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Review On Water Injection Effects on An Engine

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ABSTRACT
Water injection (WI) improves internal combustion engine performance by lowering combustion temperatures, reducing knocking, and cutting nitrogen oxides (NOx) emissions. While excessive water harms efficiency, optimized flow rates enhance torque and combustion stability. In both diesel and gasoline engines, WI reduces NOx and particulate matter by delaying ignition and cooling combustion, with injection timing (compression/expansion strokes) critically influencing power output and detonation prevention. Combining WI with exhaust gas recirculation (EGR) or lean burn strategies boosts fuel efficiency and combustion stability. Simulations highlight that higher water injection pressures suppress knocking through better atomization and reduced reactive chemical formation. Overall, WI offers a versatile solution for cleaner, more efficient engines, though further research is needed to optimize parameters and assess long-term impacts. This review underscores WI's potential as a key strategy to meet emission standards without compromising performance.

Keywords: Water injection, internal combustion engines, emissions reduction, combustion efficiency, NOx, knocking, exhaust gas recirculation.

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I. INTRODUCTION

The automotive industry is exploring water injection (WI) to reduce emissions and improve efficiency amid climate change and stricter regulations. Originally used in WWII aircraft, WI lowers combustion temperatures, reducing NOx emissions and preventing engine knock, while enabling leaner or higher-compression operation for more power.

The pursuit of enhanced efficiency and reduced emissions in internal combustion engines (ICEs) has driven research into innovative technologies, with water injection (WI) emerging as a promising strategy. By leveraging water's high latent heat of vaporization and specific heat capacity, WI mitigates combustion temperatures, suppresses knocking, and improves thermal efficiency, while addressing environmental regulations.

Water Injection (WI) reduces in-cylinder temperatures, enabling advanced ignition timing and higher compression ratios without knock in both NA and turbocharged engines. It boosts torque by 1.3–2.4% for RON 90/92 fuels. WI cuts NOx emissions by 90% at optimal water-to-fuel ratios (25%). Injection pressures above 40 bar suppress knock by enhancing atomization. Challenges include poor evaporation, wall wetting, and combustion instability at high water fractions. Tailored strategies, like late exhaust-stroke injection, maximize efficiency, while WI in lean-burn setups achieves 8.2% fuel efficiency gains, showcasing its adaptability.

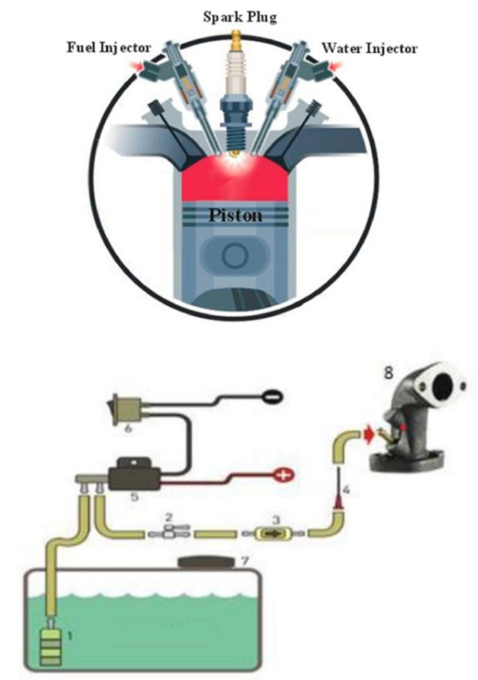

Figure 1. Schematic of water injection implementation; 1) water filter; 2) one way valve; 3) one way filter, 4) orifice; 5) vacuum solenoid; 6) on/off switch; 7) water tank; 8) intake manifold **[5]**

II. Effects of Water Injection in Spark Ignition Engine

Water injection significantly enhances engine performance across multiple parameters. Brake power increases notably from approximately 35 kW under dry combustion conditions to around 55 kW with a water injection rate of 1.5 g/s at an air-fuel ratio (AFR) of 14.5. This improvement is primarily due to reduced compression work, enhanced volumetric efficiency, and stoichiometric combustion. Additionally, thermal efficiency experiences a substantial rise of about 10%, increasing from 32% to approximately 42%, as water evaporation helps lower exhaust temperatures. The brake-specific fuel consumption (BSFC) decreases with higher water mass flow rates, improving from 240 g/kWh in dry conditions to 200 g/kWh at 1.5 g/s, indicating improved fuel efficiency. Furthermore, mean effective pressure (MEP) benefits from advanced spark timing and knock mitigation, contributing to overall engine performance enhancement. **[4]**

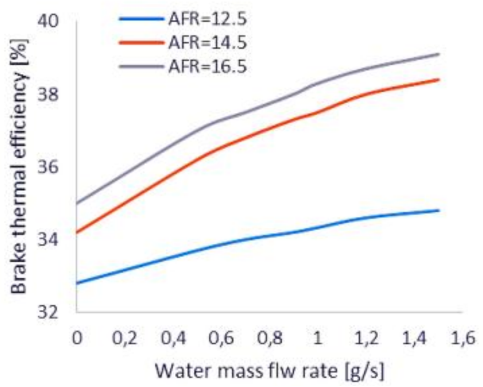

Figure 2. Effect of water injection on engine thermal efficiency **[4]**

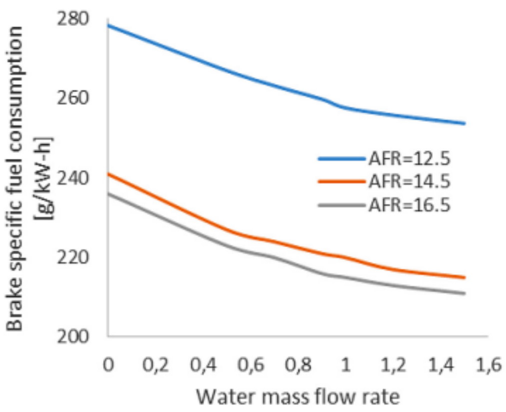

Figure 3. Effect of water injection on fuel consumption for different AFR **[4]**

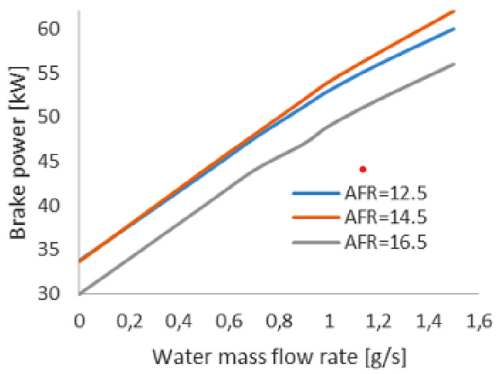

Figure 4. Effect of water injection on engine brake power for different AFR **[4]**

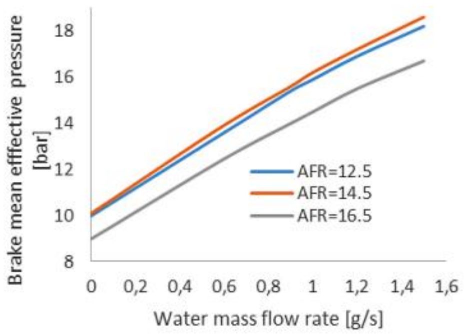

Figure 5. Effect of water injection on engine pressure [4]

An optimal water injection rate of 1.0–1.5 g/s enhances engine power and efficiency without negative effects, while exceeding 1.5 g/s leads to combustion retardation, lower cylinder pressure, and reduced thermal efficiency. A stoichiometric AFR of 14.5 delivers peak power (55 kW) with minimal HC and CO emissions. In contrast, leaner mixtures like AFR 16.5 produce higher NOx emissions but reduce CO levels, highlighting the trade-offs between emissions and performance. **[4]**

2.1 Effect of Dual Time Water Injection

WI during the compression stroke. When water is injected at 80° crank angle (CA) before top dead centre (bTDC), it absorbs heat from the compressed air-fuel mixture, lowering peak compression pressure by 2%. This reduction in compression pressure decreases the work required for compression, leading to improved fuel efficiency. At the same time, the lower combustion temperature suppresses NOx formation. Among different water-to-fuel mass ratios tested, a 15% water addition (WA) was found to be the most effective, yielding the highest in-cylinder pressure and enhancing overall engine performance.

The study also examines WI during the expansion stroke, where the injected water initially absorbs heat, causing a temporary 2.7% decrease in in-cylinder pressure. However, as the water evaporates into steam, it expands in volume, resulting in a 2.5% pressure increase during the second phase of combustion. This dual-stage effect contributes to better power output and improved efficiency. The study further highlights that increasing the water injection temperature to 200°C leads to a 4% rise in peak in-cylinder pressure, demonstrating that heated water can further enhance performance.

Another significant advantage of WI is its role in reducing heat losses and controlling engine temperatures. Water injection reduces the amount of heat transferred to engine components such as the piston crown, cylinder liner, and combustion chamber walls, which helps in preventing excessive wear and detonation. With a 25% WI mass, the study recorded notable surface temperature reductions of 46K for the piston crown, 83K for the cylinder liner, and 35K for the combustion chamber. These reductions not only improve thermal efficiency but also contribute to extended engine life and prevent pre-ignition issues caused by overheated hotspots. **[2]**

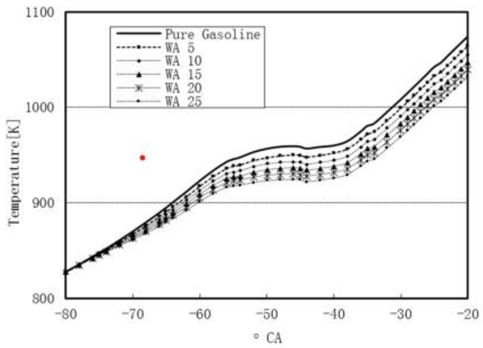

Figure 6. The decrease in compressed charge temperature as a consequence of injected water [N2]

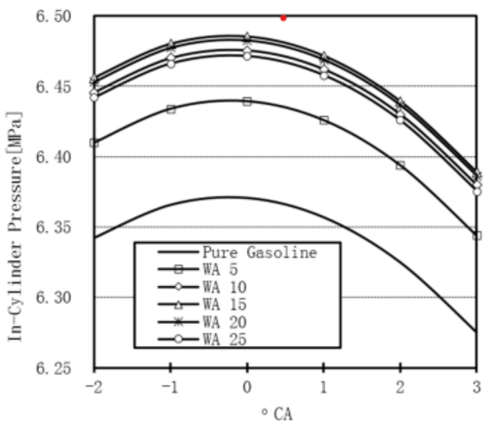

Figure 7. The increase of peak in-cylinder pressure for the volumetric expansion of steam. [N2]

III. Effect of Water Injection in Compression-Ignition Engines

It highlights that water injection plays a crucial role in improving combustion efficiency by cooling the intake charge, increasing air density, and mitigating detonation risks. By carefully regulating the water-to-fuel ratio, the study finds that a 15% water injection by mass yields the best results, leading to increase in-cylinder pressure and overall engine performance. This improvement is attributed to the cooling effect of water vaporization, which prevents premature ignition and allows for a more controlled combustion process. **[3]**

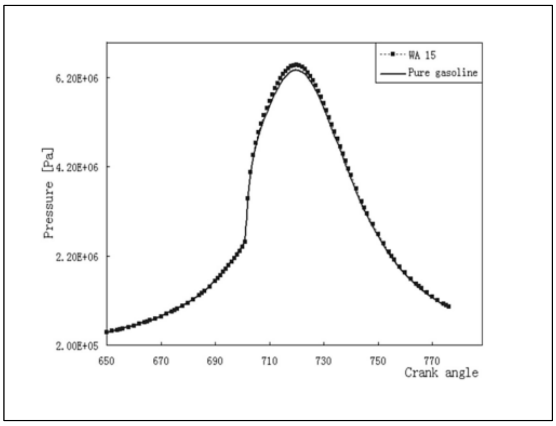

Figure 8. 7. Indicated mean effective pressure for 15% water injection compared with the pure gasoline case**. [3]**

Moreover, water injection offers notable engine cooling benefits. The study highlights that critical engine components such as piston crowns, combustion chambers, and exhaust valves experience a reduction in temperature, preventing overheating and enhancing engine durability. This cooling effect not only improves thermal efficiency but also enables the use of higher compression ratios, leading to better fuel economy. **[3]**

Water injection (WI) in a diesel engine highlights its significant impact on both reducing compression work and enhancing power output. Conducted on a 2.0L high-speed direct injection (HSDI) diesel engine, the research demonstrates that injecting water into the intake manifold in fine mist form can lower combustion temperatures, optimize fuel efficiency, and reduce emissions while maintaining or even increasing engine power. **[1]**

One of the primary advantages of WI is its ability to reduce compression work by cooling the intake charge before combustion. When water is injected, it absorbs heat during vaporization, leading to a decrease in intake air temperature. The study found that injecting 3 kg/h of water at 20°C reduced the intake manifold temperature from 91°C to 60°C.

This cooling effect lowers peak in-cylinder temperatures at the start of combustion (SOC) by approximately 100K, which in turn reduces the work required during the compression stroke. Additionally, WI increases the ignition delay—the time between fuel injection and combustion—which allows for a more homogeneous air-fuel mixture. At higher WI rates, the ignition delay was observed to increase from 0.23 ms to 0.82 ms, leading to improved combustion efficiency. **[1]**

Water injection (WI) enhances engine power by improving the rate of heat release (ROHR) and increasing peak in-cylinder pressure. At moderate WI rates, peak pressure rises, leading to more effective power strokes. Using heated water (up to 200°C) further boosts peak pressure by 4%. At high loads, WI helps maintain or increase brake mean effective pressure (BMEP), stabilizing torque. The most notable impact was at 21 kg/h of water injection, reducing NOx emissions by 77% while preserving engine performance. **[1]**

Configuration	C1	C2	C3
Cooling method	–	WI (3 kg/h)	Intercooler
P_2'' (mbar)	1800	1800	1800
T_2'' (°C)	91	60	60
NOx (g/kg fuel)	27.1	17.8	24.6
PM (g/kg fuel)	0.28	0.35	0.26
Rel. NOx reduction	–	34%	9%
Rel. PM increase	–	26%	–8%
λ	1.78	1.82	1.86

Table 1. Comparison of cooling effect of WI and the intercooler **[1]**

A study also examined the impact of water injection on the power output of a 4-stroke internal combustion engine using RON 90 and RON 92 fuels. Results showed that water injection did not significantly increase engine power. With RON 90 fuel, power output decreased by 1.74% (0.9 kW), while with RON 92 fuel, there was no change in power. However, water injection improved torque by 1.30% (1 Nm) with RON 90 fuel, though it slightly decreased torque by 0.25% (0.19 Nm) with RON 92 fuel.

Specific fuel consumption (SFC) increased by 11.9% (32.2 g/kWh) with RON 90 but decreased by 16% (43.6 g/kWh) with RON 92, indicating better fuel efficiency. Overall, water injection had a minimal effect on power output but showed potential for improving torque and fuel efficiency, depending on the fuel type. **[5]**

Engine speeds (rpm)	RON 90			RON 92		
	Power (KW)	Torque (Nm)	SFC (g/kWh)	Power (KW)	Torque (Nm)	SFC (g/KWh)
Without Water Injection						
4000	2.71	7.89	249	1.09	7.8	619
5000	3.75	7.56	225	3.84	7.8	219
6000	4.65	7.54	218	4.87	7.65	209
7000	5.2	7.39	228	5.11	7.75	240
8000	4.51	6.2	262	3.89	6.5	295
With water injection						
4000	2.71	7.89	381	1.8	7.56	374
5000	3.75	7.56	218	3.72	7.6	227
6000	4.65	7.54	248	4.55	7.52	223
7000	5.2	7.39	234	4.84	7.56	245
8000	4.51	6.2	262	3.88	6.3	295

Table 2. Experimental results **[5]**

IV. Water Injection effects on Knocking of an engine

The study finds that water injection at pressures above 40 bar significantly reduces knocking in high-compression-ratio engines. The improved atomization and evaporation of water cool the end-gas mixture, preventing auto-ignition. This reduces knock intensity, lowers peak temperatures and pressures, and decreases NOx emissions, although CO emissions increase slightly. The research concludes that direct water injection at higher pressures effectively suppresses knocking and improves engine performance. **[6]**

parameter	value
compression ratio	10.3
spark time/°CA	718
equivalence ratio	1.1 ± 0.01
total fuel injection mass/mg	65.0258
fuel injection time/°CA	440.25

Table 3. Knock condition of GDI Engine [AU6]

parameter	value
water injection temperature (°C)	25
water injection time (°CA)	640
water injection pressure (bar)	40, 60, 80, 100, 120
total water injection mass (mg)	16.256

Table 4. Water Injection parameters [6]

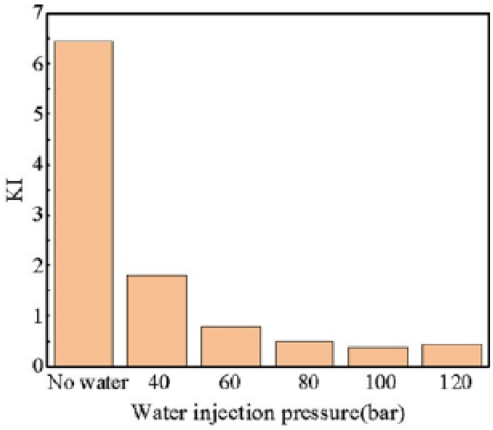

Figure 9. KI (Knocking) under different injection pressures [6]

V. NOx reduction and EGR through Water Injection in Engine

NOx emissions in internal combustion engines are primarily formed due to high combustion temperatures, where nitrogen (N_2) and oxygen (O_2) react. The main factors influencing NOx formation include combustion temperature, oxygen concentration, and residence time. Higher temperatures (above 1800 K) significantly increase NOx production, making emission control essential. **[7]**

Water injection effectively reduces NOx by lowering combustion temperatures through its high latent heat of vaporization. In the study, water was injected upstream of the throttle valve in a 1.6L, 4-cylinder gasoline engine at rates ranging from 10% to 45% of the total fuel mass. At 25% water injection, NOx emissions were significantly reduced without compromising engine performance. At 40% injection, NOx emissions dropped by approximately 38%, though a slight power loss (~4%) was observed. However, this can be mitigated by adjusting ignition timing.

The findings confirm that water injection is a practical method for NOx reduction in gasoline engines, with 25% being an optimal balance for emissions control and performance. Further research is needed to refine injection parameters for maximum efficiency. **[7]**

The study shows that water injection (WI) can lower combustion temperatures—key for reducing NOx, which is generated when high temperatures trigger the Zeldovich mechanism. In a 2.0 L naturally aspirated SI engine, injecting water advanced the spark timing by about 2–3° crank angle (CA) during the intake/compression strokes and by up to 5.6° CA during the exhaust stroke. When WI was applied at 300° CA after top dead centre (aTDC), the Brake Specific Fuel Consumption (BSFC) was reduced by as much as 4.95%. Increasing the water-to-fuel (W/F) ratio to 0.47 further improved the BSFC reduction to 6.1%. **[8]**

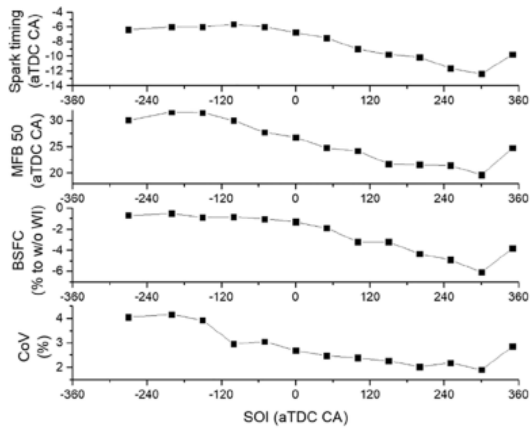

Figure 10. Water injection timing effect on combustion characteristics and fuel consumption. Engine speed of 1600 RPM, BMEP of 7 bar, injection pressure of 100 bar, WFR of 0.47 [8]

The real boost comes when combining WI with Exhaust Gas Recirculation (EGR). With a 10% EGR rate—compared to an EGR-only condition of 20.24%—the optimal water injection timing shifted to 200° CA before top dead centre (bTDC). This combination advanced the spark timing even further and improved fuel efficiency by up to 9.14% relative to the base case, and by 3.05% compared to using EGR alone. Although the report doesn't provide direct NOx emission numbers, these significant improvements in fuel efficiency and combustion control imply lower peak temperatures, which in turn reduce NOx formation. **[8]**

VI. Conclusion

- WI reduces NOx emissions by up to 50% when water is injected at 60–65% of the fuel mass, primarily through the cooling effect of water vaporization.
- WI is especially effective under high-load conditions, outperforming EGR by maintaining airflow and avoiding excess particulate matter, while EGR remains more advantageous at low loads due to its simplicity.
- With RON90, WI boosts torque by 1.30% but slightly cuts power by 1.74%, while with RON92, power remains stable and torque drops marginally (0.25%).
- WI increases SFC by 11.9% for RON90 yet reduces it by 16% for RON92, reflecting the inverse relationship between SFC and efficiency.
- Over-injecting water (beyond an optimal 15% water-to-fuel ratio) harms combustion

efficiency, emphasizing the need for precise dosing tailored to engine conditions.

- Integrating WI with lean combustion or EGR strategies can lower BSFC by 9.3%.
- High injection pressures (>40 bar) help inhibit knock in GDI engines.

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