From Cold-start Aid to Adaptive Glow System

Formerly, the glow system was simply a help when cold-starting the diesel engine. Today, such systems make an important contribution to reducing emissions during engine warm-up as well as extending the design latitude for particulate-filter regeneration. The new Bosch modular glow system was developed for global application in coping with the demands arising from these requirements. It comprises ceramic DuraSpeed sheathed-element glow plugs (GLP) as well as a modular-design glow-control unit (GCU) and a software module featuring adaptable functional scope. This means that the flexible glow system (FGS) can be adapted optimally to meet varying customer requirements.

1 Introduction

In the development of the new Bosch glow system, the target was to provide optimal support in complying with the future basic requirements as mandated by law, and to facilitate customer-specific glow strategies and system demands with a minimum of effort. In the following, the latest trends in powertrain development were taken into account.

When designing modern diesel engines, further improvements in environmental compatibility and maximum performance are at the forefront of considerations. These endeavours are accompanied by legislative measures. Technical compliance with these targets has resulted in diesel engines with reduced compression ratios of minimum 15:1 for EU6 applications. This is compared to former figures which were typically between 15.8:1 and 18:1 [1]. In order to ensure that these engines feature smooth cold-running characteristics while at the same time having lower emissions [2], it was necessary to develop glow systems with considerably longer post-glow capabilities and far higher glow temperatures. Furthermore, the glow system also permits the reduction of HC and CO emissions in the part-load range when the engine has reached its normal operating temperature [3].

Notwithstanding the fact that the level of untreated emissions continues to drop, diesel particulate filters (DPF) are already standard equipment in many countries. This trend will continue as a result of continual tightening of the emission limits together with the trade-off between NO_x and particulate emissions. High exhaust-gas temperatures are needed for DPF regeneration. In the low-load range (town traffic), such temperatures necessitate ingenious application strategies. The glow system is also applied under these special operating conditions in order to stabilise the combustion resulting in even longer glow durations and higher temperatures.

Of course, all the vehicle's systems must function reliably for as long a period as possible without any drop in performance. If one of the components which are relevant for emissions should fail though, it is imperative that this is detected immediately. These requirements call for robust glow systems with an even longer service life during which there are to be no changes in their functional characteristics which are worth mentioning. A GLP single-path diagnosis function complies with all stipulations of present-day and future OBD requirements.

In addition to these considerations, which for the most part arise from improvements in environmental compatibility, conventional requirements still apply to the glow systems: The driver's demand for cold-start and cold-running characteristics similar to those of a spark-ignition (SI) engine necessitate the glow plug heating up very quickly, and the wide range of applications for a large number of different vehicle models and segments call for a flexible, modular-design glow system which at minimum cost can be optimally adapted to specific customer requirements.

The technical trends described place significantly higher demands on future passenger-car glow systems:
- fastest-possible heating speed (1000 °C < 2 s) for cold starts similar to those with SI engines at temperatures down to -28 °C
- flexible adaptation of the glow temperature to the engine's demands
- maximum glow temperatures up to 1300 °C and permanent glow temperatures up to 1150 °C for the reduction of the exhaust-gas emissions on low-compression (17:1 and below) engines
- extended post-glow capabilities of up to several minutes for low-emission smoother running at cold idle. On low-compression engines this applies also in the warm-up phase
- intermediate-glow capabilities, as needed for example in particulate-filter regeneration
- outstanding glow efficiency for reductions in CO_2 emissions
- constant glow characteristics throughout the service life of the glow plugs (temperature and heat-up speed)
- suitable for OBDII and EOBD
- very long glow-system service life
- application of modular principles for simple and rapid adaptation to specific customer requirements
- compatibility with modern communication interfaces such as CAN or LIN
- start-stop capabilities

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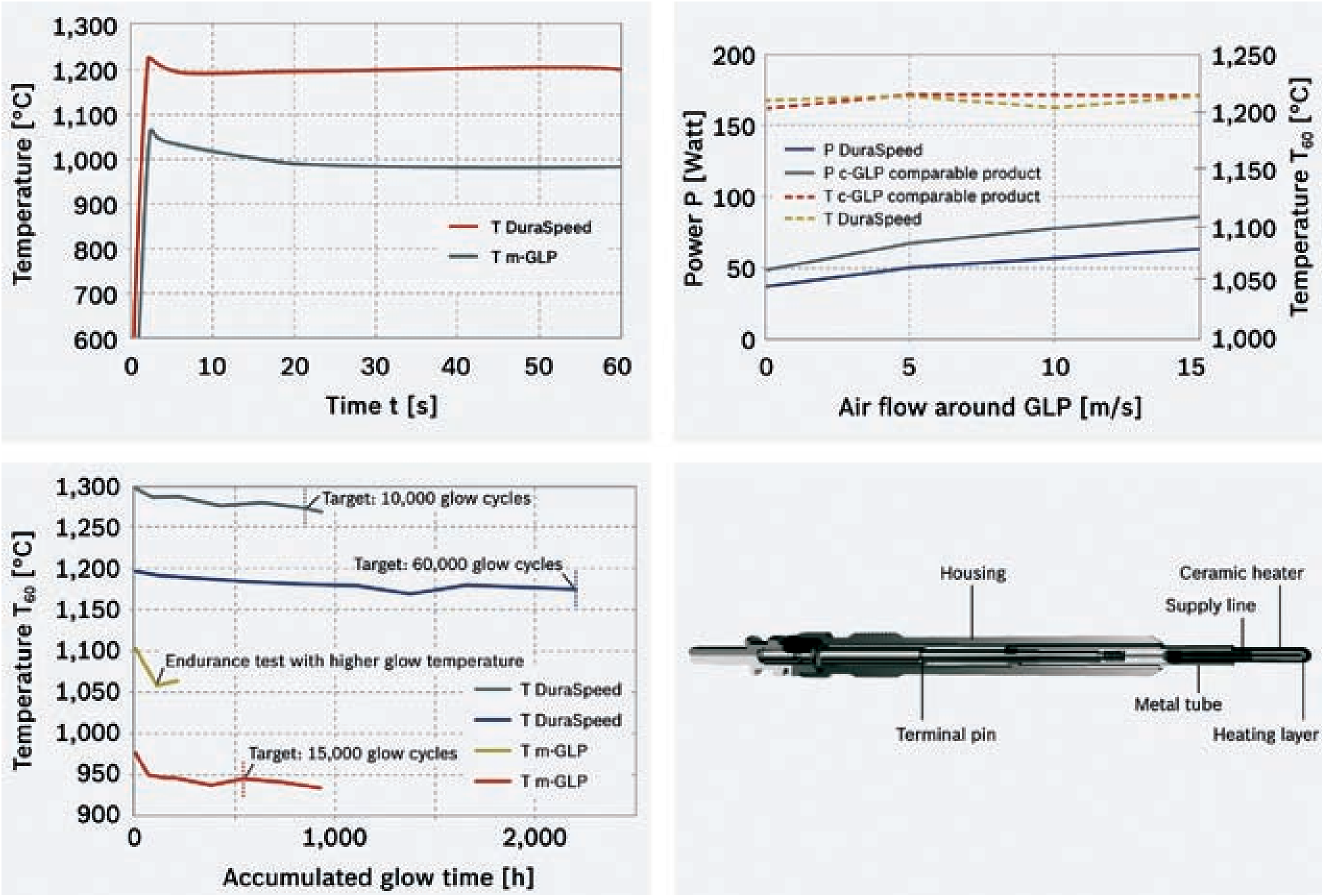

Figure 1: Characteristics of DuraSpeed ceramic glow plugs. Heat-up curve (top left) and aging of the glow temperature (bottom left) compared to a low-voltage metal glow plug (m-GLP).; glow efficiency DuraSpeed and comparison ceramic glow plug (c-GLP, top right) and longitudinal section (bottom right)

- uncomplicated and reliable application
- optimal engine mounting.

2 Function and Design

2.1 System Concept

Modern glow systems utilise low-voltage sheathed-element glow plugs and electronic glow-control units. Since the additional costs involved, together with the far higher power demands and the resultant increases in fuel consumption are not faced by any significant advantages, intake-air heaters (IAH) are rarely installed in the passenger-car segment. Furthermore, the engine requirements regarding high glow temperatures and long glow periods as listed above, have resulted in the increased use of ceramic glow plugs the triggering of which is map-base controlled. These maps are stored either in the engine management or in the glow-control unit (GCU) and are the result of painstaking application engineering. Typical map parameters are engine speed, injected fuel quantity, and coolant temperature. Not only immediate cold starts become possible with the low-voltage technology, but it has also become possible to provide for an adaptation of the glow temperature in line with the engine's operating status. For instance, as soon as the starter has disengaged, glow-plug temperature is reduced in order to increase the vehicle's energy efficiency and, as a result, contribute to reducing CO_2 emissions. The FGS glow system is characterised by a particularly low energy demand in efficiently reaching very high glow temperatures, **Figure 1**.

2.2 Ceramic Sheathed-element Glow Plugs

The low compression ratios in modern-day passenger-car diesel engines need glow plugs with maximum temperatures of up to 1300 °C and long glow periods at above 1150 °C without showing any signs of aging, Figure 1 and **Figure 2**. Using ceramic glow-plugs (c-GLP) instead of 11 Volt metal GLP has enabled cold-running emissions to be reduced by as much as 60 %. At very low temperatures, immediate cold-starting characteristics comparable to those of an SI engine necessitate heating speeds of up to 600 °C/s. The resulting danger of thermoshock and hot-gas corrosion, led to the development of ceramic glow plugs.

The ceramic heater of the Bosch DuraSpeed is comprised of the insulating material Si_3N_4, in which are embedded low-resistance supply lines and the PTC-effect (PTC = positive temperature coefficient) interior heating layer. This means that the heating and control functions are combined inside the heating layer, Figure 1.

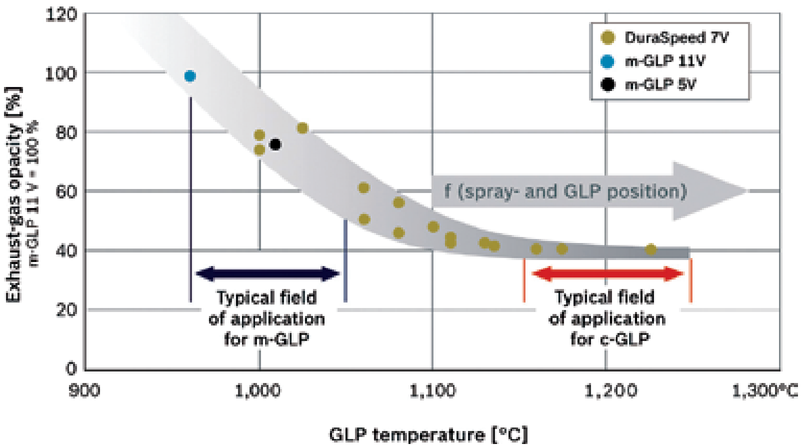

Figure 2: Exhaust-gas opacity as a function of the sheathed-element glow plug surface temperature in the first 35 s after cold start at -20 °C; four-cylinder CR engine with two pilot injections, optimized injection-spray position and compression ratio 16:1

The aging (reduction of the glow temperature) observed with the metallic GLP (m-GLP), with the attendant gradual deterioration of the cold-start and cold-running characteristics, is hardly encountered at all with ceramic GLP (c-GLP), Figure 1. Typically, taking constantly high glow temperatures of 1200 °C, the glow temperature only drops by about 30 °C after approximately 2500 hours of operation. Regarding combustion support this permits novel application strategies in the part-load range [3], as well as during particulate-filter regeneration in town traffic as shown in **Figure 3**. Here, the CO and HC emissions as a factor of the glow temperature are recorded as a measure of stability. As from about 1100 °C, stable combustion is possible throughout the entire control range. Combustion is unstable at glow temperatures below 1000 °C.

Figure 4 demonstrates the influence of GLP temperature on emissions during cold start and cold idle on a V8 engine with and without IAH. The very high temperatures which are possible using ceramic glow plugs are more effective in reducing emissions than the combination of metal-GLP and IAH (1 kW) [4]. The fact that the DuraSpeed GLP is used alone and no extra heater is needed considerably reduces the load on the vehicle electrical system during the cold-start and cold-running phases and thus lowers the energy consumption (1 kW power corresponds to as much as 1 l/100 km [5]. In addition, the throttling effects inherent in the IAH also reduce the engine's efficiency throughout its complete operating range so that CO_2 emissions are further increased [6].

2.3 Glow Control Units

In order to achieve optimal adaptation of the GLP temperature to the engine's requirements in all operating ranges, innovative triggering concepts are needed. These are based on resistance and power. On the one hand these permit the trade-off between service life and glow performance to be applied, and on the other it becomes possible to completely master the dynamic changes in the combustion modes. Future diagnosis demands will be complied with using individual GLP triggering and the monitoring of triggering voltage and current. Staggered GLP triggering will be applied to improve the electromagnetic compatibility (EMC) in the vehicle which during operation also contributes to minimising the current load on the vehicle's electrical system.

In addition, the flexible glow system's (FGS) modular design also facilitates the integration of supplementary functions such as the triggering of further actuators needed for instance for carbamide metering on SCR systems and for the optimal adaptation of the FGS to precise customer requirements. It permits autarkic (self-sufficient) glow systems in which all information on glow control is stored in the GCU or received via such interfaces as CAN, or non-autarkic systems where the glow process is controlled from the engine-management ECU.

Standardised software interfaces permit the use of modular-design glow software which can be adapted to customer requirements. Demands from the engine management for glow operation are converted to the corresponding glow temperature via autosar-compatible glow software. This reduces the application-engineering effort in all glow-system operating ranges.

3 System Integration

Careful application engineering is of particular importance in the case of low-voltage glow systems. Irrespective of operating status, the aim is to support the combustion process with the optimal glow temperature without imposing excessive loading on the glow plugs and vehicle electrical system. Furthermore, the GLP installation position in the combustion chamber must also take the injection-spray design and swirl into account. With respect to these considerations, Bosch has developed algo-

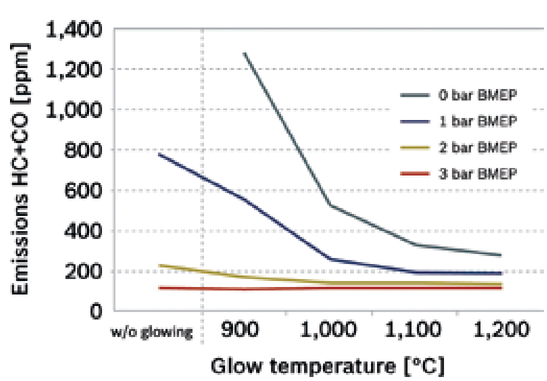

Figure 3: Influence of the glow-plug temperature on the HC and CO emissions during particulate-filter regeneration in the low-load range at 1600/min using summer diesel fuel; four-cylinder 2.2 l CR engine with compression ratio 16:1

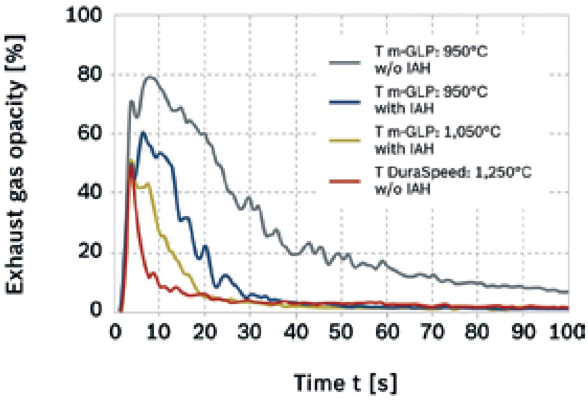

Figure 4: Exhaust-gas opacity at -20 °C using US winter diesel fuel as a function of the glow-plug temperature with and without intake-air heating (IAH, 1 kW); V8 CR engine with compression ratio 16:1 and > 0.6 l/cylinder

rithms which permit optimal positioning. In order to comply with customer stipulations, service-life models are applied for the various GLP types. With their help and the use of modern application-engineering methods, based on customer-specific data it was possible to achieve a glow-activation time which exceeded 20 % of engine operation. Here, further developments of the present glow software permit highly simplified application engineering even in the case of dynamically varying combustion modes. The application-engineering is verified during engine and vehicle endurance runs in cooperation with the vehicle manufacturer.

4 Summary

The stricter the emission legislation, the higher are the demands made on modern glow systems which are increasingly being used during part-load operation with the engine at operating temperature and for combustion support during particulate-filter regeneration. The former "cold-start aid" has thus developed into an "adaptive glow system" which on the basis of engine-specific application engineering contributes to an increase in driving comfort and a reduction in exhaust emissions.

Bosch developed the flexible glow system (FGS) with exactly this extended field of application in view. The ceramic glow plugs provide rapid heating times and high glow temperatures throughout the system's complete service life. The accompanying modular-design glow control unit provides for a high degree of flexibility with regard to design and functionality, and can thus be adapted optimally to a wide range of customer requirements.

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Acknowledgements

The authors would like to express their thanks for the support they received while writing this article from the colleagues at Robert Bosch GmbH who have not been specifically named above.