The Effect of Exhaust Gas Recirculation and Turbulence on the Burning Velocity, Dead Space Thickness, and Minimum Ignition Energy in Premixed Methane-Air Combustion

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Abstract—The dilution of a homogeneous combustible mixture with products of combustion has proven to be a successful method of reducing the oxides of nitrogen produced by a combustion process. The Exhaust Gas Recirculation (EGR) affects the flame velocity, ignition energy, and quenching behavior. An experimental program has been conducted to determine the effects of EGR on these fundamental aspects of a turbulent methane/air flame in a constant volume bomb. Data are presented showing that the decrease in flame velocity caused by the EGR can to some extent be compensated for by an increase in the turbulence intensity at a price of increased ignition difficulty. The effect of the EGR, as determined from both heat transfer and ionization measurements, is to increase the single-wall quenching distance.

1  INTRODUCTION

The provisions of the Clean Air Act and its amendments dictate the control of automotive emissions. A method used for the control of oxides of nitrogen (NOₓ) emission is Exhaust Gas Recirculation (EGR) where a fraction of the exhaust gas is recycled into the combustibles of the intake charge (Quadar, 1971; Deeter et al., 1968; Newhall, 1967). This primarily inert exhaust gas lowers the peak flame temperature, a major factor in the formation of NOₓ. Theoretical and experimental evidence indicate that besides lowering the flame temperature, the dilution of the intake charge with the exhaust gas may have some negative effects such as lowering the burning velocity of the mixture, thickening the quench layer, and increasing the required ignition energy (Newhall, 1967; Morgan and Kane, 1953; Mellish and Linnett, 1953). Such problems may lead to an undesirable increase in hydrocarbons and carbon monoxide emissions as well as to a drop in engine performance. Compensation for the first two problems is possible through the control of the cylinder turbulence. The level of turbulence may be limited, however, by ignition difficulties (Ballal and Lefebvre, 1977; Swett, 1949).

Extensive experimental work is needed before the above qualitative analysis can be cast into quantitative relationships which may be used by designers. Hence, the purpose of this research program was to study the effects of exhaust gas recirculation and turbulence on the burning velocity, the single wall quenching distance, and the ignition energy. In addition, some effects of hydrogen enrichment of the fuel were investigated.

A constant volume bomb method was selected for the present study, since it allows convenient control over most of the test parameters. In viewing the reported results, attention should be paid to the fact that the fuel used in the present study primarily consisted of methane which, unlike gasoline, contains no carbon–carbon bonds.

2  APPARATUS AND PROCEDURES

The investigation was carried out in the simple environment (when compared to that of an engine) of a constant volume bomb illustrated in Figure 1. The test bomb, (1), a straight cylinder 50-cm high and 40-cm in diameter is equipped with a pressure relief diaphragm (2) which breaks whenever the pressure in the bomb exceeds approximately 2 atm, a water injection port (3), and a strip heater

The grid is driven by a hydraulic system (13–18), which is activated by a switch (n). A mercury manometer (a) is used to monitor the partial pressure of the gases while the bomb is being filled. The supply of various gases (b–h) and a simulated EGR storage cylinder (j) complete the setup. A lamp (m) is used as a heater to ensure convective mixing of the gases stored in the EGR cylinder. For more details, see Gat (1978).

The apparatus made the actual recirculation of the burned gases impractical. Therefore, the theoretical composition of the exhaust gas under a closed-cycle operation was determined using a chemical equilibrium computer code (Gordon and McBride, 1971). Assuming that the exhaust gas freezes at the adiabatic flame temperature equilibrium composition, a mixture simulating this composition has been prepared and stored in a storage cylinder. Unstable species and trace elements such as H, O, OH and others were separated into their basic constituents and added to the mixture in the form of a more stable species (e.g. H₂, O₂). This procedure ensured an overall conservation of mass in the system. The simulated exhaust gas did not contain any water since it would condense at the room temperature. The appropriate quantity of water was injected directly into the bomb which was kept at a temperature of 340 K to prevent the condensation of the exhaust water. The fuel in the study was a city-supplied natural gas consisting of 96.6 percent methane, and 0.4 percent higher hydrocarbons.

The test procedure was as follows. First, the bomb and the feed lines were evacuated. Then the appropriate quantities of fuel, air, exhaust gas, and water were introduced into the bomb. The air-to-fuel ratio was kept constant through all the tests at \((A/F)_v = 10\), corresponding to an equivalence ratio of 0.965. The amount of EGR was varied between 0 and 30 percent according to the following definition

\[\% \text{ EGR} = \frac{\text{weight of exhaust gas} \times 100}{\text{weight of [fuel + air + exhaust gas]}}.\]  

(1)
To ensure a thorough mixing of all the constituents in the bomb, the mixture was stirred by moving the grid several times through the vessel. And finally, it was left to heat up to 340°K and to allow the turbulence in the gas to die out. Prior to ignition, a capacitor bank was charged to the desired energy, then the grid was pulled down at a preset uniform velocity, and a spark was set off at the geometrical center of the vessel. The resulting nearly-spherical flame propagated normal to the quenching surface located well within the interior of the bomb. Wall quenching was documented employing six ionization gauges, ranging in length from 76 to 1626 micrometers, and a fast response surface thermocouple. The geometrical arrangement and the ionization gauges circuit diagram are shown in Figure 3 with the surface temperature measuring circuit in Figure 4.

A typical data record, reproduced in Figure 5, obtained from a single test contains the following information.

a) The pressure history during the initial stages of combustion in the bomb (ΔP<0.6 atm.).

b) The quenching surface temperature history.

c) Output signal from each of the six ionization gauges located at various distances in front of the quenching surface.

d) A signal from a magnetic pickup used to monitor the grid speed.

e) A reference 500 Hz wave.

The burning velocity was calculated from the pressure history according to the following formula (O’Donovan and Rallis, 1959):

\[
S = \frac{1}{3} \frac{r_d \left( P_t / P \right)^{1/3} \left( \frac{dn}{dt} \right)}{1 - (1 - n) \left( P_t / P \right)^{1/3}}
\]

(2)

where

\[
\frac{dn}{dt} = \frac{1}{P_t} \frac{dP}{dt}
\]

(3)

The use of Eq. (3) is limited for as long as the fraction of the burnt gas in the bomb is small (Lewis and VonElbe, 1961, pp. 367–381). The flame propagation velocity, which is composed of the burning velocity and the expansion velocity of the burnt gas, was calculated from the time derivative of the flame radius, as given by

\[
r_b = r_d \left[ 1 - (1 - n) \left( P_t / P \right)^{1/3} \right]^{1/3}
\]

(4)

O’Donovan’s model assumes, among other things, the existence of a spherical flame of a negligible thickness. However, as the level of EGR or as the level of turbulence increase, flame thickness is expected to increase as well. To check the validity of the calculations, the flame radius, based upon the pressure history, was calculated (Eq. 4). The time at which the calculated flame radius is equal to 13.3 cm was compared with the time the ionization gauges were triggered (from the experimental traces in Figure 5). The difference between these two times never exceeded one percent validating the model’s assumptions for all practical purposes.

The measurements of the turbulence characteristics in the apparatus require equipment (e.g., LDV) which was unavailable at the time the study was performed. Therefore, turbulence characteristics were calculated using empirical correlations derived for grid-generated turbulence in wind tunnels (considered to be a nearly isotropic
homogeneous turbulence). Although in this study the grid moved through a stationary gas, whereas in a wind tunnel the gas flows past a grid, some analogy exists between the two cases, since turbulence—a function of the shear stresses in the fluid—depends on the relative velocity between the grid and the fluid. The following turbulence decay laws were selected:

Turbulence intensity (Baines and Peterson, 1951)

\[ \frac{v'}{U} = 1.12 \left( \frac{U t}{d} \right)^{-5/7} \]

Taylor's dissipation scale

\[ \lambda_g^2 = 7 v t. \]

Integral scale of turbulence (Sato and Yamamoto, 1976)

\[ \frac{I_g}{\lambda_g} = 0.0114 \text{Re}^{1.23} + 0.530. \]
EFFECT OF EGR IN PREMIXED METHANE COMBUSTION

Comparison between the range of turbulence characteristics in the present apparatus and in other systems according to Andrews et al. (1975)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$v'$ cm/sec</th>
<th>$l$ cm</th>
<th>$\lambda$ cm</th>
<th>$\eta$ cm</th>
<th>$Re_t$</th>
<th>$Re_h$</th>
<th>$Re_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present system</td>
<td>46.7</td>
<td>1.21</td>
<td>0.83</td>
<td>0.08</td>
<td>145.0</td>
<td>62.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Bunsen burner</td>
<td>200</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>IC engine</td>
<td>100</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>Pulverized coal burner</td>
<td>200</td>
<td>30.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>850</td>
</tr>
<tr>
<td>Gas turbine combustor</td>
<td>350</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>550 (idle)</td>
</tr>
</tbody>
</table>

Kolmogoroffmicroscale

$$\eta = \lambda_0 15^{-1/4} (Re_g)^{-1/3}.$$  \( (8) \)

(In subsequent equations, for convenience, the subscript $g$ is dropped.) Gat (1978) provides the arguments for the selection of these equations.

Due to the apparatus design, the various turbulence characteristics were limited. Table I summarizes the maxima of the turbulence parameters which were obtained during this test program. For comparison purposes the table gives some values of these parameters in practical combustion systems, according to Andrews et al. (1975).

3 RESULTS AND DISCUSSION

Some general observations can be made in regards to the output traces (e.g. for 0 and for 30 percent EGR, in Figure 5). The ignition point is indicated on these traces and the time axis runs from that point to the left. First, the pressure rise during an explosion is related to the burning velocity and as the EGR level increases, the rate of pressure rise significantly drops (as a comparison between the appropriate traces in Figure 5 clearly shows).

Next, as the flame travels toward the quenching surface (located 13.3 cm from the bomb center) it first triggers the circuit of the longest ionization gauge. Then, the rest of the gauges are triggered in a sequence of decreasing length. When the flame is highly turbulent this triggering sequence is destroyed, however. The ionization current decreases with the decrease in the length of the ionization gauges (i.e., as the flame approaches closer to the wall). As the level of turbulence increases, so does the ionization current. Gauge number 4 was found defective, however, and the ionization current is always high since the insulating coating broke off this gauge.

Quenching surface temperature shows a slow temperature rise starting at the ignition instant until the flame hits the wall (corresponding to the adiabatic compression of the gases in front of the flame). At that instant a sharp increase in surface temperature is noticed. Figure 5 reveals that this temperature rise is higher for mixtures without EGR.

When the pressure inside the bomb exceeds about two atmospheres, a pressure relief diaphragm breaks, resulting in an uncontrolled completion of the combustion in the bomb. This combustion reactivated the ionization gauges.

3.1 The Pressure Rise During the Initial Stages of the Combustion in a Constant Volume Bomb

The pressure history, plotted on a log-log scale, has been inspected for a large number of tests. An analytical expression given below for the pressure rise as a function of time was obtained by curve fitting the experimental data. Two typical curves
are shown in Figure 6. In general it is concluded that the relationship in such plots is nonlinear, and therefore an equation of the type (Bradley and Mitcheson, 1976; Perlee et al., 1974)

\[ \Delta P \propto t^\beta, \quad (9) \]

does not adequately describe the pressure rise in the bomb. On a log-log graph, Eq. (9) should give a straight line with a slope equal to \( \beta \). Perlee et al. (1974) used a bomb of a relatively large volume and found that the slope of the pressure vs. time logarithmic plot changed from 3 to 4.3 as the pressure rise became larger than 0.5 atm. Such a change in the slope was not reported by other investigators who used a relatively small bomb.

In light of the results from the present study it is believed that the combustion duration in a small bomb is too short to reveal the exact shape of the pressure history curve. The present results indicate that the slope of the logarithmic pressure vs. time curve increases continuously toward an asymptotic value. This phenomena is best described mathematically by an equation of the form

\[ \frac{(\ln(\Delta P) + C_1)^2}{C_2} - \frac{(\ln(t) + C_3)^2}{C_4} = 1, \quad (10) \]

or explicitly,

\[ \Delta P = \exp\left[-C_1 + \frac{C_2}{C_4} (\ln(t) + C_3)^2 + C_4 \right]^{1/2}. \quad (10a) \]

This is an equation of a hyperbola which in the limit, as time becomes large, approaches the asymptote

\[ \ln(\Delta P) = \beta \ln(t) \quad (11) \]

\[ \Delta P \propto t^\beta. \quad (9) \]

Equation (10) was found to apply to turbulent as well as to laminar combustion in the bomb. The values of the parameters \( C_1 \) through \( C_4 \) have to be determined by a nonlinear regression analysis.

As already mentioned, the burning velocity was calculated from Eqs. (2) and (3). The expression for the derivative \( dP/dt \) was obtained from Eq. (10) after the determination of the coefficients \( C_1 \) through \( C_4 \). Explicitly,

\[
\frac{dP}{dt} = \frac{C_2}{C_4} \ln(t) + C_3 \\
\times \exp\left[\frac{C_2^2}{C_4} + (\ln(t) + C_3)^2\right]^{1/2},
\]

\[ (12) \]

3.2 The Burning Velocity

Laminar burning velocity was measured in the bomb in an identical way to the measurement of turbulent burning velocity except that the mixture was ignited only after sufficient time elapsed for the turbulence in the bomb to die out (~10 min). The effect of EGR on the laminar burning velocity of a homogeneous natural gas/air mixture at an initial temperature of 340 °K and a pressure of 1.09 atm is given in Table II. According to Andrews and Bradley (1972), the laminar burning velocity of a methane/air mixture can be predicted using the formula

\[ S_L = 10 + 0.000371 T^2 \text{ cm/sec.} \quad (13) \]

For \( T = 340^\circ\text{K} \) this formula gives \( S_L = 52.9 \text{ cm/sec.} \). Considering the use in the present study of natural gas rather than pure methane, the difference, of less than 2 percent, between the predicted and measured burning velocity (see Table II, 0 percent EGR) is insignificant.
The laminar burning velocities and other parameters in the turbulent burning velocity equation (see text)

\[ T_1 = 340^\circ \text{K}, \ P_1 = 1.09 \text{Atm.}, \ \phi = 0.965 \]

<table>
<thead>
<tr>
<th>% EGR</th>
<th>( S_L ) cm/sec</th>
<th>( k_1^{1/8} )</th>
<th>( k_2 )</th>
<th>( k_2/F_e )</th>
<th>( \delta_{pr} ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>53.7</td>
<td>3.71</td>
<td>0.0 906</td>
<td>0.06906</td>
<td>0.043</td>
</tr>
<tr>
<td>5</td>
<td>41.4</td>
<td>2.99</td>
<td>0.07224</td>
<td>0.06625</td>
<td>0.055</td>
</tr>
<tr>
<td>10</td>
<td>32.7</td>
<td>2.60</td>
<td>0.07953</td>
<td>0.06741</td>
<td>0.070</td>
</tr>
<tr>
<td>15</td>
<td>25.2</td>
<td>2.03</td>
<td>0.10536</td>
<td>0.07481</td>
<td>0.091</td>
</tr>
<tr>
<td>20</td>
<td>19.2</td>
<td>1.66</td>
<td>0.12473</td>
<td>0.07829</td>
<td>0.119</td>
</tr>
<tr>
<td>25</td>
<td>13.3</td>
<td>1.36</td>
<td>0.15469</td>
<td>0.14167</td>
<td>0.247</td>
</tr>
<tr>
<td>30</td>
<td>9.3</td>
<td>1.05</td>
<td>0.25469</td>
<td>0.23489</td>
<td>0.319</td>
</tr>
</tbody>
</table>

The effect of turbulence on the burning velocity is shown by the data given in Figure 7. The lines in the figure are the best curve fit for an equation of the form (Putnam, 1976):

\[ \frac{S_T}{S_L} = \left[ \frac{1 + k_1 (v')^{1/8}}{S_L} \right]^{1/a} \]  \hfill (14)

It should be noted that as \( v' \) becomes very small this equation gives

\[ S_T = S_L \]  \hfill (15)

and as \( v' \) becomes very large, a linear relationship is obtained

\[ \frac{S_T}{S_L} = k_2 v' \]  \hfill (16)

The flame thickness was assumed to be equal to the preheating zone thickness which was calculated following Damköhler (1940)

\[ \delta_{pr} = \frac{4.6 \bar{\delta}}{S_L C_p \rho} \]  \hfill (19)

Where the numerical value 4.6 comes from an arbitrary selection of the boundaries of the preheating zone of the flame (values calculated by Eq. (19) are listed in Table II). The calculations indicated that, in nearly all the cases, the parameter \( \Gamma \) was less than unity. Hence, combustion was assumed to take place in the wrinkled laminar flame mode which also may explain the increase in the slope \( k_2 \) with the level of EGR, (Shelkin, 1943).

In order to determine the combustion mode in the present study, the Kovasznay (1956) parameter was calculated

\[ \Gamma = \left( \frac{v' / \lambda}{S_L / \delta_{pr}} \right) \]  \hfill (18)

One of the controversial points in the field of premixed turbulent flames is the proper parameters with which the burning velocity should be correlated, as reflected through the many attempts made by various authors (Andrews et al., 1974; Abdel-Gayad and Bradley, 1976; Smith and Gouldin, 1977). In the present study, the burning
velocity ratio $S_T/S_L$ was plotted as a function of the following parameters:

$$v', v'/S_L, Re_l = \frac{v'}{v}, Re_\lambda = \frac{v_\lambda}{v}, Re_\eta = \frac{v_\eta}{v}$$

The results are given in Figures 7, 8, 9, 10 and 11, respectively.

In attempting to fit the data with various curves, it was concluded that an equation of the type

$$\frac{S_T}{S_L} = \left[1 + k_3 \text{ (Parameter)}^a\right]^{1/3} \tag{20}$$

was superior in all the cases to a linear or a parabolic equation. Also, of all these parameters, the burning velocities ratio best correlates (largest value for the correlation coefficient) with the turbulence intensity $v'$. However, since the various turbulence characteristics were calculated rather than measured, the uncertainty in the values of the various Reynolds numbers is relatively large (since a product of two calculated quantities is involved). Therefore, no firm conclusion can be drawn in regards to the best correlation for $S_T/S_L$. The figures do show, however, that the addition of EGR does not change the basic relationship between the burning velocity and the turbulence characteristics.

Reducing each curve in Figure 7 by a factor

$$F_x = \left[\frac{S_L(\text{at 0% EGR})}{S_L(\text{at x% EGR})}\right]^{1/3} \tag{21}$$

brings all of the lines into a narrow band as shown in Figure 12 (Hires et al., 1978), thus scaling to some extent the effect of the exhaust gas recirculation.
3.3 The Dead-Space Thickness

A primary problem in investigating the dead-space thickness is that there is no formal definition of what the dead space is. Such a definition would depend on the geometry which in the present investigation was a flat-flame-front moving perpendicularly toward the wall (the spacing of the ionization gauges, see Figure 3, relative to the radius of the flame when it approaches the quenching surface is such that for all practical calculations a flat flame can be assumed). As the flame approaches closer to the wall it would quench at a certain distance from the wall. There are numerous options for defining the dead-space thickness for such a situation. For instance, the distance between the wall and the luminous zone of the flame or the distance between the wall and the reaction zone (i.e., the inflection point in the temperature profile), could both serve as definitions. It is possible to use other definitions as well, however, not all definitions are amenable to a simple experimental measurement. In the present study two methods were employed to measure the dead-space thickness. One is based on the temperature gradient of the gas in the quench layer and the other based on the ionization phenomena occurring in a hydrocarbon flame.

With the first approach, the dead-space thickness was estimated from the heat flux to the wall from the flame at the instant of quenching (maximum of the heat flux), via the relationship

\[ \dot{q} = \frac{\delta}{\delta q} (T_f - T_w) \]  \hspace{1cm} (22)

where

\[ T_f = \int \kappa(T) \, dT \]  \hspace{1cm} (23)

\[ \delta = \frac{T_f - T_w}{T_f} \]

and

\[ \delta = \frac{h}{\delta q} \]  \hspace{1cm} (24)

To find the heat flux, \( \dot{q} \), the following procedure was followed. The temporal heat transfer equation for the quenching surface was solved, using the experimental surface temperature history as a boundary condition.

\[ \frac{\partial T_w}{\partial t} = \frac{\partial^2 T_w}{\partial x^2} \]  \hspace{1cm} (25)

The boundary conditions are

\[ T_w(0, t) = f(t) \]
\[ T_w(1, t) = 0 \]

and the initial condition

\[ T_w(x, 0) = 0 \]

where \( f(t) \) is the experimentally determined wall temperature.

The heat flux was found then by evaluating the following expression

\[ \dot{q} = -\kappa(T) \frac{\partial T_w}{\partial x} \bigg|_{x=0} \]  \hspace{1cm} (26)

A typical plot of the measured wall temperature and the calculated heat flux during the flame approach for a 20 percent EGR mixture is shown in Figure 13.

It is possible to distinguish, in Figure 13, among three regions. The temperature rise in region one is due to the adiabatic compression of the gases in front of the flame. The flame interacts with the wall
in region two, where the interaction time is approximately equal to the ratio between the flame thickness and the burning velocity. Finally, the slow temperature rise in region three is due to the contact with the hot reaction products, the post-flame reactions, and the isentropic compression of the burned gases. Quenching of the flame occurs at point Q when the heat flux is at its peak. The area under the curve in region two gives the total heat transfer to the wall during the flame-wall interaction. However, it was found that the total heat transfer is not a controlling parameter. The maximum heat flux, \( q_{\text{max}} \), at point Q, was found to be nearly a constant for a particular mixture regardless of the turbulence in the bomb, a somewhat surprising result. The heat losses which a flame can sustain without quenching depend on the rate of heat release by the flame, which in turn depends on the burning velocity. Therefore, the above observation can be understood only if the flame approaches the wall at a constant burning velocity regardless of the turbulence. In other words, turbulence seems not to affect the flame in the close proximity of the wall. This occurs, perhaps, due to the presence of a laminar sublayer which results from the nature of the flow field in the vessel (i.e., a decaying, turbulence with a mean flow velocity equal to zero). This sublayer, however, must be much thinner than the dead space defined by the ionization signal. Actual quenching may occur in a laminar burning regime, dominated by molecular transport phenomena rather than turbulent diffusivity.

Figure 14 shows the change in the value of \( q_{\text{max}} \) and the heat transfer coefficient, \( h \), as a function of EGR. The latter parameter

\[
 h = \frac{q_{\text{max}}}{T_f - T_w}
\]

was calculated by substituting the adiabatic flame temperature \( T_{ad} \), which is an upper limit for \( T_f \) in Eq. (27), hence giving the lower limit of \( h \). The thickness, \( \delta_q \), should be considered, therefore, a higher limit of the dead space (see Eq. 24). The gas thermal conductivity (for use in Eq. 24) was taken as an average of the conductivity at the wall temperature and the conductivity at the ignition temperature of \( \text{CH}_4/\text{air} \) flame, i.e., 340 and 1300°K, respectively.

Next, the quenching Peclet number was calculated using the experimental value of the laminar burning velocity and the heat transfer coefficient as follows:

\[
 Pe = \frac{\rho C_p S_L}{h} = \frac{S_L \delta_q}{\mu}
\]

Here,

\[
 \mu = \frac{\kappa MW}{C_p \rho_{340}}
\]

\[
 \kappa = \frac{1}{2} (\kappa_{340} + \kappa_{1300})
\]

Thus, the Peclet number is based on both the unburned and the burned gas properties.

The results of these calculations are summarized in Table III.

It should be noted that the values of the Peclet number with EGR are somewhat less than 4.6, as predicted by the thermal quenching theory of Ishikawa and Branch (1977). The quenching Pe also decreases uniformly with the flame temperature.

As already mentioned, ionization gauges were employed in a simultaneous attempt to measure the dead space by an alternative method, first described by Ellenberger et al. (1971). Figure 15 shows the ionization current for each of the six ionization gauges for laminar combustion and for turbulent (with \( v' < 50 \text{ cm/sec} \)) combustion, at various levels of EGR. Data from the 890 \( \mu \text{m} \)

![Figure 14: Effect of EGR on heat transfer.](image-url)
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The upper limit of the quenching Peclet number and the dead space thickness from the heat transfer data

<table>
<thead>
<tr>
<th>% EGR</th>
<th>$\overline{\theta}$ kW/m²</th>
<th>$p_e$</th>
<th>$\delta_e$ cm (10⁻² inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>325.1</td>
<td>3.35</td>
<td>0.035 (90)</td>
</tr>
<tr>
<td>5</td>
<td>293.7</td>
<td>2.77</td>
<td>0.038 (96)</td>
</tr>
<tr>
<td>10</td>
<td>267.9</td>
<td>2.31</td>
<td>0.040 (102)</td>
</tr>
<tr>
<td>15</td>
<td>199.3</td>
<td>2.29</td>
<td>0.051 (130)</td>
</tr>
<tr>
<td>20</td>
<td>193.0</td>
<td>1.72</td>
<td>0.051 (129)</td>
</tr>
<tr>
<td>25</td>
<td>157.5</td>
<td>1.38</td>
<td>0.059 (149)</td>
</tr>
<tr>
<td>30</td>
<td>128.6</td>
<td>1.11</td>
<td>0.068 (172)</td>
</tr>
</tbody>
</table>

FIGURE 15 Ionization current at various distances from the wall.

gauge has been ignored since it was found that the insulation broke off this gauge during some early tests. A cut-off current of approximately 28 $\mu$Amp was selected to distinguish between those gauges which were within the dead space (i.e., having a current below 28 $\mu$Amp) and those gauges in the burning zone (with a current above 28 $\mu$Amp). A value of 28 $\mu$Amp was selected since for laminar combustion at 0 percent EGR this current corresponds to a dead space thickness of 635 $\mu$m. This calibration is obtained by taking 40 percent of the smallest quenching thickness reported in the literature (Potter, 1960) for methane/air combustion under similar conditions. The results of this study would be considered, therefore, as a lower limit to the dead-space thickness. The forty percent factor is needed for a single wall correction, though the true value of this factor is still controversial (Lavoie, 1978).

Once a cut-off current is selected, it becomes possible to determine the separation between the flame and the wall and hence the dead-space thickness for the various levels of EGR, both for turbulent and for laminar combustion. The quench-layer thickness as obtained from the ion probe data is indicated by the dashed lines of Figure 15. For larger amounts of EGR the quench layer was thicker than the longest ionization gauge. In all cases, the turbulent quench layer is thinner than the laminar.

Finally, as a comparison, the dead-space thickness, as obtained by the two different methods, is shown as a function of EGR level in Figure 16. Typically, quenching occurred at pressure between 1.3 to 1.6 atmospheres.

For reasons discussed earlier, the curve obtained by the heat transfer method and that obtained by the ionization method should be an upper and a lower limit, respectively. There is no reason, however, to expect the two curves will give the same results, since they were obtained by measuring different physical phenomena.

3.4 The Minimum Ignition Energy

The effect of EGR on the minimum ignition energy of a stationary mixture is shown in Figure 17. The ignition energy is calculated from the stored energy in the capacitance ignition system. Unsuccessful attempts were made to measure directly the energy released in the spark by use of a high frequency current transformer and a voltage probe. Traces displayed on a CRT screen showed multiple
the required ignition energy as a function of EGR.

The line with a slope equal to three has been added to the figure in accordance with the formula

$$E_{\text{min}} = \frac{\alpha \kappa}{\rho C_v (T_{ad} - T_0)}$$

which was derived for slightly different considerations by Sokolik (1960) and Ballal and Lefebvre (1977).

No measurements of turbulent ignition energy were made. Although, as turbulence level increased in the bomb, it became necessary to charge the ignition system with higher energy to be able to ignite the mixture. With a maximum stored energy of 1 Joule, it was not possible to ignite the 25 and 30 percent EGR mixtures above approximately $v'$ equal to 30 and 13 cm/sec, respectively (see Figure 7).

3.5 Effect of Hydrogen Enrichment

It may be possible to compensate for the detrimental effects of EGR through the addition of small quantities of hydrogen which extend the lean flammability limit of the mixture, and increase the burning velocity.

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discharges occurring within about 5–10 microseconds.

The operation of the ignition system and the details of the electrodes were discussed earlier. Although the actual energy released in a spark is only a fraction of the stored energy (due to dissipation losses), the information in Figure 17 is valuable since it indicates the relative increase in
The laminar burning velocity of a 15 percent EGR mixture at various levels of hydrogen enrichment is shown in Figure 18. The amount of enrichment is defined as $a$ moles of hydrogen per mole of fuel, i.e.,

$$\text{fuel} = (1 - a) \text{CH}_4 + a\text{H}_2. \quad (33)$$

These results demonstrate the ability of hydrogen enrichment to partially restore the burning velocity of a vitiated mixture.

The effect of hydrogen on the dead-space thickness of a 15 percent EGR mixture is shown in Figure 19. In this case, the shortest ionization gauge (#6) is never activated by the flame, indicating that up to an enrichment level of 0.25 moles of H$_2$ the flame never approaches close enough to the wall. Furthermore, gauge #5 shows only a small current while gauges 3, 2 and 1 show an increase in the ionization current with an increase in H$_2$ enrichment (the data from gauge #4 were ignored for the reasons mentioned above). The longest gauge (#1) shows a saturation level and it is probable that the same would happen to the other

![Figure 19 Effect of H$_2$ enrichment on ionization current (15% EGR).](image)

gauges as the enrichment level goes up. Using a certain cut-off current (e.g., 25 $\mu$Amp) it is possible to determine the dead-space thickness. It is believed that the observed increase in ionization current indicates a real decrease in the dead-space thickness and not a higher level of ions in the flame, since hydrogen flames are known to have a much lower level of ionization than hydrocarbon flames do (Lewis and VonElbbe, 1961, p. 558; Gaydon and Wolfhard, 1970).

4 CONCLUSIONS

1) The pressure-time relationship during combustion in a constant volume bomb of a relatively large volume has been found to follow a relationship

$$\Delta P = \exp \left[ -C_1 + \frac{C_2}{C_4} (\ln(1) + C_3)^2 + C_4^{a1/2} \right].$$

2) Exhaust gas recirculation substantially reduces the burning velocity. A decrease in excess of 80 percent has been measured as EGR level increased to 30 percent.

3) The ionization gauges cannot serve as a “go/no-go” flame detector due to the high mobility of the electrons which penetrate the dead space. With the proper selection of a cut-off current it is possible, though, to quantitatively estimate the thickness of the dead space for a flame approaching the wall head on. It is possible that the cut-off current has to be re-evaluated for each level of EGR since the flame temperature goes down with increased dilution and the non-equilibrium electron concentration in the flame may drop too. For the case of H$_2$ enrichment, the same ionization levels will not be achieved as in a hydrocarbon flame. The use of a constant cut-off current may lead to an overestimation of the dead-space thickness.

4) The single-wall-quenching Peclet number appears to be temperature dependent and it varies from 3.35 to 1.11 as EGR increases from 0 to 30 percent.

5) The two methods employed for estimating the dead space are based upon measurements of different phenomena. Although these phenomena are not unrelated to each other, it is not expected to obtain exactly the same results. Further, there are some uncertainties which may contribute to a discrepancy between the results obtained by the heat transfer and by the ionization methods. First, the 40 percent correction for a double wall quenching may not be the proper value, and the flame temperature at the instant of quenching should be known. Secondly, the possibility that turbulent flames display higher ionization levels...
than do laminar flames should be further investigated (Arrigoni et al., 1973).

6) A significant increase in the required minimum ignition energy has been measured as the EGR level increased. This ignition energy increased by a factor of 100 as the EGR level increased from 0 to 30 percent. At high levels of EGR, high levels of turbulence precluded ignition.

7) Both turbulence and hydrogen enrichment enhance the burning velocity and decrease the dead-space thickness of EGR-diluted charges.

**NOMENCLATURE**

\[ C_1, C_2 \] Regression constants in the pressure-time history
\[ C_a, C_d \] Regression constants
\[ C_p \] Specific heat at a constant pressure
\[ d \] Width of turbulence-generating grid bar
\[ E_{\text{min}} \] Minimum ignition energy
\[ F_x \] Factor defined by Eq. (21)
\[ h \] Heat transfer coefficient
\[ k_1, k_3 \] Regression constants
\[ k_2 \] Regression constant
\[ k \] Thermal conductivity
\[ L \] Lateral integral scale of turbulence
\[ n \] Molecular weight
\[ \alpha \] Mass fraction of the charge that was burned
\[ p \] Pressure
\[ Pe \] Peclet number
\[ P_i \] Initial pressure in the bomb
\[ P_a \] Final pressure in the bomb at the completion of the combustion
\[ q \] Heat flux from flame to wall
\[ Re \] Reynolds number
\[ r_a \] Equivalent radius of the bomb
\[ r_b \] Flame radius
\[ S \] Burning velocity
\[ S_L \] Laminar burning velocity
\[ S_T \] Turbulent burning velocity
\[ T_0 \] Initial mixture temperature
\[ T_a \] Adiabatic flame temperature
\[ T_f \] Flame temperature
\[ T_w \] Wall temperature
\[ t^* \] Non-dimensional time
\[ U \] Grid velocity
\[ x^* \] Non-dimensional distance
\[ y^* \] Non-dimensional distance
\[ (A/F)_e \] Air-to-fuel ratio on volume basis

**Greek Symbols**

\[ \alpha \] Regression constant; Hydrogen enrichment level
\[ \beta \] Pressure-time exponent
\[ \gamma_n \] Specific heat ratio of unburned gas
\[ \Gamma \] Kovasznay parameter
\[ \delta_f \] Flame thickness
\[ \delta_{pr} \] Preheating zone thickness
\[ \delta_q \] Dead-space thickness
\[ \kappa \] Thermal conductivity
\[ \kappa_w \] Thermal conductivity of wall
\[ \lambda_g \] Lateral Taylor’s dissipation microscale
\[ \mu \] Thermal diffusivity
\[ \nu \] Kinematic viscosity
\[ \rho \] Density
\[ \eta \] Kolmogorov’s microscale of turbulence

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**REFERENCES**


