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Autoignition behavior of a spherical cluster consisted of a center fine droplet and surrounding twelve fine droplets

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Abstract

Autoignition behavior of spherical clusters of pure droplets was experimentally examined near the ignition limit. The fuel with the melting points little above room temperatures was selected as the test fuel. The three-dimensional droplet clusters having hexagonal closest packing structure were selected as the test clusters, which consisted of a center droplet and surrounding twelve droplets (thirteen droplets in total). The initial diameters of the droplets were much reduced from the authors' previous studies. The results showed that the ignition delay of the three-dimensional droplet clusters also had a minimum at a certain droplet spacing, which has been predicted by Niioka and coworkers as a result of rate-controlling process transition between reaction and evaporation. Autoignition of the droplet clusters could be achieved for the center fine droplet, which is out of ignition limit when isolated, in combination with finer surrounding droplets.

Keywords: Droplet combustion; Droplet cluster; Autoignition; Ignition delay, Group combustion

1. Introduction

Combustion of isolated fuel droplets has been one of main fundamental topics related to spray combustion, and extensive knowledge has been reported on isolated droplet combustion. Reduced gravity environment is a strong tool for the droplet combustion experiments, which are providing deeper understanding of the isolated droplet combustion. Autoignition behavior of isolated fuel droplets has been successfully elucidated by Niioka and coworkers [1–3]. The isolated fuel droplets autoignite after the induction time, or the ignition delay, when the droplets are quickly introduced into a high-temperature gaseous environment. Saitoh et al. [1] showed that the ignition delay of pure fuels increases with decreasing the initial droplet diameter in the region near to the ignition limit. Takei et al. [2] showed that the ignition delay of highly-volatile n-heptane droplets

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slightly increases with decreasing the initial diameter while autoignition of less-volatile n-hexadecane droplets occurs earlier with smaller initial diameters. They explain that the increased ignition delay with decreasing the initial droplet diameter is attributed to the enhanced mass flux of the vaporized fuel, resulting in the prolonged reaction time for ignition. The evaporation process, which precedes autoignition, becomes rate-controlling and the ignition delay increases with increasing the initial diameter when the fuel is less-volatile and the initial droplet diameter is large. They also examined the ignition delay of the binary mixture of highly- and less-volatile fuels, and have found that the droplet ignition delay has a maximum as a function of the initial diameter. The primary attention to the autoignition of the isolated droplet has been shifting to that at elevated pressures, where the staged ignition occurs due to low temperature oxidation, which is relevant to the combustion processes in internal combustion engines [3–9].

The primary attention to ignition or beginning behavior of combustion of fuel droplets has been also shifting to that of plural or multiple droplets for the goal to elucidate spray combustion. On the basis of theoretical analyses, Umemura has divided the beginning behavior of combustion of linear droplet arrays into seven modes with the droplet spacing (relative to the droplet diameter) and the ambient temperature (relative to the droplet latent heat) as parameters [10,11], which is summarized in his following study on the beginning behavior of combustion of three-dimensional droplet clusters [12]. At lower temperatures, flame spread occurs along the linear droplet array and the spread behavior varies with the droplet spacing. Leaping flame spread occurs with larger droplet spacing at moderate temperatures due to radiative heating of the neighboring droplet by the spreading flame. At higher temperatures, the linear droplet array autoignites as a whole or individually. Experimental studies on the flame spread along linear droplet arrays have been performed under reduced gravity conditions [13–18]. Numerical simulations of the flame spread based on his theoretical study has also been conducted [19,20].

Autoignition behavior of plural or multiple droplets has been also elucidated by Niioka and coworkers [21–23], as an extension of their studies on autoignition of the isolated droplets. They used ceramic balls of 1 mm in diameter and soaked the balls with liquid fuels for experimental convenience. Droplet arrangements of one-dimensional droplet array [21,23] and two-dimensional droplet matrix [22] could be achieved with the balls and suspending fibers. The results showed that the ignition delays of the array and the matrix increase with smaller droplet spacing in general. The ignition delay, however, shows a minimum at a certain spacing, that is, the ignition delay becomes shorter than that for the isolated droplets under the same conditions, when the droplet is highly-volatile and the initial diameter is small. They explains that the mass flux of the vaporized fuel is reduced due to cooling effect of the neighboring droplets when the reaction is the rate-controlling process for autoignition, resulting in the reduced reaction time. This has been successfully confirmed by the numerical simulation [24].

The autoignition and following combustion behaviors of three-dimensional droplet clusters have been examined by the present authors [25,26]. The fuels with the melting points little above room temperatures are selected as the test fuels. Each spheroidal solid fuel suspended on fiber(s) quickly melts to a droplet at the beginning of transfer, when the clusters are introduced into furnaces. This is followed by evaporation, autoignition and combustion of the clusters. Although the phase of the fuel changes among solid, liquid and possibly dense gas during experiments, it is called as a fuel "droplet" in the present paper. The arrangement, spacing and initial diameter of the droplets in the clusters are well-controlled with the pure fuels.

In the first phase of the experiment [25], the effects of the arrangement and spacing on the combustion characteristics of the clusters which autoignite and burn in a high-temperature air were examined under reduced gravity conditions. The initial diameter of each droplet was set to uniform (monodispersed) and constant, and the arrangement effect was examined by changing dimension or droplet number. The three-dimensional arrangement showed rather longer ignition delay and much shorter burning time than the two-dimensional arrangement. The observation of the flame behavior of the autoignited droplet clusters offered an interesting feature, which would be relevant to the group combustion concept proposed by Chiu and coworkers [27–29]. Individual flames were formed around each droplet with the larger droplet spacing, while group flame was formed with the smaller droplet spacing. When the droplet spacing was in the intermediate range, a transition of flame mode occurred from the individual flames to the group flame.

In the second phase of the experiment [26], autoignition and early flame behaviors of spherical clusters of forty-nine monodispersed droplets were examined under reduce gravity conditions. The clusters had the HCP (hexagonal closest packing) structure. The flame just after ignition changed from the group flame to a cluster of the individual flames either with increasing the droplet spacing or decreasing the initial droplet diameter. Each of the individual flames merged into the group flame with the lapse of time. Burning sphere diameter decreased at the beginning, and then increased. The transition from the individual flames to the group flame occurred around the