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THE THERMODYNAMICS OF COMBUSTION IN THE OTTO CYCLE ENGINE

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In thermodynamic analyses of the Otto cycle, the combustion process is normally dismissed with the sentence "heat is added at constant volume."

As early as 1906, Hopkinson (reference 1) indicated the thermodynamic nature of the process of combustion by experiments in a closed vessel. In 1934, Lewis and von Elbe (reference 2) took up this work, and showed very conclusively the nature of "constant-volume" combustion in a closed vessel. There has been rather a widespread feeling, however, that the combustion process in an engine might be essentially different from that in a bomb because of the part played by turbulence in spreading the flame.

Recent experiments by Rassweiler and Withrow (reference 3) indicate what might have been predicted from previously available evidence, i.e., the essential similarity of the combustion process in engines and enclosed vessels. Turbulence is, of course, extremely effective in equalizing any existing temperature differences that may momentarily exist in the cylinder but, since the rate of flame propagation depends on the transfer of heat from the burned to the unburned gas, turbulence is equally effective in increasing the flame velocity.

The evidence presented by Rassweiler and Withrow indicates a temperature difference existing in the cylinder immediately after combustion of about 600° F. The nature of the measurement leads one to believe that the actual temperature difference is somewhat greater than the measured difference because of

a) the use of a stroboscopic method with a phenomenon that does not repeat exactly,

b) the practical difficulty, with the sodium-line reversal method, of measuring average temperatures at points within a given volume (i.e., the flame front) without including points outside this volume, and

c) the impossibility of getting instantaneous values with the consequent necessity for accepting time averages.

Because of these factors, the experimental values of the temperature difference may be said to represent the lower limit of this quantity. It is quite simple to determine an upper limit by analysis and, in addition, the analytical method clarifies the picture of the process.

In order to represent mathematically any physical phenomenon, certain simplifying assumptions must be made. For the purpose of calculation, we shall make the following assumptions, discussing the degree of approximation to actual conditions later:

(1) The working medium is a perfect gas.

(2) The piston motion during combustion is negligible.

(3) At any instant, the pressure in all parts of the cylinder is the same.

(4) The combustion process requires a finite time.

(5) Heat is added to the working fluid <u>only</u> at the flame front.

(6) The heat transfer within the gas during the combustion process is negligible.*

Assumptions (1), (2), and (3) are the assumptions ordinarily made for perfect gas cycles.

Statement (4) is not an assumption but an observed fact.

Assumptions (5) and (6) are those made by Lewis and von Elbe (reference 2) and are useful for the simplification of the reasoning that follows from the consideration of a finite combustion time.

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*A somewhat similar analysis, but based upon isothermal compression of the burned gases, is given in reference 4.

Let us now consider the "constant-volume" cycle as represented by 1, 2, 3, and 4 in figure 1. Note that the abscissa scale is <u>specific</u> volume (cu. ft. per lb.).

All of the gas in the cylinder is compressed from P_1, V_1 to P_2, V_2 and consequently at point 2 it is at a uniform temperature, T_2. At point 2 ignition occurs at some definite point or points in the cylinder.

Let us now consider what happens to a small volume of gas immediately adjacent to the point of ignition. Since combustion is now considered to occupy a finite time, the medium occupying the small volume in question is <u>free to expand</u> against the unburned gas in the cylinder. If the volume chosen is infinitesimal, it will expand without affecting the general cylinder pressure. Thus heat is added to this small volume at <u>constant pressure</u> and it will expand to point 2' on the diagram (fig. 1). As combustion proceeds, this small volume of gas will be compressed to point 3' (adiabatically since we are assuming no heat interchange). It will then be re-expanded by the motion of the piston to the exhaust pressure.

If we consider now the last part of the charge to burn, we see that it is compressed <u>before combustion</u> to the maximum cyclic pressure at point 2". The heat of combustion then expands it (at <u>constant pressure</u> since it is small compared to the total volume of gas) to point 3" whence it is expanded by the motion of the piston. Similarly, any intermediate small volume of gas will go through a cycle in which heat is added at some intermediate pressure level. Thus we see that the "constant-volume cycle" is really the resultant of the sum of an infinite number of different cycles in each of which heat is added at constant pressure. We also observe that there is a difference in specific volume and, therefore, in temperature from the last part of the charge to burn to the part near the ignition point. In order to indicate the possible magnitude of this temperature difference, it has been calculated for an assumed case where the compression ratio is 5, the inlet conditions are $p_1 = 14.7$, $T_1 = 600°$ F. absolute, $C_v = 0.169$, $C_p = 0.238$. Heat added, 650 B.t.u. per pound of air. (This value was chosen to give approximately the pressures found in practice.) The tabulation below gives the results of the calculation:

Point	P	v	T
2	140	3.02	1140
3	611	3.02	4990
2'	140	10.2	3870
2"	611	1.05	1740
3'	611	2.57	5900
3"	611	2.71	4470

$T_{3'}$ represents the temperature near the spark plug after combustion is complete. $T_{3'}$ is some 1,500° F. higher than $T_{3''}$, the temperature of the last part of the charge to burn at the same instant.

This temperature gradient is the maximum that can exist under the circumstances. The fact that there is heat transfer within the gas during combustion will, of course, reduce the gradient. The gradient will also be reduced by the fact that heat is added not in an infinitesimally thin layer at the flame front but in a layer of finite thickness. The change with temperature of the specific heat of the working fluid will likewise operate to reduce the temperature difference.*

It will be noted that the effect of the change in specific heat and the effect of heat transfer upon the temperature gradient depend upon the existence of such a gradient and are, therefore, second-order effects.

The thickness of the reaction zone and the duration of reaction at a point within the gas has been investigated by several different methods. Withrow, Lovell, and Boyd (reference 5), using a sampling valve, show a maximum value of 17° duration at 1,000 r.p.m. The same investigations in a later publication (reference 6) estimate from flame photographs that the reaction zone is from 3/8 to 1½ inches thick and has a duration of from 3 to 10 crankshaft degrees at 1,000 r.p.m. Marvin (reference 7), measuring the radiation from the flame, estimates 22° duration at 1,000 r.p.m. All of this work is subject to criticism as to its accuracy and it is probable that the estimates show only the order of magnitude of the duration and thickness of the reaction zone. The methods used, however, give

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*A method of calculation, making allowance for the change in specific heat is given in reference 2.

results that are likely to be greater than the actual values. (See discussion, reference 3.) Undoubtedly, operating variables, especially the fuel-air ratio and the turbulence, affect the thickness of the reaction zone. More accurate information is needed on this point before the effect of a finite reaction-zone thickness can be accurately evaluated.

Since all the assumptions for our computation lead to high values and since the experimental values, for reasons outlined above, are low, the temperature difference existing in the cylinder lies between the experimental 600° F. and the theoretical 1,500° F.

In the study of detonation the sodium-line reversal method of measuring temperatures is of little value in indicating even an approximation to the actual condition, since the extremely high local pressure can only exist for a time that is very short compared with the time necessary for making a measurement. Here again, it is possible analytically to establish upper limits on the temperature and pressure.

It is now fairly well accepted that detonation is a rapid reaction in the last part of the charge to burn, probably initiated by compression ignition ahead of the flame front. If the reaction is sufficiently rapid, combustion can no longer be at constant pressure but will approach the conditions of constant volume. In the limiting case of instantaneous combustion of the last part of the charge to burn, the combustion from point 2" at constant volume would cause a local pressure of 1,960 pounds per square inch, with a corresponding temperature of 5,590° F. absolute. Owing to the increase in specific heat and the change in chemical equilibrium at high temperatures as well as to the fact that combustion is never instantaneous, this pressure and temperature will never be reached but they are the limiting values that may not be exceeded under the conditions of our assumption. Although we are dealing with approximations, the temperature of the gas participating in detonation is probably <u>lower</u>, and certainly not very much higher, than the temperature elsewhere in the cylinder. Thus, it cannot be the high temperature alone that causes the destructive effects of detonation but perhaps a combination of extremely high pressures and increased local heat conduction due to the high density of the detonating part of the charge.

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Cambridge, Mass., April 16, 1935.

REFERENCES

1. Hopkinson, B.: Explosions in Gaseous Mixtures and the Specific Heat of the Products. Engineering, vol. 81, 1906, p. 777.

2. Lewis, B., and von Elbe, G.: Determination of the Speed of Flames and the Temperature Distribution in a Spherical Bomb from Time-Pressure Explosion Records. Jour. of Chemical Physics, vol. 2, May 1934, p. 283.

3. Rassweiler, Gerald M., and Withrow, Lloyd: Flame Temperatures Vary with Knock and Combustion-Chamber Position. S.A.E. Jour., vol. 36, no. 4, April 1935, pp. 125-135.

4. Midgely, Thomas, Jr., and Janeway, Robert: The Pressure-Volume-Quantity Indicator-Card. S.A.E. Trans., Part I, 1923, pp. 77-94.

5. Withrow, Lloyd, Lovell, W. G., and Boyd, T. A.: Following Combustion in the Gasoline Engine by Chemical Means. Ind. & Eng. Chem., vol. 22, no. 9, September 1930, pp. 945-951.

6. Withrow, Lloyd, and Boyd, T. A.: Photographic Flame Studies in the Gasoline Engine. Ind. & Eng. Chem., vol. 23, no. 5, May 1931, pp. 539-547.

7. Marvin, Charles F., Jr.: Observations of Flame in an Engine. S.A.E. Jour., vol. 35, no. 5, November 1934, pp. 391-398.

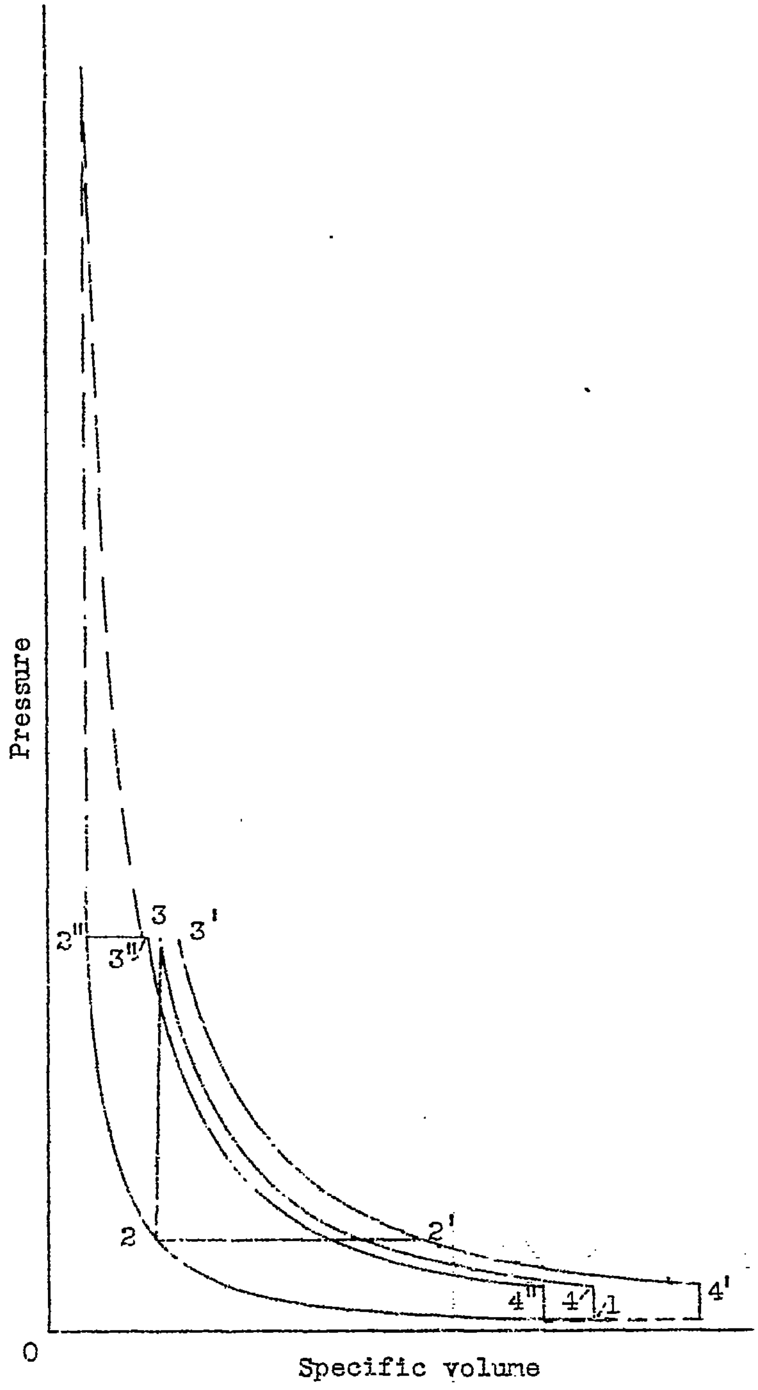

Figure 1.