

Applications of CFD Modeling in GDI Engine Piston Optimization

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ABSTRACT

This paper describes a CFD modeling based approach to address design challenges in GDI (gasoline direct injection) engine combustion system development. A Ford in-house developed CFD code MESIM (Multi-dimensional Engine Simulation) was applied to the study. Gasoline fuel is multi-component in nature and behaves very differently from the single component fuel representation under various operating conditions. A multi-component fuel model has been developed and is incorporated in MESIM code. To apply the model in engine simulations, a multi-component fuel recipe that represents the vaporization characteristics of gasoline is also developed using a numerical model that simulates the ASTM D86 fuel distillation experimental procedure. The effect of the multi-component model on the fuel air mixture preparations under different engine conditions is investigated. The modeling approach is applied to guide the GDI engine piston designs. Effects of piston designs on the fuel air mixture preparation are presented. It is found that the multi-component fuel model is critical to the accuracy of the model prediction of the fuel air preparation process, particularly under cold start conditions.

INTRODUCTION

As engine technology advances, the complexity of the new technologies makes it increasingly challenging to design and optimize combustion systems that meet both performance demands and FE and emission regulations. To design a modern gasoline engine, it is almost impossible to rely solely on the traditional experimental trial-and-error approach as the major development measure. For example, during the GDI engine cold start development, the engine needs to be cooled down to a desired low-temperature condition between two

consecutive cold-start tests. This lengthy testing process, plus the lack of physical understanding of the fuel air mixture preparation mechanism under rapidly changing transient conditions makes it very difficult to obtain an optimized cold-start strategy among a large test matrix that is a combination of sizable parameters. As another example, it is very difficult if not impossible to design stratified-charge GDI combustion system based on thermodynamic engine testing alone, without visualization and understanding of the interaction between the multi-hole spray jets and the piston top design.

By contrast, with the improvement of both accuracy of physical sub-models and computational efficiency, analytical CFD model driven upfront design and optimization process has played an increasingly important role in the combustion system development by providing physical insights of in-cylinder fuel air mixing and combustion process as well as fast turn around time in analysis of design iterations. As discussed in [1,2,3,4], an upfront design and optimization process has been developed at Ford Motor Company and has been applied to develop various DISI (direct injection spark ignition) engine combustion systems. At the core of the process is the in-house developed MESIM (Multi-dimensional Engine Simulation) CFD code. MESIM is developed based on KIVA-3V [5, 6] with an enhanced dynamic mesh moving algorithm [7]. It has improved physical sub-models including the spray atomization and vaporization models, spray wall interaction models, and wall film dynamic models [8,9,10]. Based on the work from Engine Research Center of University of Wisconsin [11], a multi-hole injector spray injection and atomization model is developed and validated with measurements from both optical bench and optical engine experiments [12]. The importance and efficiency of applying this analytical approach to the engine combustion system

design is further demonstrated by the critical role that this analytical design process played in the development and optimization of the Ford 3.5L V6 EcoBoost Engine [13,14,15].

In the past CFD simulations of GDI engines, gasoline fuel is often modeled as a single component fuel, typically iso-octane. However, gasoline fuel is multi-component in nature and behaves very differently from the single component fuel representation under various operating conditions [16, 17,18]. For example, the boiling points of components of actual gasoline fuel range from 300 to 500 K, and therefore the gasoline fuel would behave significantly differently during the vaporization process from a single component fuel that has only one boiling point. It will be demonstrated by the studies shown in this work that the multi-component fuel model is critical to the accuracy of the model prediction of the fuel air mixture preparation process, particularly under cold start conditions. To address this need, a multi-component fuel model that has been developed by the engine group of University of Illinois at Urbana-Champaign [17,19,20] is incorporated in the MESIM code. To apply the model in engine simulations, a multi-component fuel recipe that represents the vaporization characteristics of gasoline is required. In addition, the recipe needs to be limited to a small number of fuel species for computation efficiency. This is achieved by using a numerical model that has been developed in Ford to simulate the ASTM D86 fuel distillation experimental procedure [21]. A seven-component fuel recipe and a three-component fuel recipe have been developed to simulate the vaporization characteristic of the gasoline fuel. And a method of simulating the in-cylinder fuel-air mixing process during the engine cold start using multi-component fuel modeling is established [14].

The paper is organized as follows: First, the multi-component fuel models are briefly described. Next, the model predicted behaviors of the three-component fuel under several different conditions are examined in comparison with the predictions using a single component fuel model. It is identified that the multi-component fuel representation provides more accurate and consistent prediction, especially under engine cold start conditions, and the multi-component fuel modeling is necessary to the engine cold start simulations. Then, as an illustration of model application in combustion system design and optimization, some detailed analysis of fuel-air mixture preparation process for GDI engine piston top design optimizations is presented. Finally, the findings from the model studies and applications are summarized.

MULTI-COMPONENT FUEL MODEL

In past CFD simulations of GDI engines, fuel is often modeled as single component. In these simulations, iso-octane fuel is typically used under warm-up conditions because it approximately represents the middle point of the distillation curve of the gasoline fuel. Under colder condition, n-hexane is sometimes selected due to its

lower boiling temperature. As shown by the distillation curves in Figure 1, however, the distillation behaviors of single component fuels are very different from that of the actual fuel. As a result, it can be expected that using single component fuels could over-predict the fuel vaporization under certain conditions while under-predicting under other conditions.

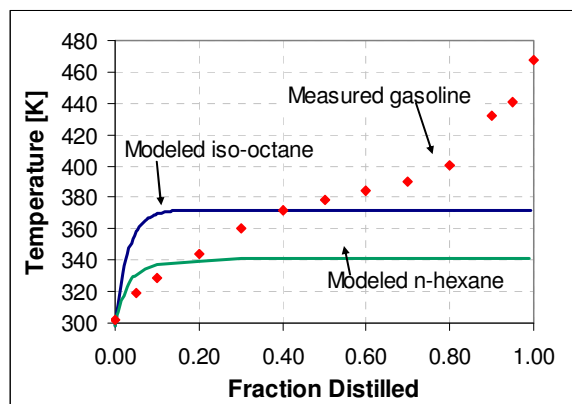


Figure 1, Comparison of distillation curves between model simulated result of iso-octane fuel and n-hexane fuel and the measurement of a gasoline fuel

Actual fuel is a mixture of many components, each having its own physical properties such as molecular weight and boiling temperature. The fuel property determines its vaporization characteristic and affects the fuel air mixture preparation and subsequent combustion process. To account for the multi-component nature of the fuel and improve the accuracy of engine CFD simulations, there is a critical need to develop multi-component vaporization model capability in a CFD code.

A multi-component fuel model has been developed and implemented into the Ford MESIM code to improve predictions of fuel vaporization and fuel-air mixing process. The model implementation is based on the work of the engine group of University of Illinois at Urbana-Champaign [17,19,20]. The model is based on discrete fuel components. The next section briefly summarizes the main features of the model. The details of the model formulations and validations can be found in the above references.

For the droplet vaporization model, the novel aspect of the model is its ability to accurately reproduce the combined effects of preferential vaporization and finite diffusion within the liquid droplet without actually resolving spatial governing equations of the mass and energy transport inside the droplet. Instead, these effects are accounted for by a set of ordinary differential equations, which describe the evolution of the non-uniform distributions of diffusion variables (i.e., temperature and mass fractions) inside the droplet. The non-uniformity is represented by the difference between surface and average values of the diffusion variables. The effect of internal circulation is also taken into consideration by using the effective diffusivities rather than the physical diffusivities. Compared to the

infinite diffusion model that is often used in the past, the current model only increases the computational time by a small proportion while improving the accuracy significantly. The film vaporization model consists of the coupling of the gas-phase and liquid-phase sub-models. The gas-phase sub-model accounts for the multi-component fuel effect on the mass and energy transports of the gas turbulent boundary layer above the liquid film. The effects of the temperature and concentration gradients due to non-uniformity inside the liquid film are represented in the liquid-phase sub-model. A third-order polynomial is used to simulate the temperature and mass fraction profiles and the governing equations for the mass and energy transports are reduced to a set of ordinary differential equations. The primary benefit of this model is the substantial decrease in computational time while producing only minor loss of accuracy compared to the model that directly solves the strict governing equations for the film.

To apply the model in engine simulations, an accurate multi-component representation "fuel recipe" that represents the vaporization characteristics of real gasoline is required. In addition, the recipe needs to be limited to a small number of fuel species for computation efficiency. The fuel recipe is developed from components commonly found in real fuels using a numerical model that has been developed in Ford to simulate the ASTM D86 fuel distillation experimental procedure [21]. The D86 simulation has been experimentally proven to accurately predict the distillation of multi-component fuel mixtures. Both seven component and three component fuel recipes have been developed to represent the actual gasoline fuel [22]. The seven component fuel has been run in a PFI multi-cylinder engine and gave equivalent fuel vaporization performance to full range gasoline. The three component fuel has been run in a motored optical engine under cold start conditions and been shown to behave very similar to full range gasoline, while a single component iso-octane fuel did not (Appendix A). In summary, Ford has developed multi-component model fuel recipes, experimentally confirmed their distillation matches real gasoline and experimentally confirmed they behave like real gasoline in both multi-cylinder thermodynamic engines and optical engines. For this study, a three-component fuel recipe is used and its composition is shown in Table 1. The model predicted distillation of the three-component fuel is compared with experimental measurements of that from a gasoline fuel. As shown in Figure 2, the agreement is good in the entire range of volume fractions distilled.

Table 1. The three-component fuel recipe

Fuel Name	Formula	Mass fraction
n-pentane	c5h12	0.22
iso-octane	ic8h18	0.58
n-decane	c10h22	0.20

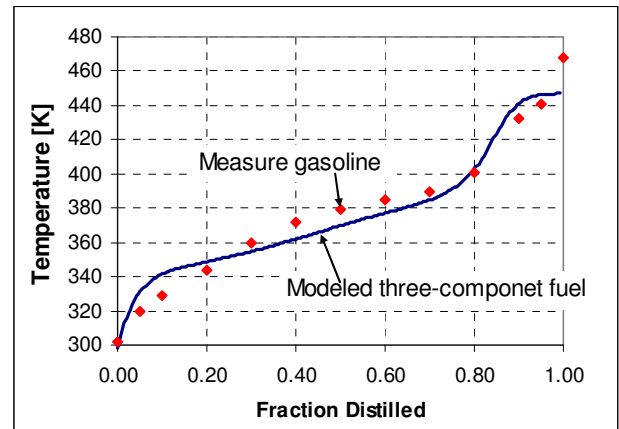


Figure 2. Comparison of distillation curves between the model simulated result of the three-component fuel and the measurement of a gasoline fuel

COMPARISON BETWEEN THREE-COMPONENT FUEL AND SINGLE COMPONENT FUELS

Fuel properties, in particular, fuel volatility affect fuel evaporation and mixture preparation. To examine the behavior of the three-component fuel in the CFD simulation, test simulations are carried out in both a closed vessel and a GDI engine combustion system domain.

The closed vessel is a cylindrical domain that has the dimension of 83 mm diameter and 150 mm height. A typical 6-hole GDI injector is used in the simulation. The injection fuel pressure, injected fuel mass and injection duration are set based on a typical engine part load condition. The simulations do not include the effect of wall impingement.

The conditions for the first test in the closed vessel are set to be ambient temperature 450 K, ambient pressure 0.5 bar and fuel temperature 314 K. The condition is representative of a GDI engine part load condition. The comparison of vapor fuel budget between the three-component fuel and two single component fuels: iso-octane and n-hexane is shown in Figure 3. The comparison shows that under this condition, n-hexane produces fastest vaporization while the three-component fuel produces the slowest due to the slower vaporization of its heavy component. As expected, results show that each different component has a different evaporation rate and light component has the fastest evaporation rate. The results also show that the vaporization rate of the three-component fuel is almost identical to that of iso-octane fuel up to 3 ms after the start of injection. Both of these two fuels vaporize relatively fast under this condition. Within the first 5 ms of the start of injection, about 82% for three-component fuel and 90% of the iso-octane vaporize. Therefore, even though there are differences in total vapor amount between these two fuels during 4-10 ms, the differences are relatively small so that using the iso-octane fuel may be sufficient in terms of predicting fuel-air mixing process under this condition.

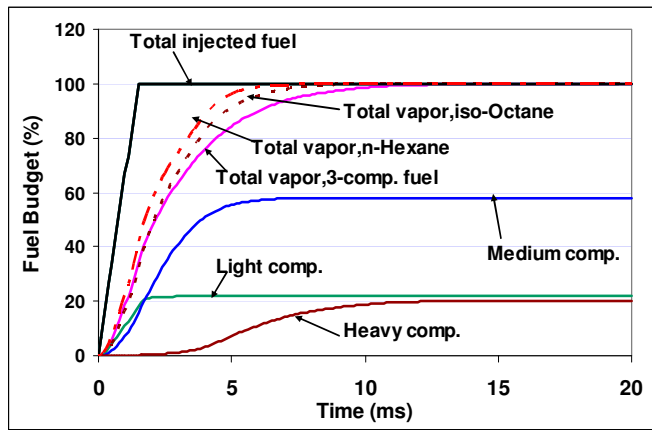


Figure 3. Comparison of fuel budget at a GDI engine part load condition between the three-component fuel and two single component fuels

In the second test, the condition is set to an ambient temperature of 550K, ambient pressure 2.2 bar and fuel temperature 314 K. The condition is similar to that of a warm up stratified-charge operating condition in a GDI engine during the compression injection. The comparison of vapor fuel budget is shown in Figure 4. As results show, with high ambient pressure and temperature, the light component evaporates almost instantaneously during the injection. Even the heavy component vaporizes only slightly slower than the iso-octane fuel. The predicted overall fuel vaporization rates of three-component fuel and single component fuels are very similar. This indicates that under this condition, the single component fuel model could be sufficient in predicting the fuel vaporization process.

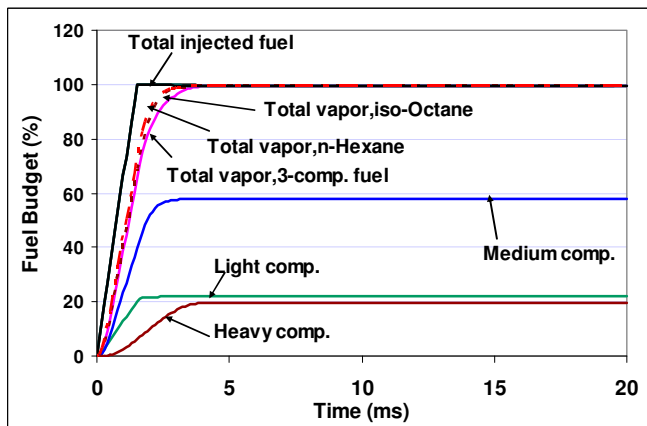
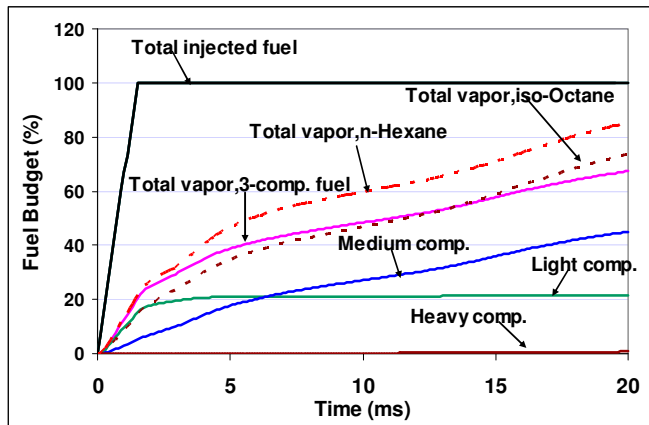


Figure 4. Comparison of fuel budget at a GDI engine late compression injection condition between the three-component fuel and two single component fuels

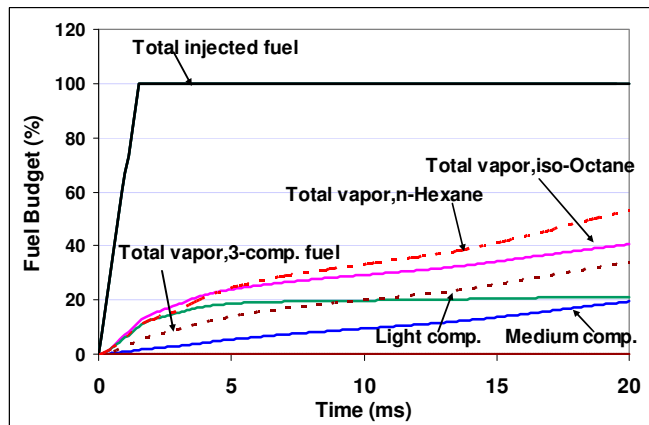
The next tests are performed for three engine cold start temperatures: 293 K, 266 K and 244 K. with an ambient pressure of 1 bar. The fuel pressure, injected fuel mass and injection duration are kept the same for comparison purposes. The Figure 5 shows the comparison of the vapor fuel budget for these three cases. At ambient temperature of 293 K, there is almost no vaporization from the heavy component of the three-component fuel. Due to the fast vaporization of the light component, the initial (0-1.5 ms) vaporization rate of the three-component fuel during the injection is almost identical to that of n-hexane fuel and is faster than that of iso-octane fuel. After the end of injection, three-component fuel and iso-octane fuel produce similar vaporization rate overall, while n-hexane fuel over-predicts the fuel vaporization under this condition.

When the ambient temperature decreases to 266 K, the light component generates larger portion (more than 50%) of the total fuel vapor for the three-component fuel, especially during the injection phase. From 0-5 ms, vaporization rate of the three-component fuel is approximately similar to that of n-hexane fuel. However, after 5 ms, n-hexane fuel over-predicts the vaporization compared to the three-component fuel. In the meantime, iso-octane fuel under-predicts the vaporization compared to the three-component fuel.

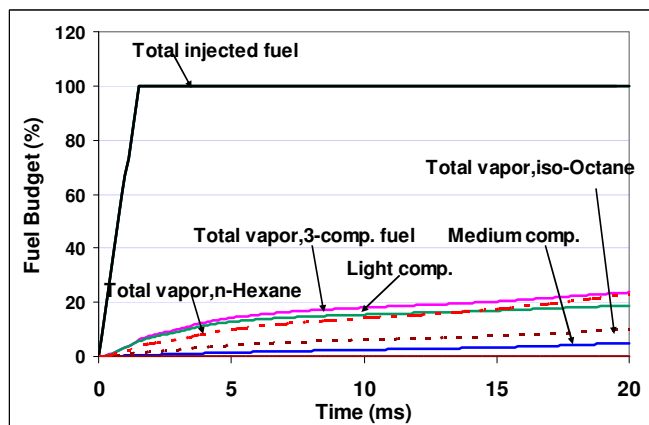
When the ambient temperature further decreases to 244 K, the light component generates the majority of the fuel vapor for the three-component fuel. Both n-hexane and iso-octane fuels under-predict the fuel vaporization. In summary, the comparisons of these three fuels under cold start conditions show that single component fuels could over-predict the fuel vaporization under certain conditions while under-predicting the vaporization under other conditions. Therefore, to make a consistent prediction under various cold start conditions, the multi-component fuel model and a fuel recipe that simulates the vaporization characteristics of real gasoline fuel are needed.



a) ambient temperature=293K



b) ambient temperature=266K



c) ambient temperature=244K

Figure 5. Comparison of fuel budget at three GDI engine cold start temperatures between the three-component fuel and two single component fuels: a) ambient temperature=293K; b) ambient temperature=266K; c) ambient temperature=244K

To examine the relative performance of the three-component fuel model under GDI engine cold start conditions, the simulations are also carried out in an

engine configuration. Figure 6 shows a domain of the combustion system of a Ford 3.5L V6 EcoBoost (D35 EcoBoost) engine including the runner, intake port, combustion chamber and the piston top. The combustion system has a side-mounted 6-hole injector and bowl-in-piston design. More details about the engine and combustion system can be found in Ref. [13].



Figure 6. The simulation domain of a D35 EcoBoost engine

In this GDI engine, the bowl-in-piston design has been developed to facilitate the clean and efficient engine crank and run up cold start operation with a split injection strategy. The fuel preparation mechanism with the bowl-in-piston design and split injection strategy is that the first pulse of injection produces a lean but more homogeneous fuel air mixture in the cylinder at the time of the compression stroke. Then the second injection will interact with the piston bowl and create a rich fuel cloud around the spark plug. The local fuel enrichment around the plug ensures stable combustion and lower NOx emissions. The details of this fuel preparation mechanism are discussed in the Ref. [14]. From the description of the mechanism, the distribution of the fuel cloud around the spark plug is the key to the combustion process. An accurate prediction of the fuel-air mixture is critical in terms of applying the modeling approach in the cold start development for the combustion system.

To examine the performance of the multi-component fuel model under cold start condition, simulations are carried out at the same three cold start temperatures as those used in the closed vessel tests: 293 K, 266 K and 244 K. Other simulation conditions are listed in Table 2. Surface temperatures are set based on the cold start temperature. The injected fuel mass is input from engine measurement under 293 K start and kept the same for the other two start temperatures for the comparison purposes. Simulations start at 60° BTDC during the exhaust stroke, continue through the intake stroke and the compression stroke and end at TDC of combustion.