ANALYSIS OF KEY FUEL PROPERTIES INSIDE COMBINATION ELECTRONIC UNIT PUMP FUEL PIPELINE

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Submitted: Aug. 10, 2013            Accepted: Nov. 16, 2013            Published: Dec. 23, 2013

Abstract - Because of high pressure fluctuations in Combination Electronic Unit Pump (CEUP) system during fuel injection cycles, physical properties of diesel fuel including density, acoustic wave speed and bulk modulus also vary. These physical properties of fuel have significant importance in predicting the fuel injection behavior and its optimization. A 1D viscous damped mathematical model of wave equation has been developed in MATLAB not only to simulate the pressure fluctuations in fuel pipeline at various operating conditions of diesel engine but also to determine and analyze the variations in these physical properties of diesel fuel.

Index terms: Mathematical model, Fuel pipeline, Wave equation; Density, Acoustic wave speed, Bulk modulus.
I. INTRODUCTION

Operating pressure in diesel fuel injection systems can reach as high as 100 MPa [1]. In an efficient fuel injection system like CEUP it can increase as high as 150 MPa [2][3][4][5]. CEUP meets Chinese strict emission requirements [3] and help in restricting air pollution caused by emissions which is a health risk especially in urban areas [6]. CEUP is a high pressure (HP) fuel injection system and it consists of a combination of pumps, fuel pipelines, injectors and solenoid control units [3][4][5]. Fuel pipeline between pump and mechanical injector is an important component and impacts in developing and propagating high pressure fuel developed at pump end and injector end [4]. Therefore, detailed experimental and theoretical studies have been carried out along with the support of numerical and mathematical models to investigate the building up and propagation of pressures along HP fuel pipeline at various operating conditions of diesel engine. Pressure wave propagation inside fuel pipeline of CEUP has been discussed previously at various operating conditions through the comparative study of three different 1D mathematical models developed in MATLAB [2]. Viscous damped mathematical model proved to be relatively more accurate in most of operating conditions of CEUP [2].

Physical properties of fuel including density, acoustic wave speed and bulk modulus impact the performance of fuel injection system [7-12]. In past decade many researchers have carried out experimental and numerical studies investigating the effects of these fuel properties as a function of varying pressures and temperatures on fuel injection systems. Andre’ L. Boehman, David Morris and James Szybist [7] have measured bulk modulus of compressibility of diesel, biodiesel and soybean fuel and its impact on injection timing of inline pump. Breda Kegl and Ales Hribernik working on biodiesel, diesel and their blends studied these physical properties of fuel with varying pressure and temperatures and their impact on injection characteristics of inline pump system [8] whereas Flavio Caresana concluded the effect of bulk modulus of biodiesel on injection characteristics [9]. Marzena Dzida and Piotr Prusakiewicz [10] studied the effect of pressure and temperature on the speed of sound in diesel and biodiesel fuels between 0.1-101MPa and 293-218K respectively. They also measured densities at atmospheric pressure and between 273-363K temperatures. Mustafa E. Tat and Jon H. Van Gerpen [11] have introduced correlation equations for density, speed of sound and isentropic bulk modulus while working on blend of biodiesel and diesel fuels at pressures ranging from 1 atmosphere to 32.46 MPa and temperatures.
of 20°C and 40°C. Boban D. Nikolic, Breda Kegl, Sasa D. Markovic and Melanija S. Mitrovic [1] following a non-destructive pressure varying experiment on three kinds of fuels including pure rapeseed oil, rapeseed methyl ester (biodiesel) and diesel fuel have presented polynomial expressions for calculating density, speed of sound and bulk modulus. Wang Jun-Xiao, Lu Jia-Xiang, Zhang Jin-Yang and Zhang Xi-Chao [12] have also developed empirical formulas for density, dynamic viscosity, speed of sound and bulk modulus as a function of changing pressures during diesel fuel injection process.

In this paper 1D viscous damped mathematical model [13][14][15][16] of pressure wave inside HP fuel pipeline using a wave equation has been developed in MATLAB in order to study and investigate the diesel fuel pressure and in depth analysis of variations in the key fuel properties including density, acoustic wave speed and bulk modulus predicted by the mathematical model particularly in CEUP fuel pipeline as a function of varying pressures at different operating conditions of diesel engine.

AMESim numerical model of CEUP one unit fuel injection system has also been modeled and validated experimentally. 1D mathematical model has been validated by comparison the results with AMESim numerical model of CEUP at various operating conditions of diesel engine. The comparative results are quite coherent thus validate both AMESim and MATLAB models. Lab experiments have been carried out on CEUP at various operating conditions of diesel engine. Experimentally measured pump side and injector side pressures have been used as boundary conditions for mathematical model.

The rest of this paper is organized as follows. CEUP fuel injection system, its operating principle and AMESim numerical model have been described briefly in Section II. Experimental setup and results are described in section III. 1D viscous damped mathematical modeling and its validation is presented in section IV. Simulated results of key fuel properties are presented and explained in Section V. Conclusions are made in Section VI.
II. CEUP FUEL INJECTION SYSTEM, AMESIM NUMERICAL MODEL AND ITS VALIDATION

CEUP fuel injection system consists of four or more units of pump unit, fuel pipeline, mechanical injector and solenoid control unit. Schematic of one unit CEUP is shown in figure 1.

![Figure 1. Schematic of CEUP fuel injection system](image)

We have used a four unit CEUP fuel injection system as shown in figure 3 in our lab experiments. In a four unit CEUP four pump units along with their solenoid control units are jointly mounted on a low pressure combination box. Cam drives pump unit plunger and pushes-in and pushing-out fuel from plunger chamber by it’s upwards and downwards motion respectively. Plunger resets to its rest position by a plunger spring. Solenoid control unit controls the quantity, timing and flow of fuel flow either towards the injector or towards the fuel tank [3]. When the control valve of the solenoid control unit is open fuel inside the plunger chamber returns back to the fuel tank by upward motion of plunger. Whereas, when the control valve is closed the fuel is
pushed towards the delivery chamber and sac chamber of the mechanical injector through fuel pipeline by upward motion of plunger. Control valve opens and closes by turning the power off and on of solenoid control unit respectively. When the control valve is closed fuel pressure inside plunger chamber, fuel pipeline, delivery chamber and sac chamber starts to increase with upward motion of plunger. When the fuel pressure inside delivery chamber and sac chamber exceeds the closing pressure of the injector needle, it lifts up and fuel is injected into the chamber. Injector needle resets to its rest position by a needle spring.

AMESim numerical model of one unit CEUP fuel injection system has been modeled as shown in figure 2. It consists of a pump unit, solenoid control unit, fuel pipeline and a mechanical injector. Simulated pump side pressure and injector side pressure have been observed at locations shown in the figure 2. AMESim numerical model has been validated by comparing the simulated pump side and injector side pressures with experimentally measured pump side pressure and injector side pressures respectively on experimental setup shown in figure 3.

Figure 2. Numerical model of one unit CEUP fuel injection system
III. EXPERIMENTAL SETUP AND RESULTS

Series of experiments have been conducted in controlled temperature environment and with sufficient gap intervals so as to minimize the effect of temperature on the measured results. These tests were carried out at combination of operating conditions mentioned in table 1. Pump side and injector side pressures along with other fuel injection characteristics including injected fuel pressures and injected fuel quantities were recorded. Experimental setup is shown in figure 3.

![Figure 3. Schematic of CEUP fuel injection system](image)

**Table 1: Test bench operating conditions**

<table>
<thead>
<tr>
<th>Cam Rotational Speed (rpm)</th>
<th>Cam Angle (°CA)</th>
<th>Pipe length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500, 700, 900, 1100 and 1300</td>
<td>2,6,10 and 14</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Pump side and injector side pressures were recorded using KISTLER 4067 piezoresistive pressure sensors [17]. Combination of single pump unit, single solenoid control unit and single mechanical injector has been used during experiments. Pressures measured by pump side sensor and injector side sensors have been used to validate AMESim numerical model as well as set of Dirichlet boundary conditions for 1D mathematical model. Pump and injector pressures varied.
between 500 bars to 1500 bars depending upon the cam rotational speeds (rpm) and cam angles (°CA).

Comparisons of experimentally measured pump and injector pressures with AMESim numerical model at cam rotational speed and cam angle of 900rpm and 10°CA are shown in figure 4(a) and 4(b) respectively. Whereas comparisons at cam rotational speed and cam angle of 1300rpm and 12°CA are shown in figure 5(a) and 5(b). The results are coherent and therefore validate AMESim numerical model of CEUP with single HP pump unit and mechanical injector.

![Figure 4. Comparison of experiment and AMESim model results at 900rpm and 10°CA](image-url)

![Figure 5. Comparison of experiment and AMESim model results at 1300rpm and 12°CA](image-url)
IV. 1D MATHEMATICAL MODEL AND ITS VALIDATION

The following assumptions have been made for preparing the mathematical model.

1. The fuel flow is from pump side to injector side.
2. The fuel is Newtonian fluid.
3. The flow is laminar with Reynolds number less or equal to 2300.
4. Pressure is constant across the cross section of pipe.
5. Fuel is homogeneous and without any bubbles.
6. Pipe walls are rigid and
7. Temperature is considered constant.

Compressional wave is described by following time domain equation

\[ \nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} + \alpha \frac{\partial}{\partial t} \nabla^2 p = 0 \]  \hspace{1cm} (1)

where \( p \), \( c \), \( t \) and \( \alpha \) are pressure, acoustic wave speed, time and frequency independent constant parameter respectively. For viscous damping frequency independent constant parameter is given by following equation 2 [13] or equation 3 [18].

\[ \alpha = \frac{4 \eta}{3 \rho c^2} \]  \hspace{1cm} (2)

\[ \alpha = \frac{4 \nu}{3 c^2} \]  \hspace{1cm} (3)

where \( \eta \), \( \rho \) and \( \nu \) are absolute or dynamic viscosity, density and kinematic viscosity respectively. Absolute or dynamic viscosity is related to kinematic viscosity by the following relation

\[ \nu = \frac{\eta}{\rho} \]  \hspace{1cm} (4)

Equations 1-4 are true for following initial conditions and Dirichlet boundary conditions

\[ p(x,0) = p_{initial} \quad \frac{\partial p}{\partial t}(x,0) = 0 \] \( x \in (0,L) \) and \( t \in (0,T) \)

\[ p(0,t) = p_{pump} \quad p(L,t) = p_{injector} \]  \hspace{1cm} (5)
where $P_{\text{initial}}$, $P_{\text{pump}}$ and $P_{\text{injector}}$ are initial pressure, experimentally measured pump side and injector side pressures respectively. $L$ and $T$ are total length of pipe and total time of measured/simulated results respectively.

As concluded by the researchers that physical characteristics including density, acoustic wave speed and bulk modulus of the fuel changes with varying pressures [7-12] therefore dynamic values have been considered in the mathematical model. Polynomial expressions presented by Boban D. Nikolic et al. [1] have been used. These polynomial expressions with values are reiterated as follows

$$
\rho(x,t) = D_0 + D_1 p(x,t) + D_2 p^2(x,t) \\
c(x,t) = S_0 + S_1 p(x,t) + S_2 p^2(x,t) \\
B(x,t) = B_0 + B_1 p(x,t) + B_2 p^2(x,t)
$$

where $D$, $S$ and $B$ are density, acoustic wave speed and bulk modulus polynomial coefficients respectively. Values of $D_0, D_1, D_2, S_0, S_1, S_2, B_0, B_1$ and $B_2$ are 839.4, 0.483, -5.32x10^{-4}, 1359.35, 4.05, -5.0x10^{-3}, 1.54x10^9, 1.07x10^7 and -2.69x10^3 respectively.

Equations (1) with initial and boundary conditions (5) are solved by using Finite Difference Method (FD). Temporal domain (0,T) and spatial domain (0,L) are divided into finite number of fixed size mesh points

$$
x_n = (n-1)\Delta x \quad n = 1, 2, 3, \ldots, L \\
t_i = i\Delta t \quad t = 1, 2, 3, \ldots, N
$$

where $\Delta x = x_n - x_{n-1}$ and $\Delta t = t_i - t_{i-1}$ such that the solution converges and remains within the stability criteria of $c(\Delta t/\Delta x) \leq 1$ [13].

The mathematical model has been simulated at combinations of operating conditions mentioned in table 1 and compared to AMESim numerical model at 11 equidistant locations along the fuel pipeline [2]. Fuel pressure has been calculated at each mesh point along the fuel pipeline. Comparisons of simulated pressure results of mathematical model with AMESim numerical model validate the model. Figure 6(a-e) shows some comparative results of MATLAB mathematical model with AMESim in the middle of pipe at 500rpm and 6°CA, 700rpm and 10°CA, 900rpm and 14°CA, 1100rpm and 6°CA and 1300rpm and 2°CA respectively. It is clear from the figure 6(a-e) that diesel fuel pressure varies from 400 bars, figure 6(e), to up to 1400 bars, figure 6(e).
Figure 6. Comparison of AMESim and MATLAB results at (a) 500rpm and 6°CA (b) 700rpm and 10°CA (c) 900rpm and 14°CA (d) 1100rpm and 6°CA (e) 1300rpm and 2°CA
Comparisons of all the results are coherent thus validating the mathematical model. All results of mathematical model are also quantitatively analyzed and compared with AMESim numerical model by using model evaluation statistical techniques like “Root Mean Square Error” (RMSE) and “Index of Agreement” (IA) [19] using equations (8) and (9) respectively. Model with lower RMSE or IA near to 1 is accepted as a better one [19]. A maximum of 73.64 bar of RMSE is observed at 1300 rpm and 14 °CA as shown in figure 7. It has been observed that at higher cam rotational speeds (rpm) and at higher cam angles (°CA) RMSE is relatively higher. Moreover a minimum of 0.8817 IA is observed at 1100 rpm and 2 °CA as shown in figure 8.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_{AMESim,i} - P_{Model,i})^2}{n}}
\]  

(8)

\[
IA = 1 - \left[ \frac{\sum_{i=1}^{n} (P_{AMESim,i} - P_{Model,i})^2}{\sum_{i=1}^{n} (abs(P_{Model,i} - mean(P_{AMESim,i})) + abs(P_{AMESim,i} - mean(P_{AMESim,i})))} \right]
\]  

(9)

RMSEs and IAs at all combinations of operating conditions mentioned in table 1 are shown in figures 7 and figure 8 respectively.

![Figure 7. RMSEs of mathematical model as compared to AMESim numerical model](image-url)
V. SIMULATED RESULTS OF KEY FUEL PROPERTIES

Variation in the diesel key fuel properties including density, acoustic wave speed and bulk modulus as a function of varying pressures have also been simulated at 11 different and equidistant points along the fuel pipeline at all combinations of operating conditions mentioned in table 1. Simulated results are discussed at different cam rotational speeds. Simulated results in the middle of HP fuel pipeline have been presented and discussed.

a. 500 rpm

Figure 9(a-d) shows variation of densities, acoustic wave speeds and bulk moduli at 500 rpm and 2°CA, 6°CA, 10°CA and 14°CA respectively. Variations are similar at same cam angle but different from other cam angles. Increase in density, acoustic wave speed and bulk modulus is observed with the increase of cam angle.
Maximum density, acoustic wave speed and bulk modulus at 500 rpm are 885.01 kg/m$^3$, 1786.8 m/s and 2.66 GPa at 14°CA respectively. Whereas minimum density, acoustic wave speed and bulk modulus at 500 rpm are 839.17 kg/m$^3$, 1356 m/s and 1.54 GPa at 14°CA respectively.

Figure 9. Densities, acoustic wave speeds and bulk moduli at 500 rpm and (a) 2°CA (b) 6°CA (c) 10°CA and (d) 14°CA
b. 700 rpm

Figure 10(a-d) shows variation of densities, acoustic wave speeds and bulk moduli at 700 rpm and 2°CA, 6°CA, 10°CA and 14°CA respectively. Variations are similar at same cam angle but different from other cam angles. Increase in density, acoustic wave speed and bulk modulus is observed with the increase of cam angle.

Maximum density, acoustic wave speed and bulk modulus at 700 rpm are 893.04 kg/m³, 1875.18 m/s and 2.89 GPa at 14°CA respectively. Whereas minimum density, acoustic wave speed and bulk modulus at 700 rpm are 838.96 kg/m³, 1355.41 m/s and 1.53 GPa at 14°CA respectively.
c. 900 rpm

Figure 11(a-d) shows variation of densities, acoustic wave speeds and bulk moduli at 900 rpm and 2°CA, 6°CA, 10°CA and 14°CA respectively. Variations are similar at same cam angle but different from other cam angles. Increase in density, acoustic wave speed and bulk modulus is observed with the increase of cam angle.

Maximum density, acoustic wave speed and bulk modulus at 900 rpm are 900.4 kg/m³, 1961.4 m/s and 3.11 GPa at 14°CA respectively. Whereas minimum density, acoustic wave speed and bulk modulus at 900 rpm are 838.94 kg/m³, 1355.26 m/s and 1.53 GPa at 14°CA respectively.

Figure 11. Densities, acoustic wave speeds and bulk moduli at 900 rpm and (a) 2°CA (b) 6°CA (c) 10°CA and (d) 14°CA
Figure 12(a-d) shows variation of densities, acoustic wave speeds and bulk moduli at 1100 rpm and 2°CA, 6°CA, 10°CA and 14°CA respectively. Variations are similar at same cam angle but different from other cam angles. Increase in density, acoustic wave speed and bulk modulus is observed with the increase of cam angle.

Maximum density, acoustic wave speed and bulk modulus at 1100 rpm are 904.47 kg/m³, 2011.78 m/s and 3.23 GPa at 14°CA respectively. Whereas minimum density, acoustic wave speed and bulk modulus at 1100 rpm are 838.968 kg/m³, 1355.42 m/s and 1.53 GPa at 14°CA respectively.
Figure 13(a-d) shows variation of densities, acoustic wave speeds and bulk moduli at 1300 rpm and 2°CA, 6°CA, 10°CA and 14°CA respectively. Variations are similar at same cam angle but different from other cam angles. Increase in density, acoustic wave speed and bulk modulus is observed with the increase of cam angle.

Maximum density, acoustic wave speed and bulk modulus at 1300 rpm are 910.07 kg/m^3, 2084.5 m/s and 3.417 GPa at 14°CA respectively. Whereas minimum density, acoustic wave speed and bulk modulus at 1300 rpm are 838.741 kg/m^3, 1353.52 m/s and 1.529 GPa at 10°CA respectively.
Densities, acoustic wave speeds and bulk moduli also fluctuate along the length of fuel pipeline with varying cam rotational speeds and cam angles as shown in figure 14(a), (b) and (c) respectively. Figure 14(a-c) shows the maximum values of these fuel properties at all combinations of operating system mentioned in table 1. It is quite clear from the figures that values increase with the increase of either cam rotational speed or cam angle.

Moreover, with the increase of either cam rotational speed or cam angle the difference between maximum and minimum fuel properties (maximum-minimum) at any particular mesh node also increases as shown in figure 15 (a-c). It shows the difference between maximum and minimum values of density, acoustic wave speed and bulk modulus at various operating conditions. Maximum and minimum simulated key fuel properties considering all operating conditions mentioned in table 1 have been summarized in table 2.
Figure 14. Maximum (a) densities, (b) acoustic wave speeds and (c) bulk moduli along the pipeline
Table 2. Simulated ranges of key fuel properties during operating conditions mentioned in Table 1

<table>
<thead>
<tr>
<th>Fuel Properties</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>838.7417 (1300 rpm and 10°CA)</td>
<td>910.0747 (1300 rpm and 14°CA)</td>
</tr>
<tr>
<td>Acoustic wave speed (m/s)</td>
<td>1353.5 (1300 rpm and 10°CA)</td>
<td>2084.5 (1300 rpm and 14°CA)</td>
</tr>
<tr>
<td>Bulk modulus (GPa)</td>
<td>1.5298 (1300 rpm and 10°CA)</td>
<td>3.4174 (1300 rpm and 14°CA)</td>
</tr>
</tbody>
</table>

Figure 15. Variation in (a) densities, (b) acoustic wave speeds and (c) bulk moduli along the pipeline at various operating conditions
VI. CONCLUSIONS

A 1D viscous damped mathematical model of fuel pressure inside high pressure fuel pipeline of CEUP using wave equation has been developed in MATLAB in order to investigate variations in key fuel properties of diesel fuel including density, acoustic wave speed and bulk modulus at various operating conditions of diesel engine. AMESim numerical model of CEUP has also been developed and validated against lab experiments. MATLAB mathematical model has been validated using numerical model of CEUP developed in AMESim. Variations of key diesel fuel properties including density, acoustic wave speed and bulk modulus have been simulated and analyzed at various operating conditions of diesel engine. It is observed that these properties increase with the either the increase of cam rotational speed or cam angle. Their values also fluctuate along the fuel pipeline length. Maximum density, acoustic wave speed and bulk modulus of 910.07 kg/m$^3$, 2084.5 m/s and 3.41GPa respectively are recorded at 1300 rpm and 14 °CA. Where as minimum density, acoustic wave speed and bulk modulus of 838.74 kg/m$^3$, 1353.5 m/s and 1.529 GPa respectively are recorded at 1300 rpm and 10 °CA.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (NSFC 51379041, 51279037), Program for New Century Excellent Talents in University (NECT-11-0826), the Fundamental Research Funds for the Central Universities (HEUCF13) and the Key Project of Chinese Ministry of Education (113060A).

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