On Quenching Distance of Mixtures of Methane and Hydrogen with Air*

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The quenching distances of mixtures of methane and hydrogen with air are determined. The quenching distances are given as a function of hydrogen percentage of the hydrogen-methane mixtures, excess air ratio and pressure of unburnt gas. It is observed that the flame quenching phenomenon has probability nature at the region where the distance of the two discs approaches the quenching distance. Furthermore, the correlation of stretch factor and quenching distances is derived and the relation of hydrocarbon emission levels of piston engines and quenching distances is discussed.

1. Introduction

In order to widen the availability of natural resources for fuel production and to reduce pollutants in exhaust gases of internal combustion engines, boilers and furnaces, the application of alternate fuels including coal, shale and biomass has been studied. One way of using the alternate fuels is to mix together more than two kinds of them, for example alcohol-gasoline blends and addition of a small amount of hydrogen to gasoline. Therefore, the information on the fundamental combustion characteristics of a mixture of different kinds of fuels becomes necessary. Our interest here is the quenching distance which is one of the important combustion characteristics concerned with the unburnt hydrocarbons in the exhaust of spark ignition engines. The quenching distances for single substances have been studied by various investigators1-5. On the contrary there are very limited data on mixtures with different kinds of fuels. The quenching distances of methanol/iso-octane blends were recently measured by Ishikawa and Branch6 and Yama and Ito7, but they reached different conclusions.

In this paper new data on quenching distances are presented for mixtures of methane and hydrogen with air as a function of fraction of hydrogen, excess air ratio and pressure of unburnt gas. Furthermore, the correlation of stretch factor and quenching distances is derived and the relation of hydrocarbon emission levels of spark ignition engines and quenching distances is discussed.

2. Nomenclature

\[ C_p: \text{Specific heat at constant pressure} \]
\[ \text{cal/kgK} \]
\[ d: \text{Quenching distance mm} \]
\[ D_r: \text{Distance between two parallel discs mm} \]
\[ K: \text{Stretch factor} \]
\[ K: \text{Thermal conductivity kcal/mhK} \]
\[ M: \text{Molecular weight of gases} \]
\[ P: \text{Initial pressure of unburnt gas mmHg} \]
\[ S_l: \text{Laminar burning velocity cm/s} \]
\[ V: \text{Volume of gases cm}^3 \]
\[ W: \text{Probable region of quenching mm} \]
\[ X: \text{Fraction of hydrogen in fuel} \]
\[ Y: \text{Decreasing ratio of quenching distance} \]
\[ Z: \text{Percentage of quenching}\]
\[ \lambda: \text{Excess air ratio} \]
\[ \rho_b: \text{Density of burned gas kg/m}^3 \]
\[ \phi: \text{Stoichiometric ratio} \]

Subscripts

\[ a: \text{Air} \]
\[ m: \text{Methane} \]
\[ h: \text{Hydrogen} \]

3. Experimental Apparatus

![Fig.1 Schematic diagram of combustion chamber](image)

The apparatus employed is shown in...
Fig.1. Apart from a few improvements and modifications, it is essentially the same as the one used in the literatures\(^1,6,7\).

Two parallel discs 25.4mm in diameter are installed between two stainless steel cylindrical bombs with an inside diameter of 50mm. In order to prevent gas leakage, a built-in micrometer outside the test bomb for adjusting the distance of two discs is not used, two discs are fixed on the test bomb and rubber O-rings are used. Initial pressure of the unburned gas in the bomb is measured by the digital pressure gauge. The pressure-time records of the burned gas are taken by the pressure transducer. The electrode connects the ignition system through the plugs on the test bomb. To prevent gas leakage through the threads of the pressure transducer and the plugs, liquefied packing and seal tape are used.

![Diagram of test bomb and quenching discs](image)

Fig.2 Details of the quenching discs

The details of the quenching discs are shown in Fig.2. A 1mm diameter copper wire is embedded at the center of the discs. The copper electrode is carefully insulated by thin plastics. Two discs are fixed by three stud bolts.

4. Procedure

In the present study attention is focused on the effects of fraction of hydrogen, excess air ratio and initial pressure on quenching distances of the mixtures of methane and hydrogen with air.

1) Mixture

The fuel and air are carefully measured by graduated cylinders and mixed in a fuel mixer. The excess air ratio \(\lambda\) is calculated by the relation

\[
\lambda = \left( \frac{V_{m}V_{h}}{V_{m}V_{h}} \right) / \left( \frac{1}{1+\lambda} \right)
\]

(1)

Water vapor in the homogeneous mixture is absorbed by silicon.

2) Induction of mixture, initial pressure, temperature and distance between two parallel discs.

The burned gases in the test bomb at the previous experiment can be purged by the vacuum pump which is also used for pressure control of the unburned gas. After evacuating the gas cylinder, a proper mixture is introduced and initial pressure is measured by the digital pressure gauge with an accuracy of 1 mmHg. The temperature of the mixture is measured by the thermocouple attached to the outer surface of the cylinder. The temperature of the mixture is controlled at 15 ±2°C through out this experiment.

As noted earlier we cannot change the position of two discs at the outside of

![Schematic diagram of test facility](image)

Fig.3 Schematic diagram of the test facility
the test bomb thus, every time the distance between the discs is to be measured we have to remove the flanges at the center of the bomb. The distance between two parallel discs is controlled by various kinds of the washers and measured by various kinds of the thickness gauges with an accuracy of 1/100 mm. The parallelism of two discs is confirmed by measuring the distance at a few different points of the disc by the thickness gauges. After the bomb is assembled, leakage test is carried out at P=5 mmHg.

(3) Determination of quenching distance.

The electrodes are connected to a system of fixed condenser through the ignition coil as shown in Fig.3. The composite spark generates from the circuit. The ignition energy is constant (about 20 mJ) throughout the experiments. Unless a quenching of flame between the plates occurs, the flame can propagate in the bomb and an abrupt pressure rise can be measured by the pressure gauge attached to the surface of the bomb. Quenching distance can be determined as the minimum distance between the discs where the flame can propagate through the gap between the discs.

5. Experimental Results

5-1. Initial experiments

Initial experiments are conducted with methane-air mixtures and hydrogen-air mixtures at 1 atm. The result is shown in Fig. 4 along with the data from Ref. [1]. The air ratios as a function of fraction of hydrogen in fuel $X=\frac{\text{体积}(V_H)}{(V_H+V_A)}=100\%$. As can be seen, the quenching distance decreases monotonously with an increasing fraction of hydrogen at any excess air ratio. Ishikawa and Branch reported that the fuel blends were found to have larger quenching distances than either pure fuel for methanol/iso-octane/air mixture. However, Yano and Ito recently reached a different conclusion that the quenching distances were never larger than that of either pure fuel for the same mixture used by Ishikawa and Branch. Therefore, our results have the same trend as observed by Yano and Ito.

The influence of excess air ratio and fraction of hydrogen on decreasing ratio of quenching distance $\frac{(D_{\text{H}_2}-D)}{(D_{\text{H}_2}-D_{\text{H}_2})} \times 100\%$ is illustrated in Fig.5. The value of $\gamma$ shows a rapid rate of increase in the range of $\lambda=0-20\%$ at excess air ratio $\lambda=1.4$ and 1.6. This result means that the addition of a small amount of hydrogen produces a rapid decrease of quenching distance for lean mixtures. For the stoichiometric mixture an approximate linear relationship is found to exist between decreasing ratio of quenching distance and fraction of hydrogen.

5-3. Initial pressure

The effect of initial pressure of mixtures on quenching distance is illustrated in Table 1.

<table>
<thead>
<tr>
<th>$%$</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
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<td>2.15</td>
<td>2.41</td>
<td>3.53</td>
<td>5.02</td>
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<td>9.1</td>
<td>3.08</td>
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<td>2.92</td>
<td>4.28</td>
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<tr>
<td>23.1</td>
<td>2.64</td>
<td>1.82</td>
<td>2.07</td>
<td>2.46</td>
<td>3.21</td>
<td></td>
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<td>33.3</td>
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<td>1.70</td>
<td>1.77</td>
<td>2.13</td>
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<td>1.16</td>
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<td>1.45</td>
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<td>0.67</td>
<td>0.64</td>
<td>0.69</td>
<td>0.77</td>
<td>0.89</td>
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<tr>
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<td>0.85</td>
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<td>0.64</td>
<td>0.65</td>
<td>0.67</td>
<td>0.75</td>
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</table>

Fig.4 Comparison of the data of the quenching distance between this experiment and Ref. [1] figure shows our experimental result agrees approximately with Lewis's result. If examined in detail, however, there are delicate differences between the two results. The differences are caused by improvements and modifications of our apparatus, because the material of the wall and ignition energy are not found to affect the quenching distance as described in our previous work [8].

5-2. Fraction of hydrogen in fuel

Table 1 shows the numerical values of the measured quenching distances for methane-hydrogen-air mixtures at initial pressure $P=760 \text{ mmHg}$ and six different excess
in Fig.6. The solid lines show the empirical relation
\[ d = C \left( \frac{P}{760} \right)^{-\beta} \]  \hspace{1cm} (2)

![Graph showing influence of initial pressure and fraction of hydrogen on quenching distance](image)

Fig.6 Influence of initial pressure and fraction of hydrogen on quenching distance

where the values of C and \( \beta \) are correlated from the experiment using the least squares method. The values of C and \( \beta \) are shown in Table 2.

Table 2 The values of C and \( \beta \) in equation (2)

<table>
<thead>
<tr>
<th>X%</th>
<th>1.0</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>0</td>
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<tr>
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<tr>
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<td>75</td>
<td>0.98</td>
</tr>
<tr>
<td>100</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Fig.6 shows that the quenching distances increase with a decreasing initial pressure at any value of fraction of hydrogen and excess air ratio. However the experimental data do not always lie on a straight line at low initial pressure. The result may be explained as follows: the ignition energy in this experiment approaches the minimum spark ignition energy as the initial pressure becomes lower, because the quenching distances decrease with an increasing ignition energy and come closer to the line of equation (2) at this region. The values of C decrease with an increasing \( \lambda \) but it is difficult to find out a specific relation between the values of \( \beta \) and \( \lambda \) as in Table 2. And also the value of \( \beta \) does not always equal to 1.0.

The influence of the initial pressure on \( Y \) is illustrated in Fig.7, in which \( Y \) is plotted against \( X \) for three excess air ratios. It is also found that the value of \( Y \) shows a rapid rate of increase in the range of \( X = 0 \) to 20% in lean mixture at low initial pressure.

5-4. Percentage of quenching

As the distance between two parallel discs approaches the quenching distance, it is observed that a region of quenching in two discs does happen or not. This probability nature of quenching is similar to that of ignition which is already reported by many authors. Here, the percentage of quenching \( Z \) is defined as the ratio of the number of experiments in which quenching is observed to the total number of experiments and probable region of quenching \( W \) is defined as a width of distance of the discs where quenching occurs with probability. Fig.8 shows the relation of \( W \) and quenching distance \( d \). The values of \( W \) decrease with a decreasing \( d \) or an increasing \( X \) and an increasing initial pressure \( P \). The effect of initial pressure on the values of \( W \), however, is not so significant at low pressure condition. This probable phenomenon is first observed by using the apparatus in which the distance of two parallel discs is controlled with an accuracy of 0.01 mm, because the values of \( W \) are about 0.01-0.09 mm as shown in Fig.8.

![Graph showing effect of fraction of hydrogen, excess air ratio and initial pressure on decreasing ratio of quenching distance](image)

Fig.7 Effect of fraction of hydrogen, excess air ratio and initial pressure on decreasing ratio of quenching distance

![Graph showing typical plots of probable region of quenching VS quenching distance](image)

Fig.8 Typical plots of probable region of quenching VS quenching distance
The effect of non-dimensional parameter \([(d_r - d_r)/W]\times100\% on the percentage of quenching \(Z\) is illustrated in Fig.9. There can be found any correlation of \(Z\) with excess air ratio, fraction of hydrogen in fuel and initial pressure.

5.5. Correlation using stretch factor

Fig.10 shows the correlation of stretch factor \(K=4K_{s}/Cp_{s}d_{b}\) with the fraction of hydrogen in the fuel. The plots of laminar burning velocity in Fig.10 are the experimental data reported by Scholte. \(^{11}\) The values of \(K\) are seen to be mostly constant for the values of \(X\). Thus, it is possible to recognize a substantial measure of correlation between the measured quenching distances and the burning velocities, densities, and specific heats of gases in hydrogen-methane-air mixtures. Because the value of \(4K_{s}/Cp_{s}d_{b}\) changes from 3.2 to 3.8 when the fraction of hydrogen \(X\) changes from 0 to 1.0, the approximation that the quenching distance \(d_r\) is roughly inversely proportional to the laminar burning velocity \(S_u\) is sufficient. Therefore, the rapid decrease of quenching distance by the addition of a small amount of hydrogen at lean condition as already shown in Fig.5 can be explained by the data of laminar burning velocity which rapid inraas by the addition of a small amount of hydrogen. Livuma-Pukusawa reported that the values of \(S_u\) of lean CH\(_4\)-H\(_2\)-air mixtures increased rapidly by the addition of a small amount of hydrogen and the reason for this behavior might be explained by the effect of diffusional stratification of the mixture.

The data of quenching distance for the iso-octane/methanol blends by Ishikawa-Branch and Yano-Ito can also be explained by the laminar burning velocities. According to the above discussion, we have great difficulty to explain the data reported by Ishikawa-Branch. However, we have no data on \(S_u\) for the iso-octane/methanol blends and we must leave this for a future study.

Let us now consider the relationship between the unreacted hydrocarbons from spark ignition engines and the quenching

![Fig.9 Typical plots of percentage quenching VS [(dr-d)/W]×100%](image)

![Fig.10 Effect of fraction of hydrogen on stretch factor and laminar burning velocity](image)

![Fig.11 Effect of fraction of hydrogen on decreasing ratio of quenching distance unburnt hydrocarbons](image)
distances. The unreacted mixtures in the wall quenching layer have been considered one of the major sources of hydrocarbons in the exhaust of an engine operating at lean conditions without a misfire. The data on exhaust emissions from the engine operating with methanol-hydrogen-air mixtures, which were reported by one of the authors, Korematsu, are employed here, because there are on data on operating with methane-hydrogen-air mixtures. Fig.11-(a) shows the effect of fraction of hydrogen on the decreasing ratio of quenching distance and Fig.11-(b) shows the effect on the decreasing ratio of hydrocarbons defined as \[ \frac{[HC]_{CH_3OH -}[HC]}{[HC]_{CH_3OH-HC}] \]. The tendencies of the decreasing ratio of the quenching distances and of hydrocarbons with an increasing fraction of hydrogen are similar. This result indicates that the unreacted hydrocarbons in an engine primarily originate in a wall quenching process and the emission level of hydrocarbons can be controlled by the addition of hydrogen. It may sound strange that the thickness of the quench layer in an engine where the gas motion may be turbulent can be estimated by the laminar quenching distance. The reason may be explained by the existence of a viscous sublayer near the wall proposed by Ferguson. However, it should be noted that there are uncertain factors in this result, for example the effect of the lubricating oil, oxidation in the exhaust system, quenching in ring crevice, and difference of combustion properties between methane and methanol.

6. Conclusions

Experiments on the quenching distances were performed for methane-hydrogen-air mixtures using an apparatus devised for determining the quenching distances. The following results were obtained:

1. The quenching distance decreases monotonously with an increasing fraction of hydrogen. The addition of a small amount of hydrogen produces a rapid decrease of quenching distance for lean mixtures.

2. The quenching distances increase with a decreasing initial pressure at any value of fraction of hydrogen and excess air ratio. The decreasing ratio of quenching distance also shows a rapid rate of increase at low initial pressure due to the addition of a small amount of hydrogen.

3. As the distance between two parallel discs approaches the quenching distance, it is observed that a region where quenching in two discs happens or does not. Probable region of quenching decreases with a decreasing quenching distances or an increasing fraction of hydrogen and with an increasing initial pressure.

4. The values of stretch factor \( K \) are mostly constant for the values of fraction of hydrogen.

5. The tendency of the ratio of the quenching distance to decrease and that of the hydrocarbons to decrease with an increasing fraction of hydrogen are similar at lean conditions.

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