Large-eddy simulation of friction heating and turbulent cavitating flow in a Diesel injector including needle movement

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Abstract

Recent technical progress in the automotive industry is strongly driven by the desire to enhance sustainability. This goal is directly linked with the reduction of emissions of greenhouse gases, which is a key factor to fight global warming. Transportation accounts for approximately 25% of global CO2 emissions (**Fig. 1**). Consequently, legislative rules of the European Union demand a reduction in CO2 emissions and limit particulate matter mass for Diesel engines (EU6 norm). To meet future emission standards and to reduce global CO2 emissions, automotive manufacturers and suppliers focus, for example, on the optimization of combustion engines.

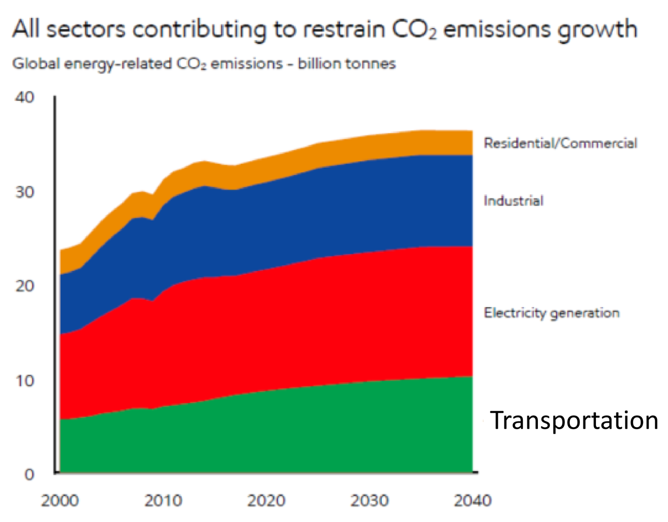

Figure 1. Global annual CO2 emissions by 2040. Source: ExxonMobil, The Outlook for Energy: A View to 2040, 2018.

Industrial Problem

Modern heavy Diesel engines and Diesel fuel injection systems, (**Figs. 2 & 3**) play a key role by offering a more efficient mixing and combustion process, which thus have a direct impact on fuel economy and emissions. This trend aims at enhancing jet break-up and mixing to improve the combustion and reduce emissions.

In-cylinder soot formation can be significantly reduced when injection pressure above 2200bar is utilised by today's nozzles. Unfortunately, at such injection pressures and temperatures, cavitation/boiling appears as an issue even for tapered nozzles, (**Fig. 3**). The advection of a vapor cavity in regions where the static pressure of the surrounding liquid is above the vapor pressure results in the sudden recondensation or collapse of vapor cavities accompanied by a high acceleration of the surrounding liquid towards the centre of the cavities and the formation of strong shock waves. When vapor bubbles collapse near a solid wall, liquid jets directed towards the wall surface are created, which can lead to material erosion, (**Fig. 4**).

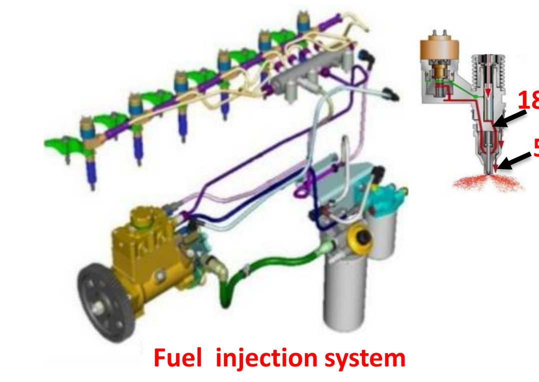

Figure 2. Single fuel system, Diesel Injector. Source: Caterpillar®, Cat Fuel System.

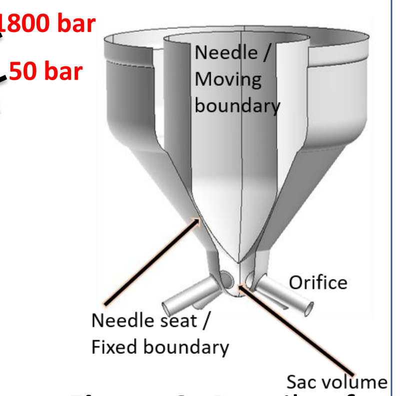

Figure 3. Details of Diesel injector needle.

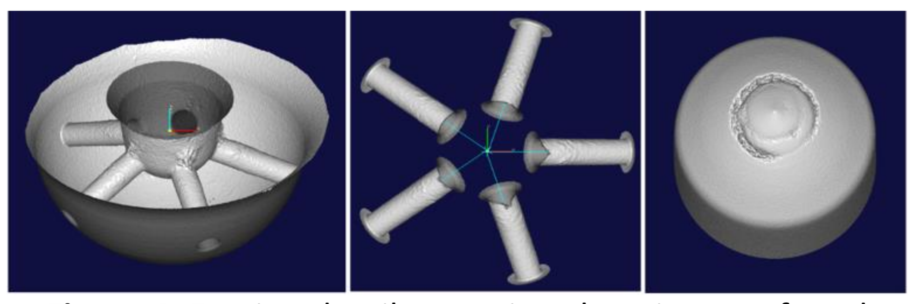

Figure 4. Erosion details at various locations, as found on the surfaces of examined injector. Left column: Sac volume. Center column: Orifices. Right column: Needle surface.

Underpinning Research

The turbulent cavitating flow, inside rail Diesel injector and the **effect of cavitation on erosion** and the **increase liquid temperatures due to friction heating** are investigated for the opening cycle of the injection. An explicit density-based solver of the compressible Navier-Stokes (NS) equations of the Arbitrary Lagrangian–Eulerian (ALE) formulation[**1**], suitable for cavitating flows is implemented in the open-source CFD code OpenFOAM®. The hybrid scheme provides a Mach number consistent numerical flux, suitable for subsonic up to supersonic flow conditions[**2,3**]. The Wall Adapting Local Eddy viscosity (WALE) LES model was used to predict incipient and developed cavitation, while also capturing the shear layer instability, vortex shedding and cavitating vortex formation.

Thermodynamic closure 1: The thermodynamic model is based on a barotropic Equation of State (EoS)[**4**] for the liquid and vapour phases[**5**]. The cavitation model is based on a thermodynamic equilibrium assumption and the compressibilities of the liquid and the liquid-vapor mixture are taken into account.

Thermodynamic closure 2: The thermodynamic model is based on tabulated data[**4**] derived from Perturbed-Chain, Statistical Associating Fluid Theory(PC-SAFT) EoS[**6**], in order to calculate the thermodynamic properties of the liquid, vapour and mixture composition during cavitation.

Results/Conclusions

The comparison revealed that the barotropic model suppressed the vortex cavitation into the orifice and the backflow pattern in the sac volume and predicts different flow and vapour pattern in comparison with the fully thermodynamic approach. Furthermore, due to high injection pressure significant variations of the thermodynamic properties of the fuel (density, viscosity, temperature and thermal conductivity) take place into the injector volume. Transient effects of needle motion and the temperature history have a serious impact in predictions of the actual phenomenon, especially at low lifts. Also, the temperature, pressure and velocity field exhibits differences in opening and closing phase which progressively diminish as the high needle lifts. During, the injection phase two opposing processes strongly affecting the fuel injection mass rate and its temperature. The first one, the fuel cooling process is related to the de-pressurisation of the fuel; the low pressure due to fuel acceleration and the second one, the strong viscous heating produced by wall friction.

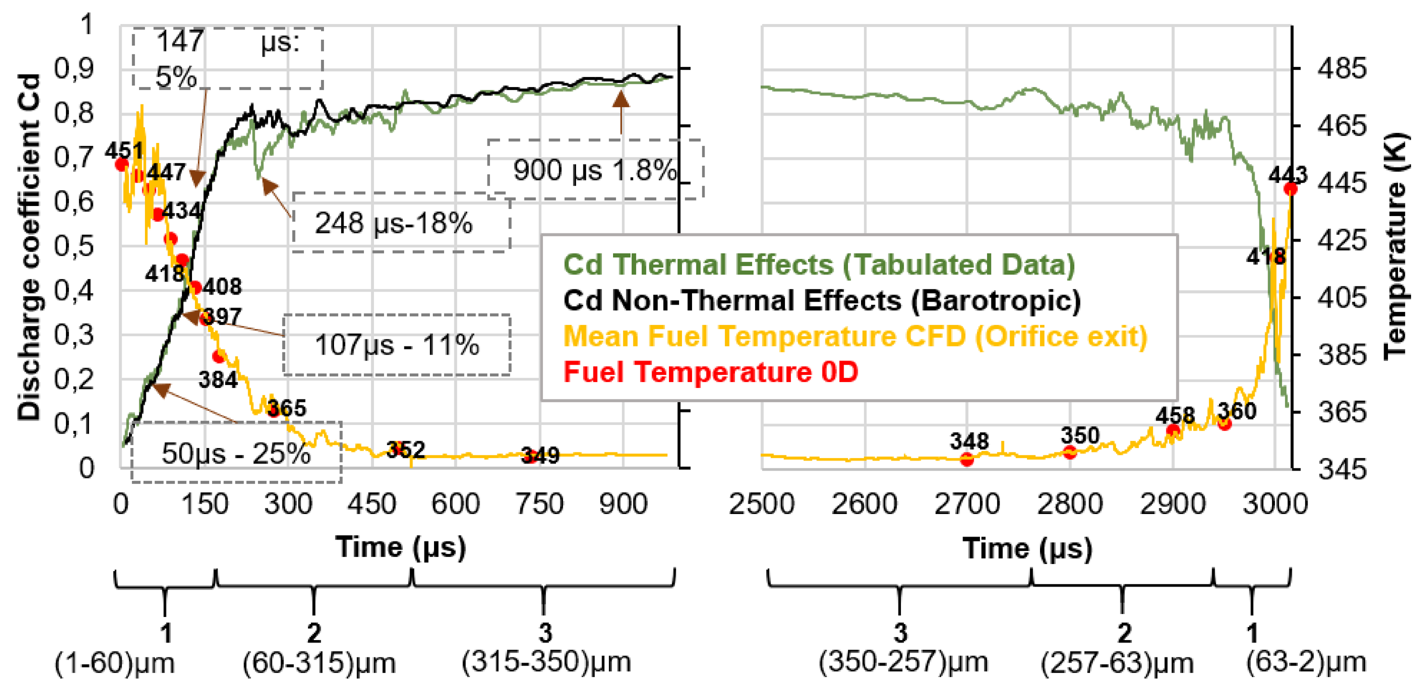

Figure 5. Fuel heating during the opening (left) and closing (right) phase as function of the injection time. The Figure shows the mean fuel temperature at the exit of the orifice from CFD predictions, the discharge coefficient from CFD predictions and the fuel Temperature from CFD predictions.

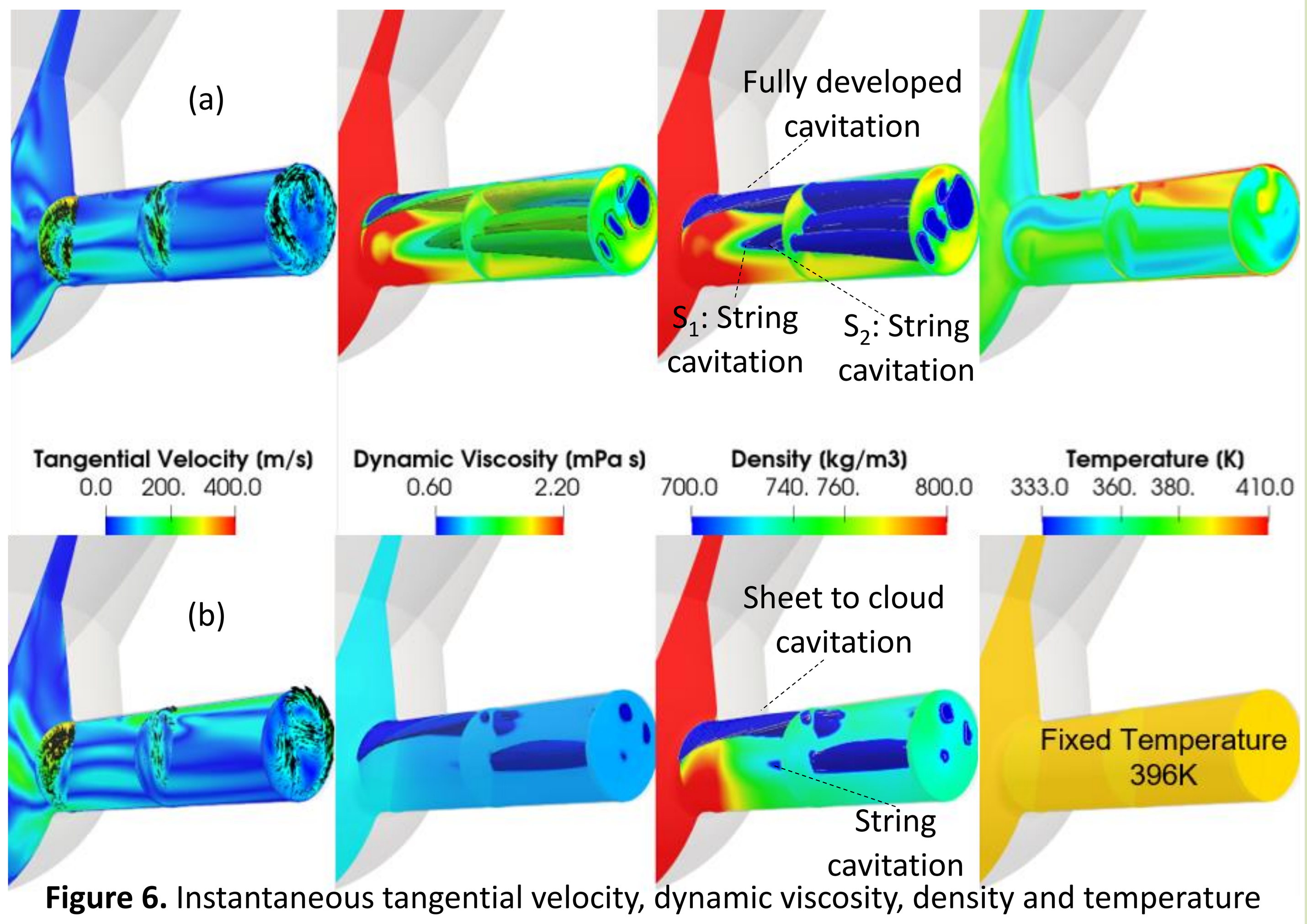

Figure 6. Instantaneous tangential velocity, dynamic viscosity, density and temperature distribution on slices normal to the orifice and at the midplane of the injector, at time instant 248μs (132 μm needle lift) using (a) thermodynamic closure 2 and (b) thermodynamic closure 1. The vapor volume fraction α = 0.01-1.0 is coloured by the dynamic viscosity and by the density.

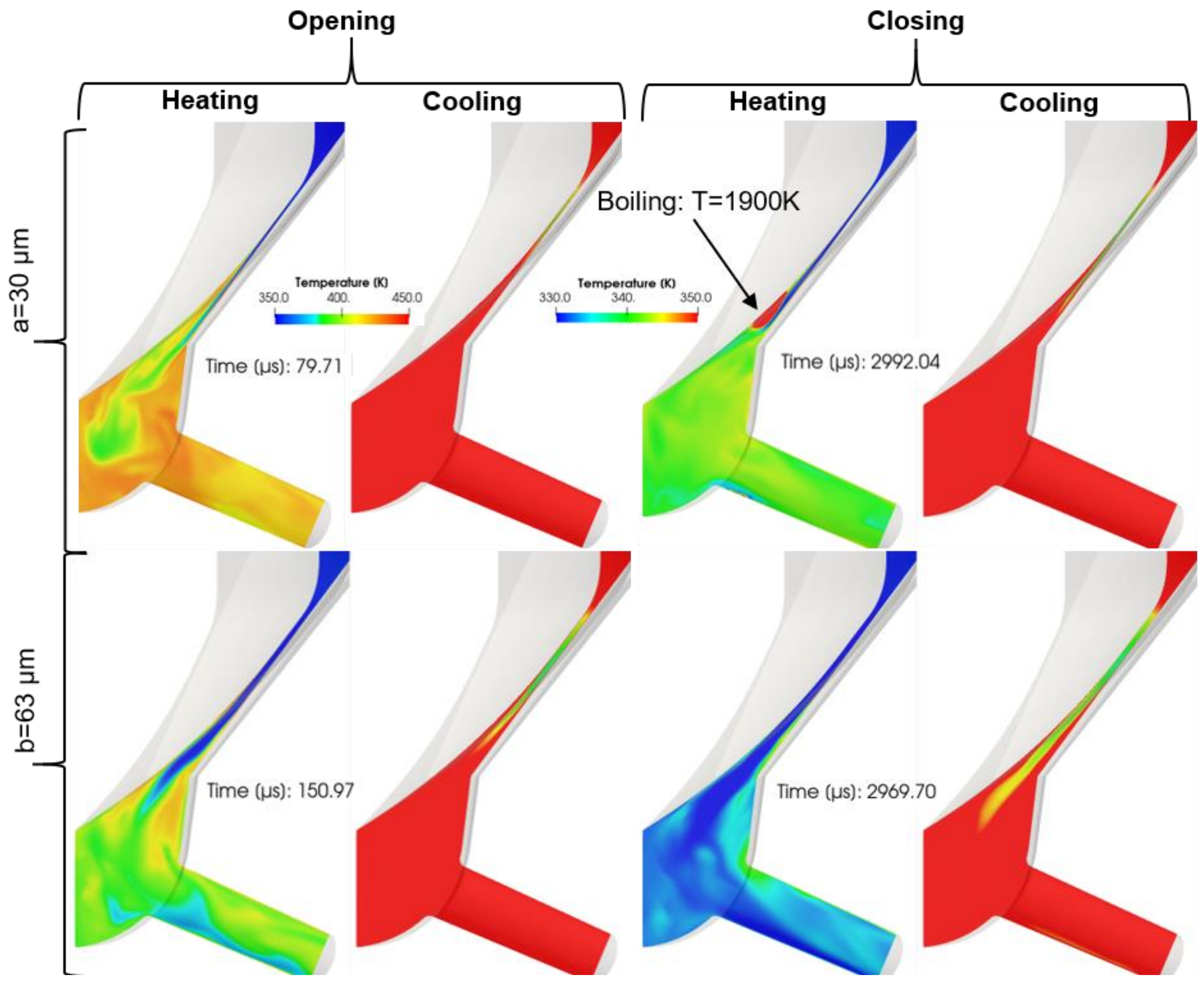

Figure 7. Snapshots of time instants (a) – (b) during the needle opening closing phase. At every time instant the instantaneous temperature field; fuel heating and potential boiling; fuel cooling at the mid-plane of the injector using the thermodynamic closure 2.

Impact

The characteristic nozzle size for Diesel injectors is of the order of several hundred micrometres. This geometric scale makes experimental flow characterization within an injector challenging. CFD provide insight to all the aspects of the underlying flow dynamics needed for the optimization. On the broader perspective, understanding of the complex fluid dynamic taking place in cavitation, phase-change, thermal effects and mixing at extreme conditions, requires advanced simulation models, such as those mentioned here.

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