Influence of Water Injection on Performance and Emissions of A Direct Injection Jet Ignition Engine

Albert Boretti[1,*] and Joseph Scalzo[2]

[1]*Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, Engineering Science Building, 395 Evansdale Dr., P.O. Box 6106, Morgantown, WV 26506-6106*

[2]*Scalzo Automotive Research Pty Ltd, Melbourne, Australia*

Abstract: A computational model is used to describe the operation of a four cylinder, turbocharged, ignition controlled by spark, direct injection engine fuelled with different fuels, including hydrocarbons, oxygenates and hydrogen. The intercooled engine features port and direct water injection plus jet ignition. The direct water injection permits a further enhanced control of the conditions within the cylinder prior, during and after combustion. Thanks to water injection, a much higher compression ratio is adopted. The port injection of water drastically reduces the temperature of the inlet air, thus permitting more air to enter the cylinder. This translates in more fuel being introduced, for an increased torque and power output. The lower temperature of the air coupled to the direct injection during the compression stroke also improves the resistance to knock, and reduces the heat loss at the walls of the combustion chamber, further improving the fuel conversion efficiency that is already boosted by the use of an higher compression ratio. The enhanced control of the injection of water in the port and the direct injection of fuel in the cylinder is aimed to achieve near to knocking conditions in a stoichiometric mixture about top dead centre that is then ignited almost instantaneously by the jet ignition device. This permits very high fuel conversion efficiencies and high power density during the full load operation. The direct water injection further improves the in-cylinder conditions especially after combustion. Further investigations are needed to better optimise the port and direct water injections.

Keywords: CAE simulations, water injection, turbocharging, jet Ignition, direct injection.

1. INTRODUCTION

Water injection is not a novel concept, as it was introduced in aircraft engines back in the 1940s [1-5]. The concept was extended to automotive applications shortly afterwards [6-11]. Water injection, generally allowed for greater compression ratios and essentially eliminated the problem of knock in spark ignition gasoline engines, even if emission reduction and metal temperatures below threshold values were other goals of the water injection. The interest towards water injection dropped considerably after the introduction of the charge cooler after the compressor in turbocharged engines, and the production of mostly naturally aspirated engines of significantly reduced costs and better peak fuel conversion efficiency. The return of interest for high power densities highly turbocharged engines has brought back attention to water injection [12-17]. Water injection is presently studied by a number of manufacturers and suppliers, including BMW, FEV and Bosch, especially in applications to turbocharged engines [18-24]. BMW [24], Figure **1**, claims a compression ratio increment of 1.5, translating in more top power and torque as well as a better fuel conversion efficiency over the full range of speeds and loads, when port and direct water injection are used in a spark ignited directly injected supercharged gasoline engine. This innovation permits 3-8% better fuel economy over the certification cycles as for example the cold start new European driving cycle whose operating points typically fail in the low load low speed range of the engine operation. Port and direct water injection were previously used by the authors in [14-17].

Numerous water injection devices utilize a blend of water and methanol (around 50/50), with small amount of a water-solvent oil. The water gives the essential cooling impact. The methanol is burnable. The motivation behind the oil is to avoid corrosion and erosion by water. Having some fuel injected with the water, the main fuel supply is reduced to ensure stoichiometric conditions. Especially in directly injected turbocharged engines, water injection is indeed a simple but very efficient way to improve both the amount of mixture introduced within the cylinder and the fuel energy conversion efficiency.

Here a novel dynamic use of water injection for every operating point is used to achieve very high compression ratios otherwise impossible for knocking, and introduce significantly larger amount of fuel air mixtures that are controlled to prevent auto-ignition prior of top dead centre. Top dead c entre jet ignition then produces an almost isochoric combustions of the

*Address correspondence to this author at theDepartment of Mechanical and Aerospace Engineering (MAE), Benjamin M. Statler College of Engineering and Mineral Resources, West Virginia University (WVU), Morgantown, WV; Tel: 304.293.3111; Fax: 304.293.6689; E-mail: alboretti@mail.wvu.edu

E-ISSN: 2311-8741/15

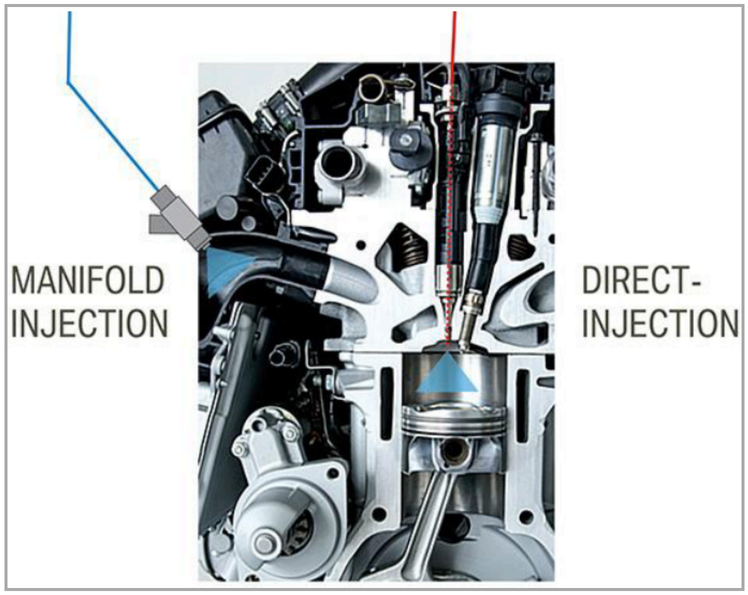

Figure 1: BMW direct water injection schematic (image modified after http://cdn.bmwblog.com/wp-content/uploads/2015/07/03_Direct_Water_Injection_Schematic_Design.jpg). The port and the direct water injectors may be operated synergetically to deliver the best performances. The traditional spark plug may also be replaced by a jet ignition device to provide faster combustion rates, translating in higher pressures and temperatures about top dead centre during the expansion stroke.

premixed mixtures. Temperature of intake air is controlled by a port injector, but temperatures of combustion gases are further controlled by direct water injection. The proposed system uses two water injectors, one in the intake pipe to help charging efficiency and knock prevention, and a direct water injector to further control the temperature of the charge before and after combustion is completed. The vaporization of the water in the intake pipe reduces the air temperature thus increasing the air density, more air may be drawn within the cylinder, the fuel directly injected in a relatively cooler environment is less susceptible to knock approaching top dead centre. The direct water injector provides a further control of the temperatures within the cylinder and out to turbine. Temperatures deemed excessive during the expansion stroke may be reduced by water injection. Temperatures of gases to turbine are always controlled to be below threshold values.

2. METHODS AND RESULTS

Engine performance simulations have been performed for a 2 litre, in-line four cylinders, turbo charged, with intercooler, direct injection gasoline engine. The engine parameters are presented in Table **1**. The engine has direct fuel injection within the combustion chamber, plus port and direct water injection. Simulations are performed by modelling the combustion with a Spark Ignition (SI) turbulent flame combustion model. The injection of water is a variant to the validated baseline gasoline engine model. Similarly, the jet ignition replacing the standard spark plug ignition and the use of different fuels like methanol, ethanol, indolene and isooctane (liquid) and hydrogen (gas) are numerically investigated.

Table 1: 2 Litre in-line Four Spark Ignition Engine Parameters

Displacement per cylinder [l]	0.4995
Number of cylinders	4
Engine layout	L-4
Compression ratio	13
Bore [mm]	86
Stroke [mm]	86
Connecting rod length [mm]	143
Wrist pin offset [mm]	0
Clearance vol. [l]	0.0550
Engine type	S.I.
No. of intake valve per cylinder	2
Intake valve dia. [mm]	34.5
Intake valve max. lift [mm]	10.05
No. of exhaust valve per cylinder	2
IVO [deg]	358(-2)
IVC [deg]	619 (+79)
Exhaust valve dia. [mm]	31
Exhaust valve max. lift [mm]	10
EVO [deg]	131 (-49)
EVC [deg]	384 (+24)

The SI turbulent flame combustion model is used to predict in-cylinder burn rate for traditional spark ignited engines. The model is well-suited for homogeneous fuel-to-air mixtures. The SI turbulent combustion model is calibrated to measured data for the baseline spark ignition configuration. The laminar speed is computed for the prescribed fuel. Different fuel options that include isooctane, methanol, hydrogen and ethanol may be accommodated.

The SI turbulent flame combustion model includes a Flame Kernel Growth Multiplier. This Multiplier is used to scale the calculated value of the growth rate of the flame kernel. This variable influences the ignition delay. Larger numbers shorten the delay, advancing the transition from laminar combustion to turbulent combustion. With jet ignition, this number is double to reflect the faster combustion as measured and computed with detailed kinetic models [25-31].

The SI turbulent flame combustion model also includes a Turbulent Flame Speed Multiplier. This Multiplier is used to scale the calculated turbulent flame speed. This variable influences the overall duration of combustion. Larger numbers increase speed of combustion. Again, with jet ignition, this number is double to reflect the faster combustion as measured and computed with detailed kinetic models.

Finally, the SI turbulent flame combustion model also uses a Taylor Length Scale Multiplier. This multiplier is used to scale the calculated value of the "Taylor microscale" of turbulence. The "Taylor microscale" modifies the time constant of combustion of fuel/air mixture entrained into the flame zone by changing the thickness of the plume and mostly influences the tail part of the combustion and is relatively insensitive. No change is considered moving from spark to jet ignition.

Knock is modelled by using the Douaud and Eyzat model [32]. The induction time continually decreases as combustion progresses and the unburned zone temperature rises. The end-gas auto-ignites (knocks) if the induction time is less than the flame arrival time. Knock occurrence is modulated through a single parameter, the Octane number, that is taken equal to 100 for isooctane and indolene, and equal to 130 for methanol, ethanol and hydrogen.

NOx, CO and HC are computed by using simple kinetics models with forward and backward reactions modelled through Arrhenius formulae as described in [33]. Same constants are used for spark or jet ignition and different fuels.

Figure **2** presents a sketch of the engine model featuring direct injection and port and direct water injection. A throttle and a waste gate are used to control the load. The water injectors only inject water and not a mixture of water, methanol and oil, because the combustion model may only deal with a single fuel.

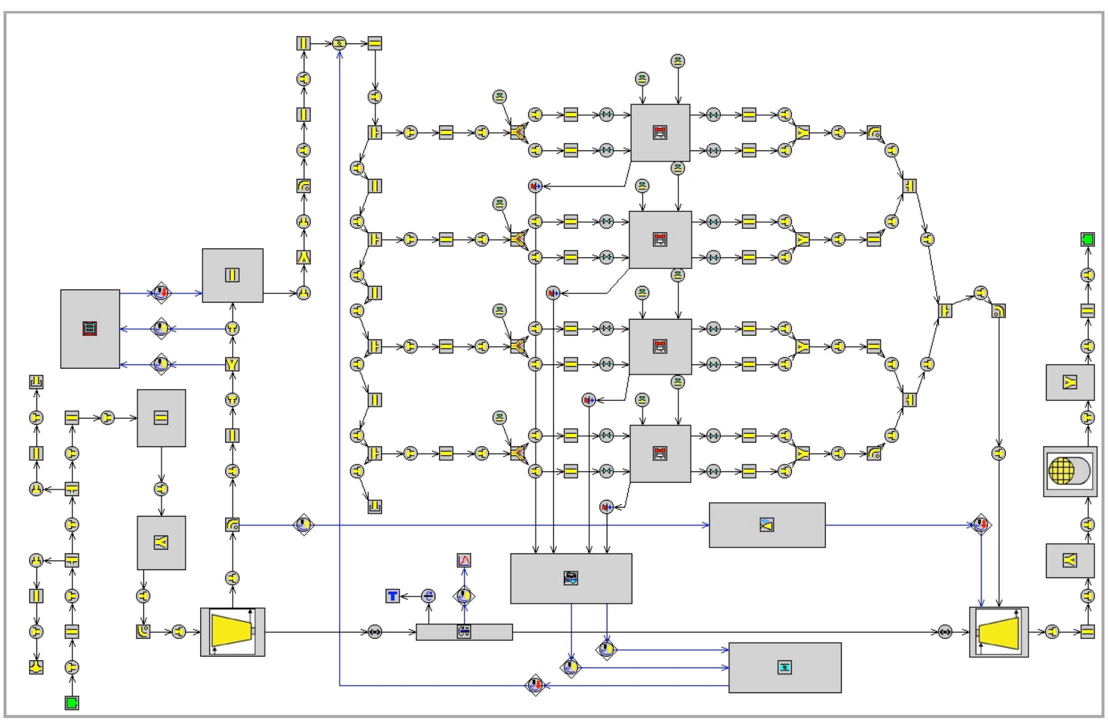

Figure 2: Sketch of the engine model featuring direct injection and port and direct water injection.

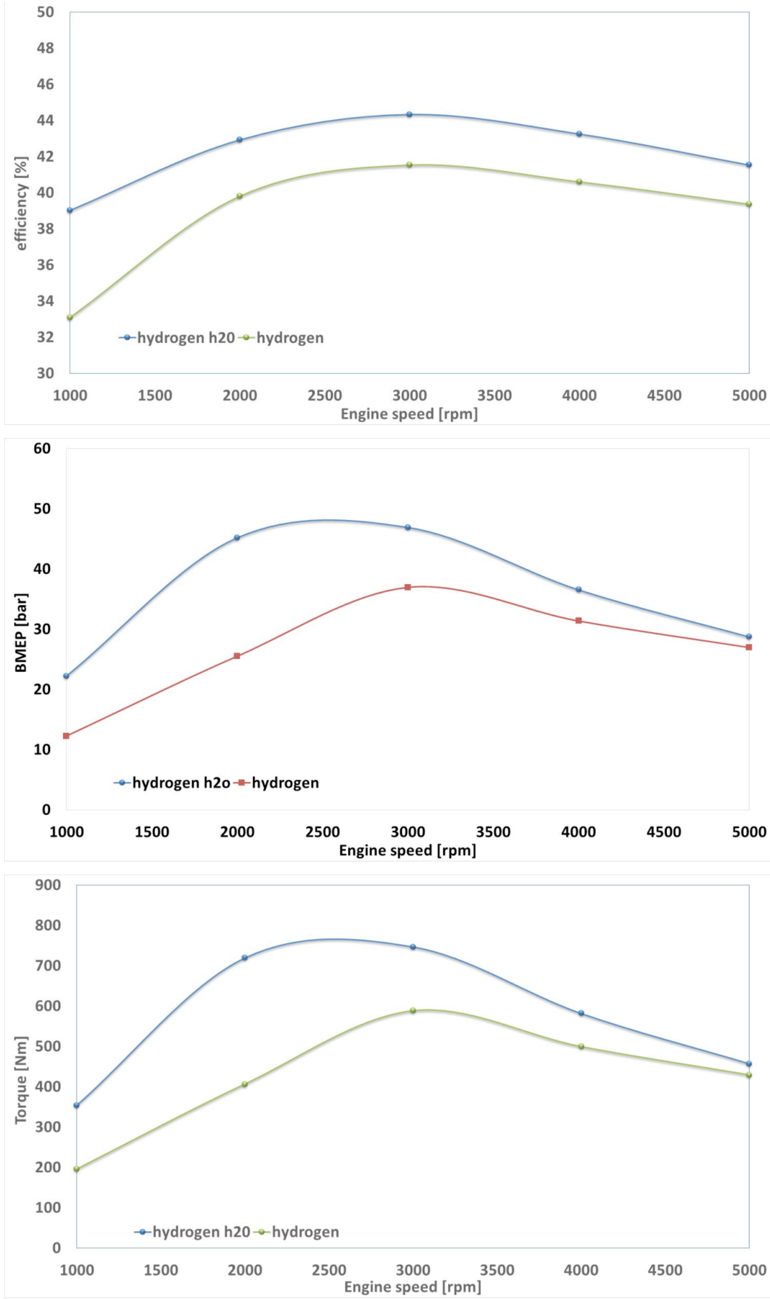

Figure 3: Efficiency, BMEP and power for the hydrogen engine with and without water injection. A constant higher compression ratio is considered with water injection that is tuned for the best performances within the constraints of knock and temperature to turbine.

The direct fuel injector is only nominally the same for hydrogen (gas) and the liquid fuels, as the densities are very different. The hydrogen injector injects a gaseous fuel. The liquid fuel injector injects a liquid fuel with the percentage of fuel that immediately vaporizes after injection a constant 20% for all the fuels. Different spray behaviors are expected moving from indolene and isooctane to methanol and ethanol, but this aspect is presently neglected. By moving towards very high injection pressures of about 500 bars and good atomization, the differences may be reduced. However, the different fuels properties starting from the latent heat of vaporization determine otherwise very different spray patterns. The water is supposed to completely vaporize immediately after the injection. This may be achieved with high pressures and very good atomization.

Figure **3** presents the efficiency, brake mean effective pressure (BMEP) and power for the hydrogen engine with and without water injection. A constant, higher compression ratio is considered with water injection that is tuned for the best performances within the constraints of knock and temperature to turbine.

This higher compression ratio otherwise impossible to achieve is 10:1 with isooctane and indolene and 13:1 with hydrogen, methanol and ethanol. Being the model very crude in many assumptions and the water injection system very far from being optimised following simple engine performance simulations, the following results are therefore indicative only of a general trend. Improvements are particularly relevant moving to lower speeds. The throttle is wide open.

Figure **4** presents the efficiency, BMEP and torque for the hydrogen, ethanol, methanol, isooctane and indolene engines always with water injection. The throttle is wide open.

These figures are only preliminary results but show the opportunity to achieve up to 40-44% fuel conversion efficiencies while working stoichiometric for top BMEP values of 40 bars (and above) thanks to the higher knock resistance, higher compression ratio, and increased amount of mixture trapped within the cylinder, plus the almost isochoric combustion, and lower heat losses.

In terms of emissions, water injection generally permits lower brake specific NOx emissions, as well as lower brake specific CO_2 emissions. In terms of brake specific CO and HC emissions, the advantages are more controversial and the computed differences are too small and subject to large inaccuracies to permit any claim. The benefits on some pollutants are however usually minimal at the catalytic converter, as the most part of the pollutants are easily converted in the three way catalytic converter.

3. DISCUSSION AND CONCLUSIONS

Injection of water upstream of the engine cylinder has numerically proved effective in drastically reducing the temperature of air through the intake, of the air fuel mixture prior of combustion, of the gases after combustion within the combustion chamber and of the gases at the entry of the turbine. This translates in higher power densities and better fuel conversion efficiencies for same limit to knock and same temperature to turbine. The port water injection controls the inflow of air and the pre combustion state of the mixtures, and in some extent also the conditions after combustion.

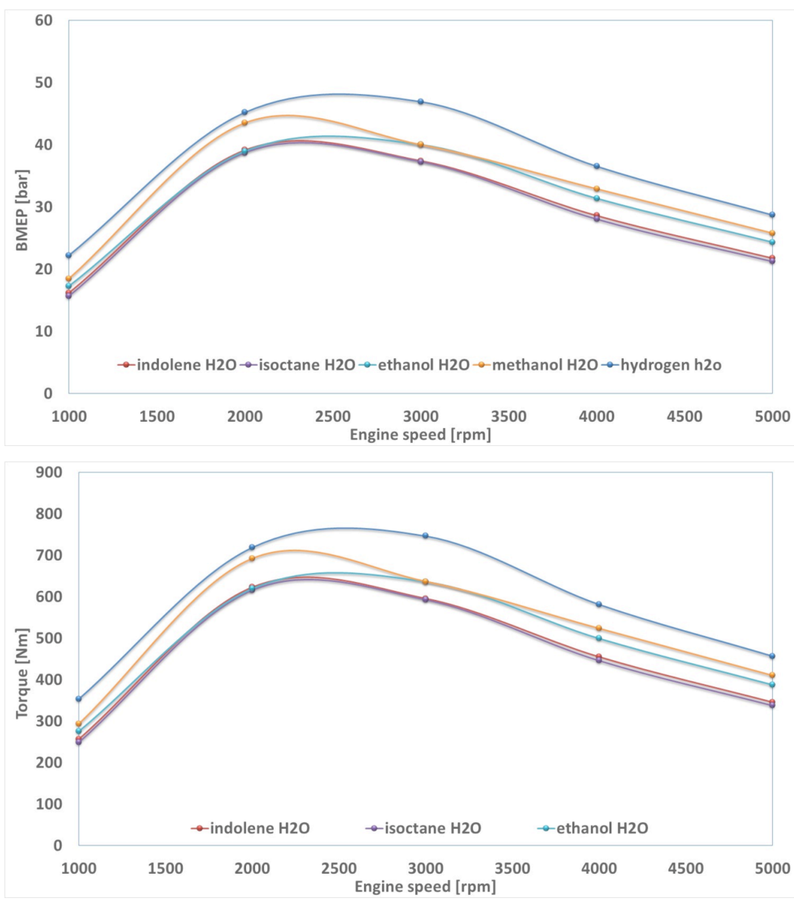

Figure 4: Efficiency, BMEP and torque for the hydrogen, ethanol, methanol, isooctane and indolene engines always with water injection. The water injection strategy is only marginally adjusted to the different fuel.

Direct water injector not only permits a further enhanced control of the in-cylinder conditions before combustion, but also the precise control of the conditions after combustion of the burned gases. The direct injector permits to introduce water before, during and after the combustion event when and if needed with significantly enhanced flexibility.

The proposed results are only computational but clearly show the opportunity of achieving much better fuel conversion efficiencies at any load thanks to the much higher compression ratio. A proper experimental campaign is certainly needed to better determine the limits and opportunities of this old technique returned popular only recently, further expanded here to include optimised port and direct water injection.

Compared to the BMW system [24], this further enhanced system is expected to permit higher compression ratios, to deliver larger increments of power and torque outputs, and to provide better fuel conversion efficiencies over the full range of engine speeds and loads, at only the expenses of a larger use of water. This ultimately translates in better fuel economies over the cold start driving cycles as the New European Driving Cycle used for certification in Europe, where port and direct water injection plus direct injection and jet ignition has the potential to deliver better than 10% improvements in fuel economy at an additional cost possibly within the 100-150$ per engine in mass production.

REFERENCES

[1] Rothrock AM, *et al*. The induction of water to the inlet air as a mean of internal cooling in aircraft engine cylinders. NACA, 1942; report no. 756. [Cited 2015 Oct 20]: Available from: http://www.rbracing-rsr.com/downloads/naca_H2O.pdf

[2] Brun RJ. End zone water injection as a means of suppressing knock in a spark-ignition engine, NACA 1944; restricted bulletin no. E4127. [Cited 2015 Oct 20]: Available from: http://www.rbracing-rsr.com/downloads/naca_H2O.pdf

[3] Ladd GT. Water injection for aircraft engines, SAE 1944; P. 460192.

[4] Colwell AT, *et al*. Alcohol-water injection, SAE 1946; P. 450196.

[5] Eaton DC. Cruising economy by use of water injection, SAE 1946; P. 460198.

[6] Porter JC. Alcohol-water injection for high compression engines. SAE P 1950; 500042.

[7] Nicholls JE, El-Messiri IA and Newhali HK. Inlet Manifold Water Injection for Control of Nitrogen Oxides — Theory and Experiment, SAE 1969; P. 690018.

[8] Weatherford WD and Quillian RD. Total Cooling of Piston Engines by Direct Water Injection, SAE, 1970; P.700886. http://dx.doi.org/10.4271/700886

[9] Lestz SS, Meyer WE and Colony CM. Emissions from a Direct-Cylinder Water-Injected Spark-Ignition Engine, SAE, 1972; P. 720113. http://dx.doi.org/10.4271/720113

[10] Bratkov AA, Azev VS, Radchenko ED, Gladkikh VA and Livshits SM. Experience In Use Of Water-Fuel Emulsions. Chemistry and Technology of Fuels and Oils 1982; 16(11-12): 731-735.

[11] Tsao KC, Wang CL and Miller EM. Performance Of Gasoline-Water Fuel In A Modified Si Engine, SAE 1984; P. 841399.

[12] Nande AM, Wallner T and Naber J. Influence of water injection on performance and emissions of a direct-injection hydrogen research engine, SAE 2008; P. 2008-01-2377.

[13] Chen R, Chiang L, Wu M and Lin T. Gasoline displacement and NOx reduction in an SI engine by aqueous alcohol injection, Fuel 2010; 89(3): 604-610. http://dx.doi.org/10.1016/j.fuel.2009.07.015

[14] Boretti A. Stoichiometric H2ices With Water Injection. International Journal of Hydrogen Energy 2011; 36: 4469-4473. http://dx.doi.org/10.1016/j.ijhydene.2010.11.117

[15] Boretti A. Stoichiometric H2ice With Water Injection And Exhaust And Coolant Heat Recovery Through Organic Rankine Cycles. International Journal of Hydrogen Energy 2011; 36(19): 12591-12600. http://dx.doi.org/10.1016/j.ijhydene.2011.06.124

[16] Boretti A, Osman A and Aris I. Direct injection of hydrogen, oxygen and water in a novel two stroke engine. International Journal of Hydrogen Energy 2011; 36: 10100-10106. http://dx.doi.org/10.1016/j.ijhydene.2011.05.033

[17] Boretti A. Water Injection In Directly Injected Turbocharged Spark Ignition Engines. Applied Thermal Engineering 2012; 52(1): 62-68. http://dx.doi.org/10.1016/j.applthermaleng.2012.11.016

[18] FEV. Gasoline Combustion Beyond 2020. [Cited 2015 Oct 20]: Available from: http://spectrum.fev.com/53/en/index.html

[19] Thewes M, Hoppe F, Baumgarten H and Seibel J. Water Injection for Gasoline Combustion Systems. MTZ worldwide 2015; 76(2): 10-15. http://dx.doi.org/10.1007/s38313-014-1012-0

[20] Hoppe F, Thewes M, Baumgarten H and Dohmen J. Water injection for gasoline engines: Potentials, challenges, and solutions. International Journal of Engine Research 2015. http://dx.doi.org/10.1177/1468087415599867

[21] BMW. Innovative water injection system. More power and reduced formation of hazardous substances. [Cited 2015 Oct 20]: Available from: http://www.m-power.com/_open/s/varlink2.jsp?id=3301&lang=en

[22] Bulander R. Powertrain optimization using a comprehensive systems approach. Brochure presented to the 2015 36th Vienna Motor Symposium. [Cited 2015 Oct 20]: Available from: http://www.bosch-presse.de/presseforum/download/BroschuereA5_Wiener_Motorensymposium_2015_EN.pdf.

[23] Brooke L. Bosch developing new water-injection system for production engines. Automotive Engineering Magazine 2015; 02-Jun. [Cited 2015 Oct 20]: Available from: articles.sae.org/14176/.

[24] BMW Blog. BMW 1 Series with Direct Water Injection – First Drive. [Cited 2015 Oct 20]: Available from: http://www.bmwblog.com/2015/07/02/bmw-1-series-with-direct-water-injection-first-drive/.

[25] Hamori F. Optimising the application of HAJI to the supercharged engine. University of Melbourne 2006, PhD Thesis.

[26] Dober G. Geometric control of HC emissions. The University of Melbourne. 2002, PhD Thesis.

[27] Mehrani P. Predicting knock in a HAJI engine. The University of Melbourne. 2008, PhD Thesis.

[28] Boretti AA, Brear MJ and Watson HC. Experimental and numerical study of a hydrogen fuelled IC engine fitted with the hydrogen assisted jet ignition system, 16th Australasian fluid mechanics conference. Gold Coast. Australia; December 2007.

[29] Boretti A and Watson HC. Development of a direct injection high efficiency liquid phase LPG spark ignition engine. SAE 2009; P. 2009-01-1881.

[30] Boretti A and Watson HC. Development of a direct injection high flexibility CNG/LPG spark ignition engine. SAE 2009; P. 2009-01-1969.

[31] Boretti A, Paudel R and Tempia A. Experimental and computational analysis of the combustion evolution in direct injection spark controlled jet ignition engines fuelled with gaseous fuels. Journal Proceedings of the Institution of Mechanical Engineers. Part D: Journal of Automobile Engineering 2010; 224(9): 1241-1261. http://dx.doi.org/10.1243/09544070JAUTO1465

[32] Douaud AM and Eyzat P. Four-Octane-Number Method for Predicting the Anti-Knock Behavior of Fuels and Engines, SAE 1978; P. 780080.

[33] Heywood JB. Internal Combustion Engine Fundamentals. McGraw-Hill. New York 1988.

Received on 16-10-2015 Accepted on 18-11-2015 Published on 31-12-2015

DOI: http://dx.doi.org/10.12974/2311-8741.2015.03.01.4