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Influence of biofuels on the internal flow in Diesel injector nozzles

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Abstract

In this paper, the behavior of the internal nozzle flow of a standard diesel fuel has been compared against a biodiesel fuel (soybean oil) at cavitating and non-cavitating conditions, using a Homogeneous equilibrium model. The model takes into account the compressibility of both phases (liquid and vapour) and use a barotropic equation of state which relates pressure and density to calculate the growth of cavitation. Furthermore, turbulence effects have been introduced using a RNG k-ε model.

The comparison of both fuels in a real diesel injector nozzle has been performed in terms of mass flow, momentum flux, effective velocity at the outlet and cavitation appearance. The decrease of injection velocity and cavitation intensity for the biodiesel noticed by numerical simulation at different injection conditions, predict a worse air-fuel mixing process.

Keywords: cavitation, biodiesel, OpenFOAM®, internal flow, diesel injector, nozzle

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1. Introduction

It is well known that fossil fuels reserves will not provide energy eternally. That is why a lot of companies are interested in making the engines more efficient to reduce the fuel consumption. Another solution that seems to be a great alternative is the use of vegetable oils, animal fats and algae as carburant that should provide enough power to run the actual thermal engines as they do with fossil fuels.

In addition, biofuels such as biodiesel, can be use as a method to reduce the emissions of the engines [1]. Indeed, the environmental benefits can reach to reduce emissions of carbon monoxide by 40%, carbon dioxide by 80% and eliminate the sulfur particulates and HC emissions.

However, despite of their beneficial effects for the environment, the repercussions on the internal flow and therefore on the injection process have not been studied yet. Up to now, biofuel studies have been focused only in the performance and emissions of the engine [2] treating the engine as a “black box”, without study in depth how biodiesel influences on the injection process or what are the repercussions of its use on the air-fuel mixing process.

The present paper has been divided in 6 sections. First of all, a brief description of the cavitation phenomena and the code used will be performed in section 2. The geometry simulated and the fuel properties used in the calculations will be explained in section 3 and 4 respectively. The results of the study will be presented in section 5 and finally, the main conclusions will be drawn in section 6.

2. Description of the CFD approach

Under the injection conditions in modern Diesel engines (with pressures which can reach up 180 MPa) cavitation often occurs in fuel injection nozzles, whose length is about 1 mm and whose diameter ranges from about 0.1 mm to 0.2 mm. When a fluid of high velocity passes through a contraction like a nozzle and the pressure falls below the saturation pressure, the liquid will cavitate, and as a consequence a local change of state from liquid to vapour takes place.

Due to high pressures and velocities that occur in diesel injectors, the use of a homogeneous equilibrium model which assumes that liquid and vapour are always perfectly mixed in each cell, together with a barotropic equation of state is the most suitable method to model cavitation [3].

The code used in the present work is implemented in OpenFOAM 1.5 and was validated and optimized improving the convergence and the accuracy of the results and choosing the most suitable numerical schemes by Salvador et al. [4].

As shown several experimental investigations and numerical studies, turbulence has an important effect on cavitating flows [5]-[7], playing an important role on the flow features. In this case, the turbulence effects have been introduced using a RANS method. This method solves the Reynolds-averaged Navier Stokes equations with models for turbulent quantities, decomposing the fluid properties to averaged and fluctuating component.

In addition, a complete analysis using the different RANS models has been performed in order to choose the most suitable one in terms of convergence and accuracy, being the RNG k-ε model the best option.

3. Geometry and nozzle mesh description

The geometry simulated in this report is a multi-hole microsac nozzle with six orifices. However, due to the nozzle symmetry and with the aim of speed up the calculations, the domain simulated has been reduced to 60° (one orifice). As can be seen in Table 1, where the internal characteristics are reported, the nozzle is cylindrical and so, it is inclined to cavitate [8].

Nozzle	D_i [μm]	D_o [μm]	k-factor [-]	r [μm]	r/D_o [-]	L/D_o [-]
6-hole	170	170	0	13	0.074	5.71

Table 1: Nozzle's geometrical characteristics.

As shown Fig. 1, the domain simulated corresponds to the volume occupied by the fuel between the needle and the nozzle internal wall, including the needle seat and the whole orifice, where the fuel flows toward the combustion chamber of the engine.

Preliminary studies were performed to assess the most appropriate mesh fineness and fulfill with other important considerations from others authors related to the mesh quality [9]-[11]. Fig. 2 shows some results of these studies, where it has been possible to choose the optimum mesh which has 115252 hexahedral cells, doing a particularly refine in the orifice wall with a boundary layer made up of 3 layers with cell sizes ranging from 9 μm in the orifice core to 1.15 μm in the wall.

The simulations calculated in the present study have been performed using two different injection pressures (30 and 80 MPa) and varying the back pressure between 1 and 29 MPa.

4. Fuel properties

Table 2 depicts the density, viscosity of both fuels used in the calculations. The fluid properties for diesel fuel (obtained in CMT-Motores Térmicos) belong to a Repsol CEC RF-06-99 fuel for a temperature of 23°C, whereas biodiesel properties were obtained from a fuel made from soybean oil at 23°C estimated from [12].

	Diesel	Biodiesel
Density [kg/m^3]	830	869.47
Viscosity [kg/m·s]	0.0032826	0.005776

Table 2: Properties for both fuels.

5. Results

5.1. Mass flow and cavitation pattern

The mass flow as a function of pressure drop squared, being the pressure drop the difference between the injection pressure and the backpressure, has been plotted in Fig. 3 for two different injection pressures (30 and 80 MPa) and different backpressures. The large amount of backpressures simulated (indicated above of each point of the graph) allows studying in depth the behavior of both fuels at cavitating and no cavitating conditions. As expected, due to the highest value of density, biodiesel injects more fuel at the same pressure drop for all the points simulated. However the most important difference between both fuels is related to critical cavitation conditions (CCC), characterized from the mass flow choking beginning. As can be seen, mass flow collapse is reached earlier for the diesel fuel, so it is possible to state that biodiesel inhibits cavitation compared to standard diesel fuel.

Indeed, comparing the vapour field average in the middle plane of the orifice, diesel fuel cavitates more than biodiesel for the same pressure conditions. As an example, Fig. 4 shows cavitation distribution for the injection pressure 80 MPa and the backpressures 17 and 18 MPa (red colour represents pure vapour and blue colour pure liquid).

5.2. *Momentum flux and injection effective velocity*

Apart from mass flow and cavitation intensity, the comparison between standard diesel and the fuel made from soybean oil has been done also in terms of momentum flux at the orifice outlet. Although the momentum flux is always higher for the standard diesel, the differences found as shown in Fig. 5 are small.

Once mass flow and momentum flux have been obtained, it is possible to calculate the effective velocity at the nozzle exit using Eq. (1):

$$u_{\text{eff}} = \frac{\dot{M}}{\dot{m}} \tag{1}$$

As expected taking into account the evolution and the differences of the mass flow together with the momentum flux, the effective velocity for biodiesel fuel is lower than diesel (Fig. 6).

5.3. *Influence on the mixing process*

It is well known that for the same geometry, the air-fuel mixing process in the combustion chamber depends on the injection effective velocity and the spray cone angle and both increase with cavitation intensity [8, 13].

As seen before, for a given pressure condition the effective velocity of biodiesel is lower. Furthermore, in cavitating conditions it presents less cavitation intensity, so, small spray cone angle [8] is expected for biodiesel. As a conclusion, a worse air-fuel mixing process is expected for biodiesel leading to a worse combustion process.

6. Conclusions

From the present study the following main conclusions can be drawn:

- A code to model cavitation phenomena taking into account the turbulence effects has been applied for compare the behavior of a conventional diesel fuel and a biodiesel one made from soybean oil.

- Biodiesel injects more fuel and reaches later critical cavitation conditions. As a consequence, cavitation intensity is lower for the same pressure conditions.

- As a consequence of the decrease of injection velocity and cavitation intensity for the biodiesel, the air-fuel mixing process gets worse.

Acknowledgments

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Nomenclature

D_i: inlet diameter
D_o: outlet diameter
k-factor: conicity factor
L: orifice lenght
$\dot{m}$: mass flow/ mass flux
$\dot{M}$: momentum flux
P_back: discharge back pressure
P_inj: injection pressure
r: curvature radius
u_eff: injection effective velocity
Greek symbols:
ΔP: pressure drop, $\Delta P = P_\mathrm{inj} - P_\mathrm{back}$

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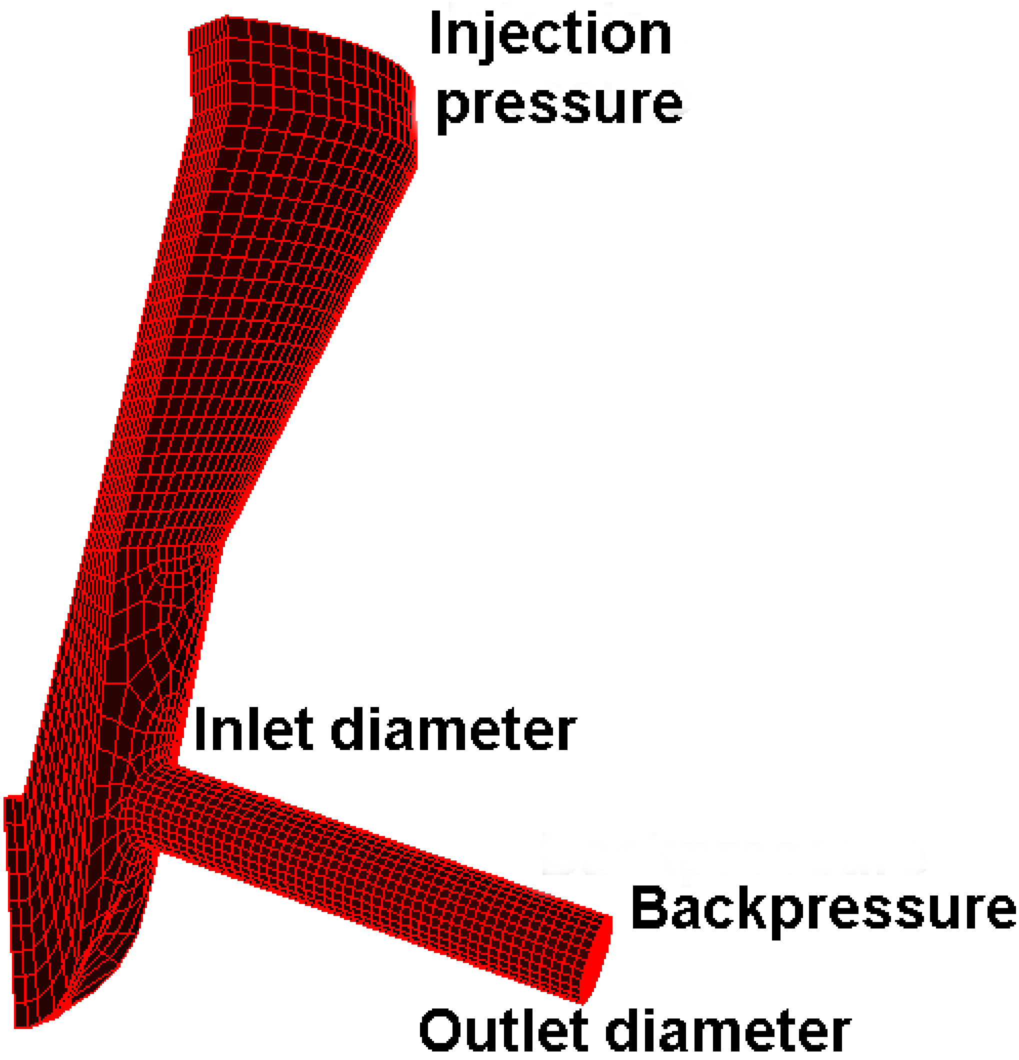

Figure 1: Nozzle mesh simulated.

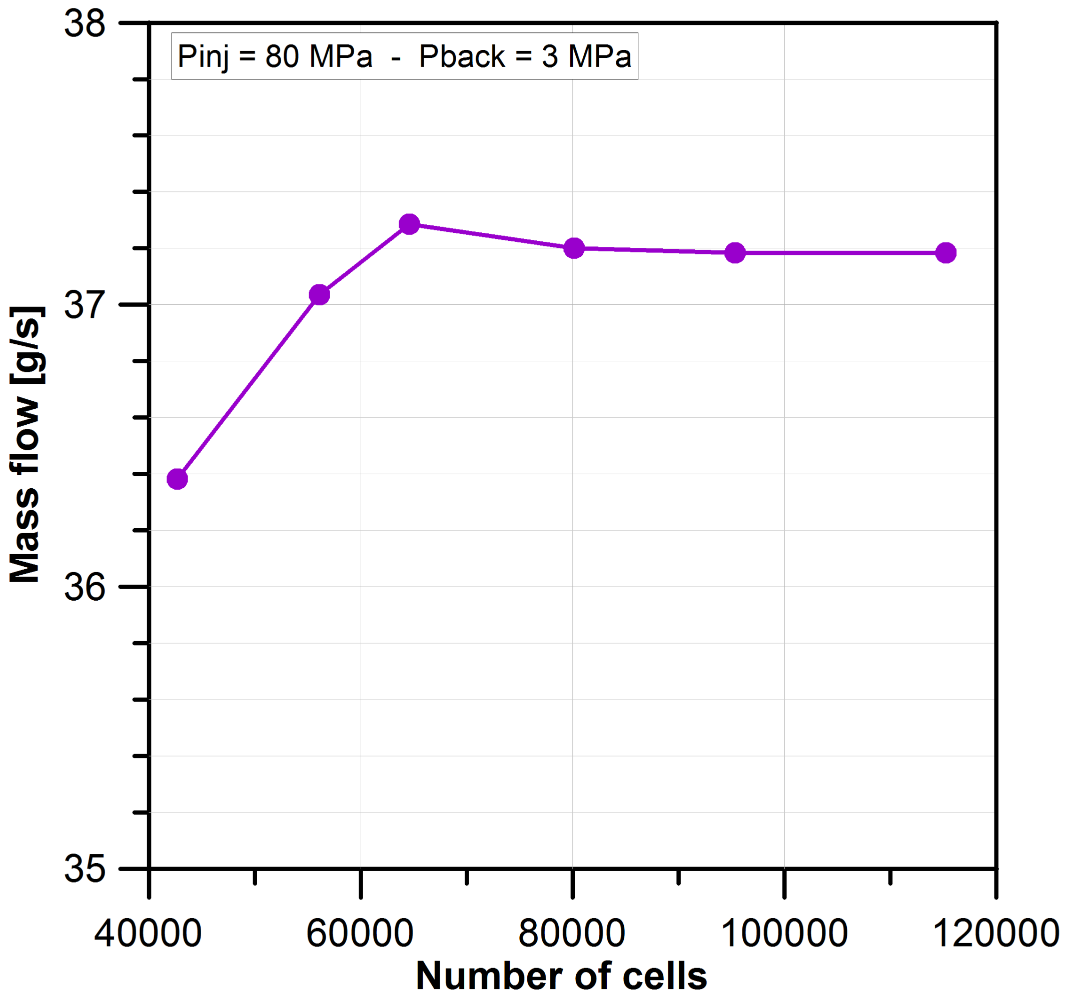

Figure 2: Mesh sensitivity study.

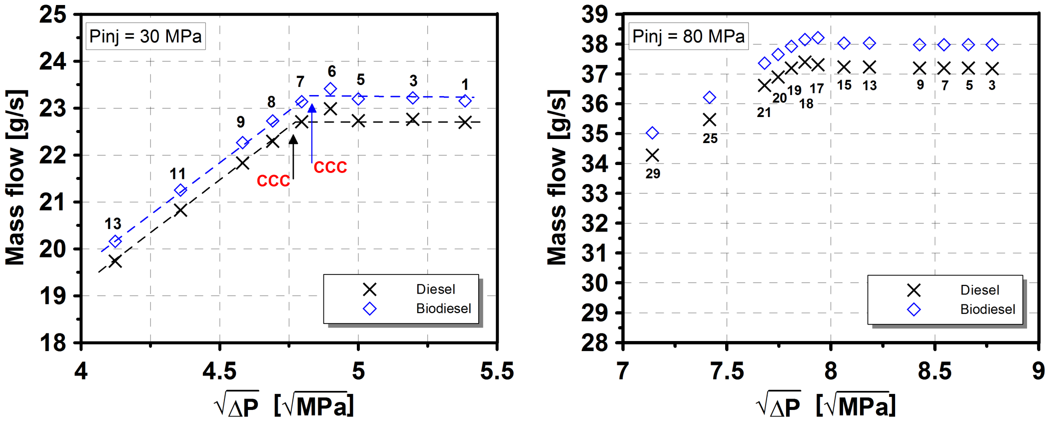

Figure 3: Comparison of both fuels in terms of mass flow.

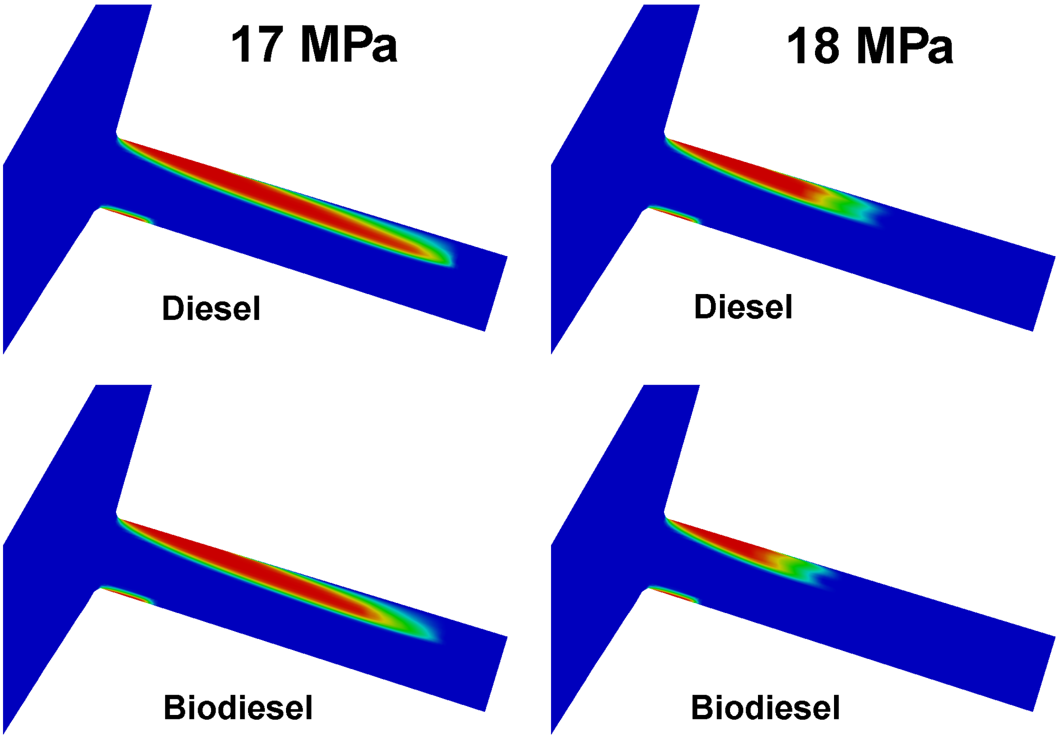

Figure 4: Comparison of vapour field average ($P_{\text{inj}} = 80$ MPa $-$ $P_{\text{back}} = 17$ and 18 MPa).

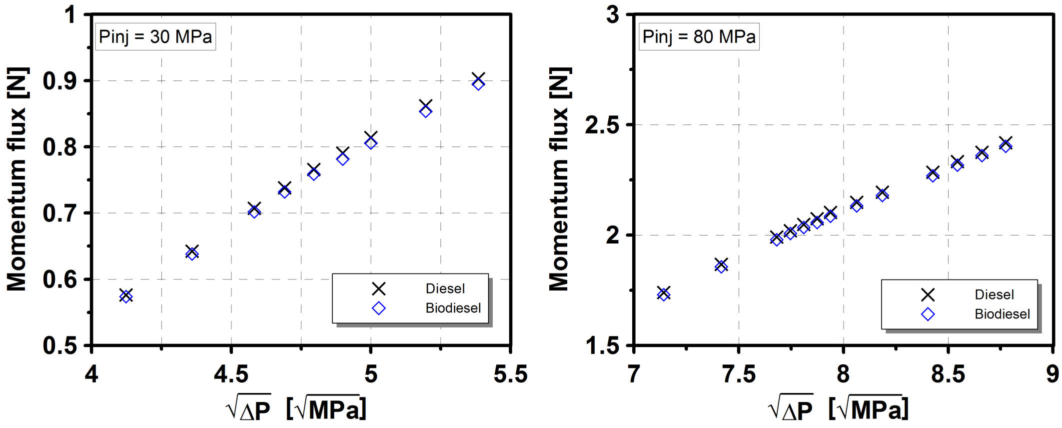

Figure 5: Comparison of both fuels in terms of momentum flux.

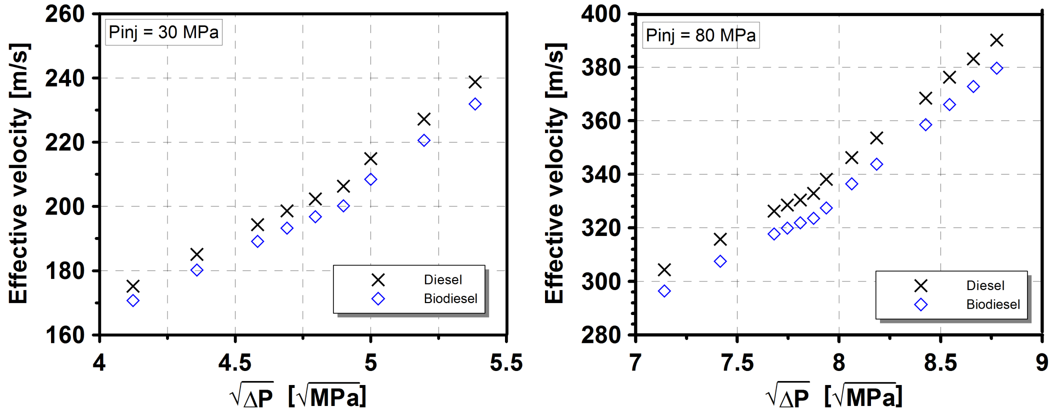

Figure 6: Comparison of both fuels in terms of effective velocity.