Experimental study of combustion of composite fuel comprising n-decane and aluminum nanoparticles

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A B S T R A C T

The paper addresses the analysis of diffusion combustion of composite preliminary vaporized fuel composed of n-decane with small amount of non-oxidized Al nanoparticles. For the experimental study, the special burner has been developed. The distribution of temperature both along the flame and in the transversal direction has been measured by using CARS diagnostic system. It has been shown that, upon burning of composite fuel with 2.5% Al nanoparticle content (per mass), the temperature both at the near flame axis and near flame front regions has been notably higher (by 300–400 K) than that upon burning of pure n-decane. The possible explanation of this effect has been proposed.

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1. Introduction

For past decades a great interest has been expressed to the combustion of metallic particles in various environments. This interest is due to substantial thermodynamic advantages of metal particle combustion against burning of traditional organic fuels. Metallic particles possess rather high calorific power and high heats of combustion and enable to release large energy per unit volume. Therefore, one of the most promising strategies to improve the combustion of traditional organic fuels and increase the energetic output is the addition of highly energetic metallic compounds to the fuel itself. Analysis, conducted in [1], exhibited that the usage of such composite fuels can notably improve the specific characteristics of gas turbine, ramjet and rocket engines. As was demonstrated, the most promising compounds in this point of view are beryllium, boron, aluminum and their hydrides.

For recent years a few attempts to study the features of combustion of such composite fuels were undertaken [2–7]. So, Jackson et al. [2] revealed that addition of 5% aluminum nanoparticles of 100 nm diameter to the n-dodecane aerosol notably decreases the ignition delay at the initial temperature higher than 1175 K. Latter Allen et al. [3], using the aerosol shock tube technique, found that the addition of

2% aluminum particles with diameter of 50 nm in ethanol shortened the ignition delay by 32%, and for the JP-8 aviation fuel this effect was even more pronounced. Van Devener and Anderson [7] demonstrated the catalytic effect of CeO_2 soluble nanoparticles on the combustion of JP-10 fuel.

It should be emphasized that some researchers proposed to use as additives to hydrocarbons also other metals, such as Zr, Fe, Ti, Li, Mg. However, as it is seen from Fig. 1, which depicts the values of mass specific heat H_u and working capable $\alpha = RT_e$, where R is the gas constant of the combustion products and T_e is the final combustion temperature, the usage of these metals as additives is less promising.

Aluminum is one of the widely spread metals. It is a third most abundant element in the Earth's crust. Due to its high reactivity and relatively large volumetric combustion enthalpy, aluminum is commonly utilized as a fuel ingredient in solid propellants to improve the combustion in rocket engines [8–10]. Although burning of aluminum particles has been long investigated over past decades, the most previous works were concentrated on micron or even larger-sized particles [11–15]. Much less efforts were focused on the studies of the combustion of nano-sized particles, especially when they are used as additives to hydrocarbons.

As it was demonstrated by a number of researches, particle diameter plays a significant role in burning of particles in different oxidizers [16–22], and nanoscale metallic particles offer some significant advantages over micrometer-sized ones. So, they have smaller melting point, lower ignition temperature and higher flame speed [20–25]. For example, nano-sized aluminum particles ignite in air at the temperature of 900 K, whereas the micron-sized particles cannot
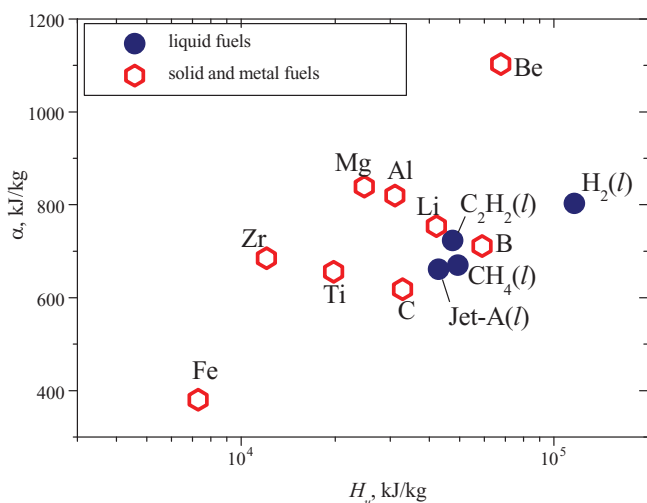
Fig. 1. Characteristics of traditional liquid fuels as well as some solid and metal fuels in α–H_u diagram.

Fig. 2. Histograms of particle size distribution at different residence time before measurement: 0, 495, 660, 1657 s (curves 1–4).

be ignited at the temperature below 2350 K. It is believed that small size non-oxidized nanoparticles undergo the explosion due to fast oxidation of surface layer, and aluminum reacts with oxidizer in a liquid or gas phase [26–28]. Recent modeling studies based on molecular dynamic methods exhibited that, even for primary oxidized particles of tens nanometer size, the surface oxide layer consisting of alumina undergoes the destruction or deformation upon heating the particle [29,30] and liquid or gaseous aluminum comes into environment.

It should be emphasized that previous works, concerning the analysis of combustion of composite liquid fuels comprising Al nanoparticles, were performed for primarily oxidized particles. The main objectives of this work are to study experimentally the combustion of composite fuel composed of *n*-decane and small-sized Al nanoparticles in a diffusion flame and to obtain the data on the distribution of the local values of temperature in the flame upon burning of pure *n*-decane and composite fuel.

2. Experiment: devices and diagnostics

In contrast to the previous works [2,3,31,32], that were addressed the investigations of ignition and combustion of liquid hydrocarbons with addition of small amount of primarily oxidized Al nanoparticles, i.e. particles comprising oxide shell, in this study we analyzed the combustion of composite fuel with non-oxidized rather small particles with diameter of approximately 20 nm.

2.1. Method of composite fuel production and fuel characterization

For the preparation of homogeneous composite *n*-decane-based fuel with additives of aluminum nanoparticles, the method of plasma decomposition of organoaluminum compounds without presence of oxygen, followed by rapid cooling of the decomposition products by liquid hydrocarbon fuel was used. In the concrete device, triethylaluminum was previously evaporated and, then, was mixed with argon and supplied into the electric discharge cell. Plasma jet, produced by electric discharge, was cooled by degassed *n*-decane sprayed through the micro-pinholes. The sharp cooling of plasma jet stopped the particle growth ensuring the particle mean diameter of ∼20 nm. *n*-Decane was pumped continuously through the closed loop. Change in the composition of composite *n*-decane-based fuel was achieved by means of the variation of deposition time of Al nanoparticles in the reactor. Both processes: plasma decomposition of triethylaluminum and mixing of decomposition products with *n*-decane were combined in a common compact reactor. The resulting mixture of *n*-decane with nano-Al was sampled in the vessel without contact with
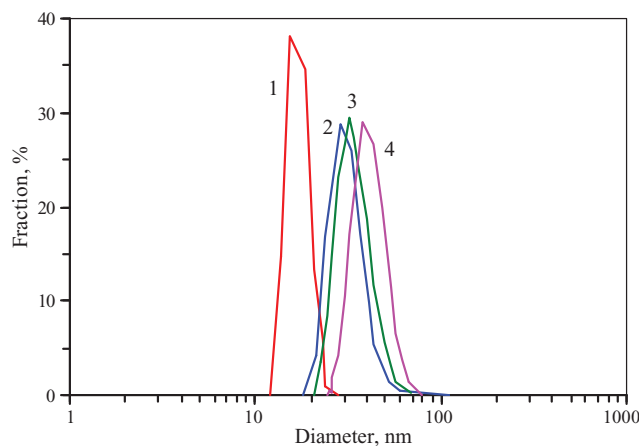
oxygen and this vessel was sealed. Upon the preparation of solution, the surfactant was not used.

The prepared composite fuel was homogeneous, transparent liquid painted in a light brown tone. The color intensity of the mixture of *n*-decane with nano-Al increased with increasing the concentration of nanoparticles. The optical characteristics of the samples of composite *n*-decane-based fuel remained unchanged during 2 months until the use of the fuel in experiments.

It should be emphasized that, if the prepared sample of solution was exposed to air, an intense oxidation of nanoparticle surface began immediately that leaded to heating of *n*-decane and its partial evaporation. After some time, the color of the solution changed from clear, light brown one, to gray, opaque, and, then, an intensive sedimentation of particles began.

Directly before the experiments, the characterization of composite fuel with the usage of dynamic scattering diagnostic system "Zetasizer Nano S" of Malvern Company was performed. The results of fuel characterization are presented in Fig. 2, which depicts the histograms of particle size distribution obtained upon measurements at different time instants. It is worth noting that, for the characterization of particles, the prepared mixture with Al nanoparticles concentration of 2.5% per mass was diluted with the conventional non-degassed *n*-decane by 100 times.

The initial distribution of particles obtained immediately after the dilution was approximately monodisperse one with characteristic particle size of 20 nm (curve 1). Further, because of the oxidation of particulate Al by oxygen, dissolved in non-degassed *n*-decane, and coagulation of oxidized primary particles, particle size increases. The total measurement time was about 27 min. During this time, the mean particle diameter increased by a factor of 4.

2.2. Burner design

An important issue in the experimental study of the combustion of fuels composed of hydrocarbons and non-oxidized metallic nanoparticles is the creation of special experimental techniques and diagnostic systems for the control of characteristics of particles themselves and detecting the parameters and composition of the combustion products of such fuels.

To study the effect of nanoparticles addition on the combustion of hydrocarbon fuel, a special burning device with diffusion mixing of fuel and oxidizer was constructed. The schematic and photo of this burner are presented in Fig. 3.

Because aluminum nanoparticles without surface oxide layer possess high reactivity, the processes of atomization and evaporation of composite fuel in this burner were separated from mixing of fuel and oxidizer. Designed burner comprised special heated reactor for