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# Design of innovative solutions for high-pressure fuel injection systems, optimization of measuring techniques for injected flow-rate and modeling of 1D flows


By

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# Abstract


In order to mitigate the engine emissions as well as the manufacture costs, the common rail injection system, which is generally fed with diesel, have been diffused and applied to all types of road cars. Over the years, more and more injection shots over one engine cycle and types of irregular injection rates have been realized by means of such a device. Meanwhile, some complex designs of layouts and of control strategies have been developed to achieve certain specific functions. Whereas, further improvements in this system, in the related flowmeters as well as in the mathematical models can be still applicable.

The current study is focused on the experimental and mathematical analyses of the injection rate flowmeters and of the injection systems. Structural optimizations have been applied to both instruments, and an innovative control strategy for the injection system has been developed and experimentally investigated. Finally, the polytropic process has been adopted to analytically and numerically interpret the classic viscous adiabatic flow analytical model in a constant cross section duct.

The injection rate of a common rail injector has been evaluated by means of both Bosch and Zeuch method-based flowmeters. A slight decline of the slope in the rate rising phase, an anomalous tail at the end of an injection event and a delay in the entire injected flow-rate trace have been found in the result obtained through Bosch method. A 1D numericial model of the hydraulic circuit, pertaining to the flowmeter that applies Bosch method, has been developed. The cause and effect relationship between the design and the measured flow-rate has been then investigated, and the design keys of the Bosch method-based flowmeters have been provided.

With respect to the injection system layout, in order to simplify the installation and to reduce the production cost, the Common-Feeding (CF) system has been designed and has been manufactured for a light-duty commercial vehicle diesel engine. In the CF instrument, a delivery chamber of approximately

10 $cm^3$ is integrated at the outlet of the high-pressure pump, and the other side is connected to the injectors with the tubes. The experimental tests in terms of single and double injections have been performed at the hydraulic rig to compare the performance of the prototypal CF instrument with that of the standard common rail system equipped with different rail volumes. The testing results prove that the general performance of the CR systems, even though the rails feature different volumes, and that of the CF system are analogous. The primary difference, which is a change of the slope, occurs at the rising phase of the injection rate. Moreover, the cycle-to-cycle dispersion of the injected mass ascends to certain degree, as the accumulator (the rail or the delivery chamber at the pump outlet) size reduces. In addition, the variation in the free wave frequency after the injection event can be ascribed to the modification of the accumulator shape.

As far as the rate-shaping strategies are concerned, an injection system equipped with solenoid injectors have been experimentally tested. The cycle-to-cycle dispersion in the injected mass evidently rises in the regime of closely-coupled injections. Meanwhile, the overall injected mass increases sharply as the dwell time reduces. Whereas, when the dwell time is further reduced within the injection fusion range, the cycle-to-cycle dispersion again improves, and such a phenomenon confirms that it is applicable to apply the continuous rate-shaping strategy to solenoid injectors. A 1D numerical model of the hydraulic circuit of the injection system with solenoid injectors has been developed and validated. The parametric analyses on the injector setups, such as the mechanical, the electromagnetic and the hydraulic parameters, have been carried out to examine their influences on the rate-shaping injection patterns. In addition, two state-of-the-art solenoid injectors, featuring different hydraulic layouts, have been tested and compared in terms of closely-coupled injections, and the results provided by the numerical model have been verified.

Besides, an innovative closed-loop control strategy of injected mass has been developed. The pressure time histories measured at the rail-to-injector tube have been captured to calculate the instantaneous mass flow-rate entering the injector through two different methods. The first method uses the mean instantaneous frequency of the pressure trace to obtain the key time instants of injector dynamics. The hydraulic performance data experimentally acquired have been then employed to correlate those timings with the injected mass.

The second method directly applies the physical laws of fluid dynamics. The derived flow-rate has been afterwards integrated, and has been correlated well with the injected mass. A prototypal hardware, based on the second calculation method, has been realized in order to control the injected mass in a closed-loop. Such a system is capable to significantly improve the accuracy of the injected mass within different thermal regimes. In addition, under steady states, as a mean injected mass of 45 mg per engine cycle is applied, the error of the effective injected mass was below 1 mg for single injections and is within 2 mg for pilot-main injections. The dynamic response to the transients of either a step or a ramp in the rail pressure and in the injected mass was as well improved significantly.

Finally, as regards the viscous adiabatic flow model, by eliminating the steady flow energy equation and by following a polytropic process, the compressible flow in constant-area ducts with friction has been analytically expressed. Under the identical boundary conditions, the comparison between flow properties pertaining to the new method and those of the classic analysis have been as well performed. The results show that following the polytropic method, although flow properties are capable to lead to the analogous values at both the extremities of the pipe as the classic method results for not choked cases, they follow different routes. In addition, in order to improve the accuracy of the computed flow properties obtained through the polytropic method, a practical numerical method has been introduced. The polytropic exponents obtained piece by piece along the duct following the classic analysis has been thus applied to the corresponding nodes of the code, and the final numerical results by following the polytropic method are approximately identical to those of the classic method.

**Keywords:** common rail, flowmeter, Bosch method, Zeuch method, Common-Feeding, injector setup, rate-shaping, closed-loop, Fanno flow, polytropic.