

# Transient Thermal Analysis of Diesel Fuel Systems

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## ABSTRACT

In this paper, a transient thermal analysis model for Diesel fuel systems is presented. The purpose of this work is to determine the fuel temperature at various locations along the system, especially inside the tank and at the returned fuel inlet to the tank. Due to the fact that the fuel level is continuously changing during any driving condition, the fuel mass inside the tank is also continuously changing. Consequently, the fuel temperature will change even under steady driving or idle conditions, therefore, this problem should be analyzed using transient thermal analysis models. Effective thermal management requires controlling the surface temperature of the fuel tank, fuel lines and the fuel temperature at the fuel return line as well as inside the tank [1, 2]. Based on the thermal analysis results, it is possible to determine the major source of heat input at several locations of the fuel system. If necessary, a cooling module can be designed to bring down the returned fuel temperature to an acceptable limit. Other thermal protection options that are investigated, in this work, include shielding the fuel tank, fuel supply and return lines and modifying the fuel system materials and dimensions. The results of the mathematical models are compared to test data from physical vehicle testing with respect to various driving scenarios. A Design For Six Sigma (DFSS) process is applied in this work for evaluation robust design and determination of most influential design factors.

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## INTRODUCTION

### Diesel Fuel System

In the Diesel fuel systems (Figure 1), a low pressure pump is used to lift the fuel and feed it to the high pressure pump. High pressure pump will pressurize a metered amount of fuel, transport it to the injector nozzle, and inject an atomized fuel spray into the combustion chamber. Excess fuel, which is used for lubricating and cooling the high pressure components, is returned back to fuel tank. The fuel return system routes fuel from the fuel injectors and the fuel injection pump. The fuel rail pressure regulator (relief valve) is located in the rear of the fuel rails. A fuel cooler may be required to lower the temperature of the returned fuel.

During vehicle development phases, it is required to predict thermal issues early in the development phases before actual vehicles become available for testing. It is possible to collect temperature data for the fuel system during testing for verification purposes. However, it will be too costly to fix any thermal issues in a late stage in development. Therefore, it is required to find out any potential issues through simulations and therefore appropriate measures can be

considered to resolve issues in a timely and cost effective manner.

### Diesel Fuel Composition

Diesel fuels consist of complex mixtures of hydrocarbons. Diesel Fuel oil no. 1 (straight-run kerosene) is a light distillate which consists primarily of hydrocarbons in the C<sub>9</sub>-C<sub>16</sub> range; fuel oil no. 2 is a heavier, usually blended, distillate with hydrocarbons in the C<sub>11</sub>-C<sub>20</sub> range. In this work, a mixture of hydrocarbons (C<sub>9</sub>-C<sub>11</sub>) is assumed. Several studies [3, 4, and 5] have been conducted to evaluate the effect of fuel composition and fuel volatility on the vehicle performance and emissions.

## ANALYSIS

The objective of this work is to determine the diesel fuel temperature at several locations along the fuel system. The in-tank fuel temperature should be maintained below a certain limit. Therefore, it is required to investigate the effect of different design options for better management of the fuel temperature. A best combination of the design parameters (control factors) should have the lowest fuel temperature. Thermal analysis requires the following steps:

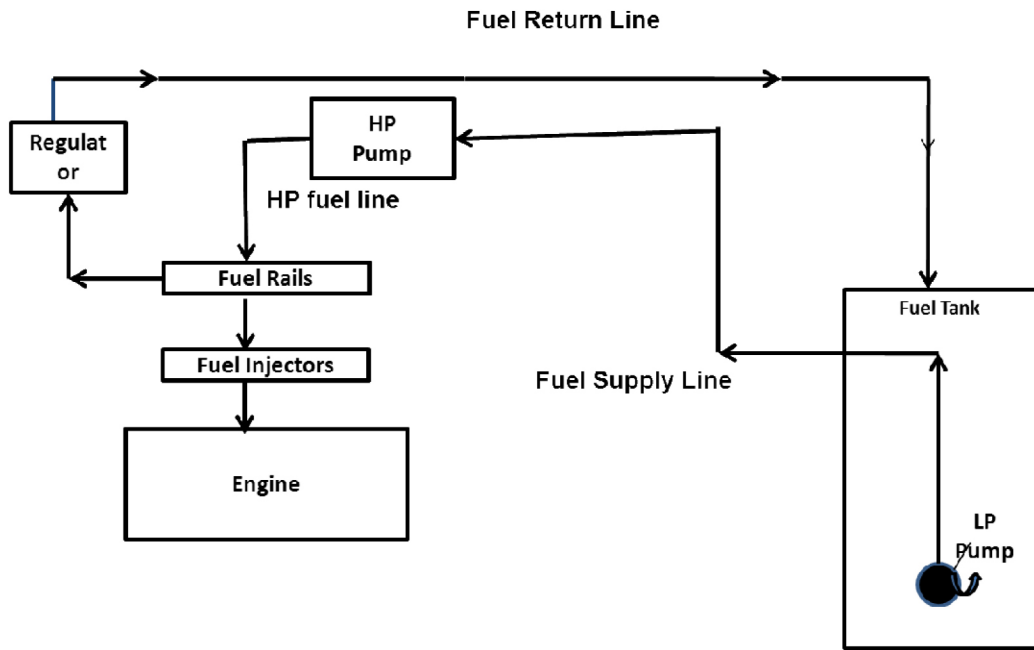


Figure 1. Schematic diagram of Diesel fuel system

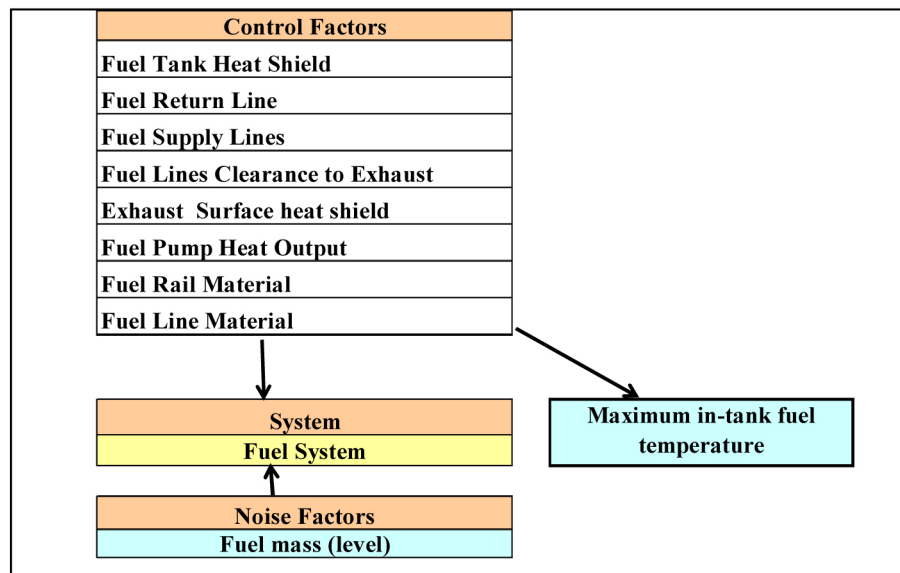


Figure 2. Control and noise factors

- Develop a transient fuel thermal analysis model that considers the fuel system characteristics (dimensions, material).
- Using a fuel vapor model, determine the rate of fuel vapor generation and the rate of evaporative emissions.
- Verify the transient versus steady state analysis using real test data.
- Determine the fuel temperature for any given driving schedule.

- Apply the Design for Six Sigma (DFSS) for selection of best combination of control factors (CF) that can result into the lowest in-tank fuel temperature.

The relationship between the CF's and noise factors is illustrated in [Figure 2](#). The major noise factor for thermal analysis of the fuel system is the initial fuel mass (fuel level) inside the tank. In this work, two levels are considered; 20% full and 80% full.

The developed thermal model is applied to carry out the required simulations. The procedure of selecting these simulations is explained in reference [6].

Table 1. Control factors and analysis level

|   | Control Factor Description      | Level 1          | Level 2             | Level3              |
|---|---------------------------------|------------------|---------------------|---------------------|
| A | Fuel Tank Heat Shield           | No Shield        | Shielded            |                     |
| B | Fuel Return Line                | With Return Line | No Return Line      | Finned return Line  |
| C | Fuel Supply Lines               | Nylon            | Steel               | Aluminum            |
| D | Fuel Lines Clearance to Exhaust | 60 mm            | 90 mm               | 120 mm              |
| E | Exhaust Surface Heat Shield     | No Shield        | Single layer shield | Double layer shield |
| F | Fuel Pump Heat Output           | 50 Watt          | 75 Watt             | 100 Watt            |
| G | Fuel Rail Material              | Nylon            | Steel               | Aluminum            |
| H | Fuel Line Material              | Nylon            | Steel               | Aluminum            |

Table 2. Simulation matrix

| # of Runs | A | B | C | D | E | F | G | H | Fuel Tank Heat Shield | Fuel Return Line   | Fuel Supply Lines | Fuel Lines Clearance to Exhaust | Exhaust Surface Heat Shield | Fuel Pump Heat Output | Fuel Rail Material | Fuel Line Material |
|-----------|---|---|---|---|---|---|---|---|-----------------------|--------------------|-------------------|---------------------------------|-----------------------------|-----------------------|--------------------|--------------------|
| 1         | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | No Shield             | With Return Line   | Nylon             | 60 mm                           | No Shield                   | 50 Watt               | Nylon              | Nylon              |
| 2         | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | No Shield             | With Return Line   | Steel             | 90 mm                           | Single layer shield         | 75 Watt               | Steel              | Steel              |
| 3         | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | No Shield             | With Return Line   | Aluminum          | 120 mm                          | Double layer shield         | 100 Watt              | Aluminum           | Aluminum           |
| 4         | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 3 | No Shield             | No Return Line     | Nylon             | 60 mm                           | Single layer shield         | 75 Watt               | Aluminum           | Aluminum           |
| 5         | 1 | 2 | 2 | 2 | 3 | 3 | 1 | 1 | No Shield             | No Return Line     | Steel             | 90 mm                           | Double layer shield         | 100 Watt              | Nylon              | Nylon              |
| 6         | 1 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | No Shield             | No Return Line     | Aluminum          | 120 mm                          | No Shield                   | 50 Watt               | Steel              | Steel              |
| 7         | 1 | 3 | 1 | 2 | 1 | 3 | 2 | 3 | No Shield             | Finned return Line | Nylon             | 90 mm                           | No Shield                   | 100 Watt              | Steel              | Aluminum           |
| 8         | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 1 | No Shield             | Finned return Line | Steel             | 120 mm                          | Single layer shield         | 50 Watt               | Aluminum           | Nylon              |
| 9         | 1 | 3 | 3 | 1 | 3 | 2 | 1 | 2 | No Shield             | Finned return Line | Aluminum          | 60 mm                           | Double layer shield         | 75 Watt               | Nylon              | Steel              |
| 10        | 2 | 1 | 1 | 3 | 3 | 2 | 2 | 1 | Shielded              | With Return Line   | Nylon             | 120 mm                          | Double layer shield         | 75 Watt               | Steel              | Nylon              |
| 11        | 2 | 1 | 2 | 1 | 1 | 3 | 3 | 2 | Shielded              | With Return Line   | Steel             | 60 mm                           | No Shield                   | 100 Watt              | Aluminum           | Steel              |
| 12        | 2 | 1 | 3 | 2 | 2 | 1 | 1 | 3 | Shielded              | With Return Line   | Aluminum          | 90 mm                           | Single layer shield         | 50 Watt               | Nylon              | Aluminum           |
| 13        | 2 | 2 | 1 | 2 | 3 | 1 | 3 | 2 | Shielded              | No Return Line     | Nylon             | 90 mm                           | Double layer shield         | 50 Watt               | Aluminum           | Steel              |
| 14        | 2 | 2 | 2 | 3 | 1 | 2 | 1 | 3 | Shielded              | No Return Line     | Steel             | 120 mm                          | No Shield                   | 75 Watt               | Nylon              | Aluminum           |
| 15        | 2 | 2 | 3 | 1 | 2 | 3 | 2 | 1 | Shielded              | No Return Line     | Aluminum          | 60 mm                           | Single layer shield         | 100 Watt              | Steel              | Nylon              |
| 16        | 2 | 3 | 1 | 3 | 2 | 3 | 1 | 2 | Shielded              | Finned return Line | Nylon             | 120 mm                          | Single layer shield         | 100 Watt              | Nylon              | Steel              |
| 17        | 2 | 3 | 2 | 1 | 3 | 1 | 2 | 3 | Shielded              | Finned return Line | Steel             | 60 mm                           | Double layer shield         | 50 Watt               | Steel              | Aluminum           |
| 18        | 2 | 3 | 3 | 2 | 1 | 2 | 3 | 1 | Shielded              | Finned return Line | Aluminum          | 90 mm                           | No Shield                   | 75 Watt               | Aluminum           | Nylon              |

The list of control factors and the corresponding levels of analysis is shown in table 1.

Considering all CF's and the noise factors, a series of 18 simulations are required [6]. The combination of all simulation runs is shown in table 2.

## THERMAL MODELS

### FUEL TANK THERMAL MODEL

A conduction thermal model is used to determine the tank surface temperature. Heat transfer through the tank walls is governed by the following equation:

$$\frac{\partial T_t}{\partial t} = \left( \frac{k_t}{\rho_t c_t} \right) \left( \frac{\partial^2 T_t}{\partial x^2} \right) \quad (1)$$

The following boundary condition applies at the tank outer surface:

$$-k_t \frac{\partial T_t}{\partial x} \bigg|_{x=0} = h_{t-air} (T_{air} - T) \bigg|_{x=0} + \sigma \epsilon F (T_{exhs}^4 - T_t^4) \bigg|_{x=0} \quad (2)$$

The following boundary condition applies at the tank inner surface:

$$-k_t \frac{\partial T_t}{\partial x} \bigg|_{x=x_t} = h_{t-fuel} (T_t - T_f) \bigg|_{x=x_t} \quad (3)$$

The following initial condition applies:

$$\text{At } t = 0, T_t = T_f = T_{airi} \quad (4)$$

### FUEL THERMAL MODEL (INSIDE FUEL TANK)

The transient model for the in-tank fuel temperature is described by the following equation:

$$\frac{dT_f}{dt} = \left( \frac{1}{m_{f(t)} c_f} \right) \left[ (h_{t-f} A_{f(t)} (T_t - T_f) \bigg|_{x=x_t} - \dot{m}_f c_f T_f + \dot{m}_{Rf} c_f T_{Rf} + \dot{Q}_p \right] \quad (5)$$

The following initial condition applies:

$$\text{At } t = 0, T_f = T_{ff} = T_{airi}$$

Equation 5 is an energy balance which accounts for the heat added by returned fuel, by convection from the tank inner wall, heat added by the fuel pump and the heat removed by the pumped fuel. The critical heat transfer area to the fuel mass inside the tank is the wetted surface area which is always in contact with the fuel. As the fuel mass is continuously changing, the fuel level and consequently the wetted surface area will vary with time. The fuel mass balance is given by the following equation:

$$\frac{\partial m_f}{\partial t} = -\dot{m}_{f(t)} - \dot{m}_{fv(t)} + \dot{m}_{rf(t)} \quad (7)$$

At  $t = 0$ ,

$$m_f = m_f^0 \quad (8)$$

Equation 7 represents the transient fuel mass balance. The fuel mass is affected by the amount of fuel pumped out of the tank, fuel evaporation and by the returned fuel. Therefore, the fuel mass is continuously changing as long as the engine is running. Therefore, from equations 5 and 7, it can be concluded that the simulation of fuel tank temperature is a transient problem and cannot be approximated by a steady state solution. In light driving conditions when the fuel consumption is minimum, the fuel temperature may become steady for short time duration. However, for a typical driving condition especially at high speed or at high load, the fuel temperature is very transient.

### FUEL LINES THERMAL MODEL

The following equations apply to the fuel supply lines, fuel rails and fuel return lines. The equations consider conduction through the wall and then heat convection from the inner side of the line material to the fuel. The thermal conduction model allows investigation of different material types, wall thickness and insulation. The fuel rail model includes conduction from engine block to the fuel rail brackets and then from fuel brackets to fuel rails. The conduction model is described by the following equation:

$$\frac{\partial T_s}{\partial t} = \left( \frac{k_s}{\rho_s c_s} \right) \left( \frac{\partial^2 T_s}{\partial x^2} \right) \quad (9)$$

The following boundary condition applies at the outer surface:

$$-k_s \frac{\partial T_s}{\partial x} \Big|_{x=0} = h_{s-air} (T_{air} - T_s) \Big|_{x=0} + \sigma \epsilon F (T_{exhs}^4 - T_s^4) \Big|_{x=0} \quad (10)$$

Equation 10 implies that the heat transferred by convection and radiation to the outer surface is equal to the

heat conducted through the wall. The following boundary condition applies at the inner surface:

$$-k_s \frac{\partial T_s}{\partial x} \Big|_{x=th} = h_{s-fuel} (T_s - T_f) \Big|_{x=th} \quad (11)$$

With following initial condition:

$$\text{At } t = 0, \quad T_s = T_{airi} \quad (12)$$

Equation 11 states that the heat transferred by conduction through the wall thickness is equal to the heat transferred by convection from the inner surface of the fuel lines to the fuel passing through it. Therefore, the internal heat transfer coefficient depends on the flow rate and fuel thermal properties.

Where,

$h_{s-air}$  : is the heat transfer coefficient at the air and the fuel line outer surface

$h_{s-fuel}$  : is the heat transfer coefficient at the inner surface of the fuel line

$th$  : is the fuel supply line thickness

### FUEL THERMAL MODEL (INSIDE FUEL LINES)

The fuel line is divided into a number of sections along its length. The following equation applies to the fuel passing through each section:

$$\frac{\partial T_{fs}}{\partial t} = \left( \frac{1}{m_{fuel} C_{p_{fs}}} \right) \left( \dot{m}_{fuel} C_{p_{fs}} (T_{fs,in} - T_{fs,out}) - h_{s-fuel} A_{fs} (T_{si} - T_{fs}) \right) \quad (13)$$

Where,

$T_{fs}$  : is the fuel temperature inside section  $i$ .

$T_{fs,in}$  : is the temperature of fuel entering section  $i$ .

$T_{fs,out}$  : is the temperature of fuel leaving section  $i$ .

$m_{fuel}$  : is the mass of fuel inside a given section.

$\dot{m}_{fuel}$  : is the fuel mass flow rate