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Reduction of NO_x and Soot Emission by Water Injection During Combustion in a Diesel Engine

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The numerical and experimental investigation of NO_x and soot emission reduction by 3 methods of water addition to a Diesel engine has been presented. Of the 3 methods, 2 add water in air and one adds water in fuel. The Water-in-Air methods are valve port injection of water or spraying water continuously into the turbocharger inlet. Experimentally these two methods of water in air are considered. Numerical investigations of the chemical kinetic aspects of the combustion of n-heptane/water mixture are performed assuming the model of concentric shells of a homogenous reactor. However, a simplified turbulent mixing and detailed chemical kinetics have been considered. Thermo chemical data and the detailed chemical kinetics for each shell are computed by the CHEMKIN package of numerical codes.

Keywords: diesel engines, emissions, water injection

INTRODUCTION

Along with the reduction of combustion noise and of nitrogen oxides, the reduction of particle and soot emission is a major goal in developing future contemporary diesel engines [1]. Conventional procedures established to reduce pollutants inside the engine like e.g. exhaust gas recirculation and the variation of the injection time show the effect of a trade-off between the production of soot and of nitrogen oxides. There are several methods that reduce both, soot and NO_x; one of them is the water addition into air (WIA) as done for example by Koketsu et al 1996 [2], Velji, et al 1996 [3]. Another method presented in this paper is water in fuel (WIF). In this WIF case the combustion of two different water emulsions of 10% and 20 % by vol. has been numerically investigated under the constant volume ignition conditions. In contrast to WIA injections, which mainly have a thermal effect on the combustion process, WIF affects the chemistry of the combustion reducing especially soot emission more effectively than in the case of WIA.

Two methods of WIA in diesel engine are presented in this paper. In the first method (WIA1), water is injected periodically into the air stream in the port of the intake valve while in the second case (WIA2) the continual water injection into the rotor of the turbo charger has been performed.

NUMERICAL INVESTIGATIONS

A model of complete chemistry and turbulent mixing is too vast. Usual simplifications are moderately detailed fluid mechanics with simplified chemical kinetics. Here we simplify the turbulent mixing and retain detailed chemical kinetics. Detailed description of the numerical model is given in the Andreatta Thesis [4].

THE SUMARRY OF THE NUMERICAL MODEL

The model divides the flow and reaction field inside the combustion chamber into a series of concentric deformable shells than can be arbitrarily convoluted by convection and turbulence; each shell is modeled as a well-mixed reactor (WMR). Thermo chemical data and the detailed chemical kinetics for each WMR are computed by the CHEMKIN package of numerical codes. Mixing between adjacent reactors is empirically specified.

For a single WMR as shown in Figure 1, the basic differential equations can be derived from conservation of mass, species, and energy, respectively [5]

$$\frac{dm}{dt} = \sum_{i=1}^{N_i} \dot{m}_i - \dot{m}_e \qquad (1)$$

$$\frac{d\xi_s}{dt} = \frac{1}{m}\sum_{i=1}^{N_i} \dot{m}_i (\xi_{is} - \xi_s) + \frac{\dot{\omega}_s W_s}{\rho} \qquad (2)$$

$$\frac{dT}{dt} = \frac{1}{\bar{c}_p m}\sum_{i=1}^{N_i} \dot{m}_i \left[\sum_{s=1}^{N_s} (h_{is} - h_s)\xi_{is}\right] - \sum_{s=1}^{N_s} \frac{\dot{\omega}_s h_s M_s}{\rho \bar{c}_p} - \frac{1}{\rho \bar{c}_p}\frac{dp}{dt} \qquad (3)$$

Since the fluid properties are the same at all exits, the flow at all exits may be lumped together into a single exit flow, even though there may be more than one exit. In the above equation the *dp/dt* term needs to be related to other variables [4].

Figure 1. A well-mixed reactor (WMR) with multiple inlets and a single outlet.

In the multiple reactor case, as shown in Figure 2, the outlets of one reactor become the inlets of the adjacent reactors. If the first reactor were ignited, hot gas would flow into the second reactor, which would soon reach the ignition temperature and ignite. This ignition process repeats itself as the hot gas in the second reactor goes into the third reactor and so forth. By adjusting the mass flow rates between reactors one can vary the mass burn rate to match an engine.

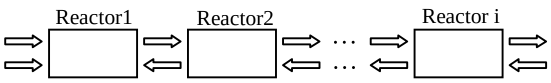

Figure 2. A series of WMR's.

Applying the series of various numbers of WMR's of different size the typical combustion chamber of constant volume ignition conditions can be modeled as shows a conceptual picture of a 12 reactor system in Figure 3.

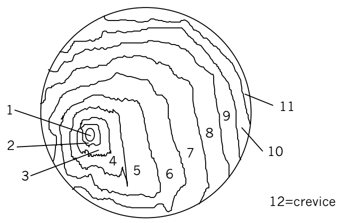

Figure 3. Conceptual picture of typical locations of the reactors.

COMBUSTION SIMULATION IN THE CASE OF WIA

At first the thermal aspects of water injection on the NO_x and soot emission reduction have been investigated. For these calculations a stoichiometric mixture of n-heptane has been applied considering a detailed n-heptane kinetic mechanism including also the corresponding soot and NO_x formation reactions [6]. In this case the first reactor (Figure 3) involves n-heptane only at the 300 K, the other reactors involve the corresponding amount of air with water added during injection process either periodically before intake valve or into the turbocharger. It has been assumed the air and water have been well mixed and to have the temperature about 950 K assuring the auto ignition conditions

Figures 4 and 5 show the overall time dependent temperature profiles; NO_x, OH and soot mass fractions in the combustion chamber for the various amount of water added to the air.

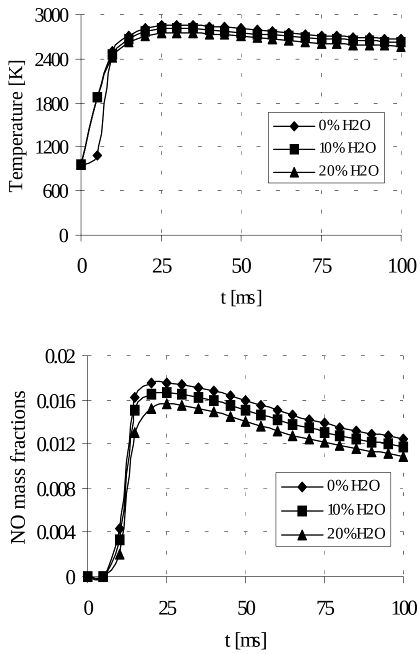

Figure 4. Temperature and NO mass fraction profiles at the water injection

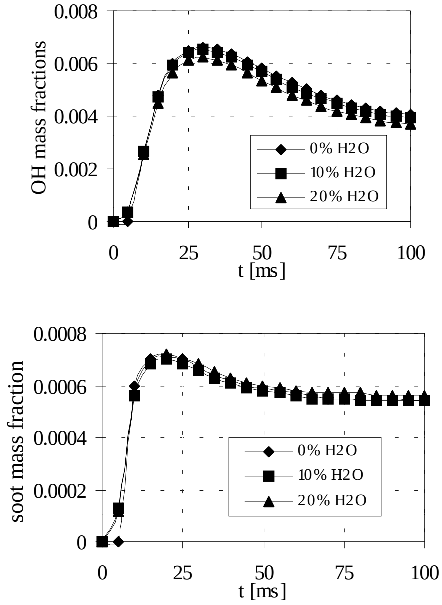

Figure 5. OH and soot mass fraction profiles at the water injection.

From the last diagram in Figure 5 it can be seen the poor effect only of WIA on the soot emission reduction. The detailed chemical kinetics reveals that the WIA reduces of OH radical concentration. The OH radicals play an important role at the soot oxidation, especially at higher temperatures they become the leading oxidators of soot whereas oxygen in its molecular form is consumed by the flame [7]. Numerically obtained overall effect of water injection on NO_x and soot emission reduction is summarized presented in Table 1

Table 1. Reduction of NO and soot emission by WIA.

Variable	10% of H_2O	20% of H_2O
Temperature	2%	4%
NO emission	5%	10%
Soot emission	0%	-3.6% (growth)

COMBUSTION SIMULATION IN THE CASE OF WIF

In this case of the numerical calculations the chemical-physical aspect of water addition to the fuel (n-heptane) has been investigated. The numerical conditions have been the same as in the previous calculation case except the reactors content. The first reactor involves now the mixture of given amount of water and n-heptane. The fuel chemical composition has been theoretically changed on that way resulting in a higher OH production during combustion what finally means less soot emission in the combustion products. Figure 6 shows the overall history of temperature and NO mass fraction in the case of emulsion combustion prepared with 0%, 10%, 20% of water and n-heptane.

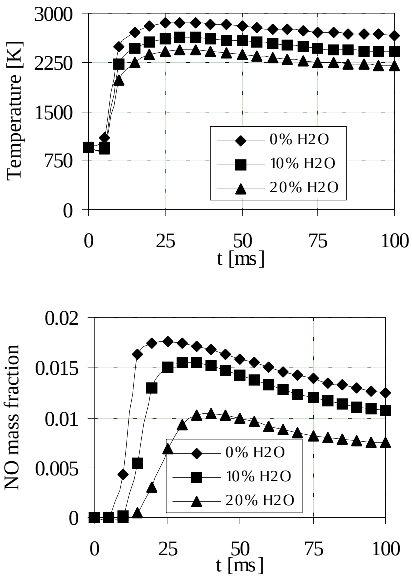

Figure 6. Temperature and NO mass fraction profiles at the combustion of n-heptane/water emulsion.

Much higher temperature drop can be found in this case of fuel/water emulsion combustion than in case of water injection shown in Figure 4. It results also in a higher NO emission abatement. However the OH concentration drop is also much more significant especially because of their consumption during soot oxidation as shown in Figure 7.

Adding some other additives to the fuel instead of water (i.e. H_2O_2) it is possible to produce higher OH concentration resulting in higher soot emission abatement [8]. The overall results of the combustion simulation of fuel/water emulsions are collected in Table 2.

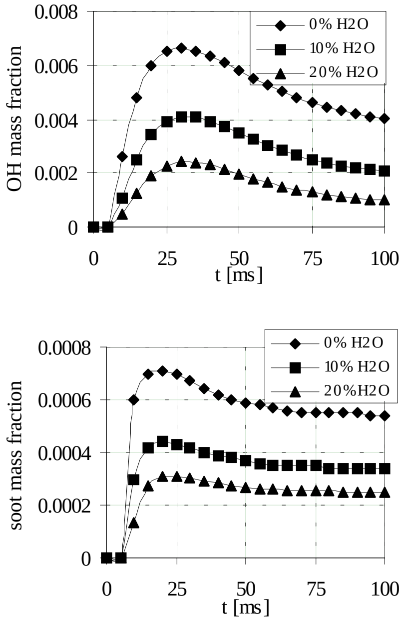

Figure 7. OH and soot mass fraction profiles at the combustion of n-heptane/water emulsion.

Table 2. Reduction of NO and soot emission at the combustion of n-heptane/water emulsion.

Variable	Emulsion with 10% of H_2O	Emulsion with 20% of H_2O
Temperature	10%	15%
NO emission	15%	35%
soot emission	35%	60%

EXPERIMENT

In order to study the influences of the water injection on exhaust emission a four-cylinder air cooled DI diesel engine has been employed with the specifications given in Table 3.

Table 3. Test-engine specifications.

Model	TAM F4L 515FRC	Compression ratio	18:1
Capacity	7118 cm^3	Valve	8
Max. Power	150 kW	Injection pump	Bosch PES 4
Max. Torque	315 Nm	Turbo-charger	Holset H1E

Test engine has been equipped with the special setup to make possible the corresponding experiments of water injection.

THE FIRST METHOD OF WIA

The injection of water with the first method has been carried out by setup shown in figure 8, which allows adjusting a free ratio between air and water.

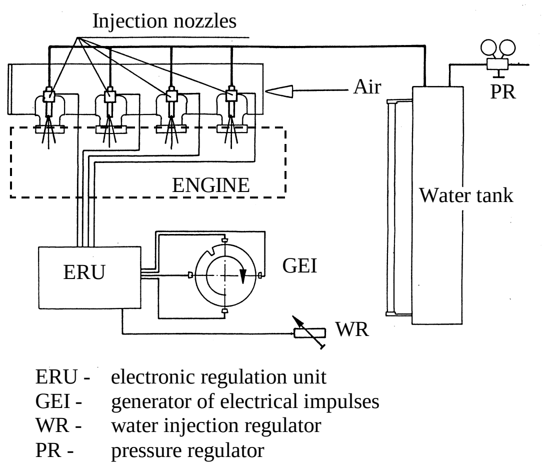

Figure 8. The first system of WIA – WS1.

The amount of water injected into air stream depends on injection pressure, which can be adjusted by regulation the pressure in water tank and applying the electronic pressure regulator for the fine regulation. The water injection starts 20 ^{o}CA after TDC during the suction stroke and ends when the intake valve is closed. The position of water injection nozzles is shown in Figure 9.

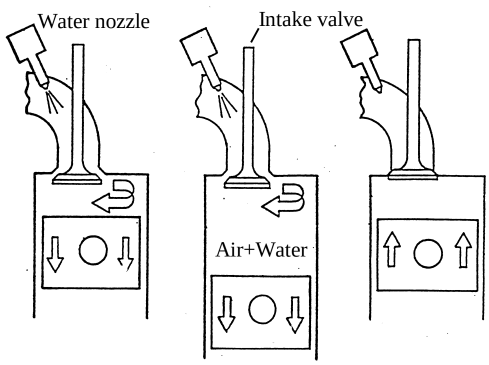

Figure 9. The position of water injection nozzle.

THE SECOND METHOD OF WIA – WS2

In this case water has been injected continuously into the turbocharger as shown in Figure 10

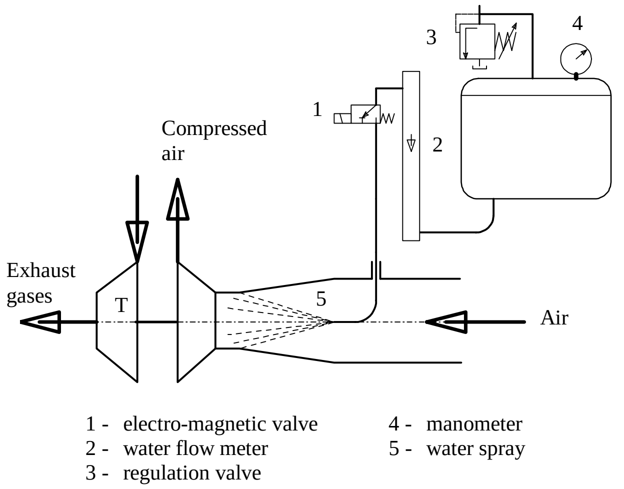

Figure 10. The second system of WIA – WS2.

The great advantage of this water injection system is in the construction simplicity in comparison with the multipoint injection system presented before and others [9]. It represents a real cost effective solution of the water injection devices for turbocharged diesel engines to reduce especially NO_x emission and thermal loading.

RESULTS

The effect of both water injection systems (WIS1 or WIS2) on the NO_x emission reduction has been practically the same. Except the influences on the engine thermal loading where the second system has given better results as shown in Figure 11 for different water/fuel (W/F) ratios at the given engine operation conditions on the maximum power at 2150 min^{-1}. Figure 12 show the NO_x emission reduction obtained by either first or second water injection system for the engine operating conditions at 1300 min^{-1} and different loading expressed in mean effective pressure p_e. Figure 13 show the soot emission expressed in Bosch units also for different W/F ratios and the given engine operating conditions at the maximum torque, where exist the most convenient conditions for soot formation. It has been found out the minor influence of water injection on soot reduction what is in good agreement with the numerical investigations. However, in this case of experimental investigations we could not make the experiments using fuel/water emulsions.

CONCLUSIONS

The numerical and experimental investigations of water injection to reduce NO and soot emission in diesel engine have been presented. Although there are a lot of water injection systems developed already it has to be noted each of them affects on its own way to the pollutant emission reduction depending strongly on the engine type and its operating condition. However two different water injection systems have been presented in this paper. Both of them showed practically the same influence on the NO emission reduction and poor effect on the soot emission reduction what is in a good agreement with numerical investigations performed on the base of detailed chemical mechanism of n-heptane. Regarding engine thermal loading better results have been obtained applying the second water injection system.

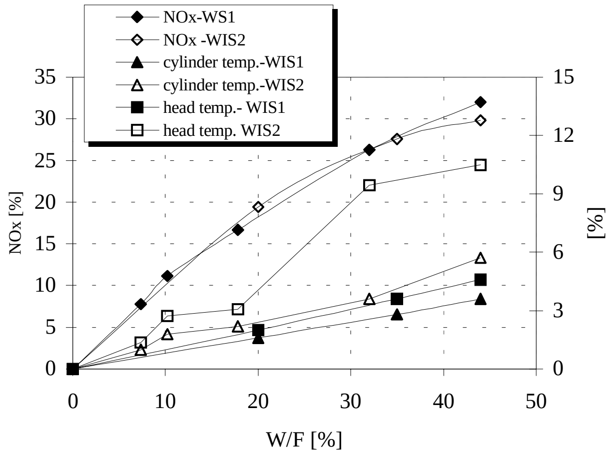

Figure 11. NO_x emission and thermal loading reduction by two different water injection systems at the maximum power engine operating conditions at 2150 min^{-1}.

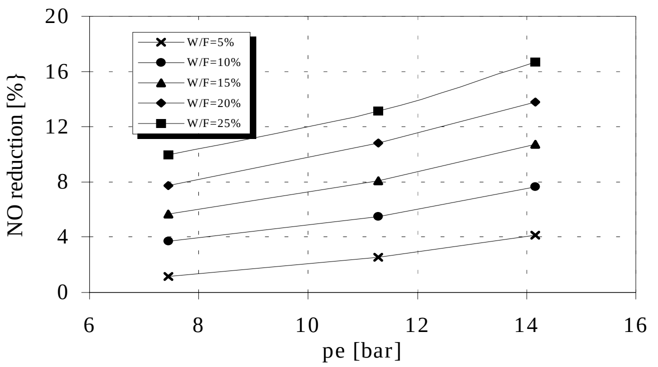

Figure 12. NO reduction for various W/F ratio.

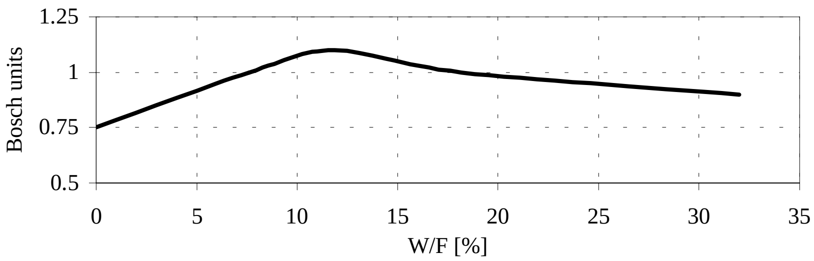

Figure 13.The influence of water injection on soot emission.

NIMENCLATURE

m	mass inside of reactor
$\dot{m}_i$	mass flow rate into reactor at inlet *i*
$\dot{m}_e$	total mass flow rate out of the reactor
N_i	number of inlets, ξ_s - mass fraction of species
ξ_{is}	mass fraction of species *s* at inlet *i*
N_s	number of chemical species
$\dot{\omega}_s$	production rate of species s (calculated using CHEMKIN)
M_s	molecular mass of species *s*
ρ	mass density in the reactor
T	temperature
$\bar{c}_p$	mean specific heat at constant pressure in the reactor
p	pressure.

t time

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