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Large Eddy Simulation of Diesel injector including cavitation effects and correlation to erosion damage

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ABSTRACT

The present paper focuses on erosion development due to cavitation inside Diesel injectors. Two similar injector designs are discussed both in terms of numerical simulation and experimental results from X-ray CT scans. In order to capture the complex flow field and cavitation structures forming in the injector, Large Eddy Simulation along with a two phase homogenous mixture model were employed and compressibility of the liquid was included as well. During the simulation, pressure peaks have been found in areas of vapour collapse, with magnitude beyond 4000 bar, which is higher than the yield stress of common materials employed in the manufacturing of such injectors. The locations of such pressure peaks correspond well with the actual erosion locations as found from X-ray scans. The present work is the first to correlate pressure peaks due to vapour collapse with erosion development in industrial injectors with moving needle including comparison with experiments.

1. Introduction

Diesel injection systems play a fundamental role in internal combustion engines since they affect the formation of the fuel spray, atomization and combustion, the formed emissions and the engine efficiency. The jet velocities formed are of the order of 500 m/s, with upstream pressures around 2000 bar. Current trends show injection pressures to even rise to 3000 bar, in order to meet the future EU legislations in emissions. However, higher pressure levels causes very high velocities through the tight passages in the Diesel injector and strong accelerations in sharp direction changes (corners, fillets etc.), which lead to static pressure dropping locally below the saturation pressure and causing cavitation. Furthermore, cavitation may lead to erosion damage and serious degradation of the injector performance, even catastrophic injector failure, which could damage the engine, if the injector tip breaks off.

Various researchers have worked on the subject of cavitation development inside Diesel injectors under varying assumptions; Sezal et al. worked on simple 2D axis-symmetric nozzles [1] and 3D nozzles [1,2] with a fully compressible approach, capable of predicting cavitation collapse pressure peaks that could be linked to cavitation erosion. Salvador et al. have done extensive work on Diesel injector cavitation, starting from validation studies [3], examining various geometrical features [4] and needle lift influence [5] on the flow pattern inside the injector. In continuation of the aforementioned work, Molina et al. [6] examined the influence of elliptical orifices on cavitation formation and Salvador et al. [7] performed LES studies in Diesel injector nozzles using OpenFOAM. However all the aforementioned literature work did not involve needle motion; instead needle was fixed either at full or partial lift. A recent numerical work by Örley et al. [8] on Diesel injectors involves the immersed boundary method, needle motion, compressibility of liquid, vapour and free gas, though the focus is mainly on the developed turbulent structures and less on pressure peak/erosion development.

On the other hand, several works have included the needle motion for the prediction of flow pattern inside the injector, however either resorted to using RANS or omitted compressibility effects. For example Patouna [9] focused on the simulation of injectors at steady or moving needle conditions, however the liquid was assumed incompressible and there was no effort to correlate with possible erosion development. Strotos et al. [10] studied the thermodynamic effects of Diesel fuel heating/cooling inside the Diesel injectors at both steady and moving needle conditions, with main interest on next-generation injectors that could reach up to discharge pressures of 3000 bar. Devassy et al. [11] implemented a 1D-3D coupling for Diesel injector simulations throughout the

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Nomenclature

D_{in}	orifice entrance diameter (m)	$\mathbf{u}$	velocity field
D_{out}	orifice exit diameter (m)	R_e	evaporation rate (kg/m^3/s)
p	pressure (Pa)	R_c	condensation rate (kg/m^3/s)
B	bulk modulus (Pa)	μ_V	vapour dynamic viscosity (Pa s)
ρ	density (kg/m^3)	R	bubble radius (m), index 0 denotes initial radius
$\rho_{sat,L}$	density at saturation (kg/m^3)	p_∞	pressure at far field (Pa)
n	Tait equation exponent (for liquid) (–)	τ	Rayleigh time (s)
p_{sat}, p_v	saturation/Vapour pressure (Pa)	λ_g	Taylor length scale (m)
μ_L	dynamic viscosity of the liquid (Pa·s)		
a	vapour fraction (–)		
ρ_v	vapour density		

whole injection pulse; the 3D simulation involved needle motion and a simplistic liquid compressibility model.

There have been several efforts for the prediction of the cavitation erosion in Diesel injectors, see e.g. the work of Gavaises et al. [12] and Koukouvinis et al. [13]. The aim of the current work is to simulate the flow inside a Diesel injector in a more fundamental level, including needle motion, compressibility effects of the liquid phase and also using a Large Eddy Simulation for describing turbulence. Mesh motion is necessary for describing the transient effects in the injector. The reason for employing compressibility effects is that the fuel density can vary as much as 10% within the injector [14], not to mention the high liquid velocities that can reach a Mach number of 0.5 or more. Furthermore, resorting to Large Eddy Simulation techniques is because RANS/URANS are inadequate for capturing the complicate vortex patterns which affect cavitation formation [15], while even modified RANS turbulence models are situational [16]. To the authors knowledge there is no other work in literature that resolves the compressible turbulent flow in a moving needle Diesel injector with LES, including the prediction of vapour collapse pressures and correlation with actual erosion damage from CT scans of actual injectors. Furthermore, the methodology discussed in the present paper involves a modified cavitation model, in order to move closer towards thermodynamic equilibrium; if such a modification is not employed then unphysically high tension is predicted in the liquid.

The current paper is organized as follows: first an indicative description of two injector tip geometries will be given, along with testing conditions and X-ray scans of the erosion damage from the endurance test. Then, the numerical methodology will be presented. The simulation results of the Rayleigh collapse of a vaporous bubble is examined as a fundamental test case of the methodology used. Indeed, the aim of the current study is to detect the regions of the collapse of cavitation structures, which is directly linked with the formation of extreme local pressure and therefore erosion damage. Furthermore the simulation results of a simple throttle flow that has been previously studied by Edelbauer et al. [16] will be presented as a more applied benchmark case. Finally, indicative results of the simulated injectors will be shown and will be compared with the X-ray scans from the experiments, showing a good correlation.

2. Description of the examined injectors and testing conditions

2.1. Injector geometry and operating conditions

The examined injectors are common rail injectors. The accelerated cavitation test is performed in an endurance test rig, located at Caterpillar US research and development centre. Endurance testing is conducted for several thousand hours, with injection pressure at 1.1–1.5 times the injector rated operating pressure. The testing fuel is periodically replaced to maintain quality. The injectors are mounted on the head block of the test rig and the injected fuel is collected by the collector block and the rate tube, with downstream pressure adjusted by the pressure regulator at the end of the rate tube. The test rig also has a heat exchanger to keep Diesel fuel temperature controlled at around 40 °C in the fuel tank and a computer which collects data and controls the injection frequency.

Two injector designs are examined, which will be referred to as Design A and Design B hereafter. Both injectors have 5 hole tip and share exactly the same needle, as shown in Fig. 1. Design A has cylindrical holes (k-factor 0), while Design B injector has slightly tapered holes (k-factor is 1.1). Moreover, Design B has a significantly smaller sac volume comparing to Design A. This characteristic makes the Design B tip somewhat shorter than the equivalent of Design A. A summary of the most important dimensions of the two injectors is given in Table 1.

The injector operating pressure is ~1800 bar with inlet fuel temperature at ~75 °C. The collector back pressure is ~50 bar. Design B injector has a slightly higher needle lift, but shorter injection pulse duration comparing to Design A. The total injection duration is ~3 ms. Fig. 2 shows the pressure inlet boundary condition and needle motion for the two designs, as predicted using the 1-D system performance analysis software, developed internally by Caterpillar Inc. The 1-D model includes the entire hydraulic circuit of the endurance bench fuel systems as well as the electronic control system. The input parameters of the 1-D model include engine speed, fuel pressure and temperature, injection duration, and regulator back pressure, etc. In the present work, simulation results mainly of the opening phase of the injectors will be presented, i.e. for a lift from 0 to ~300 μm (for Design A) or ~350 μm (for Design B).

From hereafter the following naming convention will be used to refer to various injector parts, surfaces and volumes, see also Fig. 3.

- The injector tip volume is split into several sub-volumes, which can be identified as follows, starting upstream the injector tip and following the fuel flow: *annulus*, *needle/needle seat passage*, *sac volume* and *orifice* or *hole*.
- The injector tip surfaces are split into the following: the surface of the *annulus* that corresponds to the larger diameter will be referred as *body*. The *needle seat* and the *needle* walls define the *passage* volume. *Sac wall* is bounding the *sac volume*. *Orifice entrance* is the geometrical transition (which is usually a fillet) from the *sac wall* to the *orifice* surfaces. The orifice surface may be split further into the *upper* and *lower surfaces*; here *upper surface* corresponds to the surface that is closer to the inlet, i.e. faces towards the upstream direction, and *lower surface* faces towards the downstream flow direction, i.e. the combustion/injection chamber.