Effect of inhibitor addition on the Markstein length in a distorted premixed dimethyl ether/air flame

A A Chernov1,2, A G Shmakov1, O P Korobeinichev1, K V Toropetsky2, V N Moskvin2 and V I Tatarenko2

1 Voevodsky Institute of Chemical Kinetics and Combustion, Siberian Branch RAS
3 Institutskaya str., Novosibirsk, 630090, Russia
2 Siberian State University of Geosystems and Technologies
10 Plakhotnogo str., Novosibirsk, 630032, Russia
chernov@kinetics.nsc.ru

Abstract. The paper presents the results of measuring the propagation velocity and Markstein length of pure and inhibited laminar axisymmetric dimethyl ether/air flames using the PIV method. Their dependence on equivalence ratio and the concentration of inhibitor is studied. Trimethyl phosphate is used as an inhibitor. The measurement results show a strong dependence of the Markstein length on the concentration of the inhibitor. This suggests the use of this parameter as a measure of inhibition effectiveness of turbulent flames.

1. Introduction
The main ideas that led to the modern understanding of the nature of hydrodynamic instability (or Darrieus-Landau instability (DL)) were set out by Darrieus and Landau [1, 2], who considered the flame as a structureless surface separating burned and unburned gases and moving at a constant speed with respect to the gas flow. In subsequent work, Markstein [3] took into account the effects of diffusion, thermal conductivity, and chemical reactions in the flame front on the flame speed by introducing a correction term, which was later called the Markstein length. DL instability affects the surface shape (topology) and speed of laminar and turbulent flames [4, 5]. Nonlinear theory and its numerical simulation show that hydrodynamic instability does not lead to the occurrence of a turbulent flame. Instead, a characteristic topology of the flame surface in the form of bulges and elongated cusps is formed. As the ratio of the Markstein length to the size of the flame region decreases, the curvature of the flame surface increases due to the formation of sharp peaks and a 20%–50% increase in flame speed compared to laminar flat flames [5]. Thus, the Markstein length is related to the local burning velocity and area of the distorted flame; therefore, this parameter becomes a more important indicator of the inhibitor effect on turbulent flames.

This paper presents the results of measuring the dependence of the Markstein length on the addition of inhibitor to a distorted dimethyl ether flame. Dimethyl ether (DME, CH3-O-CH3) is an environmentally friendly fuel derived from natural gas, coal or biomass. Its combustion produces 90% less nitrogen oxides than in the case of pure diesel fuel. In addition, it has a lower soot formation tendency, a high cetane number, and an almost complete absence of exhaust smoke. However, due to the physicochemical properties of dimethyl ether, its use as a fuel requires special fire and explosion safety measures, including the search for effective inhibitors, since unstable reactive peroxide compounds can form in DME/air mixtures exposed to light.
A premixed DME/air flame stabilized on a Bunsen burner with a nozzle diameter of 1 cm was studied by particle image velocimetry (PIV). The setup is shown schematically in Figure 1. A brief overview and experimental results of applying the techniques we use to study the Bunsen cone flame by PIV can be found in [6, 7]. It has been found that measurement errors are primarily due to the limited temporal and spatial resolution of PIV devices and the inertia and catalytic ability of flow tracer particles. Experimental results and theoretical estimates show that the employed method and procedures provide fairly accurate measurements of gas velocity in the flame front, tracer particles at a mass concentration > 0.02% have a slight catalytic effect, and the error in measuring the burning velocity in an optically transparent flame does not exceed 1%.

2. Experimental setup
The experiments were carried out at a temperature of the combustible mixture from 25 to 55 °C and a pressure of 748-753 mm Hg. The volumetric flow rate of the DME/air combustible mixture was selected for the corresponding stoichiometric coefficient so that the height of the flame cone was no more than 9 mm and was within the observation area of the CCD camera. Trimethyl phosphate (TMP) was added to the combustible DME/air mixture using a syringe driven by a stepper motor and an evaporator. For PIV measurements, submicron TiO₂ particles (specific surface area ~3.6 m²/g) were introduced into the air flow at a mass concentration of no more than 0.02%. The length of the tubes supplying gas to the burner was about 1.5 m. The average size of the particles recorded by the PIV optical system at the exit of the burner nozzle was about 600 μm. Particle size and concentration were measured by an AZ-10 diffusion aero-sol spectrometer counter [8, 9].

The system for recording and processing tracer particle image consisted of two pulsed Nd:YAG lasers (wavelength 532 nm, pulse duration 5 ns, pulse energy 45 mJ, beams collimated to the same axis), CCD cameras (1360×1024 pixels, each pixel size 4.65x4.65 μm) with the option of two-frame shooting, a Tamron SP AF 180 mm optical lens (the magnification factor was 0.34, the aperture number was maximal: f# = 32), a synchronizing processor, and a PC with Actual Flow software. The
measurement plane with a laser knife thickness of 100 μm passed through the axis of symmetry of the flow of the combustible mixture. The optical resolution of the system was about 10 μm/pixel. The particle displacement in the interval between a pair of laser flashes (with a time interval of 20 μs) was calculated using an adaptive iterative cross-correlation algorithm with 50% overlapping and continuous displacement of the computational domains in the first and second frames. The cross-correlation image processing method used is described in [10]. The final size of the computational domain from which the particle group velocity was determined corresponded to 32×32 pixels (0.32×0.32 mm). From the measured tracer particle images, 500 instantaneous velocity fields were calculated, which were averaged to minimize the random measurement error. These measurements were used to determine the dependence of the local flame speed on the curvature of the flame front. The normal flame speed was obtained by linear extrapolation of these values to the zero curvature of the flame front. In the linear extrapolation, we used only values that did not undergo additional distortions in the region of the truncated flame cone, in accordance with the recommendations of [11]. The standard deviation was 0.3 (for the doped flame) to 1 cm/sec (for the undoped flame). This is due to a significant change in the transparency of the flame with increasing concentration of the inhibitor additive in the combustible mixture. The procedures for determining the line of the flame front with a maximum gas velocity gradient and its local curvature are based on recommendations from [12–16].

3. Result and discussion
For DME, these procedures were first used in [17]. The obtained data on the dependence of the burning velocity on the TMP additive concentration are in good agreement with the results of numerical simulations based on detailed kinetics and published data [18].

The dependences of the flame speed and the first Markstein length on the stoichiometric coefficient and TMP concentration in the combustible mixture are shown in Figure 2. It can be seen that a small addition of TMP has a significant effect on both the burning velocity and the Markstein length. Moreover, the effect of the addition of TMP on the Markstein length is significantly higher in absolute value than predicted by the Zel'dovich mathematical theory of combustion, but is similar in the nature of the normal flame speed dependence [18]. As this theory predicts, the higher the flame speed, the lower the proportionality coefficient in the dependence of the speed on flame front curvature — the Markstein length.

![Figure 2. Results of measuring the flame propagation speed DME / air (a) and the first Markstein length (b).](image-url)
4. Conclusion
We suggest that the inhibition of the turbulent flame by the addition of TMP involves a threefold effect: a decrease in the normal flame speed, a decrease in the local burning velocity, and a reduction in flame area as a result of a decrease in the number and size of characteristic topologies in the form of bulges and cavities. In this case, it becomes appropriate to use the Markstein length as an indicator of the inhibitor effect in turbulent flames.

References
[1] Darrieus G 1938 La Technique Moderne (Paris)
[2] Landau L 1944 Zh. Eksp. Teor. Fiz. USSR 14(6) 240-244
[3] Markstein G 1964 Non-steady Flame Propagation (New York: Pergamon)
[4] Matalon M and Matkowsky B J 1982 J. Fluid Mech. 124 239–259
[5] Patyal A and Matalon M 2018 Combustion and Flame 195 128–139
[6] Korobeinichev O P, Shmakov A G, Chernov A A, Markovich D M, Dulin V M and Sharaborin D K 2014 Combustion Explosion and Shock Waves 50 510-517
[7] Bolshova T A, Korobeinichev O P, Toropetskii K V, Shmakov A G and Chernov A A 2016 Combustion Explosion and Shock Waves 52 155-166
[8] Dubtsov S, Ovchinnikova T, Valiulin S, Chen X, Manninen H E, Aalto P P and Petaj T T 2017 Journal of Aerosol Science 105 10-23
[9] Onischuk A A, Valiulin S V, Baklanov A M, Moiseenko P P and Mitrochenko V G 2018 Journal of Aerosol Science and Technology 52 841-853
[10] Tokarev M P, Markovich D M and Bilsky A V 2007 J. Comput. Technol. 12 109-131
[11] Fristrom R M 1965 Physics of Fluids 8 273-280
[12] Choi C W and Puri I K 2001 Combust. Flame 126 1640-1654
[13] Cohé C, Chauveau C, Gökalp I and Kurtulus D F 2008 Proc. Comb. Inst. 32 1803-1810
[14] Gao X, Zhang Y, Adusumilli S, Seitzman J, Sun W, Ombrello T and Carter C 2015 Combustion and Flame 162 3914-3924
[15] Tamadonfar P and Gulder O L 2015 Combustion and Flame 162 115-128
[16] Giannakopoulos G K, Gatzoulis A, Frouzakis C E, Matalon M and Tomboulides A G 2015 Combustion and Flame 162 1249-1264
[17] Knyazkov D Alyanova N Bolshova T Chernov A Shvartsberg V Shmakov A 2018 37-th Int. Symp. Comb. Dublin, 29 July - 3 August 2018, Book of abstracts 16657
[18] Knyazkov D A, Bolshova T A, Shvartsberg V M, Gerasimov I E, Shmakov A G and Korobeinichev O P 2019 Proceedings of the Combustion Institute 37 4267-4275
[19] Zeldovich Ya B, Barenblatt G I, Librovich V B and Makhviladze G M 1985 The Mathematical Theory of Combustion and Explosion (Netherlands: Kluwer Academic) p 618