Transient Fuel Supply Characteristics in a Carburetted SI Engine under Accelerating Conditions

Yukio Hohsho  
Faculty of Engineering, Hiroshima University  
Shitami, Saijo, Higashi-hiroshima

Hiroyuki Nakai  
Suzuki Motor Co., Ltd.  
Takatsu, Kami-mura, Shizuoka-ken

Toshikazu Kadota  
Faculty of Engineering, Hiroshima University

ABSTRACT

A mathematical model was developed for predicting the transient fuel supply characteristics in an intake system of carburetted four cylinder SI engine for automobile use during accelerating drive. The behavior of vaporized fuel, fuel droplets floating in an air stream and liquid fuel film on the wall of intake manifold was formulated in terms of transfer functions to determine the transient air fuel ratio in combustion chamber as a function of intake air flow rate. The results showed that the transient air fuel ratio in combustion chamber increased with time reaching a maximum which was liable to be out of the combustible range of mixture immediately after the beginning of acceleration. Thereafter, it decreased approaching the normal ratio as the liquid fuel film arrival at the combustion chamber. The model was proved to be capable of predicting the results consistent with the facts observed in the experiment.

INTRODUCTION

Car driving is accompanied with frequent acceleration and deceleration. It is of great importance to study the response characteristics of spark ignited engine under transient driving conditions for fuel economy, reduction of noxious emissions and improvements of drivability. It has widely been accepted that one of the important factors affecting the transient response of engine is the fuel supply characteristics in an intake system and extensive studies have been made of this process. Transient characteristics of fuel flow in a carburetor were analyzed by Hohsho and Ohmava(1). Shinoda et al.(2) reported that the accumulation of liquid fuel on a throttle valve and a wall of intake manifold caused the excessively lean mixture supply into combustion chamber during acceleration. Sawa and Hori(3) made the measurements on the behavior of liquid fuel film in intake manifold of a methanol fueled single cylinder engine under accelerating conditions. Tanaka and Durbin(4) proposed an approximate theory on the fuel film flow to explain the results of transient response of a carburetted engine. Aquino(5) developed a simple continuous flow model to predict the effects of manifold air charging and wall wetting on the transient air fuel ratio characteristics of a central fuel injection engine. Hires and Overington(6) assumed a simple phenomenological model of liquid fuel film behavior in their work to investigate the causes for tailpipe mixture strength excursions during transient operation of an electrically controlled central fuel injection engine. Fujieda and Ohyama(7) made the analysis of transient mixture transportation in an intake manifold of carburetted engine taking account of fuel distribution among combustion chambers. Hohsho et al.(8) recently proposed a mathematical model to describe with the aid of transfer functions the transient fuel supply characteristics in carburetor and intake manifold during acceleration of a carburetted engine.

The main objective of the present study is to extend the previous model(8) both from qualitative and quantitative point of view. The transient behavior of vaporized fuel, fuel droplets floating in an air stream and the liquid fuel film on the wall of intake manifold were formulated in terms of transfer functions to determine the time histories of air fuel ratio in combustion chamber as a function of intake air flow rate. To obtain the informations needed for determining arbitrary constants in the derived expressions and to confirm the validity of the analysis, an experimental study was also performed by using a carburetted four cylinder SI engine. Measurements were made mainly of the transient velocity and thickness of liquid fuel film and the air fuel ratio in combustion chamber during acceleration of the engine.

THEORETICAL ANALYSIS

Figure 1 shows schematically the processes in carburetor and intake manifold to be included in the present analysis. Transient behaviors of fuel and air are to be formulated with the aid of transfer functions to predict the air fuel ratio in the combustion chamber. Figure 2 shows typical examples of time histories of intake air flow rate and fuel flow rates anticipated at several positions in intake system as an engine is accelerated in such a way that a throttle valve is opened from $\theta_0$ to $\theta_1$ at a constant rate. Since a quasi-steady assumption is made for the intake air flow on the basis of throttle valve opening, the intake air flow rate increases also at a constant rate. Before acceleration, a slow system of carburetor is only active in supplying fuel. It is
most likely that the fuel discharged at high velocity from the slow system of carburetor would either be finely atomized or vaporized. Therefore, it is assumed that any relative velocity between air and the fuel supplied from the slow system is negligible and that no formation of liquid fuel film is caused on the wall of manifold. A main system supplies fuel from the outlet of main nozzle located in a small venturi at the intake air flow rate higher than the main system under accelerating operation, however, is accompanied with the delay $t_{d}$ behind the steady state values. The transfer function for this process is

$$G_{23}(s) = \frac{1 - K_{a}(s)}{1 + T_{a}(s)}$$

After the beginning of fuel discharge, the fuel flow rate in main system increases gradually as shown in Fig. 2. The flow rate of fuel discharged from the main system is considered to be approximately of the first order response expressed as

$$G_{23}(s) = \frac{A}{1 + T_{a}(s)}$$

A fraction of the fuel supplied from main system comes in touch with the side wall of carburetor riser resulting in the formation of liquid fuel film on it. It is assumed that the ratio of flow rate of liquid fuel film to the total fuel flow rate remains constant during acceleration. Thereafter, the liquid fuel film flows along the wall of intake manifold arriving at the combustion chamber at the time $t_{p2}$. Transfer function is

$$G_{p2}(s) = K_{p2} \exp(-t_{p2}s)$$

The balance of the fuel supplied is transported either as droplets or vapor to the bottom of riser during the period of time $t_{r2}$. Transfer function is

$$G_{r2}(s) = \frac{1 - K_{r2}(s)}{1 + T_{r2}(s)}$$

The fuel arriving at the bottom of riser is further divided into two categories. A fraction of the fuel impacts on the bottom wall of riser to form liquid fuel film. The balance of the fuel is either vaporized or of sufficiently small droplet size so that any relative velocity to the intake air stream is negligible. The transient flow rate of liquid fuel film is assumed to be of the first order response behavior. Since it takes the period of time $t_{h2}$ for the liquid fuel film to be transported from the bottom of riser to the combustion chamber, transfer function is expressed as

$$G_{h2}(s) = K_{h2} \exp(-t_{h2}s)$$

The equilibrium is assumed between the competitive processes of fuel droplet deposition on the liquid fuel film and fuel reentry into the intake air stream in manifold behind the riser. The fuel which is not trapped on the bottom wall of riser arrives at the combustion chamber in $t_{h2}$. Transfer function is

$$G_{h2}(s) = \frac{1 - K_{h2}(s)}{1 + T_{h2}(s)}$$

All the transfer functions are summarized in
Fig. 3. From the above equations, the transfer function for the whole processes is derived.

\[ G(s) = G_{d1}(s) \cdot G_{d2}(s) \cdot G_{r2}(s) + G_{r1}(s) \cdot (G_{r2}(s) + G_{r2}(s)) \]  

(7)

This gives the time history of air fuel ratio in combustion chamber as a function of intake air flow rate.

**EXPERIMENTAL PROCEDURE**

In order to obtain the informations needed for determining arbitrary constants in the derived equations and to confirm the validity of the analysis, an experimental study was also performed. Figure 4 shows the schematic diagram of an experimental apparatus. A four cylinder 1.5 engine I was tested of which primary specifications are shown in Table 1. A Zenith-Stromberg type carburetor 2 without acceleration system was installed in the engine. The engine was mounted four degrees front up so that the intake manifold was set horizontally. It was coupled with an eddy current dynamometer 3 of which constant eddy current was kept during acceleration with a control unit 4. The temperature of cooling water was held within 80°2 °C and the intake air temperature was 17°2 °C. The throttle valve of carburetor was opened or closed at expected constant rates with the aid of a linear head operated by a reversible motor 5 and its angle was measured by using a variable resistor 6. The cylinder pressure was measured with the use of a piezo-electric type pressure transducer 10 and an amplifier 11. A torque meter 14 and an amplifier 15 were available.

![Fig. 4. Experimental apparatus](image)

![Fig. 5. Installation for detecting the fuel discharge from main system](image)

**Table 1. Engine specification**

<table>
<thead>
<tr>
<th>Type</th>
<th>A 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel delivery</td>
<td>Carburetor</td>
</tr>
<tr>
<td>Piston displacement</td>
<td>1.397</td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>76.0</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>77.0</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9.0</td>
</tr>
<tr>
<td>Max. power (kW/rpm)</td>
<td>58.8 / 6000</td>
</tr>
<tr>
<td>Max. torque (Nm/rpm)</td>
<td>113 / 3600</td>
</tr>
<tr>
<td>Fuel</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Firing order</td>
<td>1-3-4-2</td>
</tr>
</tbody>
</table>
Fig. 6 Probes to measure liquid film thickness

Fig. 7 Probes installed in intake manifold

The measurements of liquid fuel film velocity as shown in Fig. 8. The mixture of ethanol and sodium acetate was allowed to issue periodically from a hypodermic needle into the liquid film of base gasoline. Its trace was monitored with the use of two electrodes installed behind the hypodermic needle. The period of time between two signals detected by the electrodes gave the velocity of liquid fuel film. The measurements of liquid fuel film velocity was also made possible with the aid of optical observation by using a video camera set through glass windows fixed on the intake manifold. The air fuel ratio in combustion chamber was determined from the experimental results of cylinder pressure as has been done in the previous work (4). In the preliminary measurements under steady driving conditions, air fuel ratio was correlated as a function of peak cylinder pressure at various ignition timings, engine speeds and manifold depression. An example of a set of results is shown in Fig. 9.

All the measurements were made under the following accelerating conditions. Before acceleration, the engine was driven at the constant speed 1300 rpm, engine torque 13.7 N·m, manifold depression -45.3 kPa, small venturi depression -0.3 kPa and throttle valve opening 7 deg from the fully closed position. These correspond to the condition that the car weight 1095 kg is driven at 33 km/h on a horizontal flat road. The engine acceleration was made by opening the throttle valve from 7 to 22 deg at various constant rates ranging 4.5 through 71 deg/s. The fuel provided was the mixture of ethanol and base gasoline (3:7 in volume ratio) except in the case of measurement of liquid fuel film velocity when the base gasoline was utilized.

RESULTS

Figure 10 shows the relationship between the velocity of liquid fuel film on the wall of intake manifold and the intake air velocity which is defined as the volumetric air flow rate divided by the sectional area of intake manifold under steady driving conditions. It is evident that the film velocity increase almost linearly with an increase in air velocity and that the manifold depression does not have any appreciable influence on the film velocity. The film velocity is observed to be of the order of one fiftieth of the intake air.
velocity. Figure 11 shows the ratio of liquid film flow rate to total fuel flow rate at the section BB under steady driving conditions. No appreciable effect of manifold depression on it is found. Although the data are fairly spreaded, there seems to be a definite trend between the ratio and the air flow rate. It decreases approaching a minimum at about 70 kg/h of air flow rate. Thereafter, it shows an increase with increasing air flow rate. The initial decrease might be caused by the enhanced atomization of liquid fuel with an increased air velocity in a small venturi of carburetor. The increase of ratio in the range of air flow rate higher than 70 kg/h might be due to the increased inertia force of air fuel mixture.

Figure 12 shows an example of a set of data on transient response. Illustrated here are the time histories of intake air flow rate, cylinder pressure, manifold depression, thickness of liquid fuel film on the bottom of riser, mean thickness of liquid fuel film at the section BB, engine torque and throttle valve opening. The throttle valve opened from 7 to 22 deg at a constant rate 68 deg/s. A short period of time elapses after the beginning of acceleration followed by the start of increase in a liquid fuel film thickness at the bottom of riser. Torque fluctuation begins to occur and continues for a while. The thickness of liquid fuel film at the section BB starts to increase at about 0.7 s showing the tendency to approach an asymptote.

Figure 13 shows the transient velocity of liquid fuel film and intake air at the throttle valve opening rate of 68 deg/s. Also shown with a dotted line is the quasi-steady velocity of liquid fuel film derived from Fig. 10. It is evident that the transient film velocity is much lower than the quasi-steady velocity during early stage of acceleration and approaches each other at about 3 s. Figure 14 shows the transient ratio of liquid fuel film velocity to air velocity under various acceleration rates. The ratio is approximately one hundredth at first and increases with the time elapsed up to one fiftieth which is the same value observed under the steady driving conditions. In this range of experimental conditions, the reduced acceleration rate results in the lower liquid fuel film velocity.

Figure 15 shows the time history of flow rate of liquid fuel film at the section BB. The smoothed curve is obtained by averaging the
Fig. 14 Ratio of liquid film velocity and air velocity

Fig. 15 Liquid film flow rate

Fig. 16 Delay times in fuel flow measured results indicated with the solid line.

Fig. 17 Time constant for liquid film thickness and liquid film transportation time

Fig. 18 Air fuel ratio in combustion chamber

The results show the first order response behavior which verify the validity of assumption adopted in the analysis. Three kinds of delay time defined in Fig. 12 and the delay time relevant to the beginning of fuel discharge from main nozzle are correlated as a function of throttle valve opening rate in Fig. 16. All of them show the similar trend to decrease with an increase in throttle valve opening rate and to approach an asymptote. The difference between $t_2$ and $t_2$ is available to determine the period of time for the liquid fuel film to be transported from the bottom of riser to the combustion chamber. The time constant for transient liquid film thickness at the section BB is obtained from the difference $t_2 - t_2$. These are shown in Fig. 17. It is evident that both of them decrease with an increase in a throttle valve opening rate approaching asymptotic values. This indicates that the increase in throttle valve opening rate causes the delay in liquid fuel film flow though the quick response is observed in intake air flow.

Figure 18 shows the calculated results of transient air fuel ratio in the combustion chamber during acceleration at the throttle valve opening rate 30 deg/s. It is evident that the air fuel ratio increases with the time elapsed and reaches a maximum which is out of the combustible range of mixture immediately after the beginning of acceleration. Then it decreases approaching the normal air fuel ratio as the liquid fuel film reaches the combustion chamber at about 3.5 s.
Misfiring or unstable combustion of the mixture might occur during the period of time near the peak of air fuel ratio and cause the following torque fluctuation observed in the experiment. The results predicted by the present model agree fairly well with the measured results. The discrepancy between both results during 0.8 s through 4 s might partially be due to the neglect of evaporation or reentry of fuel from the liquid fuel film into the air stream in intake manifold behind the riser which is more or less likely to occur in a practical engine.

CONCLUSIONS

A mathematical model was developed for predicting the transient fuel supply characteristics in an intake system of carburetted four cylinder SI engine for automobile use under acceleration. The behavior of vaporized fuel, fuel droplets floating in air stream and liquid fuel film on the wall of intake manifold were formulated in terms of transfer functions to determine the time histories of air fuel ratio in the combustion chamber as a function of intake air flow rate. To obtain the informations needed for determining arbitrary constants in the derived equations and to confirm the validity of the analysis, the experimental study was also performed.

The principal conclusions reached in the present study are as follows.

(1) The velocity of liquid fuel film on the wall of intake manifold varies with time elapsed after the beginning of acceleration in the range of 1/100 through 1/50 times of intake air velocity while it is almost constant at 1/50 under steady driving conditions.

(2) The flow rate of liquid fuel film that increases with time approaching an asymptote shows the first order response behavior.

(3) The time constant for transient thickness of liquid fuel film decreases with an increase in throttle valve opening rate. At high rate of acceleration, however, it shows a tendency to approach an asymptote causing a marked transportation delay of the liquid fuel film.

(4) The transient air fuel ratio in the combustion chamber increases with time reaching a maximum which is liable to be out of the combustible range of mixture immediately after the beginning of acceleration. Then it decreases approaching the normal air fuel ratio.

(5) The mathematical model developed in the present analysis is proved to be capable of predicting the results consistent with the facts observed in the experiment.

NOMENCLATURE

\( Pa \) : fuel air ratio
\( G_{in} \) : intake air flow rate \( \text{kg/s, kg/h} \)
\( G_{acc} \) : intake air flow rate before acceleration \( \text{kg/s} \)
\( G_{acc} \) : intake air flow rate to cause the beginning of fuel discharge at main system under steady driving conditions \( \text{kg/s} \)
\( G_{f} \) : intake air flow rate at the end of acceleration \( \text{kg/s} \)
\( G_{f} \) : total fuel flow rate \( \text{kg/s} \)
\( G_{conc} \) : fuel flow rate into combustion chamber \( \text{kg/s} \)
\( G_{l} \) : liquid fuel film flow rate \( \text{kg/s} \)
\( R_{B} \) : mean liquid fuel film thickness at the section \( \text{BB mm} \)

\( R_{B} \) : liquid fuel film thickness at the riser bottom \( \text{mm} \)
\( R_{B} \) : ratio of the liquid fuel film flow rate to the total fuel flow rate at the riser bottom
\( R_{B} \) : ratio of the liquid fuel film flow rate to the total fuel flow rate at the side wall of riser
\( R_{d} \) : cylinder pressure \( \text{V} \)
\( P_{d} \) : manifold pressure \( \text{KPa} \)
\( s \) : Laplace operator
\( T_\text{acc} \) : time constant for fuel flow rate in the main system of carburetor \( \text{s} \)
\( T_{c} \) : time constant for the liquid fuel film thickness at the section \( \text{BB s} \)
\( t_{d} \) : time at \( G_{acc} = G_{conc} \) \( \text{s} \)
\( T_{del} \) : delay in fuel discharge from the main nozzle of carburetor \( \text{s} \)
\( T_{acc} \) : time for transportation from riser to combustion chamber \( \text{s} \)
\( t_{del} \) : time for the transportation of liquid fuel film between the riser and the combustion chamber \( \text{s} \)
\( T_{del} \) : time at the beginning of fuel discharge from main nozzle \( \text{s} \)
\( T_{del} \) : time for droplets leaving the outlet of main nozzle to arrive at the riser bottom \( \text{s} \)
\( T_{del} \) : time for the transportation of liquid fuel film from the side wall of riser to the combustion chamber \( \text{s} \)
\( T_{del} \) : acceleration period \( \text{s} \)
\( V_{acc} \) : intake air velocity \( \text{m/s} \)
\( V_{conc} \) : liquid fuel film velocity \( \text{m/s} \)
\( \theta_{d} \) : throttle valve opening deg
\( \theta_{d} \) : throttle valve opening at the beginning of acceleration deg
\( \theta_{d} \) : throttle valve opening at the end of acceleration deg
\( \theta_{d} \) : throttle valve opening rate deg/s
\( \tau \) : engine torque \( \text{N-m} \)

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