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EGEE 520 Section 001

Alternative Fuel Spray Length Characterization: Comparing Diesel and Biodiesel Fuels

Introduction:

I have chosen to model the spray of fuel from a diesel fuel injector while varying the physical properties of the fuel. The reasoning behind modeling a diesel fuel injector is to study the effects that biodiesel has on engine lubrication oil dilution.

Post power-cycle fuel injection has recently been incorporated into most production diesel engines as a strategy to regenerate diesel particulate filters after they become filled with soot. It has been seen that some of the diesel spray during these post injections “wets” the cylinder wall with fuel. The fuel in turn is washed down into the oil sump and dilutes the engine oil. When running the engine through standard tests biodiesel tended to cause an increase in the oil dilution compared to that of regular diesel [Graboski 1998].

I hope to prove or disprove the theory that small variations in the viscosity and density of biodiesel compared to petroleum diesel cause an increase in spray length [He 2008]. An increase in spray length, or mixing length, of the fuel jet is theorized to increase the amount of cylinder wall wetting and engine lube oil dilution with biodiesel.

Characteristic Equations:

The two most important governing equations with the diesel spray characterization are the Navier-Stokes and mass transport/diffusion equations. Comparing the physical properties of petroleum diesel with biodiesel it can be seen that there is an increase in density and viscosity and a decrease in the vapor pressure of biodiesel compared to petroleum diesel. All of these properties, listed in table 1, should come together to form larger fuel droplets in the biodiesel fuel spray and not allow them to evaporate as quickly. Long-lived and larger fuel droplets of biodiesel should allow for the fuel spray to penetrate more deeply into the combustion chamber before vaporizing.

Table 1: Comparison of Fuel Properties

	Diesel	Biodiesel
Specific Gravity	0.835	0.886
Viscosity (cSt)	3.933	7.105
Vapor Pressure at 300K (mmHg)	0.400	0.150

Equation 1: Navier-Stokes Equation

$$\rho * \left(\frac{dv}{dt} + \nabla v\right) = -\nabla P + \mu \nabla^2 v + \rho g \nabla h$$

Equation 2: Diffusion Equation

$$A * \frac{dc}{dt} + \nabla(-D\nabla c) = R$$

When inputting the variables into the above equations, vapor pressure is not needed. However, since diffusivity data is not available for diesel fuels (not to mention the variable nature of diesel composition) the best approximation available that can be equated to diffusivity is the vapor pressure. It is especially applicable due to the two-phase system (liquid fuel injected into a gaseous air-charge).

Solution:

An issue that was experienced early on in the solution process was the extremely high Reynolds number. Injection pressures of modern diesel engines range between 300 and 1300 bar (4000 – 19000 PSI) resulting in Reynolds numbers well into the turbulence regime. Unfortunately COMSOL does not handle turbulent flow well and to get accurate results the Reynolds number must remain below one. To stay at this level the pressure difference over the injector could only be approximately 10 Pa when using realistic in-cylinder conditions of viscosity and density.

For a solution to the issues of the Reynolds number the time of injection was extended. Since the allowable pressure difference over the fuel injector was many orders of magnitude lower than that experienced in the engine, to more accurately portray the penetration of the fuel spray the injection time was increased by an order of magnitude. Keeping in mind that the idea is to measure a change in cylinder wall wetting between diesel and biodiesel, once the Reynolds number problem was solved the spray pattern length could be calculated. Results for diesel and biodiesel can be seen below in figure 1 and 2 respectively.

Figure 1: Diesel Fuel Spray

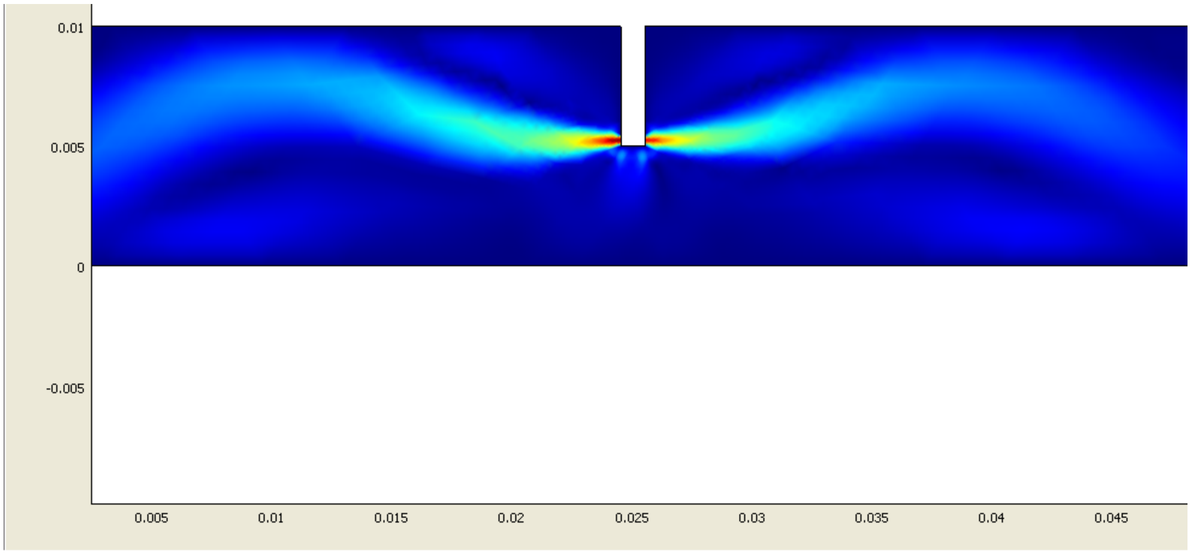
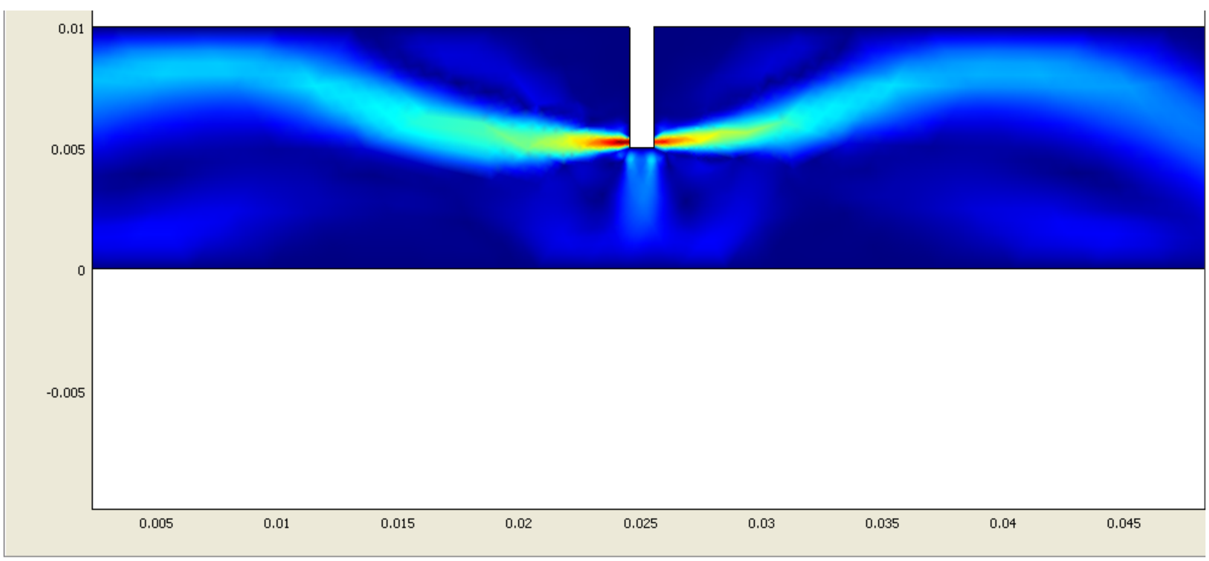


Figure 2: Biodiesel Fuel Spray



There is a definite difference between the sprays seen with diesel and biodiesel showing deeper penetration with biodiesel. However a two-phase flow has not yet been included in the COMSOL simulation resulting in the sprays shown above. Further refinement will be used to attempt to more accurately depict liquid in gas spray.

Verification:

After learning how to simulate two-phase flow, it was incorporated into the model. The two different results are shown below in figure 3 and figure 4.

Figure 3: Verified Diesel Spray

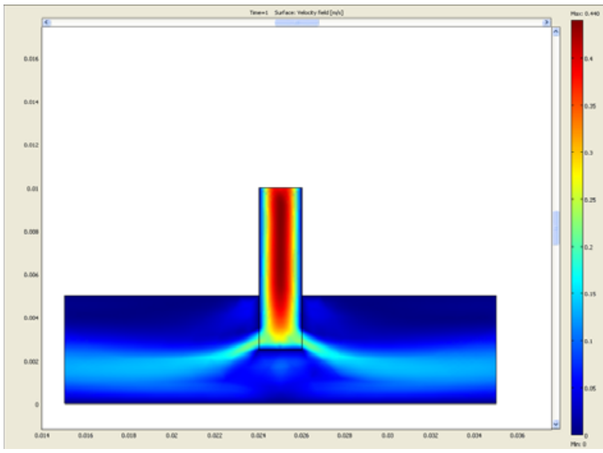
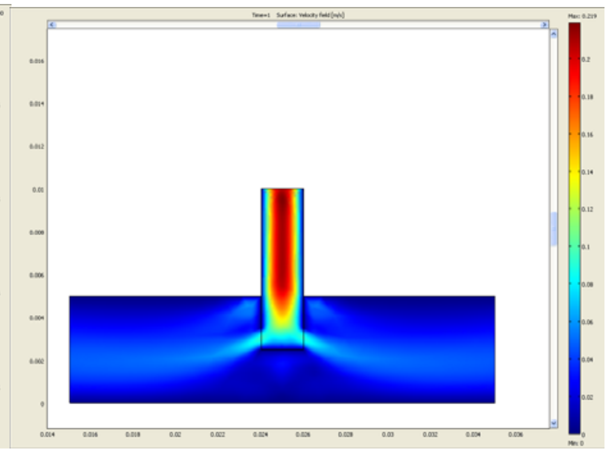


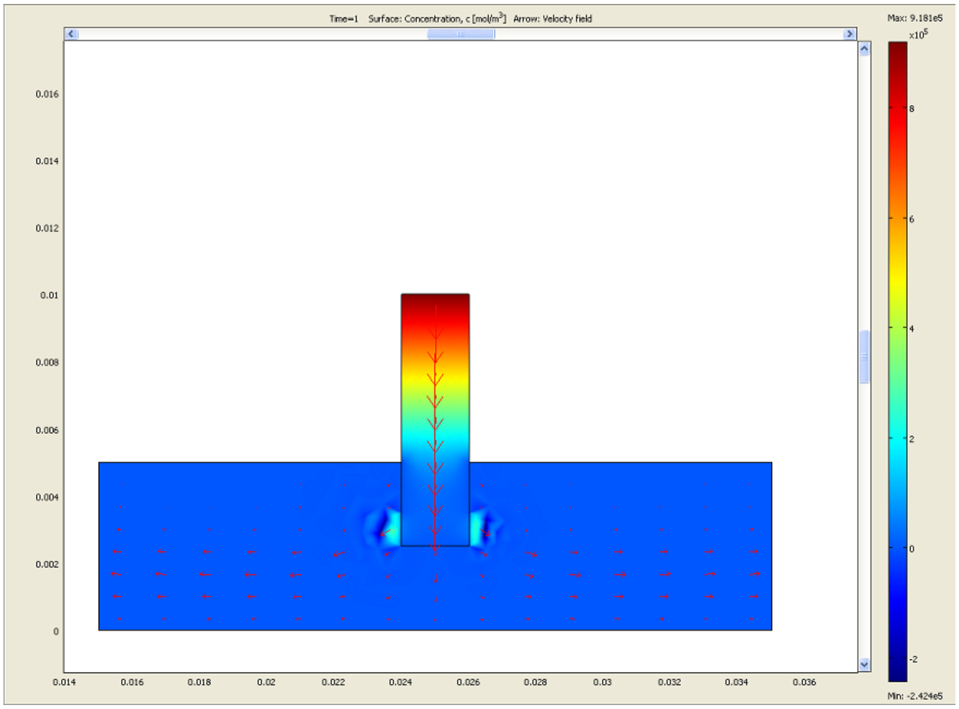
Figure 4: Verified Biodiesel Spray



From above, it can be seen that within the limitations of COMMSOL the standard diesel spray attained a higher velocity and deeper penetration into the cylinder than the biodiesel spray. Unfortunately this is contrary to the hypothesis and commonly observed trends in modern diesel engines where the use of pure biodiesel causes issues stemming from cylinder wall wetting. Reasons for the opposite result from the hypothesis is that COMMSOL will only accurately simulate laminar fluid flow. Due to the extremely high pressures in modern diesel injection systems a highly turbulent fuel spray develops.

To examine whether adding diffusion to the model can help to more accurately depict the diesel spray a model was developed with arrows indicating the velocity field and the concentration of fuel as the surface color (shown in figure 5).

Figure 5: Diffusion Simulation



Based on the results of the diffusion simulation, even with a high diffusion coefficient there is minimal diffusion that takes place compared to mechanical mixing (shown by the velocity field). This is consistent with modern diesel research where diffusion is often found to be the limiting factor in the reaction of the fuel. Higher injection pressure and smaller injector orifices aid in the mixing process by enhancing turbulent mixing but cannot replace the diffusion of fuel into the cylinder air charge.

Finally verification in the form of basic calculations was performed by hand for laminar fluid flow rates. Using a simple form of the Navier-Stokes equation, the velocity was calculated to be 2 m/s. Figure 3 and 4 show velocities of approximately 0.44 and 0.25 m/s respectively in the injector that is simulated with a simple pipe 0.0075 meters long and 0.002 meters wide. The verification was assuming a fully developed fluid flow which takes between 10 and 20 times the width of the pipe. In this case only 4 times the width of the pipe was allowed for the flow to develop: hence the artificially low simulated velocity compared to the velocity calculated by hand. But even without the fully developed flow, the validation can still be considered a success since all calculated speeds were within an order of magnitude of each other.

Parametric Study:

For the parametric study a convection term was added to the transport equation for the most complete understanding of possible effects. The viscosity and the density of the liquid representing the fuel was then varied to study the effects that would come about from changes that occur between standard petroleum diesel and biodiesel. Results from the parametric study showed that increasing the viscosity and density of the liquid fuel both resulted in slower and shallower penetration into the cylinder. Once again, this refutes the theory of why engine oil dilution is worsened by use of biodiesel instead of regular diesel. This makes sense when put into context of the Navier-Stokes equation but cannot represent an actual diesel spray due to COMSOLs inability to simulate turbulent flows. Figures 6 through 9 represent the fuel velocity and concentration of petroleum diesel and biodiesel fuels with the same pressure drop over the injector in the laminar flow regime.

It is important to note that even with the velocity difference the results of the concentration distribution using convection indicate a uniform charge of approximately the same concentration of fuel was created in both cases. This is because of the combination of relatively high flow rates and high diffusivity of the vaporized fuel in the cylinder.

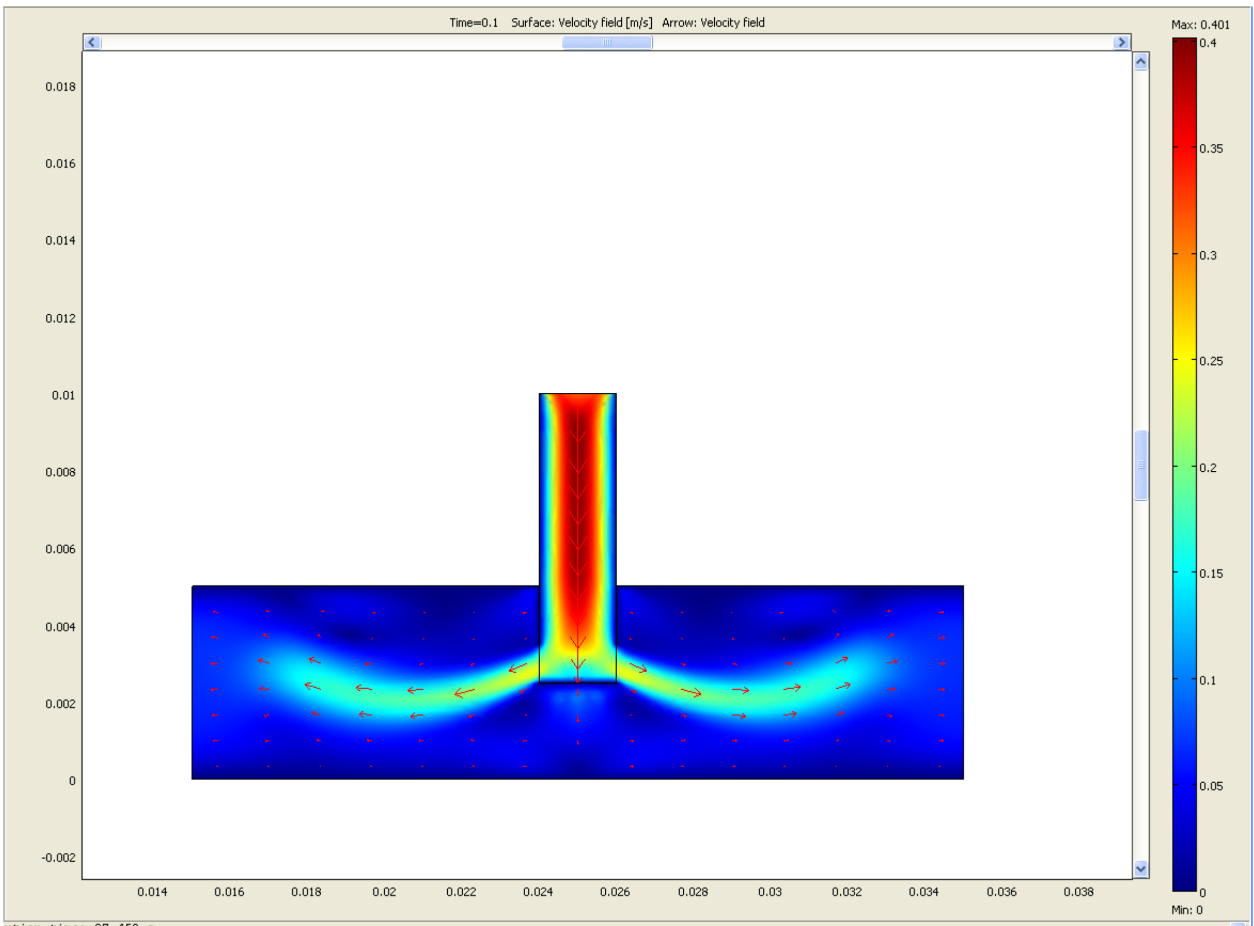


Figure 6: Velocity Distribution of Diesel Fuel

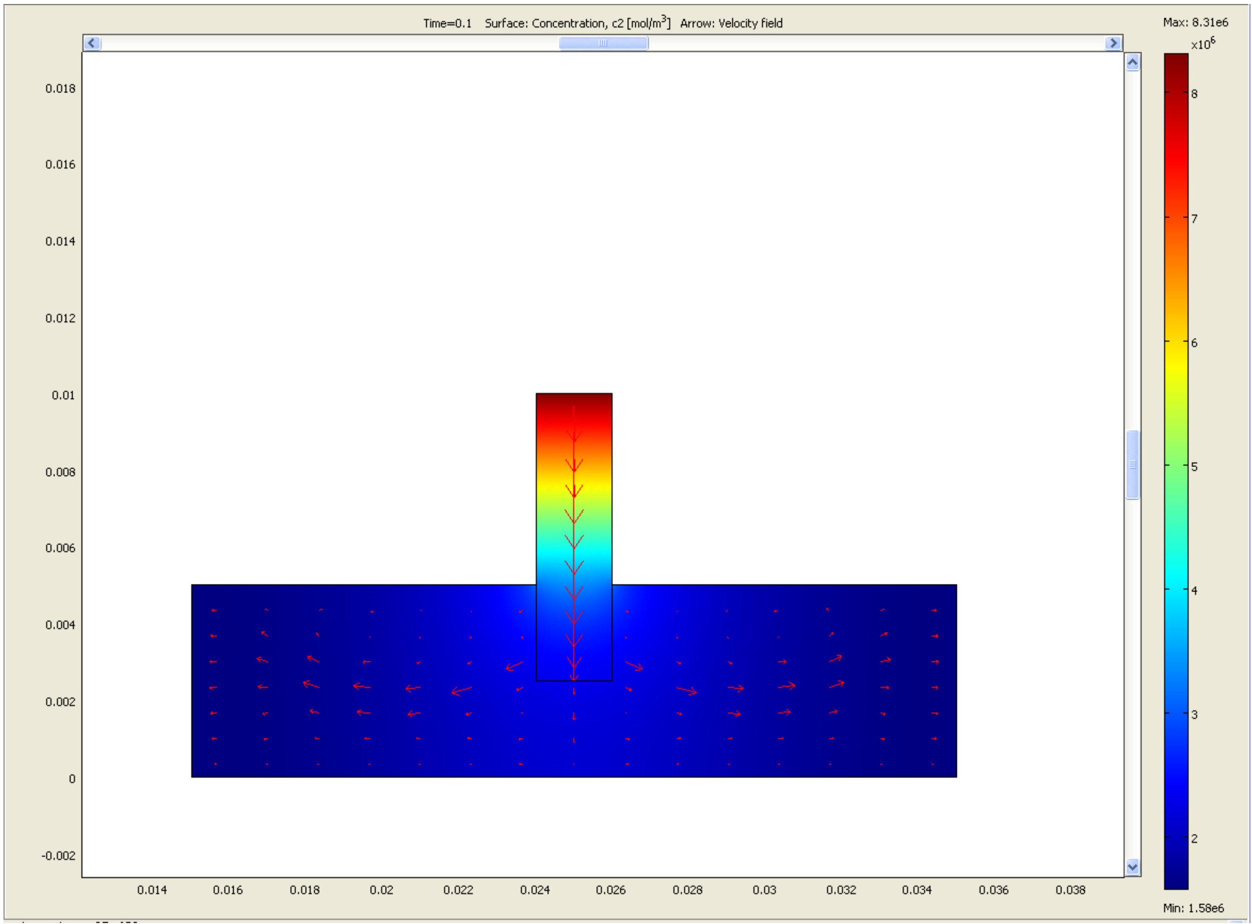


Figure 7: Diesel Concentration Distribution

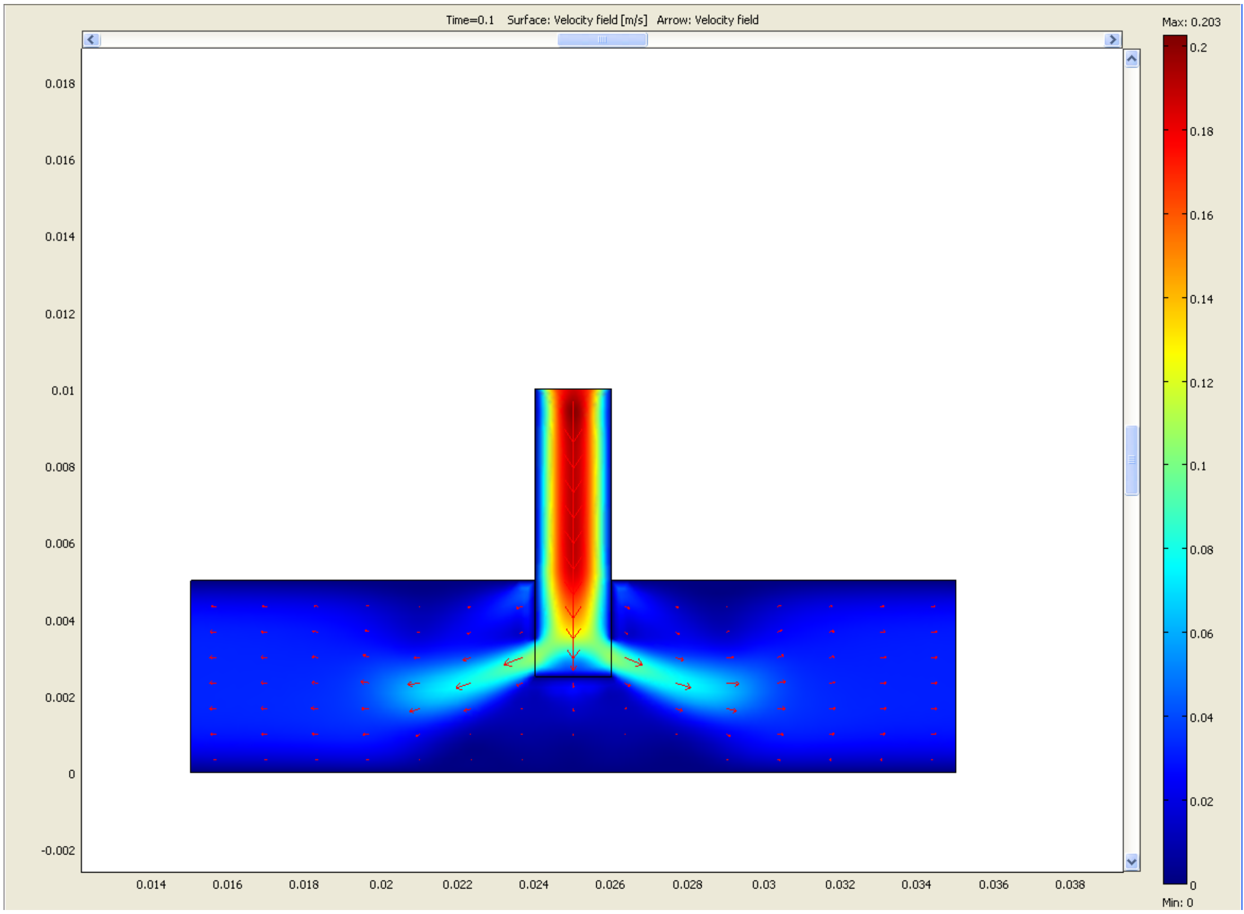


Figure 8: Velocity Distribution of Biodiesel Fuel

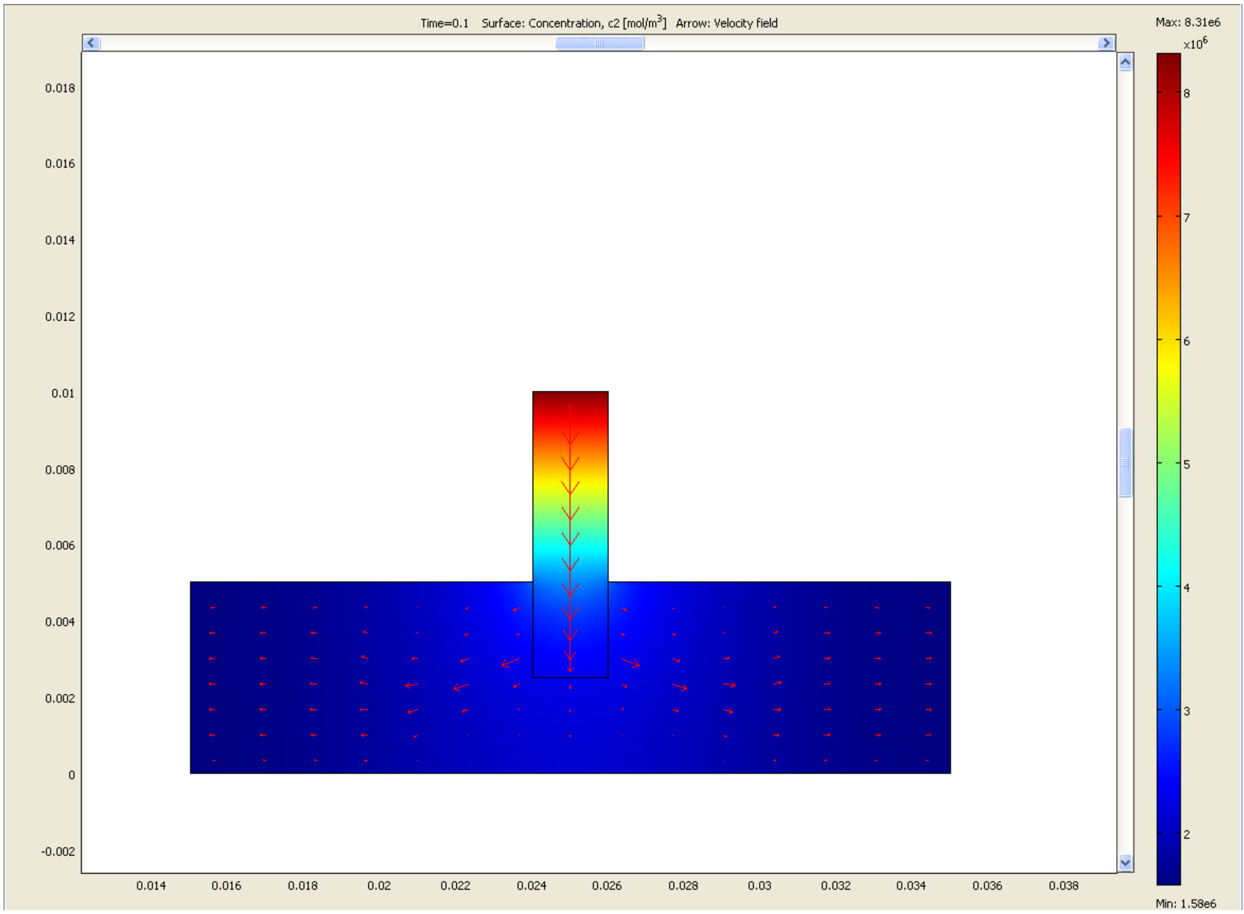


Figure 9: Biodiesel Concentration Distribution

Conclusions:

Based on the above simulations it was found that the small increase in density and viscosity of biodiesel versus petroleum diesel caused a significant change in velocity and penetration of the fuel spray in the cylinder. Unfortunately due to the inability of COMSOL to simulate turbulent flow, the final solution could not be considered representative of an actual highly turbulent diesel fuel injector spray. Results from the simulations showed a fuel spray velocity nearly three times higher for standard petroleum diesel fuel compared to biodiesel, refuting the theories of why increased engine oil dilution occurs with biodiesel compared to petroleum diesel. Observed changes in the velocity did not change the final distribution of fuel within the cylinder according to the simulation.

To simulate an actual diesel spray pattern in an engine, parameters to be included in a future model in addition to the turbulent flow are heat transfer and combustion models. After the turbulent flow parameters simulate the injection and atomization of the fuel, the heat transfer and already incorporated diffusion/advection model will simulate the vaporization and mixing of the fuel in the cylinder. Finally the combustion model is required to assure that fuel that may have deeper penetration due to the above effects is not combusted earlier in the spray.

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