Estimation of the characteristic chemical time scale in a flame by the PIV

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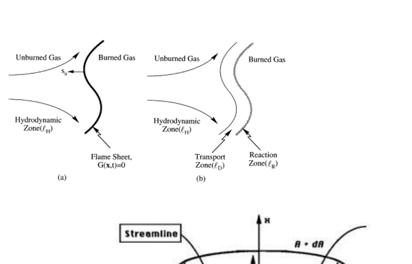
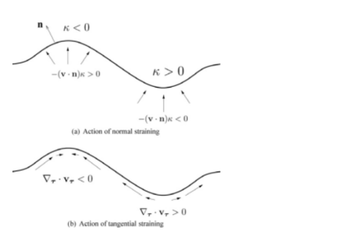
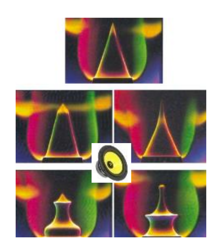
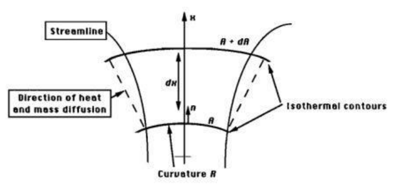
Deceleration of Darrieus-Landau instability.









the Markstein mechanism hydrodynamic stability Darrieus-Landau instability

$$\mathbb{K} = \frac{1}{A}\frac{dA}{dt} = \nabla[\vec{n}\times(\vec{v}_s\times\vec{n})] + (\vec{U}\cdot\vec{n})(\nabla\cdot\vec{n})$$

Zeldovich – Barrenblatt hypotheses (result the Euler equation calculation)

The gas flow near the flame front on both sides of the front obeys the Euler equation and the continuity equation

$$\frac{\partial\vec{U}}{\partial t} + (\vec{U}\nabla)\vec{U} = -\frac{1}{\rho}\nabla P \qquad div\vec{U} = 0 \qquad U_f \equiv \frac{\int_{-\infty}^{+\infty}\dot{\omega}(\vec{n}\cdot d\vec{x})}{\rho Y_R} \qquad \dot{\omega} = \rho Y_R{}^n Y_{O_2}{}^m A T^b exp\left(-\frac{E}{RT}\right)$$

Looking for the perturbation increment: ω ($\sigma=\rho_0/\rho_{burn}$)

Landau (1944): $U_f = U_0 \quad l_f = 0 \qquad P_0' - P_{burn}' = 0$

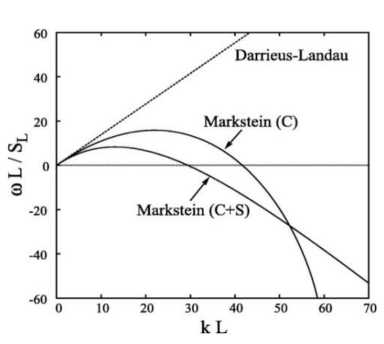
$$\left(\frac{\omega}{\sigma k u_n^0}\right)^2 + \frac{2}{1+\sigma}\cdot\frac{\omega}{\sigma k u_n^0} + \frac{1-\sigma}{\sigma(1+\sigma)} = 0 \qquad \omega = -\frac{\sigma k u_0}{\sigma+1}\left(1 \pm \sqrt{\frac{\sigma^2+\sigma-1}{\sigma}}\right) \neq 0$$

Zeldovich – Barrenblatt result the Euler equation calculation (1960) $\quad P_0' - P_{burn}' \neq 0$

$$l_f = {}^{\chi}/_{U_0} \qquad P_0' - P_{burn}' = -2\rho_1(u_0)^2(\sigma-1)\mu\frac{\partial^2 x_f}{\partial y^2}$$

$$U_f = U_0\left(1+\frac{L_m}{R_f}\right) \qquad \left(\frac{\omega}{\sigma k u_n^0}\right)^2 + \frac{2}{1+\sigma}\cdot(1+\mu k)\frac{\omega}{\sigma k u_n^0} + \frac{2k\sigma\mu + 1 - \sigma}{\sigma(1+\sigma)} = 0$$

$$Ze = \frac{E(T_{max}-T_0)}{RT_{max}^2} \qquad \omega = -\frac{\sigma k u_0}{\sigma+1}\left(1 + L_m k \pm \sqrt{\frac{\sigma^2+\sigma-1}{\sigma} + L_m k(L_m k - 2\sigma)}\right) = 0$$



$$L_m = \left[l_f\frac{D}{\chi}\right]_{ThDiff} + \left[l_f\frac{(\chi-D)}{\chi}\frac{Ze}{2}\right]_{ThChem}$$

$$L_m = \left[l_f\frac{D}{\chi}\right] = l_f \quad \leftarrow Le_s = \frac{D}{\chi} = 1$$

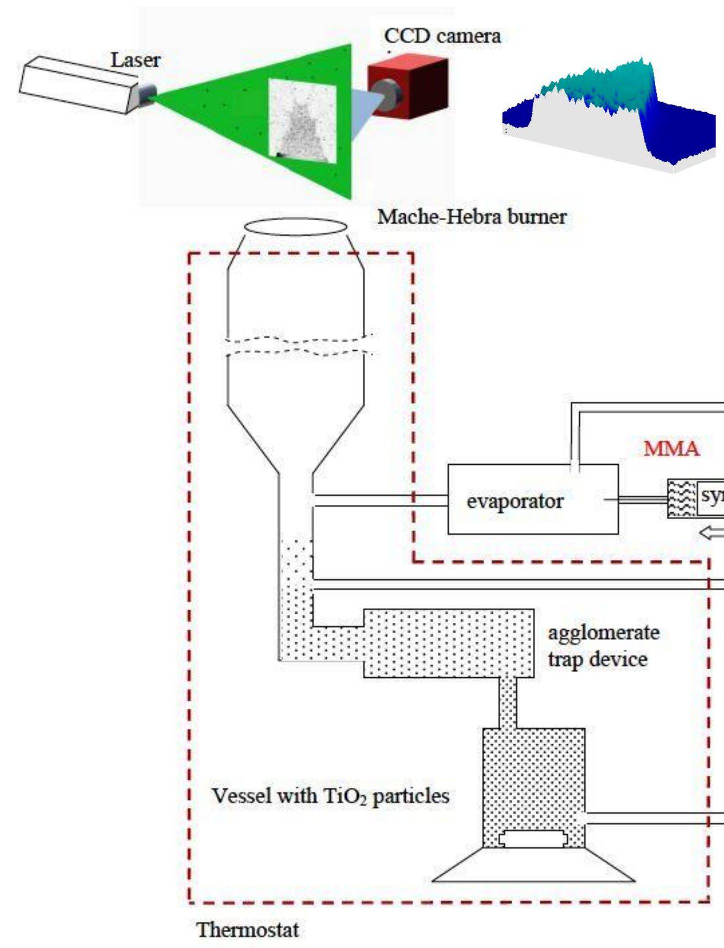
$$\tau_{chem} = \tau_{chM} = {}^{L_m}/_{U_0}$$

Ya B. Zeldovich, G. I. Barenblatt, V. B. Librovich, G. M. Makhviladze, The Mathematical Theory of Combustion and Explosions, Consult. Bureau, 1985

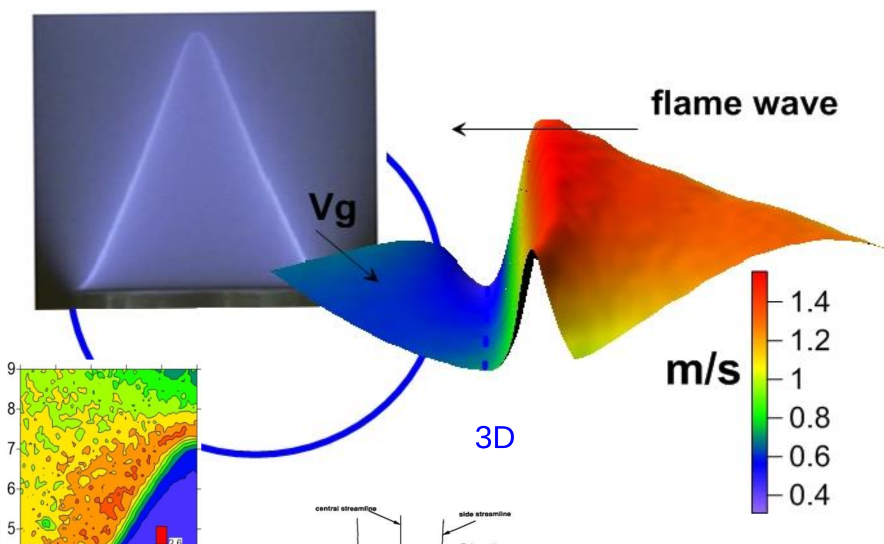
F. Creta , M. Matalon, Strain rate effects on the nonlinear development of hydrodynamically unstable flames, Proceedings of the Combustion Institute Volume 33, Issue 1, 2011, Pages 1087-1094

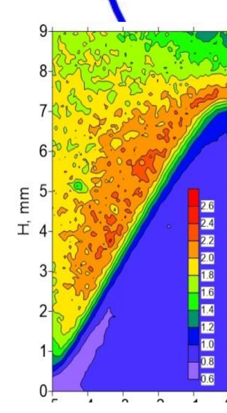
Experimental visualization of the combustion wave . Method PIV.

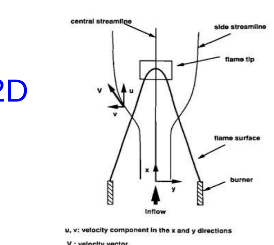
Normal burning velocity of the Fuel/air flame was determined by extrapolating the dependence of the local burning velocity on the local curvature of the flame front to the zero curvature



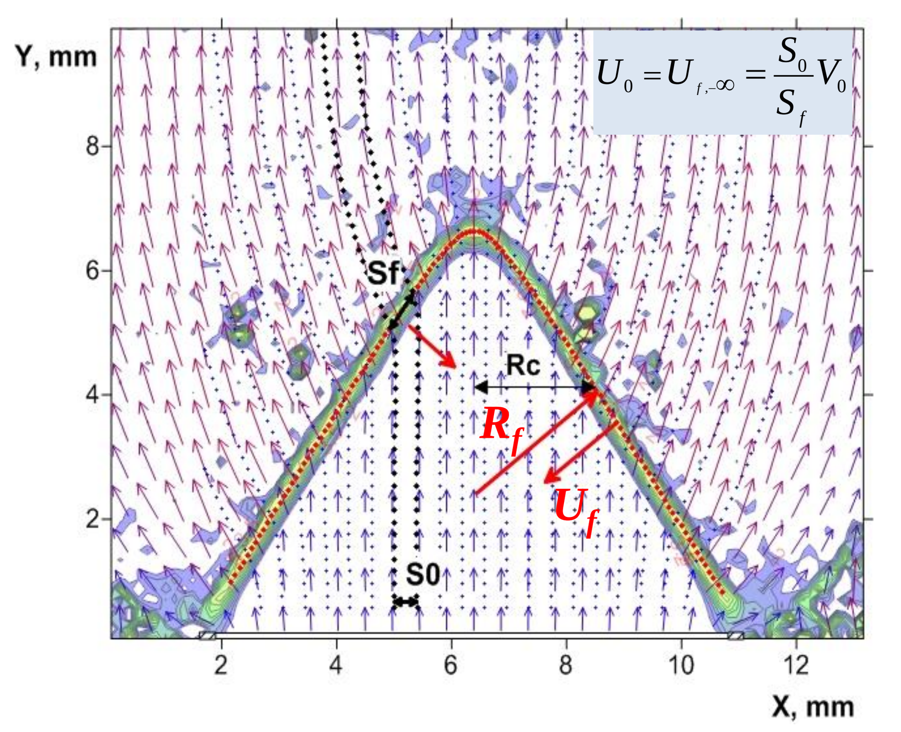
- two pulsed Nd:YAG lasers
- pulse duration 5 ns
- CCD camera 1360×1024
- Pixel sieze ~9x9 μm

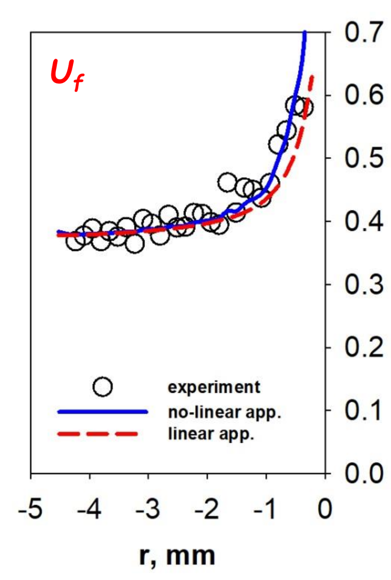






$$U_f \equiv \frac{\int_{-\infty}^{+\infty}\dot{\omega}(\vec{n}\cdot d\vec{x})}{\rho Y_R}$$





Dependence of local U_f on the radius of curvature R_f

- - - Linear theory Zeldovich, Clavin, Matalon....

$$U_f = U_0\left(1+\frac{L_{CCML}}{R_f}\right)$$

— Non-linear theory Law, Sung.....

$$U_f = \frac{U_0}{\left(1-\frac{L_{CCML}}{R_f}\right)} = U_0\left(1+\frac{L_{CCML}}{R_f}\right)\left(\frac{1}{1-\left(\frac{L_{CCML}}{R_f}\right)^2}\right)$$

Gas stream tubes. To determine the geometric parameters of stream tubes, the experimental data were processed as follows. The discrete points obtained experimentally by PIV were used to construct a two-dimensional velocity field by cubic spline interpolation:

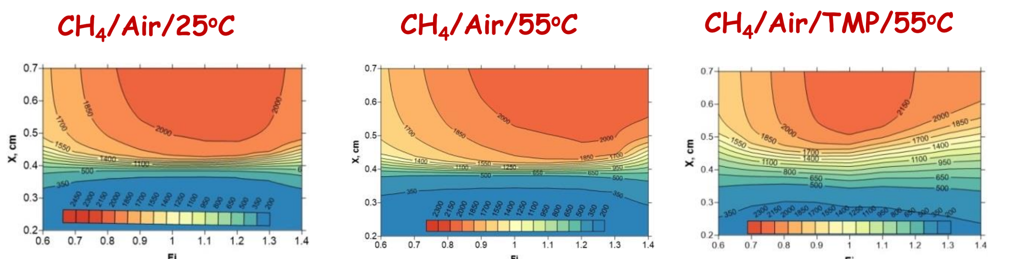
$$\{Vx_i, Vy_i, (X_i, Y_i)\} \to Vx(x,y), Vy(x,y) \qquad (1)$$

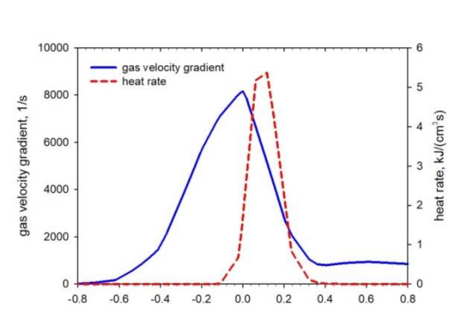
Streamlines are obtained by numerically integrating the equations:

$$\frac{\partial y}{Vy(x,y)} = \frac{\partial x}{Vx(x,y)} \mid y(x=x_0) = y_0 \qquad (2)$$

1D-CHEMKIN model flame thickness

Temperature dependence on X and equivalence ratio





Total thickness flame:

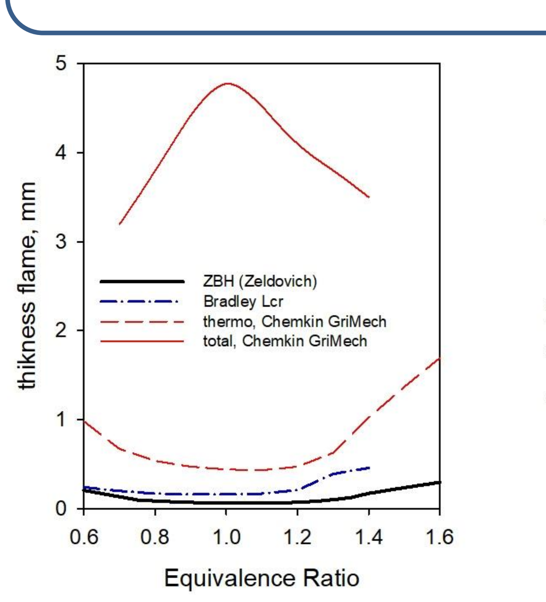
$$l_f = [1.01\cdot T_0, 0.99\cdot T_{max}]$$

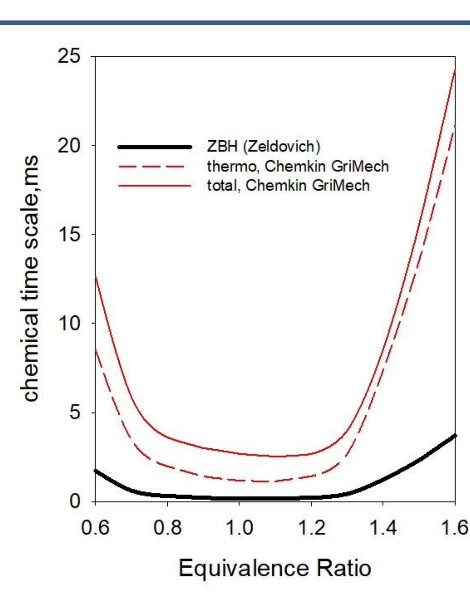
Thermal thickness flame:

$$l_f = l_{th} = (T_{max} - T_0)/(\partial T/\partial x)_{max}$$

ZBH thickness flame and chemical time scale (Zeldovich et al.) :

$$l_f = {}^{\chi}/_{U_0}, [mm] \qquad \tau_{chem} = \frac{\left({}^{\chi}/_{U_0}\right)}{U_0}, [s]$$





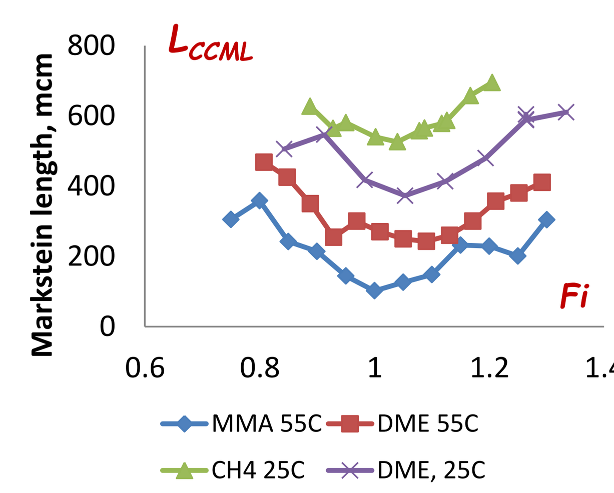
Experimental results

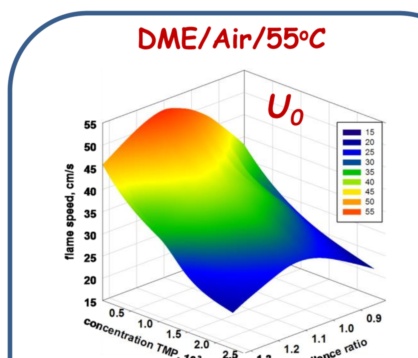
Experimental result measurements consumption curvature Markstein - Zeldovich – Barrenblatt length L_{CCML} and chemical time scale $\tau = L_{CCML}/U_0$

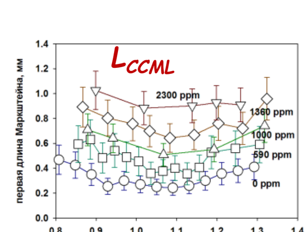
Fuel:
- CH4 – methane
- DME – dimethyl ether
- MMA – methyl methacrylate

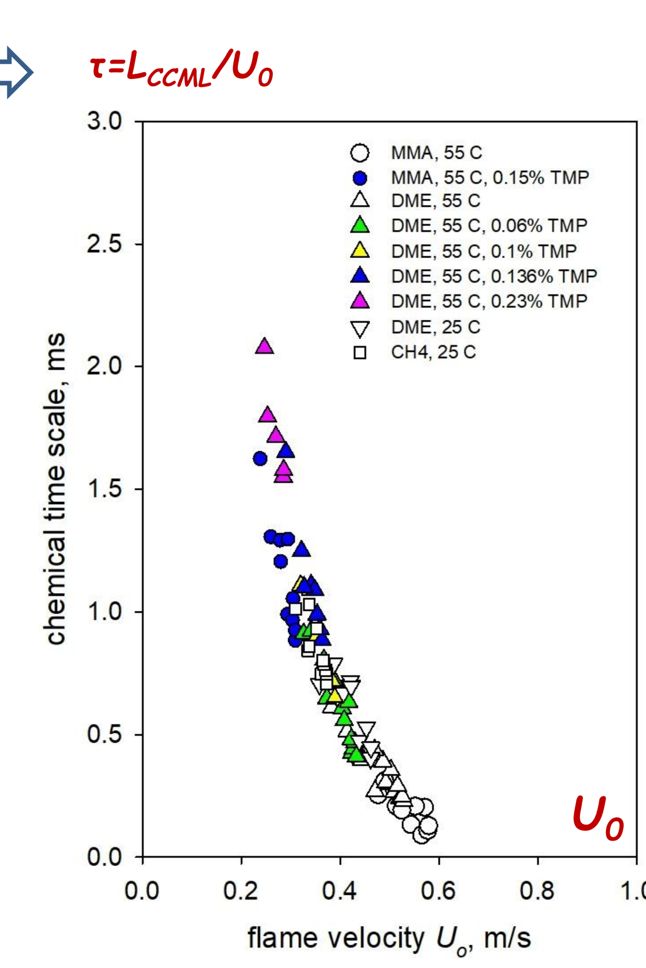
Inhibitor:
- TMP – trimethyl phosphate

Experiment conditions:
- Fuel/Air flame
- P=1 atm
- t=25 and 55 °C





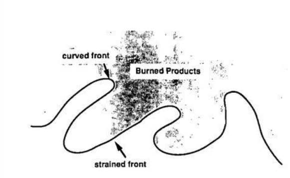




Industrial combustion

Zimont correlation has been used for many engineering problems for 20 years and is used by default in the ANSYS Fluent software

The turbulent combustion velocity, U_t - function of the physico - chemical properties of combustible mixture and turbulence parameters:

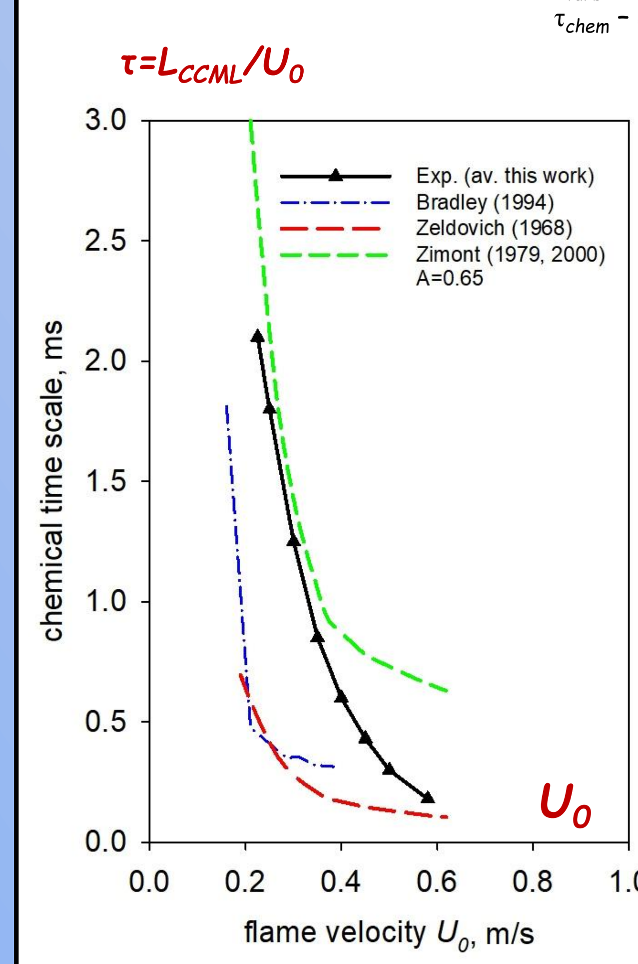


$$\frac{\partial}{\partial t}(\rho c) + \nabla\cdot(\rho\vec{v}c) = \nabla\left(\frac{\mu_T}{Sc_T}\nabla c\right) + \rho S_{chem}$$

$$\rho S_{chem} = \rho_0 U_T \nabla(1 - [Fuel]/[Fuel_0])$$

Zimont correlation, (1979, 2000): $\quad U_T \approx u_{RMS} \times \left(\frac{\tau_{turb}}{\tau_{chem}}\right)^{1/4}$

u_{RMS} – RMS (root-mean-square) velocity
τ_{turb} – turbulence time scale (s)
τ_{chem} – chemical time scale (s)



$$\tau_{chem} = \left(\frac{1}{A}\right)^4 \frac{\left({}^{\chi}/_{U_0}\right)}{U_0}, [s]$$

$(A = 0.5 \div 1.2)$

Here, a new experimental method is presented to obtain data for fine calculations of turbulent combustion.

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