Flame-Jet Ignition of Fuel-Air Mixtures. Experimental Findings and Modeling

Mayinger F.[a)], Jordan M.[a)], Zaslonko I.S.[b)], Karpov V. P.[b)] and Frolov S. M.[b)]

[a)]Technische Universitat Munchen, Lehrstuhl A fur Thermodynamik, Germany

[b)] N.N. Semenov Institute of Chemical Physics, 4, Kosigin str., Moscow 117944, Russia

e-mail: zaslonko@center.chph.ras.ru

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Objectives

The aim of the study is to provide experimental and theoretical grounds for better understanding flame-jet ignition of fuel-air mixtures, studied elsewhere [1-8]. Several experimental facilities are employed (small-, middle- and large scale) to reveal the effect of scale on the phenomenon. Various measuring techniques are used (high-speed Schlieren cinematography and self-emission detection, pressure histories, LDV, ionization probes, LIF of OH radicals) for obtaining a scope of data on physical and chemical variables involved. A hierarchy of theoretical models is developed (from simple zero-dimensional to multi-dimensional) and applied for getting better insight into the processes.

Experimental

All experimental facilities consist of two chambers separated by a partition with a single circular orifice of diameter d. Total volumes of the facilities are $1.6 \cdot 10^{-4}$, $3.75 \cdot 10^{-4}$, and 1.53 m^3. Hydrogen-, methane-, and propane-air mixtures are investigated. Fuel-air mixture in the first chamber is ignited by a spark plug. Ignition-induced flame propagates in the first chamber and, due to pressure raise, a jet of fresh mixture followed by combustion products emerges through the orifice into the second chamber. Depending on the experimental conditions and the orifice diameter, the mixture in the second chamber is either ignited or not. Ignition can occur due to transmission of turbulent flame through the orifice (at relatively large d), or due to combustion revival after a certain time delay between flame quenching in the orifice and flame re-ignition in the turbulent jet of combustion products.

Figure 1 shows the dependence of the flame re-ignition delay on the orifice diameter, as well as the pressure difference between the chambers, measured in a small-scale facility [5] by ionization current and pressure detection techniques. The facility consisted of a cylindrical main chamber (100 mm in diameter, 20 mm in height), and a pre-chamber 4 cm^3 in volume filled by propane–air mixture. Fuel-air (F/A) ratio in the pre-chamber is 1.67 and in the

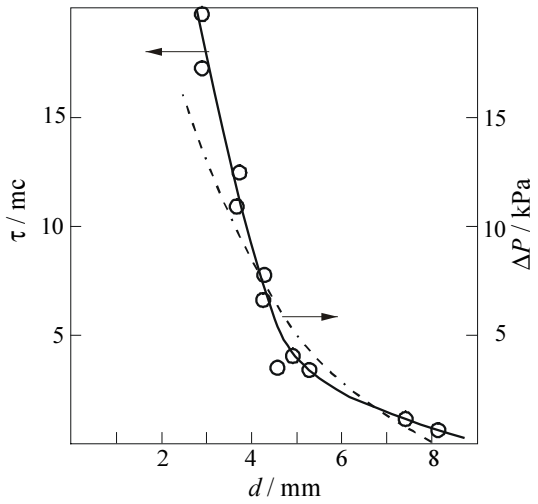

Figure 1

main chamber 0.62. Initial pressure 150 kPa, temperature 293 K. It is found, that there exists a critical orifice diameter such that ignition in the main chamber fails to occur. The critical diameter depends on mixture composition in the main chamber (F/A ratio ranged from 0.6 to 1.0), initial pressure (from 0.1 to 4.0 bar), and N_2/O_2 ratio (from 2 to 6). Fan-induced turbulence in the main chamber also contributes to the jet-flame ignition: when turbulence intensity exceeds a certain threshold level, ignition ceases, other conditions being equal.

Middle-scale test facility consists of two chambers 50x50 mm and 100x50 mm, respectively. A large-scale facility is a cylindrical tube 0.677 m in diameter, divided by a partition into two parts (1.05 m and 3.20 m long). Figure 2 shows Schlieren pictures of flame re-ignition in the second chamber of the large-scale facility, initially filled with 12% hydrogen-air mixture at pressure 1 bar, and temperature 300 K (time between frames 0.33 ms). Clearly, flame re-ignites at a certain distance from the orifice and propagates back to the partition. Flame propagation velocity in the second chamber is considerably higher than in the first chamber, which is obviously caused by enhanced turbulence intensity in the former. The flame re-ignition delays are found to be strongly dependent of the orifice diameter, irrespective of the test scale. Many other peculiarities of the phenomenon under variation of mixture composition and orifice diameter were observed.

Modeling

Jet ignition is a sophisticated phenomenon with interplay of chemical kinetics, gas dynamics and mass, momentum, and energy transfer processes. Mathematical models of different complexity may be developed which are capable of representing the phenomenon to a certain level of knowledge. A set of models of jet-ignition is developed, namely (1) a thermal explosion model based on induction time approximation, (2) a detailed kinetic scheme for chemical processes in a jet mixing zone, (3) a gas-dynamic model for non-reactive jet flows, and (4) full-scale model of turbulent flame ignition, propagation, quenching, and re-ignition in connected chambers, based on either reduced or detailed fuel oxidation chemistry.

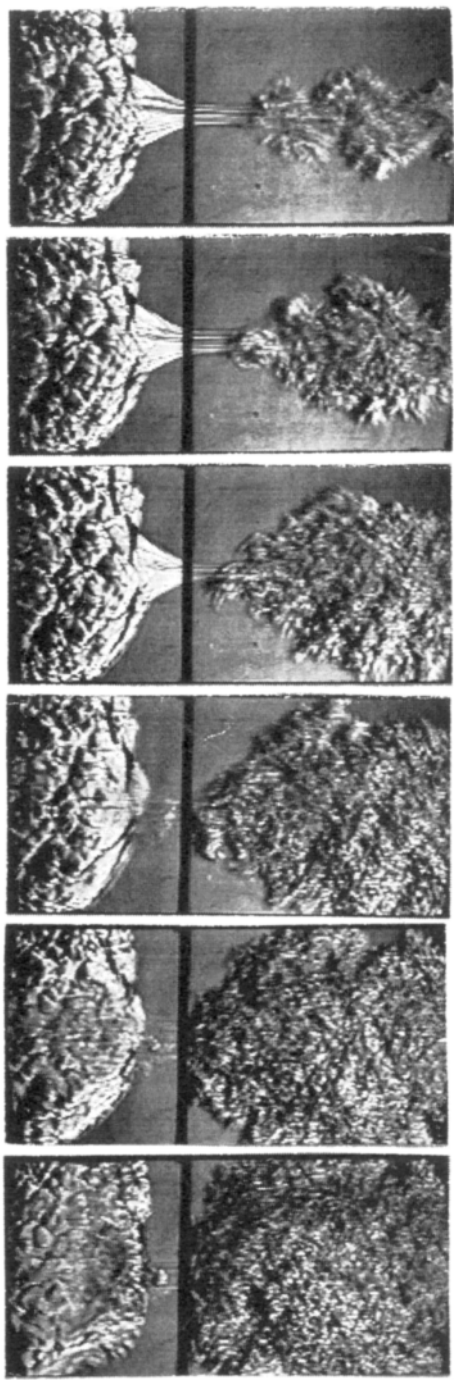

Figure 2

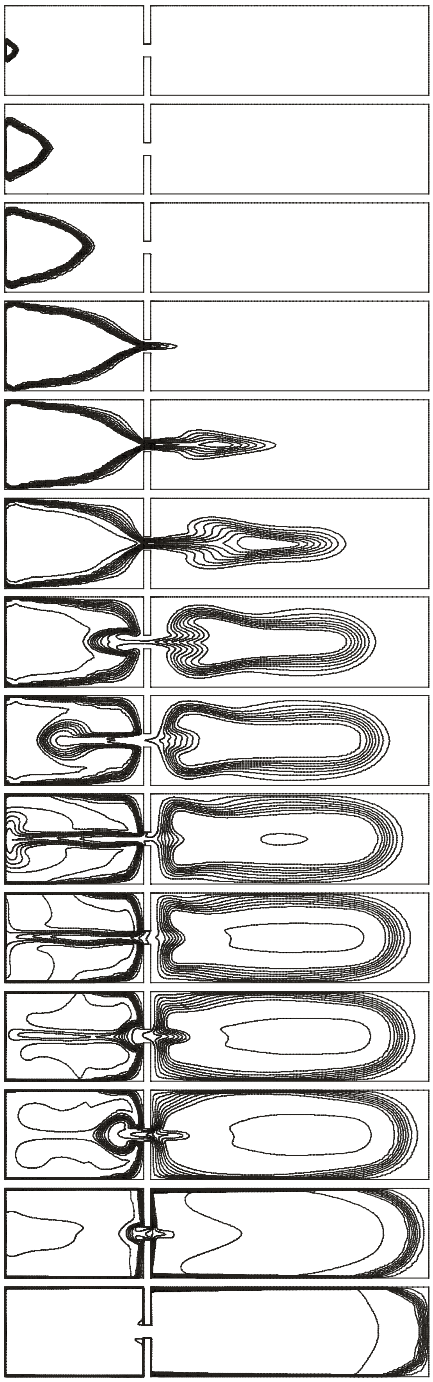

Figure 3

The use of a simple thermal explosion theory allows to qualitatively explain the strong dependence of the flame re-ignition delay on the orifice diameter, observed in test facilities of different scales (see Fig.1). The following correlation is obtained:

$$\tau_{ind} \cdot \propto t_{ia}^2 \cdot \tau_{mix}^{-1} = A \cdot t_{ia}^2 \cdot \alpha^2 / d^n \propto 1/d^n$$

where τ_{mix} is the characteristic mixing time obtained by using available correlations on vortex structure, t_{ia} is the adiabatic ignition delay, n is the exponent ranging from 2.5 to 3.0, α is the F/A ratio, A is constant. This criterion provides a good qualitative agreement with experimental findings.

Figure 3 shows the results of detailed 2D calculations of jet-flame ignition in a large-scale facility filled with stoichiometric methane-air mixture at initial pressure 1 bar and temperature 300 K. Orifice diameter in this simulation is 10 mm. Mathematically, the model is based on the Favre averaged conservation equations of mass, species, momentum and energy, supplemented by the standard k-epsilon model of turbulence and the presumed probability density function method for the mean reaction rate [9]. Detailed reaction mechanism of methane oxidation containing 280 elementary reactions and 35 species is applied [10]. Frames in Fig.3 (from up to down) show isotherms corresponding to the following times (in ms): 6, 20, 32, 44, 48, 52, 58, 62, 68, 72, 76, 80, 100, 160. The isotherms divide the entire temperature interval, from the initial temperature to the combustion temperature into 10 uniform parts. At the fifth frame, flame re-ignition occurs in the second chamber, followed by fast flame propagation towards the partition, as in experiments. In the course of combustion, secondary jets of fresh mixture and combustion products repeatedly emerge to the first and second chambers, as is seen from Fig.3. Severe pressure oscillations are detected in computations, which influence flame propagation and the overall combustion time.

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