37th INTERNATIONAL SYMPOSIUM ON COMBUSTION – Dublin, Ireland: 29 July – 3 August 2018

Simulation of Spark-Ignited Engines with Water Injection using the Stochastic Reactor Model

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Introduction

Water injection is investigated for turbocharged spark ignition (SI) engines to limit knock probability and therefore enable higher engine efficiency [1, 2]. This work presents an integrated simulation-based optimization process to assess port water injection. The fast running quasi-dimensional (QD) stochastic reactor model (SRM) is coupled with tabulated chemistry to account for water effects on laminar flame speed and combustion chemistry. The physics-based QD SRM accounts for the mixture and temperature in-homogeneities within the cylinder [3-5]. This approach allows to predict local effects of fuel composition on flame propagation, auto-ignition and emission formation. The detailed chemistry for multi-component surrogates used in this work is based on the methodology of reaction mechanism development and reduction introduced by Seidel [6]. To reduce the computational cost of the QD SRM simulations the reaction-progress-variable-based tabulation strategy of Matrisciano et al. is applied [7].

Simulation Process and Tabulated Chemistry

In the engine development process, the prototype engine and its base calibration must be tested for many operating conditions. Therefore, an integrated process based on detailed 3D CFD models, fast running two-zone QD SRM and multi-objective optimization tools can be incorporated (see Figure 1) [8, 9].

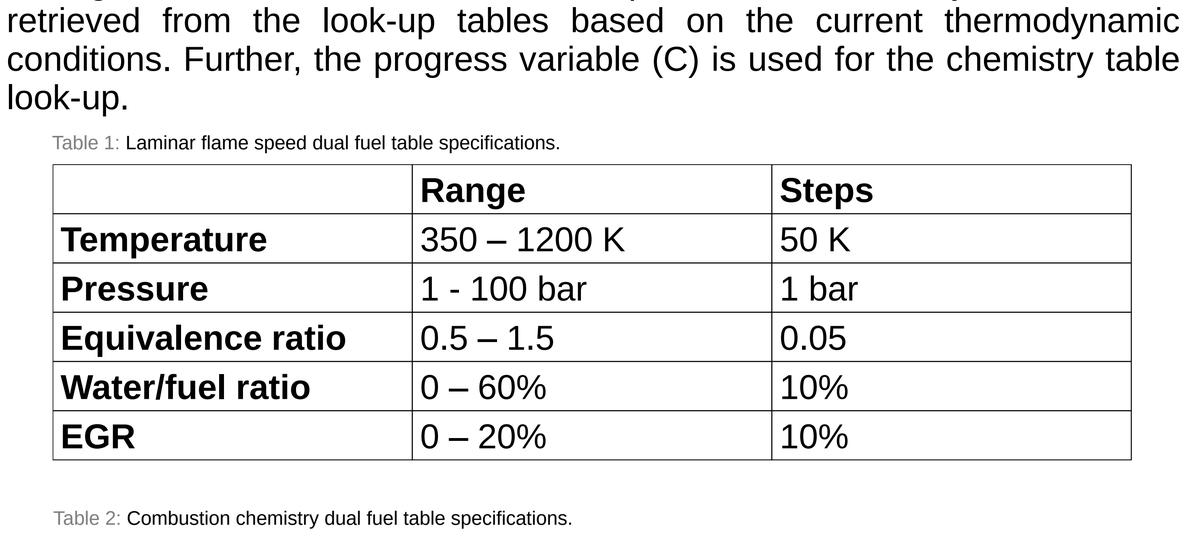

Figure 1: QD SRM and 3D CFD integrated simulation-based optimization process with detailed chemistry.

The laminar flame speeds and the combustion chemistry are stored in pre-compiled look-up tables (see table ranges in Table 1 and Table 2). A dual fuel approach for an Ethanol Toluene Reference Fuel (ETRF; Ethanol, Toluene, iso-Octane, n-Heptane) surrogate and water is used. The first stream is composed of 5.3% Ethanol, 49.2% iso-Octane, 9.1% n-Heptane and 36.4% Toluene in mass percent. The second stream is composed of 100% water. During the simulation laminar flame speeds and chemistry sources are retrieved from the look-up tables based on the current thermodynamic conditions. Further, the progress variable (C) is used for the chemistry table look-up.

Table 1: Laminar flame speed dual fuel table specifications.

	Range	Steps
Temperature	350 – 1200 K	50 K
Pressure	1 - 100 bar	1 bar
Equivalence ratio	0.5 – 1.5	0.05
Water/fuel ratio	0 – 60%	10%
EGR	0 – 20%	10%

Table 2: Combustion chemistry dual fuel table specifications.

	Range	Steps
Temperature	250 – 1400 K	25 K
Pressure	1 - 200 bar	2.5 bar
Equivalence ratio	0.2 – 4.0	0.2
Water/fuel ratio	0 – 40%	10%
EGR	0 – 30%	10%

Numerical Test Case

The QD SRM calibration and validation results for cylinder pressure, heat release rate and exhaust emissions (CO_2, H_2O, CO and NO_x) compared to 3D CFD are shown in Figure 2 [10].

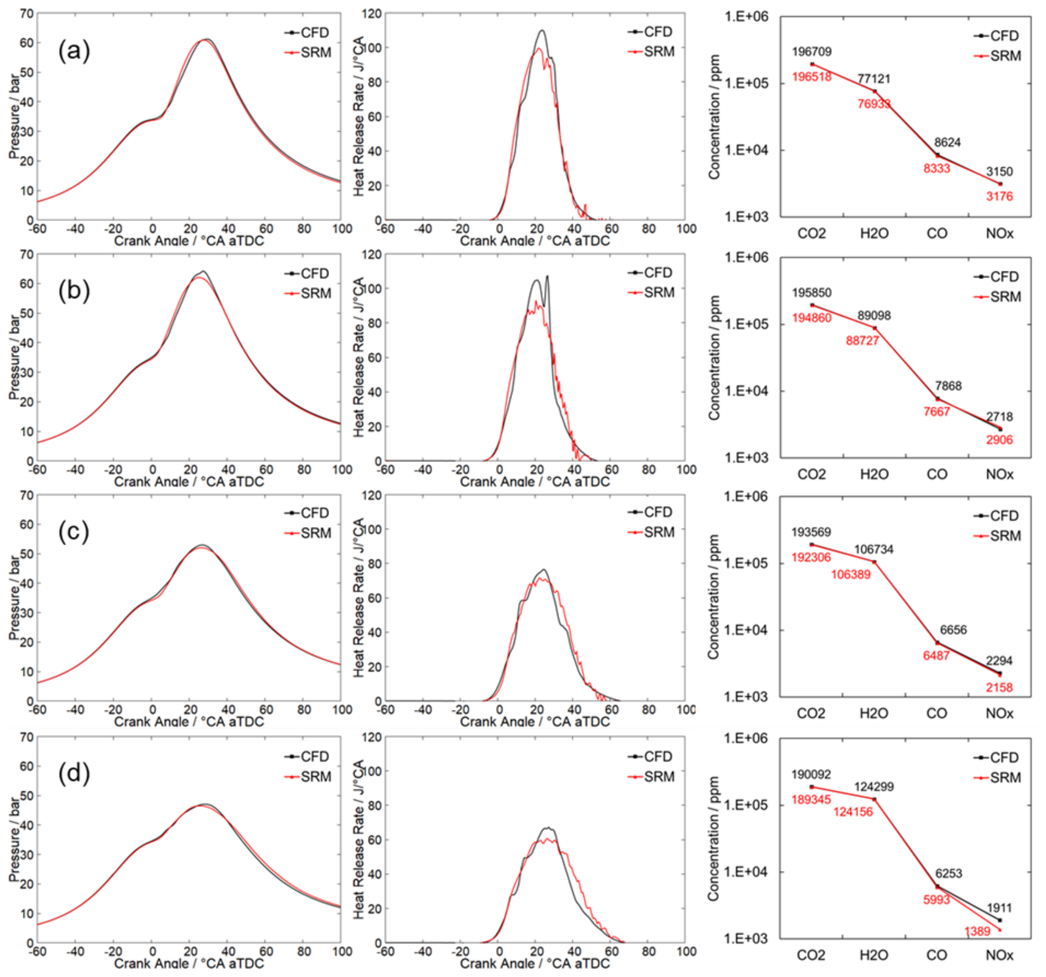

Figure 2: 3D CFD and QD SRM with detailed chemistry - training results for case (a) with 0% w/f ratio and 16.2bar IMEP and the validation results for the cases (b) with 20% w/f ratio and 16.2bar IMEP, (c) with 50% w/f ratio and 15bar IMEP and (d) with 80% w/f ratio and 14.1bar IMEP.

Multi-Objective Optimization with QD SRM

In Figure 3 and 4 the average engine parameters of Cluster-1 and Cluster-2 are compared to the base engine parameters. On the one hand, to reduce fuel mass, one must increase compression ratio, decrease pressure at IVC and shift spark timing to earlier crank angles (light grey line). On the other hand, to reduce knock probability, one must limit compression ratio and retard spark timing (dark grey line). Both clusters share a similar water fuel ratio of 25% to 30%. This finding shows that a high w/f ratio is beneficial for low fuel mass and low knock probability at the same time.

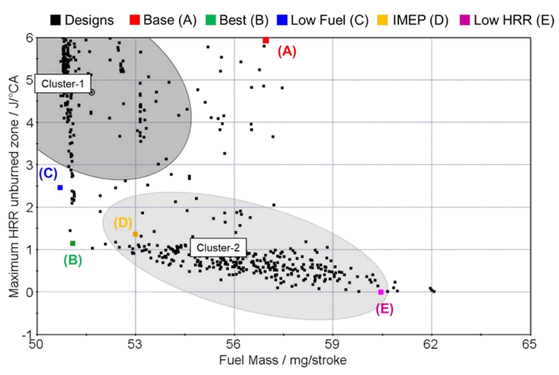

Figure 3: QD SRM optimization results with tabulated chemistry. The dark and light grey colored ellipses highlight clusters of designs sharing similar sets of engine parameters.

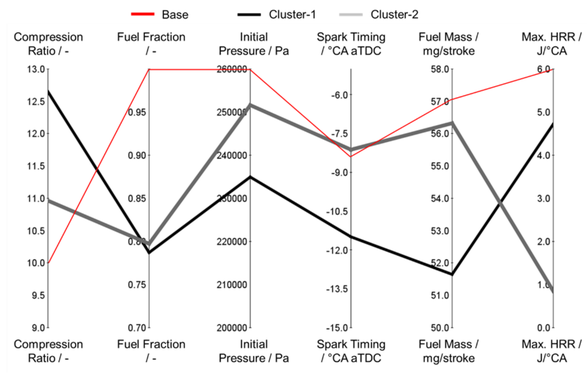

Figure 4: QD SRM optimization results with tabulated chemistry. The red line shows the base engine parameter values. The black and grey colored lines highlight the average engine parameter values for Cluster-1 and Cluster-2.

Conclusions

The general knowledge from SI engine development could be confirmed by the QD SRM optimization. The reduction of fuel consumption is favored by increased compression ratio and earlier spark timing. In contrast, the lower knock probability is influenced by low compression ratios and later spark timings. The presence of water is beneficial for reducing fuel consumption and knock probability at the same time. An optimum w/f ratio in the range of 25% to 30% is found for this operating condition.

Acknowledgments

The presented work is carried out within the FVV research project 1256 “Water Injection in SI Engines”. The authors gratefully acknowledge the support received from the Research Association for Combustion Engines (FVV) eV and from all project participants.

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