Applied Energy 151 (2015) 367–376

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The new-generation of solenoid injectors equipped with pressure-balanced pilot valves for energy saving and dynamic response improvement

Alessandro Ferrari *, Federica Paolicelli, Pietro Pizzo

Energy Department, Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino 10129, Italy

HIGHLIGHTS

- Distinct pilot-valve setups, typical of modern Common Rail injectors, are compared.
- The analysis focuses on injector static leakages and the injector dynamic response.
- Experimental results are integrated or explained by means of simulation data.

ARTICLE INFO

Article history:
Received 1 August 2014
Received in revised form 23 February 2015
Accepted 16 March 2015
Available online 15 May 2015

Keywords:
Fuel injection systems
Solenoid injector
Pressure balanced pilot-valve

ABSTRACT

A numerical–experimental analysis on a new generation of hydraulically controlled servo solenoid injectors for Euro 6 Diesel engine applications has been carried out. The main innovation of these high-pressure injectors is the replacement of the standard pilot-valve configuration with a pressure-balanced layout. The new setup is aimed at reducing clearance leakages and at improving the dynamic response of the needle to the electrical command.

A previously developed advanced one-dimensional code for the simulation of Common Rail injection systems has been adapted to simulate the innovative injectors. In particular, electromagnetic, hydraulic and mechanical submodels have been set up for the pressure-balanced pilot-valve simulation.

The validated numerical model of the injector has been applied to investigate the mechanics of the pressure-balanced pilot-valve and the sensitivity of the dynamic response of the needle to some of the innovative pilot-valve layout design parameters. Furthermore, the developed simulation tool has been used to examine the real impact that the replacement of the standard pilot-valve layout with a pressure-balanced one could have on the injected flow-rate performance.

The comparative investigation between the standard and the innovative pilot-valve has been completed with an analysis of their experimental static leakages. A comparison has also been made with static leakages measured for hydraulically-controlled servo piezoelectric injectors. Finally, a simple and accurate thermodynamic flow model has been developed to predict static leakages in indirect-acting solenoid and piezoelectric injectors. This model has pointed out the significant dependence of static leakages on temperature and pressure.

1. Introduction

Diesel injection systems are required to realize high fuel metering accuracy and provide elevated injection pressure to meet the strict pollutant emission and fuel consumption regulations currently in force, while ensuring high engine performance and fun to drive [1–3].

Injector performance is a key-factor to meet these demands. In the last few years, many investigations, carried out on hydraulically controlled (or indirect-acting) servo injectors, have been aimed at the optimization of pilot-valve performance [4].

Since the high-pressure pump has to deliver more fuel than the sum of the injected quantities, efforts have been made to reduce the static leakages that occur through the pilot-valve, thus saving on power losses [5]. A high-pressure pump driving power of more than 1 kW can be induced by injector static leakages for a 4-cylinder engine running under a nominal rail pressure close to 2000 bar.

* Corresponding author. Tel.: +39 0110904426; fax: +39 0110904599.
E-mail address: alessandro.ferrari@polito.it (A. Ferrari).

http://dx.doi.org/10.1016/j.apenergy.2015.03.074
0306-2619/

Nomenclature

A	geometrical area
c_p	specific heat at constant pressure
CR	Common Rail
d	diameter in the standard pilot-valve
d_1, d_2	diameters in the pressure-balanced pilot valve
ET	energizing time
F_m	magnetic force
F_p	net axial fuel pressure force on the pilot-valve
F_r	radial pressure force on the armature
F_{sp}	spring preload acting on the pilot-valve
G	injected mass flow-rate
h	fuel enthalpy
I	electrical current
K	pilot-valve geometrical factor
k	spring stiffness
L	length of the leakage path between the armature and the fixed rod
L_{cp}	length of the leakage path between the control piston and its sleeve
m	mass
$\dot{m}_{leak}$	static leakage mass flow-rate
N	number of windings in the solenoid
NOD	nozzle opening delay
NCD	nozzle closing delay
p	fuel pressure
$\bar{p}$	average pressure of the fuel
p_{cc}	control chamber pressure
p_{tank}	pressure level in the tank (1 bar)
r	radial coordinate in the leakage path
r_{cp}	radius of the control piston
$\mathrm{r}_{\mathrm{rod}}$	radius of the fixed rod
R	solenoid resistance
S	contact surface of the armature and valve seat
S'	balanced surface of the pressure action (pilot valve)
S_p	net surface of the pressure action (pilot valve)
s	radial thickness of surface S_p
t	time
t_o	initial time instant in the simulation tests
$\overline{T}$	average fuel temperature
T	fuel temperature
u_r	radial velocity of the fuel in the leakage path
V	voltage signal; fuel volume
x_n	needle lift
x_{pv}	pilot-valve displacement
α	angle of the ball valve seat
β	damping coefficient, thermal expansivity
δ	equivalent axial clearance between the armature and valve seat
ε	radial clearance between the armature and the fixed rod
$\varepsilon_{\mathrm{cp}}$	radial clearance between the control piston and its sleeve
ν	kinematic viscosity of the fuel
μ	discharge coefficient
μ_0	magnetic constant
$\Re$	magnetic reluctance
ρ	density of the fuel
Σ_1, Σ_2	cross sections of the magnetic circuit
Φ	magnetic flux

Subscripts

bs	basement
cc	control chamber
$disch$	at the pilot valve discharge
I	injection
$leak$	static leakage
M	maximum
nom	nominal
pv	pilot-valve
ref	reference value used to normalize data
sp	spring

These pressure levels can occur in the low end torque area or at rated power conditions [6]. In general, it has been shown that, thanks to the injector clearance leakage reduction (injector clearance leakages include pilot-valve static leakage, static leakage at the sliding control piston and static leakage at the sliding needle), about a 1% fuel consumption diminution is possible for both passenger car and heavy duty applications over the whole map area [7].

In addition to fuel consumption benefits, the reduction in the injector clearance leakages leads to an improved idle start and stop functionality. In fact, the pressure can easily be maintained in the rail for several minutes after the engine stops, and the fuel for the injectors becomes available directly from the rail for the next startup. Furthermore, the increase in injector clearance leakages can augment the risk of fuel deterioration, due to the high local temperatures in the fuel return lines [6]. Finally, a control of injector leakages is mandatory in order to increase the maximum pressure level beyond 2000 bar [7].

Direct-acting piezoelectric injectors are characterized by very reduced fuel leakages, due to the absence of a pilot-valve [8,9]. Even indirect-acting piezoelectric injectors are claimed to have lower static leakages than solenoid injectors [10], since the pressure force in piezoelectric injectors tends to close the pilot-valve. However, the increased costs of piezo technology and the high robustness and long lifetimes of the solenoid systems justify the attempts that have been made by manufacturers to design innovative solenoid injector pilot-valve setups with a faster dynamic response and reduced fuel leakages [10,11]. The pressure-balanced pilot-valve, which has been introduced recently into solenoid injectors [12], is an effective way of accomplishing these objectives in terms of reduced fuel static leakage and multiple injection control. Different injection apparatus suppliers, such as Denso [6], Delphi [13] and Bosch [12], have recently proposed new generation solenoid injectors with pressure-balanced pilot valve layouts. However, there is still a lack of data and analyses in the scientific literature about this innovative typology of injectors.

In the present work, the performance of a pressure-balanced pilot-valve has been examined by means of an integrated numerical–experimental approach. The static leakage of solenoid injectors, featuring pressure balanced pilot valves, has been measured and compared with that of both standard indirect-acting solenoid injectors and indirect-acting piezoelectric injectors. The numerical investigation of the innovative pilot-valve setup has been conducted with the support of a one-dimensional advanced model of the new solenoid *CR* injector. The analysis has focused on the most important geometrical characteristics of the pilot-valve and on the effects that modifications of some relevant design parameters of the pressure-balanced pilot valve could have on injector performance.

2. Experimental setup

The experimental campaign has been conducted on the Moehwald-Bosch hydraulic test bench installed at the ICEAL laboratory at the Politecnico di Torino [14]. The test rig is equipped