Ducted Fuel Injection: a mixing enhancement strategy to abate soot emissions in compression-ignition engines

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Abstract

The compression-ignition (CI) engine powered by diesel fuel, also known as *Diesel engine*, is a leader technology in freight road transportation and shipping sectors, and will remain so for the next decades. This technology is based on the peculiar diesel combustion process, in which the injected high-reactivity fuel in a high-pressure-temperature environment spontaneously ignites at locally fuel-rich composition, thus leading to the formation of uncomplete combustion products such as soot (or *black carbon*). For this reason, diesel engines are today among the major anthropogenic emission sources of soot, which is toxic for the human health and a major short-lived climate forcer. Therefore, it is of paramount importance pushing nowadays research for a low-soot diesel combustion process. For this purpose, strategies that can reduce the fuel-to-air ratio composition before the auto-ignition region (or lift-off length, LOL) have been widely studied and, among them, one of the most promising is the ducted fuel injection (DFI) concept, patented by Sandia National Laboratories few years ago. DFI is based on injecting fuel down the axis of a small cylindrical pipe in the combustion chamber, placed at a small distance from the injector orifice exit, in order to improve the mixture quality at the LOL. In the scientific literature, there is experimental evidence that DFI can abate soot formation in both constant-volume and CI engine conditions. However, although several studies have focused on DFI from both a fundamental physics-based and an implementation-based point of views, a key knowledge gap is still present regarding the understanding of its working principles, the impact of duct design and operating conditions, and the real feasibility of its integration on series-production engines working on the whole operating map. In light of this, the present PhD work aims to contribute in bridging the open knowledge gap towards the complete success of this new concept.

Thanks to a collaboration with *Università degli Studi di Perugia*, an extensive experimental campaign has been carried out to collect data related to both free and ducted sprays under several non-reacting constant-volume conditions, considering a single-hole injector configuration which can be relevant for heavy-duty applications. The experimental data have been then exploited to develop a high-fidelity 3-dimensional computational fluid dynamics (3D-CFD) virtual test rig for the investigation of DFI concept. In particular, large eddy simulations

coupled with statistical analysis were primarily used to obtain a robust knowledge on DFI working mechanisms under non-reacting conditions, such as entrainment and turbulent mixing enhancement. This high-fidelity (¿80% resolved turbulent structures) dataset was then used as a target to assess a RANS model for the same case study, in order to extend the number of analyses at an affordable computational cost. The RANS model has proven reliability, at least in terms of major trends, thus a further step was the integration of combustion and emissions models, based on detailed chemistry solver and detailed soot modelling. Combustion simulations provided robust results, in line with the available data from the literature. After that, the validated RANS combustion model was used for understanding the impact of the main duct geometrical features, figuring out an optimal duct design, and engine parameters, defining preliminary DFI-oriented calibration requirements.

Finally, in collaboration with *PUNCH Torino S.p.A.*, the potential benefits coming from DFI implementation on a series-production diesel engine for light duty applications were explored, firstly, through 3D-CFD simulations, secondly, through optical engine analyses. Even though DFI capability to reduce soot formation was confirmed, some criticalities were observed regarding soot oxidation, highlighting the need for combustion system optimization and engine calibration.