Internal Combustion Engines Water Injection fed by Exhaust Water Recirculation: a feasibility analysis

A. VAUDREY^{*,1,2}

¹Univ. Lyon, ECAM Lyon, INSA-Lyon, LabECAM, F-69005, France.

²Pontificia Universidad Católica del Peru (PUCP), Laboratorio de Energía, Lima, Peru.

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Water injection (WI) is one of the ways usable to mitigate the tail pipe pollution of internal combustion engine propelled vehicles. Despite its well-known good points, such a process may require the presence of an additional liquid water tank on board. In this paper, we assess the possibility to recycle some water vapour contained within the engine exhaust gas stream in order to supply WI and then reduce as far as possible the size of the water tank. The influence of parameters such as the ambient humidity, the fuel chemical composition, the Water-Fuel Ratio and the water recycling system effectiveness are taken into account. Obtained results are really encouraging: in considering the effectivenesses of existing water recycling membranes usable with exhaust gas streams, almost all water needs of WI processes could be satisfied, for both liquid (gasoline and Diesel) and gaseous fuels (hydrogen and natural gas). The Exhaust Water Recirculation system presented in this paper is thus probably one of the key components WI will need to be used more widely on actual vehicles.

Keywords : Water injection, Fogging, Exhaust Water Recirculation.

1. Introduction

Despite some recent and quite blaring announcements by politics, industrialists or journalists [1], of the coming end of Internal Combustion Engine (ICE) propelled vehicles era (supposedly replaced soon by electrical ones), their complete disappearance is probably not likely to happen any time soon. Such shift, when actually occurring, will be gradual, partly because of the time needed for dedicated industries and infrastructures to grow [2], but also because of the large financial capacity required from the whole society to invest in such new technologies [3, 4]. We will thus certainly have to stand for ICE and its harmful polluting emissions during decades more. Decreasing these pollutions, including carbon dioxide, is then an immediate priority and must be achieved by any mean possible.

Different technologies can be used to decrease the amount of pollutants produced by ICE, and among them a specific one with a quite lively history: *water injection* (WI). Injecting liquid water into ICE is an idea as old as the ICE itself: some of the first gas engines developed near the mid XIX century, as the one of Hugon for example [5], used this process to “control” their combustion phenomena. Later, such a strategy has been used at different times and in different contexts, from the famous supercharged World War II aircraft engines [6] to the recent BMW M4 GTS model [7], through some Renault 1980s

F1 supercharged engines [8]. While all these applications of WI were dedicated to performance improvement — and can have, *ceteris paribus*, an indirect positive effect on the amount of fuel consumed, and then on the amount of pollutants rejected — the same process is also relevant to mitigate some polluting emissions, and first of all those of nitrogen oxides (NO_x).

Whatever it be, the use of WI on an ICE propelled vehicle requires to carry on board the sufficient amount of liquid water for so, in a supplementary water tank for instance. The aim of this paper is to assess the possibility to use, thanks to an Exhaust Water Recirculation (EWR) process, some liquid water extract by condensation from the ICE exhaust gas stream, in order to supply the WI system, and then to reduce the size of the concerned water tank. Whereas this idea has been already proposed in different patents [9–11], its feasibility has apparently not been yet analysed from a larger point of view, considering different consumed fuels or different ambient conditions.

After a short review of the known effects of WI on the performance and polluting emissions of ICE, a complete water balance of such an engine is presented. From that, a new criterion of WI self supplied operation is introduced. The influence on such a criterion of usual parameters as the *Water-Fuel Ratio*, the ambient humidity or the consumed fuel chemical composition, is detailed. Thanks to this analysis, we conclude that, considering the per-

^{*}Corresponding author : alexandre.vaudrey@ecam.fr, ORCID iD: 0000-0002-8613-774X

formance of already existing water recycling membranes, such a process can self supply engines WI systems in almost any situations, even within a very dry ambient air and whatever the fuel consumed, liquid or gaseous.

We are confident that such results are of a great interest for anyone interesting in implementing WI on vehicles, and we are quite surprised that such an idea has not been more widely tested so far.

2. Effects of water injection on internal combustion engines

2.1. Effects on performance

Liquid water can be practically injected either into the engine intake port, we then talk about *port/indirect water injection* (IWI), *inlet manifold water injection* or sometimes about *intake fumigation* [12, 13] ; or directly within the latter cylinder(s), via a *direct water injection* (DWI) strategy [14].

When IWI is used, the liquid water injected into the intake manifold evaporates and the enthalpy of vaporisation thus absorbed is removed from the enthalpy of the whole intake stream, and cools it down. The fresh mixture is subjected to a temperature drop and then to an increase of its density. The amount of fuel aspirated (for spark ignited engines) or directly injected into the engine cylinder (for compression ignited engines) is thus increased [15]. Power and efficiency increase whereas specific fuel consumption and specific production of carbon dioxide, per kWh produced, decrease.

IWI and DWI can also lead to a lower compression stroke required mechanical work, the gas to compress being initially at a lower temperature and some remaining liquid water being potentially vaporised during the compression in order to “internally” refrigerate it [16]. Both WI strategies decrease the combustion flame temperature, the fresh mixture being at lower temperature at the end of the compression stroke and the heat of combustion being released in a larger amount of gas. The probability of *knock* phenomena is thus reduced, and the fresh mixture octane number is increased [17, 18]. Higher compression ratios can then be reached. Finally, the amount of gas involved in the expansion stroke is increased and so the mechanical work provided by the latter.

2.2. Effects on polluting emissions

Considering engines polluting emissions, WI participates to decrease the amount of *nitrogen oxides* (NO_x) finally rejected by the combustion, in decreasing the flame temperature [19–24], the main source of NO_x being the oxidation process of atmospheric nitrogen contained in the air composing the fresh mixture, due to a too high combustion peak temperature [25]. On the contrary, the production of unburnt hydrocarbons increases, purportedly because of an enlargement of the quenching layers of combustion, due to the cooling process of the cylinder inner surface [26, 27]. Finally, WI can whether decrease or increase the production of *carbon monoxide* (CO), depending on the specific experimented configuration [28].

3. Internal combustion engines water balance

3.1. Ambient humidity

The first amount of water, as vapour, which is always involved in the operation of ICE is the one naturally contained in the ambient air. Expressed as an aspirated mass flow rate, and noted $\dot{m}_0$, it can be written as the products:

$$\dot{m}_0 = \dot{m}_{\text{air}} \cdot \omega_0 = \dot{m}_{\text{fuel}} \cdot \text{AFR} \cdot \omega_0 \quad (1)$$

$\dot{m}_{\text{air}}$ and $\dot{m}_{\text{fuel}}$ are the mass flow rates of *dry air* and *fuel*, respectively, which are required by the engine combustion process. AFR is the *Air-Fuel Ratio* defined as:

$$\text{AFR} = \frac{\dot{m}_{\text{air}}}{\dot{m}_{\text{fuel}}} \quad (2)$$

whom actual value depends on the fuel chemical composition and of the *Air-Fuel equivalence Ratio*, often noted λ and defined as:

$$\lambda = \frac{\text{AFR}}{\text{AFR}_{\text{st}}} \quad (3)$$

The subscript “st” means *stoichiometric*: $\lambda = 1$ for a stoichiometric combustion, while $\lambda > 1$ for a lean combustion, i.e. with excess air, and $\lambda < 1$ for a rich combustion [25]. Values of AFR_{st} corresponding to the fuels considered in this paper are presented in Table 1.

The last parameter involved in equation (1) is the *specific humidity* ω (sometimes called *moisture content*, *humidity ratio* or *mixing ratio*), defined as the ratio of the amount of water vapour (so the subscript “vap”) mixed with ambient dry air, to the amount of the latter [30, chapter 6]:

$$\omega = \frac{m_{\text{vap}}}{m_{\text{air}}} \quad (4)$$

Such a parameter can be practically measured in the ambient air thanks to a common humidity sensor [30, chapter 14].

For a gasoline fed engine ($\text{AFR}_{\text{st}} \simeq 14.5$) with a stoichiometric combustion ($\lambda = 1$) and an ambient air at temperature of 20°C and a relative humidity of 50%, which corresponds to a specific humidity $\omega_0 \simeq 0.007$, we obtain for example $\frac{\dot{m}_0}{\dot{m}_{\text{fuel}}} = \text{AFR} \cdot \omega_0 \simeq 0.102$.

3.2. Water-Fuel Ratio

The second water mass flow rate involved is the one we specifically inject into the engine during WI process, noted $\dot{m}_{\text{inj}}$. This rate is usually related to the consumed fuel one, thanks to the *Water-Fuel Ratio*, noted WFR:

$$\text{WFR} = \frac{\dot{m}_{\text{inj}}}{\dot{m}_{\text{fuel}}} \quad (5)$$

Depending on the concerned engine and of the WI purpose (performance increase or pollution mitigation), the Water-Fuel Ratio can be typically adjusted such as $0.2 \leq \text{WFR} \leq 1.5$ for usual liquid fuels [14, 27, 31–33], so values clearly larger than the ones related to the ambient humidity. For gaseous fuels, the values of WFR are usually larger, reaching sometimes $\text{WFR} \simeq 3$ for natural gas fed spark ignited engines [35] and $\text{WFR} \simeq 9$ for hydrogen ones [34].

Table 1: Main properties of some current fuels consumed in internal combustion engines. Octane and Cetane are the reference fuels for spark ignited and compression ignited engines, respectively [29]. Properties of the E10 blend are obtained thanks to calculations detailed in Appendix A.1 page 6.

Fuel	x	y	z	M_{fuel} [g/mol]	AFR _{st}	β
Hydrogen (H ₂)	0	2	0	2.016	34.06	8.936
Natural gas ($\sim$ CH ₄)	1	4	0	16.04	17.12	2.246
Ethanol (C ₂ H ₅ OH)	2	6	1	46.07	8.94	1.173
E10	6.8	13.2	0.2	98.22	13.99	1.211
Usual gasoline ($\sim$ C ₈ H ₁₅)	8	15	0	111.20	14.51	1.215
Octane (C ₈ H ₁₈)	8	18	0	114.23	15.03	1.419
Usual Diesel fuel ($\sim$ C _{13.2} H _{24.4})	13.2	24.4	0	183.14	14.47	1.200
Cetane (C ₁₆ H ₃₄)	16	34	0	226.44	14.86	1.352

3.3. Water produced by the combustion process

Some water is also produced by the combustion process itself, with a resulting mass flow rate henceforth noted $\dot{m}_{\text{comb}}$. The combustion process taken into account is the complete one of an (oxygenated) hydrocarbon fuel of composition C_xH_yO_z, with air. *Complete* means that the possible production of more complex and often hazardous components such as *unburnt hydrocarbons*, *carbon monoxide* and *nitrogen oxides* (see §2.2), are not considered, neither the potential involvement of water in another chemical reaction.

The molar balance of such a combustion process can be described by the follow equation:

ν_{air} is the air related stoichiometric coefficient, used to calculate the stoichiometric Air-Fuel Ratio value of equation (3), and whom expression is:

$$\nu_{\text{air}} = x + \frac{y}{4} - \frac{z}{2} \quad (7)$$

α is the nitrogen to oxygen molar fraction in dry air : $\alpha = x_{\text{N}_2, \text{air}} / x_{\text{O}_2, \text{air}} = 0.79 / 0.21 \simeq 3.76$. The respective numbers of carbon, hydrogen and oxygen atoms in balance (6), so x, y and z, are presented for some usual fuels in Table 1. From equation (6), it is easy to notice that the amount of water produced by such a combustion process is solely related to the hydrogen content of the consumed fuel, represented by the number y.

Considering any given equation similar to (6), we can relate the molar flow rate $\dot{n}_j$ of any product j to the one any reactant i by:

$$\dot{n}_j = \frac{\nu_j}{\nu_i} \cdot \dot{n}_i \quad (8)$$

Both molar flow rates are here counted as positive. When applied to fuel and water in Equation (6), this relation gives:

$$\dot{n}_{\text{comb}} = \frac{\nu_{\text{H}_2\text{O}}}{\nu_{\text{fuel}}} \cdot \dot{n}_{\text{fuel}} = \frac{y}{2} \cdot \dot{n}_{\text{fuel}} \quad (9)$$

The same relation, but expressed in mass, involves the fuel and water respective molar masses, and gives:

$$\dot{m}_{\text{comb}} = \frac{y}{2} \cdot \frac{M_{\text{H}_2\text{O}}}{M_{\text{fuel}}} \cdot \dot{m}_{\text{fuel}} = \beta \cdot \dot{m}_{\text{fuel}} \quad (10)$$

β is then the amount water produced, through the combustion reaction, by each unit of mass of the consumed fuel. Values of β for previously mentioned fuels are presented in Table 1 as well. We can notice that the lower value of β , that corresponds to neat ethanol, is already within the highest part of the range of Water-Fuel Ratio, which is an optimistic indicator for the rest.

3.4. Water extraction from exhaust gas stream

If water is not supposed to be involved in any other chemical reaction than (6), the vapour mass flow rate contained in the exhaust gases one can be expressed, according to previous relations (1), (5) and (10), as:

$$\begin{aligned} \dot{m}_{\text{exh}} &= \dot{m}_0 + \dot{m}_{\text{inj}} + \dot{m}_{\text{comb}} \\ &= \dot{m}_{\text{fuel}} \cdot (\text{AFR} \cdot \omega_0 + \text{WFR} + \beta) \end{aligned} \quad (11)$$

In the rest, only a fraction ε of this water vapour flow rate is supposed to be liquefied and recycled, as presented in Figure 1. This rate, henceforth noted $\dot{m}_{\text{recy}}$, is:

$$\dot{m}_{\text{recy}} = \varepsilon \cdot \dot{m}_{\text{exh}} \quad (12)$$

ε is then also the *effectiveness* of the water recycling system used to get back water from the exhaust stream.

According to Moses-Debusk et al. [36] for instance, the use of already existing inorganic tubular membranes can lead to an effectiveness of such a water recycling process such as :

$$50\% \leq \varepsilon \leq 70\% \quad (13)$$

We will consider the same range of values for ε in the rest.

3.5. Water injection self supplying coefficient

Let us now consider the possibility to supply the WI system with the sole recycled water flow rate coming back from the exhaust stream. For so, we can consider for example the follow parameter, called Exhaust Water Recirculation (EWR) *self supplying coefficient* :

$$\psi = \frac{\dot{m}_{\text{recy}}}{\dot{m}_{\text{inj}}} \quad (14)$$

Figure 1: Representation of the flow rates exchanged by an ICE equipped with a WI system. Here the Exhaust Water Recirculation system is such as $\psi = \dot{m}_{\text{recy}}/\dot{m}_{\text{inj}} < 1$, and some water has to be consumed from the water tank (not drawn to scale).

The WI process can then be supplied by the sole EWR if $\psi = 1$, whereas a supplementary tank is required if $\psi < 1$. Combining equations (5), (11) and (12), we can express ψ in another way:

$$\psi = \varepsilon \cdot \left(1 + \frac{\text{AFR} \cdot \omega_0 + \beta}{\text{WFR}} \right) \quad (15)$$

The ability of the EWR system to properly supply the WI process is then logically favoured, for a given fuel, by high values of the recycling effectiveness ε and of the ambient specific humidity ω_0 , as well as by a low value of the required Water-Fuel Ratio. It is then possible to define a maximum value of the latter which ensures, for a given effectiveness ε , a self supplying operating mode of the whole system, corresponding to a value $\psi = 1$:

$$\text{WFR}_{\text{max}} = \frac{\text{AFR} \cdot \omega_0 + \beta}{1/\varepsilon - 1} \quad (16)$$

Let us consider now the application of previous relations on some practical example of WI use for vehicles.

4. Results and discussion

4.1. Influence of ambient humidity

Considering the positive role of the water vapour extract from the ambience, represented by the factor $\text{AFR} \cdot \omega_0$, on both values of ψ and WFR_{max} in equations (15) and (16), we will consider in the rest only a pessimistic value of the former, corresponding to cold and relatively dry weather

situations. Hence, for a cold air with a temperature of 0°C and a relative humidity of 50%, we have a minimum ambient specific humidity $\omega_0 \simeq 1.89 \cdot 10^{-3}$, [30, chapter 6]. Any other situation, with a larger value of ω_0 , would make things better for the WI process.

4.2. Usual liquid fuels

Values of the maximum Water-Fuel Ratio WFR_{max} of equation (16), for recycling effectivenesses given by (13), and stoichiometric combustion of three usual liquid fuels, are presented in Table 2. In the same table are also presented the required values of the effectiveness ε that make the system able to be self supplied for two extreme values of WFR extract from literature [14, 27, 31–33]. The same results are summarised in Figure 2. All these results are clearly in favour of the use of EWR for supplying WI processes in concerned engines. Even the most reasonable values of recycling effectiveness ($\varepsilon = 50\%$) makes possible the supply of Water-Fuel Ratio located within the highest part of the usual range of values. Furthermore, the difference between gasoline and Diesel fuel is insignificant and suggests that the same apparatus would be setup indifferently on spark ignited and compression ignited engines propelled vehicles.

4.3. Gaseous fuels

The situation is also favourable to gas fed engines, by *hydrogen* (H_2) or by *natural gas* (represented here the *methane* CH_4), mainly because of the higher hydrogen contents of such fuels (see the values of β in Table 1),

Table 2: Values of the maximum Water-Fuel Ratio of equation (16) for two typical values of the water vapour recycling efficiency ε , and of ε of equation (15) corresponding to the minimum and maximum values of WFR found in the literature.

Fuel	λ	WFR _{max}		ε	
		$\varepsilon = 50\%$	$\varepsilon = 70\%$	WFR = 0.2	WFR = 1.5
Gasoline	1	1.242	2.899	13.9%	54.7%
E10	1	1.237	2.864	13.9%	54.8%
Diesel fuel	1	1.237	2.887	14.0%	55.0%
Hydrogen	2	9.064	21.150	WFR = 3	WFR = 9
Natural gas	2	2.310	5.391	56.5%	49.8%

but also because of the larger amount of air needed for their proper combustion, that aspirate more ambient humidity in the combustion process. The values of WFR_{max} and ε of equations (16) and (15) for lean combustions of hydrogen [37] and natural gas [38], so with $\lambda = 2$, are presented in the lower part of Table 2. The optimal amount of injected water highlighted by some authors, of about 9 for hydrogen fed spark ignited engines by Subramanian, Mallikarjuna, and Ramesh [34] and of about 3 for natural gas ones by Arruga et al. [35], is still within the available range of effectiveness of current membranes.

The EWR strategy is then potentially relevant to be setup also on future hydrogen or natural fed ICE propelled vehicles.

5. Conclusions

Liquid water injection into internal combustion engines is a well-known strategy of both performance improvement and pollution mitigation. However, when applied to ac-

tual vehicles, the question quickly arises of the origin of the water needed for so. Do we have to carry on board a supplementary water tank? Of how much size?

To avoid as far as possible such a supplementary constraint, and its resulting costs, the principle of recycling the water vapour contained within exhaust gases has been considered for a while, and has been the goal of several patents¹. However, as far as we know, no global assessment of such strategy has been led to date.

Such an assessment is proposed in the current paper, with an analysis of the potential impacts of the fuel chemical composition, of the ambient humidity and of the actual Water-Fuel Ratio required by the water injection process. Considering the water recycling effectivenesses of existing membranes, already used for such a purpose, as long as the most pessimistic situations regarding to ambient humidity, we conclude that the Exhaust Water Recirculation (EWR) is a very promising solution, applicable to both liquid and gaseous fuels. Even the lowest values of this recycling effectiveness are compatible with the values

¹Incidentally, the same idea is practically used for a while in *fuel cells*, the water produced in the heart of such systems being recycled and used to humidify the air absorbed by the intake [39].

Figure 2: Evolution of the maximum Water-Fuel Ratio WFR_{max} of equation (16) vs. the water recycling effectiveness ε , for stoichiometric combustions of gasoline and usual Diesel fuel. Ambient specific humidity is here $\omega_0 \leq 0.002$.

of Water-Fuel Ratio commonly found to be effective for such engines.

The results presented in this paper are probably not advanced enough to draw any definitive conclusion, but they are clearly encouraging and we hope they will encourage scientists and engineers involved in this topic to lead some related experiment, and hopefully to give further credibility to such an idea.

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A. Appendix

A.1. Ethanol-gasoline blend fuels

A.1.1. Chemical composition

Lets us consider an ethanol-gasoline blend fuel called "EX" with X the ethanol concentration **in volume**, as e.g. for the famous E10 commonly available in Europe and in the USA. If ρ_{eth} and ρ_{gas} are the respective densities of ethanol and gasoline, the blend one noted ρ_{EX} is given by:

$$\rho_{\text{EX}} = X \cdot \rho_{\text{eth}} + (1 - X) \cdot \rho_{\text{gas}} \quad (17)$$

And the corresponding *mass fraction* of ethanol (noted here with the letter w) is:

$$w_{\text{eth}} = \frac{m_{\text{eth}}}{m_{\text{eth}} + m_{\text{gas}}} = \left(1 + \frac{1 - X}{X} \cdot \frac{\rho_{\text{gas}}}{\rho_{\text{eth}}}\right)^{-1} \quad (18)$$

Introducing the molar masses of these components, we can express the one of the blend as:

$$M_{\text{EX}} = \frac{m_X}{n_X} = \left(\frac{w_{\text{eth}}}{M_{\text{eth}}} + \frac{1 - w_{\text{eth}}}{M_{\text{gas}}}\right)^{-1} \quad (19)$$

The corresponding *molar fraction* of ethanol is then:

$$x_{\text{eth}} = w_{\text{eth}} \cdot \frac{M_{\text{EX}}}{M_{\text{eth}}} \quad (20)$$

From that, the equivalent contents of carbon, hydrogen and oxygen of each mole of the blend, so the x , y and z variables previously introduced, can be calculated thanks to:

$$\begin{aligned} x_{\text{EX}} &= x_{\text{eth}} \cdot x_{\text{eth}} + (1 - x_{\text{eth}}) \cdot x_{\text{gas}} \\ y_{\text{EX}} &= x_{\text{eth}} \cdot y_{\text{eth}} + (1 - x_{\text{eth}}) \cdot y_{\text{gas}} \\ z_{\text{EX}} &= x_{\text{eth}} \cdot z_{\text{eth}} + (1 - x_{\text{eth}}) \cdot z_{\text{gas}} \end{aligned} \quad (21)$$

As presented in Table 1, we have for ethanol the values $x_{\text{eth}} = 2$, $y_{\text{eth}} = 6$ and $z_{\text{eth}} = 1$.

A.1.2. Application to the E10 blend

Considering the practical case of the usual E10 blend, considering $\rho_{\text{gas}} \simeq 789 \text{ kg/m}^3$ and $\rho_{\text{eth}} \simeq 732 \text{ kg/m}^3$, we obtain thanks to (17), a blend density $\rho_{\text{E10}} \simeq 783 \text{ kg/m}^3$. According to (18), we have the respective mass fractions of both components $w_{\text{eth}} \simeq 9.35\%$ and $w_{\text{gas}} \simeq 90.65\%$. Based on the molar masses $M_{\text{eth}} = 46.07 \text{ g/mol}$ and $M_{\text{gas}} = 111.20 \text{ g/mol}$ and on relation (19), the molar mass of the blend is thus $M_{\text{E10}} \simeq 98.22 \text{ g/mol}$. Using (20), we obtain $x_{\text{eth}} \simeq 19.65\%$ and $x_{\text{gas}} \simeq 80.35\%$. Carbon, hydrogen and oxygen contents of the blend are then $x_{\text{E10}} \simeq 6.8$, $y_{\text{E10}} \simeq 13.2$ and $z_{\text{E10}} \simeq 0.2$, and so the equivalent chemical composition $\text{C}_{6.8}\text{H}_{13.2}\text{O}_{0.2}$ presented in Table 1.

Nomenclature

Notations

m	Mass, [kg]
$\dot{m}$	Mass flow rate, [kg/s]
M	Molar mass, [kg/mol]
$\dot{n}$	Molar flow rate, [mol/s]
T	Temperature, [$^{\circ}\text{C}$]
w	Mass fraction
x	Molar fraction
x	Carbon content of fuel
X	Volumetric fraction
y	Hydrogen content of fuel
z	Oxygen content of fuel

Greek symbols

α	Nitrogen to oxygen molar fraction in dry air
β	Amount of water produced through combustion reaction for each unit of fuel consumed
ε	Effectiveness of the water recycling system
λ	Air-Fuel equivalence Ratio
ν	Stoichiometric coefficient
ω	Specific humidity
ψ	Exhaust water recirculation self supplying coefficient
ρ	Density, [kg/m ³]

Subscripts

0	Surroundings
air	Dry air
comb	Water produced by combustion
eth	Ethanol
exh	Exhaust gases
fuel	Fuel consumed
gas	Gasoline
inj	Water injection into the engine
liq	Liquid water
recy	Exhaust recycled water
st	Stoichiometric proportions
vap	Water vapour

Acronyms

AFR	Air-Fuel Ratio
CI	Compression Ignited engines
DWI	Direct Water Injection
EWR	Exhaust Water Recirculation
ICE	Internal Combustion Engines
IWI	Indirect Water Injection
SI	Spark Ignited engines

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