# MIXING PROCESS IN A FREE TURBULENT FLARE IN A JET

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The authors have made a comparative investigation of variation in diffusion coefficient in a free turbulent flare in a jet of methane. An analysis is made of the reason for the differences and their relationship with the speed of the mixing process as a whole.

In the analysis of different kinds of flows in which combustion processes occur, one of the most important questions is the determination of the turbulent-diffusion coefficient. From the papers dealing with mixture of gases of various densities [1, 2], one can expect that local variations in density, for example, in a diffusive flare, can generate peculiarities in the distribution of transport coefficients.

In this paper experimental measurements are used as a basis for analysis of the behavior of the diffusion coefficient in a cold jet and in a free diffusing flare of methane.

The equation for the diffusion coefficient (D) can be obtained by integrating the conservation equations for an inert mixture and the continuity equation. If, following [3], we introduce the concept of a stream tube of radius $r_s$, so that $\int_0^{r_s}\rho u y dy = \text{const}$, then the expression for the diffusion coefficient takes the form

$$\frac{D}{u_0 d} = \frac{\rho_0}{\rho} \frac{\dfrac{\partial}{\partial \bar{x}} \displaystyle\int_0^{\bar{r}_s} \frac{\rho u c}{(\rho u c)_0} \bar{y}\, d\bar{y}}{\bar{r}_s \left[ \dfrac{\partial}{\partial \bar{y}} (c/c_0) \right]_{\bar{y}=\bar{r}_s}}, \tag{1}$$

where $\rho$, u, c are the density, velocity, and concentration of the inert mixture, and $\bar{y} = y/d$, $\bar{x} = x/d$, $\bar{r}_s = r/d$.

On the jet axis this expression transforms into the simpler expression

$$\frac{D_m}{u_0 d} = \frac{u_m/u_0 \dfrac{\partial}{\partial \bar{x}} (c_m/c_0)}{2 \left[ \dfrac{\partial^2}{\partial \bar{y}^2} (c/c_0) \right]_{y \to 0}}. \tag{2}$$

The authors have investigated two situations, a diffusing turbulent flare and a free jet of methane. In both cases flow of pure methane (99%) passed through a conical nozzle of diameter 5 mm, at a speed of 20.5 m/sec (Re = $6.6 \cdot 10^3$), into a rectangular chamber in which a parallel jet (or flare) moved with the jet with small velocity (0.6 m/sec). This effect was used to insure stability with regard to external perturbations in combustion of the diffusing flare. However, the speed of the secondary air flow remained so small that the flow of the jet and air can be regarded in practice as free, particularly because the restriction of the flow by the chamber walls had no appreciable influence (the total excess air coefficient in the chamber is ~35).

In the jet and flare measurements were made of temperature, concentration of matter, dynamic pressure, and, in a number of cases, turbulent intensity.

The temperature was measured with a platinum – platinum/rhodium thermocouple of wire diameter 0.12 mm, coated with a film of silica [4] to avoid catalytic effects.

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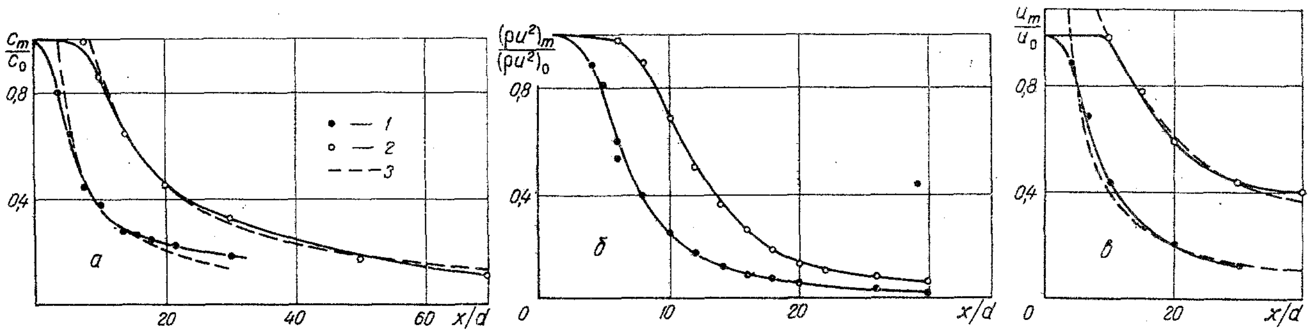


Fig. 1. Variation of: a) mixture concentration $c_m/c_0$; b) dynamic head $(\rho u^2)_m/(\rho u^2)_0$; and c) velocity $u_m/u_0$ along the axis of a jet and of a diffusion flare of methane: 1) jet; 2) flare; 3) approximate curves.

Removal of gaseous samples, and also measurements of dynamic pressure, were performed using a quartz probe [5], connected either to a micromanometer, or to a gas chromatograph, to determine the content of CO, $CO_2$, $H_2$, $CH_4$, $N_2$, $O_2$ in the sample. The supercritical pressure drop at the probe nose insured rapid "freezing" of chemical reactions in the sample withdrawn. In the tests two methods were used to determine the concentration of inert mixture. In the first case the mixture concentration of the jet was calculated from the nitrogen content of the sample, and in the second case from the carbon dioxide contained in the CO, $CH_4$, $CO_2$ components. Comparison of the methods showed that they gave the same results to within an accuracy of ~10%.

In a number of experiments the diffusion method was used to measure the turbulent intensity in transverse sections and along the flare axis. The use of the diffusion method ordinarily presumes the presence of a homogeneous turbulent field [6], and therefore its use in unmodified form for jet flows requires comment. The fact is that any point of an axisymmetric jet flow can be regarded in a plane normal to the ambient radius as a point of an almost isotropic flow [6], since in this plane, at the point of intersection of the plane and the radius, the shear stress is zero, because of symmetry of the wake behind the source. On this basis one can use the ordinary relations of the diffusion method in a small neighborhood near the point considered, to determine the turbulent intensity. It should be noted that there have been attempts to use the diffusion method to determine the diffusion coefficients in jets [7].

In the experiments with the diffusion measurements the source used was a steel tube of diameter 0.7 mm, through which carbon dioxide was supplied with a speed of 2 m/sec. The sampling section was located at a distance of 2 mm above the source exit. The corrections to the mean square deviation due to the source not being a point, were determined following calibration of the source–sampler system along the axis of an immersed air jet, where the turbulent intensity (for $x/d = 20$ $\varepsilon = 20\%$) and, therefore, the mean square deviation were known [6].

We now turn to the experimental results, taken to determine the concentration fields of the inert mixture, the velocity and density, thus determining the diffusion coefficient, in a jet and flare of methane. Examples of the distribution of inert mixture, dynamic head, and velocity along the axis of a flare and a jet are given in Fig. 1a, b, and c. A comparison of the distribution shown indicates that the mixing process in a cold jet proceeds more rapidly in comparison with the process in a diffusion flare. In this respect the drop in inert mixture concentration along the axis of the jet or flare is particularly convincing, and the combustion process should not affect the distribution. A similar tendency is seen in the distribution of dynamic head and of velocity along the jet axis.

The example of distribution of velocity, mixture concentration, and temperature in the radial direction for two transverse cross sections of a flare ($x/d = 20$ and 30) is shown in Fig. 2. The data presented, besides giving information required to calculate the diffusion coefficient, determine the location of the flame front and again stress the well-known fact that in the region of the front the combustion temperature is considerably lower than the adiabatic temperature, which is $T_c/T_0 = 7.15$ for the given conditions. The temperature fluctuations near the flame front, as recorded by the thermocouple, turn out to be very substantial ($\Delta T/T = 150°C$), and the temperatures presented in Fig. 2 are mean values.

Reduction of the measured results yields the following approximate relations for variation of velocity and mixture concentration along the axis and for concentration profile in a region of developed flow for the flare and jet:

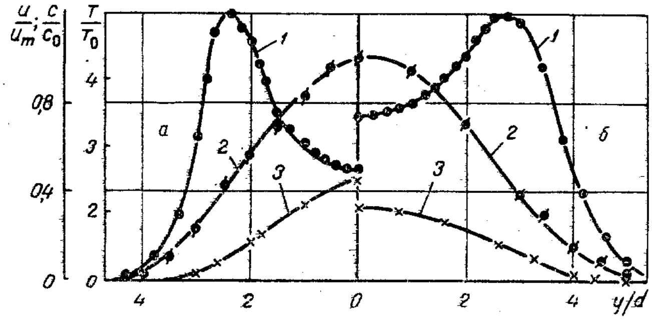


Fig. 2. Distribution of parameters in transverse cross sections of a flare: a) x / d = 20; b) 30; 1) T / $T_0$; 2) u / $u_m$; 3) c / $c_0$.

for the flare

$$\frac{u_m}{u_0} = \frac{4,9}{(x/d)^{0.7}}, \quad \frac{c_m}{c_0} = \frac{9.4}{x/d}, \quad \frac{c}{c_m} = \exp\left\{-96\left(\frac{y}{x}\right)^2\right\}, \tag{3}$$

for the jet

$$\frac{u_m}{u_0} = \frac{4.0}{(x/d)}, \quad \frac{c_m}{c_0} = \frac{3.9}{(x/d)}, \quad \frac{c}{c_m} = \exp\left\{-54\left(\frac{y}{x}\right)^2\right\}.^* \tag{4}$$

The corresponding curves are shown as broken lines in Fig. 1.

These approximations, Eqs. (3) and (4), were used to calculate dimensionless fusion coefficients along the axis of the jet and flare at certain distance from distance $D_m / u_0 d$ from the nozzle exit. The results are shown in Table 1. It can be seen from the data presented that, firstly, the diffusion coefficient on the jet axis in the flow region examined (for x / d > 10) is less than the value in the flare. Secondly, the diffusion coefficient on the flare axis increases slightly along the length, while that in the jet remains practically constant. It should be noted that a similar result was obtained in [8] in analysis of mixing processes in a jet and flare of municipal gas.

The diffusion coefficient does not itself determine the speed of the mixing process. From this viewpoint it is evidently more correct to deal with the value of the group $D_m / u_m d$, which is the ratio proportional to the product of the diffusion coefficient and the dwell time, and, for instance, uniquely determines the speed of the mixing process for the case of isotropic turbulence. In fact, as calculation shows, the value of $D_m / u_m d$ for a flare and jet increases linearly along the length, but the absolute value of this ratio

*The shape of the concentration profile in the cold jet is reminiscent of that in [8].

TABLE 1. Variation of Diffusion Coefficient and Turbulence Scale along Axis of Jet or Flare

| Jet, flare | x/d 10 | 20 | 30 | 40 |
|---|---|---|---|---|
| $\frac{D_m}{u_0 d}$ — jet | 0,0173 | 0,0176 | 0,0178 | 0,0178 |
| $\frac{D_m}{u_0 d}$ — flare | 0,0255 | 0,0303 | 0,0340 | 0,0373 |
| $\frac{D_m}{u_m d}$ — jet | 0,031 | 0,092 | 0,153 | — |
| $\frac{D_m}{u_m d}$ — flare | 0,025 | 0,05 | 0,075 | 0,093 |
| $\frac{l_m}{d}$ — jet | 0,235 | 0,41 | 0,88 | — |
| $\frac{l_m}{d}$ — flare | 0,22 | 0,386 | 0,37 | — |

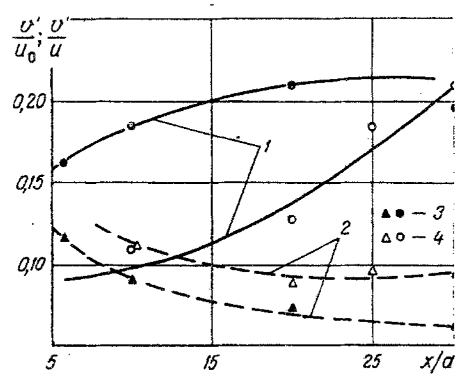


Fig. 3

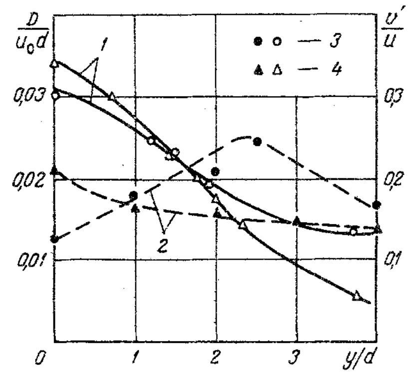


Fig. 4

Fig. 3. Distribution of turbulent intensity and velocity fluctuations along the axis of a flare and jet of methane: 1) $\varepsilon = v'/u$; 2) $v'/u_0$; 3) jet; 4) flare.

Fig. 4. Radial distribution of diffusion coefficient and turbulence intensity in a flare: 1) $D/u_0 d$; 2) $\varepsilon = v'/u$; 3) $x/d = 20$; 4) 30.

in a jet is everywhere larger than in a flare (see Table 1), in accordance with the general picture of mixing. Thus, the combustion process does not violate the general laws of mixing in a hot flare. The numerical differences in the diffusion coefficients arise evidently from the differences in the density fields, which results in a flare and jet formerly similar in initial parameters not in fact being similar. One can consider the dynamic analog of a flare in [9] to be a jet of gas propagating in a medium of combustion products.

Analysis of the physical reasons for the difference in diffusion-coefficient values in a jet and flare is rather a complex problem, associated, firstly, with the need for measurement of turbulence characteristics in reacting flows. For the basic section of a jet and flare flow such measurements have been attempted using the diffusion method. Figure 3 shows results of measurement of turbulence intensity and velocity fluctuations along the axis of a free jet and flare. We can see that the turbulence intensity is greater in the free jet, while the dimensionless velocity fluctuations are at least larger in the flare, at least for $x/d > 10$.

We note that similar data on turbulence intensity were obtained using a static pressure probe [10] in a flame of municipal gas.

If the diffusion coefficient takes the form of the product of the velocity fluctuations $v'$ and the scale $l$, then $D/u_0 d = (v'/v_0)(l/d)$, and from measurement of D and $v'$ one can determine the scale (see Table 1).

From comparison of the data presented and the data of Fig. 3 one can see that, at least for the region $x/d = 10$–$20$, the scale values for the flare and jet remain roughly the same, while the diffusion coefficients are different. Therefore, the conclusion can evidently be drawn that the diffusion coefficient on the axis in a developed flow region is determined to a large extent by the level of velocity fluctuations.

The diffusion coefficient and the turbulence intensity were measured in two transverse cross sections of a gas flare ($x/d = 20, 30$). Results of these measurements are shown in Fig. 4, where it can be seen that the diffusion coefficient in a transverse section is not constant and decreases strongly towards the edge of the flare. We note also that the presence of a flame front located at the point $y/d = 2.5$ for the cross section $x/d = 20$ and $y/d = 2.9$ for the section $x/d = 30$ (see Fig. 2), does not show a visible influence on the radial distribution of diffusion coefficient in a turbulent flare. The presence of a weak maximum in the distribution of turbulence intensity at section $x/d = 20$ evidently demonstrates the nonsimilar nature of the flow at these lengths. An estimate of the turbulence scale from the data presented indicates that in the greater part of the jet ($0 < y/d < 3$) it remains practically constant ($l/d = 0.355$–$0.38$) and increases sharply only at the edge of the jet for $y/d > 4.0$. Thus, the nature of the radial distribution of diffusion coefficient is evidently a further indication again connected to a large extent with the distribution of velocity fluctuations.

From the measured results presented one can evidently consider that the distribution of diffusion coefficient in a flare is mainly determined by the distribution of local velocity fluctuations and to a lesser extent by the scale.

## NOTATION

u, v are the velocity components;
$\rho$ is the density;
c is the concentration;
D is the diffusion coefficient;
d is the nozzle diameter;
x, y are the rectangular coordinates;
$r_s$ is the radius of stream tube;
$l$ is the scale of turbulence;
$v'$ is the fluctuating velocity;
$\varepsilon$ is the turbulence intensity;
Re is the Reynolds number.

### Subscripts

m denotes the parameters on the flare axis;
0 denotes the parameters at the nozzle exit.

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