Synthesis – PhD Thesis – Salvatore Roggio

Nowadays, for the diesel engine-based powertrains, the increasingly demanding CO_2 legislative targets and the need to comply with real-driving emission standards, are pushing toward an unprecedent technological innovation. In this scenario, the optimization of the combustion system can strongly minimize fuel consumption and emissions, while limiting the incremental cost due to the adoption of advanced aftertreatment systems. Regarding diesel engine, the design of the piston bowl has shown a strong impact on the air/fuel mixing process, enabling higher EGR tolerance for better soot-NOx trade-off.

During the early stages of the optimization process, the simulation codes have been assuming remarkable importance, providing a virtual test rig for the preliminary assessment of the best concept, while reducing the time and cost of the experimental tests. With this aim, a synergetic approach based on both 3D-CFD simulations and experimental tests was developed. Regarding the simulation methodology, an integrated and automated 1D-/3D-CFD coupling code was adopted. This approach featured a calibrated spray model and the SAGE chemical kinetic solver coupled with a detailed soot PM model for the in-cylinder soot mass prediction.

Thanks to the developed numerical model, the performances of different piston bowl designs for 1.6L diesel engine were investigated. Firstly, the numerical model was validated against the experimental tests that were carried out on a Single Cylinder Engine (SCE) for the baseline re-entrant bowl, showing great accuracy both in terms of combustion and emissions. Then, two innovative piston bowl designs were investigated: a stepped-lip and a radial-bumps designs. In the stepped-lip design the protruding lip used for the baseline re-entrant bowl was replaced by a tapered lip, where the fuel injection split can improve the air utilization in the squish region. For the radial-bumps bowl, a number of radial bumps equal to injector nozzle holes was added in the outer bowl rim, aiming to mitigate the flame-to-flame interaction. These innovative designs showed an improved air/fuel mixing process, significantly reducing the fuel consumption and the engine-out soot emissions under full load and partial load engine operating conditions. Moreover, a sensitivity analysis over different engine calibration parameters showed that no further recalibration was needed with respect to the baseline calibration of the re-entrant bowl.

Once investigated the stepped-lip and the radial bumps designs, a further step in the optimization process was carried out. With this aim, to assess the potential of a synergy between these two pistons, a hybrid piston was designed. It combined a highly-reentrant sharp-stepped bowl and a number of radial bumps in the inner bowl rim equal to the injector nozzle holes. The hybrid piston was preliminary investigated through numerical simulations. Then, the numerical results were compared with the experimental data coming from an optical access engine. In this activity, the Combustion Image Velocimetry (CIV) and the OH* chemiluminescence techniques were used for the flame characterization. Then, the 2-color pyrometry KL data were considered for the soot analysis. For the direct comparison of the numerical and experimental data, a numerical methodology was developed, providing an equivalent KL in the 3D-CFD environment. Regarding the numerical analysis, the hybrid bowl has shown a strong improvement of the air/fuel mixing. This resulted in a great soot reduction potential without any fuel consumption penalties. The numerical flame evolution and the in-cylinder soot distribution showed a good agreement with the optical data. This suggested the extension of the phenomena observed in the optical engine even under the real metal engine operating conditions. Finally, the results of the analysis were compared with experimental data of a SCE based on similar engine architecture. The experimental tests confirmed the great soot reduction potential of the hybrid bowl with respect to the conventional re-entrant bowl, while keeping comparable efficiency and NOx levels.