wear or erosion after 400 hours of testing with gasoline-like fuel. Hydraulic pump performance was uncompromised at the end of testing indicating that the sealing integrity of the ICV remained completely intact. This was a drastic improvement to the original design, which exhibited severe cavitation damage and did not pass a motored performance test after running the same durability cycle with the same fuel.

- The materials and design of the injector pilot valve were upgraded to avoid a nearly 50% loss in total injected fuel quantity that was initially observed with gasoline after 600–800 hours of durability testing. The root cause of lower fueling rate was attributed to a 30% reduction in the pilot valve stroke, which directly impacts needle lift dynamics and subsequent ROI behavior. After 800 hours of durability testing with gasoline-like fuel, the upgraded injector experienced a less than 6.5% reduction in total injected mass. This was deemed as an acceptable change because it remained within the injector-to-injector performance variation measured for fresh hardware.
- The erosion patterns of two nozzle hole designs were compared after 400 hours of durability testing and revealed some important considerations for mitigating cavitation damage due to the use of gasoline-like fuels. The trends in orifice pitting along the horizontal versus vertical dimensions of the nozzle orifice suggest that a more gradual hole inlet profile (i.e., inlet radius of curvature) and larger converging hole taper (i.e., K-factor) help to suppress cavitation. It was difficult to decouple the impact of these geometric design features because both increase when moving from the vertical to horizontal dimension of the hole. Hole-to-hole and nozzle-to-nozzle trends in erosion do not correlate well with geometric factors, likely because the dominant cavitation mechanism with the greatest variability is eccentric needle motion-induced flow patterns. Therefore, needle wobble also likely needs to be reduced for further improvement in the cavitation resistance of high-pressure gasoline injectors.

FIGURE 15 Bottom-view X-ray computed tomography images of the (a) original vs. (b) upgraded nozzle tips after 400 hours of durability test runtime with RON60 gasoline.



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Definitions

APS - Advanced Photon Source
ASTM - American Society for Testing and Materials
BBH - Bounded-box height
BBW - Bounded-box width
D - Nozzle hole diameter
(D)CN - (Derived) cetane number
E10 - Gasoline containing 10% ethanol by volume
FBP - Final boiling point
GCI - Gasoline compression ignition
GDI - Gasoline direct injection
IBP - Initial boiling point
ICV - Inlet check valve

IMV - Inlet metering valve

Kf - K-factor (nozzle hole taper)

L - Axial distance along nozzle hole

LHV - Lower heating value

MON - Motor octane number

NATO - North Atlantic Treaty Organization

NOx - Numerical sum of NO and NO_2 emissions

P - Pressure

PX - Test point number X

R_{in} - Inlet radius of curvature

ROI - Rate of injection

RON - Research octane number

RPM - Revolutions per minute

RVP - Reid Vapor Pressure

TXX - Temperature at which XX% of fuel volume has evaporated

ULSD - Ultralow sulfur diesel

WSD - Wear scar diameter

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