Supercritical Fuel State as Solution for Spark Ignition Engines with LPG Direct Injection

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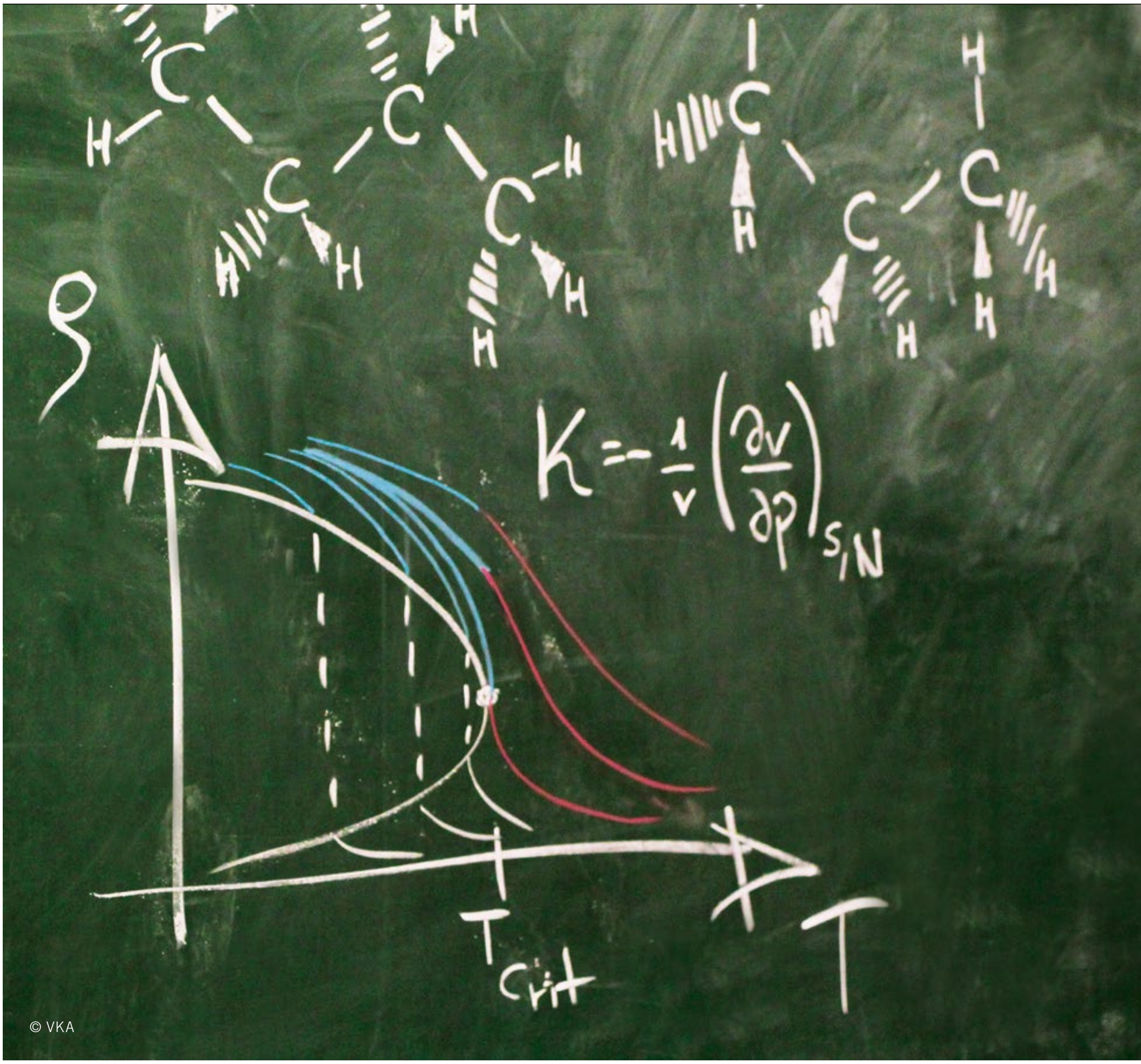
The high vapor pressure of C_3 and C_4 hydrocarbons in Liquefied Petroleum Gas (LPG) can induce fuel evaporation in the high or low pressure side of the high pressure pump (HPP) of an LPG direct injection system. This results in rapid density reduction and thus engine stall. Within the scope of the FVV project LPG direct injection executed at the VKA at the RWTH Aachen University and the IAP at the University of Applied Sciences Saarland the supercritical fuel state has been investigated as a potential solution for advanced LPG direct injection systems for modern spark ignition engines without any fuel cooling measures.



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1 MOTIVATION

In Europe, LPG is the most utilised alternative fuel for automotive use with an already adequate core infrastructure in place [1]. From a combustion perspective, LPG is an interesting alternative fuel for modern spark ignition engines, due to its high knock resistance compared to gasoline [2]. Especially direct injection of LPG allows high torques at low engine speeds in comparison to external LPG mixture formation systems [3].

The biggest challenge for the direct injection of LPG is the hot fuel handling. When using a state of the art gasoline mechanically driven high-pressure fuel pump to pressurise LPG fuels, the high vapor pressure, especially of propane and propene, can result in evaporation of LPG upstream or inside the HPP, due to heat transfer from the engine to the pump. As a result the engine stalls. This is particularly relevant under hot soak conditions. One potential solution is an increased HPP inlet pressure and to use the supercritical fuel state in order to avoid the gaseous state of the fuel.

2 RESEARCH ENGINE AND LPG FUELS

For the investigations a 1.6 l four-cylinder turbocharged gasoline engine with direct injection was provided by Ford [4]. The engine was set up on an idle rig inside a climate chamber. The conventional gasoline high pressure injection system was used without any fuel return line for direct injection of the LPG fuels. The injection system was equipped with external heating collars and several thermocouples in order to perform investigations under realistic hot soak conditions. An additional middle-pressure pump was applied upstream of the HPP in order to pre-compress the LPG fuels to a pressure level of 30 to 60 bar.

Four different LPG fuels according to EN 589 [5] were used for the investigations of supercritical LPG, **TABLE 1**. LPG 1 had the highest C_3 content according to EN 589 [5] and consisted mainly of propane and propene. This fuel offered the lowest critical temperature of all tested LPG fuels. LPG 2 represented a winter grade LPG (with a propane content of about 70 %), whereas LPG 3 and LPG 4 were homologation fuels according to R 83 [6]. The motor octane numbers (MON) of all LPG fuels were calculated according to EN 589 [5], while the methane numbers (MN) were calculated according to FVV 2-235 (AVL method) [7, 8].

–	LPG 1	LPG 2	LPG 3	LPG 4
Motor octane number (EN 589)	89.3	94.5	93.2	91.5
Methane number (AVL method)	26	28	31	15
Density (20 °C) [(kg/m³)]	508	522	515	556
at pressure [bar]	9.4	7.1	7.9	4.5
Critical pressure [bar]	44.7	42.6	43.8	41.7
Critical temperature [°C]	93.6	113.7	102.8	133.6
Propane [% (m/m)]	48.3	68.2	82.1	16.1
Propene [% (m/m)]	50.2	0.1	0.2	8.2
n-Butane [% (m/m)]	0.4	20.9	2.3	50.7
Isobutane [% (m/m)]	0.7	10.1	1.6	24.6
C_4 olefins [% (m/m)]	–	0.1	12.9	0.2

TABLE 1 Fuel properties (© VKA)

3 RESULTS

Hot idle investigations with supercritical LPG regarding hot fuel handling issues were conducted with HPP inlet pressures higher than the critical pressure of LPG 1 to LPG 4. During long hot idling phases a rail pressure drop was observed at certain fuel temperatures inside the HPP dependent on the LPG fuel. **FIGURE 1** exemplarily shows the warm-up phase with LPG 1. This fuel can be seen as the worst case LPG fuel with regard to hot soak and hot idle conditions due to the high C_3 content. **FIGURE 1** shows, that high oil and coolant temperatures in the range of 110 °C were reached during constant idling at 800 rpm. At the inlet of the HPP,

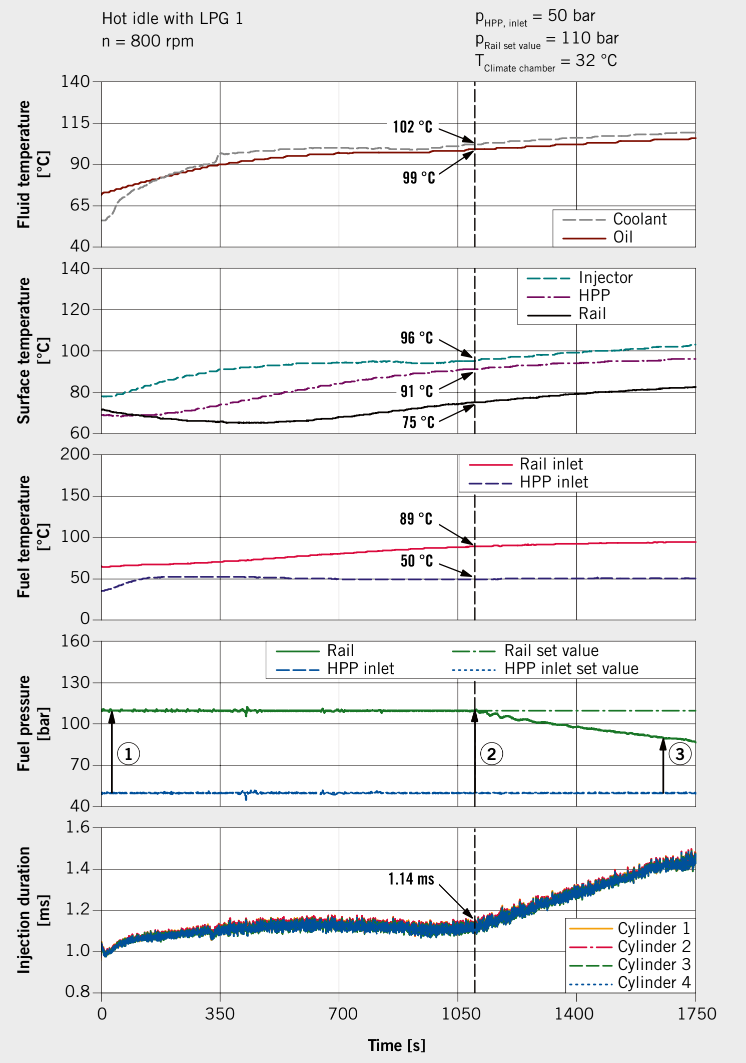

FIGURE 1 Warm-up phase with LPG 1 (© VKA)

the fuel temperature was conditioned to 50 °C, while the fuel pressure was set to 50 bar leading to liquid or supercritical fuel state depending on the fuel temperature. Outgassing of the fuel was therefore prevented. As the fuel flew downstream, it was heated and the fuel temperature increased steadily with continuous engine warm-up. This was indicated by the fuel temperature at the inlet of the fuel rail, which reached 94 °C at the end of the measurement. The fuel rail pressure was set to 110 bar.

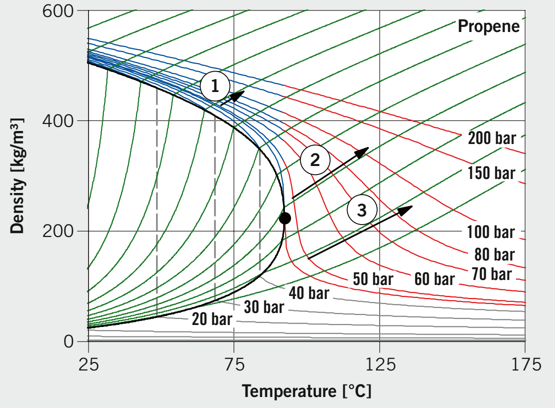

FIGURE 2 Isobaric densities [9] and isentropes of propene [10] with three estimated isentropic changes of state of LPG 1 (© VKA)

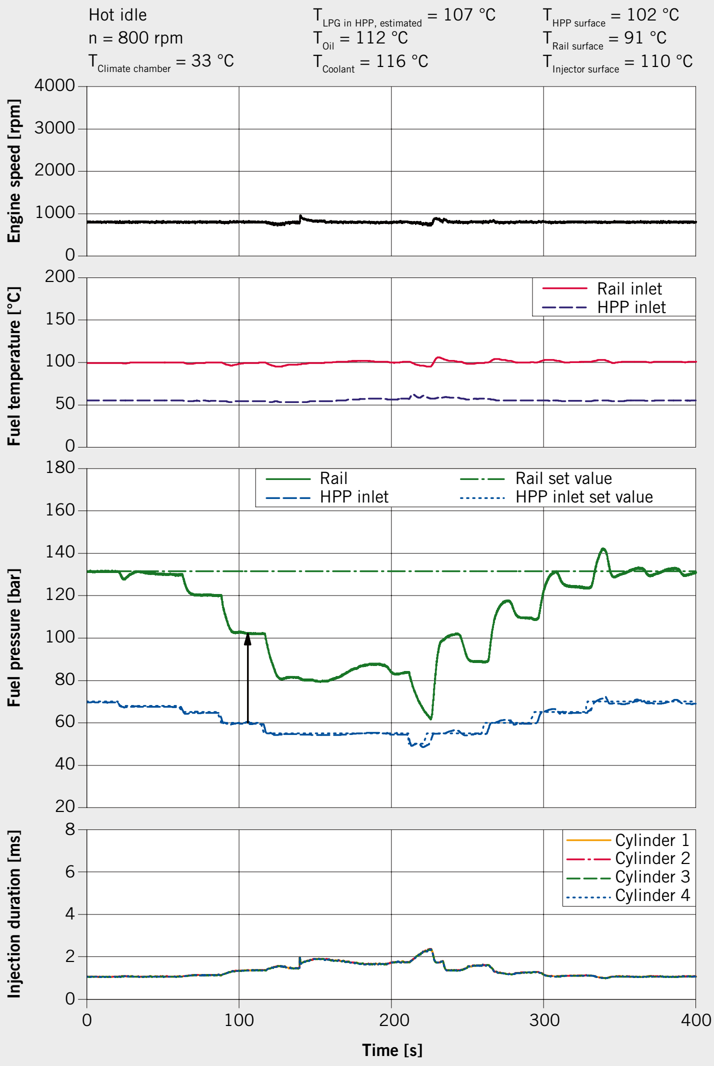

FIGURE 3 Variation of the inlet pressure of the HPP with LPG 1 (© VKA)

In **FIGURE 1**, the fuel pressure increase from the low pressure level of 50 bar to the rail pressure is illustrated exemplarily by three arrows in the diagram of the fuel pressure. Up to 1125 s, the HPP was able to deliver the required rail pressure. Afterwards a clear rail pressure drop can be observed. This can be explained by means of **FIGURE 2**, which contains the isobaric density diagram of propene as an approximation for LPG 1. Besides the isobars and the two-phase region, which ends in the critical point at 92.4 °C, the isentropes are depicted. The isobars of pressures higher than 46.6 bar show a rather constant density gradient up to 80 °C. Between 80 and 140 °C the isobars of 46.6 bar to 80 bar show a heavily nonlinear behaviour.

The three highlighted arrows in **FIGURE 2** represent estimated changes of state due to a compression by the HPP and correspond to the arrows in **FIGURE 1**. Thereby compression is considered to be isentropic. Furthermore, at the beginning of the compression the state of the fuel is described by the estimated fuel temperature inside the HPP and the pressure at its inlet. The fuel temperature inside the HPP was estimated to be an average of oil temperature and HPP surface temperature, since the HPP was exposed to the temperature of the climate chamber and its piston was driven by cams of the exhaust camshaft, which were in turn lubricated by the warm oil of the engine. Due to the fuel heating process, the estimated temperature of LPG 1 inside the HPP was 70.5 °C at the beginning of the warm-up phase. The changes of state at this temperature correspond to arrow 1 in **FIGURE 1** as well as in **FIGURE 2**. Thereby, the HPP was able to pressurise the fuel from 50 bar to the required rail pressure of 110 bar. Arrow 2 illustrates the change of state at the beginning of the rail pressure drop at an estimated fuel temperature inside the HPP of 95 °C. Finally, arrow 3 shows the change of state at an estimated fuel temperature inside the HPP of 100.5 °C. At this time, the HPP was only able to pressurise the fuel from 50 to 89 bar. The rail pressure drop with increasing temperatures can be explained by two reasons. Firstly, the strong decrease of density resulted in a reduced filling of the cylinder of the HPP, which in turn limited the maximum deliverable mass flow to the fuel rail. Secondly, the isentropic compressibility is increased as can be seen by the increasing distance between each isobar at temperatures higher than the critical one.

One measure to increase the reachable rail pressure was an increase of the HPP inlet pressure. This possibility has been analysed in an experiment, which is shown in **FIGURE 3** for LPG 1. The experiment consists of a variation of the HPP inlet pressure at high fuel and engine temperatures, which were set prior by the warm-up phase at 800 rpm, **FIGURE 1**. Lowering the HPP inlet pressure results in a severe decrease of density and an increasing compressibility. While increasing the HPP inlet pressure, gas dynamic effects and rail pressure fluctuations become visible.

To evaluate an LPG DI concept using a state of the art high-pressure fuel pump, the necessary HPP inlet pressure for reaching a rail pressure of 100 bar was measured for LPG 1 to LPG 4 after the warm-up by varying the fuel pressure. For LPG 1, this corresponds to a minimum pressure of 60 bar, read off at the arrow in the fuel pressure diagram in **FIGURE 3**. The required inlet pressure strongly depends on the C_3 content of the LPG fuel. A fairly

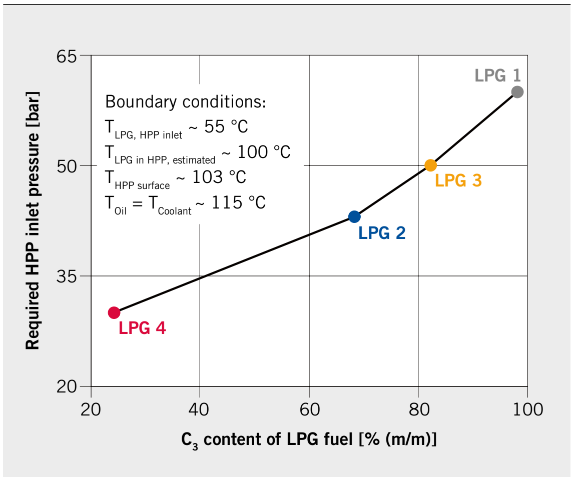

FIGURE 4 Correlation of the required HPP inlet pressure and propane/propene content of all tested LPG fuels [11] (© VKA)

linear trend can be noted in **FIGURE 4**. The higher the propane/propene content, the higher is the required pressure upstream the HPP. This is due to the compressibility increase and the density drop of the contained C_3 hydrocarbons around 100 °C compared to the butanes/butenes. Thus, for the given boundary conditions, a maximum content of 70 % (m/m) propane/propene can be recommended for an LPG DI concept using a state of the art HPP. This corresponds to LPG 2, which is the typical winter LPG fuel. In that case, the pressure at pump inlet has to be set to ~ 45 bar. However, it has to be noted, that state of the art HPP's ability to face high inlet pressures is limited and an optimised pump design for LPG DI might be highly recommended.

4 SUMMARY

Considering an LPG DI system without cooling measures, HPP inlet pressures above the critical pressure of four LPG fuels according to the current fuel standard EN 589 were investigated as a potential solution for advanced LPG DI systems. For a maximum propane/propene content of 70 % (m/m), pump functionality at hot soak fuel temperatures of about 110 °C can be maintained with a pressure of approximately 45 bar upstream the used gasoline HPP.

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