Ignition Limits for Pilot-Stabilized High-Velocity, Turbulent, Butane-Air Mixtures at Low Pressure

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Limiting velocities were determined by finding the composition at which the flame first spread into the unburned gases for a given velocity and turbulent intensity. These compositions were represented by intersections of curves of flame widths at certain combustion chamber positions plotted vs. composition.

Scurlock (*1*) has studied the effect of turbulence on stability compositions for natural gas by the use of a rod-stabilized flame at atmospheric pressure. Other investigators, Wohl and Shore (*2*) and Wohl, Shore, Von Rosenberg, and Weil (*3*), have studied combustion turbulent, flowing, butane-air mixtures. There were however no published data found that considered ignition composition limits for high-velocity, turbulent, butane-air mixtures at low pressure.

A brief description of the experimental apparatus follows. A more detailed coverage was given by Archer (*4*).

Figure 1 is a diagram of the combustion chamber, flame holder, and turbulence regulation system.

The combustion chamber was a cylindrical, water cooled, Vycor glass tube. Three separate chambers (1, 2, and 3⅛ in. diam.) were studied. The Vycor chambers permitted visual observation, provided reproducible wall conditions, and inhibited catalytic effects on the duct walls.

A small stoichiometric hydrogen-oxygen flame burning at the port of a smooth tube which was coincident with the combustion chamber's principal axis was the flame holder. This flame holder caused less disturbance than the rod or gutter type. It was also simply constructed and possessed radial symmetry. The same pilot velocity (92 ft./sec. for cold gases from the pilot) was used throughout this investigation.

Screens of 4 and 100 mesh, positioned as shown in Figure 1, were used to regulate the level of turbulence in the combustion chamber. These were placed ½ in. downstream from two 100-mesh screens which produced a flat velocity profile (*4*). The entire screen section was preceded by a 48-in. section of straight pipe which was equipped with straightening vanes at its entrance.

Empirical correlations developed by Dryden (*5*) and by Baines and Peterson (*6*) were used to calculate the fraction and scale of turbulence. Tabulation of their values and the ones used in this investigation are given in Table I.

Ignition compositions were determined by finding the composition at which the flame first spread into the unburned mixture for a given combustion chamber at a constant velocity and turbulent intensity.

This was done by taking a series of photographs of the combustion chamber for various compositions. Exposure times were varied in such a way that they were inversely proportional to the maximum flame luminosity as determined by an electric photometer. This made the maximum photographic densities of all the flame negatives approximately equal.*

Flame diameters at points 1.12, 2.24, 5.62, and 8.98 in. downstream from the pilot port were determined by densitometrically analyzing the negatives. The same downstream points were used for all the combustion chambers. These flame widths were then plotted vs. composition for each of the four characteristic positions (Figure 3).

Intersection of these plots represented the leanest composition at which flame width increased constantly with distance beyond the pilot port, the composition at which the flame first began to spread the ignition composition.

The widths in Figure 3 are readings obtained from the densitometer stage scale. There is a small variation in the intersection of the curves of Figure 3 (about 0.05 mole %). Generally variations were in this order of magnitude. The maximum variation encountered was about 0.16 mole %.

Data obtained by the densitometric analyses are plotted in Figures 4, 5, and 6 for constant turbulent intensity. Figure 7 compares the curves fitted to the data in Figures 4, 5, and 6.

The curves show an apparent linear relation between the upper velocity limit and composition up to about 300 ft./sec. for a given turbulent intensity.

The relation of the upper velocity limit to turbulent intensity seemed not to be linear but rather exponential. For a given combustion chamber the following rough semiquantitative relation was found to hold:

$$\frac{Y - C}{U - B} = \exp Af$$

Data shown in Figures 4, 5, and 6 represent the upper velocity limit for

TABLE 1. CALCULATED VALUES OF TURBULENT INTENSITIES AND *l/dw* AT VARIOUS DISTANCES BEHIND SCREENS

Screen	Distance behind screen, in.	% Turbulent intensity Reference 5	% Turbulent intensity Reference 6	% Turbulent intensity Value used	*l/dw* Reference 5	*l/dw* Reference 6	*l/dw* Value used
100 mesh	6	0.63	0.49	0.6	4.5	3.7	4.0
49% open area	12	0.40	0.30		6.4	—	
dw = 0.003 in.	18	0.32	0.23		7.9	—	
4 mesh	6	4.7	4.8	4.8	0.55	0.86	0.70
51% open area	12	2.4	2.9		1.09	1.20	
dw = 0.072 in.	18	1.8	2.2		1.44	1.40	
4 mesh	6	10.0	6.8	7.0	0.30	0.70	0.50
27% open area	12	3.7	4.2		0.69	0.92	
dw = 0.120 in.	18	2.6	3.1		1.00	1.15	

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* These photographs were taken at the University of Delaware in the course of another investigation (*4*).

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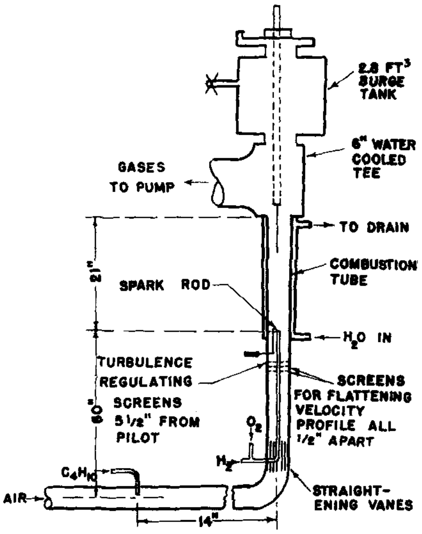

Fig. 1. Experimental apparatus.

compositions leaner than the stoichiometric mixture. There are also such velocity limits corresponding to mixtures richer than the stoichiometric. These data however are not available for this system.

Before the results are discussed a more detailed consideration of the process of ignition is needed. Earlier in this paper ignition was defined as the point at which the pilot flame first spread into the unburned gas mixture. In other words ignition may be defined as the initiation of a continuing or self-propagating combustion reaction in a gas mixture.

This initiation is believed (7, 8) to require both thermal energy and active radicals (that is oxygen, hydroxyl, or hydrogen). The thermal energy is needed to raise the gas to a temperature at which the reaction will take place at a finite rate. Active radicals are needed to initiate and maintain the characteristic chain reactions of combustion.

Possible reasons for the effects of turbulence, velocity, and combustion chamber size may now be discussed by use of the preceding background material.

It can be noted (Figures 4, 5, 6, 7) that increasing velocity and/or turbulent intensity make ignition more difficult (that is raise the ignition composition). Increased velocity causes shorter contact times between the butane-air mixtures and the pilot flame. The shorter contact times in turn result in less thermal energy and fewer active radicals being transferred, and hence make ignition more difficult. A more intense turbulence affects ignition adversely because thermal energy and radicals are dissipated much more rapidly.

The influence of combustion chamber is more complex. Figures 4, 5, and 6 indicate the following:

1. Upper velocity limit behavior is the same for the 2-and the 3⅛-in. diam. chambers at turbulent intensities of 0.6 and 4.8%.
2. The lines representing the data for the 2 and 3⅛-in. combustion chambers deviate at a turbulent intensity of 7.0%.
3. The 1-in. combustion chamber data at a turbulent intensity of 0.6% diverges from the line of the 2- and 3⅛-in. combustion chambers at low velocity but converges to it at high velocity.
4. At a turbulent intensity of 7.0% the data of the 1-in. combustion chamber fall on the same line as do those of the 3⅛in. combustion chamber.

There are two possibilities for the behavior in the 1-in. combustion chamber, quenching and the formation of turbulent boundary layers.

A quenching distance of 3 mm. was estimated with the data of Wohl (9). The total distance quenched was therefore 2 × 3 or 6 mm. This effect was of course most pronounced in the 1-in. combustion chamber. Although this seems to furnish an explanation for the deviation of the data, quenching is not a function of velocity, and hence the convergence of the 1-in. combustor data at high velocity would not be explained. While quenching may have been a factor, it apparently was not the most im-

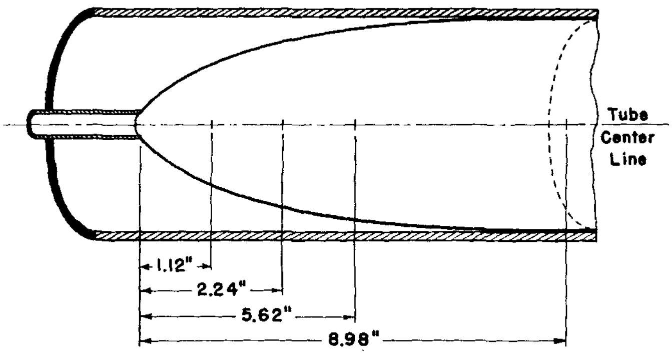

Fig. 2. Schematic diagram of flame (not to scale).

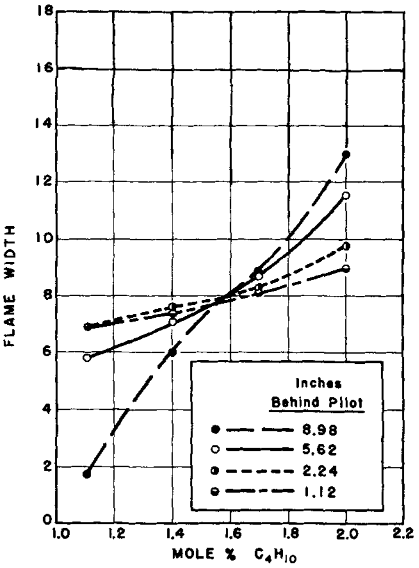

Fig. 3. Flame width vs. mole per cent butane. Velocity equals 25 ft./sec., turbulence intensity equals 4.8%, combustion chamber equals 2-in. diameter.

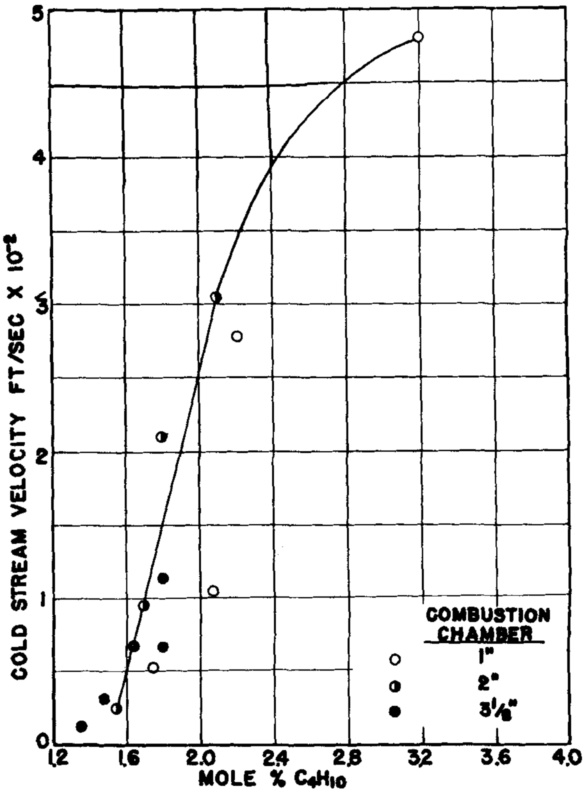

Fig. 4. Cold stream velocity vs. mole per cent butane, 0.6% turbulent intensity.

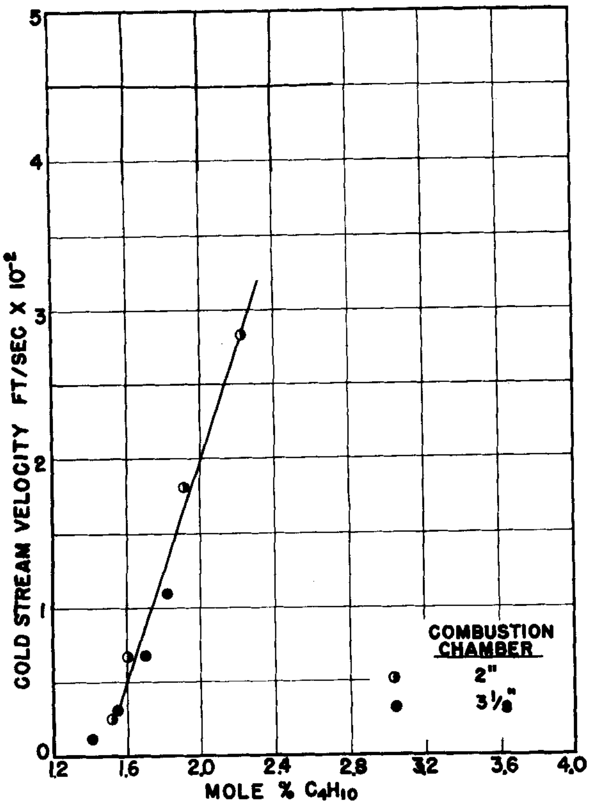

Fig. 5. Cold stream velocity vs. mole per cent butane, 4.8% turbulent intensity.

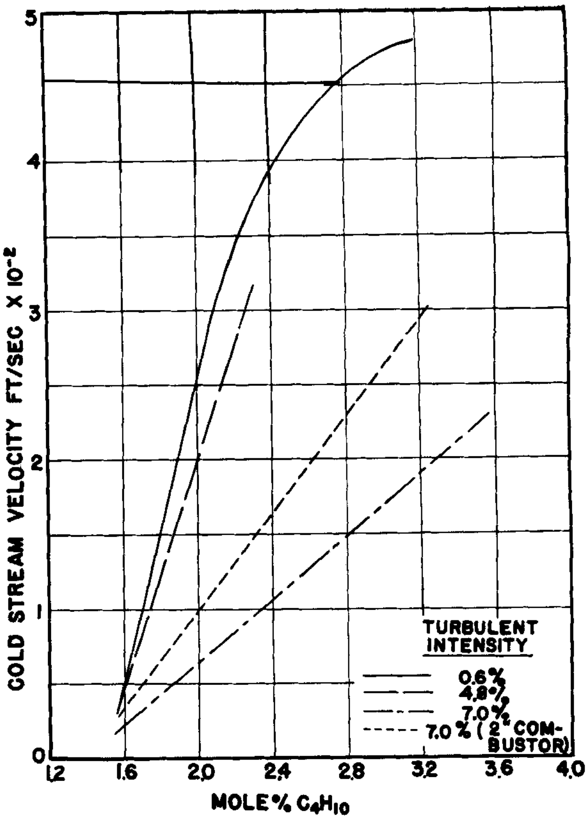

Fig. 7. Cold stream velocity vs. mole per cent butane.

portant one in determining the 1-in. combustor's data deviation.

The other possibility, turbulent boundary layer formation, appears to have been the more important. Such layers formed at the tube wall and flame holder. Additionally there were disturbances with the pilot flame itself (*4*). The combined effect of these factors would be once more greatest in the 1-in. combustor. Furthermore such layers decrease in thickness with increasing velocity (*10*), thereby furnishing a possible explanation for the convergence of the 1-in. combustion chamber data at high velocity.

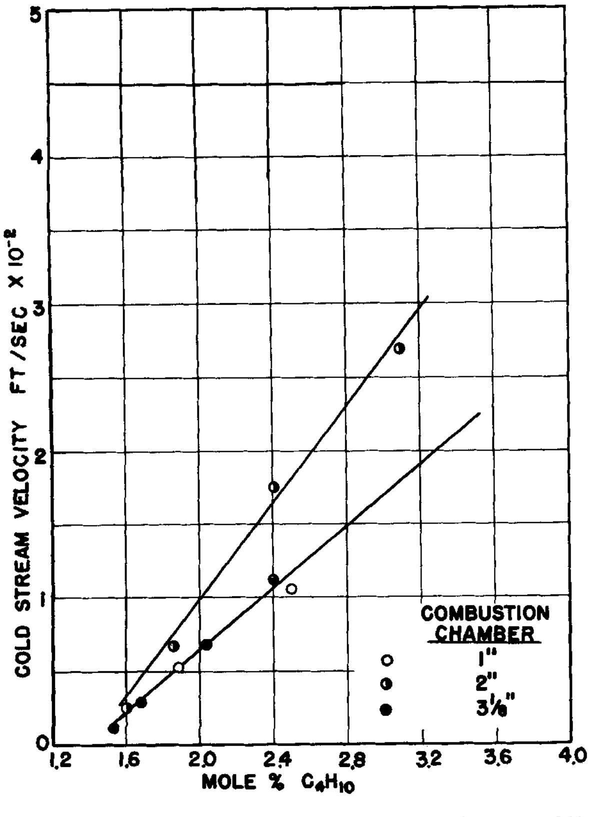

Fig. 6. Cold stream velocity vs. mole per cent butane, 7.0% turbulent intensity.

Because of the convergence and the fact that no ignition took place at 666 ft./sec. for the 1-in. combustion chamber, it was assumed that the curve for a turbulent intensity of 0.6% could be extended to the point for the 1-in. combustion chamber at the stoichiometric mixture (see Figure 4).

In addition the data of Scurlock (*1*) for natural gas showed that the complete upper velocity limit curves both rich and lean mixtures) for higher turbulent intensities were within the area enclosed by the curve for the lowest turbulent intensity studied. This indicated that no ignition would take place for any of the turbulent intensities of this investigation for velocities greater than 666 ft./sec.

Contrasting the explanation for the 1-in. combustion chamber deviation are the lack of reasons for the deviation of the 2- and 3⅛-in. combustion chamber's data at the 7.0% turbulent intensity. A possible explanation could be that the thermal energy and active radicals had to be more widely dispersed in the larger combustion chamber rendering ignition more difficult.

CONCLUSIONS

1. Ignition is made more difficult by increasing velocity and/or by turbulent

intensity for flowing gas mixtures with a pilot-stabilized flame.

2. Butane-air mixtures for the system investigated will remain unignited for velocities greater than 666 ft./sec.

3. Turbulent boundary formation and, to a lesser extent quenching, adversely affected ignition to a great degree in the 1-in. combustion chamber. Any future studies should thoroughly consider these factors.

NOTATION

A, B, C = constants
dw = thickness of screen wire
f = % turbulent intensity/100
l = scale of turbulence, in.
U = cold stream velocity ft./sec, based on empty combustion chambers
Y = composition, mole %

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A Thermodynamic Correlation of Nonpolar Gas Solubilities in Polar, Nonassociated Liquids

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The regular-solution theory of Hildebrand (*15*) and Scatchard (*31*) has received much attention in recent years. But the Hildebrand equation, Equation (23), is applicable only to nonpolar systems. Furthermore, because of its approximate nature, the Hildebrand equation has not been used as successfully in theoretical predictions of gas solubilities in liquids as in forming the basis of some semiempirical correlations (*5, 11, 29*). While the regular-solution equation consists of two terms, the internal energy of mixing and the ideal entropy of mixing, it should be noted that both terms are approximate even for nonpolar solutions. The errors resulting from these approximations however have been fortunately cancelled (*32*). The Hildebrand equation has thus been well accepted by chemical engineers and chemists because of its overall fitness to the nonpolar solutions and its convenience in application.

This paper deals mainly with nonpolar gas solubilities in polar, nonassociated liquids. Those polar liquids which exist in the form of monomers are here considered nonassociated. For internal energy of mixing the general equation of Hildebrand and Wood (*16*) is used to extend the regular-solution theory to binary solutions consisting of a nonpolar and a polar, nonassociated liquid. The entropy of mixing can also be considered ideal for such solutions especially if the solution is dilute. Empirically the partial molal entropy of mixing can be evaluated for gas-liquid solutions from the slope of the straight line when log x_2 is plotted vs. log T (*28*). Examining plots of this kind one will find that for each nonpolar gas studied in this work the slopes for polar, nonassociated liquids generally follow the slope pattern of nonpolar liquids very well. This suggests that the degree of randomness for both kinds of solution may be considered as approximately the same, and the ideal solution model for entropy of mixing can be retained for binary solutions consisting of a nonpolar and a polar, nonassociated component. Together with considerations of intermolecular forces caused by dipole-dipole interactions, an equation is derived to express the activity coefficient of the nonpolar component in such systems. This equation is then applied to gas-liquid solutions to provide the thermodynamic framework for the correlation of experimental solubility data of nonpolar gases in polar, nonassociated liquids. With this correlation it is possible to estimate low pressure gas solubilities in other polar, nonassociated liquids when no experimental data are available.

PREVIOUS APPROACHES

Most of the previous correlations, empirical or semiempirical, concerning nonpolar gas solubilities in liquids have been confined to nonpolar liquids (*5, 11, 20, 24*) or to a specific liquid (*14*). Gjaldbaek and Anderson (*10*) studied the solubilities of carbon dioxide, oxygen, carbon monoxide, and nitrogen at 25°C. in polar, nonassociated liquids and found empirically that the difference between the values of experimental solubility data and those predicted by the Hildebrand equation is qualitatively proportional to the dipole moments of the liquids for each gas. Empirically, Gjaldbaek (*8, 9*) also correlated the solubilities of methane, nitrogen, argon, and ethane in alcohols and water with the dielectric constants of the liquids and the polarizabilities of the gases. His results were satisfactory for alcohols but not for water. Recently Prausnitz and Shair (*29*), in their semiempirical correlation of nonpolar gas solubilities in nonpolar liquids, suggested an empirical plot to estimate certain gas solubilities in polar liquids, provided solubility data for other gases in this solvent are available. This empirical plot was based on the

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