The simulation and production of glow plugs based on thermal modeling

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Received: 01.07.2013 • Accepted/Published Online: 28.08.2013 • Printed: 31.12.2015

Abstract: In this work, we present the thermal behavior of a glow plug examined with thermal impedance modeling. The circuit model is based on the analogy of thermal and electrical domains and expresses the glow plug used in diesel engines to preheat the air-diesel fuel mixture. In this study, the circuit design, implementation, and simulation of a glow plug for diesel engines are illustrated. In order to verify this thermal model, 2 different glow plugs are produced. The test results of the glow plugs produced in this study show complete agreement with the simulation results. It is thought that this circuit-based model will provide fast and reliable simulations and will be beneficial in the industry for addressing different glow plug needs.

Key words: Glow plug, thermal modeling, resistive element, thermal imaging

1. Introduction

Diesel engines are a common part of our everyday lives and are largely used in cars and other diesel applications. Today, the diesel engine is the power source with the lowest specific fuel consumption and is essential for the global reduction of carbon dioxide emissions [1–4]. The aim is to reduce the emission of CO₂ in vehicles by using new generation diesel engines with Euro 5 and Euro 6 fuel. According to new European Commission regulations, such as 443/2009/EC, CO₂ emissions released from vehicles should be less than 130 g/km in 2015 [5].

Unlike the petrol engine, the diesel engine is a self-igniter. In order to function properly, diesel engines require glow plugs according to the volume and shape of the engine. The lower the temperature, the poorer the situation for very quick ignition. It is critical to heat up the air in the engine to a minimum operation temperature of 850 °C. A glow plug functions as a heat source to increase the temperature of the intake air to the required values, in order to initiate the combustion cycle.

The glow plugs obtain their electrical energy from the electric storage device. An electronic glow time control device manages the control. It warms up rapidly and makes the warming zone gleam. During the operation process, the glow plug is confronted with great temperature changes, which lead to measurable resistance alterations within the device [6–8].

The starting quality will strongly decrease (even engine start may not be possible) when the ambient temperature is not high enough to cause self-ignition [9,10]. Consequently, diesel engines are usually manufactured with glow plugs in each chamber in order to heat up the environment [11].

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In this paper, a new thermal model is proposed for the heating process of glow plugs, which can be used in manufacturing. Other modeling examples are discussed in the literature. One model uses a complex, time-based mathematical modeling, which uses mostly a one-dimensional, partially differential equation that incorporates the electrothermal interaction of the plug [12].

Another model, also using heavy mathematics, is a robust cascade model for closed-loop control of the glow plug surface temperature, which proposes an approach to develop an effective, real-time, and appropriate temperature model [13,14]. Our model differs from others in that we use electrical and thermal interaction, which simplifies the calculations for glow plug manufacturing. This thermal analogy-based model will greatly assist in production due to its simplicity and accuracy. Our aim here is to examine the heating process and produce glow plugs according to the results. In the proposed method, we explain the heat conduction and temperature increase in the glow tube. The proposed model is tested on an experiment production and the results show that the thermal model works.

The remainder of the article is structured as follows: Section 2 explains the analogy of the thermal circuit model. Section 3 gives the details of the modeling and performs the simulation of the glow plug using SPICE QUCS, and Section 4 includes the production of glow plugs according to our simulation results. The results and discussion are provided in Section 5, and Section 6 draws the conclusions.

2. Analogy of thermal circuit model

In this study, firstly, the electrical circuit model of the glow plug is designed. The equivalent circuit of the glow plug has been simulated using a SPICE-based circuit simulator, Quite Universal Circuit Simulator (QUCS) 0.0.16. To calculate the thermal resistance and heating capacity of the glow tube, we used the formulas shown in Eq. (2.1). $R_T$ is the thermal resistance that [15] explained as:

$$R_T = L \times k^{-1} \times A^{-1}$$ (2.1)

Here, $k$ is the thermal conductivity, $A$ is the actual area of the resistance, and $L$ is the length of the resistance. Thermal resistance $R_T$ increases as $L$ increases, as $A$ decreases, and as $k$ decreases. We can determine heat capacity $C$ at constant pressure. We define the heat capacity with a constant amount [15] as shown in Eq. (2.2):

$$C = q_M \times \hat{C}_M \times V$$ (2.2)

Here, $q_M$ is mass density, $\hat{C}_M$ is specific heat capacity, and $V$ is volume. The thermal circuit shown in Figure 1 possesses 3 components: a diamond-shaped current source that supplies the Joule heat power $I^2R$, a thermal capacitor $C_T$ that represents the heat capability of the resistor, and a thermal resistor $R_T$, representing the heat conduction through the resistor.

![Figure 1. Interaction between an electrical and thermal circuit [15].](image-url)
3. Modeling and simulation of the glow plug using SPICE QUCS

The resistances are selected so that $R_H \gg R_1$ at ambient temperature, as shown in Figure 2. Thus, most heat is caused by the Joule effect inside the heating resistance, creating a fast temperature rise for the tip of the actual glow plug. However, the material inside the controlling element is selected so that $R_1$ (Vacon CF8) is strongly determined by the temperature, whereas $R_H$ (Kanthal D) is independent of it. Therefore, as the temperature in the rear of the actual glow plug rises as a consequence of thermal conduction, the actual controlling resistance increases. This brings a more equally spread heat generation.

Figure 2. Heater tube of a glow plug.

Thermal conduction is energy-bound, with internal degrees of freedom, in a substance that is called motion of individual atoms, along with molecules. The actual amount of heat energy is directly related to its temperature. Firstly, we derived the thermal model of the glow plug using SPICE QUCS. We divided the glow heating tube into 5–8 parts in order to better model the structure, as shown in Figures 3 and 4. As seen in Figure 4, for every part of the glow heating tube we have the thermal conductivity for resistance calculation, heating capacity, internal and external radius, and length. Finally, we calculated the operational area of the heating tube in order to obtain thermal resistance and heat capacity for every part. We also calculated the resistance and heat capacity of the tip of the glow heater tube and of magnesium oxide (MgO) according to the current we used, which changed from 20 A to 12 A during the heating procedure. All the calculations were performed with the help of the equations.

Figure 3. Heater tube divided into 5 parts for Sample 1.

Figure 4. Heater tube divided into 8 parts for Sample 2.

Figure 5 shows the cutaway of a glow plug where the heating coil is independent of temperature. The regulating coil is strongly dependent on temperature, and MgO powdery material is used as insulation material within the glow tube.

Figure 5. Cutaway of a glow plug.

Figure 6 shows the model of Sample 1, which is divided into 5 parts. $T_0$, $T_0$, $T_1$, $T_2$, $T_3$, and $T_4$ refer to the parts of the glow tube that we separated to better model the thermal behavior during the heating
process. Similarly, we divided the plug into 8 parts for Sample 2. We depicted electrical equivalent circuits of the thermal behavior of the glow plug heat process, which are shown in Figures 6 and 7 for both plugs. Both figures depict the heat flow directions for MgO and the steel sheet. The thermal resistance of the metal cover, \( R_1 \), and front resistance, \( R_3 \), were calculated using Eq. (2.1) and the equations shown in Figure 8. Similarly, the thermal resistance of MgO, \( R_2 \), was calculated in the same way.

The heat capacity of the metal cover, \( C_1 \), the front part of the tube, \( C_3 \), and the heat capacity of MgO, \( C_2 \), were calculated using Eq. (2.2) and the equations shown in Figure 8. For the front part of the tube, \( R_3 \) and \( C_3 \) were calculated by finding the average length and area of the tube.

### 4. Production of glow plugs according to the simulation results

In this section, we provide information about the materials that we used in the production. The components and processes utilized in manufacturing are vital for the creation of a good product. There are 3 basic elements to a glow plug. These are a protective metal cover, insulating powdery substance, and resistance element. The properties of the materials used in glow plugs are shown in Table 1. The basic principle of a modern glow plug is the combination of a heating and a regulating coil to build one resistance element. This heating coil consists of a highly temperature-resistant product, whose electrical resistance is effectively independent from the temperature. It creates the heating zone, along with the front part that involves the glow tube. The actual regulating coil is mounted on the conductive connection bolt; its resistance is characterized by a huge temperature coefficient [16].

#### Table 1. Properties of the materials used in glow plug production.

<table>
<thead>
<tr>
<th>Sample</th>
<th>External radius (mm)</th>
<th>Internal radius (mm)</th>
<th>Width of the heated region (mm)</th>
<th>Volume (mm³)</th>
<th>Mass of the metal cover (g)</th>
<th>Metal cover heat capacity (J/kg °C, at 20 °C)</th>
<th>Density at (kg/dm³, at 20 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.15</td>
<td>0.7</td>
<td>7</td>
<td>205.2461</td>
<td>1.59271</td>
<td>472</td>
<td>0.00776</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>0.6</td>
<td>10</td>
<td>201.4546</td>
<td>1.563288</td>
<td>472</td>
<td>0.00776</td>
</tr>
</tbody>
</table>

#### 4.1. Magnesium oxide

MgO, which is put in the heater tube of the glow plug, is mostly used as an insulator and for resistance to high temperatures. MgO used in glow plug production is an ionic compound and thus does not conduct electricity in its solid state, because there are no delocalized electrons due to its ionic lattice structure.

There are 3 reasons for the selection of magnesium oxide as an insulator. First, it is used for resistance against wire heater corrosion that affects the external environment; it protects the metal cover of the wire so as to provide electrical isolation; and it prevents the oxidation of the resistance wire. Second, if the glow plug reaches high temperatures, the temperature of the heating element must have good electrical isolation. During the operation of the element in this region, the temperature is around 1000–1200 °C. Third, the material must fit comfortably into a powder material between the heater material and the metal tube. On the other hand, at high temperatures, thermal conduction should be low. The temperature of the heating element should be isolated from the outside with the help of MgO [17,18]. Its physical properties are shown in Table 2 [19].
Figure 6. Electrical and thermal circuit model of Sample 1.
Figure 7. Electrical and thermal circuit model of Sample 2.
Figure 8. Equations used in the thermal impedance model.

<table>
<thead>
<tr>
<th>Compound formula</th>
<th>Appearance</th>
<th>Melting point (°C)</th>
<th>Boiling (°C)</th>
<th>Density (g/cm³)</th>
<th>Thermal conductivity (W/m K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>White powder</td>
<td>2830</td>
<td>3600</td>
<td>3.58</td>
<td>45–60</td>
</tr>
</tbody>
</table>

**Table 2. Physical properties of MgO.**

4.2. Inconel ASTM/UNS 310/310S stainless steel (glow tube cover)

Stainless steel 310/310S is an austenitic heat proof alloy with perfect resistance to oxidation below mildly cyclic problems through to 1093 °C. Its high chromium and nickel contents provide comparable corrosion resistance, superior resistance to oxidation, and retention of a greater fraction of room temperature strength compared to common austenitic alloys such as type 304. Stainless steel 310 is frequently used in cryogenic temperatures, with excellent toughness in order to withstand –268 °C, and also low magnetic permeability [20].

The particular characteristics of 310 and 310S stainless steel are, generally, oxidation resistance in order to withstand 1300 °C, moderate strength at high temperature, resistance to very hot corrosion, and power in cryogenic temperature ranges. The physical properties of 310S stainless steel are presented in Table 3 [20].

**Table 3. Physical properties of 310S stainless steel.**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (g/cm³)</th>
<th>Thermal expansion coefficient (Ωmm²/m)</th>
<th>Specific heat capacity (kcal °C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.9</td>
<td>15.5 × 10⁻⁶</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4.3. Kanthal D and Vacon CF8 coil

Heating coil Kanthal D is usually a ferritic iron-chromium-aluminum (FeCrAl alloy) combination used in temperatures as high as 1300 °C. The alloy is characterized by high resistivity and good oxidation resistance. The physical properties of Kanthal D are shown in Table 4 [21].

Regulating coil Vacon CF8 is a special alloy with unique resistance and temperature characteristics. The material of Vacon CF8 displays sharp increases in resistance, depending on temperature. This unusual behavior is ideal for applications such as temperature-dependent control processes [22].
Table 4. Physical properties of Kanthal D resistance.

<table>
<thead>
<tr>
<th>Density</th>
<th>Electrical resistivity (at 20 °C, Ω mm²/m)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.25</td>
<td>1.35</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Vacon CF8 is an austenitic alloy. It displays an almost linear increase in electrical resistance up to the Curie point of about 1050 °C. The reason we used Vacon CF8 as a regulating coil is that it protects the plug from overheating, which causes damage. Although the resistance of the Kanthal does not change significantly with temperature, the resistance of Vacon CF8 is directly proportional to temperature. The physical properties of the Vacon CF8 are denoted in the Table 5 [22].

Table 5. Physical properties of Vacon CF8 resistance.

<table>
<thead>
<tr>
<th>VAC product</th>
<th>Density (g/cm³)</th>
<th>Specific electrical resistance (µΩ/m)</th>
<th>Thermal conductivity (at 20 °C, W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VACON CF 8</td>
<td>8.7</td>
<td>0.08</td>
<td>85</td>
</tr>
</tbody>
</table>

With the help of the results of the simulation and the parameters of the materials in Tables 1 and 2, two different glow plugs were manufactured, as shown in Figure 9. They have different sizes and different heating characteristics. Both can be used in different diesel engines, and their preheating cycle usually lasts from 2 to 5 s. Below we can see the entire glow plug, heater tube, and electrodes.

![Figure 9. Production of 2 different sizes of glow plugs.](image)

4.4. Tests of the manufactured glow plugs with thermal imaging

To validate the thermal model, we carried out simulations on the glow plugs. Before the start of the engine, the glow plug was energized and the tube was heated up to 1000 °C. Glow plugs can be tested by removing the glow plug and applying 12 V to it. If it is working well, it should turn bright red within approximately 5 s. As shown in Figures 10 and 11, the simulations show that the temperature of the glow plugs rose as high as 900–1000 °C, which agrees with the thermal image results. In fact, the temperature–time relationship was expected to be mostly nonlinear due to the internal resistance of the regulating coil, since its resistance is strongly temperature-dependent. Resistance changes with the temperature, and hence the current passes through it and decreases with time. Therefore, a nonlinear, saturating-type behavior was expected, and this was observed in the simulations.
Figures 12 and 13 show that the plugs that we produced were glowing. Every plug has a different temperature and glowing point.

In Figures 14 and 15, we can see the heating process with a thermal camera, which clearly shows that the temperature is over 1000 °C for Sample 1 and over 900 °C for Sample 2. The tests that we performed agree with the simulation results.

5. Results and discussion
This section analyzes the results of the experiments. The tests were completed as expected, with no unusual events that would have introduced error. The initial and final values of the current and the resistance of the glow tube are measured for the glow plug, and the rise in temperature due to heat transfer is shown in Figures 10 and 11. In addition, Figure 8 includes the equations used for calculating the parameters and simulating the glow plugs. These equations led to the thermal model and to its simulation. With these values a graph between temperature (°C) and time was created, as shown in Figures 10 and 11. As can be seen from the graph shown in Figure 10, the relationship of temperature vs. time is roughly linear up to 1000 °C; after reaching
Figure 14. Thermal imaging of Sample 1 using FLIR T440.

Figure 15. Thermal imaging of Sample 2 using FLIR T440.

this temperature, it becomes constant (nonlinear) due to the internal resistance. In our simulation, within 3 s the temperature surpassed 1000 °C, as shown in Figure 10, and 900 °C, as shown in Figure 11. This heating resistance heats up as soon as it is electrified due to its internal resistance, and then begins to emit light.

The particular heating times and glow temperatures in the plug can be changed by working with different materials, lengths, diameters, and wire thickness in the heating and regulating coils, thus designing different glow plugs that match as much as possible what is needed of the different engine types. Thermal energy, generated by electrical energy, flows into the combustion chamber to create the perfect ignition conditions for the injected fuel.

The particular glow spreads quickly, and the heating rod is usually glowing near the plug body after 2–5 s. Self-controlling plugs independently protect against overheating simply by restricting the stream of electricity from the battery to the plug due to temperature increases.

Consequently, the electrical resistance rises, and the current is also reduced to a degree such that the glow tube cannot be damaged, which means that the glow plug cannot overheat. Changes in glow plug systems and their capability to regulate glow plug temperature and duration for every cylinder individually have necessitated that glow plug technology be developed further, in order to meet these types of increased performance requirements.

6. Conclusion
In this study, the thermal behavior of a glow plug was analyzed and produced with the help of the test results. We presented a new approach to the glow plug heating process and production aspects. Simulation, basic theory, and fabrications were discussed. Firstly, the thermal behavior of a glow plug was modeled and a simulation of its heating behavior was examined. Then the heat transfer between the parts of the heater tube was observed. The thermal circuit of the system was depicted and interpreted. It was shown that the thermal heating of the glow plug can be analyzed with the help of thermal circuit simulation. As a result of these analyses, glow plugs can be produced that have better performance under harsh conditions.

Acknowledgment
This study was supported by the Scientific Research Project Office of Necmettin Erbakan University.
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