FLAME TEMPERATURES IN ENGINES

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Thermodynamic analysis of the transformation of chemical energy into mechanical energy in an internal-combustion engine may be carried out in two different ways. In the first and simplest method of analysis, the energy equation is applied directly to the process, without considering any of the various separate transformations; the engine then becomes a concealed mechanism and its performance is determined by the measurement of external effects. These external effects consist of a flow of gas into and out of the engine, and the transfer of energy in the form of heat and mechanical work to the surroundings. Energy is also transported into and out of the engine along with the gas stream. For this process the energy equation becomes

$$M_2h_2 - M_1h_1 = {}_1Q_2 - {}_1W_2$$

where M_1 and M_2 are, respectively, the number of moles of gas entering and leaving the engine, h is the enthalpy per mole of mixture, ${}_1Q_2$ is the heat transferred, and ${}_1W_2$ is the work done. The state of the entering mixture and hence the term M_1h_1 are usually known, and when any two of the remaining terms can be determined independently, the third term can be readily found from this equation. Such an analysis, while completely rigorous, gives rather trivial information about the performance of an engine, and therefore is of little practical value in considering ways and means of improving this performance.

The second method of procedure is to consider separately each of the energy transformations which occur in the engine and then determine engine performance from the net effect of all these transformations. Such a procedure has the advantage of supplying detailed information about the separate transformations, but does so at the expense of difficult and involved analysis. Thus, while the induction, mixing, and compression of the fresh charge presents little or no difficulty, the transformations during combustion and the early portion of expansion can be treated analytically only after the introduction of a number of simplifying assumptions. In addition, detailed information is required concerning the thermal, chemical, and physical properties of the gases which constitute the working medium. The ultimate test of the validity of these assumptions and the accuracy of these data is the precision with which the state of the gases can be determined at certain points throughout the cycle.

The method of analysis which has just been briefly outlined has been used in the study of ideal, or theoretical, cycles (5, 2, 12, 9) and also in analyzing experimental data from actual engine tests (19). However, before making extensive use of the method, it is very desirable to apply some such test as that just mentioned, in order to form an idea of its reliability and precision. The crucial portion of any internal-combustion engine cycle is that during which chemical energy is being transformed into thermal energy by combustion and thence into mechanical energy by expansion of the heated gas; it is needless to add that this is also the most difficult to analyze. The present discussion is chiefly concerned with the determination of the state of the working medium during combustion and the early part of expansion in an engine operating on the Otto cycle.

THE GASES IN AN ENGINE CONSIDERED AS A THERMODYNAMIC SYSTEM

In order to apply thermodynamics to the energy transformations which occur during combustion and expansion in the cylinder of an engine, it is necessary to define exactly the system and the changes of state which are to be considered. The system consists of a mixture of gases, whose state at any instant is completely determined when suitable values can be assigned to the following variables: the total volume, V, the total pressure, P, the temperature, T, and the molal concentrations, c_1, $c_2 . . . . c_n$, of each of the n constituents present. These variables are related by the equation defining concentration as

$$c_i = \frac{m_i}{V}$$

where m_i is the number of moles of constituent i in the gas mixture, and the equation of state for a gas, which may be written

$$P = R \cdot T \, \Sigma c_i$$

Which of these variables are to be regarded as independent depends upon the particular transformation under consideration. Other properties of the system such as its total mass, M, its total energy, E, its total entropy, S, etc., will also be involved, but these are usually dependent variables. The total volume, V, unquestionably should be an independent variable, since it is the only one which is always known without ambiguity. Next, in order of uncertainty, is the total pressure, P, which, if we assume it to be hydrostatic pressure, can be measured with reasonable precision at any instant during the transformation in question. At this point an important assumption must be introduced before further progress in the discussion is possible.

If definite meaning is to be attached to the temperature and concentrations, it is necessary to assume that the system is homogeneous, all components being in the gaseous phase and the properties either uniform or else varying continuously throughout the region. Therefore the system must either be in thermal and chemical equilibrium and the temperature and concentrations uniform throughout, or else it must be possible to assign to these variables average or effective values, with which are associated values for the total pressure, mass, energy, entropy, etc., which agree with the true values of these dependent variables within satisfactory limits. Such experimental investigations as those of Withrow, Lovell, and Boyd (23), Spanogle and Buckley (21), Erichsen (3), and Rassweiler and Withrow (16) indicate very definitely that the concentrations and temperature are not uniform throughout the gases in an engine cylinder, at least during combustion and the early portion of expansion. Whether or not it is permissible to use average or effective values for the concentrations and temperatures is a problem which will be reserved for later discussion.

Certainly the conclusion is unassailable that, if the application of rigorous thermodynamic analysis to the combustion process can not be accomplished without detailed consideration of temperature and concentration variations, the problem becomes exceedingly difficult. It is true that such analyses as those of Nägel (15), Flamm and Mache (4), Midgley (14), and Rosecrans (18), which take into account the variation of temperature and composition in a gas mixture during combustion, are reasonably satisfactory when applied to combustion in closed spherical or cylindrical vessels. But the oversimplification of the combustion process, which these analyses entail, makes them inadequate when considering the more complicated process of combustion in the cylinder of an engine. For here the volume is very irregular in shape and changing with time, the gases are in turbulent motion, and heat loss to the walls is an important factor. The photographic investigations of Rassweiler and Withrow (17) and of Rothrock (20) furnish convincing evidence of the complexity of the motion of the burned and unburned gas during combustion in an engine, and indicate that a rigorous analysis would probably involve hydrodynamics, with turbulent motion and heat conduction, as well as thermodynamics. Herzfeld (11) has analyzed the combustion and expansion processes in a very complete manner, including the effects of turbulence and heat transfer, but this analysis, even though extremely involved, still requires numerous questionable simplifying assumptions, for which it is difficult to find experimental verification.

An experimental investigation of gas temperature in the cylinder of an engine was undertaken at the University of Illinois in order to supply definite information with regard to such questions as those which have been mentioned above. The procedure has been to measure the gas temperatures at a series of points in the cycle during combustion and the first part of expansion, and to compare these observed values with values calculated by the method presented by Goodenough and Felbeck (6). Since the results of this investigation have been published previously (10), they will be very briefly reviewed in the present discussion, and attention will be given principally to their interpretation in the light of more recent investigations.

MEASUREMENT OF GAS TEMPERATURES IN AN ENGINE

The various methods of measuring gas temperature in an engine have been given detailed consideration in a previous paper (8). Therefore it is only necessary to state that, as a result of such consideration, the spectral-line-reversal method appears to be the only one which may be used satisfactorily to determine these temperatures. The chief advantages of this method, in addition to its simplicity, are the extremely small size and wide dispersion of the thermometric bodies, the radiating atoms, as well as the substantial amount of experimental information which is available regarding the precision and limitations of the method. Erichsen (3) has recently used a spectroscopic method of temperature measurement, in connection with an investigation of combustion in a Diesel engine, for which he claims certain advantages over the line-reversal method. However, the method depends upon the emission of a continuous spectrum of pure temperature radiation which, as the investigations of Withrow and Rassweiler (24) have clearly demonstrated, is not the case in an engine operating on an Otto cycle.

The comparison of the maximum combustion temperature found from line-reversal measurements with those obtained by calculation for a wide range of air–fuel ratios shows rather unsatisfactory agreement (10). Throughout the normal operating range of air–fuel ratios of between 12 to 1 and 15 to 1 the calculated values are approximately 600°F. higher than the measured values, and with both richer and leaner mixtures the difference increases, reaching a maximum of 1000°F. at the lean combustion limit. In order to determine, if possible, the cause of this disagreement, it is advisable to consider some of the different factors which may affect both measured and calculated temperature values.

The factors affecting the measured temperature may be divided into two groups as follows: (*a*) Experimental errors inherent in the method of temperature measurement:—non-thermal excitation of radiation from the sodium atoms; absence of thermal equilibrium between the gases and the sodium atoms; cooling effect of the sodium solution entering with the fresh charge. (*b*) Experimental errors in the method as applied to engine temperature measurements:—deposit or film on the cylinder windows; finite time of stroboscopic shutter opening.

The separate effects of the various sources of error listed above under (*a*) have been considered in previous publications (10, 8) and, on the basis of the results of numerous investigations of the temperature of stationary flames, the conclusion was reached that the combined effect of these errors could not result in such differences as those found between measured and calculated temperatures. A similar conclusion resulted for the sources of error listed under (b) above. Brevoort (1) has recently made a comprehensive study of the effect of fogging of the cylinder windows on line-reversal temperature measurements, and has found that the deposit which accumulates on the window in 200 min. may raise the apparent temperature by more than 550°F. In the measurements discussed above, however, it was found that mounting the windows flush with the cylinder wall reduced fogging to such an extent that no appreciable error resulted if a lamp-temperature calibration was made immediately after each test.

Therefore it becomes necessary to examine critically the method of calculating the temperatures, for factors which might contribute to the difference between the measured and calculated values. Here again two distinct sources of error exist: (a) Inaccuracies in the method:—incorrect thermal and chemical data for the gases under consideration; disregard of certain dissociation products. (*b*) Departure of operating conditions from assumed conditions for temperature calculations:—absence of thermal and chemical equilibrium in the gases; departure from adiabatic, constant-volume combustion; temperature gradients in the gases.

The temperature calculations were originally carried out with the specific heat and equilibrium data of Goodenough and Felbeck (6), which were based on the results of calorimetric and chemical experiments. Much more accurate and reliable data, based on spectroscopic experiments, are now available (12, 13). However, the recalculation of some of the temperatures, on the basis of these new thermal data, leaves them practically unchanged. This is due to some rather fortuitous compensating errors in the Goodenough and Felbeck data, which result in nearly the same energy at high temperatures for the two principal constituents, water vapor and carbon dioxide, with either set of specific heat data. Failure to consider the dissociation of H_2O into neutral OH, in the original calculations, was found to lead to temperatures which are about 150°F. too high, but disregarding dissociation into monatomic gases and the formation of oxides of nitrogen had little effect.

The real crux of the matter would appear to be the absence of either thermal or chemical equilibrium. The only satisfactory evidence that the gases are in some kind of stable state is the fact that it is possible to produce a reversal of the spectral line. Whenever there is an insufficient amount of sodium being excited, the dark or reversed line can not be made to appear. Such a condition exists when there is insufficient sodium present in the gases, or when, as during the early part of combustion, only a small amount of the sodium actually present is being excited. When either of these conditions obtains, accurate temperature measurements are impossible. This does not mean that the temperature is uniform throughout the region whenever reversal can be observed; but the reproductibility of the measurements is evidence of the establishment of a definite effective thermal stage in the gases, which exists, with only slight variations, at the same point in numerous successive cycles. von Elbe and Lewis (22) have considered the problem of the thermal equilibrium following combustion in closed vessels, and have suggested that a delay in the distribution of energy over the molecular vibrational degrees of freedom would serve to explain some of the observed phenomena. However, if the sodium atoms are excited by collisions with the heated gas molecules, such an explanation would require that the measured temperatures be higher than the temperatures calculated, assuming complete equilibrium. Kühl (12) discusses briefly the effect of chemical reaction rate on the attainment of chemical equilibrium during combustion in an engine, but advances no experimental evidence, his conclusions being largely speculative.

There remains for consideration the influence of heat loss and temperature gradient on the measured temperatures. In calculating the temperatures the effect of both of these factors was disregarded, but they must certainly influence the measured temperatures. From the temperature measurements of Rassweiler and Withrow (16) it is possible to estimate the magnitude of the temperature gradients which may exist in the gases in an engine cylinder, while from the results of Griffiths and Awberry (7) for reversal measurements with several flames at different temperatures, the effect of temperature gradient on these measurements may be estimated. On this basis it would seem reasonable to add a temperature gradient correction of from 150° to 200°F. to the measured temperatures. Such a correction, together with the lowering of the calculated temperatures by a similar amount, owing to dissociation to form OH, would leave a difference of some 300°F. between measured and calculated temperatures over the normal range of air–fuel ratios. From the results of calculations of heat loss, which were presented in an earlier publication (10), this would not appear to be an excessive temperature drop to be attributed to heat loss during combustion.

SUMMARY

After considering the most likely factors which may influence the measurement and calculation of gas temperatures in an engine during combustion and expansion, there appears to be reasonable agreement between measured and calculated results if (*1*) temperatures are measured by means of the line-reversal method with suitable corrections for the effect of temperature gradients in the gases, and (*2*) temperatures are calculated on the basis of thermodynamic analysis, assuming thermal and chemical equilibrium, including the effects of variable specific heat of the gases and dissociation, based on the most recent thermal and chemical data, and correcting for heat loss during combustion.

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