THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN THERMO AND FLUID DYNAMICS

Investigating Effects of Water Injection on SI Engines

JAYESH KHATRI

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2019

Investigating Effects of Water Injection on SI Engines
JAYESH KHATRI

Thesis for the degree of Licentiate of Engineering 2019:11
Division of Combustion and Propulsion Systems
Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31-772 1406

Chalmers Reproservice
Gothenburg, Sweden 2019

Abstract

In recent years, there has been a major shift towards the partial or complete electrification of vehicles that have traditionally been powered by conventional internal combustion (IC) engines; almost all major automotive manufacturers have rightly stated that they will make such a shift. This has been motivated in large part by pressure from governments and policymakers to minimize vehicular emissions, especially those of the greenhouse gas CO_2, in order to control climate change.

A widely recognized way of facilitating this shift is to introduce vehicles having both an electric motor and a downsized turbocharged spark-ignited engine. Downsized SI engines are designed to have lower fuel consumption and tailpipe emissions than conventional engines while maintaining a comparable power output by increasing thermal efficiency. Unfortunately, this generally necessitates higher cylinder pressures and temperatures, both of which increase the engine's knock propensity. At present, engine knock is mitigated by retarding the ignition timing or fuel enrichment, both of which reduce thermal efficiency. During the last decade, research building on trials conducted with aircraft engines has shown that water injection may be a viable alternative knock mitigation strategy that mainly suppresses knock by reducing local in-cylinder mixture temperatures. Adding sufficient water to the cylinder can enable knock-free engine operation under stoichiometric conditions, reducing fuel consumption and enabling full utilization of a three-way catalytic converter (TWC).

This licentiate thesis presents studies on the performance of a water injection system that were conducted within the framework of a broader project seeking to optimize SI engines for use in high efficiency hybrid powertrains. The results presented originate from two experimental campaigns. During the first campaign, a 3-cylinder 1.5L turbocharged engine was operated using 91, 95, and 98 RON gasoline fuel to assess the effects of water injection on knock mitigation, thermal efficiency, and emissions. Full- and part-load curves obtained with different fuels and water injection strategies are presented and discussed. In the second campaign, the effect of varying the moisture content of the ambient air (i.e. the relative humidity) was investigated using both experimental and theoretical methods to clarify the mechanism responsible for the knock suppression and performance enhancement caused by water injection. The engine was operated at three humidity levels that were maintained using a humidity control system developed in-house. Particulate emissions were also measured at each studied operating point and their dependence on relative humidity is discussed.

Keywords: Downsized SI engine, Water Injection, RON, Knock Mitigation, Relative Humidity, Particulates

List of publications

This thesis is based on the work contained in the following publications:

Publication A Khatri, J., Denbratt, I., Dahlander, P., and Koopmans, L., "Water Injection Benefits in a 3-Cylinder Downsized SI-Engine," SAE Int. J. Adv. Curr. Prac. in Mobility 1(1):236-248, 2019, https://doi.org/10.4271/2019-01-0034.

Publication B Khatri, J., Sharma, N., Dahlander, P., and Koopmans, L., "Effect of Relative Humidity on Performance of a Downsized SI Engine with Water Injection" submitted in *Journal of Applied Energy*.

Acknowledgements

First and foremost, I appreciate the efforts from Lucien Koopmans and Ingemar Denbratt, for offering me this position. To my supervisor, Lucien, I am grateful for his expertise, assistance, guidance and patience throughout this project. Thanks to Ingemar, my co-supervisor, for his guidance and support in the project. I have learned a great deal from both of them, and am forever in their debt.

Besides my supervisors, I extend my sincere gratitude to Petter Dahlander and Lars Jernqvist for assistance with data collection and analysis. I would also like to thank all the research engineers, specifically Alf Magnusson and Anders Mattsson - without their efforts the experiments would just have been replaced with some more simulations.

I gratefully acknowledge Swedish Energy Agency (*Energimyndigheten*) for providing the funding for this project. And Volvo Cars, especially Thomas Bernichon and Fredrik Ekström, thank you for your kind support.

I must also acknowledge all my colleagues. Thank you Elenor Norberg, for listening to my stories and mid-life crises and helping me learn some Swedish - *Jag har alltid tid för dig.* Learning Swedish, both the language and the culture, has been an incredible experience, although sometimes a challenging one! *Stort tack till* Lars Jernqvist *och* Sven Andersson: for all the history, physics and social lessons. The list of my fellow PhD students who have enriched my time here is long, and I am grateful to all of them for the many laughs and conversations we shared, from the lunch table to fika breaks and several memorable trips together. Cheers!

And finally last, but by no means least, I would like to thank my family for their moral support and sympathetic ear. Special thanks are reserved for my grandparents: you are always keen to know what I am doing and how I am proceeding, although it is highly unlikely that you have ever grasped what it is all about! I hope I am making you proud.

Contents

1 Introduction

Climate change has become a major issue in recent years because the world's rising temperature is having profound effects on the environment, inducing the melting of glaciers and ice sheets and causing major changes in ecosystems around the world. This warming is primarily due to anthropogenic emissions of greenhouse gases such as CO_2. The EPA has concluded that the transportation sector is responsible for around 14% of all anthropogenic greenhouse gas emissions[1], as shown in Figure 1.1.

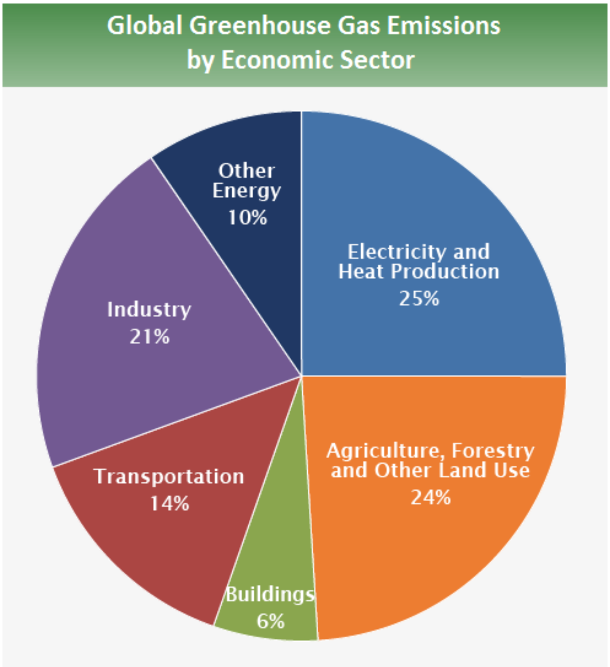

Figure 1.1: *Global Greenhouse Gas Emissions*

To control climate change, authorities around the world are imposing increasingly stringent limitations on CO_2 emissions from vehicles. New European emissions regulations will take effect from 2020, putting great pressure on the automotive industry to find ways of reducing emissions and increasing fuel efficiency. As a result, there is great interest in replacing passenger vehicles powered by conventional IC engines with pure electric vehicles (EVs) that do not consume fossil fuels and produce no tail-pipe emissions. However, current EVs are subject to a range of limitations[2], mostly relating to the high cost and relatively low storage capacity of existing batteries. Additionally, their well-to-wheel emissions can be significant despite being substantially lower than those of conventional vehicles with IC engines. Hybrid vehicles having both IC engines and electric motors with batteries can bridge the gap between low emission EVs and the capabilities of conventional modern IC-powered vehicles, and thus offer a way of reducing emissions while avoiding the limitations associated with pure EVs. Efforts to develop robust hybrids and to reduce emissions from IC engines in general has led to a strong focus on improving the efficiency of IC engines. Efforts in this area have enabled the development of downsized engines using forced induction that use fuel much more efficiently than older engines.

1.0.1 Background

Engine downsizing has helped to reduce the fuel consumption (and thus the CO_2 emissions) of new IC engines without reducing their performance by using forced induction systems such as mechanically driven turbochargers or superchargers. For example, a downsized 2.0 L engine was found to achieve up to 11% lower fuel consumption than a 6-cylinder 3L engine at the same load point [3]. Importantly, at a given vehicle load, the operating point of a downsized engine will generally be shifted (relative to that of a conventional engine) in the direction of the so-called "sweet spot" of maximum operating efficiency. IC engines generally operate more efficiently at high load and high speed because of reduced pumping and heat transfer losses. Vehicular emissions certification is currently based on fixed driving cycles such as the WLTP, which recently replaced the NEDC (New European Driving Cycle). However, real driving conditions vary widely significantly and human beings in the real world do not drive in the ways assumed in the test cycles. Therefore, current vehicle certification regimes tend to underestimate the real-world emissions of passenger cars. This is increasingly recognized by both consumers and policymakers, resulting in an increasing emphasis on regulations based on real driving emissions (RDE). To meet forthcoming emissions and fuel consumption targets based on these regulations, vehicle manufacturers will have to develop more efficient IC engines and/or adopt powertrain electrification. This has led to the emergence of marketed vehicles using combinations of electrification and engine optimization using technologies such as downsizing, high compression ratios, cooled EGR, and the Miller/Atkinson cycle.

A major challenge of engine downsizing and improving engine efficiency is an increased knock propensity. Knock in SI engines is defined as the auto-ignition of end gas before the flame reaches the charge. There is an extensive body of literature on this phenomenon and its prevention [4, 5, 6]. Knock is usually prevented by ignition retardation, which reduces engine efficiency because it lowers the Mean Effective Pressure (MEP) and causes poor combustion phasing. Additionally, under high load conditions, ignition retardation exposes the exhaust after-treatment system to harmfully hot exhaust gases. Fuel enrichment (i.e. the injection of non-stoichiometric quantities of fuel into the cylinder) can be used to reduce exhaust temperatures and prevent knock, but inevitably increases the engine's BSFC (Brake Specific Fuel Consumption). Unfortunately, the presence of excess fuel in the exhaust can adversely affect the conversion rate of the TWC (Three Way Catalyst), which must be high over the whole engine map to comply with current emissions standards.

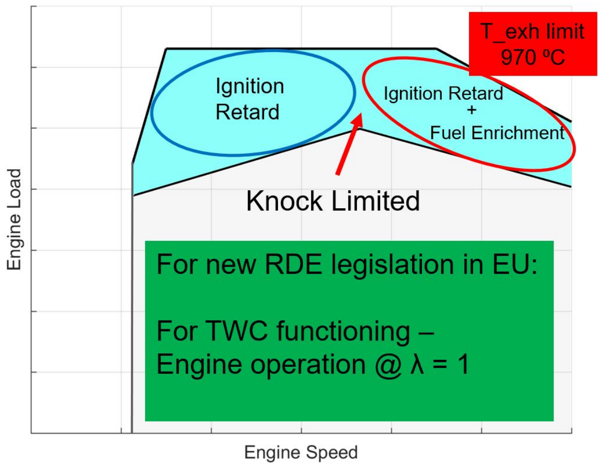

Figure 1.2: *Engine map of a downsized SI engine showing the high load region where knock is problematic and the measures used to control it.*

Figure 1.2 shows the engine map for a downsized engine. The high load region where knock must be controlled is shown in cyan. In the left-hand part of this region (which corresponds to high load but low or moderate engine speeds), ignition retardation is used to reduce the cylinder pressure and temperature so as to prevent knock. The right-hand part of this region corresponds to operating conditions with high loads and high engine speeds. Under these conditions, ignition retardation causes delayed combustion in the later part of power stroke and thus raises the gas temperature in the exhaust manifold. This is harmful to the exhaust after-treatment system, which cannot tolerate temperatures above 950-980 °C. Therefore, fuel enrichment is used in this region (in addition to ignition retardation) to induce a charge cooling effect and prevent damage to the after-treatment system. Unfortunately, this directly increases fuel consumption.

Water injection has been identified as a promising solution for preventing engine knocking without compromising BSFC. It allows the engine to be operated at or near MBT timings with a stoichiometric AFR over the entire engine map, which directly reduces fuel consumption and CO_2 emissions: in one recent study, it was shown to reduce fuel consumption by as much as 13% [7]. More impressively still, the the combination of improved combustion phasing and stoichiometric operation could theoretically increase the thermal efficiency of spark-ignited (SI) engines by up to 34% [8]. Water injection could thus be a very powerful way of increasing the efficiency of SI engines, and especially downsized SI engines, at high loads.

The mechanism by which water injection prevents knock is not entirely clear. An early study found that "with water addition to the emulsion, the research octane number rose from 91.2 to 100 for a 40 weight percent water emulsion [9]." Other authors similarly concluded that water injection increases the fuel's effective octane number and suppresses knocking because of the cooling effect of water vaporization in the cylinder [10]. Water-fuel mixtures thus act as high octane fuels, reducing knock sensitivity. However, this hypothesis has not yet been tested in an experimental campaign using fuels with different octane ratings in engines fitted with water injection systems. High RON (Research Octane Number) fuels are commonly used because they reduce the incidence of knock. However, high RON fuels are more expensive than lower octane fuels and are not available in all markets. Alcohol fuels also have high latent heats of vaporization (e.g. 952 kJ/kg for ethanol) and octane number (>100), making them promising alternatives for mitigating knock and enhancing performance. Importantly, alcohol fuels are also combustible and act as anti-freeze agents for water. Various water injection strategies using alcohols have been studied, including one using 50/50 blends of water with an alcohol (e.g. methanol) [11] and others using a range of non-gasoline fuels (e.g., LPG and hydrogen) [12, 13, 14]. Water injection systems for IC engines typically inject water into the intake manifold (referred to as port injection) or directly into the cylinder (direct injection). Several publications have assessed the pros and cons of these two water injection strategies [7, 10, 15, 16, 17] and their effects on cylinder charge properties.

1.0.2 Historical Background

Water injection technology has been used in aircraft engines since the 1940s [18, 19, 20, 21, 22]. The timeline of its historical development is summarized visually in figure 1.3.

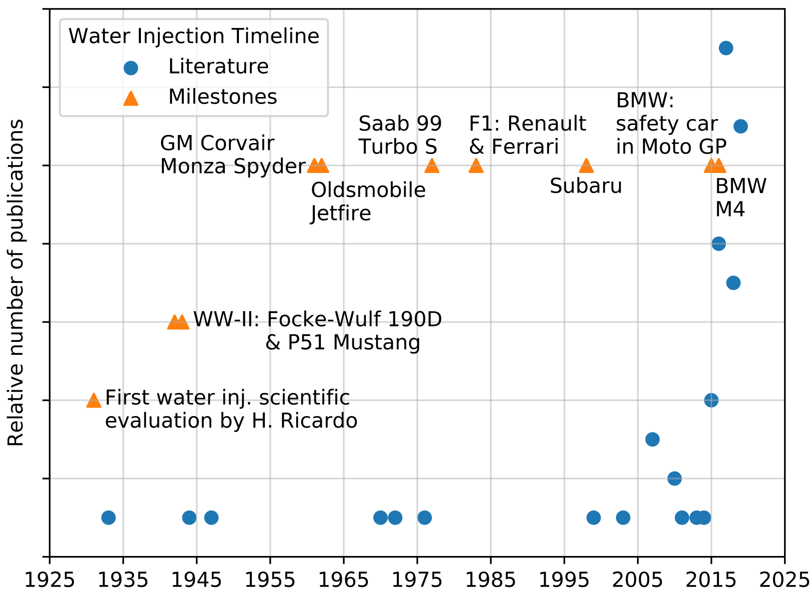

Figure 1.3: *Historical timeline of water injection research and milestones*

Following its introduction by Harry Ricardo in the 1930s, the technology was mainly used in aircraft engines between the 1940s and 1960s. It has also been used intermittently by automotive manufacturers such as General Motors (GM) and Saab, in the later parts of the 20^{th} century, and was recently (in 2015) used in a production car by BMW. The figure also shows the change over time in the number of publications discussing water injection (each publication is represented by a blue dot). It is clear that interest in water injection technology has increased significantly since 2010.

The technology was famously used in two iconic 1940s air-cooled radial aircraft engines: the 41.8-litre, 14-cylinder BMW 801 [23] that powered the Focke-Wulf 190, and the 18-cylinder Pratt & Whitney R2800 [24] used in the Republic P-47 Thunderbolt and Chance-Vought F4U Corsair. In 1950, the stock R2800 engine produced 2400 hp (1790 kW), but it was able to achieve as much as 3400 hp (2535 kW) when using a water injection system developed for emergency combat conditions [25]. The engine is shown in figure 1.4.

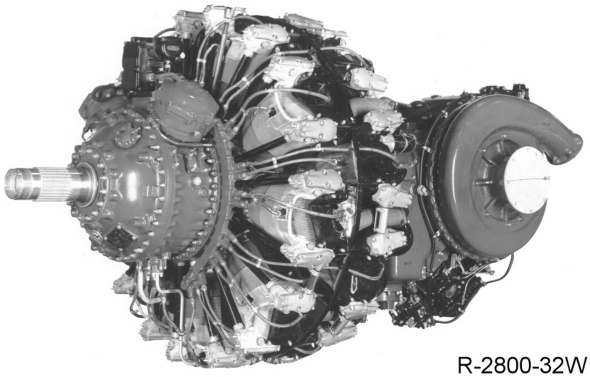

Figure 1.4: *The iconic 18-cylinder Pratt & Whitney R2800 radial series engine fitted with a water injection system. This engine powered U.S. Thunderbolt and Corsair fighters. [26]*

The liquid-cooled, 35.7-L, V12 DB 605 engine from Daimler-Benz used a MW50 (50% water-50% methanol) water injection [27] as a power-boosting anti-detonant agent. This engine was used in the Messerschmitt Bf 109 fighter aircraft. Water injection conferred a powerful charge cooling effect in these supercharged engines and allowed them to use higher boost pressures for short time periods (approximately five minutes). As a result, the aircraft achieved hundreds of extra horsepower in combat situations during World War II [28].

Water injection has seen less use in passenger cars. Its first commercial application in this context occurred in 1962, when Oldsmobile developed a high compression ratio (10.25:1) turbocharged engine, known as the Turbo-Rocket, which was rated at 215 hp.

The high compression ratio created problems due to combustion knocking, which were overcome by using a novel water-injection system to spray distilled water and methyl alcohol into the air intake system [29]. A cross-section diagram of this *jetfire* engine is shown in figure 1.5. The Swedish automotive manufacturer Saab also developed a water injection system in the late 1970s for their Saab 99 Turbo S model; this system increased the engine's maximum power by 15-20 hp [30].

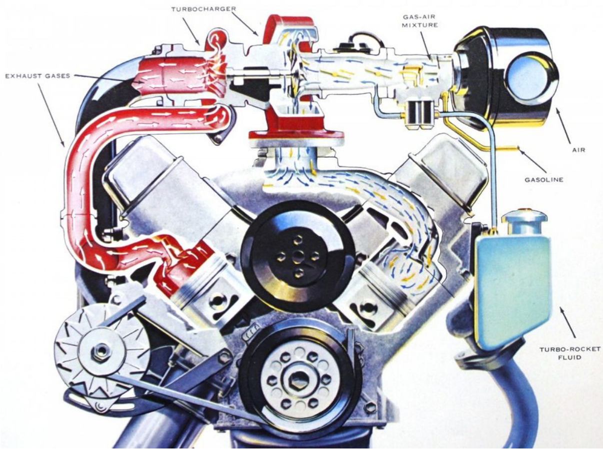

Figure 1.5: *The 1962 Oldsmobile Jetfire V8 engine. The "turbo rocket fluid" used was a blended water-methanol mixture. [31]*

Earlier aircraft and automotive engines were limited in raw power, but advances in engine technology obviated the need for water injection for some time. The technology has recently attracted fresh interest from manufacturers because of its knock suppressing capabilities. Water's latent heat of vaporization (2250 kJ/kg) greatly exceeds that of gasoline (397 kJ/kg for RON95 E5 gasoline), so injected water should absorb more heat from the charge than gasoline, thereby reducing the charge temperature and the likelihood of knock. Water also has a higher specific heat capacity than air, so water injection will also change the thermodynamic properties of the charge during the compression and combustion strokes. Several authors have argued that the benefits of water injection are mainly due to charge cooling effect caused by evaporation [32, 33].

1.0.3 Atmospheric Variables

Variation in ambient atmospheric conditions can profoundly affect engine performance. Furthermore, engines operating in vehicles sold in different geographical locations around the world will be subjected to significantly different climatic and atmospheric conditions (i.e. different ambient temperatures, pressures, and humidity levels). Changes in atmospheric conditions will in turn affect the properties of the engine's intake air and may therefore affect the thermodynamic properties of the fuel-air mixture and the engine's knock propensity. In the 1960s, Ingamells et al. conducted extensive experimental studies on the relationship between an engine's octane number requirement and selected atmospheric variables including the relative humidity [34]. They found that the octane requirement varied linearly with the humidity, and that increasing absolute humidity reduced the octane number requirement for knock-free operation. A more recent study [35] similarly indicated that injected water enhances engine performance by acting as an anti-knock agent. The effects of variation in atmospheric humidity on engine performance were investigated by Gardiner [36], who suggested the use of a correction factor to account for the effects of moisture on combustion. Taylor [37] has also highlighted the effects of atmospheric conditions (temperature, pressure and humidity) on the performance of SI engines. Using Dalton's law of partial pressures and the gas law, Taylor developed an equation that assumes that the density of inlet air is equal to the density of air at certain temperature (T_i) and pressure(P_i), multiplied by a correction factor that depends on the humidity, as shown in equation 1.1.

$$\rho_a = \frac{29p_a}{RT_i} = \frac{29p_i}{RT_i}\left(\frac{1}{1+F_i(29/m_f)+1.6h}\right) \tag{1.1}$$

$$\begin{aligned} \text{where } p_a &= \text{partial pressure of air} \\ p_i &= \text{total pressure} \\ R &= \text{gas constant} \\ T_i &= \text{temperature} \\ F_i &= \text{mass ratio of fuel vapor to dry air} \\ m_f &= \text{molecular weight of the fuel vapor} \\ h &= \text{mass of water to mass of dry air, absolute humidity} \end{aligned}$$

The correction factor is the term in parentheses and includes the humidity (which is represented by the symbol 'h'). Note that Taylor used 'h' to denote the humidity ratio which is more commonly denoted ω in the context of thermodynamics.

According to the standard definition, the humidity is the mass of water vapor per unit mass of dry air in an air-water mixture [38] and can be calculated as

$$\omega = \frac{0.622p_v}{p-p_v} \qquad \text{(kg water vapor/kg dry air)} \tag{1.2}$$

where p is the total pressure and p_v is the partial pressure of water

This quantity is known as the absolute or specific humidity. However, it is more common to discuss the relative humidity, which reflects the moisture content of the air at the prevailing ambient temperature. If the temperature is constant, lower relative humidity values correspond to lower amounts of water in the air. However, the relative humidity also depends on factors such as the saturation pressure and the partial pressure of water in the air. The air in a system with 100% relative humidity is said to be saturated. Adding water to an unsaturated mixture will result in the evaporation of water, increasing the air's moisture content until it can hold no more moisture. Once that point (the saturation point) is reached, any water added to the air will condense. In engines, water's high latent heat of vaporization can be exploited to reduce the in-cylinder temperature and cool the charge by evaporation. However, if the air/charge is saturated, no evaporation will occur, which could reduce or eliminate the knock-suppressing effect of water injection. Variation in atmospheric conditions could thus profoundly affect the performance benefits of water injection and engine performance more generally [37]. A recent simulation study [39] suggested that intake air humidification could be used to suppress knock. Furthermore, engines operating globally, in diverse geographical locations would be subjected to extreme climatic and atmospheric conditions e.g. temperature, pressure, humidity etc. Changes in atmospheric conditions (relative humidity) will affect the properties of the engine's intake air, and thus influence the engine inlet air properties. The properties of the inlet air will in turn affect the thermodynamic properties and knock propensity of the fuel-air charge, and may change the effects of water injection. Although the influence of atmospheric variables on engine behavior has been studied extensively, little is known about how ambient humidity interacts with water injection.

1.0.4 Thermodynamics

The thermodynamic properties of an engine's working fluid strongly affect its performance. The working fluid in an SI engine is usually a mixture of air and fuel (gasoline). Both air and gasoline are themselves complex mixtures with several different components; one important constituent of air is water vapor. Figure 1.6 shows how water vapor affects various thermodynamic properties of air.

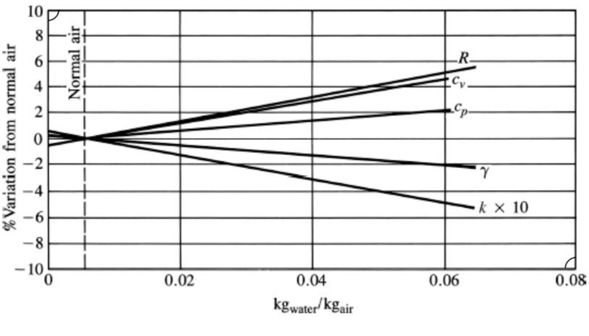

Figure 1.6: *Effect of humidity on properties of air. (From Taylor [37])*

The figure shows that water vapor increases the specific heat capacities (C_p and C_v) of the air. However, the increase in the specific heat at constant volume (C_v) is greater than that for constant pressure (C_p), so increasing the amount of water in the air reduces the specific heat ratio (γ), which is defined as C_p/C_v. This in turn reduces the efficiency of the fuel-air cycle. In thermodynamics, heat energy (Q) is also related to the specific heat at constant volume (C_v) by equation 1.3.

$$Q = mC_v\Delta T \tag{1.3}$$

For a given quantity of heat under constant volume conditions, water injection into the cylinder will increase both the total mass ($m_{total} = m_a + m_{fuel} + m_{WI} + m_{EGR}$) and the specific heat capacity (C_v) of the cylinder charge relative to the scenario without water injection. Therefore, according to equation 1.3, the temperature (ΔT) must fall. Water injection therefore cools the charge.

Equation 1.4 [40], shows the relationship between fuel conversion efficiency and the specific heat ratio (κ or γ) of the fuel-air mixture. The presence of water vapor slows down combustion and increases time losses unless the spark is properly advanced as humidity (water content) increases, as found by Gardiner et al [36].

$$\eta_{f,i} = 1 - \frac{1}{r_c^{\gamma-1}} \tag{1.4}$$

The indicated fuel conversion efficiency ($n_{f,i}$) increases as the compression ratio (r_c) increases and decreases as the mixture's specific heat ratio (γ) decreases. The indicated thermal efficiency varies with the fuel-air ratio but is also affected by the influence of water vapor on the thermodynamic properties of the working fluid (i.e. the cylinder charge) before and after combustion. Figure 1.7 presents measurements of the indicated thermal efficiency as a function of the humidity under no-knock conditions without any adjustment of the fuel injection or spark timings [37]. The overall effect of high humidity is to enable MBT spark timing to be used under most conditions, leading to higher thermal efficiency.

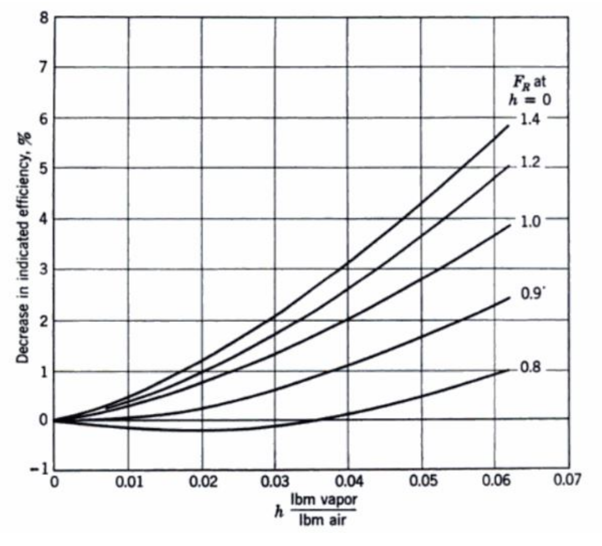

Figure 1.7: *Effect of humidity on indicated efficiency. (From Taylor[37])*

Depending upon the effectiveness of evaporation and charge cooling, the cycle efficiency can either increase or decrease. Figure 1.8 depicts the pressure-volume diagram for standard case and the case when water is injected - to demonstrate changes in SI engine cycle work. It was assumed that all water in the cylinder would be fully vaporized by 170° bTDC. Consequently, the cylinder pressure falls during the compression process, leading to a drop in compression work. However, water addition also causes the peak cylinder pressure to drop during the combustion process, reducing the cycle work during combustion. As shown in figure 1.8, the expansion work is similar in both cases. Therefore, the amount of additional work during compression is compensated for by that lost during the combustion process. In fixed compression ratio tests, water addition increases engine efficiency in some segments of the cycle and reduces it in others, with the net effect generally being modest or negligible [9]. Taylor [37] also notes that "when spark-ignition engines are run near the detonation limit humidity seems to act as a knock suppressor". A similar conclusion was drawn by Khatri et al [35], who found that water acts as an anti-knock agent when added to an air:fuel mixture by increasing the mixture's effective octane rating, provided that the ignition/spark timing is altered so as to be at or near MBT. Water addition thus improves the octane rating of the system as a whole.

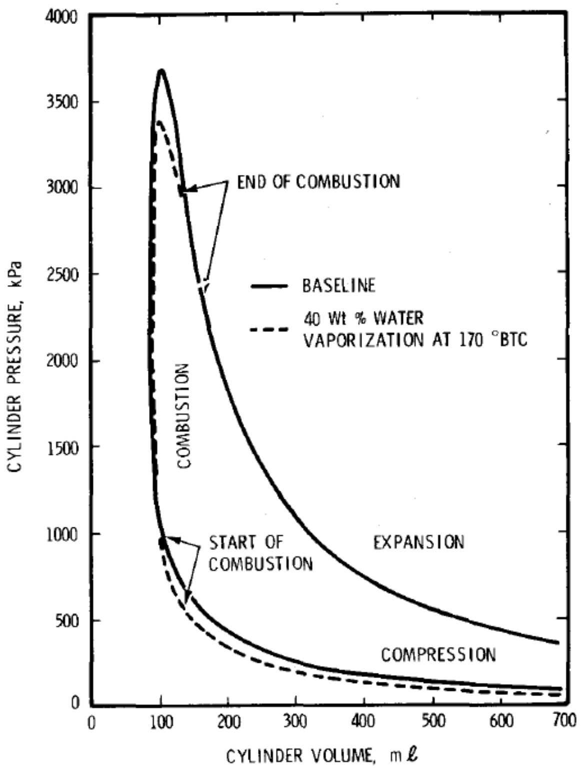

Figure 1.8: *Calculated effect of water on the indicated pressure-volume curve. [9]*

1.0.5 Water Injection and Emissions

The transport sector is a major source of particulate matter (PM) and other emissions. A notable benefit of water injection in SI engines is that it reduces engine and tailpipe NO_x and CO emissions. [12, 14, 16, 41]. The effects of water injection on PM, NO_x, and CO emissions under different conditions were also investigated in this work. PM emissions are particularly important because of their adverse effects on human health: upon inhalation, small particles tend to penetrate deep into the respiratory system [42]. Because of this, legal limits on particulate emissions are becoming increasingly stringent, necessitating new engine technologies for their reduction. The effects of water injection on particulate emissions depend on engine operating parameters such as the air:fuel ratio. Hermann et al. [43] reported that increasing the water:fuel ratio in the combustion chamber can reduce PM emissions. However, increasing the water:fuel ratio in stoichiometric regions can also increase PM emissions by reducing the in-cylinder temperature in unpredictable locations because of the heterogeneous distribution of water droplets [44, 45]. PM emissions may also be reduced by the vaporization of liquid water together with localized increases in the specific heat of the gas surrounding the flame. The timing of the water injection can also have important effects on Brake Specific Fuel Consumption (BSFC) and particulate emissions: Tajima et al. [46] have claimed that water injection during the latter half of the fuel injection period reduces soot formation.

1.1 Motivation

As mentioned in the preceding sub-sections, water injection has been used in internal combustion engines since the 1940s. Although the applications of those engines have varied over the years, the theory and mechanisms that describe and underpin water injection's effects remain the same. In recent years, the technology has been investigated, developed, and used in IC engines for compact vehicles. Forthcoming regulatory limits on fuel consumption and emissions are compelling engineers to find ways of increasing the efficiency of spark ignited (SI) engines for use in hybrid powertrain architectures that can comply with these new legal requirements. Particular emphasis has been placed on improving the efficiency of spark-ignited engines under conditions where the electric motor would not be used in a hybrid vehicle, requiring the IC engine to take over. The combination of turbocharging and downsizing enables the IC engines of hybrid vehicles to operate primarily in their high efficiency region. However, this region is also associated with a high propensity towards combustion knock due to high cylinder pressures and temperatures. Water injection is used to suppress combustion knock while maintaining stoichiometric operation (i.e. $\lambda = 1$). Unfortunately, the literature on the benefits of water injection and the mechanisms by which it operates is incomplete; the work presented here was conducted to partially fill this knowledge gap.

Pauer et al [7] constructed a cause-effect diagram that neatly explains the benefits of water injection in spark-ignited engines, as shown in figure 1.9. According to the diagram, water injection increases both engine performance and fuel efficiency. The direct improvement in performance is due to improved volumetric efficiency and thus

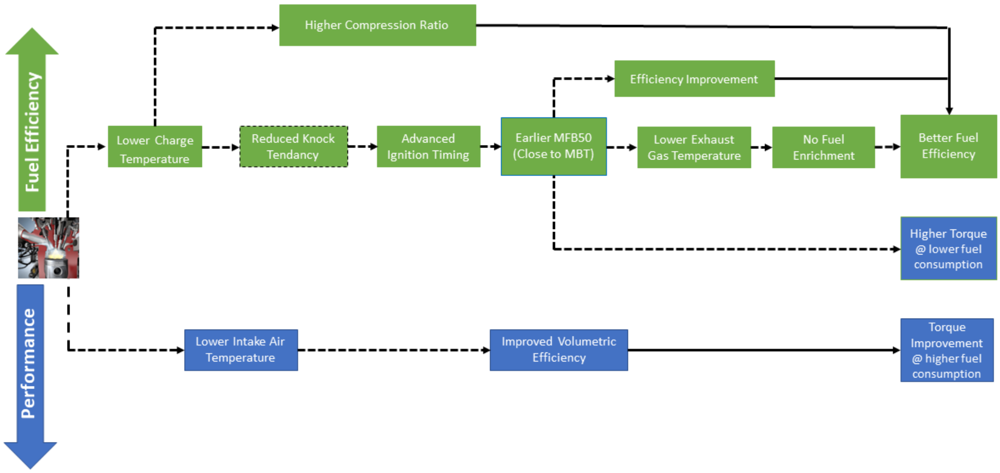

Figure 1.9: *Cause-effect diagram for the benefits of water injection in SI Engines [7]*

better torque. The fuel efficiency benefit is obtained via three different paths: water injection obviates the need for fuel enrichment, enables ignition timing advancement (so that near-MBT timings can be used), and makes it possible to operate the engine at a higher compression ratio. These effects are due to knock suppression resulting from reductions in the cylinder charge temperature.

During experimental campaign 1, it was observed that the ambient temperature, pressure, and humidity vary from day to day, and that this variation affects engine performance and other parameters. To the best of the author's knowledge, there had been no published studies on the effects of ambient atmospheric variables (especially humidity) on engine parameters when using water injection. This prompted experimental campaign 2.

If water injection is to be widely used in IC engines, it will be essential to quantify its beneficial effects on fuel efficiency and emissions. Finding new technologies to increase fuel efficiency and reduce emissions are the main goals of the larger project to which this thesis belongs. To this end, the experimental results were used to develop and validate a simulation model to predict improvements in fuel efficiency due to water injection over different drive cycles. This model is based on a 48V mild hybrid vehicle; mild hybrid designs are increasingly being seen by automotive manufacturers as a good compromise between limited micro-hybrid designs and costly full hybrids.

1.2 Objectives and Outline

This thesis is submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy (PhD), as part of a project focusing on *High Efficiency Hybrid Powertrains* *for Future Vehicles.* The project involves investigating various novel technologies that have the potential to improve the efficiency of IC engines and which could be used in future hybrid vehicles. This thesis focuses on one such technology, namely water injection. Figure 1.10 presents a fish-bone diagram (or *Ishikawa diagram*) showing various areas of ongoing research on water injection in the automotive sector. The areas and systems highlighted in green are those relevant to this work.

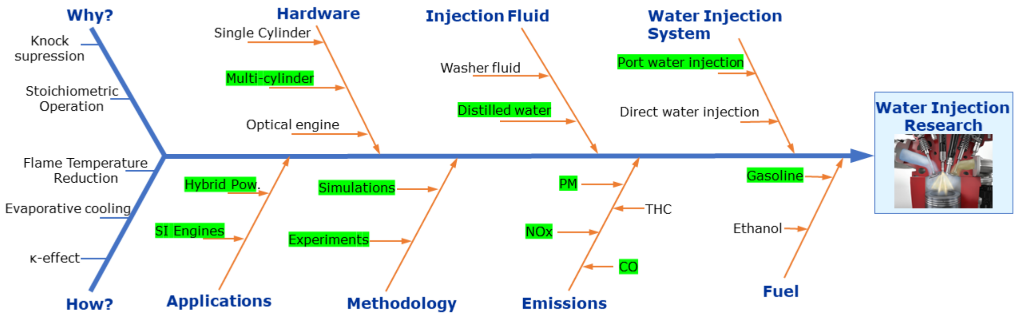

Figure 1.10: *An Ishikawa (fish-bone) diagram representing various sections and fields of water injection research in SI engines*

This work has three main objectives:

1. To investigate the beneficial effects of water injection on knock and efficiency in SI engines

2. To explain the mechanism(s) responsible for these beneficial effects

3. To determine how atmospheric variables (specifically, the relative humidity) interact with water injection to influence engine behavior

Several mechanistic hypotheses have been put forward to explain why water injection suppresses knock. Figure 1.11 shows all the possible ways in which water injection might suppress knock in SI engines. Processes and effects that reduce the likelihood of knock are indicated by green (+) symbols, and those that increase it are indicated by red (-) symbols. Yellow (?) represents processes whose effects have not yet been thoroughly investigated. The main causes of knock suppression by water injection are evaporative cooling, flame temperature reduction, and changes in the specific heat properties of the charge mixture. Water acts as a diluent, extending and slowing combustion; this increases the time needed for the flame front to reach the end-gas, and thus increases knock propensity. Another effect (not investigated here) is the dissociation of water molecules at high pressures and temperatures, which results in the formation of molecular oxygen. This effect would also alter the mixture's properties and hence the combustion process, although the effect is assumed to be very small.

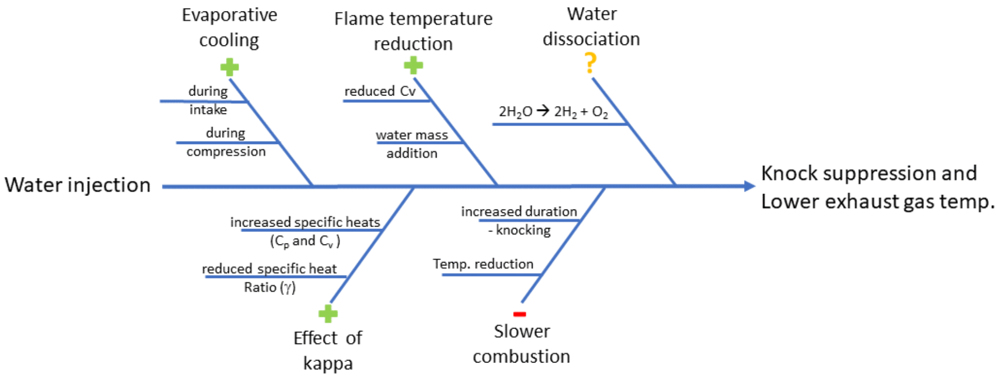

Figure 1.11: *Ishikawa diagram showing processes and phenomena that may affect knock suppression due to water injection*

For the reader's reference, the scope and outline of this PhD project are shown in figure 1.12. Different technologies used for knock suppression are enclosed in green and yellow rectangles; those in green are addressed in this thesis, and those in yellow will be investigated by the author in the future. These technologies will be investigated either independently or in various combinations to find reliable ways of reducing fuel consumption and greenhouse gas emissions.

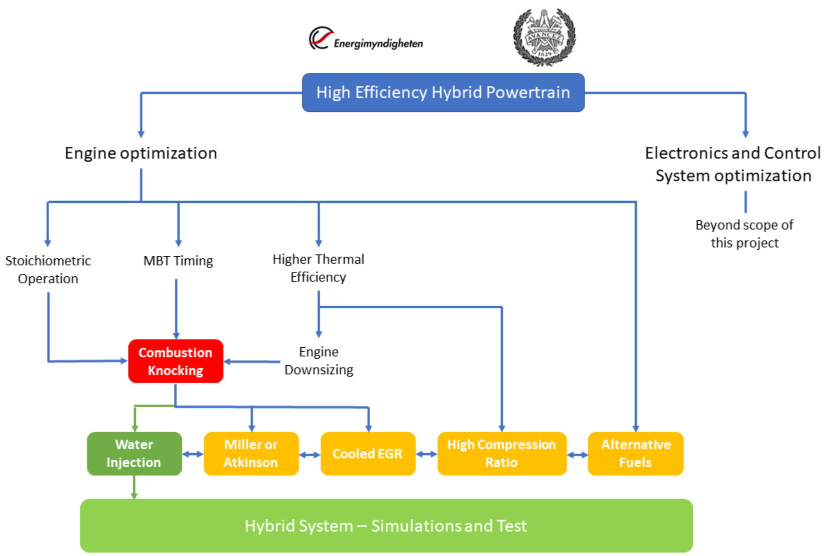

Figure 1.12: *Project Outline for this thesis*

The next chapter discusses the experimental setup and simulation model used in this work at length. The discussion addresses the engine hardware, water injection system, humidity control system, GT Suite simulation model and test methodology in separate sections. The experimental results are presented and discussed in the subsequent Results and Discussion chapter. This chapter is divided into three sections: Experimental Campaign 1, Experimental Campaign 2 and Water injection in Hybrid Powertrains. The first section is based on the work published in the first appended paper, and focuses on the benefits of water injection in an SI engine. The second section deals with the effects of ambient humidity on the impact of water injection in an SI engine. The final section describes simulations of the effects of water injection in hybrid vehicles. Finally, author's contributions to the scientific field are presented and some directions of future research are outlined.

2 Test Setup

This chapter briefly outlines the experimental setups and instrumentation used to study the effects of water injection, as well as the simulation model used to simulate various drive cycles with water injection.

2.1 Engine Hardware

All experiments presented in this thesis were performed using a 3-cylinder 1486 cc turbocharged engine from Volvo Cars. A sketch of the engine showing its basic components is shown in Figure 2.1. In the experimental setup, fuel was injected directly into the cylinder (direct injection) and water was injected into the intake runner via three dedicated injectors, one for each cylinder. This system configuration is commonly referred to as port water injection (PWI). The engine's specifications are given in Table 2.1.

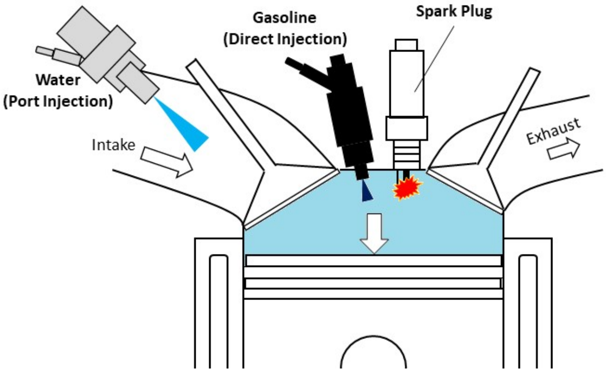

Figure 2.1: *Diagram of the water-fuel injection system installed in the engine*

Table 2.1: Engine specifications

No. of cylinders	inline, Three-cylinder
Displacement Volume	1476 cc
Bore x Stroke	82 x 93.2 mm
Compression Ratio	10.5:1
Max Torque	265 Nm
Max Power	132 kW @ 5500 rpm

For in-cylinder pressure measurements, high resolution piezo-electric pressure transducers (Kistler A6045) were installed in each cylinder. Their output was post-processed using AVL IndiCom. Two-point thermodynamic pegging was used in all experiments. Top Dead Center (TDC) was determined by setting a thermodynamic loss angle of 0.7 CAD and running the engine. The auto-calibrate function of AVL indiCom was then used for TDC calibration. TDC was then taken to be equal to the timing of maximum indicated cylinder pressure plus the thermodynamic loss angle. Intake and exhaust pressures were measured with Kistler 4007C pressure transducers. Temperatures were recorded at multiple points in the engine using standard K-type thermocouples, a CSM Thermo-Scan Mini module, and INCA Addon. The engine load was controlled by varying the throttle position and turbocharger boosting, and was measured using a National Instrument DAQ system controlled with LabVIEW. Engine speed was controlled by an AC dynamometer. The experimental setup in the test cell is shown in figure 2.2.

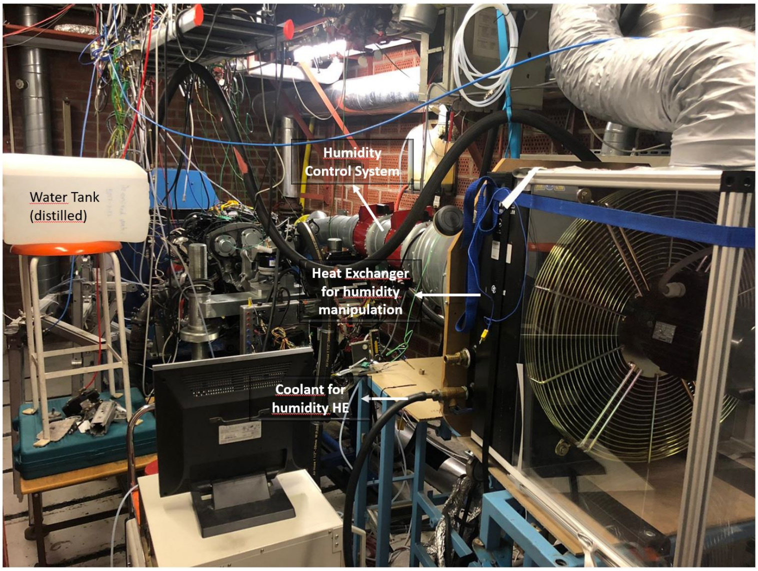

Figure 2.2: *The experimental setup in the test cell comprising the GEP3 Engine and the water injection system*

The fuel flow to the engine was measured with a coriolis-type mass flow sensor. The air-fuel ratio (λ) was controlled and measured based on the feedback from two wideband O2 sensors installed upstream and downstream of the three-way catalyst (TWC). A separate water injection system was installed upstream of the intake valves, in the intake manifold.

The engine exhaust gases were sampled before the TWC via a 180°C heated line and fed to a conditioning unit maintained at 190°C in the emission analyzer. Concentrations of NOx, unburnt HC, CO-CO_2 and O_2 in the exhaust were measured using an Eco-physics chemiluminescence analyzer, a flame ionization detector, separate non-dispersive infrared radiation detectors, and a magnetic susceptibility analyzer, respectively. PN (Particulate Number) emissions were measured using a Scanning Mobility Particle Sizer (SMPS) from TSI comprising a model 3080 classifier, a model 3081 DMA, and a model 3010 CPC. The SMPS uses a continuous fast-scanning technique to generate high-resolution counts and measurements of aerosol particles with diameters between 7.37 nm and 289 nm. MathWorks MATLAB was used to post-process the cylinder pressure traces. For PN measurements using the SMPS, exhaust samples were diluted at a ratio of 5:1 using a porous dilutor and then passed through a heated sampling line, both of which were maintained at 190°C. The diluted sample was then transferred to the SMPS for PN size distribution measurement. When analyzing the resulting measurements, a correction was applied to account for the effects of dilution. .

In addition to the engine hardware, a humidity control system was developed and fabricated to manipulate the relative humidity of the air entering the engine. The following section briefly explains this system's design and operation.

2.2 Water Injection and Humidity System

The humidity control system was developed during the second experimental campaign to study the influence of moisture in their air on the water injection concept. The system was fabricated to enable testing of engine performance and the benefits of water injection at different humidity levels. The relative humidity and temperature were measured using sensors placed at three different positions in the test setup. The locations of these sensors are indicated by the label RHS in Figure 2.3.

The objective was to record the absolute humidity (water content per kg dry air) of the air entering the engine, i.e. inside the intake manifold. A fan was used to force ambient air through a heat exchanger so as to establish an air temperature suitable for the desired humidity level. Three sensors from E+E Elektronik (two wall-type EE160 units and one probe-type EE210 unit) were used to measure the relative humidity and the air temperature.

The relative humidity was initially recorded immediately upstream of the air filter because the humidity there was assumed to be identical to that in the intake manifold. However, in retrospect it was noted that the turbocharger and/or the intercooler could potentially affect the humidity of air passing through them. Therefore, to see if the water content of the air in the intake manifold differed from that immediately upstream of the filter, another sensor was placed in the intake manifold. The air pressure in the manifold was approximately 2.3 bar, but the sensors used to measure humidity were calibrated for atmospheric conditions. Therefore, air samples from the intake manifold were expanded into a container to enable humidity measurement at atmospheric pressure (after verifying that no condensation occurred during expansion). This revealed that the humidity in the manifold differed from that immediately upstream of the filter. It had been expected

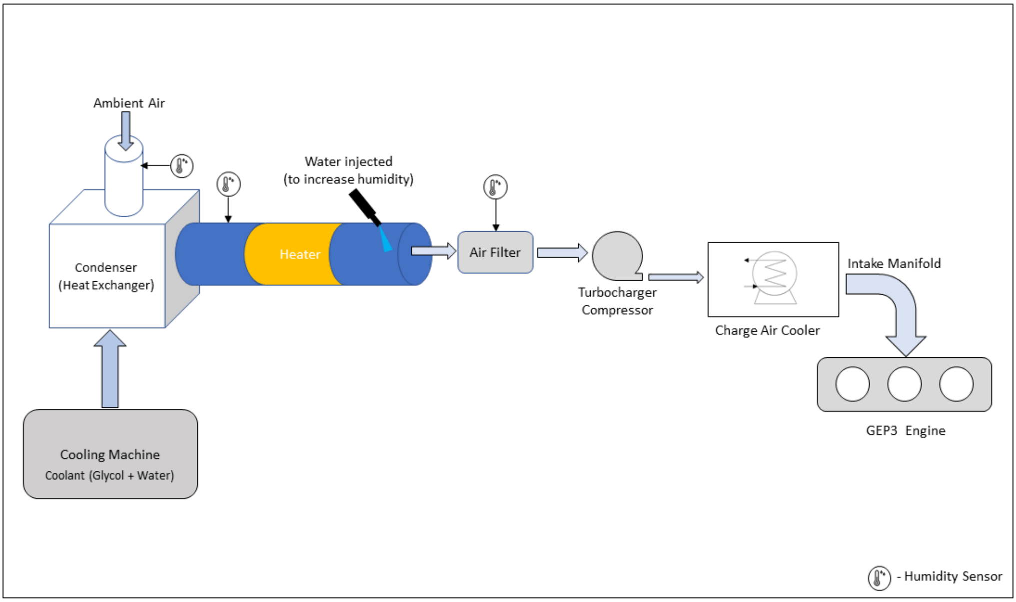

Figure 2.3: *Humidity Control System*

that the humidity in the intake manifold would be lower than that immediately upstream of the air filter because of condensation in the intercooler. In fact, the reverse was true. To determine whether this was due to a faulty sensor, the sensors at the two humidity measurement points were exchanged. This did not change the outcome, suggesting that both sensors were generating correct measurements and the humidity was indeed higher in the manifold. As yet, no plausible explanation for this outcome has been identified, so further investigations are needed to determine how the presence of a turbocharger and intercooler affects the distribution of humidity within an engine.

Based on the results discussed in the paragraph above, it was decided that humidity should be measured in the intake manifold rather than immediately upstream of the air filter. To achieve better control over the measurements several sensors were placed in a plastic container where they would be clearly visible to the test operator. The container was connected to the intake manifold via an insulated hose, allowing the air sample from the intake manifold to expand to ambient pressure. In addition to the humidity sensors (both EE160 models), pressure and temperature sensors were installed in the box to ensure that its conditions remained constant. In all of the experiments, the two humidity sensors generated virtually identical measurements, with negligible absolute differences in their outputs. The accuracy and reliability of the two humidity sensors was subsequently verified by comparing their performance to that of an alternative humidity sensor that was developed in house and which determines the humidity by measuring the dew point. This revealed that the accuracy of the original two sensors was consistent with that claimed by their manufacturer. During this testing process, the water content was measured indirectly - first measuring relative humidity with sensors and then calculating absolute humidity from the formulas. It was observed that the relative changes in the absolute humidity (water (g)/kg dry air) were higher at lower values of relative humidity and are very sensitive to relative humidity.

The *water injection system* injected water into the intake manifold (port injection), where a Druck PMP 5000 series pressure transducer was installed to monitor the injection pressure. Fuel was injected directly into the cylinder, at a pressure of 200 bar. Each cylinder was fitted with a port water injector operating at a pressure of 10 bar. Water injection parameters such as the injection timing and quantity of injected water were controlled using ETAS INCA. The positioning and orientation of the water injectors in the intake manifold profoundly affects the impact of water injection because it influences the rate of water vaporization and thus the amount of water that must be injected to achieve a given level of knock suppression. However, the positioning and orientation of the water injectors was not varied during these experiments.

2.3 Test Methodology and Procedure

All tests were performed under controlled conditions. The humidity system was designed to control the moisture content of the intake air and determine how it affected the knock-suppressing effect of water injection. The relative humidity of the engine's intake air was manipulated using the humidity control system depicted in 2.3. Low-humidity conditions were established by passing coolant at temperatures of -2 to -5 C through the heat exchanger to remove water from the air by condensation and thereby reduce the humidity. High humidity conditions were established by spraying water into the intake air (as shown in figure 2.3) to increase its water content before it entered the engine. The humidity control system was not used in experiments performed under ambient atmospheric conditions.

The tests were mainly performed at a high load of 20 bar Indicated Mean Effective Pressure (IMEP) at engine speeds of 3600 or 4800 rpm because without water injection it was impossible to use the MBT ignition timing while keeping the exhaust temperature within safe limits while using a stoichiometric air-fuel mixture at these points. For all measurement points, the engine was operated with a stoichiometric air/fuel ratio using the Knock Limited Spark Advance (KLSA) ignition timing (which is not the same as the MBT timing). Before establishing the experimental operating conditions, the engine was operated at the planned test speed with a low load, and the load was gradually increased to the planned experimental value, initially at wide open throttle (WOT) and then with the waste gate valve closed. Engine knock was detected with a knock sensor mounted on the engine and from the pressure traces recorded during the experimental measurements. Other relevant parameters were kept constant. All experiments in campaign 2 were performed using RON95 E10 gasoline. In campaign 1, experiments were conducted using this fuel as well as with RON91 and RON98 gasoline.

The measuring equipment was regularly calibrated to ensure that its accuracy was maintained. The emissions measurement systems were calibrated before every test session. The results presented here are mean values based on 300 recorded cycles at each test point. To illustrate the accuracy of the experimental results, the spread of the measurements is also reported. Since the measurements were acquired under steady state conditions established by operating the engine at a single test point for an extended period until its behavior stabilized, the instruments' response times were not monitored.

2.3.1 Polytropic Index (n) Calculation

The polytropic index (specific heat ratio) are important properties of a thermodynamic system that can be used to describe and explain changes in the system's state. Within certain intervals, changes in the cylinder pressure during the compression and expansion strokes can be described very well in terms of polytropic compression/expansion. This means that polytropic coefficients can be calculated from sampled cylinder pressure data using the polytropic expression $pv^n = c$. Note that the polytropic coefficient reflects the net effects of heat losses as well as changes in the specific heat ratio of the gas. Therefore, it may be higher than the specific heat ratio.

It is possible to calculate crank angle resolved polytropic coefficients. This is done by taking the log of $pv^n = c$ and plotting log(v) against log(p); the slope of the resulting plot will be equal to the polytropic coefficient. The slopes of such plots typically appear to be almost constant even though the polytropic coefficient varies during both compression and expansion due to heat losses and changes in temperature. This is partly because the compression ratio profoundly affects the slope. To account for this, the effect of the cylinder head's dead volume must be accounted for accurately. Because of this complication and the sensitivity of the polytropic coefficient to small changes in pressure, it cannot be computed directly from pressure measurements. Instead, to accurately detect small changes in the polytropic coefficient, a 5^th order polynomial must be fit to the cylinder pressure. The computation of the polytropic index is therefore challenging, and requires extensive numerical computation. To obtain reliable results, it is necessary to carefully determine the dependence of the results on the chosen numerical approach.

2.4 Vehicle Simulation Model

The limitations of pure electric-drive vehicles are such that the automotive sector will probably be dominated by hybrid vehicles for some time to come. Mild hybrid designs represent a good compromise between potentially limited micro-hybrids and expensive full-hybrids, and are therefore preferred by manufacturers. To evaluate the impact of water injection on the fuel consumption of a mild hybrid, simulations were performed using a model representing a vehicle with a P2 parallel hybrid architecture.

One objective of this project is to develop and validate reliable simulation models for predicting the impact of the technologies under investigation - in this case, a water injection system - on the performance of hybrid vehicles. The development of such models will accelerate the development of improved systems in future. Therefore, a full hybrid model developed at Chalmers [courtesey: Sarp Mamikoglu] was used to validate the water injection model against the experimental results. The configuration of the full vehicle model is shown in figure 2.4.

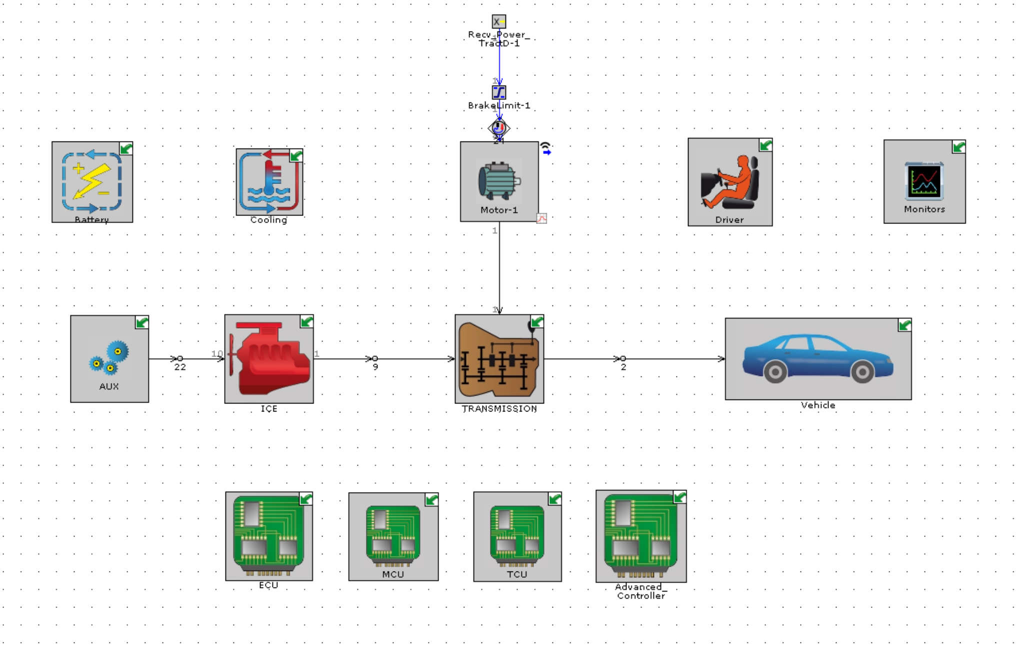

Figure 2.4: *The simulation model of a 48V Mild hybrid vehicle developed in GT Suite. The model was used to calculate the effects of water injection on fuel efficiency over various drive cycles [Courtesy: Sarp Mamikoglu]*

The specifications of the combustion engine unit for the 48V P2 Mild Hybrid architecture simulation model used in this work are given in Table 2.1. The model also includes components representing an electric motor, battery, cooling system, transmission, vehicle body, and control units. Selected vehicle parameters (drag coefficient, tyre radius, and rolling resistance) were kept constant. Vehicles with masses of 1350 kg and 1600 kg were simulated. The parameter settings for the simulated vehicles are given in Table 2.2.

Table 2.2: Parameter settings used in the vehicle simulations

Vehicle Mass	1350 and 1600
Drag coefficient (C_d)	0.27
Frontal Area (A_f)	2.1 m^2
Rolling Resistance (C_r)	0.007
Electric Motor Capacity	12, 15 and 20 kW
Drive Cycles Simulated	NEDC, WLTP and RTS95

The initial and final State of Charge (SoC) for battery differed by no more than 1%. Parameters irrelevant to powertrain were kept constant. All simulations were performed with a 7-speed dual clutch transmission and the same control strategy.

3 Results and Discussion

This chapter summarizes the results of the two experimental campaigns and the hybrid vehicle simulations. The appended publications A and B are based on the data and results from experimental campaigns 1 and 2, respectively.

3.1 Summary of Experimental Campaign 1

This campaign was conducted to investigate the effect of various water injection strategies on the performance of a multi-cylinder downsized spark-ignited engine fueled with gasoline blends of three different octane ratings.

The engine's performance was evaluated by measuring its torque when using stoichiometric air:fuel mixtures with and without water injection. Operation at full load (high IMEP) under these conditions caused the exhaust gas temperature to exceed the upper tolerable limit of the exhaust components. Therefore, to keep the temperatures within operable limits, the engine was operated under rich conditions (i.e. with the injection of more fuel than needed for combustion, resulting in a λ value of 0.9). Operating the engine under stoichiometric conditions without water injection limits the maximum torque achievable at a given engine speed. As shown in figure 3.1, the experiments revealed that water injection made it possible to increase the engine's torque while operating under stoichiometric conditions.

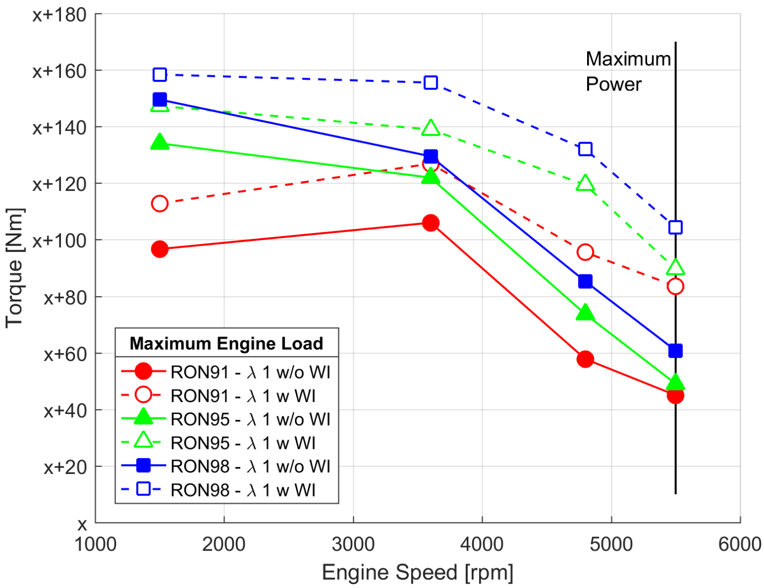

Figure 3.1: *Effects of water addition on torque when using RON91, RON95 E10, and RON98 gasoline. ["w/o WI" - without Water Injection and "w WI" - with Water Injection]*

To determine how the fuel's octane rating affects the benefits of water injection, a sweep of lambda against the quantities of injected water and fuel was performed. Three fuels were used in these experiments: RON91, RON95 E10, and RON98 gasoline. The reference operating point was characterized by a λ of 0.85 with a water/fuel (w/f) ratio of 0 at 16 bar IMEP and 4800 engine rpm. Starting from this reference point, the fuel/air mixture was made gradually leaner. At each increment of leanness, the minimum quantity of injected water necessary to sustain knock-free operation at the specified load point was determined. This process was continued until stoichiometric conditions ($\lambda = 1$) were reached. The relationship between the results are shown in figure 3.2.

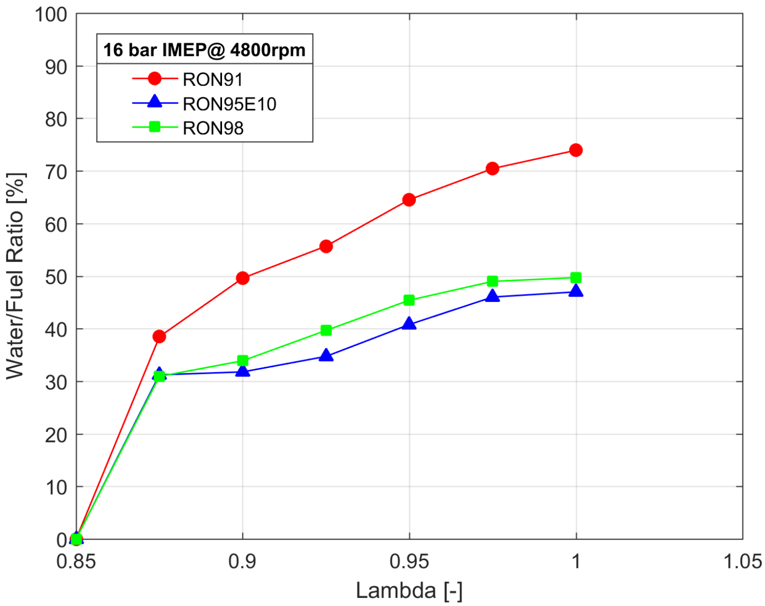

Figure 3.2: *Minimum quantity of injected water sufficient to sustain operation at the specified operating point when using gasoline blends with different octane ratings.*

Water injection enables advancement of combustion phasing (MFB50) such that spark ignition can occur at or near the MBT timing. To better understand this effect, engine experiments were conducted using fuels with different octane ratings to see how the anti-knock qualities of the fuel affect the impact of water injection. This revealed that when the W/F ratio was above 30%, the advancement of the combustion phasing varied linearly with the amount of injected water (refer to Publication A), in accordance with equation 3.1

$$y = -0.0964x + 1.1945 \tag{3.1}$$

where y is the advancement in combustion phasing (δ MFB50) and x is the water quantity added (% by mass).

To identify the mechanism by which water injection suppresses knock, water was injected at different timings during the cycle. In these experiments, the engine was operated at 15 bar IMEP and 4800 rpm. Five different water injection timings grouped into three intervals (during IVO, at maximum valve lift and when the intake valves are closed) were tested, as described in Publication A. The resulting pressure, temperature (see figure 3.3), and heat release curves showed that it was beneficial to inject all of the water just before intake valve opening. This water injection timing is referred to as Case 2 in the experimental matrix.

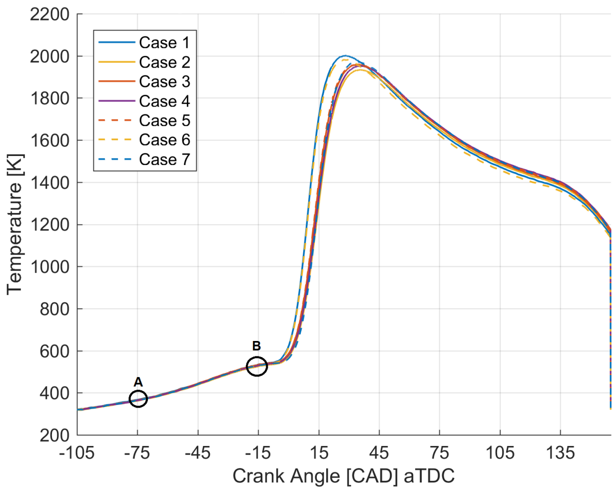

Figure 3.3: *Cycle-averaged cylinder temperature profiles achieved with the tested water injection strategies.*

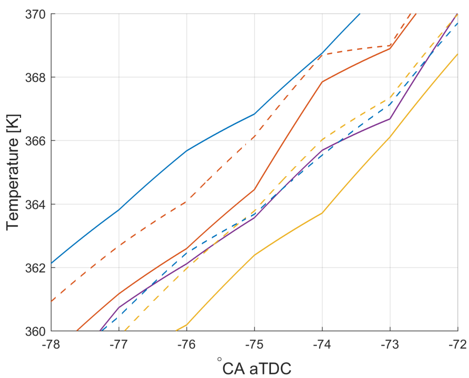

Figure 3.4: *Point A: Charge temperature profiles at 75° bTDC using different water injection strategies*

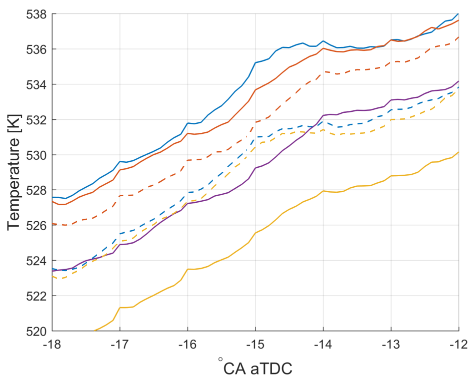

Figure 3.5: *Point B: Charge temperature profiles at 15° bTDC bTDC using different water injection strategies*

Figures 3.4 and 3.5 show expansions around two points of interest in the temperature curves for the different water injection timings: point A (75° bTDC) and point B (15° bTDC); these points are indicated by circles in figure 3.3. At both points, Case 2 (i.e. the case in which water is injected immediately before IVO) minimizes the change in the cylinder charge temperature and therefore represents the optimal water injection timing for the tested hardware.

3.2 Summary of Experimental Campaign 2

The measured effects of water injection on knock suppression and engine performance have been observed to vary from day to day. Therefore, the effects of atmospheric variables on water injection were investigated. It was assumed that the moisture content of the air (i.e. the relative humidity) would be the atmospheric property with the greatest effect on the impact of water injection.

The initial experiments of this campaign were conducted to determine the minimum amount of water required to operate at predefined load points at three different humidity levels (low, medium/ambient, and high). The working hypothesis for this experiment was that the humidity of the inlet air would influence the amount of water that had to be injected during a cycle to sustain knock-free operation, and that this effect would primarily be due to the cooling effect resulting from the evaporation of the injected water. Figure 3.6 shows the total water content of the cylinder at the tested humidity levels along with the contributions of the injected water and the water in the ambient air. In these experiments, the engine was operated at 20 bar IMEP and 3600 rpm with a stoichiometric fuel-air mixture - conditions that would cause knock in the absence of water injection. The amount of water injected was set to the minimum level required to prevent knock. The total water content of the cylinder does not vary greatly with the humidity, indicating that the latent heat of vaporization of the injected water does not contribute greatly to the knock-suppressing effect of water injection; instead, the important variable is the total amount of water in the cylinder. To explain this outcome, it was suggested that the water in the cylinder causes charge dilution and alters the charge's specific heat ratio (κ), both of which would tend to suppress knock.

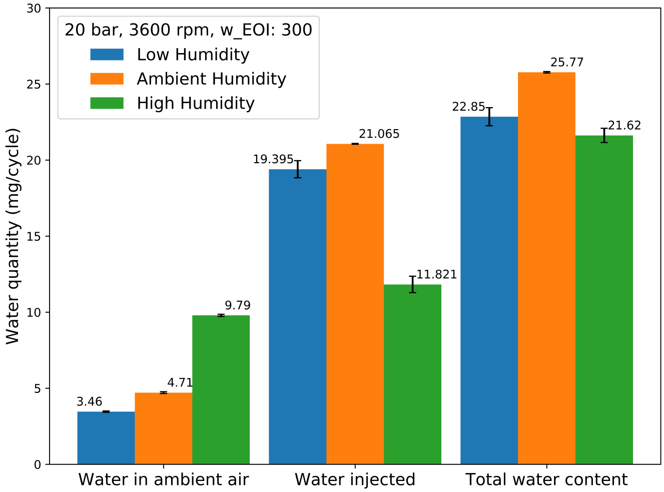

Figure 3.6: *Amount of water in the cylinder from different sources at different humidity levels.*

Subsequent analysis revealed that the effect of water on the polytropic coefficient during the compression stroke is directly related to the quantity of water in the cylinder. To investigate its effect during expansion stroke, two cases (representing high and low cylinder water contents) were considered. The evolution of the polytropic index over the course of the cycle in these cases is shown in figure 3.7.

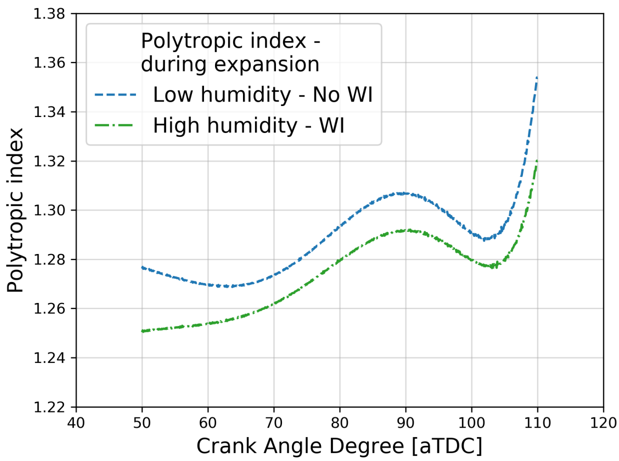

Figure 3.7: *Polytropic curves for the low and high-water content cases during the expansion stroke.*

The results in figure 3.7 indicate that water in the cylinder has significant effects on the charge properties. The blue curve represents the results obtained without water injection under rich conditions ($\lambda = 0.9$). If a stoichiometric mixture ($\lambda = 1$) had been used instead, the difference between the blue and green curves would probably have been even more pronounced, as suggested by Klein [47]. The 300 cycle-averaged pressure traces for the two cases showed that the cylinder pressure was lower for the high water content case (plotted in green). This implies that increasing the amount of water in the cylinder reduces the cylinder temperature and pressure via charge dilution.

3.3 Water Injection Application in Hybrid Powertrain

Simulations were performed to predict the fuel consumption of hybrid vehicles with and without water injection systems. Three parameters were varied in these simulations: the vehicle mass, the size of the electric motor, and the drive cycle. After investigating the effect of vehicle mass and electric motor, the values of these parameters were frozen (m = 1600 kg and EM Power = 15 kW) to calculate the fuel consumption over three different cycles. The results of these simulations are summarized in Table 3.1.

Table 3.1: Predicted fuel consumption for a 1600 kg P2 hybrid vehicle with a 15 kW EM operated with and without water injection for different drive cycles

Fuel Consumption [L/100 km]			
	w/o Water injection	with Water injection	% benefit
NEDC	4.2045	4.1817	0.54
WLTC	4.3624	4.3256	0.84
RTS95	6.5633	6.4931	1.07

The results show that water injection should yield minor reductions in fuel consumption for all drive cycles. These improvements could potentially be enhanced by optimizing the vehicle's gear-shifting strategy and shifting the engine's operation towards high load regions.

4 Contribution to the field

This main contributions of this work can be summarized as:

4.1 Paper I

"Water Injection Benefits in a 3-Cylinder Downsized SI-Engine"

The development of downsized IC engines capable of knock-free stoichiometric operation will require new methods for controlling combustion. One such method is water injection, which is used in certain production engines for passenger cars such as the BMW M4 GTS. However, the literature data on the viability, benefits, and cost-effectiveness of this method are very incomplete. This paper resolves some of the uncertainties regarding water injection and its benefits. The main author's contributions included preparing the tests and the experimental setup, operating the engine and monitoring its performance during the water injection tests, finding ways of increasing its efficiency, and developing an optimal injection strategy. The author also measured the degree of crank case oil-dilution and the engine's emissions under the test conditions. Finally, the author analyzed the data obtained in the experiments.

4.2 Paper II

"Effect of Relative Humidity on the Performance of a Downsized SI Engine with Water Injection"

The purpose of this study was to determine how the atmospheric moisture content (i.e. the relative humidity) affects the performance, behavior, and emissions of internal combustion engines with water injection systems. To the author's knowledge, there were no previously published studies on this topic despite its potential importance: humidity varies widely between countries and seasons, so it is possible that a water injection strategy that was effective under a given set of climatic conditions would be ineffective or even harmful under others. These studies also helped reveal the mechanism responsible for the knock-suppressing effect of water injection, showing that it is primarily due to charge dilution and changes in the thermodynamic properties (particularly the specific heat ratio) of the fuel-air charge rather than to local cooling. This finding may facilitate the design of more effective water injection systems and strategies. The main author was responsible for designing the experiments and for developing the humidity control system (with the assistance of various others during its fabrication and testing). After performing the tests and analyzing the data, various hypotheses about the mechanism by which water injection suppresses knock were considered and evaluated. The author was then supported in explaining the underlying theory, computing the polytropic index, and evaluating the particulate emissions by the co-authors of the paper.

5 Future Work

5.1 Investigating Other Technologies

Additional research is needed to determine whether water injection systems offer sufficient performance benefits to justify their cost. In particular, the general importance of the knock-suppression mechanisms identified in this thesis must be determined by evaluating their importance in hardware other than that used in these initial experiments. This will require further experimentation using single cylinder engines as well as optical tests to study combustion with water injection and the effects of the diluent (water) on charge properties.

As noted in the introduction section and the project outline, the goal of this project was to identify effective ways of increasing the efficiency of spark-ignited engines for use in future hybrid cars. To this end, the next experimental campaign will focus on the limitations of the methods discussed in this thesis and the potential for further improvement by using Miller/Atkinson and high compression ratio hardware with alternative fuels.

5.2 Test with a Hybrid Vehicle

The tested technologies will then be compared in the final phase of the project. Validation of simulation models will be the major focus in this phase along with experimental studies using a hybrid vehicle. The developed models and data should facilitate the comparison of various technologies and hybrid architectures.

Bibliography

[1] International energy agency. “World Energy Outlook, 2017”. In: (). URL: https://www.iea.org/weo2017/.

[2] HR Reitz, H Ogawa, R Payri, T Fansler, S Kokjohn, Y Moriyoshi, AK Agarwal, D Arcoumanis, D Assanis, C Bae, et al. *IJER editorial: The future of the internal combustion engine*. 2019.

[3] Achim Königstein, Uwe Dieter Grebe, Ko-Jen Wu, and Per-Inge Larsson. “Differentiated analysis of downsizing concepts”. In: *MTZ worldwide* 69.6 (2008), pp. 4–11.

[4] Zhi Wang, Hui Liu, and Rolf D Reitz. “Knocking combustion in spark-ignition engines”. In: *Progress in Energy and Combustion Science* 61 (2017), pp. 78–112.

[5] G Konig and CGW Sheppard. “End gas autoignition and knock in a spark ignition engine”. In: *SAE transactions* (1990), pp. 820–839.

[6] Stefano Fontanesi, Elena Severi, Daniela Siano, Fabio Bozza, and Vincenzo De Bellis. “Analysis of knock tendency in a small VVA turbocharged engine based on integrated 1D-3D simulations and auto-regressive technique”. In: *SAE International Journal of Engines* 7.1 (2014), pp. 72–86.

[7] T Pauer, M Frohnmaier, J Walther, P Schenk, A Hettinger, and S Kampmann. “Optimization of gasoline engines by water injection”. In: *37th International Vienna Motor Symposium*. 2016.

[8] Chao-Cheng Wen and Chein-Hsiun Tu. “Vapor–liquid equilibria for binary and ternary mixtures of ethanol, 2-butanone, and 2,2,4-trimethylpentane at 101.3kPa”. In: *Fluid Phase Equilibria* 258.2 (2007), pp. 131–139. ISSN: 03783812. DOI: 10.1016/j.fluid.2007.06.005. URL: http://linkinghub.elsevier.com/retrieve/pii/S0378381207003032.

[9] Bruce D Peters and Russell F Stebar. “Water-gasoline fuels—their effect on spark ignition engine emissions and performance”. In: *SAE Transactions* (1976), pp. 1832–1853.

[10] Wei Mingrui, Nguyen Thanh Sa, Richard Fiifi Turkson, Liu Jinping, and Guo Guanlun. “Water injection for higher engine performance and lower emissions”. In: *Journal of the Energy Institute* 90.2 (2017), pp. 285–299.

[11] Alberto Boretti. “Water injection in directly injected turbocharged spark ignition engines”. In: *Applied Thermal Engineering* 52.1 (2013), pp. 62–68.

[12] Abhijeet M Nande, Thomas Wallner, and Jeffrey Naber. *Influence of water injection on performance and emissions of a direct-injection hydrogen research engine.* Tech. rep. SAE Technical Paper, 2008.

[13] Hakan Özcan and MS Söylemez. "Thermal balance of a LPG fuelled, four stroke SI engine with water addition". In: *Energy conversion and management* 47.5 (2006), pp. 570–581.

[14] V Subramanian, JM Mallikarjuna, and A Ramesh. "Effect of water injection and spark timing on the nitric oxide emission and combustion parameters of a hydrogen fuelled spark ignition engine". In: *International Journal of Hydrogen Energy* 32.9 (2007), pp. 1159–1173.

[15] S Brusca and R Lanzafame. *Evaluation of the effects of water injection in a single cylinder CFR cetane engine.* Tech. rep. SAE Technical Paper, 2001.

[16] Franz X Tanner, Matthias Brunner, and German Weisser. *A computational investigation of water injection strategies for nitric oxide reduction in large-bore DI diesel engines.* Tech. rep. SAE Technical Paper, 2001.

[17] Matthieu Cordier, Matthieu Lecompte, Louis-Marie Malbec, Benjamin Reveille, Cedric Servant, Faycal Souidi, and Nicola Torcolini. *Water Injection to Improve Direct Injection Spark Ignition Engine Efficiency.* Tech. rep. SAE Technical Paper, 2019.

[18] M. R. ROWE and G. T. LADD. "WATER INJECTION for Aircraft Engines". In: *SAE Transactions* 54 (1946), pp. 26–44. ISSN: 0096736X, 25771531. DOI: 10.2307/44548241. URL: http://www.jstor.org/stable/44548241.

[19] DC Eaton. *Cruising economy by use of water injection.* Tech. rep. SAE Technical Paper, 1946.

[20] AT Colwell, RE Cummings, and DE Anderson. *Alcohol-water injection.* Tech. rep. SAE Technical Paper, 1945.

[21] Addison M Rothrock, Alois Krsek Jr, and Anthony W Jones. *The induction of water to the inlet air as a means of internal cooling in aircraft-engine cylinders.* Tech. rep. NATIONAL AERONAUTICS and SPACE ADMIN LANGLEY RESEARCH CENTER HAMPTON VA, 1943.

[22] Rinaldo J Brun, H Lowell Olsen, and Cearcy D Miller. *End-Zone Water Injection as a means of suppressing knock in a spark-ignition engine.* Aircraft Engine Research Laboratory, 1944.

[23] John Christopher. *Race for Hitler's X-Planes: Britain's 1945 Mission to Capture Secret Luftwaffe Technology.* The History Press, 2012.

[24] Graham White. *R-2800 Pratt & Whitney's Dependable Masterpiece.* SAE, 2001.

[25] United Aircraft Corporation. *The Pratt & Whitney Aircraft Story.* 1952.

[26] The Aviation History Online Museum. *Pratt Whitney R-2800*. [Online; accessed 7-October-2019]. 1996. URL: http://www.aviation-history.com/engines/pr-2800.htm.

[27] Wikipedia contributors. *Daimler-Benz DB 605 — Wikipedia, The Free Encyclopedia*. [Online; accessed 7-October-2019]. 2019. URL: https://en.wikipedia.org/w/index.php?title=Daimler-Benz_DB_605&oldid=916974720.

[28] Wayback Machine. *The Daimler-Benz DB605*. [Online; accessed 7-October-2019]. URL: https://web.archive.org/web/20050916000302/http://w1.1861.telia.com/~u186104874/db605.htm.

[29] Wikipedia contributors. *Oldsmobile V8 engine — Wikipedia, The Free Encyclopedia*. [Online; accessed 7-October-2019]. 2019. URL: https://en.wikipedia.org/w/index.php?title=Oldsmobile_V8_engine&oldid=904194546.

[30] Wikipedia contributors. *Saab 99 — Wikipedia, The Free Encyclopedia*. [Online; accessed 7-October-2019]. 2019. URL: https://en.wikipedia.org/w/index.php?title=Saab_99&oldid=919554869.

[31] Matt Kimberley. *Oldsmobile's Jetfire Was A World First Turbo Car With A Fatal Flaw*. [Online; accessed 7-October-2019]. 2018. URL: https://www.carthrottle.com/post/oldsmobiles-jetfire-was-a-world-first-turbo-car-with-a-fatal-flaw/.

[32] Fabian Hoppe, Matthias Thewes, Henning Baumgarten, and Jürgen Dohmen. "Water injection for gasoline engines: Potentials, challenges, and solutions". In: *International Journal of Engine Research* 17.1 (2016), pp. 86–96. DOI: 10.1177/1468087415599867. eprint: https://doi.org/10.1177/1468087415599867. URL: https://doi.org/10.1177/1468087415599867.

[33] Corinna Netzer, Tim Franken, Lars Seidel, Harry Lehtiniemi, and Fabian Mauss. "Numerical analysis of the impact of water injection on combustion and thermodynamics in a gasoline engine using detailed chemistry". In: *SAE International Journal of Engines* 11.2018-01-0200 (2018), pp. 1151–1166.

[34] John C Ingamells, RK Stone, NH Gerber, and George H Unzelman. *Effects of Atmospheric Variables on Passenger Car Octane Number Requirements*. Tech. rep. SAE Technical Paper, 1966.

[35] Jayesh Khatri, Ingemar Denbratt, Petter Dahlander, and Lucien Koopmans. *Water Injection Benefits in a 3-Cylinder Downsized SI-Engine*. 2019. DOI: https://doi.org/10.4271/2019-01-0034. URL: https://doi.org/10.4271/2019-01-0034.

[36] Arthur W Gardiner. *Atmospheric Humidity and Engine Performance*. Tech. rep. SAE technical Paper, 1929.

[37] Charles F Taylor. "The internal combustion engine in theory and practice, 1985". In: *Volume* 1 ().

[38] Yunus A Cengel and Michael A Boles. “Thermodynamics: an engineering approach”. In: *Sea* 1000 (2002), p. 8862.

[39] Bin Chen, Li Zhang, Xi Chen, and Qing Zhang. “Thermodynamic and numerical analysis of intake air humidification of a turbocharged GDI engine”. In: *Sādhanā* 43.5 (2018), p. 79.

[40] JB Heywood. “1988, Internal Combustion Engine Fundamentals, McGraw-Hill, New York”. In: ().

[41] R Lanzafame. *Water injection effects in a single-cylinder CFR engine*. Tech. rep. SAE Technical Paper, 1999.

[42] Nikhil Sharma and Avinash Kumar Agarwal. “Effect of the fuel injection pressure on particulate emissions from a gasohol (E15 and M15)-fueled gasoline direct injection engine”. In: *Energy & Fuels* 31.4 (2017), pp. 4155–4164.

[43] Ingo Hermann, Claus Glahn, Matthias Kluin, Martin Paroll, and Werner Gumprich. “Water Injection for Gasoline Engines-Quo Vadis?” In: *International Conference on Knocking in Gasoline Engines*. Springer. 2017, pp. 299–321.

[44] B Durst, C Landerl, J Poggel, C Schwarz, et al. “BMW Water Injection: Initial Experience and Future Potentials”. In: *38th International Vienna Motor Symposium*. 2017.

[45] Martin Böhm, Werner Mährle, Hans-Christian Bartelt, and Stephan Rubbert. “Functional integration of water injection into the gasoline engine”. In: *MTZ worldwide* 77.1 (2016), pp. 36–41.

[46] D TSURU, H KATO, and H TAJIMA. “Numerical and Experimental Study of Reduction of NOx on Diesel Combustion by Using Water Injection Systems”. In: ().

[47] Marcus Klein. *A specific heat ratio model and compression ratio estimation*. Division of Vehicular Systems, Department of Electrical Engineering . . ., 2004.

Nomenclature

Abreviation	**Description**
AFR	Air Fuel Ratio
aTDC	after Top Dead Centre
BMEP	Break Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
bTDC	before Top Dead Center
CAD	Crank Angle Degree
CO	Carbon Monoxide
CoV	Coefficient of Variation
CO_2	Carbon dioxide
C_p	Specific Heat Ratio at constant Pressure
CPC	Condensation Particle Counter
Cv	Specific Heat Ratio at constant Volume
DAQ	Data Acquisition
DMA	Differential Mobility Analyze
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EOI_w	End of Water Injection
EV	Electric Vehicles
HEV	Hybrid Electric Vehicle
IC	Internal Combustion
IMEP	Indicated Mean Effective Pressure
IVO	Intake Valve Opening
KLSA	Knock Limited Spark Advance
LD	Light Duty
LHV	Latent Heat of Vaporization
MBT	Maximum Brake Torque
MFB50	Mass Fraction Burn 50%
mg/cycle	milligram/cycle
MHEV	Mild Hybrid Electric Vehicle
NEDC	New European Drive Cycle
P	Pressure
PHEV	Plug-in Hybrid Vehicle
PM	Particulate Matter
PSD	particle number size distribution
PWI	Port Water Injection
RDE	Real Drive Emission

RHS	Relative Humidity System
rpm	revolutions per minute
RON	Research Octane Number
RTS95	Standardized Random Test 95
SI	Spark Ignition
SMPS	Scanning Mobility Particle Sizer
TDC	Top Dead Center
TWC	Three Way Catalyst
V	Volume
WI	Water Injection
WLTC	Worldwide harmonized Light-duty vehicles Test Cycle
WOT	Wide Open Throttle

Greek characters	**Description**
ρ	Density
λ	Actual to stoichiometric air-fuel ratio
η	Polytropic coefficient
γ	Ratio of specific heats (C_p/C_v)
ω	Humidity ratio (Absolute humidity)

List of Figures

List of Tables

Appended Publications A–B