

Model Based E85 Cold Start Optimization for DISI Engines

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ABSTRACT

The startability of SI engines, especially of DISI engines, is the greatest challenge when using ethanol blended fuels. The development of a suitable injection strategy is therefore the main engineering target when developing an ethanol engine with direct injection. In order to limit the test efforts of such a program, a vaporization model has been created that provides the quantity of vaporized fuel depending on pressure and on start and end, respectively number and split relation of injections. This model takes account of the most relevant fuel properties such as density, surface tension and viscosity. It also considers the interaction of the spray with cylinder liner, cylinder head and piston. A comparison with test results shows the current status and the need for action of this simulation model.

INTRODUCTION

When it comes to reducing CO₂ emissions from road traffic, the next few years will see a growth in the significance of bio fuels. Furthermore, growing market penetration of bio-fuels might reduce the extent to which road traffic depends on crude oil. Next generation bio-fuels can be produced from non-food feed stocks to reduce the competition between food and fuel. For SI engines, ethanol is currently the dominating alternative fuel. It might replace a considerable share of gasoline in the next decades [1]. Typically, ethanol is blended with gasoline in order to limit the minimum vapor pressure. So called Flex Fuel Vehicles are capable of running with blends of up to 85% ethanol. There are some

advantages to using these blends for SI engines, such as high knock resistance or high evaporation heat, but there are also some drawbacks as well. One of the most important handicaps of ethanol is the poor cold start ability due to low vapor pressure. This problem occurs particularly with direct-injection engines as there is only little time for mixture formation within the cylinder. As pre-heating systems are often not fast enough and cause increased design effort and costs, a suitable strategy has to be defined for enhancing cold start behavior. The main task of this strategy is to provide enough vaporized fuel at the point of ignition, even at very low temperatures.

MAIN SECTION

FUEL PROPERTIES AND THEIR INFLUENCE ON COLD START MIXTURE FORMATION

When using ethanol-based fuels in spark-ignition engines, the enhanced antiknock resistance resulting from a higher octane number and the far higher enthalpy of vaporization, particularly in view of the different calorific values, must be seen as extremely positive. On the other hand, the high enthalpy of vaporization has a negative impact on cold start mixture formation at low temperatures.

Altogether, cold start mixture formation with E85 fuel deteriorates compared to gasoline primarily with regard to the following properties:

- Reduced vapor pressure
- Higher enthalpy of vaporization
- Greater increase in viscosity at decreasing temperatures.

In principle, the properties are proportional to the share of ethanol in the fuel.

The influence of the ethanol share on vapor pressure is known. As an example, Figure 1 shows the vapor pressure curves for winter gasoline, E85 (winter fuel with 80% ethanol) and pure ethanol at low temperatures.

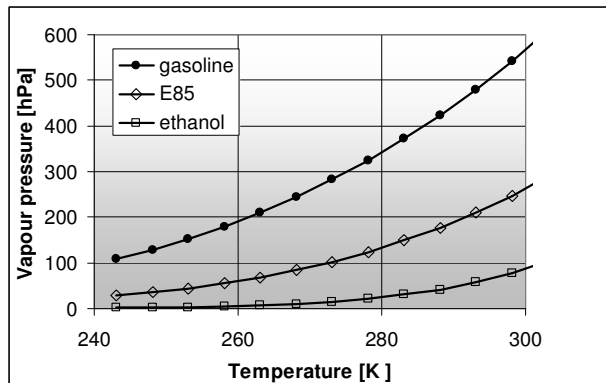


Figure 1: Fuel vapor pressure as a function of temperature

The specific enthalpy of vaporization for pure ethanol is about twice as high as for gasoline; in E85 with 80% ethanol share, this results in a specific value which is about 81% higher. In addition, the different specific calorific value is taken into account, resulting for E85 in a 2.61x enthalpy of vaporization referred to the same quantity of energy.

As temperatures fall, the viscosity of ethanol and E85 undergoes a far greater increase than gasoline (Figure 2).

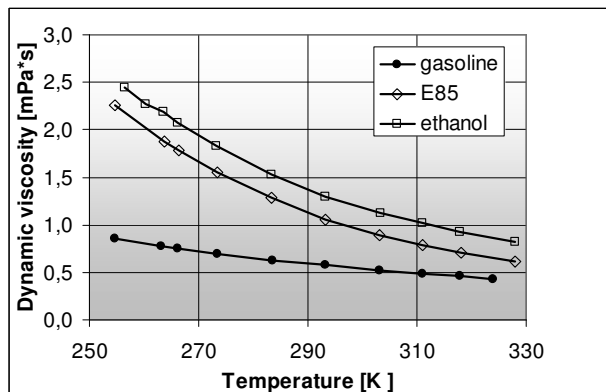


Figure 2: Dynamic viscosity as a function of temperature

This results on the one hand in a marginally lesser injector flow at the same rail pressure, for the higher viscosity η_{Fl} of the flowing fluid results in a smaller Reynolds number according to (Equation 1):

$$Re_{Fl} = \frac{a \cdot w'_a \cdot \rho_{Fl}}{\eta_{Fl}} \quad (\text{Equation 1})$$

In turn, the smaller Reynolds number indicates a thicker boundary layer of the flow in the injector nozzle and thus a smaller effective cross section.

On the other hand, the higher viscosity indicates a slightly deteriorated primary disintegration of the injection spray. According to Ohnesorge, disintegration of the spray is more intensive, the higher the Reynolds and Ohnesorge number of the spray (Figure 3, according to [2]). While calculating the Reynolds number (Equation 1) gives linear consideration to viscosity in the same way as when calculating the Ohnesorge number (Equation 2),

$$Oh = \frac{\eta_{Fl}}{\sqrt{a \cdot \rho_{Fl} \cdot \sigma_{Fl}}} \quad (\text{Equation 2})$$

as viscosity increases, the type of disintegration more closely approximates Rayleigh disintegration (Figure 3).

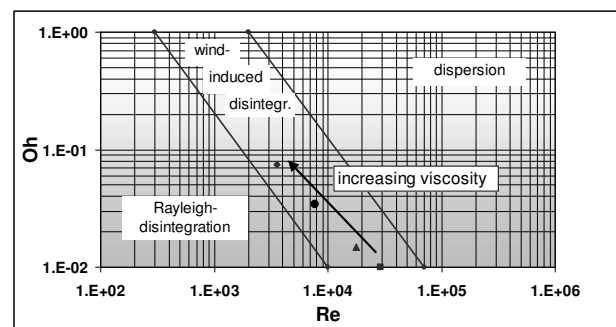


Figure 3: Impact of fuel viscosity on spray disintegration

To summarize, it can be said that the lower vapor pressure, higher enthalpy of vaporization and higher viscosity of E85 essentially impair cold start mixture formation. This is also indicated by the results of optical spray tests in the pressure chamber. It transpires that the spray has a more stringy form and that vaporization takes place more slowly.

SIMULATION MODEL REQUIREMENT

DI spark-ignition engines offer the possibility of high-pressure injection into the working gas of the combustion engine with the gas already pre-heated by compression. This means that in spite of the poorer cold start fuel properties of E85, a reliable cold start can still be warranted even at low temperatures without additional measures such as fuel pre-heating. However, there is also a risk of intensive wetting of the cylinder walls, which can result in a correspondingly high entrainment of fuel to the engine oil and possibly even mechanical damage of the cylinder liners. In addition, in order to minimize emissions of carbon monoxide, harmful hydrocarbons and particulate matter at the start, it is necessary to minimize the fuel quantity required for a reliable start in the first injection cycle to avoid wetting the wall as far as possible.

Modern direct-injection systems for spark-ignition engines always offer the following degrees of freedom:

- Number of injections
- Split relations of injections
- Start or end of injection
- Fuel injection pressure.

In addition, some systems also offer degrees of freedom regarding the current profile of the injector actuation and thus of the needle lift. All parameters are also to be ideally calibrated for all relevant start temperatures.

Based on empirical values and any possible technical limitations (e.g. possible number of injections per cycle, speed of rail pressure build-up), it is possible to restrict the parameter space. But ascertaining the optimum configuration of all parameters just by tests is extremely time-consuming and takes up extensive test-stand capacities. Consideration should also be given to the fact that a long conditioning phase is necessary after every single start attempt, particularly at very low temperatures, in order to warrant reproducibility of the tests. This clearly shows that a suitable simulation model is practically vital for pre-optimization of the individual parameters.

SIMULATION MODEL DESCRIPTION

An evaporation model has therefore been developed which takes account of all major parameters of the engine process (air and fuel mass, temperatures, pressures, piston position) together with the relevant fuel properties and characteristics of the fuel spray under stipulated marginal conditions. The task of the model is to evaluate whether the chosen parameters will result in an ignitable mixture in the combustion chamber at the selected ignition point.

In principle, CFD simulation is suitable for advance calculation of mixture formation in the combustion chamber. Spatial resolution permits visualization of the inhomogeneity of the mixture distribution and, in particular, the fuel/wall interaction. However, this method does have the following major drawbacks:

- Model comparison entails optical measurements of great complexity, particularly for necessary quantification of the vaporous fuel.
- A huge workload is involved in pre- and post-processing alone for the extensive parameter variations that are necessary in view of the large number of degrees of freedom. In addition, even with state-of-the-art computers, the required computing times are too large to permit an adequately wide parameter variation in a short period of time.
- The results from CFD simulation can only be transferred to other engine concepts (other injector position, other spray geometry, changed piston geometry, etc.) to a limited extent, i.e. a very large workload will again be involved in optimizing other engine concepts.

While a simulation method without spatial resolution only permits limited detail accuracy, a fundamental prediction of a spatially averaged state in the cylinder (as a result of thermodynamic effects) is quite sufficient when looking for an optimum within a very large parameter space. In addition, a simulation program without spatial resolution can be supplemented by adding functions to consider fuel/wall interaction, as indicated below. The results shown here can be obtained using a simulation program without complete spatial resolution.

The starting point consists of a program package for work process simulation used at IAV which has been supplemented for simulating cold starts with alternative fuels.

Spray characterization

The central starting point for resilient simulation of fuel evaporation is the size of the injected fuel droplets. Given that no satisfactory results were obtained using known empirical methods for ascertaining the Sauter mean diameter (SMD) on the basis of injection pressure, injector geometry and fuel data ([3], [4]) an option was integrated for stipulating SMD or droplet size distribution.

Droplet size distribution and SMD for the used injector type were ascertained in a pressure chamber for observing the injection spray using a Malvern SprayTec unit. E85 fuel was used for the tests, which measured droplet size distribution for cooled fuel at the major injection pressures and chamber temperatures and pressures. Figure 4 shows exemplarily a measured droplet size distribution used for the simulation.

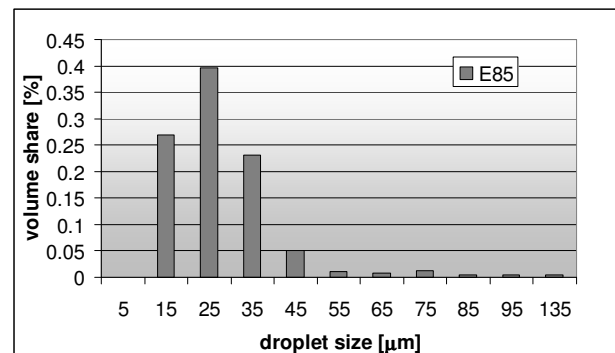


Figure 4: Fuel droplet size distribution for the used injector under cold start conditions

In addition, Schlieren measurements were carried out to characterize the spray geometry over time.

Evaporation model

One core aspect of the simulation model is to reproduce fuel vaporization and evaporation for individual droplets in the following steps:

1. Heating the droplet up to a given vaporization temperature