A review of water injection applied on the internal combustion engine

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Abstract:

As a promising technique to reduce the in-cylinder temperature and exhaust temperature, mitigate combustion knock, improve combustion phasing and decrease NO_x emissions, water injection applied on different types of engines has attracted extensive attention in recent years to further improve fuel economy and fulfill stricter emission regulations. Since mechanisms of water injection with different aims are distinct, benefits on engine performances and emissions are also varied. This paper intends to give a comprehensive review of water injection applied on the internal combustion engine. First, different implementations of water injection are introduced, followed by a detailed description of water evaporation processes. Second, mechanisms of the in-cylinder combustion process with water addition are discussed with respect to the heat release rate, knock tendency and emission formations. Next, recent works of water injection applied on different kinds of engines are reviewed with special attentions given to the comparisons of different implementations and injection parameters. Furthermore, comparisons and combinations of water injection with other advanced engine techniques are summarized. Finally, critical issues of current research on the water injection technique are discussed.

Key words:

Internal combustion engine; Water injection; Knock; NO_x emissions; Fuel efficiency.

Nomenclature:

AFR	Air fuel ratio
AFTDC	After firing top dead center
AI	Auto ignition
AKI	Anti-knock index
ATDC	After top dead center
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTDC	Before top dead center

CAC	Charge air cooler
CAD	Crank angle degree
CFD	Computational fluid dynamics
CI	Compression ignition
CO	Carbon monoxide
CR	Compression ratio
DISI	Direct injection spark ignition
DOC	Diesel oxidizing catalysts
ECU	Electronic control unit
EGR	Exhaust gas recirculation
GDI	Gasoline direct injection
HC	Hydrocarbons
HCCI	Homogenous charge compression ignition
ICE	Internal combustion engine
IMEP	Indicated mean effective pressure
ISFC	Indicated specific fuel consumption
IVC	Intake valve closing
MFB	Mass fuel burned
MW	Methanol/water
NA	Naturally aspirated
NO_x	Nitrogen oxides
PFI	Port fuel injection

PM	Particulate matter
SI	Spark ignition
SOI	Start of injection
TIT	Turbine inlet temperature
VCR	Variable compression ratio
WI	Water injection
WLTC	Worldwide harmonized Light vehicles Test Cycles
WOT	Wide open throttle

Contents

1 Introduction

1.1 Background and significance

The ongoing changes to legislation are imposing more and more stringent constraints on tailpipe emissions and fuel consumption for the ICEs (internal combustion engines). This trend is pushing engine manufacturers to look for new solutions to obtain lower pollutant levels without lowering engine performance and market appeal [1].

Gasoline engine design trends are now oriented towards the adoption of the so-called downsizing and down-speeding techniques, while preserving their performance targets. Therefore, BMEP (brake mean effective pressure) is markedly increasing, leading to increased risks of knock onset and abnormal combustion. The above needs will be even more stringent in the near future, since more severe driving cycles are going to be imposed on manufacturers for vehicle testing, such as WLTC (Worldwide harmonized Light vehicles Test Cycles) [2].

For the highly efficient and widely used diesel engine, fulfilling stricter emission regulations (e.g. implemented EURO 6 standards for vehicles and IMO Tier3 for marine engines, upcoming China 6 regulations, etc.) has intensified research efforts investigating new in-cylinder strategies and/or aftertreatment devices. Even though levels of HC (hydrocarbons) and CO (carbon monoxide) are comparatively lower in diesel engines compared to gasoline due to the inherently lean combustion, NO_x (nitrogen oxides) and soot emissions can be significant. In addition, the contradictory formation conditions of NO_x and soot make it challenging to devise in-cylinder strategies to decrease these emissions simultaneously [3, 4].

1.1.1 Knock combustion

Knock is an abnormal combustion phenomenon which can constrain the engine performance and thermal efficiency. It can also result in severe engine damage under certain operating conditions. For SI engines, especially the downsized gasoline engine, the increased boost level for the prescribed high-load performance promotes the onset of knock or even pre-ignition phenomena [5, 6]. Many methods have been proposed to suppress knock, such as increasing turbulence and combustion speed, reducing CR (compression ratio) and end-gas temperature, adopting anti-knock additives and alternative fuels [7]. However, most of them have their own drawbacks especially when applied on a heavily downsized SI engine, such as difficult implementing in a wide operating range, decreasing the engine thermodynamic efficiency, less effective, high cost, unwanted side effects or not appealing to the market. Thus, knock is still commonly prevented by retarding the spark timing and combustion phasing, which results in a low thermodynamic efficiency and high exhaust temperature.

The increased TIT (turbine inlet temperature) may also cause thermal and structural problems for the turbine wheel and the catalytic converter. For this reason, an enrichment of the AFR (air fuel ratio) is usually adopted at high speeds to maintain the amount of indicated work with further BSFC (brake specific fuel consumption) penalties and lower efficiency of the catalytic converter. Besides the legislative road map for the reduction of NO_x and PM (particulate matter) from passenger vehicles over standard driving cycles, stricter legislation for CO emissions under real driving conditions is also widely expected in the immediate future [8, 9]. This increases the pressure to use alternative technologies for component protection instead of fuel enrichment. To meet these new regulations, gasoline engine technologies enabling lambda 1 operation across the entire engine map are highly desirable. The introduction of inert species into the cylinder, such as WI (water injection), can be used to decrease the in-cylinder temperature, which is a promising approach to mitigate knock and maintain lambda 1 operation simultaneously.

1.1.2 NO_x emissions

Diesel engine manufacturers are currently intensifying their efforts to meet stricter NO_x emission limits, such as the IMO Tier 3 regulation requiring an 80% reduction of NO_x from ships compared with the Tier 1 standard and the EURO 6 regulation requiring a 56% reduction of NO_x from diesel vehicles compared with the EURO 5 limitation [8]. Hydrogen as an alternative fuel has been studied for several decades, and recent researches have primarily focused on improving the trade-offs of power-efficiency-NO_x emissions, which have a strong correlation with the AFR [10, 11]. Biofuels are also regarded as promising renewable and environmentally friendly options for reducing petroleum-dependence and greenhouse gas emissions in the transportation sector [12, 13], while many studies have reported that engines running with biofuels emit NO_x in higher concentrations [14, 15].

Various methods have been used to control NO_x formation such as retarded injection timing and EGR. However, use of these techniques is accompanied with penalties in specific fuel consumption and soot. Aftertreatment is a good option to efficiently reduce NO_x emissions efficiently, but the additional costs including initial investment, maintenance and additional energy consumption by the devices, make it an expensive and complex option [16, 17]. A promising technology for NO_x reduction especially for heavy-duty diesel engines is the addition of water to the combustion chamber to reduce the combustion temperature and NO_x emissions.

1.2 Water injection

With a large latent heat of vaporization, water has the effect of substantially cooling the charge air as the liquid water vaporizes. Furthermore, the water vapor acts as a diluent in the combustion process, decreasing NO_x emissions and suppressing knock reactions in much the same way as the cooled EGR gas. The application of water cooling is not a novelty in ICEs, and the first successful use of WI for suppressing combustion knock can be traced back to the early 1930s [18]. During World War II, similar use of WI was made in the operation of high output aircraft engines [19-21], and additional studies were conducted on various kinds of engines until the 1980s [22-25].

To fulfill more and more rigorous CO_2 and pollutant emissions regulations recently, the WI technique has again been investigated to explore its potential benefits on both the SI (spark ignition) and CI (compression ignition) engines [26, 27], and a detailed review of the literatures will be presented in Section 4. To summarize, cooling effects suppressing knock combustion in turbocharged SI engines result in possibilities to apply a higher CR, higher boost level and advanced spark timing thus improving power output and efficiency as well as better part load performance. For the turbocharged CI engine, due to NO_x reduction achieved with water addition in the combustion processes, strict emission regulations could be fulfilled, and other measures, such as optimizing the fuel injection timing, can be adopted to further minimize the fuel consumption and soot emission.

However, many problems still need to be addressed with respect to utilization on different types of engines, such as mechanisms of WI with different aims, comparison of different implementations, optimum WI parameters and maximum potential. In addition, the on-board vehicle utilization of WI brings some new issues regarding cost, robustness, water consumption and emissions. Although lots of research on WI has been reported in recent years, no systematic review of those problems is conducted to the authors' knowledge.

This paper aims to present a comprehensive review of research progresses and future trends of WI to improve the combustion, emissions and efficiency of the ICE. First, the injection and evaporation processes of water are discussed, followed by mechanisms of the in-cylinder combustion process with water addition to give a deeper understanding of this technique. Next, current research activities on WI applied on different types of engines are summarized. Furthermore, comparisons and combinations of WI with other engine techniques are reviewed. Finally, some other critical issues of WI applied on the ICE are presented.

2 Water injection and evaporation

The water injection and evaporation processes determine the mixture (fuel, air and water) formation, evolution and combustion processes in the cylinder, which should be reviewed first before further exploring mechanisms and comparing applications on various kinds of ICEs.

2.1 Implementations of water injection

The main goal in all these WI techniques is to disperse the water to achieve an efficient cooling of the hottest spots within the cylinder, while at the same time the negative effects and the amount of injected water are minimized. To introduce water into the cylinder, many possible locations can be selected as the WI points, which have their own advantages and drawbacks especially when applied on different types of ICEs. As shown in Fig. 1, typical WI implementations can be categorized into three kinds with respect to injection locations and methods:

a) Single point WI upstream or downstream of the compressor or post charge air cooler;

b) Multipoint WI into the intake runner or intake port;

c) Direct WI into the cylinder via a separate injector or the same injector as fuel.

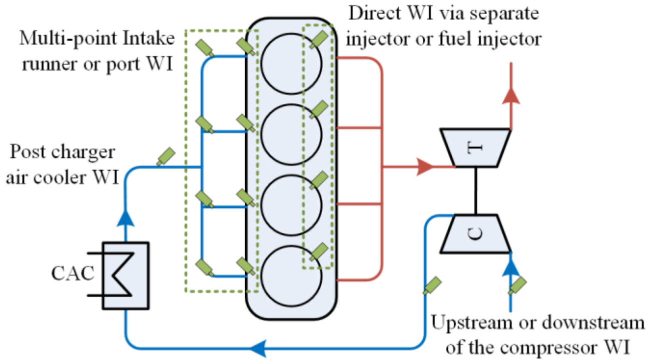

Figure 1. Potential implementations of water injection

2.1.1 Pre/after the compressor or charge air cooler water injection

For the turbocharged ICEs, water can be directly injected into pipes upstream of the compressor, downstream of the compressor or downstream of the charge air cooler, which is commonly known as intake air humidification or fumigation [28]. To evaluate those different implementations, some guiding factors should be considered, such as the maximum allowable intake air humidity, good evaporation, ease of application and maintenance. Good evaporation is especially important for the intake air humidification in order to avoid water condensation and accumulation in the intake system, to ensure even distributions of water flowing into each cylinder, to limit cycle to cycle variations and abnormal emissions, to eliminate possibilities of cylinder liner corrosion problems and contaminations of lubrication oil.

Since the temperature before the compressor is near ambient unless it is pre-heated, good evaporation of water droplets upstream of the compressor could be a problem although the low pressure upstream of the compressor favors the evaporation. With air mist flowing into the compressor, some water droplets continue to evaporate, which decreases the compression temperature and results in a high compressor efficiency. The addition of water increases compressor work but the additional mass flow will also increase the turbine work of the turbocharger. The fluid properties will change which will also affect the compressor and turbine work. However, big water droplets can lead to serious damage of the compressor blades. It is challenging to atomize the water to a small enough particle size to avoid damage and to ensure complete evaporation. If proper precautions are taken, humidification of intake air is possible before the compressor with the advantage of long residence time and good mixing of air and vapor before flowing into the intake manifold.

For the WI after the compressor, the charge air temperature is high and often greater than the boiling point of water, which can accelerate the evaporation process of the injected water. With this humidification process, the charge air temperature can be cooled down so that the coolant flow across the intercooler could be reduced to maintain a desired post-intercooler temperature, and a mist catcher should be adopted to avoid droplet condensation in the intake manifold [28]. Under some conditions, it may even be possible to eliminate the intercooler altogether and rely solely on the evaporation of water [29, 30].

Another possible location for WI downstream the compressor is after the intercooler. Since the humidification potential is less due to the low temperature and high pressure of the charged air out of the intercooler, only a small amount of water can be held in the cooled charge air. In addition, the available time for water evaporation is much shorter here compared with the above two locations since the injection point is quite close to the combustion chamber. Therefore, the post charger air cooler injection may be a feasible injection system, if only small amount of water is either sufficient for operation or if it is combined with another injection system.

With those characteristics, the intake air humidification is especially attractive for engines operating on heavy fuel oil where the use of EGR is difficult and expensive. In addition, intake air humidification is more easily integrated on large marine engines due to the spacious installation room, low engine and compressor speeds, steady operating conditions and easy water acquisition [27]. To get a high proportion of water addition, the humidity of the air should be near saturation as it enters the cylinder, and the intake manifold temperature should be as high as the engine can tolerate. Sulphuric acid corrosion, often referred to as cold corrosion, is another significant problem in marine engines even with low-Sulphur fuels, and advanced cylinder liner and piston technologies should be considered. But for those high-speed vehicle engines, intake air humidification may not be a good choice if a large amount of water is required, and specific precautions should be considered seriously for the injection and evaporation processes in a large operating range.

2.1.2 Intake runner or port water injection

The intake runner and intake port are another two alternative locations for the WI, and the main advantage is the easy implementation similar to a PFI (port fuel injection) system. In general, the gasoline PFI system can be directly used for the WI with little modifications [31], which shows the highest probability for short term series production. Furthermore, the amount of water injected into each cylinder is controlled by the water injector directly to ensure even distribution. Since the injection points are very close to the combustion chambers, not enough time is available for the water to fully evaporate before flowing into the cylinder, and the relatively low temperature and high pressure of the cooled charge air also slow down the evaporation rate. Therefore, it is hard to assume a fully evaporation process outside the cylinder for the intake runner or port WI, which will be further discussed in Section 2.2. Thus, those features make the intake runner or port WI more suitable for the knock control in the gasoline engine.

2.1.3 Direct in-cylinder water injection

Water can also be injected into the cylinder directly with a separate injector, a traditional fuel injector or a specially designed fuel/water injector. The main advantage of direct in-cylinder WI is the flexible control of water amount and distributions in the cylinder at the right time, which can adjust the fuel/air/water concentrations in the combustion zone and decrease the water requirement. Drawbacks are also obvious, such as the cost of a high-pressure injection system, packaging and robustness.

The primary benefit of WI via a separate injector is that both the injected mass flow rate and the injection timing can be controlled separately from the fuel injection. WI during the intake stroke and compression stroke may have different effects on the engine volumetric efficiency, in-cylinder evaporation and mixture evolution. In general, water should be injected to ensure that there is no liquid film build upon the cylinder wall and that evaporation is complete before the end of the compression stroke. However, inappropriate WI timing and spray with respect to the fuel injection will locally quench the flame, contaminate lubrication oil, increase the cycle-to-cycle variation and other emissions [32]. For the GDI (gasoline direct injection) engine, integrating the water injector into the combustion chamber consumes a lot of the package volume available. A more feasible solution may be the combination of port fuel injection and direct water injection or emulsion water injection.

Stratified fuel/water direct injection with a specially designed injector, often adopted on the diesel engine, is slightly better than the direct WI with a separate injector. The amount of water injected in sequence with fuel from the same injector can also be varied although the timing of injection is dependent on the fuel injection and water/fuel ratio. The liquid water is inserted close to the flame and away from the cylinder wall. With stratified injection, it is easier to cool the flame zone directly rather than cool the entire combustion chamber [33]. This allows for high NO_x reduction without compromising other values such as fuel consumption and emissions like HC and CO. This arrangement can also minimize the negative impact on overall engine reliability compared with a poorly placed nozzle which may over-cool the combustion chamber and lead to ignition delay and incomplete combustion [34]. However, additional cost on modification of the injector make this system less popular compared to other WI systems.

Fuel/water emulsion with the addition of emulsifier, primarily adopted on the diesel engine for NO_x reduction, needs almost no engine modification for the implementation [35]. The presence of a surfactant (or emulsifier), which is a typical chemical additive attracting the immiscible liquids, plays an important role in forming a stable emulsion. In addition, different types and percentages of the chemical additives determines the type of emulsions. With larger amounts of surfactant, normally up to 10%, micro-emulsion can be generated compared to the normal emulsion with up to 2% of surfactant [36, 37]. Thus, micro-emulsion has a much smaller dispersed water droplet with the diameter size ranging from 5~20 nanometer compared to 1~10 micron of the normal emulsion. Regarding the engine power and emission performances, Ithnin et al. [37] indicated that not much difference can be observed with those two types of emulsion fuels. Even though the micro-emulsion has more stable thermodynamic properties, the high cost of micro-emulsion restricts its commercialization.

The main disadvantage of using fuel emulsion technology is the limitation of the amount of water that can be added to the system [38]. For fuels emulsified with water, there is always an inherent risk that an excess of water may be injected into the cylinder either too early or too late in the combustion process. This can cause cooling of the entire cylinder and lead to increased ignition delay, engine noise and retarded combustion. Another disadvantage is that engine operation at low loads and at stops and starts are sometimes hindered, which limits the utilization of this technique on vehicle engines. In addition, an increased engine operation cost, like a more extended and developed distribution network of fuel/water emulsion or a complex on-board emulsion production system equipped on the engine, should be evaluated seriously.

For the gasoline engine, the technology of pre-mixed macro emulsions of water and gasoline is proposed and investigated. In this system, water is metered into a mixing chamber filled by the pre-pressurized fuel flow of 4-5 bar, where those two fluids are mechanically sheared by a static mixing device [39, 40]. Thus, short-term time-resistant emulsions can be obtained, and emulsifying additive is avoided. Pumped by the high-pressure pump, stabilized emulsions flow through the fuel supply system to the fuel injectors. With no modification of the cylinder head, this implementation is relatively easy to integrate into an existing engine. Since water is directly injected into the combustion chamber with fuel, chamber-wall wetting can be minimized, which shows great potential for the future gasoline water injection.

2.2 Water evaporation

After being injected, water should first mix with the air flow and then evaporate, which has significant effects on the engine intake, compression and further combustion processes. Hoppe et al. [41] separated the effects of specific heat and vaporization enthalpy of water on the in-cylinder compression temperature based on the fuel-air cycle, which showed the charge cooling effect of WI is almost entirely due to the high latent heat of vaporization. Therefore, the water evaporation process, which depends on not only the implementations discussed above but also the engine operating conditions, should be discussed thoroughly especially for the intake runner/port WI and the direct in-cylinder WI.

Under suitable conditions, water vaporization may result in cooling, and hence, increase density of the inlet fuel-air mixture just prior to closing of the intake valve. On the other hand, if sufficient time is not available especially with high engine speeds, low charge temperature or short distance between the injection point and the intake valve, the induction process will be unaltered by the injection of water. In addition, for highly boosted engines with a highly efficient charge air cooler, the cooled fresh charge may be at or near 100% relative humidity [26]. Under this condition, water injected in the intake runner/port will not evaporate. Instead, liquid water will enter the cylinder and evaporate during the compression stroke as the in-cylinder pressure and temperature rise. Nicholls et al. [22] evaluated effects of two different water evaporation models on the intake and compression processes. The phase equilibrium model assumes the water vapor existing in a continuously shifting phase-equilibrium with liquid water during the induction process, and the liquid phase model is based on the assumption that sufficient time is not available for water evaporation throughout the induction process. Thus, those two models correspond to the two possible extremes of water vaporization rate. Theoretical analysis indicated that the intake charge density and IMEP (indicated mean effective pressure) are much higher with the phase equilibrium model compared with those of the liquid phase induction model, while no obvious increase in volumetric efficiency was observed in the later experimental research.

To simplify the simulation of the water evaporation process, the gasoline evaporation process can be used as a good reference. With the water injector located upstream the port fuel injector and the maximum water/fuel ratio of 0.3, De Bellis et al. [42] assumed 20% of the total mass of water vaporizes immediately upon the injection and described the in-cylinder water evaporation rate with a semi-empirical correlation resembling the fuel evaporation process in a 1D simulation model. Although no data was available to verify the reliability of this assumption, De Bellis et al. [42] also stressed that problems such as oil dilution, misfire, or partial combustion were not detected in the experimental campaign, which suggested a good evaporation in the real engine. To simulate a more accurate evaporation process of port WI with a 1D model, Cavina et al. [43] adopted a port injector and a fictitious direct in-cylinder injector to split the evaporation proportions of the injected water in the intake runner and the cylinder, but this modelling approach was not predictive. However, to realize a similar evaporation process as the gasoline, WI with the gasoline injector needs a much higher injection pressure due to the low evaporation saturated vapor pressure compared with that of the gasoline. If the water droplet is also assumed to be of similar size as the gasoline, the water droplets potentially never undergo full vaporization process before combustion like the gasoline [44]. Therefore, special attentions should be paid when injecting water with traditional gasoline injectors.

Battistoni et al. [45] indicated that the primary atomization quality, which ultimately depends on the nozzle design and injection pressure, is a key point to improve the performance of the WI system. The location and targeting of the water injector are also very important. CFD (computational fluid dynamics) simulations of liquid water distributions shown in Fig. 2 indicated that the installation of the water injector very close to the inlet valves, mimics a “quasi-direct” WI with respect to the installation far upstream in the intake runners. Wall film formation that reduces charge cooling and premature vaporization outside of the cylinder are the main causes for the lower efficiency of the intake runner installation, which decrease substantial gains in terms of combustion control and knock suppression. With a 3D simulation model of the port WI on a GDI engine, d' Adamo et al. [46] compared evaporations of the liquid fuel and water in the cylinder at different engine speeds. The results showed that a lower in-cylinder temperature level can slow down the phase transition processes, and liquid water is more affected than liquid fuel because of its higher latent heat of vaporization. Under low to medium speed conditions, no more than 50% liquid water is evaporated at 700 CAD (crank angle degree).

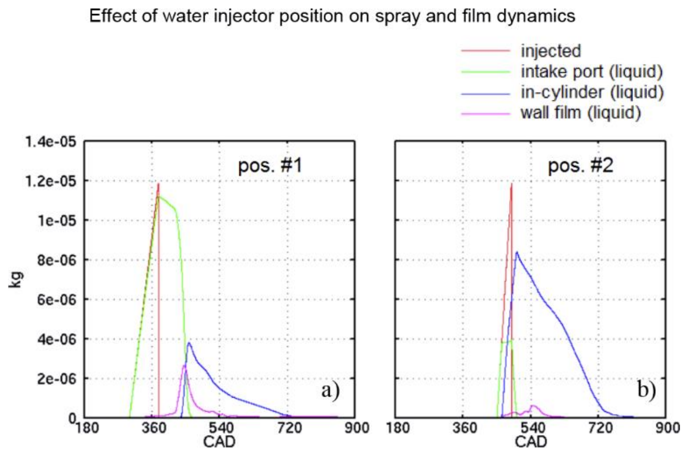

Figure 2. Effect of injector positions (pos.#1: upstream of the intake runner, pos.#2 close to the inlet valves) on liquid water mass balance [45].

With the in-cylinder water injection timing at the IVC (intake valve closing) timing, Kim et al. [44] superimposed the saturation temperature and dew-point temperature lines on the in-cylinder temperature and pressure buildup map in order to roughly evaluate the phase of the water. As shown in Fig. S1, a delay of evaporation process would occur when the in-cylinder temperature is lower than the saturation temperature of water early in the compression stroke, and rapid vaporization of water accompanying effective charge cooling would be expected when the in-cylinder temperature is higher than the saturation temperature of the water as the "evaporation zone" depicted in Fig. S1 (a). Bhagat et al. [32] conducted CFD simulations of the vaporization profile and liquid film formation over the crank angle with the in-cylinder water injection timing of 60 degree and 90 degree BTDC (before top dead center). The results showed that the crank angle of 50% water evaporation with injection timing of 90 degree BTDC is 100 degree crank angle earlier than that with injection at 60 degree BTDC at the engine speed of 2000rpm, and a 28% increase in wall film mass was predicted for injection at 60 degree BTDC compared to injection at 90 degree BTDC.

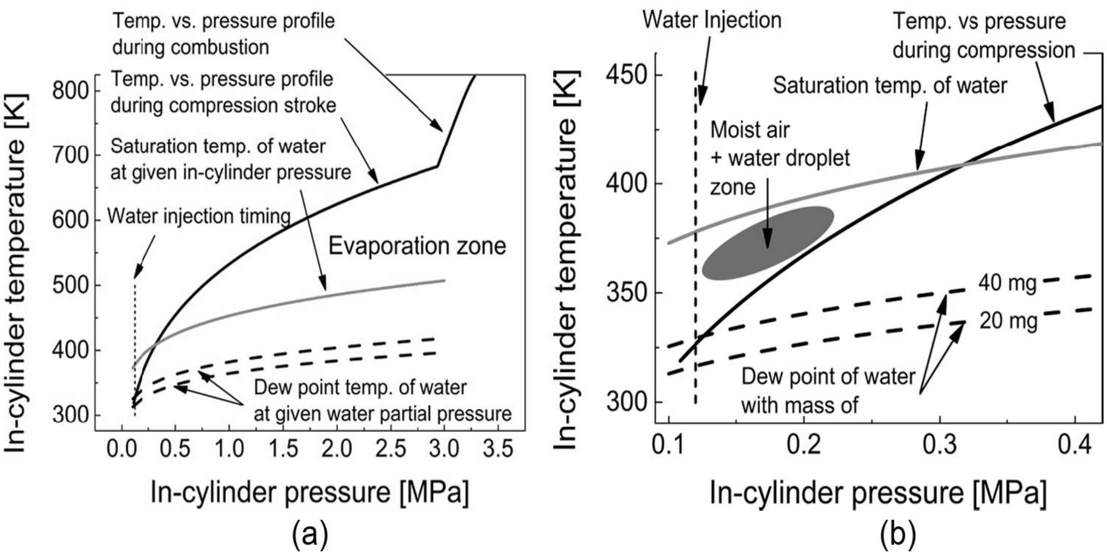

Figure S1. (a) Water injection evaluation on the in-cylinder temperature and pressure profile and (b) enlargement of (a) in the pressure range of 0.1-0.4 MPa [44].

Thus, an accurate evaluation of the water evaporation shows great importance in the design and optimization of different WI systems and also for an accuracy calculation of heat release rate. Sometimes it is necessary to judge whether the injected water fully evaporates or not especially since this may have implication on avoiding corrosion problems or lubrication oil contaminations. Since it is unrealistic to detect the water phase with a sensor, an empirical evaluation with the measured or calculated temperature can be used to approximate whether the air is saturated or unsaturated as shown in [44].

3 Mechanisms of the in-cylinder combustion with water addition

The low in-cylinder temperature at the end of the compression stroke due to the water evaporation might affect the ignition delay and combustion speed, and other engine parameters need to be adjusted simultaneously to target the engine performance and emissions. Therefore, it is not surprising to get inconsistent results of engine performances and emissions from different references. To provide a deep understanding of WI with different aims on various types of ICEs, mechanisms of the in-cylinder combustion with water addition needs to be discussed thoroughly. To the best of the authors' knowledge, studies on chemistry kinetics of water/fuel combustion are mostly limited to specific reactant components [47, 48] (like hydrogen, carbon monoxide, iso-octane and syngas mixtures) with rapid compression machines or special burners [49, 50], and research focusing on real engines was rarely reported. Considering the limited knowledge of water/fuel interactions under practical conditions of engine combustion, thermophysical effects of water injection are mainly illustrated in this review article.

3.1 Heat release rate

For the CI engine, the combustion process consists of two parts, the premixed combustion and the diffusive combustion. The premixed combustion part is mainly determined by the amount of injected fuel during the ignition delay period, and the diffusive combustion speed is governed by the amount of air entrained by the fuel spray per unit of time [51]. Since a large quantity of water results in a long ignition delay due to the cooling effect, the proportions of those two combustion parts are varied and further influence the combustion profile. When WI is used, the spray entrains a water/air mixture instead of pure air, so that a decrease in combustion speed could be expected similar as the case of EGR. Tauzia et al. [52] indicated that at higher speeds and higher loads, the combustion is almost purely diffusive with a relatively short ignition delay, and much smaller influences of WI on the combustion profile can be expected with a large AFR. In the case of water/fuel emulsion or stratified injection with fuel, water does not replace air but is added to the fuel spray, and the influence of water addition on heat release rate is negligible or even positive due to the long liquid penetration and water evaporation [53]. Hountalas et al. [54] compared two different water addition strategies (fuel/water emulsion and intake manifold water injection) on a heavy-duty diesel engine with the multi-zone simulation model and the water fuel ratio ranging from 0 to 30%. Simulation results of fuel/water emulsion at 1800 rpm showed that the specific fuel consumption decreases linearly with the increase of water percentage at low and part loads. However, the intake manifold water injection observed a linear increase of fuel consumption with increasing water percentage. Thus, they summarized that the presence of excessive water inside the combustion chamber has a positive effect on combustion and engine efficiency when water is introduced from the "fuel side" (as the stratified fuel/water injection or emulsion). On the other hand, a small negative effect on efficiency is inevitable when water is introduced into the fuel jet from the surrounding "air side" (as the port injection).

For the SI engine, the laminar and turbulence flame speeds are two important parameters to determine the combustion heat release rate [55]. Assuming water acts in the same way as any other inert specie, Bellis et al. [42] attributed effects of the water presence on the gasoline burning rate to variations of laminar flame speed based on a two-zone SI turbulence flame combustion model, and experimental and simulation results of the in-cylinder pressure and burn rate showed good agreements with the water/fuel ratio ranging from 0 to 0.3 and spark timing of -5 and -9 CAD AFTDC (after firing top dead center). Bozza et al. [56] tried to separate effects of the water addition from other diluent of EGR on the laminar flame speed based on a chemical kinetic solver. The importance of such refinement is highlighted in Fig. 3, which shows that water causes a stronger decrease in the flame speed than EGR, up to about 40% for water mass fraction of 0.1. Berni et al. [57] compared the turbulent kinetic energy fields of pure fuel and WI cases, and the similar 3D simulation results showed that intake port WI does not noticeably affect the in-cylinder flow structure with a low-pressure injection system.

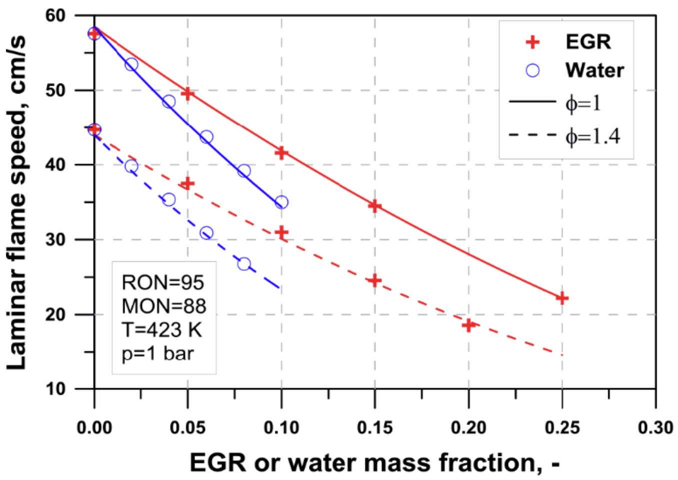

Figure 3. Sensitivity of the laminar flame speed to the addition of water or exhaust gas [56].

Since many of the sub-models needed with WI are missed, not tuned or not sufficiently validated, modelling of the actual combustion process is difficult to set up. Despite an unfavorable effect of WI on the laminar speed of SI combustion, Bellis et al. [42] indicated the combustion duration can be slightly shortened if the spark timing is advanced to move the combustion process closer to the top dead center. 3D simulations conducted by Berni et al. [57] also showed that the combustion duration is not significantly affected by the water presence due both to the small changes of laminar flame speed at ignition and to the advanced spark timing for the WI case. With an experimental test matrix of different water/gasoline ratios and spark timings under full load conditions of a twin cylinder gasoline engine, Iacobacci et al. [58] compared the combustion phasing and in-cylinder pressure, and similar variation trends were obtained at different engine speeds. Results at 3500 rpm shown in Fig. 4 indicated that with the same spark advance, water injection can slow down the combustion, which retards the MFB (mass fuel burned) 50 and decrease the in-cylinder peak pressure.

Further combined with the advance of spark timing to maintain the same MFB 50, the in-cylinder peak pressure almost remained the same. Thus, for small percentages of WI, compensated by an advance of the spark discharge, the use of a constant Wiebe function is not expected to change the predicted trends significantly [59].

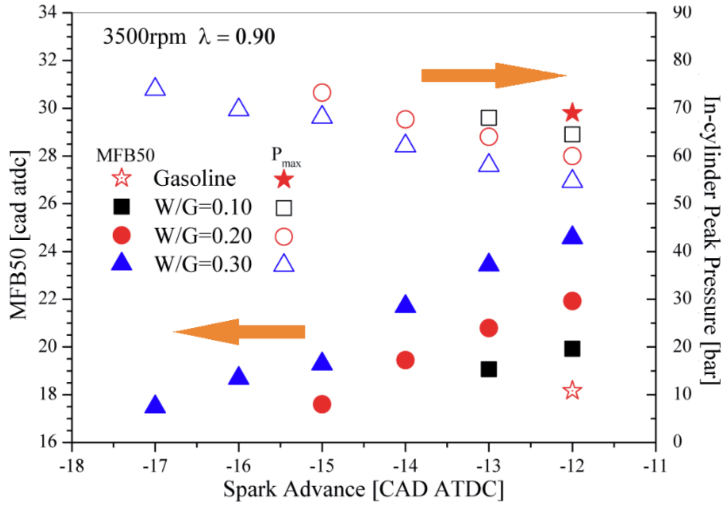

Figure 4. Effects of water injection on combustion phasing and in-cylinder peak pressure at 3500rpm [58].

By conducting experiments of WI on a NA (naturally aspirated) gasoline engine under full load conditions with the water/fuel mass ratio increasing from 0 to 250%, Kim et al. [44] also analyzed the effects of water mass on the combustion duration. Results at 1500 and 2000 rpm shown in Fig. S2 indicated that advancing spark timing with increased water mass flow decreases the combustion duration due to the high-temperature and high-pressure environment near top dead center, and further increasing the water mass decreases the reactivity of the air–fuel mixture due to dilution. The combustion duration eventually increases when the negative effect by the dilution is greater than the benefit gained from advancing the spark timing. Increased combustion duration is disadvantageous for the engine BMEP and BSFC, due to the deviation from the ideal cycle with constant volume combustion process.

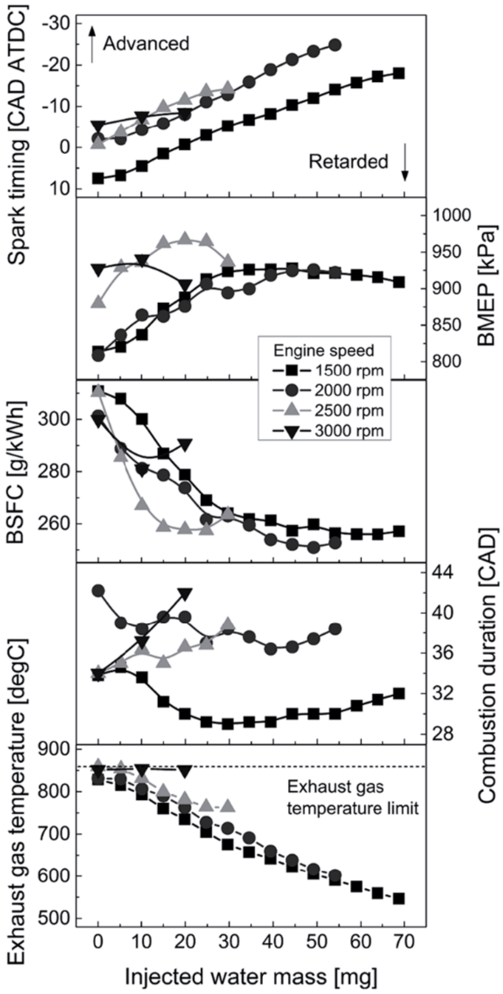

Figure S2. Effects of water injection on engine performance and fuel consumption at full-load condition [44].

3.2 Knock mitigation

Knock is well known as a major barrier for further improving the SI engine thermal efficiency. It is generally accepted that engine knock is the result of autoignition of the end-gas before it is being reached by the flame front emanating from the spark plug [7]. As an effective knock mitigating solution, the use of WI in highly downsized SI engines has been reported in many references. Analyzing from the combustion viewpoint, the cooling effect of water introduction can not only delay the fuel autoignition time but also extend the combustion duration, and results from those antagonistic influences determine the potential gain or loss in using water addition. Kim et al. [44] stated that the negative effect of increased combustion duration with WI is more pronounced than any other positive effect when the water mass exceeds the optimum, and the combustion duration on the crank angle timescale is increased drastically at high speeds.

In order to foresee whether a trade-off region exists between the increase in autoignition delay time and the slowdown of burning velocity, Berni et al. [60] treated water as an EGR species and established a 0D constant chemical reactor model based on the assumption that the low-pressure port WI does not influence the in-cylinder turbulence level, which had been verified based on a heavily downsized gasoline engine. Fig. 5 shows results from 0D analysis of extension in combustion duration and in AI (auto ignition) delay. Case Reference, A, B and C refer to in-cylinder fuel air equivalence ratio of 1.21, 1.1, 1.0 and 0.9 and injected water mass of 0, 4.93, 9.23, 13.55 mg respectively. As can be observed, a clear trade-off between the beneficial increase in AI delay time and the undesired slowdown of the burning velocity is identified, and case B with the equivalence ratio of 1.0 shows best performances on the knock resistance and fuel economy. To separate different chemical and physical quantities of water injection on the combustion process in a boosted SI engine, Netzer et al. [61] adopted a laminar flame speed table based on different water/fuel ratios in the 3D CFD simulation. The results showed that the laminar flame speed has the largest impact on the knock limit spark advance, and the effect of charge cooling due to the vaporization of water is found to be the second most significant one, followed by chemical equilibrium and water vapor heat capacity.

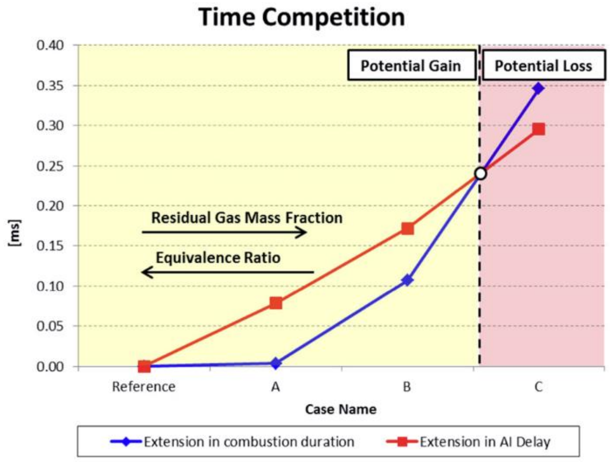

Figure 5. Results of combustion duration elongation and increased knock resistance for several equivalence ratio and water addition levels [60].

3.3 NO_x and PM

Similar to the EGR species, effects of WI on the NO_x emissions can be attributed to three aspects: dilution effect, thermal effect and chemical effect [62]. Concerning PM (particulate matter) emissions, variations of flame temperature, global AFR and flame lift-off length all have effects on the soot production rate. Thus, it is more advisable to review effects of water injection on those emissions with respect to different types of engines and injection implementations.

3.3.1 NO_x and PM emissions from the CI engine

To separate those three effects of water injection on NO_x emissions, Ma et al. [63] conducted CFD simulations on a turbocharged diesel engine with part of the intake oxygen replaced by the same amount of water and nitrogen. Simulation results showed that the dilution effect on the NO_x deduction reflected by the nitrogen replacement is much larger than the other two effects which are represented by the difference between the water and nitrogen replacements. Since the AFR of the original condition is much larger, the soot generation mainly depends on the in-cylinder combustion temperature, which results in a decrease of the soot with the increase of the replacement ratio. In addition, Ma et al. [63] stated that the chemical effect has limited effect on engine combustion and emissions. Nicholls et al. [22] also indicated charge dilution by water vapor is primarily responsible for the effectiveness of WI in reducing in-cylinder temperature and NO_x compared with water vaporization. With experimental research conducted on a production diesel engine, Serrano et al. [64] testified the cooling effect of water injection follows the hard relationship between NO_x formation and combustion temperature of the Zeldovich mechanism.

Ladommatos et al. [62, 65] compared effects of CO_2 and water vapor contained in EGR on the diesel engine emissions. Results of the experiment and chemical equilibrium model showed that the dilution effect is the most significant one. Furthermore, the dilution effect for CO_2 is higher than that for water vapor because EGR has roughly twice as much carbon dioxide than water vapor. On the other hand, the water vapor has a higher thermal effect in comparison to that of CO_2 due to the higher specific heat capacity. The chemical effect of water addition can be further explained as that the increased OH radicals might have a significant impact in soot oxidation and reduce the soot formed in the gas phase [66]. The relation between the normalized soot number density and OH radicals in-cylinder was described by Fujimoto et al. [67]. They cited that the normalized soot number density shows the maximum when OH radicals start to be detected and decreases with increase in OH emission. OH radicals immediately form just after the ignition and is used in the oxidation of soot and other hydrocarbons.

Compared to the separated fuel/water injection, the fuel/water stratified injection has the advantage of having the liquid water close to the flame and away from the cylinder wall, which result a large decrease of the NO_x formation. If too much water is used, the soot emissions might be increased due to the long injection duration. CFD simulations conducted by Bedford et al. [53] indicated the liquid penetration increases approximately 35% with 23% of the fuel volume replaced by water, due mostly to the increase in latent heat of vaporization. Engine simulations showed that the vaporization of liquid water as well as a local increase in specific heat of the gas around the flame result in lower NO_x and soot formation rates. In addition, due to the significant reduction in NO_x, it is possible to optimize injection timing and thus reduce PM emissions and brake specific fuel consumption.

Regarding the water/diesel emulsion, the suspended water has a lower evaporation temperature compared to the diesel. The water vapor explosion during the combustion promotes the formation of fine air/fuel mixtures. The mechanism of micro-explosion of emulsified fuel droplets which leads to a better atomization and thus air-fuel mixing has been proposed and understood from a theoretical view to a certain extent for the emulsion fuel combustion [68-70]. Vellaiyan et al. [71] reviewed articles on the water-in-diesel emulsion and indicated that there is an inconsistency in the domain of emulsion fuel in terms of specific fuel consumption, brake power, HC and CO emissions due to the complexity in combustion analyses. However, in terms of NO_x and PM emission levels, all the studies agreed on the improvements. Park et al. [72] identified micro-explosion of emulsified fuel droplets in the luminous flames near the tip of the spray in a rapid compression and expansion machine. However, some investigations on sprays indicated that there is no clear evidence that micro-explosion occurs in modern diesel engine combustion process. Zhang et al. [73] indicated that in the high-pressure environment, such as the combustion chamber of the diesel engines, the micro-explosion of the emulsion should have little effect on combustion, and the water particles in emulsified fuel cause a rapid vaporization and expansion phenomenon. Eckert et al. [74] stated that an increased liquid penetration length, an increased flame lift-off length and a leaner spray of diesel fuel-water emulsions result in an improved NO_x and PM trade-off.

With various implementations of WI, the reduction of NO_x levels in the CI engine should be different [75]. Since the water is injected directly into the combustion zone, implementations of water/fuel emulsion and direct WI result in large decrease of combustion temperature and thus much lower NO_x emissions. Ishida et al. [76] indicated that the NO_x reduction with direct WI or water/fuel emulsion is around twice as high as with the intake manifold WI at a given quantity of injected water. Ishida et al. [76] further explained this phenomenon theoretically. According to equations of a two-zone combustion model, the amount of water moving from the unburned zone into the burned zone is determined by the entrained air rate with the assumption of a uniform distribution of water/air mixtures in the cylinder for the case of port WI. If the amount of entrained air for combustion is about half of the total in-cylinder charge, only half of the water can be entrained into the combustion zone.

3.3.2 NO_x and PM emissions from the SI engine

Different from the CI engine, NO_x in the tailpipe of the SI engine is less of a big problem, because of conversion in the three-way catalyst. Considering the main aim of knock mitigation on the gasoline engine, other parameters like spark timing and AFR are always adjusted to optimize the combustion efficiency, which also have significant effects on the NO_x and PM emissions [58, 77]. In general, NO_x emissions from gasoline engines depend on the peak temperature achieved during combustion, oxygen concentration and time available for the reactions (ignition timing, flame speed). Tornatore et al. [78] compared the NO emissions of a downsized gasoline engine at WOT (wide open throttle) with and without intake runner WI, and experimental results shown in Fig. 6 indicated that the NO emitted with WI is higher than the original standard ECU (Electronic control unit) operation. Although the cooling effects of water addition reduces combustion temperature, the predominant factor in this case is the different lambda (excess air coefficient). In the standard ECU case (rich operation, lambda<1), the concentration of available oxygen is lower and is therefore the limiting factor for the NO formation. In the WI case, the stoichiometric lambda results in a high temperature and promotes the NO formation. In addition, advancing the spark timing increases the in-cylinder peak pressure (and temperature) and thus increases NO emission. With the same lambda and spark timing as the standard ECU calibration, Iacobacci et al. [58] indicated the NO decreases with the increase of injected water, and the amplitude of variations depends on the engine speed and fuel enrichment. Experiments conducted by Durst et al. [79] showed that the intake manifold water injection with the water fuel ratio of up to 50% can decrease the NO_x emissions up to 25% at low speeds at partial load, while NO_x emissions increase continuously and reach four times the base level at full load and high speeds. However, the majority of the NO_x can be converted by the three-way catalytic converter. Sun et al. [80] also indicated that water injection has a negligible effect on the three-way catalyst conversion efficiency under stoichiometric conditions according to their experimental results at high load conditions.

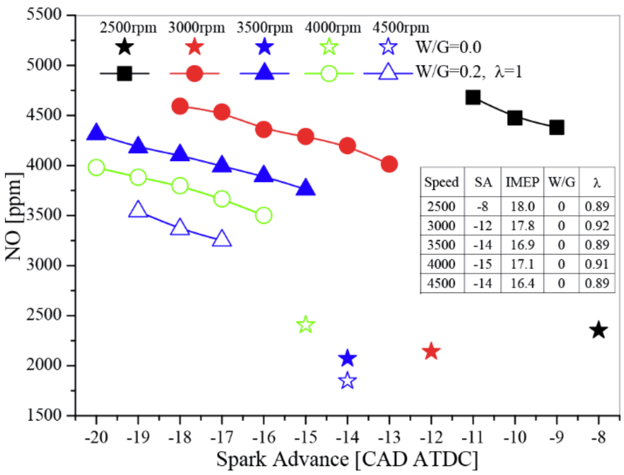

Figure 6. NO emissions against spark advance for engine speed from 2500 to 4500 rpm [78].

Although the direct injected gasoline engine provides higher efficiency, emission of small particulates is greatly increased due to the inhomogeneous air fuel mixing and more than 10 times greater in mass per mile driven than that from the port injected engine [81]. Hermann et al. [40] indicated that within the engine enriched area, less fuel enrichment is required with the increase of water fuel ratio, which results in a decrease of the PM emission. Increasing the water fuel ratio further in the stoichiometric region, the particulate number strongly increases due to the reduced combustion temperature and uneven water distribution. Similar results are reported in [79, 82]

3.4 HC and CO

HC (hydrocarbons) are organic compounds formed when fuel molecules do not burn or burn only partially in the engine because of crevice volumes, rich fuel-air ratio, or flame quenching [83]. CO is a byproduct of incomplete combustion when carbon in the fuel is partially oxidized rather than fully oxidized to CO_2 [83]. An increase of the water/fuel ratio might cause higher HC and CO emissions due to the dilution effect of the water, the reduction of the combustion temperature and possible presence of water droplets that do not evaporate before combustion. In addition, water is expected to be heterogeneous especially with the direct in-cylinder WI, a decrease in the local temperature where the vaporization of water occurs can be a source of increased HC emissions due to quenching [23, 24, 44, 84].

3.4.1 HC and CO emissions from the SI engine

Taking the benefit of knock suppression, water injection can advance the spark timing and shift the combustion center near to the top dead center, which reduce the unburned HC. With the exhaust temperature controlled by water injection instead of fuel enrichment, the gasoline engine can also decrease the unburned HC and CO emissions [58]. Tornatore et al. [78] compared variations of HC and CO emissions with the intake runner WI on a downsized gasoline engine. It can be observed from Fig. 7

that the HC emission with WI is lower than the corresponding full load points at standard ECU operation, which is clearly due to the different lambda of the two cases. Moreover, the higher turbulence intensity at high speeds decreases flame quenching in crevice regions at the cylinder wall, which result in a decrease of the HC emissions with increasing engine speed. As a general trend, it can be seen that the concentration of exhaust HC is not strongly affected by the spark advance angle. The CO emitted with WI is significantly lower than the corresponding baseline (no WI) case at any speed due to the stoichiometric combustion. Iacobacci et al. [58] stated that HC and CO emissions increase with the port water injection when running the same lambda and spark timing as the base ECU calibration.

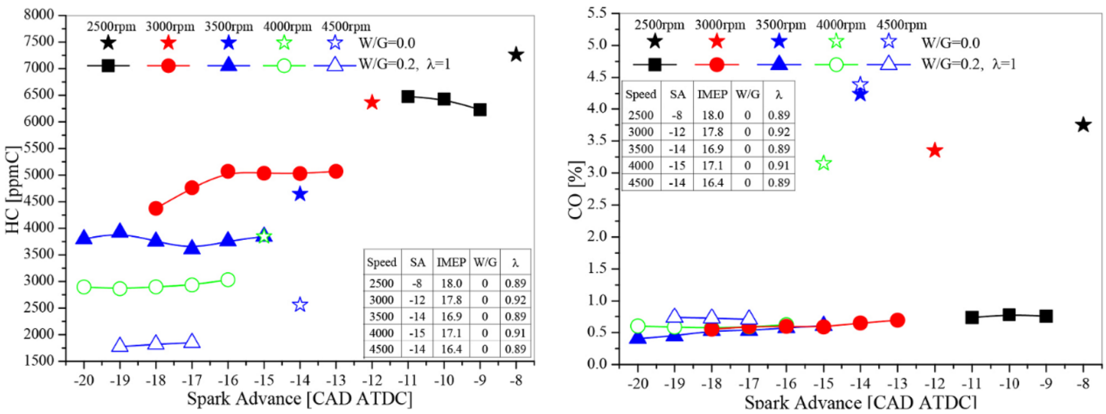

Figure 7. Unburned HC and CO emissions against spark advance for engine speed from 2500 to 4500 rpm [78].

3.4.2 HC and CO emissions from the CI engine

Different from the SI engine, HC and CO in the tailpipe of the CI engine is less of a big problem, because of the oxygen-enriched combustion. Experimental research on a high speed automotive diesel engine conducted by Tauzia et al. [52] presented that the increase of dilution ratio due to intake manifold WI results in an increase of CO flow rate upstream the DOC (diesel oxidizing catalysts), which may affect the final CO emissions if the DOC is unable to oxidize a higher CO flow rate. Furthermore, the decrease of exhaust gas temperature induced by WI may reduce the conversion efficiency of the DOC. The impact of WI on CO and HC emissions as well as their after-treatment in the DOC should be further investigated before any industrial application. Udayakumar et al. [85] also observed an increase in HC and a decrease in engine performance with the increase of water/fuel ratio in experiments of inlet manifold WI conducted on a diesel engine. Subramanian et al. [75] conducted experimental research of effects of the intake manifold WI and water-diesel emulsion on performances, combustion and emissions of a diesel engine at different loads. With the same water to diesel ratio of 0.4:1 by mass, experimental results showed that the water-diesel emulsion is superior to manifold injection at all loads, especially at part loads. Smoke reduction with water-diesel emulsion resulted in higher CO and HC emissions compared with intake manifold WI.

3.5 Steam injection

Apart from the WI, studies of steam injection have also been reported. With steam injection, the cooling effect due to water evaporation is removed, but the dilution and chemical effects of water addition are still retained. In addition, the problem of cold corrosion arising from liquid water flowing into the cylinder can be eliminated [86]. Zaidi et al. [87] pointed out that partial humidification of the intake air with superheated steam (less than 3%) neither influences the ignition delay period nor the start of premixed combustion as the water does not have to evaporate, thus the fuel consumption does not deteriorate as expected with water or wet steam injection.

To avoid water evaporation in the cylinder and subtract the water latent heat of vaporization from the heat released during the combustion process, Nour et al. [88, 89] proposed to introduce water into the exhaust manifold to utilize the enthalpy of exhaust gases to evaporate injected water, and by opening the exhaust valve during the intake stroke, the evaporated water and exhaust gases flow into the cylinder and participate in the combustion. Thus, the thermal effect of WI is reduced, and other effects such as chemical and dilution effects of water vapor are expected to promote soot oxidation and decrease the NO_x formation. Experimental work conducted on a single diesel engine showed that NO_x emissions can be decreased by 80% for 25% EGR ratio accompanying with a large increase of soot emissions. Combining EGR with WI, soot emissions can be decreased by up to 40% compared to the EGR case but still higher than the conventional diesel combustion. Gonca et al. conducted research into port steam injection on various engines fueled with diesel [90], gasoline [86] and biofuel [15] to improve emissions and engine performances. To further decrease the in-cylinder temperature and minimize NO_x emissions, Gonca et al. also proposed to combine cooled EGR [91] or Miller cycle [92, 93] with the steam injection, which showed that higher efficiency and less NO_x emissions can be obtained compared to the original steam injection engine.

4 Summary of water injection on different types of engines

4.1 Water injection applied on the gasoline engine

For the highly boosted and downsized gasoline engine, WI shows great potential to extend the knock limit without increasing the TIT and fuel enrichment. The turbine inlet temperature limit and rich misfire are the major limitations of existing knock mitigating techniques (before reducing the power/torque). However, the optimum injection parameters, like the location, timing, flow rate and pressure, still need to be clarified.

To reach the lowest temperature at the end of the compression stroke, maximizing the amount of water drawn into the cylinder and the water droplets evaporation in the combustion chamber are two criteria for determining the injector location and injection timing with runner/port WI. With a single-hole water injector and injection pressure of approximate 5 bar, Berni et al. [57] compared different water injection timings and injector locations (one close to the intake port junction and another close to the intake valve) with 3D simulations. The results showed that more liquid water droplets are trapped in the cylinder with the injector close to the intake valve. In addition, there exists an optimum injection timing (around 100 CAD before intake valve open) to lower the charge temperature before the start of combustion, and the optimum WI timing varies at different speeds due to the very different flow velocities in the intake port as well as the physical time allowed for water to enter the cylinder. For the use of WI as a substitute of the excess fuel, fuel injection timing should be adjusted due to the reduced amount of fuel. Berni et al. [57] also indicated that keeping the same end of injection timing as the original case can result in leaner end gases and slightly richer equivalence ratio near the spark plug. For better comprehension of the mixture flow field with port

WI, Hermann et al. [40] recorded the air/water/fuel behavior with in-situ video in both intake channels and the cylinder. The in-cylinder videos showed that the mixing of water and gas was not perfect, and the injected water mass shot from the intake valve across the cylinder to the opposite walls without being involved in the tumble especially with high water rates. In addition, the tumble will be affected in a negative way, and the inhomogeneous mixing will waste the evaporation enthalpy due to the wall wetting.

For the direct in-cylinder WI, a low-pressure level in the WI system would be cost-efficient. However, a lower injection pressure worsens the primary breakup of water droplets and increases the time span of injection and evaporation, and water droplets might not be fully evaporated at the end of the compression stroke. Consequently, the in-cylinder end gas temperature and knock propensity are not reduced as well as with higher pressure levels [41]. Thus, an optimum injection pressure for the engine performance should be determined to guarantee complete evaporation of water droplets. This also impacts the optimum injection timing. With the same end of injection timing of direct WI with separated injectors, Hoppe et al. [41] evaluated different injection pressures ranging from 50 to 200 bar at three loads. Experimental results showed that a constant increase of the knock reduction with higher rail pressure was already visible at the lowest load point, and the benefit grows with increasing load and thus injected water mass.

Hoppe et al. [94] also stated that there exists an optimum injection timing for the direct in-cylinder WI, and further advancing or retarding the start of injection results in reduced gains in MFB 50 and increased burn duration. The optimal timing for direct injection of water can be found during the compression stroke. It is almost independent from the IVC timing, the engine load and the injected water mass. However, it was found that the optimal injection timing of water shifts to earlier timings with increasing engine speed. In addition, the CR also has an influence on the optimal WI timing. The reason for this can be attributed to the higher cylinder pressure and temperature at a certain crank angle during the compression for the higher CR which reduces spray penetration length and thus shifts the trade-off for the optimal injection timing to slightly earlier SOI (start of injection).

From a system perspective, there is one big disadvantage for direct water injection with separate injectors: within the cylinder roof, the water injector tip must be cooled in order to avoid thermal damage. That means, a minimum amount of water needs to be injected during each cycle, even when it would not be needed for the engine thermodynamically. The handicap of direct mixture injection is the homogeneous mixture distribution to each cylinder. Pre-mixture WI experiments conducted by Hermann et al. [40] on the operation point 5000 rpm/280 Nm of a 1.6 L demonstrator engine confirmed that the distribution over the four cylinders was not homogeneous and does not follow a clear rule with water fuel ratio higher than 15%. To obtain better transient performances, the rail with a small volume is required. On the other hand, a large volume is preferable to decrease the pressure fluctuations caused by the high-pressure fuel pump. Therefore, a dedicated design for the high-pressure fuel rail is needed. As shown in Fig. 8, BMW [82] employed a volume divider that slips into the series fuel rail, and the hollow interior of the volume-divider insert was hydraulically connected to the feed volume and provides an additional volume of fuel to reduce the pressure fluctuations.

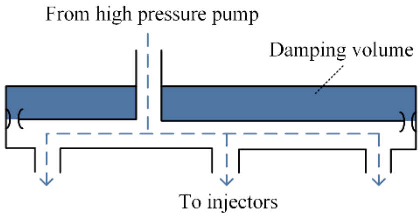

Figure 8. Schematic diagram of volume splitter in the fuel-injection rail from BMW

Evaluating from the same amount of water for the cooling effects of the cylinder, Cavina et al. [43] indicated that direct injection is undoubtedly the best solution, and port injection solution with an injector installation as close as possible to the intake valve is better than a single-point configuration located upstream the intake manifold. Table 1 shows summarized comparisons of three different implementations of WI systems for the gasoline engine [40, 95]. Port WI with a low-pressure system (5-20 bar) has the advantage of simplicity, low cost and robustness for corrosion and freezing issues, but its main drawback with respect to the other possible solutions is the higher water consumption. The compromises of the direct in-cylinder water injection mixed or separated with fuel are the higher cost of the high-pressure injection system, the corrosion damage and also the packaging. As a result of previous considerations, according to [40][80] the port WI concept is the best candidate for series production. For the higher water consumption of port WI, spray targeting and reduction in droplet size can be used to reduce water usage [96, 97].

Table 1. Comparison of possible implementations for water injection systems [40, 95].

	Port water injection	Direct fuel/water mixture injection	Direct water injection with separate injector

Comb. Benefits	Good	Good	Good
Cost	Low	High	High
Robustness	High	Complex	Complex
Packaging	Modular and compact	Non-modular	Extra circuit for water
Energy efficient	Low energy demand	High energy demand	High energy demand
Water consumption	Higher	Lower	Lower
Transient operation	Good	Poor	Good
Distribution to cylinders	Good	Poor	Good

It should be mentioned that comparing the work done by various people is not easy and may result in different conclusions due to differences in design and operating parameters of the engines and WI systems. Therefore, some conclusions in the references are valid only under some conditions and cannot be treated as general ones. To provide a better comparison of different WI implementations on the gasoline engine, Table 2 lists selected researches with respect to the engine specifications, research methods, injection parameters, engine parameter adjustments, engine performances and emissions. It can be safely concluded that WI combined with advancing spark timing can maintain lambda 1 operation within the whole engine map and improve the engine BSFC and BMEP by mitigating knock. However, these benefits and the required WI parameters depend on the engine specifications and operating conditions.

Table 2. Water injection applied on the gasoline engine.

ICE specifications	**Methods**	**Injection location and parameters**	**Parameters adjustments**	**Engine performances and emissions**	**Refs.**
3.8L 8V DISI turbocharged engine with CR of 9.6	3D CFD simulations at 7000, 4000 and 2000 WOT	Water injector close to the intake valve with SOI at 250 CAD, injection pressure limited to 5 bar, injection mass approximately meeting the same charge cooling of	Spark timing is recalibrated for the same IMEP, and fuel/air equivalence ratio is adjusted to 1	BSFC decreases by 2%, 10% and 22% at 2000, 4000 and 7000 rpm respectively	[46,57]

	conditions	excess gasoline			
1.6L NA PFI engine with CR of 13.5 and Atkinson cycle technique	Experiments at speed ranging from 1500 to 3000 rpm WOT conditions	Direct injected with a GDI fuel injector at -120 CAD ATDC with water injection pressure of 50 bar, water/fuel ratio ranging from 0 to 250% for different speeds	Spark timing is advanced, and over-fueling is eliminated up to knock and TIT limitations	BMEP increases by 14%, and BSFC is improved by 16-17% at the speed of 1500-2000 rpm. Unburned HC increases, NO_x decreases, and CO variations depend on speeds	[44]
0.875L twin-cylinder PFI turbocharged engine with CR of 10	Experiment and 1D simulations at 3500, 4000 and 4500 rpm under full loads	WI upstream of the standard fuel injector in the port with the same injection timing as the gasoline, discontinuous injection of water with pressure of 4 bar and water/fuel ratio ranging from 10 to 30%	Spark timing is advanced at constant fuel/ air equivalent ratio up to knock occurrence	IMEP increases by 7.3% at 3500 rpm, and the increase is around 3% at high speeds. Spark advance reduces the HC, and NO_x decrements depend on speeds	[42,56]
2.0L 4-cylinder DISI turbocharged engine with CR of 9.2	Experimental research under WOT conditions with different anti-knock fuels	Water is injected with Bosch fuel injector into intake runners; injection pressure is limited by the standard compressed air of 8.6 bar; water/fuel ratio is larger than 150% to achieve a targeted CA50	Spark timing is recalibrated for a target CA50 or knock limitation, and lambda was adjusted to 1	Improvements of BMEP and BSFC with 87AKI fuel are up to 5% and 34% compared with production ECU calibration with 91AKI fuel. Emulsified water/oil mixture was observed in crank case	[31]
DISI single cylinder engine with CR of 13.5 and the adoption of	Experimental research under part and high loads	Water is injected via a side injector at an optimum injection timing of 120 CAD BTDC; injection pressure ranges from 25-150 bar, and	Spark timing is recalibrated for an optimal MFB50 of 7-8 CAD ATDC, and knock combustion is	Efficiency increases by 3.3%-3.8% in the region of the minimum fuel consumption, and 16% improvement is possible at full load	[41,94]

Miller cycle	with / without EGR	water/fuel ratio is smaller than 60%	avoid simultaneously	operation. HC increases, and NO_x changes slightly especially under EGR conditions	
1.6L demonstrator engine of GM/Opel, no specification list	Experimental research at 3000, 4000 and 5000 rpm WOT conditions	Port WI with an electrical water pump of up to 10 bar pressure, and water/fuel ratio ranging from 0 to 80%	Spark timing is advanced to maintain same knock intensity, and fuel enrichment is reduced with the TIT limitation	Water fuel ratio of 65% is required to fulfill Lambda 1 operation at 5000 rpm. CO linearly decreases with the water fuel ratio. Variations of UHC, NO_x and PM emissions depend on Lambda and water fuel ratio.	[40]
1.5 L three-cylinder engine with CR increase from base value of 9.5 to 11	Experimental research under full map condition	Plenum water injection (water/fuel ratio < 5%) plus water fuel mixture injection (water/fuel ratio < 30%)	Lambda 1 operation with knock and TIT limitation	Engine performance increases from 150kW/300Nm to 160kW/320Nm. Intercooler load and engine thermal load decrease by 30% and 10% at 5500 rpm.	[82]
0.5L single-cylinder test engine with CR of 10 and a centrally positioned fuel injector	Experimental research at 2500 rpm with different IMEP	Water injector is positioned on the side of the cylinder head with different injection pressure, timing and amount	Reducing knock tendency and advancing the center of combustion to optimized efficiency values.	A minimum injection pressure of approx. 100 bar to assist water vaporization, and the optimum injection window is approx. −120 °CA AFTDC.	[97]

4.2 Water injection applied on the diesel engine

For the CI diesel engine, the cooling effect of WI is mainly used to decrease the NO_x emissions. Although lots of works have been reported in recent years, comparative analyses of different WI implementations still need to be conducted to figure out the best choice under different utilizing conditions.

With CFD simulations of intake air fumigation and direct WI on a large two-stroke marine diesel engine, Chryssakis et al. [98] concluded that direct WI is more effective in reducing NO_x emissions compared to the intake air fumigation. Further by systematically varying the locations of the direct water injectors as well as fuel injection timing, it is possible to maintain a high level of NO_x emissions reduction with only milder penalties in fuel economy and soot emissions. Experiments conducted by Samec et al. [99] indicated that port WI and pre-compressor WI show similar NO_x reduction with a water/fuel ratio ranging from 0 to 40%. Additionally, the pre-compressor WI showed a good performance regarding the engine thermal load.

For obtaining a maximum NO_x reduction with a minimum water consumption, water should be targeted to the right location at the right time, namely to those locations in the combustion chamber where the highest temperatures prevail for considerable periods of time. In this regard, inlet manifold WI and direct WI with a separate injector are unfavorable. With a specially designed injection nozzle, Wirbeleit et al. [100] applied a stratified fuel/water injection on a single-cylinder heavy duty diesel engine. In the 13-mode ECE test they obtained a NO_x reduction of 55% for the same PM and BSFC with the application of stratified fuel/water injection combined with EGR. The advantage of this method is the variable amount of injected water depending on engine speed and load, however disadvantages are the greater complexity and higher cost of the injection nozzle. Wirbeleit et al. [100] also indicated that there exists an optimum water injection timing for the stratified fuel/water injection in respect of the NO_x and

PM trade-off. Kohketsu et al. [101] pointed out that for the stratified fuel/water injection with the same injector, the magnitude of NO_x reduction depends almost solely on the water injection quantity and is affected only slightly by other factors. With a two-zone characteristic time model based on the dominant physical and chemical sub processes occurring in the cylinder, Mello et al. [102] analyzed effects of stratified fuel-water-fuel injection on the NO_x emissions. They indicated that the fraction of water entering stoichiometric eddies increases as the water/fuel mass ratio is increased, and the NO_x reduction potential is about 90 % at the highest water-to-fuel mass ratio. In conclusion, the stratified WI offers a very high potential in NO_x reduction due to the well-directed addition of water into the spray.

With the concept structure shown in Fig. 9, Murotani et al. [103] designed a new injection system for instantaneous mixing of fuel and water in the combustion chamber by injecting water in a mixing passage located in the periphery of the fuel spray. Experimental work and CFD simulations showed good correlation in that the combustion speed and cylinder temperature decrease with an appropriate water injection timing. This resulted in a drastic NO_x reduction with simultaneous decrease of soot emissions. A two-needle type fuel and water injection nozzle with a single injector body was manufactured and tested by Tajima et al. [104], to investigate the optimum water injection timing regarding the fuel economy, NO_x and PM emissions. The results showed that the soot formation inside the flame could be clearly reduced by applying the water injection covering the latter half of the fuel injection duration.

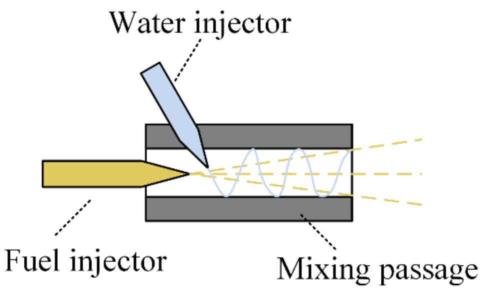

Figure 9. Concept of instantaneous mixing of fuel and water

Tanner et al. [105] compared WI techniques including the injection of water via separate injectors, the injection of fuel/water mixtures and the stratified injection of fuel/water via specially designed nozzles. CFD simulations on a large-bore diesel engine showed both the stratified and the emulsified injections yield best NO_x reductions per injected water mass for the same power outputs and at identical peak cylinder pressures. Kegl et al. [106] conducted experiments of different WI methods (multipoint injection into the manifold, mono-point injection before and after compressor, and fuel/water emulsion injection into the cylinder) on a four-cylinder truck diesel engine. Comparative results with the same water/diesel volume ratio ranging from 0 to 20% showed that water/diesel emulsion is the most proper approach to decrease NO_x and PM simultaneously without worsening the fuel consumption. Mono-point injection after the compressor showed a worse potential in NO_x reductions compared with the other two WI locations, but the reason was not discussed in detail in the published article.

Wirbeleit et al. [100] compared different WI methods regarding achievable NO_x reduction (related to the amount of water injected), PM reduction, variability of water addition, effects on cold start, lubricating oil dilution and expenditure as shown in Table

3. To obtain a maximum combustion benefit, water should be brought to the right location at the right time during the combustion period, thus WI with the same nozzle as the diesel shows better performance on NO_x and PM emissions compared to other methods, which reduce the temperature level all over the combustion chamber. The main drawbacks of fuel/water emulsion are the nonadjustable water/fuel ratio and its effect on cold start. The technological advantage vs. the financial expenditure has to be considered, especially for the injector of the stratified fuel/water injection.

Table 3. Comparison of water introduction methods [100].

	Inlet manifold water injection	Direct water injection with separated nozzle	Diesel fuel-water emulsion	Stratified fuel/water injection
Relative NO_x reduction	-	-	+	++
Effect on PM emission	--	--	++	++
Variability of water addition	+	++	--	++
Effect on cold start	None	None	--	None
Lubricating oil dilution	--	-	-	None
Expenditure	-	--	-	--

4.3 Other utilizations of water injection

4.3.1 Water injection with different fuels and combustion modes

Current and future emission regulations are becoming more stringent, and the fossil fuel demand is continuing to increase all over the world. This compels the world to focus on developing/finding alternative fuels to the existing fossil fuels. Biodiesel is one of the most promising alternative fuels that can be used in a diesel engine without any engine modification. Compared to conventional diesel fuel, use of biodiesel is generally found to reduce emissions of HC, CO and PM but with an increase of NO_x emissions [107, 108]. Palash et al. [109, 110] reviewed impacts of biodiesel combustion on NO_x emissions and pointed out that WI and water/fuel emulsion are two promising techniques for NO_x reduction. Experimental results on a biodiesel turbocharged engine from Tesfa et al. [111] showed that the water injected into the intake manifold reduces the NO_x emission by up to 50% over the entire operating range. However, the CO emission increases by about 40%.

To further improve the lubricity, stability and combustion efficiency of emulsion fuels, metal-based nano-additives have drawn much attention in recent years. Hasannuddin et al. [112] indicated nano-additives with different metals impact the water/diesel emulsion fuel properties, performance and emissions differently, and evaluation results of various nano-additives showed that Al_2O_3 is the best nano-additive and yields the highest reduction of fuel consumption, CO and NO_x emissions. Koc et al. [113] tested different water concentrations (5%, 10% and 15%) in a biodiesel nano-emulsion fuel on a 4-cylinder diesel engine, which showed strong evidences of emulsified biodiesel fuel for reducing NO_x and soot emissions. E et al. [114] compared varied mixtures of biodiesel-diesel, water and cerium oxide nanoparticles components on a marine medium-speed engine with respect to combustion and emission performances. Experimental results showed that the proper water additive and metal-based additives can effectively improve the engine thermal efficiency and decrease the CO, PM, NO_x and HC emissions due to the micro-explosion phenomenon and the catalytic activity. Similar conclusions were also claimed by Gharehghani et al. [115].

Hydrogen fueled internal combustion engines have the potential for high thermal efficiencies compared to conventionally fueled engines. Depending on the source of the hydrogen, fuel-based carbon emissions can be reduced or eliminated entirely. In order to maximize the hydrogen engine efficiency over a broad range, the entire operating regime should remain at equivalence ratios much leaner than stoichiometric. The issue of high NO_x formation in a hydrogen fueled engine is well-known and has been investigated by many researchers. The method of WI would be one of the best solutions to reduce NO_x formation [116, 117]. Nande et al. [118] examined effects of combining an advanced direct hydrogen injection strategy with WI for efficiency benefits and emission reductions on a SI engine with a CR of 11.5:1. Experimental results showed that water injected into the intake manifold results in a decrease of the NO_x emissions up to nearly 55% with a marginal loss in efficiency. Younkins et al. [119, 120] conducted experiments of water injection on a hydrogen engine with two different configurations, port injection of water with direct injection of hydrogen and direct injection of water with port injection of hydrogen. The results showed the potential of more than 85% NO_x reduction is available on both of those two configurations, without any significant fuel consumption penalty. Chintala et al. [121] tried to improve the hydrogen energy share in a CI dual fuel engine with WI and CR reduction to suppress knocking. The hydrogen share was improved from 18.8% to 66.5% with water injection and improved further to 79% combining water injection and a reduced CR. Bleechmore et al. [122] compared dilution strategies of EGR and WI using a dual fluid direct injector on a hydrogen fueled engine and indicated that WI is an effective alternative to EGR in extending load range and reducing NO_x emissions.

Compared to conventional diesel combustion, which is mainly diffusion combustion, HCCI (homogenous charge compression ignition) uses a homogeneous premixed fuel-air mixture resulting in lower smoke and NO_x emissions [123, 124]. However, the heavy load operation range is limited by knock due to an exceptionally high heat release rate. To help solve this problem, direct WI has been suggested to lower the local temperatures that seem to cause knock in HCCI. Iwashiro et al. [125] investigated effects of the direct in-cylinder WI on the knock control of a HCCI engine to reduce heat losses and expand the operating load range. The results indicated the IMEP of HCCI operation can be increased from 460 kPa to 700 kPa maintaining low NO_x levels, while the HC and CO emissions increased due to wall wetting, especially with an early water injection timing. Another major problem of HCCI combustion is controlling the ignition timing over a wide load and speed range. Christensen et al. [126] indicated it is possible to control the ignition timing in a narrow range, using an amount of injected water similar to the amount of fuel. However, an increase in the already high emissions of unburned hydrocarbons was observed, which indicated poor combustion quality.

4.3.2 Water injection as supplementary working fluid

The injected water can also be treated as supplementary working fluid in the cylinder or through the turbine. With the traditional four-stroke Otto or Diesel engine followed by a two-stroke steam cycle, the six-stroke engine concept had been considered for a long time [127]. Conklin et al. [128] proposed to trap and recompress some of the exhaust from the fourth piston stroke, followed by a water injection and expansion of the resulting steam/exhaust mixture. With assumptions of instantaneous water evaporation and mixing processes, calculation results with an ideal thermodynamics model showed that the net mean effective pressure of the steam expansion stroke ranges from 0.75 to 2.5 bar compared to the mean effective pressures of the naturally aspirated gasoline engines of 10 bar, which means water injection has the potential to significantly increase the engine efficiency and fuel economy. Arabaci et al. [129] retrofitted a single cylinder four-stroke engine to a six-stroke engine, which was similar as the configuration described above. Test results showed that the exhaust gas temperature and specific fuel consumption can be decreased by around 7% and 9% respectively with the adoption of water injection.

The pre-turbine water/steam injection has also drawn much attention in recent years. Fu et al. [130] proposed a steam-assisted turbocharging system to increase the turbine output, and simulation results on a 1.8 L turbocharged gasoline engine showed that this system can improve the engine low-speed performances and make the peak torque shift to the low-speed area. Zhu et al. [131, 132] testified the pre-turbine steam injection combined with Miller cycle can be used to improve the turbocharging system matching with the engine, experimental results showed the fuel economy under full load conditions can be improved by up to 5.9%. Zhao et al. [133] evaluated the combination of steam injection and turbo compounding on a turbocharged diesel engine, which showed the fuel economy can be increased by 6.0–11.2% at different speeds.

5 Comparisons and combinations with other advanced techniques

5.1 Water injection vs. EGR

Both EGR and WI introduce inert species into the cylinder, which can effectively lower the combustion temperature and decrease NO_x emissions [134]. The main drawbacks of EGR are the increase of PM emissions and the required high boost pressure to maintain AFR or the BMEP at a suitable level [135]. One advantage of WI compared to EGR is the possible reduction of NO_x emissions either at low loads and high loads without a substantial increase in PM emissions.

5.1.1 Comparisons on the gasoline engine

In gasoline engines, the adoption of an external cooled EGR circuit for knock avoidance has also been analyzed in a number of papers [135, 136]. This technique, however, may induce a higher cyclic variability and a lower power output. Simultaneously, fluid-dynamics and thermal inertia of the EGR circuit pose control problems during fast transient operation.

With validated turbulence combustion and knock models, Bozza et al. [137] compared the low-pressure cooled EGR and ported WI in a simulation model of a two-cylinder gasoline engine under full load at different engine speeds. In all calculations, the spark timing was automatically modified to realize operation at the same knock threshold as the base configuration, and the waste-gate valve opening was adjusted by a PID controller targeting the prescribed load levels. Also, constraints of TIT, boost pressure, turbocharger speed and in-cylinder peak pressure were considered to obtain more realistic results. Fig. 10 shows a comparison of best EGR and best WI calibrations. The BSFC benefits can be mainly ascribed to a higher knock resistance that allows optimization of the combustion phasing and/or a reduction in fuel enrichment. The heat subtracted by the water evaporation enhances the above effects, resulting in larger BSFC benefits with respect to the EGR technique in most cases. However, the BSFC advantages are limited by the maximum allowable in-cylinder pressure, TIT, turbocharger speed and boost level.

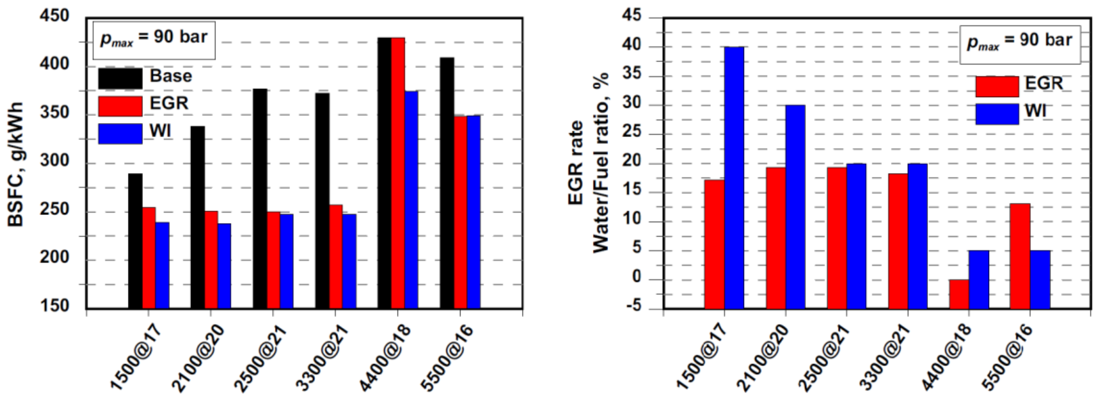

Figure 10. Comparison of best EGR vs. best water injection calibrations [137].

5.1.2 Comparisons on the diesel engine

Tauzia et al. [52] [138]conducted an experimental study of EGR and WI under different load conditions of an automotive diesel engine. As shown in Fig. 11, at low load conditions when excess air is naturally high, EGR and WI have the capability to reduce NO_x emissions and PM simultaneously (due to the high AFR). A major drawback is that CO and HC emissions increase a lot at these temperatures, while combustion efficiency and fuel economy decrease. At these conditions, from a practical point of view, EGR seems to have an advantage compared to WI because it does not require liquid water in addition to fuel. At higher loads, WI has the capability to reduce NO_x emissions without a large increase of PM emissions, because the air flow rate remains approximately constant. At these operating points, EGR can reduce NO_x emissions, but the PM emissions increase significantly due to the reduced air flow rate.

Thus, the WI technique has a clear advantage in terms of NO_x reduction, while maintaining PM emissions, compared to EGR at higher loads.

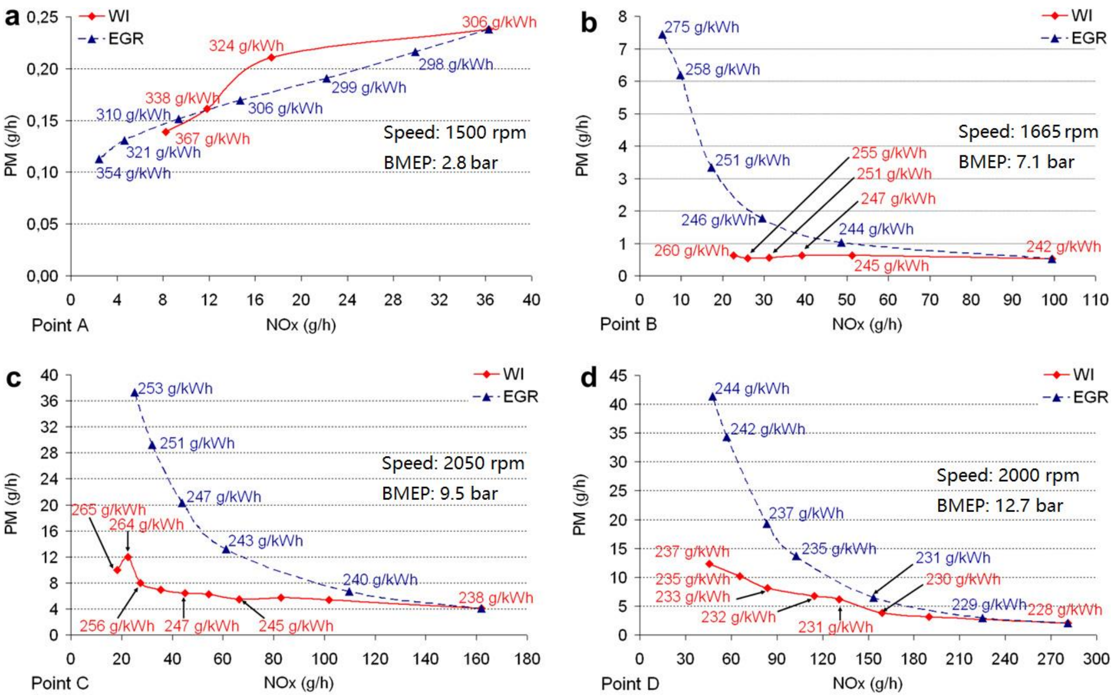

Figure 11. Influences of water injection and EGR on NOx and PM trade-off with the load increasing from Point A to D [52].

Hountalas et al. [139] conducted comparative evaluations of EGR, intake manifold WI and fuel/water emulsion with a calibrated multi-zone phenomenological combustion model. The results showed that for a similar NO_x reduction of about 30% (limited by the fuel/water emulsion), the use of fuel/water emulsion is the most favorable one, followed by intake water addition and EGR, considering both emissions and BSFC. Chadwell et al. [34] developed a new real-time WI system, in which water and diesel mix in the injector tip and water mass can be controlled cycle by cycle. Experimental researches of this new WI system compared to and combined with an EGR system were conducted on an 11.7L heavy-duty diesel engine. As shown in Fig. S3, by adding 30% water, the $BSNO_x$ was reduced by 42% with a 2.1% increase in

BSFC. In comparison, 10% EGR rate reduced the $BSNO_x$ by 65%, but at a BSFC penalty of 8.6%. Using a combination of 12% EGR and 30% water, a further 50% decrease of $BSNO_x$ was obtained compared to the 10% EGR only case. Additionally, an advantage of PM emissions was observed with the opacity decreased from an unacceptable value of 4.5% (10% EGR only case) to 1% (12% EGR and 30%water). Chadwell et al. [34] also pointed out that a faster torque rise rate can be obtained with this real-time WI system since a richer AFR limit can be used with no opacity spikes observed.

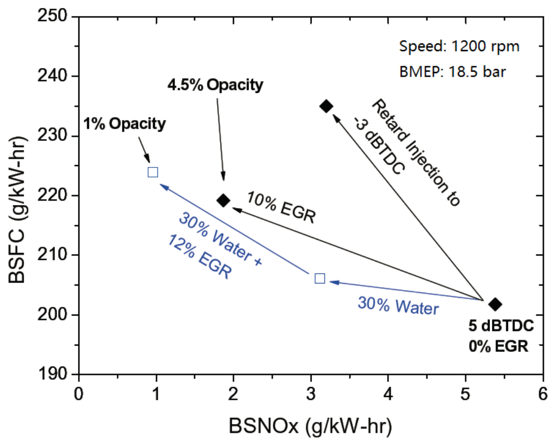

Figure S3. Comparison and combination of EGR and water addition to reduce NOx [34].

5.2 Combinations of water injection with other techniques

5.2.1 Applications on the gasoline engine

Hoppe et al [41] demonstrated a potential efficiency increase of 3.3-3.8% in the region of the minimum specific fuel consumption, on a stoichiometric combustion concept with Miller cycle and cooled external EGR. Using WI in addition to homogenous lean combustion, an efficiency gain of 4.5% in the region of the minimum specific fuel consumption was achieved, due to the lower heat losses and higher combustion efficiency. Hoppe et al. [94] further indicated that the combination of WI with a high CR of 14.7 and Miller cycle valve timings is very attractive as it resulted in low fuel consumption at part load operation, with a large sweet-spot area ranging to full load operation with ISFC (indicated specific fuel consumption) below 210 g/kWh.

Teodosio et al. [140] conducted 1D numerical analysis of different solutions, including the variable compression ratio, the port WI, the external cooled EGR and their combinations in reducing the BSFC on a downsized turbocharged SI engine. Optimization results showed that the WI shows higher benefit at medium-high load due to its knock suppression capability, while cooled EGR can effectively reduce the pumping work at low load. Combining the above techniques provides BSFC reductions of 6.9%, 5.2% and 9.0% at low, medium and high load at 1800 rpm, respectively. With knock mitigation on the SI engine, a higher affordable BMEP level can be obtained with WI, and it is meaningful to quantify the potential of WI as an enabler for ultrahigh boost with multistage air charging system. The ability of WI to lower the exhaust gas temperature is also of interest since it may be used as an enabler for employing variable geometry turbines even in gasoline engines, thus allowing further downsizing potential. Alternatively, it may be used to reduce material costs on the turbochargers due to reduced thermal stresses on the component.

5.2.2 Applications on the diesel engine

It also appears that water injection using emulsion or stratified strategy could be used in combination with EGR to achieve the maximum NO_x reduction. This is attributed to the fact that its use has no penalty in engine BSFC (except for high load) while it reduces soot on the entire engine operating range [139]. Liang et al. [141] and Zhang et al. [142] stated the combination of oxygen enriched combustion and water emulsion appears to be one of the most effective ways to control PM and NO_x simultaneously and maintain a comparable fuel consumption. Bertola et al. [143] indicated that with the use of water-diesel emulsion combined with high percentage of EGR and high injection pressures, NO_x emissions below 1.0 g/kWh and PM emissions of about 0.01 g/kWh are realized at low loads without appreciable changes in fuel consumption. Wirbeleit et al. [100] suggested that the stratified diesel fuel-water-diesel fuel injection combined with EGR is the most efficient in-cylinder NO_x and PM reduction technology without any negative effect on fuel economy. Nazha et al. [144] compared hot EGR, inlet manifold WI (water fuel ratio of 1.5:1), 20% water-in-diesel fuel emulsion and their combined effects on a 2.5L four-cylinder diesel engine. Experimental results at full load showed that a combination of EGR and WI reduces NO_x emissions by over 70% with the smoke increased by close to 60%. The combination of emulsion and EGR reduces both NO_x and smoke by about 55% and 45% respectively. The increased unburnt HC in both cases are still relatively low, and the fuel consumption is similar to the baseline engine case.

5.3 Comparisons with other downsizing techniques

De Cesare et al. [95] compared advantages and drawbacks of promising technologies for new generation SI engines including GDI lean combustion, Miller cycle, variable CR, WI, cylinder deactivation, external EGR and multistage air charging.

Johnson et al. [145] also evaluated those technologies with respect to the potential CO_2 reduction, challenges and implemented status. Based on the results of both studies, Table S1 shows an overview of typical CO_2 reduction technologies for downsized gasoline engines. It can be safely concluded that WI, which is still in development, is a cost-effective approach for decreasing CO_2 emissions. De Cesare et al. [95] also pointed out that combined with high CR, WI can benefit the whole gasoline engine operating map even at low loads, while influences of other techniques are often limited to certain engine operating zones.

The legislated restriction of CO emissions under real world driving conditions will be a new challenge for the higher power region of the engine operating envelope, where fuel enrichment is currently employed for component protection. In order to avoid power loss while operating at lambda = 1 in the entire engine map, two options can be adopted: a decrease of the exhaust gas temperature, and the usage of enhanced materials. Busch [146] evaluated the potential of different technologies including the adoption of improved turbine material, two-stage variable CR and WI on two base engines with specific power outputs of 110 kW/l and 90 kW/l. The results showed that the adoption of optimized turbine material enabling up to 1050°C TIT still suffers a power loss of 6% with lambda 1 operation on the base engine of 90 kW/l. Both the two-stage variable CR and the WI can completely avoid power losses on the base engine of 90 kW/l, while only the WI is feasible for the base engine of 110 kW/l due to the high cooling potential in the combustion chamber.

Table S1. Overview of typical CO2 reduction technologies [95, 145].

ICE technology	Advantages and drawbacks	CO_2 reduction[(a)]	Δ Cost [€]
GDI lean combustion	-lower pumping loss and heat loss, knock mitigation with high efficiency; -Expensive after-treatment for NO_x, higher cycle by cycle variation, combustion chamber needs redesign.	10-20%	385
Atkinson/Miller cycle (CR+2)	-lower pumping loss, high CR enabled, knock mitigation; -high boosting and variable valve timing required.	5-12%	200
Variable CR (CR+2)	-high efficiency at low load, very effective coupling with Miller cycle; -high cost and complex.	4-9%	125/350[(b)]
Water injection (CR+2)	-knock mitigation, high CR enabled, fuel enrichment avoided; -water consumption and corrosion.	4-6%	95/130/180[(c)]
Cylinder deactivation	-pumping and heating loss reduction at low loads; -high noise, vibrations, cost, package.	2-10%	200
External EGR	-knock mitigation, lower heat loss and reduced throttling loss and NO_x; -high cycle by cycle variation, turbo matching and transient response problems.	3-4%	115
Multistage air charging	-low end torque increase, downsizing and down speeding enabled, scavenging reduction, improved drivability; -cost, package and complexity control.	12%	200/400[(d)]

NOTE: (a) CO_2 reduction values were from different literatures, which might be varied based on different evaluation criterion; (b) cost of two stage and continuous variable CR; (c) cost of port WI, fuel/water mixture injection and separated injection; (d) cost of two-stage turbocharging and eBooster.

6 Other critical issues

6.1 Alcohol/water injection

WI systems using a mixture of water and alcohol with trace amounts of water-soluble oil also have attracted interests of researchers. The water provides the primary cooling effect due to its great density and high heat absorption properties. The alcohol is combustible, and also serves as antifreeze for the water. The purpose of the oil is to prevent corrosion of WI and fuel system components. The alcohol mixed into the injection solution is often methanol or ethanol [7].

6.1.1 *Methanol/water mixtures*

Port injection of methanol-water mixtures is receiving increasing interest. Unlike the water injection alone, the presence of a second fuel allows the engine to meet higher performance. Moreover, the latent heat of vaporization of methanol is three times that of gasoline, which can further reduce the mixture temperature before the start of combustion. In addition, the octane number of methanol is much higher than that of gasoline. Since the laminar flame speed of methanol is higher than that of gasoline, burn rate is also expected to be improved, but the increased in-cylinder pressure level may potentially cancel out the mentioned anti-knock benefits [13]. As an energy source and a customer cost, methanol also has to be taken into account for the calculation of specific fuel consumption.

Maintaining the same charge cooling effect in a 3D simulation model, Breda et al. [60, 147] compared different port injected MW (methanol/water) mixtures with methanol ratios ranging from 0 to 100% by mass fraction at 7000 rpm of a downsized gasoline engine. The spark advance was increased to preserve the knock safety margin as the baseline 100% gasoline case. As illustrated in Fig. 12, approximately the same IMEP is obtained for all the cases, with the pure water case having the lowest ISFC and the pure-methanol case having the highest ISFC. Breda et al. [60, 147] also indicated that MW mixtures may be a better choice at lower speed conditions due to the reduced charge temperature and turbulence intensity and higher evaporation rate of the methanol, which should be further investigated.

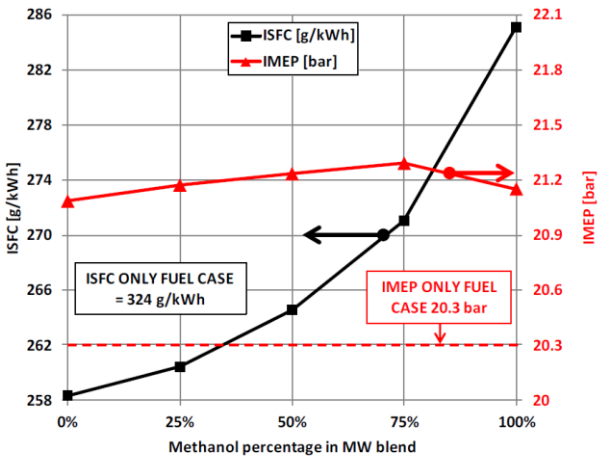

Figure 12. Comparisons of ISFC and IMEP with ported mixture injections of different MW ratios [147].

6.1.2 Ethanol/water fumigation

Morsy et al. [148] assessed ethanol/water mixtures fumigation into the inlet air on the performance and exhaust emissions of a single cylinder diesel engine. The results indicated that NO_x emissions tend to decrease with mixtures containing water and tend to slightly increase with pure ethanol fumigation. Slight improvements in thermal and exergy efficiencies with ethanol/water mixtures fumigation are found, which confirm the potential use of ethanol/water fumigation in diesel engines for better energy and exergy efficiencies and lower NO_x emissions. In addition, the encountered weaknesses of increased CO and HC emissions could be partially resolved by using the right proportion of ethanol and water along with aftertreatment, e.g. using a DOC.

6.2 Potential CO_2 reduction

Although effectiveness of the WI has been proved both experimentally and numerically at high loads, its usefulness still needs to be quantified in terms of CO_2 emissions along a vehicle driving cycle. This information is indeed relevant at industrial level to estimate the real potential of the WI technique in contributing to meet actual and future CO_2 emission targets.

In order to quantify the impact of a WI strategy on fuel economy and CO_2 emission over a real driving cycle, Bozza et al. [56] superimposed the engine operating points over a WLTC on a computed contour map of BSFC reduction with WI as shown in Fig. 13. Evaluation results showed that the operating points that mostly contribute to the overall CO_2 emission frequently lie in a region of null or very small BSFC improvement, and only a 0.61% reduction of CO_2 emission is obtained. The lower fuel enrichment level and the largely incomplete water evaporation are the main reasons for the minor impact of WI at low speed points.

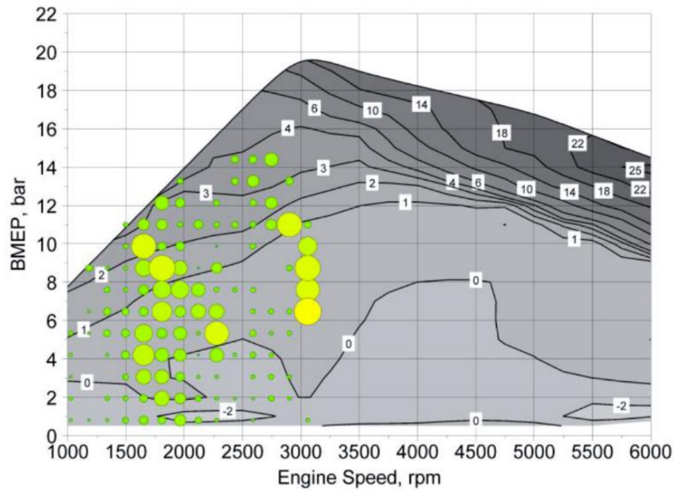

Figure 13. Contour map of percentage decrease of BSFC due to WI and bubble chart of fuel consumption along the WLTC [56].

Hoppe et al. [94] evaluated the effects of WI with a CR of 13.5 and a Miller camshaft on driving cycles of NEDC (New European Driving Cycle), $WLTC_{high}$ and

RTS (Standardized Random Test Sequence) 95. As shown in Fig. S4, the red spots indicate distributions of load points in the corresponding driving cycle. Due to the low share of load points above 10 bar BMEP in the NEDC, the fuel consumption reduction potential with WI is limited to 1.29%, and the water consumption is below 1L/100km. For the $WLTC_{high}$ and RTS 95, which comprise higher power demands, the fuel consumption benefits are 3.08% and 5.53% respectively with increased water consumptions. In addition, the water consumption is relatively small compared to the fuel consumption in a real driving cycle.

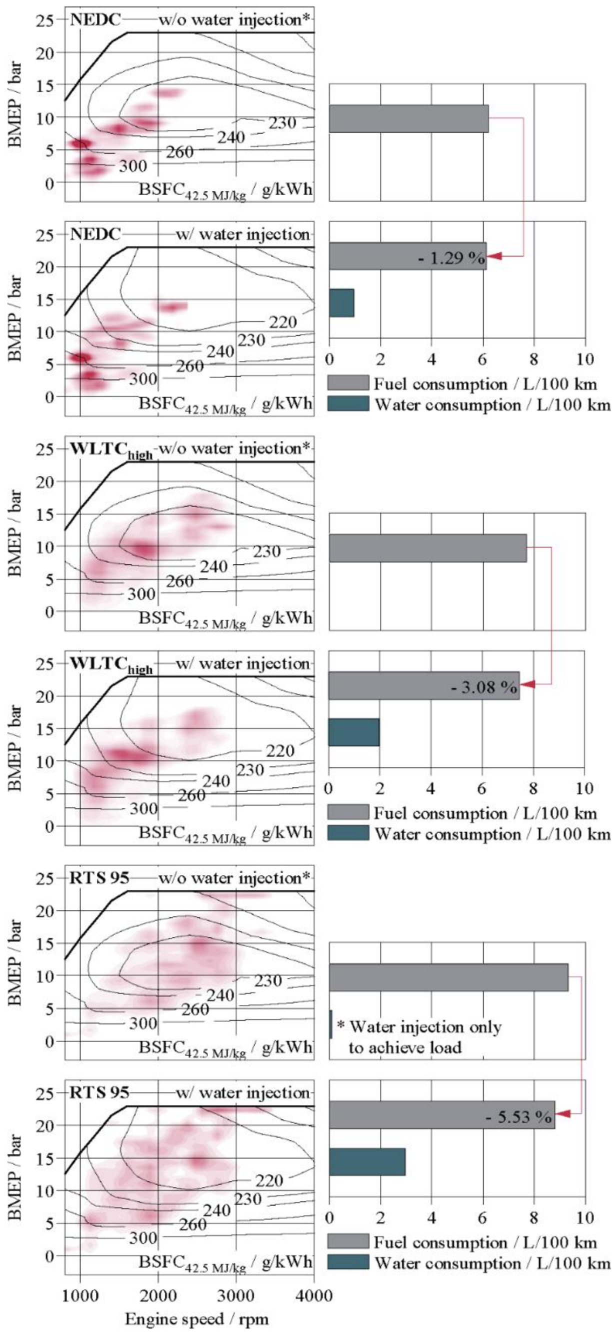

Figure S4. Fuel share diagrams, fuel and water consumption with/without water injection for NEDC, WLPC$_{high}$, and RTS 95 [94].

6.3 System integration on the gasoline engine

BMW produced the limited edition M4 GTS vehicle powered by a turbocharged inline six-cylinder gasoline engine with water injection for increasing specific power, and experiences gained on the road and on racetracks have confirmed the system robustness [79]. However, providing water for the onboard operation still brings some new issues regarding the water tank size, onboard water recovery, required water quality, bio-decontamination and protection against filling with wrong liquid.

The water consumption depends on both the engine/vehicle character and the customer's driving profile. Furthermore, the water requirement is also a function of the ambient temperature, and more water is consumed in a warm climate than under cold conditions. Three possible solutions including refilling by the user, A/C condensation & rainwater harvesting and exhaust gas condensation are possible for the required amount of water [79, 96]. The first one is the most promising because it is cheap and accepted by the end-customer. Detailed customer surveys conducted in Germany and USA, which were commissioned by Bosch, indicated that the end-consumers were willing to refill distilled water at an interval of 6000 km [96]. The other solutions are being developed to minimize the end-user impact and refilling costs. If the WI is combined with the latter two water supply technologies, the trade-off considerations between water and fuel consumption can be mitigated or even avoided [94].

Condensing water from the air conditioning system is also a simple approach. Investigations have shown that the pH value of the recovered water does not drop below 6 with even low air quality, which means corrosion of engine components is not a problem. The disadvantage of this system is that no water recovery is possible in cold environmental conditions, despite the fact that the water requirement is also low.

To condense water from the exhaust gas, a temperature of approximately 40~56 ˚C would need to be achieved to fall below the dew point depending on the pressure level and the relative AFR. Barros et al. [149] designed a water recycle loop from the exhaust gas and stated that the exhaust temperature out of the heat exchanger is inversely proportional to the amount of water recaptured. At high engine speeds, a higher flow velocity tends to carry moisture with the flow before there is a chance to condensate the water vapor. Sun et al. [80] tested three different water separation prototypes including a passive cyclone separator, a passive membrane separator and an active separator on a low-pressure EGR engine. Evaluations of the condensate collection efficiency with different separators, at different locations (after the EGR cooler or charge air cooler), pressure drops and condensate quality were conducted in detail, which showed the potential of water recovery from gasoline engine exhaust for future implementations of water injection. Another disadvantage of the system is the low pH value of the condensate as a result of acid formation in the exhaust gas. Sun et al. [80] also indicated the use of high-sulfur fuel results in a more acidic condensate with the pH value ranging from 2.8 to 4, which leads to significant corrosion on the components of the injection system and the basic engine. With the use of low-sulfur fuel, the collected condensate has pH of 6.5~8.5 depending on the collecting location. Moreover, this system requires large installation space, and its complexity also leads to higher costs.

In addition, an efficient on-board diagnostic strategy needs to be developed for WI applied on the vehicle, which should ensure that a minimum allowable level of water is available and also trigger conventional knock mitigating strategies with WI failing [26]. Unlike a fuel tank, a water tank provides an environment in which microorganisms can exist, which brings a new problem of avoiding biogenic deposits. Water tank heating and chemical disinfection are possible solutions. Another major concern of WI is the possibility of oil dilution in the engine crankcase caused by a poor water atomization especially with large injected quantities of water, and further damage or wear to the engine may be problematic in a long-term lifespan of the ICEs [56]. Finally, although neither misfire nor unstable combustion was observed with WI in any of the published works, the requirement of an improved ignition system for the SI engine may need to be considered for a fast and safe ignition of the cylinder charge [44].

7 Conclusions and future research directions

Water injection, with an effective cooling effect for the in-cylinder combustion process, has attracted extensive attentions in recent years due to the potential knock mitigation and NO_x reduction. This paper provides a critical review of the current state of the art research on this technique. After detailed introductions of water injection and evaporation processes, mechanisms of the in-cylinder combustion with water addition were discussed thoroughly. An in-depth survey of WI applied on different types of ICEs was then conducted followed by the comparisons and combinations of WI with other engine techniques. Finally, some critical issues were addressed.

From the above discussions, the following conclusions are obtained:

(1) Wall film formation that reduces charge cooling and premature vaporization outside of the cylinder are the main causes for the lower efficiency of the intake runner/port WI implementation, compared to direct or emulsion WI. An accurate evaluation of the water evaporation shows great importance of the design and

optimization of different WI systems, and also for an accurate calculation of the heat release rate.

(2) For the CI engine, water addition from the “fuel side” has a positive effect on the combustion, while a small negative effect on efficiency is inevitable with the water addition from the surrounding “air side”. The dilution effect of WI is much larger than the thermal effect and chemical effect on the NO_x reduction of the CI engine. Water directly injected into the combustion zone allows larger decreases of the combustion temperature and therefore the NO_x emissions. This also benefits the NO_x and PM trade-off, where NO_x reduction is possible without significant impact on PM.

(3) For the SI engine, water injection mainly slows down the laminar flame speed, but the combustion duration is not significantly affected when combined with an advanced spark timing with a small amount of injected water. Effects of WI on emissions of SI combustion should be considered with the engine operating conditions and the adjustments of other parameters like the spark timing and AFR. With the increase of WI amount and the decrease of fuel enrichment, HC and CO decrease simultaneously, but trends are different with WI under stoichiometric operating conditions. Variations of NO_x and PM emissions also depend on both the amount of injected water and the in-cylinder air fuel ratio.

(4) WI has been shown as a cost-effective approach for the downsized gasoline engine operating without fuel enrichment (lambda = 1), and the required water fuel ratio for stoichiometric operation depends on the WI implementation, engine specifications and driving cycles. Evaluating from an in-cylinder charge cooling point of view, using

the same amount of water, direct in-cylinder WI is the best choice, and port WI is better than the upstream WI. Injection pressure, timing and location of water should be optimized with consideration given to the water evaporation, combustion and emissions. In addition, the selection of WI implementations should be considered with respect to benefits, robustness, packaging and expenditure.

(5) WI is a good alternative to EGR for introducing inert species into the cylinder, therefore mitigating knock combustion on the SI engine and reducing NO_x emissions from the CI engine. A combination of WI and EGR can further decrease the NO_x emissions in the CI engine, and PM emissions (smoke) also decrease compared to the sole EGR solution.

(6) Combined with a high CR, multistage air charging system or Miller cycle, WI shows great potential on the SI engine for further downsizing, which has been shown to be a cost-effective approach to reduce CO_2 emissions for the new generation of SI engines. The decreased TIT maybe used as an enabler for employing variable geometry turbines on the gasoline engine, and material costs on the turbocharger can be decreased due to the reduced thermal stress.

It should also be stressed that water injection is still not a mature technique for commercial vehicles. Fundamentals of both thermophysical and chemical kinetic effects of water addition on combustion phenomena and emissions need to be further investigated with respect to different water injection implementations and engine types. In addition, only limited amount of studies regarding long term operation using water injection have been published, and friction analysis on piston ring and engine block, carbon deposit on water injector, metal debris and water content on lubricating oil and corrosion analysis need to be further evaluated for water injection commercialization.

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Appendix A. Supplementary Material

Supplementary figures (Fig S1-S4) and table (Table S1) associated with this article can be found in the Supplementary Material.

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