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The influence of flash-boiling on spray-targeting and fuel film formation

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ABSTRACT

The variety of fuels used in GDI engines is constantly increasing. This affects the combustion process because the spray formation and the mixture preparation is greatly influenced by the fuel properties. In particular, the reduction of the saturation temperature is promoting the so-called flash-boiling effect, when the bulk liquid or a component of the fuel mixture becomes superheated during the injection into the low-pressure combustion chamber.

This study reveals the enormous influence of flash-boiling on the spray/wall interaction and the consequent deposition of fuel wall films. This is of major importance because the formation of wall films must be avoided, since they are the main route to soot particle emissions.

In order to increase the understanding of the wall film formation the spray/wall interaction is investigated under conditions representative of a homogeneously charged gasoline engine. Gasoline and isooctane are injected using a modern six-hole nozzle. Emphasis is placed on the influence of the initial fuel temperature. Using high-speed imaging and infrared thermography, the spray propagation, the spray-targeting and the evaporation duration of the wall films are analysed.

It is found that increasing the fuel temperature does not lead to a constant reduction of the wall film problem. Rather, the flash-boiling-induced 'contraction' of the spray leads to an accumulation of the wall film mass in a small area. This delays the evaporation process to a great extent and can lead to increased soot particle emissions. From the results, a critical value of the degree of superheat is identified and the findings transferred to various single component fuels, in order to avoid undesired fuel film accumulation.

1. Introduction

The essential objectives of the development in the field of gasoline engines with direct injection are the reduction of pollutant emissions and fuel consumption. Previous investigations showed a crucial influence of mixture formation on these two issues. Here the generation of a homogeneous air/fuel mixture is based on an effective atomisation and rapid evaporation of the fuel. Due to the limited combustion chamber volume it is common that spray droplets reach the piston or the cylinder walls during the injection. This process of droplet impingement has a big influence on the mixture formation and it becomes even more probable because of the reduction of combustion chamber volume – due to the ongoing effort of engine downsizing – and increasing rail pressures.

When the spray droplets impinge on the combustion chamber walls a fuel film can develop. This fuel accumulation delays the evaporation and generates a fuel rich zone above the film. It is known that such fuel rich zones are the major source for the formation of soot particles [1,2]. Newer emission standards (e.g. EU6 Emission Standard) also include a limit for the particulate number. Therefore, the avoidance of soot emissions came also into the focus of the development of GDI engines.

In order to reduce soot emissions, the occurrence of fuel wall films has to be prevented. Due to the complexity of the spray/wall interaction a forecast of the wall film behaviour is very difficult. To gain a deeper understanding of the wall film formation the influence of rail pressure, cylinder temperature, fuel type, cylinder pressure, injection timing, spray impingement angle and wall temperature has been identified in extensive studies, see, e.g. [3–6].

Another, less well investigated parameter which has a significant influence on the mixture formation and the wall film formation is the fuel temperature. This is gaining in importance, especially considering the trend of engine downsizing and increasing power density, which increases the thermal load on combustion chamber walls. Under certain engine operation conditions this leads to high fuel temperatures within the nozzle.

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Nomenclature

DISI	direct-injection spark-ignition
$d_{noz/wall}$	distance btw nozzle and wall
GDI	gasoline direct injection
IR	infrared
RON	research octane number
s	specific entropy
p_{rail}	rail pressure
p_a	ambient pressure
p_s	saturation pressure
t_{asoi}	time after start of injection
ϑ_{inj}	initial fuel temperature

If the fuel temperature inside the nozzle exceeds its saturation temperature – in relation to the cylinder pressure during the injection – the so-called flash-boiling effect will occur [7]. Here a part of the injected fuel will promptly evaporate, due to the rapid pressure drop during the injection process.

This influences the spray properties and the desired orientation of the spray can change [8]. Under certain conditions flash-boiling leads to the total collapse of the spray. Such flash-boiling conditions are common in homogeneously operated DISI gasoline engines [9], because throttling can reduce the cylinder pressure below the (temperature dependent) vapour pressure of gasoline.

The effect of the initial fuel temperature on spray formation had been studied for Diesel applications [10–12] and for gasoline sprays injected by swirl injectors [13–15]. When multihole injectors began to be used in modern gasoline engines, it was necessary to investigate these as well. It was found, that increasing fuel temperature decreases the droplet size [16–18], influences the penetration and spray angle [19–22]. Simultaneously, the internal flow in an orifice has been investigated [23–25]. Recent studies focus on the effect of fuel temperature on different fuel blends, especially ethanol blends [26–28,21,22].

Although most authors link flash-boiling with significant changes in the orientation of the spray plumes, the cross-section the spray of multihole gasoline nozzles has hardly been systematically investigated. One reason is probably that it is difficult to access the inner structure of the spray due to the strong multiple scattering of the dense outer spray regions. Therefore eight-hole nozzles have been investigated by the group around Xu and Zhang [19,17] applying a light-sheet and injecting n–hexane, while Parrish et al. [29] applied an optical patternator and injected Indole, but not reaching the flare-flash stage. Aori elt al. [30] used n–hexane to investigate the spray plume orientation of different nozzle configurations. The targeting change in an optical engine was measured by Serras-Pereira et al. [31] using different fuels but only for two initial fuel temperatures. The systematic variation of the degree of superheat using iso-octane – as commonly used substitute fuel – will allow the comparisons and the extrapolation of other measurements performed under non-flashing conditions. Therefore we choose iso-octane and additionally gasoline (RON95) to be able to show differences to real fuel behaviour.

But practical applications differ from the classical spray-targeting experiments using light-sheets, because in an engine the spray movement and the total fluid flow is interrupted by the cylinder walls. This becomes important for the process of wall film formation. To visualise the changes of the spray-targeting on a surface and the resulting wall films a method based on infrared thermography was applied. This technique determines the temperature changes at the wall surface during spray impingement and the shape of the fuel wall films. In practical application one of the most important wall film properties is the evaporation duration, because this will dominate the liquid residuals on the wall at the start of ignition. Therefore we performed high-speed imaging to analyse the effect of the degrees of superheat on the film evaporation duration.

Although the advantages of flashing sprays (e.g. smaller droplets) are known, in modern engines the fuel is not heated up to reach intense flash boiling. The reason for this is, that it is known that this will not reduce but significantly increase the emission of unburned hydrocarbons and soot particles under certain operation conditions. Considering the current knowledge, the depth of penetration of a spray in the flare-flash stage might increase but the overall liquid fuel mass, which reaches the wall, will decrease due to intensified evaporation. Therefore the fuel mass deposited on the wall surface should decrease and can not be the reason for increased emissions – but what is the reason for the increase of the emissions?

With the data presented in our paper for the first time a reasonable answer is given to the question above. Furthermore the present study shows the tremendous influence of the degree of superheat: on the spray-targeting directly on a wall surface, on the wall film formation, on the resulting wall temperature profile and on the evaporation duration.

2. Set-up and method

The present study focuses on the influence of the initial fuel temperature on wall films using high-speed imaging of the spray and infrared thermography of the wall. The experimental set-up illustrated in Fig. 1 was applied to simulate the injection process of a centrally positioned injector under the conditions representing those of homogenously charged gasoline engines. Here, the piston was substituted by a thin, heated plate, which allows the detection of the local temperature changes on the surface. For this, an IR8800 infrared camera (Infratec) was positioned underneath the heated plate.

The plate consists of the nickel alloy Inconel 600 and measures $100 \times 150\,\text{mm}^2$. Due to its high electrical resistance, Inconel 600 can be heated by means of an electrical current. To achieve a high emissivity, the plate is coated with a thin graphite layer at the

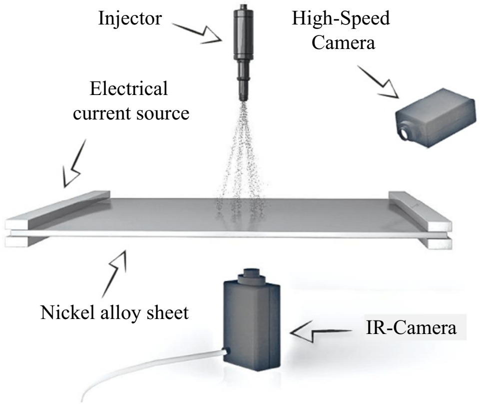

Fig. 1. Schematic experimental set-up.