Influence of modern diesel cold start systems on the cold start, warm-up and emissions of diesel engines

Dr.-Ing. Bernd Last, Dipl.-Ing. Hans Houben, Dipl.-Ing. (BA) Marc Rottner, Dipl.-Ing. Ingo Stotz, BERU AG, Ludwigsburg

1 Introduction

Today the diesel engine is the power source with the lowest specific fuel consumption and is essential in the global reduction of carbon dioxide emissions. The success of the diesel engine is due to a precisely controlled combustion process and high technology exhaust after treatment. This combination yields very low fuel consumption combined with the lowest possible emissions. In order to support these low emission targets, the compression ratio of many of the new generation Diesel engines is around 16:1. This creates cold start and warm-up problems, which can be resolved with BERU technology.

In Europe, systems like BERU Instant Start System with the ability to have gasoline-like key-start without waiting, stable idling, instant transient reaction without visible smoke have set the standard by which all others are to be judged. For the North American market there are similar goals, but with an even heavier emphasis on visible smoke.

Besides additional requirements of fuel quality the application of optimized cold start systems are necessary to overcome the effects of the reduced compression ratio effectively.

This article describes the functionality and potential of modern cold start systems.

2 Cold start of a diesel engine

All engine situations when the engine and the fluids have not reached operating temperature are deemed to be cold starts. At temperatures below 60°C changing the injection timing and amount is required. These changes should optimize the combustion stability and reduce the emissions during the warm-up phase of the engine. Temperatures below 0°C require further and more radical changes. The starting quality will strongly decrease depending on lower ambient temperatures up to the point where an engine start is not possible anymore. [1]

The cold start and warm-up phase of the engine depends on the engine characteristics like displacement, compression ratio, battery size and charge state, starter and auxiliary equipment, the injection system and the cold start aids. The characteristics of the engine oil, fuel, air system and the transmission all have an influence on the cold start and warm-up phase.

Figure 2-1 shows the most important engine parameters that influence the cold start quality and the connection between these parameters.

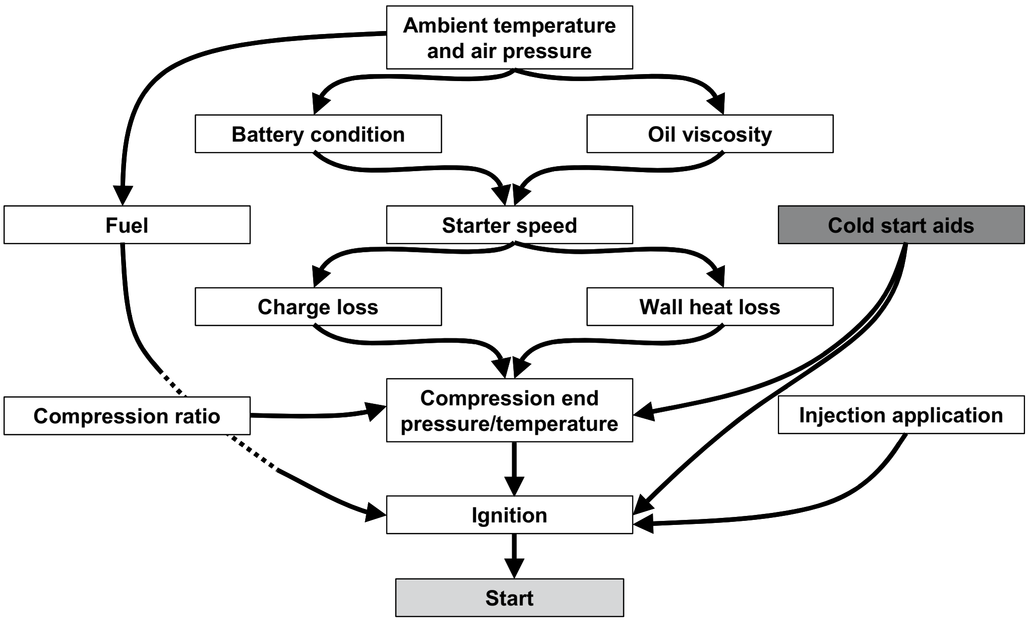

Fig. 2-1 Influencing parameters on cold start

Low temperatures decrease the battery power and increase both engine friction and oil viscosity. This leads to a higher torque demand of the engine and to a lower achievable starter speed resulting in a slower rotational speed of the engine during the cold start. Under extreme temperature and / or altitude conditions the available engine power is not sufficient to ramp up engine speed above low idle. This leads to longer starting time.

During cranking and low idle the increased heat losses cause a reduced compression end temperature and peak pressure. Additional the chemical and physical injection delay times are increased. The combination of these effects results in a deterioration of self-ignition and in worst cases misfire. Low compression ratios as used in modern diesel increase these effects. [2]

To overcome these problems an improved injection application and cold start system are required. For a cold start system two strategies are available. The intake air heater increases the compression end temperature globally. On the other side the glow plug is used as a local hot spot to ignite the fuel spray.

Figure 2-2 shows a cold start and warm up phase with glow plugs at an ambient temperature of -25°C. The cold start phase is the time between the start of the cranking where the starter accelerates the engine in combination with a system voltage drop until the engine speed reached a defined level (typically 1000 rpm). When cranking the engine, the first injections of the fuel take place after sufficient fuel pressure is reached. During the ignition delay the injected fuel is mixed with the air in the combustion chamber and a mixture with locally different conditions is generated. The cold start aid glow plug allows the ignition of the fuel mixture during the cold start and the warm-up phase.

The warm-up phase starts after engine idle speed is reached.

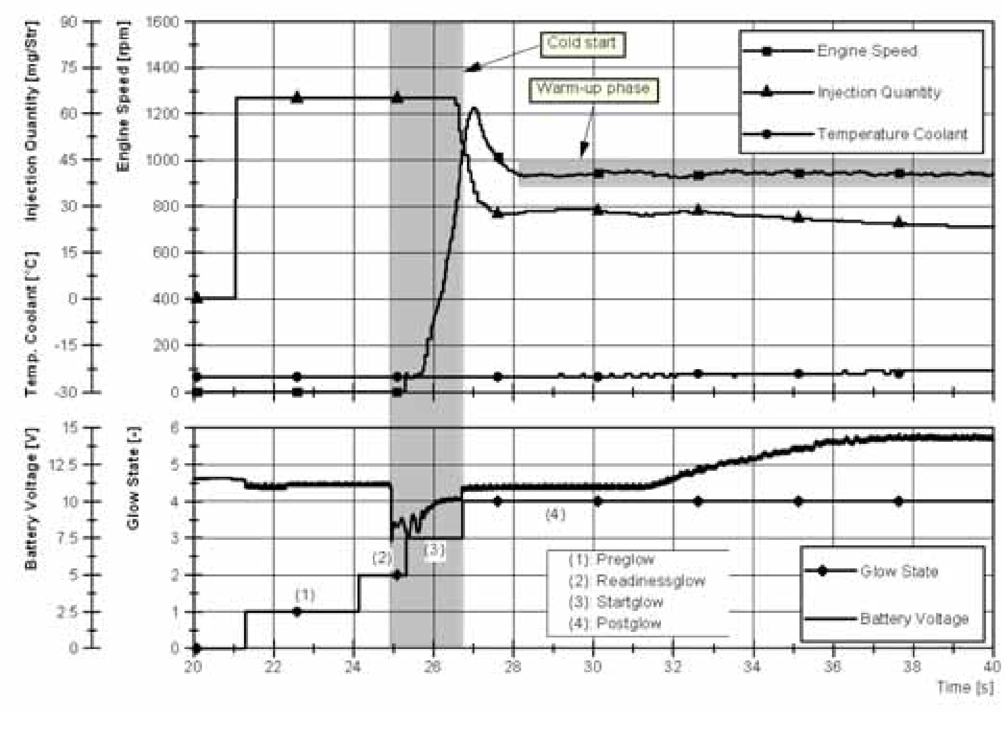

Fig. 2-2 Cold start and warm-up of engine

3 Evaluation methods for the quality of cold start, engine warm-up and emissions

The following chapter describes how the quality of cold start, engine warm-up and emissions are evaluated. Table 3.1 gives an overview about the evaluation methods.

In recent emission regulations [3] for diesel engines no regulations for cold starts below 0°C can be found. On the other side the cold start quality can be measured objectively. Therefore the criteria emissions, starting time, combustion quality and engine speed stability are used. Furthermore subjective criteria of the driver can be taken under consideration. These are typically comfort criteria like noise, vibration, exhaust odor, visible emissions, the starting time itself and last but not least the instant transient reaction [4].

Table 3.1 Evaluation criteria for cold start, warm-up and emissions

Chapter	Evaluation Criteria	Cold Start	Warm-up	Emissions
3.1	Starting time	**X**		
3.2	Indicated mean effective pressure	**X**	**X**	
	Number of misfires	**X**	**X**	
3.3	Engine speed stability		**X**	
3.4	HC-Emission			**X**
	CO-Emission			**X**
	NOx-Emission			**X**
	Opacity			**X**

3.1 Starting time

In this paper the starting time is defined as the time between the first voltage drop during cranking and the engine reaching a defined engine speed of 1000 rpm. The starting time allows a validation of the optimization degree of all parameters and influence values during the cold start.

3.2 Pressure indication

By monitoring the cylinder pressure information it is possible to calculate thermodynamic values in the combustion chamber. The pressure is measured over crank angle. In order to evaluate cold start and warm-up qualities values like standard deviation of the indicated mean effective pressure and misfire detection are typically used.

With pressure sensor glow plugs, such as the BERU PSG, it is possible to measure the cylinder pressure in series applications. The calculation and evaluation of the mentioned values could be done by the engine control unit. This allows a controlled combustion process even during cold start and warm-up phase.

The different cylinder pressure of 100 cycles is printed in figure 3-1.

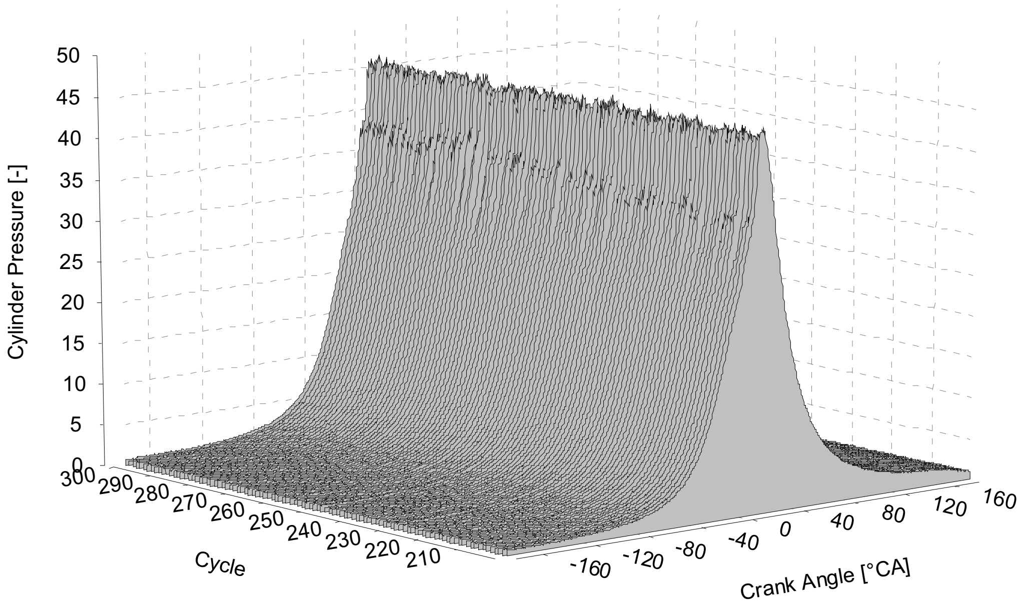

Fig. 3-1 Cylinder Pressure Indication

3.3 Engine speed stability

The idle stability depends strongly on the combustion process. Misfires have a negative effect on the idle stability. Glow control units with power management strategies, such as the BERU ISS 2nd Generation [5], have a positive influence on the idle stability. Switching on and off of high current devices like glow plugs could disturb the power management system of the vehicle, which has an oscillating effect on the generator resulting in an idle instability of the engine.

During cold start application high engine speed stability is one of the main targets.

3.4 Emissions

In regulations the emissions are defined as: soot and particle emission, hydrocarbons, carbon monoxide and nitrogen oxides [3]. Additionally the prevention of visible smoke emissions is important for the customer.

Cold start systems tend to have a high improvement potential regarding the hydrocarbons [5]. Therefore the focus of this paper regarding emissions is put on them.

Hydrocarbons (HC) are a summary of chemical bonds of hydrogen and carbon. Those are the most important elements of the fuel. If the combustion is incomplete, unburned fuel will be expelled from the combustion chamber. A second reason for a high HC concentration is misfires, meaning all of the HC passes from the engine unburned.

Figure 3-2 shows the first 120 seconds of a typical cold start with an engine temperature of 0°C.

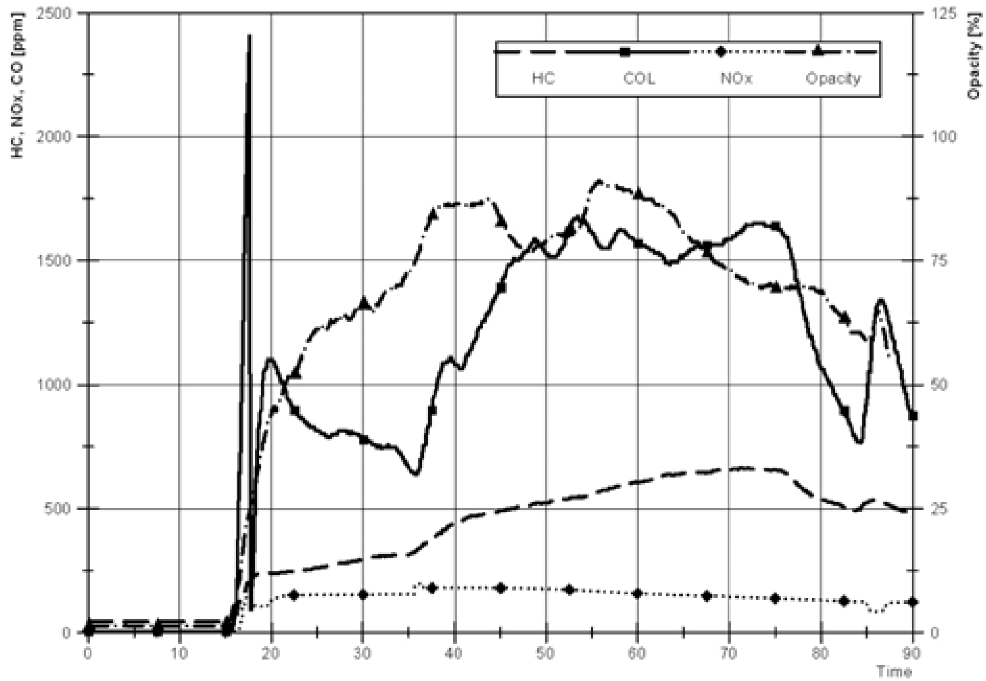

Figure 3-2 Exhaust gas during a cold start and warm-up phase of an engine (0°C)

4 Cold start systems

In this chapter the components of a cold start system are explained. While the first section introduces into the cold start system devices the second section addresses the control variables.

4.1 Components of a cold start system

In figure 4-1 a complete cold start system is shown. The cold start system consists of a glow plug control unit, glow plugs and an intake air heater.

Fig 4-1 Overview of a cold start system

4.1.1 Glow plug

The glow plug is mounted in the cylinder head and provides a local high temperature spot supporting surface ignition during cold start and warm-up of diesel engines. Glow plugs are used typically in diesel engines with up to 1 dm^3 displacement per cylinder. [6]

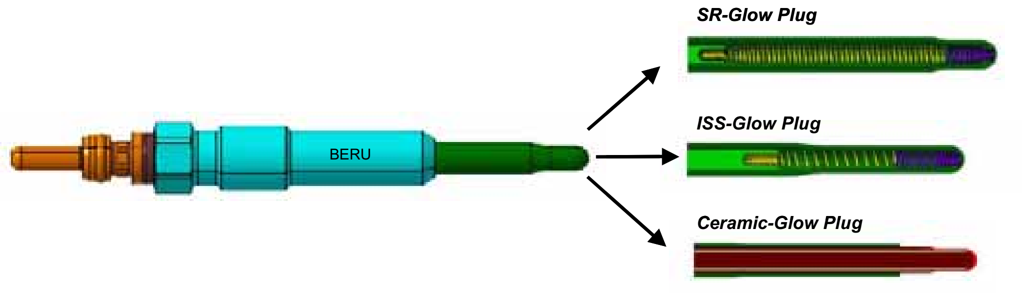

Fig 4-2 Different types of glow plugs

Figure 4-2 shows the different types of glow plugs currently in the market. With metal glow plugs glowing temperatures up to 1050°C are reachable. If in low compression diesel engines higher glowing temperatures are required, it is necessary to switch over to ceramic glow plug technology with typical 1250°C tip temperature.

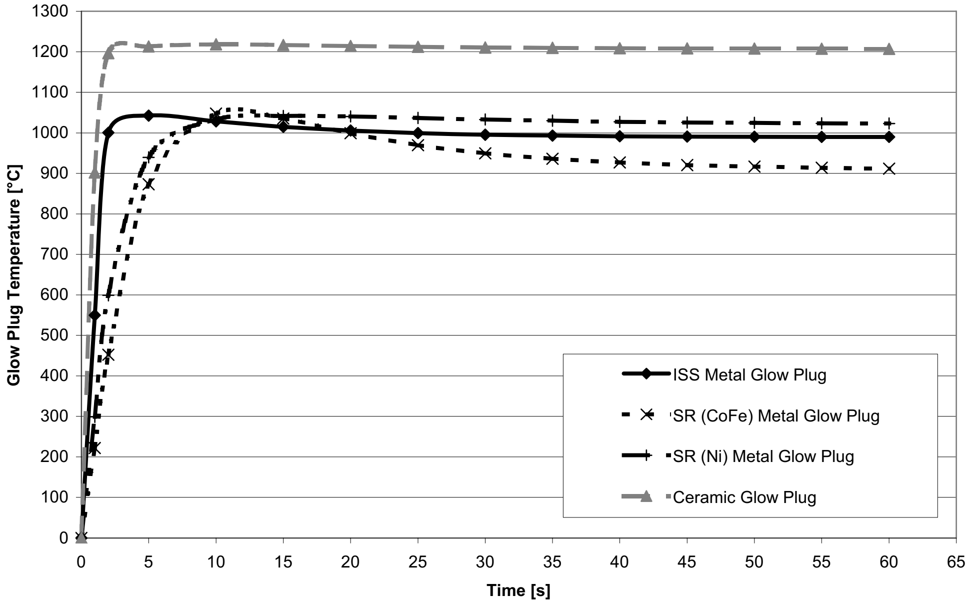

Fig 4-3 Heating characteristics of different glow plug types

Figure 4-3 shows the typical heat up characteristics of different glow plugs types. Standard voltage glow plugs with regulating coils are called SR (self regulated) glow plugs and their thermal behavior has to be adjusted engine specific by the design of the heating element. The regulating coil material characterizes the heat-up profile basically.

Low voltage glow plugs like the BERU ISS (Instant Start System) glow plugs have a nominal voltage lower than the battery voltage of a car. In order to drive a low voltage glow plug, a GCU (glow plug control unit) is required that adjusts driving voltage to the actual operation situation.

This allows both an extremely fast heating up process and a much more stable temperature behavior over all engine-operating points. Additionally the heat-up profile and the temperature level may now be adjusted by calibration and it becomes possible to have a standard heating element for different engine applications.

4.1.2 Pressure sensor glow plugs (PSG)

Pressure sensor glow plugs, like the BERU PSG shown in figure 4-4, provide combustion pressure trace even during cold start. This signal is used as feedback control for closed loop combustion control. The glowing function of the BERU PSG is provided by a standard ISS heating rod that is seamless integrated into the PSG. [7]

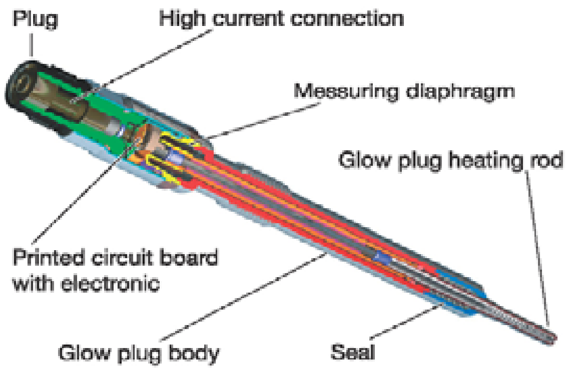

Fig 4-4 BERU PSG (Pressure Sensor Glow plug)

The step from the industry standard feed forward combustion control to feed back control allows alternative combustion processes with less pollutant in exhaust gases [8]. Additionally transient engine situations like cold start may be significantly stabilized if information about the combustion is available. This makes a PSG a perfect tool to stabilize cold run situations (see figure 4-5). In current prototype applications this combined approach allows lower glow plug temperature without any deterioration of engine stability. This saves energy and increases lifetime of the heating element.

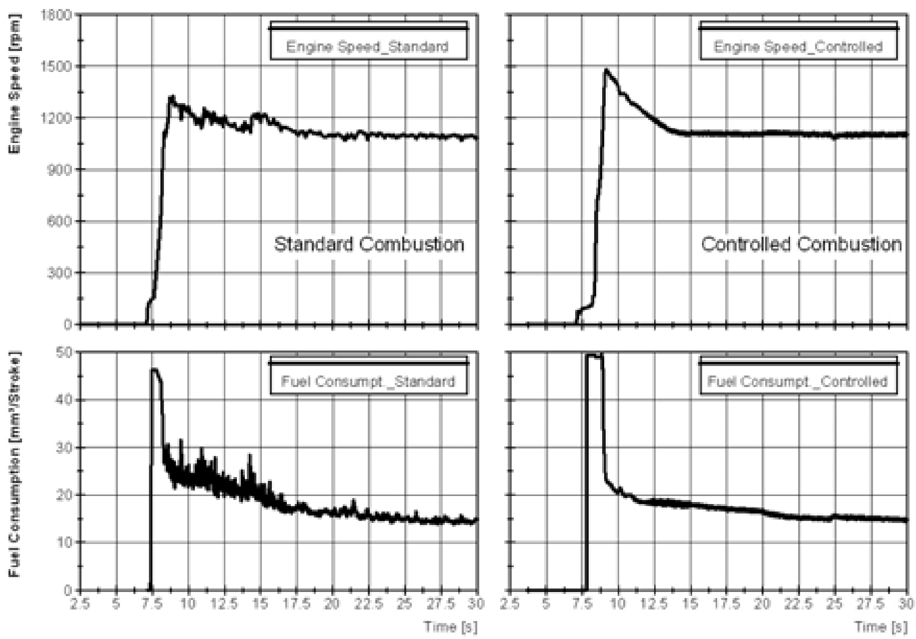

Fig 4-5 Starting quality improvements by combustion control with BERU PSG

4.1.3 Intake air heater (IAH)

Another well-known cold start assist method is increasing intake air temperature by an IAH in the intake air system [9]. This allows the engine to reach self-ignition temperature during cranking.

IAHs are mainly used in 2 types of configurations as it is shown in Table 4.1.

Table 4.1 Configuration Table

System Configuration	System Set up	Typical usage
IAH as cold start aid	*Stand alone 1-2 kW IAH*	*Truck segment with cylinder displacement more than 1 liter*
IAH as warm-up aid	*Glow plugs + 1 kW IAH (+ glow control unit)* *(e. g. BERU 2nd Generation cold start system)*	*Light truck segment with cylinder displacement up to 1 liter*

The current paper puts its focus to the second type of system configuration: IAH as warm-up aid. This configuration is currently mainly used in the light truck segment [5]. The cold start is supported by fast glow plugs and during warm-up the IAH supports engine speed stability, improves emissions, and helps to prevent smoke.

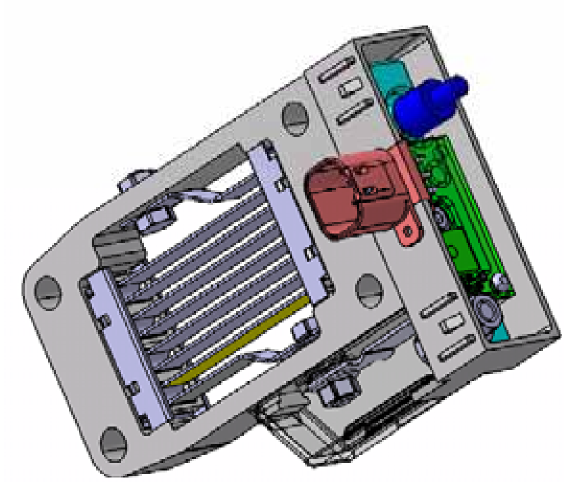

Fig 4-6 BERU Intake air heater

An intake air heater with integrated power electronic is shown in figure 4-6. It is very important to optimize the heater grid area in order to minimize pressure losses. Any large pressure loss will deteriorate engine efficiency.

4.2 Control variables of a cold start system

After discussing the devices of a cold start system their control variables are described in this subsection.

4.2.1 Glow plug tip position

One very important variable is the glow plug tip position. The position is mainly defined by the mounting hole in the cylinder head and frozen during cylinder head design. Afterwards only one degree of freedom is left: The glow plug protrusion length can be changed for each glow plug application easily and should be optimized for each engine application.

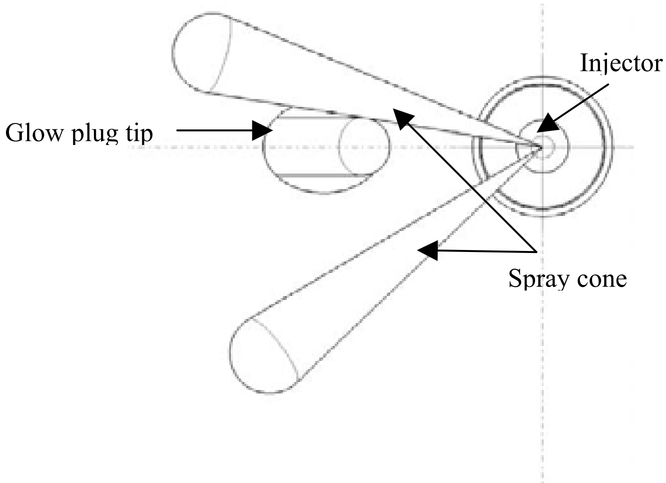

Fig 4-7 Glow plug and injection spray cone position

In order to prevent spray abrasion on the glow tube it is necessary to keep the glow plug out of the injector spray cone. It is recommended to do some experiments during glow plug positioning in order to determine the optimum position.

4.2.2 Glow plug temperature

An appropriate temperature level for the ISS glow plugs is determined during cold start application procedure and programmed in different look up tables in the glow plug control unit and / or the engine control unit.

If the temperature level is too low, cold start quality is deteriorated. If the temperature is above the optimal level the lifetime of the glow plugs will be compromised. This means the temperature adjustment of glow plugs during cold start application is an optimization between cold start behavior and lifetime of glow plugs.

4.2.3 Intake air heater power

Due to different operating points the power consumption of the heater varies based on air mass flow in combination with a Positive Temperature Coefficient characteristic of the heater band and on supply voltage. Fig 4-8 shows for example a quite low heating power at cranking speed due to large load on the batteries. Despite the low IAH power consumption during cranking the temperature increase of the intake air is remarkable 100 K because the air mass flow is low at this operating point.

On the contrary the power consumption is significantly increasing with turbo influence at engine speed above 1500 1/min.

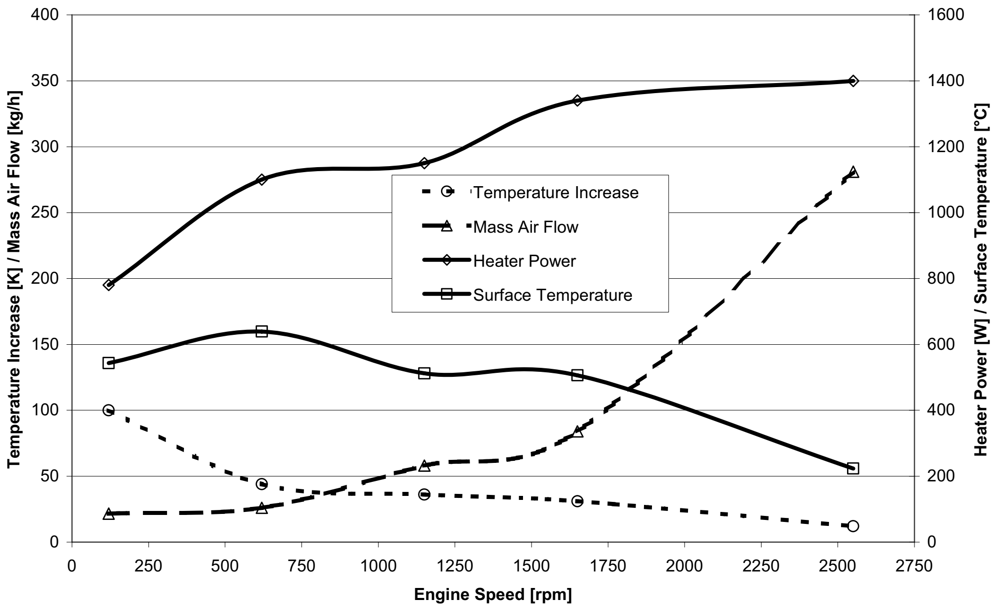

Fig 4-8 Power consumption and intake air temperature increase over engine speed in a typical IAH application

5 Evaluations on cold start and warm-up

The following chapter shows in three subsections the influence of above described different control values:

- Protrusion length
- Glow plug temperature
- Intake air heater power.

Considered was the effect of the starting time, engine speed stability, HC-emissions and the standard deviation of the indicated mean effective pressure.

All tests were performed at the R&D center of BERU AG in Ludwigsburg. Background of the tests were: a 3.0 l inline 6 cylinder with a compression ratio of 17 and a 3.0 l V-angle engine with a compression ratio of 14.5 (research engine).

The cold start and the warm-up were investigated with a stepped increase of the engine speed from idle to 3000 rpm (figure 5-1) with no load. During the test sessions, the engines were fitted with different cold start systems. First they were prepared with metal and then with ceramic glow plugs. For the last test a 1.1 kW intake air heater was included. The engines were started at different engine temperatures (-25°C, -10°C and 0°C).

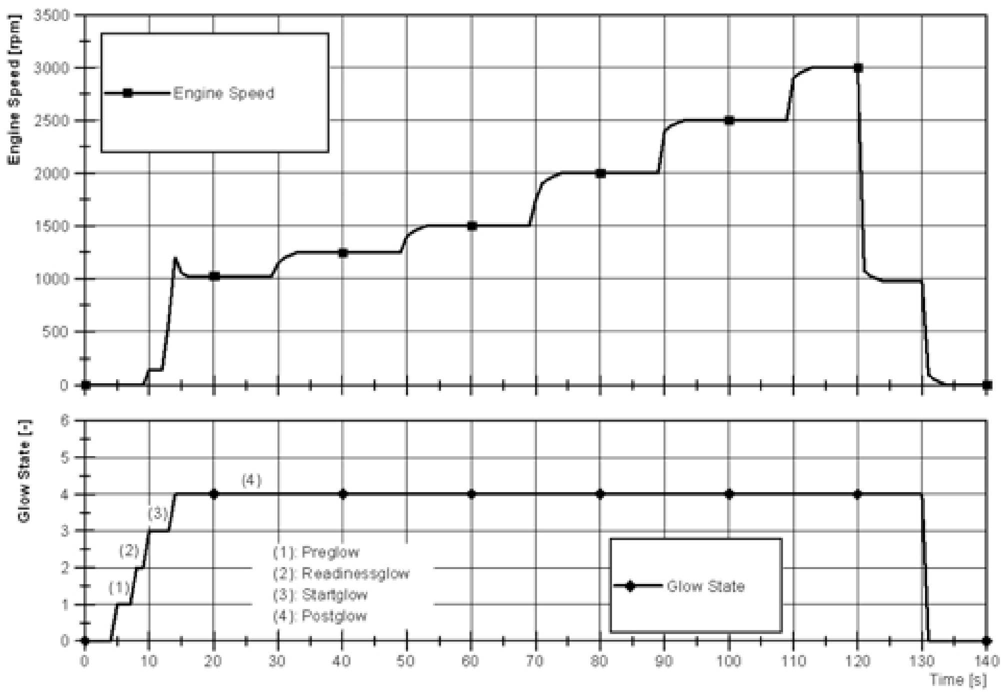

Fig. 5-1 Engine speed for the simulated cold start an warm-up phase

5.1 Position of the glow plug

The influence of the position of the hot spot of the glow plug on the HC emissions is shown in Fig. 5-2. The engine ran in a steady state idle condition during the warm-up phase. The parameters glow plug protrusion length and glow plug temperature were varied. The standard protrusion length at the glow plug temperature 1050°C is used as reference value 100 %. An optimized glow plug protrusion length in combination with the glow plug temperature between 850°C and 1050°C (metal glow plugs) can produce nearly a 40 % reduction of the HC emissions.

A too long protrusion length of the glow plug tip could disturb the spread of the injected spray and the combustion process. At the glow plug temperature 850°C and a longer protrusion length the HC emissions were 40 % higher.

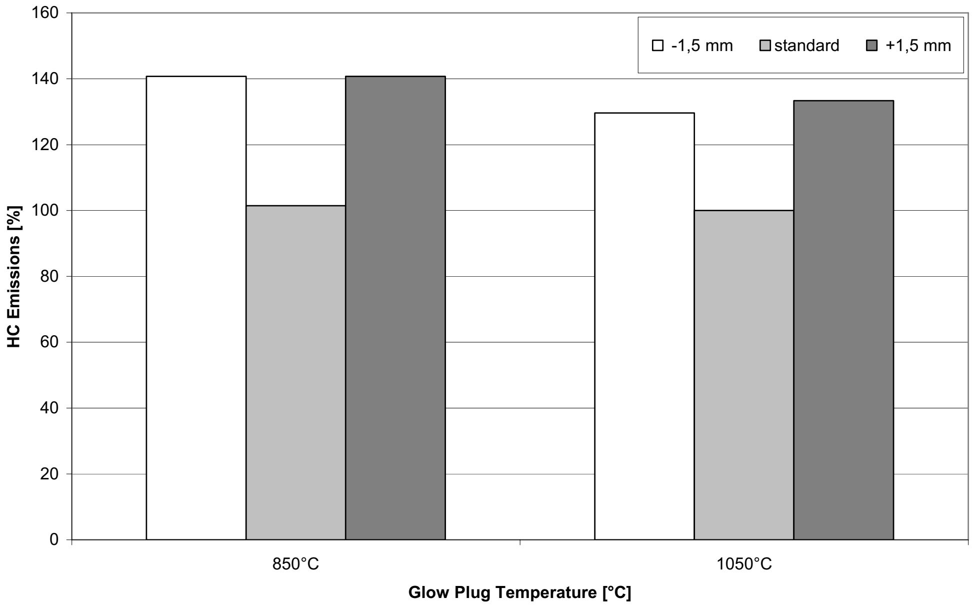

Fig. 5-2 Influence of protrusion length on HC emissions of the V-angle engine

5.2 Glow plug temperature

Two glow plug surface temperature levels are investigated:

- 1050°C with ISS metal glow plug
- 1250°C with ceramic glow plug

The glow plug temperature levels were calibrated in several pre-tests with special thermocouple glow plugs.

5.2.1 Starting time

Figure 5-3 shows the starting times of the different engine temperatures. The results show an arithmetic mean over 5 tests.

There is no significant difference between the different glow plug temperatures. The starting times with the metal glow plugs and ceramic glow plugs are comparable.

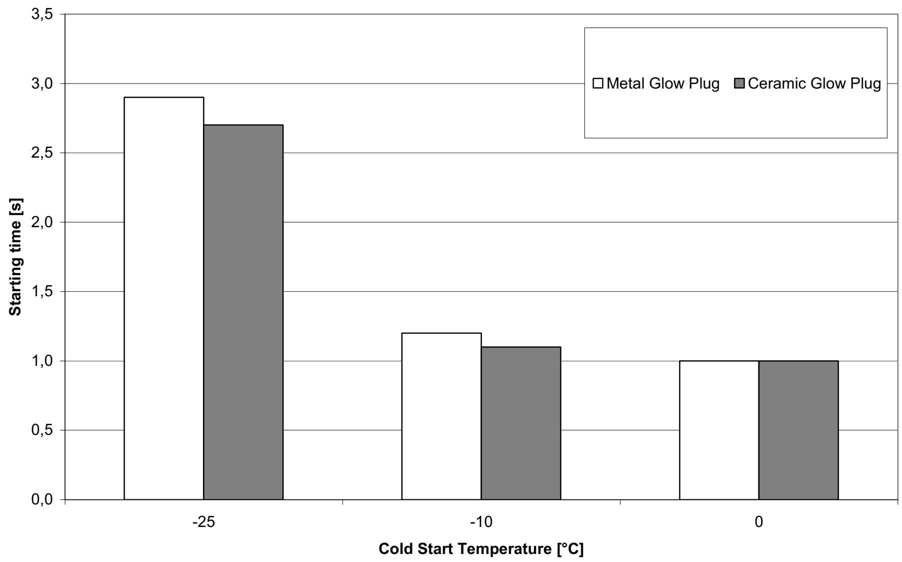

Fig. 5-3 Starting times with different glow plug surface temperatures and engine temperatures of the V-angle engine

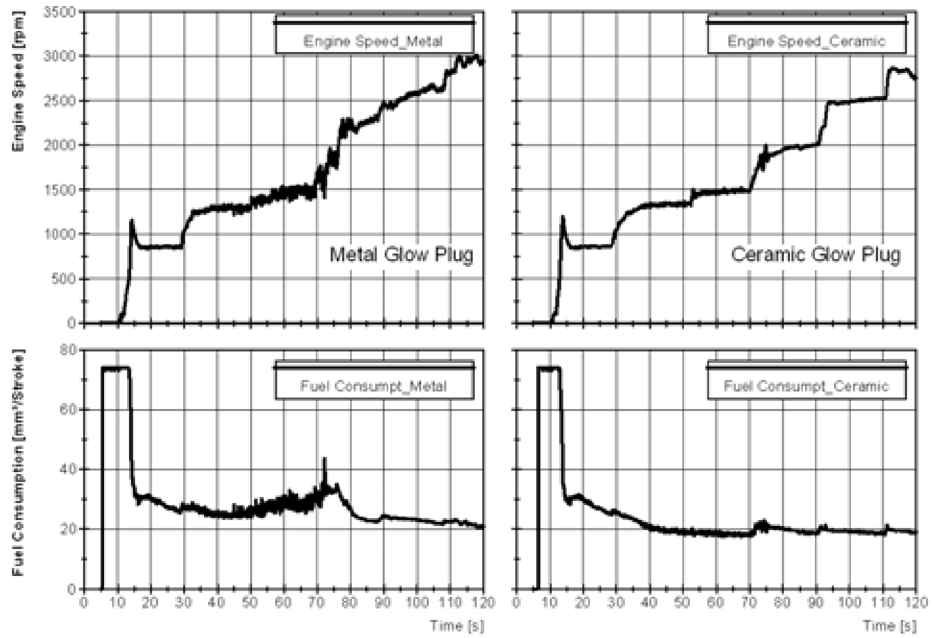

Fig. 5-4 Comparison cold start with metal and ceramic glow plugs (-25°C) of the V-angle engine

5.2.2 Engine speed stability

Figure 5-4 shows two cold starts with the different glow plugs. The engine speed and the injection quantity during the cold start with a metal glow plug oscillate. Both engine parameters are more stable with a ceramic glow plug.

5.2.3 Emission

Figure 5-5 shows the HC emissions during two cold starts. The first cold start was performed with an engine temperature of -25°C. The second start was with an engine temperature of 0°C. The emissions are listed over the whole time of the cold start.

The first HC peak can be explained by the high injection quantity before cranking.

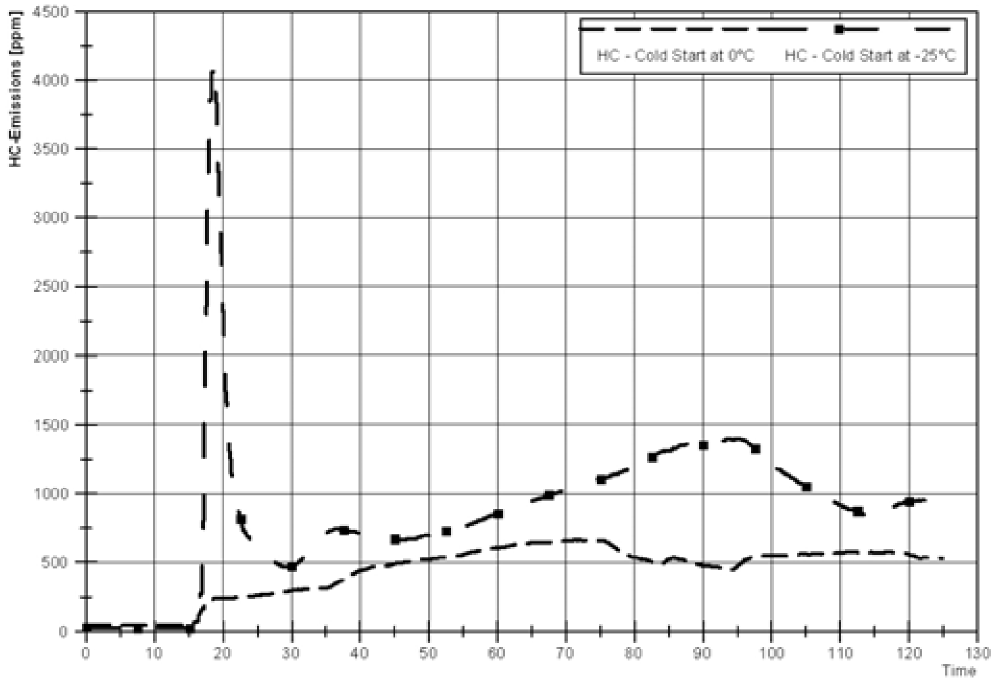

Fig. 5-5 Comparison of HC emissions during a cold start with -25°C and 0°C of the V-angle engine

Figure 5-6 shows the HC emissions that were produced during the different cold starts by the V-angle engine. The emissions were averaged over the complete test and referenced to the -25°C cold start with the metal glow plug. During all these starts with a metal glow plug the engine produces a lot more hydrocarbon than the system with a ceramic glow plug. At the cold start at -25°C the ceramic glow plug can reduce 70% of the HC level.

The same tendency is also seen at the inline engine.

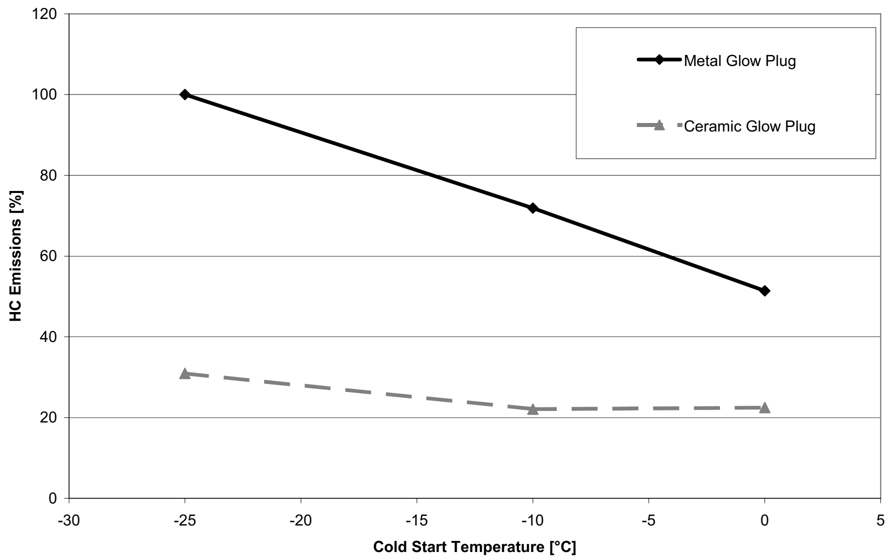

Fig. 5-6 Change of emissions with different glow plug temperatures of the V-angle engine

5.2.4 Cylinder pressure signal

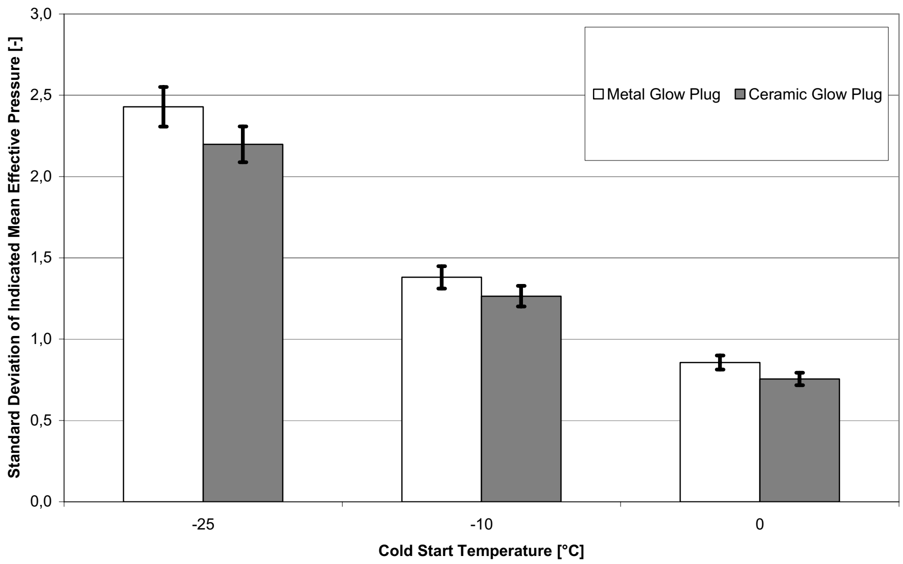

Fig. 5-7 Change of the standard deviation of indicated mean effective pressure with different glow plug temperatures of the inline engine

Figure 5-7 shows the calculated standard deviation of the indicated mean effective pressure during the different cold starts of the inline engine. The standard deviation is calculated over the total duration of the cold start. During all these starts with a ceramic glow plug the engine run is slightly more stable than with a metal glow plug. [10]

5.3 Effect of the intake air heater

The intake air heater is placed behind the air intercooler. During tests with the V-angle engine the IAH was powered from the vehicle electrical system. Due to the power consumption of the IAH a battery voltage drop of about 1 Volt can be recognized during IAH operation (see figure 5-8).

During tests with the inline engine the IAH was supplied by an external power supply to eliminate this influence on the electrical system. By this it was possible to individually evaluate the effect of the intake air temperature increase.

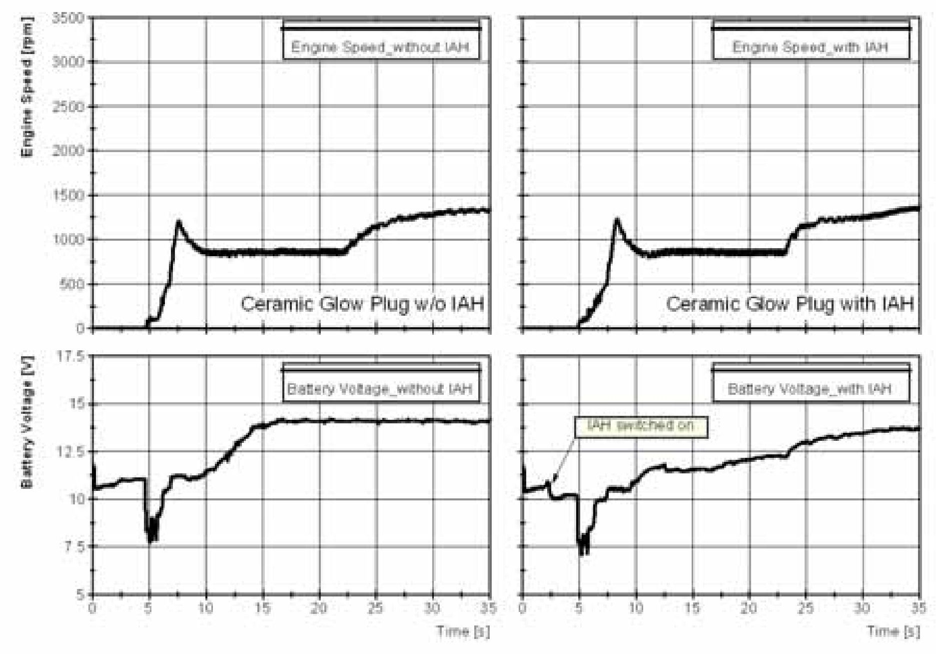

Fig. 5-8 Battery voltage behavior with and without IAH (-25°C) of the V-angle engine

5.3.1 Starting time

The starting times were longer with an intake air heater. (Fig 5-9) This could be explained with the lower vehicle electric system power if the heater is switched on. For that reason the starter does not get enough power and the starter speed decreases.

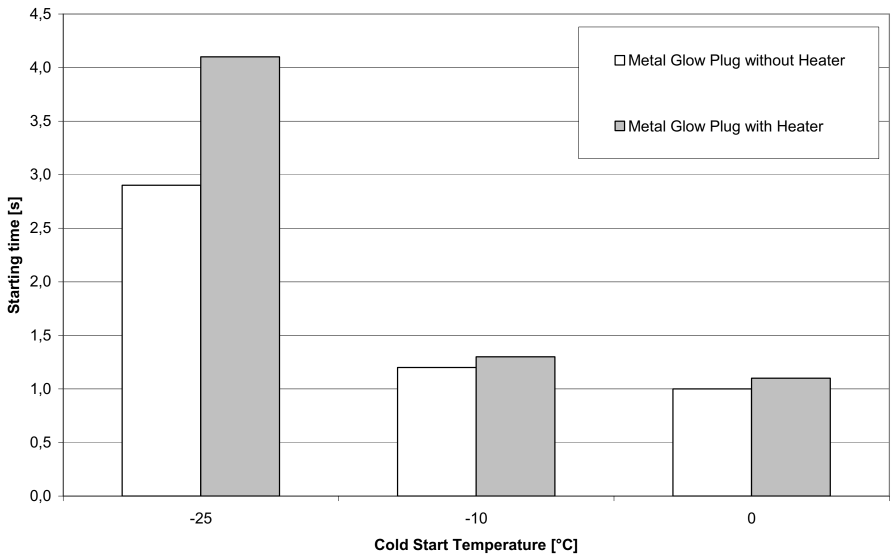

Fig. 5-9 Starting time differences by system with and without intake air heater of the V-angle engine

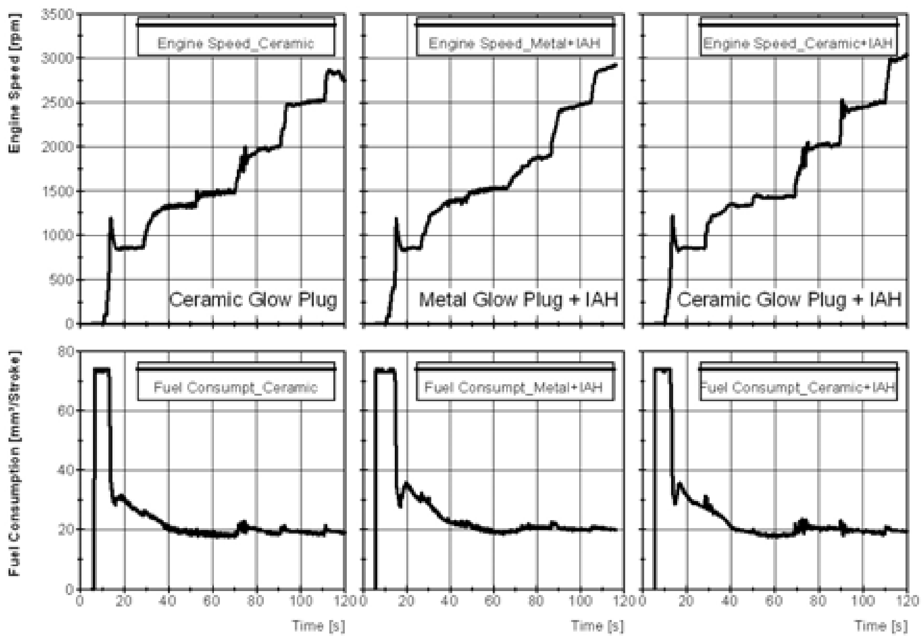

Fig. 5-10 Comparison cold start with metal and ceramic glow plugs and an intake air heater (-25°C) of the V-angle engine

5.3.2 Engine speed stability

Figure 5-10 shows the engine speed and the injection quantity during the different cold starts. The engine temperature at the beginning of the start was -25°C. The comparison shows a start with ceramic glow plugs, a start with metal glow plugs and an intake air heater and a start with ceramic glow plugs and an intake air heater.

No significant difference regarding the engine speed stability between the three configurations can be seen.

5.3.4 Emissions

Picture 5-11 (V-angle engine) and 5-12 (inline engine) shows the results of several cold starts at -25°C, -10°C and 0°C. The HC emissions are referenced to the cold start at -25°C of the ceramic glow plug.

Both configurations with intake air heater improve the results of the stand-alone ceramic glow plugs.

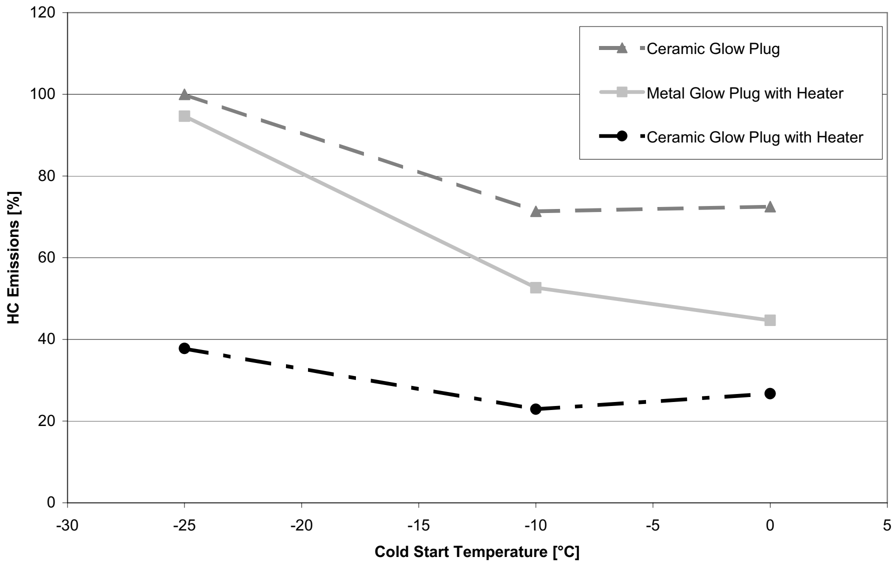

Fig. 5-11 Comparison of the HC emission during the different cold starts of the V-angle engine

Figure 5-12 shows additional the influence of different intake air power levels on the HC emissions of the inline engine. The configurations with 500 W, 700 W and 1100 W and metal glow plugs lead to lower HC emissions compared to the ceramic glow plug.

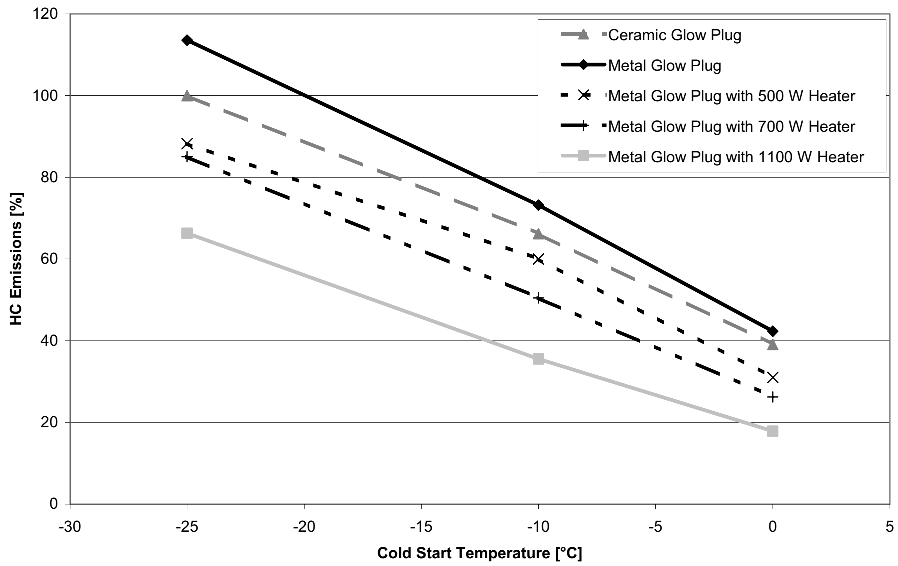

Fig. 5-12 Comparison of the HC emission during the different cold starts of the inline engine

5.3.4 Cylinder pressure signal

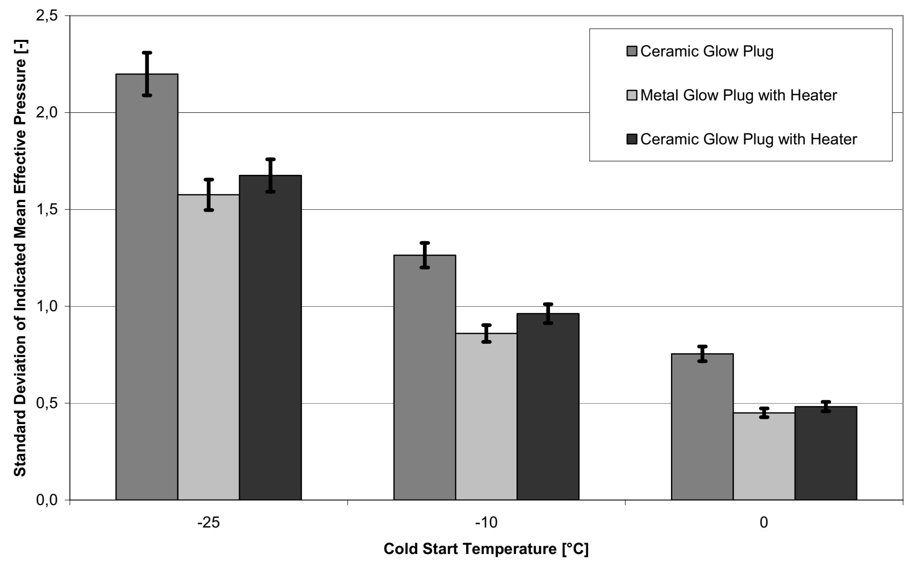

Fig. 5-13 Change of the standard deviation of indicated mean effective pressure with different glow plug temperatures of the inline engine

Figure 5-13 shows the calculated standard deviation of the indicated mean effective pressure during the different cold starts of the inline engine.

Both configurations with intake air heater improve the results of the ceramic glow plugs during all measured cold starts.

6 Summary and Outlook

Various tests regarding the influence of cold start systems were performed at the R&D center of BERU AG in Ludwigsburg. In this chapter the main findings of the performed investigations and conclusions are summarized:

1. The position of the glow plug hot spot in relation to the fuel spray has a tremendous effect on the combustion quality. Optimized protrusion length decreases the HC emissions.

2. The higher glow plug temperature of a ceramic glow plug shows no significant effect on the starting time. Both combustion stability and HC emissions during the warm-up phase are strongly improved by a higher glow plug temperature.

3. Intake air heaters significantly reduce the HC emissions during all regarded tests. Even an intake air heater with a power of 500 W reaches lower HC emissions than a ceramic glow plug. By using an IAH the standard deviation of the indicated mean effective pressure is significantly lower. If the IAH is powered during starter engagement the starting time is deteriorated. Starting strategies that momentarily reduce IAH power during starter engagement are under investigation.

4. A cylinder pressure control can optimize the combustion process and stability during cold start and warm-up.

BERU is planning additional investigations on other engines in order to confirm the above listed conclusions.

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With a world market share of over 40% for glow plugs and electronically controlled instant-start systems for diesel engines, BERU AG is the world’s leading supplier of Diesel Cold-Start Technology. It is also one of Europe´s four leading suppliers in the field of ignition technology for gasoline engines. And BERU is rapidly expanding in the electronics sector with a focus on complete electronic systems for the automotive industry. This long-established company, founded in 1912, also produces sensors and ignition systems for the oil and gas burner sector. BERU´s customers include nearly all of the world’s car and engine manufacturers. BERU AG is represented at 23 locations on three continents, and the company´s headquarters are in Ludwigsburg, Germany.

Contact

BERU Aktiengesellschaft, Mörikestraße 155, D-71636 Ludwigsburg

Phone +49 7141 132-0
Fax +49 7141 132-350
E-Mail info@beru.de