Experimental and Theoretical Studies of the Influence of Initial Turbulence on Premixed Methane-Air Flame in Turbulent Flows

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Introduction

Flame propagation process in turbulent gas-air mixtures still requires extensive research. Such combustion has numerous practical applications. Explosions of gas mixtures which can occur in various branches of industry could also be pointed out as a typical example of the turbulent combustion.

In order to get to know better the turbulent combustion mechanism, it had been necessary to carry out basic research enabling comparatively simple control of main parameters characteristic for turbulent flow, i.e. flow velocity, turbulence intensity and scale.

The aim of the research presented below was to get to know the influence of the flow velocity, root mean square velocity (RMS), turbulence scale and inflammable mixture composition on the turbulent burning velocity for homogeneous mixtures and for homogeneous mixtures and for aerosoles.

Research Stand and Measuring Methods

In order to fulfil the intended research program a special stand was designed and constructed, enabling studies of flame development and propagation in gaseous, hybrid and dust mixtures at different flow velocities and different turbulences.

The scheme of the research stand is given in Fig. 1. Radial fan -1, with controlled rotation, forces the air flow inside the tube. The vertical section of the tube (of 190 mm internal diameter and of 2150 mm of length) was used to produced the turbulent flow of gas-air, hybrid or dust-air mixtures. The flow velocity of the above mixtures was stable and could be regulated in the range of $2.5 \div 10$ m/s.

Turbulence close to isotropic one was generated by means of grids. The grids were fixed inside the tube at various distance from the tube end. The distance

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depends on the grid geometry and was chosen so that the turbulence near the tube end was close to that of isotropic one. Inflammable gaseous mixture was made by supplying methane from a steel bottle into an air stream inside the diffuser -3, through a set of electromagnetic valves EV1 ÷ EV4.

The ignition source of the mixture was a single electric spark. The ignition was initiated in a free stream of the mixture at the tube outlet. It was also possible to ignite the mixture inside the tube at the distance of 190 mm. from the outlet cross-section. The detailed description of the research stand was given in [1].

Results of the Research

Before starting actual research, the measurements were made of turbulence in air stream at various distances from the tube end, for various grids and flow velocities. For that purpose velocity profiles and RMS at chosen flow cross-section were measured. Five flow velocities (measured in the flow axis) in the range of 2.5-10 m/s were taken under consideration.

.It was found that the most isotropic turbulence in open flow was obtained for the stream of diameter equal to ~100 mm and for the distance from the tube end not bigger than two tube diameters. The rapid turbulence increase can be noticed close to the free stream border.

The investigation into combustion process of a turbulized gas mixture showed, that the turbulent burning velocities increases along with an increase of RMS and turbulence scale of the mixture and with an increase of fuel concentration. Fig. 2 shows the flame propagation in a confined turbulent flow of gas-air mixture. The obtained pictures show not only the flame shape but also the flame structure. Small scale vortices can be observe inside the flame [2].

It can be noticed, that turbulent burning velocity increases along with an increase of RMS, turbulence scale and fuel concentration.

Theoretical modelling

Two distinct theoretical approaches have been used for modelling 2-D turbulent flame, namely, the Eddy-Dissipation (ED) model [3], and the Joint Velocity-Composition Probability Density Function (JVC-PDF) method [4]. The ED model is based on the assumption that the combustion process in turbulent flow is primarily controlled by turbulent transport processes rather than by chemical reaction kinetics. It is widely used for simulating turbulent combustion in various applications. The principal disadvantage of the ED model is that it can not be applied to slow chemical processes (e.g. for fuel lean or reach mixtures, etc.).

Contrary to the ED model, the JVC-PDF method incorporates the effect of chemical kinetics in turbulent flame. Therefore, this method is capable of predicting various critical phenomena in turbulent flame evolution caused by competition between turbulent transport and chemical processes. However, the dimensionality of the joint velocity-composition PDF is very large for practical systems, which constitutes the principal disadvantage of the JVC-PDF method. For overtaking this problem, overall reaction mechanisms of methane oxidation have been used in numerical calculations.

Results of calculations

1) Eddy-Dissipation Model

The mean reaction rate in the ED model is defined as

$$R_{fu} = \frac{C_{fu}}{\tau_r}\rho \min\left(m_{fu}, \frac{m_{ox}}{S}, \frac{C_p m_p}{1+s} \right) \qquad (1)$$

where C_{fu} and C_p are the empirical coefficients (in our calculations $C_{fu} = 20$ $C_p = 0.5$), τ_r is a characteristic time scale for turbulence controlled combustion ($\tau_r \approx k/\varepsilon$, k is the characteristic turbulent kinetic energy, ε is the characteristic dissipation rate), the "minimum" operator is used for determining the limiting specie concentration (either fuel m_{fu}, oxygen m_{ox}, or combustion products m_p) with S being the stoichiometric oxygen requirement.

Ignition has been modelled by adding a prescribed amount of energy to the gas in a certain location over a certain period of time.

Variation of grids in the experiments is modelled theoretically by means of changing the characteristic turbulent kinetic energy and the turbulent length scale l_t. Both parameters effect the τ_r value, $\tau_r \approx l_t k^{-1/2}$.

The ED model is also sensitive to the variation of the initial mixture composition. The latter is taken into account by the value given by the "minimum" operator in Eq. (1).

The calculations revealed different models of flame propagation depending on grid parameters and initial mixture composition. At low values of k, large values of l_t, and for fuel lean (rich) mixtures flame ball separation phenomenon has been observed in calculations (Fig. 3). Satisfactory agreement with experimental results has been pointed out.

2) Joint Velocity-Component PDF Method

In the JVC-PDF method, the chemical process can be calculated, without any approximation. A reasonably short overall reaction mechanism of methane oxidation has been used.

The JVC-PDF method has been applied for studying near critical regimes of flame propagation. Flame extinction in lean and rich mixtures has been detected in numerical calculations under conditions correlating with experimental observations.

The temperature isolines after ignition are shown in Fig. 4. The comparison of theoretical and experimental results is presented in Fig. 5.

Conclusions

1. Turbulent burning velocity in gas-air mixtures increases along with an increase of flow turbulence (RMS) and for lean mixtures - with an increase of fuel concentration.
2. Turbulent burning velocity increases also with an increase of turbulence scale, but

this influence seems to be smaller than the RMS one.

3. The numerical calculations results show the good agreement with the experiments.

Acknowledgements

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List of figures:

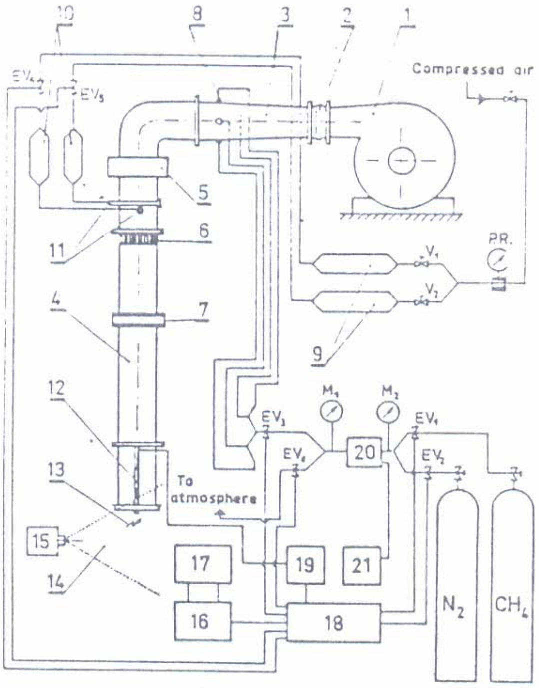

Fig. 1. Scheme of the research stand. 1 - ventilator, 2 - rubber joint, 3 - diffuser, 4 - tube, 5, 6 - turbulence stifle systems, 7 - grid, 8 - methane injectors, 9 - compressed-air tanks, 10 - dust containers, 11 - dust injectors, 12 - spark igniter, 13 - ignition point, 14 - measurement area, 15 - camera, 16 - camera driving system, 17 - operating system of the camera, 18 - delay block, 19 - high voltage spark generator, 20 - flow meter, 21 - multimeter;

EV - electromagnetic valve,

M - manometer;

PR - pressure reducer, V - valve.

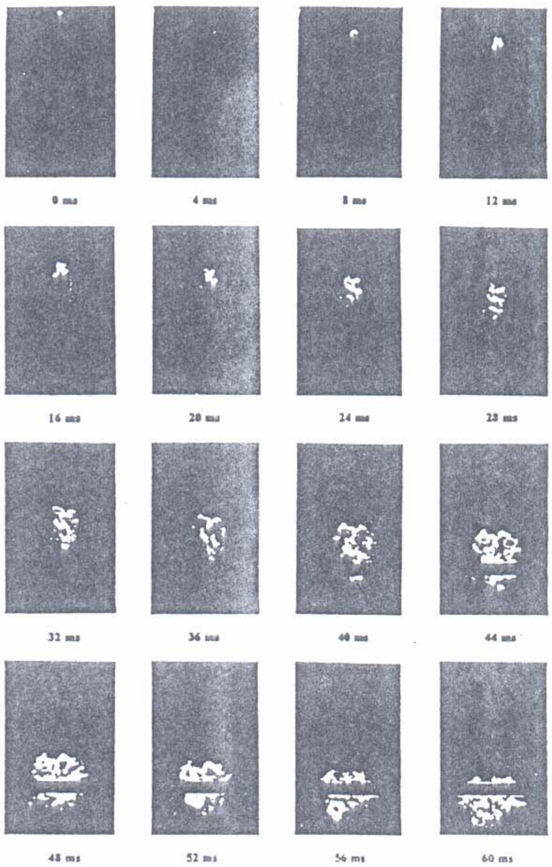

Fig. 2. Flame propagation in a confined, turbulent flow of methane-air mixture. Ignition inside the tube, $CH_4 \approx 5.5\%$, $v = 2.7\ m/s$.

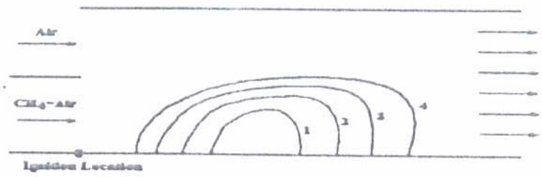

Fig. 3. Flame ball separation predicted by ED model. Curves represent temperature isolines: 1- T=2200 K, 2- T=1600 K, 3- T =1000 K, 4 -T=400 K.

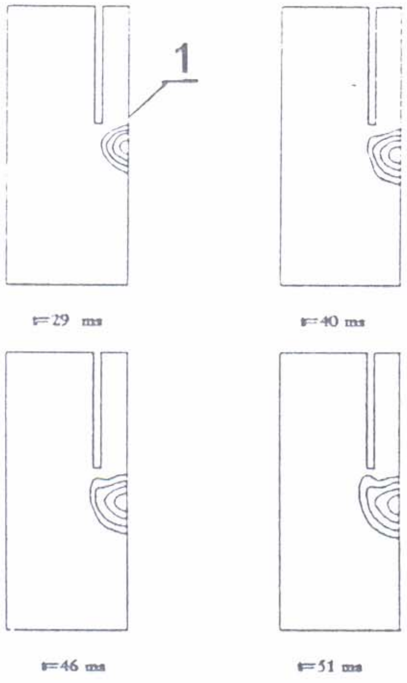

Fig. 4. Temperature isolines after ignition.
Methane-air mixture, equivalence ratio
equal to 0.58, v=2.7 m/s, RMS=0.1 m/s,
turbulence scale = 4.8 mm
1 - ignition point

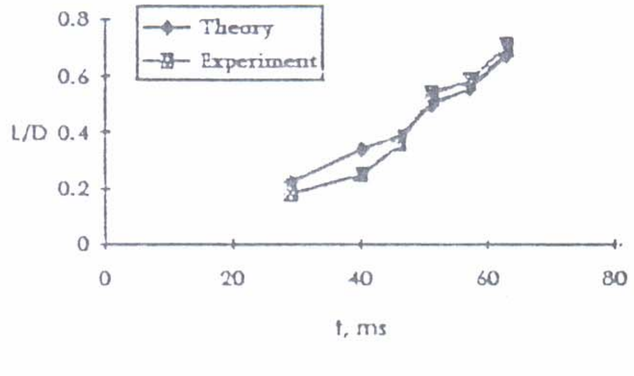

Fig. 5. The dependence of the distance L travelled by the flame kernel vs time (D is the tube diameter).