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Original citation: Salemi, R., Koukouvinis, P., Strotos, G., McDavid, R., Wang, L., Li, J., Marengo, M. & Gavaises, M. (2015). Evaluation of friction heating in cavitating high pressure Diesel injector nozzles. Journal of Physics: Conference Series, 656(1), 012083. doi: 10.1088/1742-6596/656/1/012083

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Evaluation of friction heating in cavitating high pressure Diesel injector nozzles

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Abstract. Variation of fuel properties occurring during extreme fuel pressurisation in Diesel fuel injectors relative to those under atmospheric pressure and room temperature conditions may affect significantly fuel delivery, fuel injection temperature, injector durability and thus engine performance. Indicative results of flow simulations during the full injection event of a Diesel injector are presented. In addition to the Navier-Stokes equations, the enthalpy conservation equation is considered for predicting the fuel temperature. Cavitation is simulated using an Eulerian-Lagrangian cavitation model fully coupled with the flow equations. Compressible bubble dynamics based on the R-P equation also consider thermal effects. Variable fuel properties function of the local pressure and temperature are taken from literature and correspond to a reference so-called summer Diesel fuel. Fuel pressurisation up to 3000bar pressure is considered while various wall temperature boundary conditions are tested in order to compare their effect relative to those of the fuel heating caused during the depressurisation of the fuel as it passes through the injection orifices. The results indicate formation of strong temperature gradients inside the fuel injector while heating resulting from the extreme friction may result to local temperatures above the fuel's boiling point. Predictions indicate bulk fuel temperature increase of more than 100^{o}C during the opening phase of the needle valve. Overall, it is concluded that such effects are significant for the injector performance and should be considered in relevant simulation tools.

1. Introduction

Cavitation phenomena are known to affect the injection performance and nozzle durability [1]. High injection pressures reaching 3000bar are needed for more efficient heavy duty Diesel engines. Computational methodologies have a strong potential in understanding the nature of cavitation under real operating conditions. Several methodologies have been proposed such as treating the cavitating fluid as a single mixture [2], the two-fluid method in which conservation equations are solved for both

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phases separately [3], bubble based cavitation models [4], modified VOF methodologies [5], models which account for compressibility effects [6, 7], homogeneous equilibrium models which estimate the cavitation growth by using a barotropic equation [8], as also Eulerian-Lagrangian models which implement the full Rayleigh-Plesset equation including thermal effects [9]. The challenging task of quantifying the effect of needle motion in fuel injectors has attracted interest and various computational techniques have been used to simulate the needle movement. Due to the small timescales involved with the whole phenomenon, the majority of the aforementioned studies are based on the assumption of isothermal flow, but under extreme pressurisation conditions, the flow is characterized by strong friction forces which induce fuel heating and this may even lead to fuel boiling. The present work aims to shed light on these thermal phenomena occurring in high pressure Diesel nozzles by solving the energy equation and including the heating induced by friction forces. In the following sections, the simulation model and the results obtained are presented.

2. Numerical model and fuel properties

The flow solver used has been developed by the authors' group and solves the Navier-Stokes equations in an unstructured mesh. With regards to cavitation, the Eulerian-Lagrangian model used is based on the CFD code developed by [10]; this work is an extension of [11, 12], quantifying the effect of the motion of the injector's needle valve. The presence of the cavitating phase is taken into account through the calculation of the liquid volume fraction in a computational cell; the corresponding source terms that can be found in [13] and account for the interaction between the two phases. These source terms include the energy exchange due to mass transfer, the interfacial heat transfer and the work of viscous interfacial forces. The turbulent viscosity μ_{turb} is calculated from the k-ε turbulence model and the turbulent Prandtl number Pr_{turb}, is taken equal to 0.85. It has to be noted that the solved equations contain both the reversible and the irreversible work of viscous forces; the latter is commonly known as viscous heating and represents the heating induced by the friction forces. The fuel used is the so-called "summer diesel" and its properties were taken from [14] as function of temperature and pressure. For the purposes of the present work, they have been extrapolated up to 3000bar and 400^{o}C for all cases simulated. The extrapolation method adopted, uses the functions given in [14] but extents the limits of pressure and temperature up to the point at which the property under consideration reaches a local minimum or maximum; beyond this point, each property is assumed to be equal to the corresponding value of the local minimum or maximum.

3. Diesel injector geometry and simulation results

3.1. Injector geometry

The geometry has been provided by Caterpillar; it is a 5-hole tapered injector (see Fig. 1a). The computational domain was split in a set of moving, deforming and stationary zones. The current production injector operates at an average inlet pressure level of ~2000bar and outlet pressure of 50bar; however, as industrial developments target much higher pressures, simulations have been performed for pressures as high as 3000bar. The pressure pulse and the corresponding needle motion were calculated using 1-D tools (Fig 1b) and were used as boundary conditions for the simulation. The needle motion (see Fig. 1b) is assumed to be in the axial direction only, so any eccentricity effects were omitted. In reality eccentricity effects are significant during the early opening and late closing phases, but introduction of such effects will impose the simulation of the complete injector geometry, which will be much more complicated. In the current simulation, only 1/5th of the domain was solved and periodic boundary conditions have been employed at the sides of the domain. The computational mesh used is block-structured, with the exception of a zone in the sac prior to the orifice entrance, which is unstructured tetrahedral. Inflation layers were introduced in the area of interest, such as sac and orifice to capture the boundary layers. Mesh motion was introduced by a smoothing algorithm at low lifts and the mesh layer addition at higher lifts. The mesh size was approximately 1 million cells at the beginning of the simulation; the needle motion introduces additional cell layers inside the volume denoted with blue colour in fig. 1a, so the actual cell count increases over time.

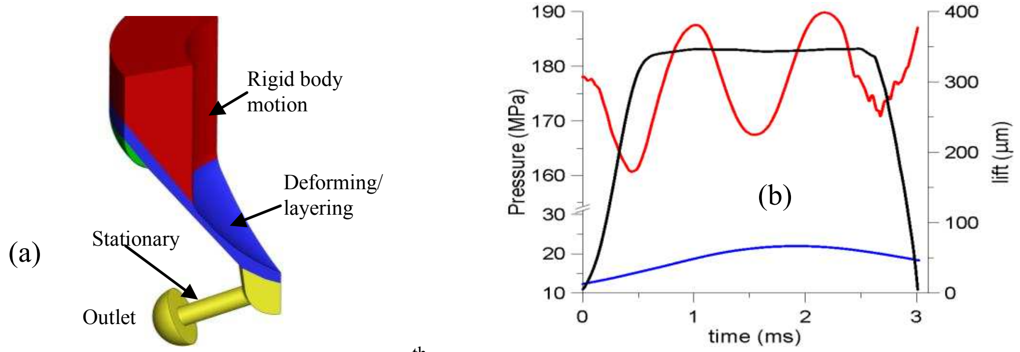

Fig. 1. (a) Grid particioning of the 1/5th sector of the injector examined, (b) needle lift, injection and back pressure profiles considered in the simulations

3.2. Simulation results

Moving needle simulations which resemble a realistic injection event are examined in this section. In these cases the lift law plays important role, due to the timescales involved. Generally an injection event has a small duration and the flow may not reach a quasi-steady state, while the closing phase is usually much shorter than the opening phase. As a result, different behaviour of the fuel heating is observed in the opening and closing phase. In Fig. 2a the fuel heating for two inlet pressures (2000 and 3000bar); both single-phase and two-phase flow simulations are presented. In Fig. 2b the fuel heating and the nozzle's discharge coefficient are presented for both cases.

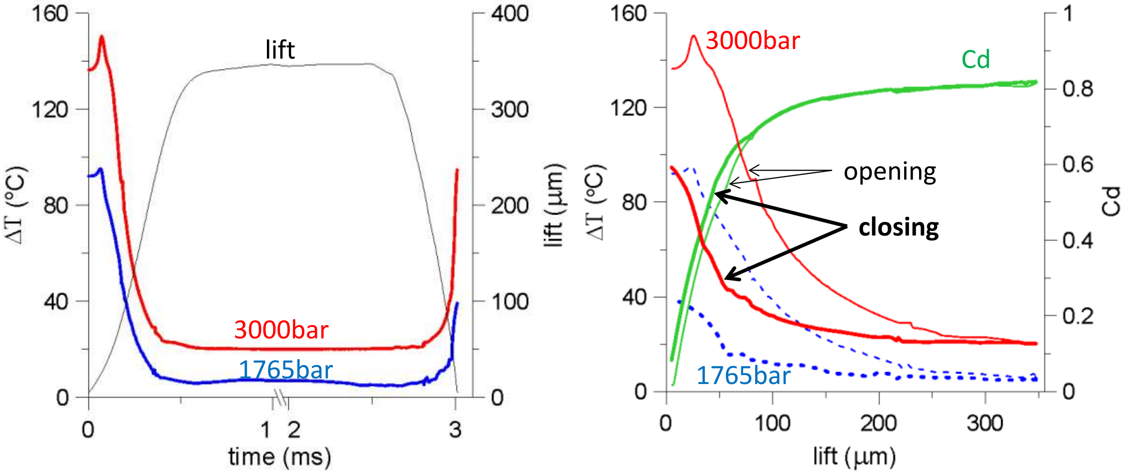

Fig. 2. (a) Fuel heating versus time for two inlet pressures. (b) Fuel heating and discharge coefficient versus lift

The nozzle's discharge coefficient shown in Fig. 2b varies at low lifts, while it approaches an asymptotic value for lifts higher than 80μm. Furthermore, at lifts lower than 80μm the amount of liquid injected in the opening and the closing phases is different. This hysteresis is ought to the presence of the sac volume. In the opening phase mass is accumulated to the nozzle's sac volume, while in the closing phase the already accumulated mass is pushed from the downwards needle motion towards the nozzle hole. Thus, a higher flow rate is observed in the closing phase. Regarding the fuel heating, the fuel is abruptly heated in the opening phase reaching its maximum value at 20μm and then the fuel is gradually cooled tending to reach the steady state heating predicted from the constant lift simulations. During the needle's closing phase, the fuel starts to heat-up again but lower values are predicted compared to those of the opening phase. This is attributed to the fact that closing is faster than opening and the flow has not enough time to reach a "steady" state. In Fig. 2a the fuel heating for the two inlet pressures simulated is also presented. It is obvious that increasing inlet pressure results in more heating. The effect of cavitation on the mean liquid temperature becomes appreciable for needle lift values exceeding 40μm.

4. Conclusion

The thermal phenomena appearing in the flow inside a high pressure Diesel injector nozzle have been studied with a CFD model. The model includes variable fuel properties as a function of pressure and temperature. A significant temperature increase is predicted with increasing injection pressure. The moving needle simulations are shedding light on the differences observed in opening and closing phase respectively. The temperature field is affected by the needle motion, while two-phase flow simulations show decreased mass flow rate and reduced fuel heating.

Acknowledgements

The research leading to these results has received funding from the People Programme (IAPP Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n. 324313.

References

1. Arcoumanis, C., et al., *Cavitation in Real-Size Multi-Hole Diesel Injector Nozzles.* SAE Paper 2000-01-1249, 2000.
2. Chen, Y.L. and S.D. Heister, *Two-Phase Modeling of Cavitated Flows.* Computers & Fluids, 1995. **24**(7): p. 799-809.
3. Alajbegovic, A., H.A. Grogger, and H. Philipp. *Calculation of Transient Cavitation in Nozzle Using the Two-Fluid Model*. in *Proc. 12th ILASS*. 1999. Indianapolis, Indiana, USA.
4. Yuan, W. and G.H. Schnerr. *Cavitation in Injection Nozzles - Effect of Injection Pressure Fluctuations*. in *Proc. CAV2001, Fourth International Symposium on Cavitation*. 2001. Pasadena, California, USA.
5. Singhal, A.K., et al. *Mathematical basis and validation of the full cavitation model*. in *Proc. of FEDSM'01 - 2001 ASME Fluid Engineering Division Summer Meeting*. 2001. New Orleans, Louisiana, USA.
6. Ando, K., T. Colonius, and C. Brennen, *Numerical simulation of shock propagation in a polydisperse bubbly liquid.* International Journal of Multiphase Flow, 2011. **37**: p. 596–608.
7. Zeravcic, Z., D. Lohse, and W. Saarloos, *Collective oscillations in bubble clouds.* Journal of Fluid Mechanics, 2011. **680**: p. 114–149.
8. Salvador, F.J., et al., *Computational study of the cavitation phenomenon and its interaction with the turbulence developed in diesel injector nozzles by Large Eddy Simulation (LES).* Mathematical and Computer Modelling, 2013. **57**(7–8): p. 1656-1662.
9. Keller, J. and M. Miksis, *Bubble oscillations of large amplitude.* Journal of the Acoustical Society of America, 1980. **68**(2): p. 628–633.
10. Giannadakis, E., M. Gavaises, and C. Arcoumanis, *Modelling of cavitation in diesel injector nozzles.* Journal of Fluid Mechanics, 2008. **616**(1): p. 153–193.
11. Theodorakakos, A., et al., *Friction-induced heating in nozzle hole micro-channels under extreme fuel pressurisation.* FUEL, 2014. **123**: p. 143-150.
12. Strotos, G., et al., *Transient heating effects in high pressure Diesel injector nozzles.* Int J heat and Fluid Flow 2015. **51**: p. 257–267.
13. Städtke, *Gasdynamic Aspects of Two-Phase Flow*. 2007: Wiley-VCH Verlag GmbH and Co. KGaA.
14. Kolev, N., *Multiphase Flow Dynamics 3: Turbulence, Gas Absorption and Release, Diesel Fuel Properties*. 2002: Springer Verlag Berlin Heidelberg.