SOME NOTES ON THE FLAME STRUCTURE
OF A HOMOGENEOUS MIXTURE

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1. The applied theory of combustion of gases has recently been making slow but steady progress from the qualitative interpretation of individual phenomena to a quantitative analysis of the process, though admittedly only in the simplest cases. The difficulties are well known, being principally the complexity of the turbulent-flow and combustion calculations [1] and the lack of effective ("global" [2]) kinetic constants. These two obstacles to the full utilization of the results of modern combustion theory must be removed by combining experiment with computer calculations.

The present article is concerned with the aerodynamic structure of a homogeneous jet flame. A full solution of the problem would have to be found by making a numerical analysis of the two-dimensional (plane or axisymmetric) flame on the basis of the Navier-Stokes equations, whether rigorous in the laminar case or supplemented by empirical data in the case of a turbulent flow. In these equations it would be necessary to take into account one of the semiempirical turbulent transport mechanisms that have been proved reliable in jet and flame calculations and suitably selected constants characterizing the overall kinetics of the combustion reactions. Examples of this kind and a detailed procedure for numerically solving the elliptic equations with allowance for the combustion process in the presence of a finite reaction rate are given, for example, in [3].

It is desirable, without resorting to such a complex procedure, to consider in a preliminary way the qualitative aspects of the process and to investigate the possibility of a developed analysis and interpretation of the experimental results on the basis of simple physical considerations. This would also be useful because the numerical solutions in question must inevitably be based on a detailed experimental investigation of the turbulent flame. Specifically, we shall be concerned with the effect, detected a relatively long time ago by a number of authors (see, for example,[4, 5] etc.), of acceleration of the gas as the free turbulent flame of a homogeneous mixture crosses the combustion zone. It is strange but to some extent significant that at the recent Third All-Union Symposium on Combustion and Explosion in connection with a paper on the numerical analysis of a laminar flame [6] certain doubts were expressed with regard to the validity of the approximate isobaric flow mechanism (calculations within the framework of boundary layer theory) and in connection with a paper on the experimental investigation of a turbulent flame [7] with regard to the possibility of acceleration of the gas in a supposedly constant-pressure field. The latter observation is probably related with the widely accepted theory of turbulent jets used as a basis for the analysis of gas jet combustion.

In his well-known monograph on applied gas dynamics [8] G. N. Abramovich* remarks on the constancy of the pressure and velocity in the combustion zone of the flame of a homogeneous mixture. However, there is no serious basis for the unconditional extension to a homogeneous flame of the approximation $p \approx \text{const}$ valid for jets and the diffusion flame. In fact, in the flame a sort of struggle takes place between two opposing tendencies: jet expansion and deceleration of the flow and a local pressure drop in the combustion zone. As a result the gas velocity passes through a maximum and the pressure through a minimum. In particular, when a homogeneous mixture burns in an open turbulent flame, and this is confirmed by direct measurements (including flow visualization experiments, for example, in [9]; for a laminar flame see [10]), across the combustion zone the gas velocity increases by a factor of approximately 1.5 or more and then

* These remarks are missing from the latest 1968 edition.
falls in connection with the general deceleration of the jet. We note that, in principle, the aerodynamic structures of the laminar and averaged turbulent flames are the same, although there are sharp quantitative differences. Both cases are characterized by nonuniformity of the pressure field in the combustion zone and, as a consequence, local acceleration of the gas. The difference in the structures of the plane and axisymmetric free flames is only quantitative—in the former the acceleration of the gas and the pressure drop are more strongly expressed.

2. The streamlines, isotherms, and isobars in the normal and inverted stationary flames of a homogeneous fuel mixture are shown schematically in Fig. 1. For simplicity jet effects at the outer edges of the flame, where it mixes with the ambient medium, have been neglected. In connection with the turbulent flame in Fig. 1 and subsequent figures we have shown the streamlines and other characteristic curves for the average flow. We shall dwell briefly on the experimental origin of diagrams of this kind. The streamlines can be obtained by flow visualization using light particles (for the averaged turbulent flow appropriate statistical averaging is necessary) or by means of pneumatic probes that indicate the direction of the average flow. If the flow visualization method is employed for measuring the magnitude and direction of the velocity, then the information obtained is quite sufficient for a closed calculation. When only the direction of the streamlines or only the magnitude of the dynamic pressure $p u^2$ is determined with a probe, then for the purposes of a calculation corresponding to the model shown in Fig. 1 it is also necessary to measure the temperature (for example, with a thermocouple; for quantitative data on the $p u^2$, $\Delta T$, and $p$ fields for a turbulent flame see, for example, [7]).

The relations between the variables along one of the stream filaments are the most simple. We refer all the variables to the values at the nozzle exit:

$$
\bar{p} = \frac{\bar{p}}{\bar{p}_0}; \quad \bar{p} = \frac{\bar{p}}{\bar{p}_0}; \quad \bar{u} = \frac{\bar{u}}{\bar{u}_0}; \quad \bar{T} = \frac{\bar{T}}{\bar{T}_0},
$$

and so on for the density, pressure, gas velocity, cross-sectional area of the stream tube, etc. (all the notation is standard); henceforth we shall omit the bar over the relative variables. Then, in nondimensional form we obtain

$$
\rho u f = 1; \quad \rho = \rho T \approx 1; \quad \frac{dp}{\Delta T} = -\frac{\gamma M_0^2}{u} \frac{du}{f(u)}.
$$

Here all the variables are functions of the coordinate $s$ reckoned along the streamline; for the central tube $s = x$. From the measured values of $u$ and $f$ (flow visualization) we immediately find $\rho$ and then $T \approx 1/\rho$ (since $\Delta p/\rho \ll 1$); next, integrating, we calculate the pressure drop:

$$
\Delta p = -\gamma M_0^2 \frac{u}{f(u)} \frac{du}{f(u)}.
$$

We note that here we have made an additional assumption: friction losses (viscous and turbulent) have been disregarded. For a narrow central stream tube in the region of almost constant parameters this is perfectly permissible; as one moves away from the flame axis into the region of appreciable velocity gradients, the error associated with neglecting friction (and the weak centrifugal effect created by the curvature of the streamlines) increases. All this can be taken into account in a numerical two-dimensional calculation, but from the qualitative standpoint the consequences are not so important. If $f$ and $T$ are measured, we calculate $\rho \approx 1/T$ and then $u$ and so on.

Finally, when $\rho u^2$ and $T$ are measured, we successively calculate $\rho$, $T$, and $u$, then $f$, and, finally, $\Delta p$. This, experimentally the simplest case for a turbulent flame, involves certain errors owing to the difference between the mean of the products of two or more quantities and the product of the means (see below).