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Proceedings of the Combustion Institute 30 (2005) 2001–2009

Proceedings of the Combustion Institute

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Numerical study on flame spread of an *n*-decane droplet array in different temperature environment under microgravity

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Abstract

A series of numerical calculations of flame spread of an *n*-decane droplet array was conducted at different ambient temperatures ($T_a = 300$ and 573 K) for S/d_0 from 1.5 to 10, where S is the droplet interval and d_0 is the initial droplet diameter. The authors compared these numerical results with experimental results under similar conditions at different ambient temperatures for the first time in this study. Good qualitative agreement in flame spread behavior between numerical results and microgravity experiments is obtained. Flame spread mode changed with an increase in S/d_0. Also, appearance of the flame spread mode in a stepping-stone manner (Mode III in [Jpn. Soc. Mech. Eng. 68 (672) (2002) 2423]) in a normal temperature environment was verified by numerical calculations and microgravity experiments, although it was not predicted in the theoretical analysis. In addition, good qualitative agreement of flame spread rate V_f versus S/d_0 was obtained between numerical and experimental results, although numerical results were at least twice as large as experimental results. V_f had a maximum peak at a specific S/d_0 for a different ambient temperature. Employment of improved reaction model and consideration for thermal radiation heat transfer are expected to produce quantitatively better results. An increase in surface temperature of unburned droplets and the development of a flammable gas layer around the droplets were promoted in a high-temperature environment, due to an increase in heat transfer from ambient air to the droplet. As a result, V_f was increased by the higher ambient temperature, suggesting that ambient temperature plays a significant role both in the flame spread mode and the flame spread rate through promotion of a flammable gas layer around unburned droplets.

Keywords: Droplet array; Flame spread; High-temperature environment; Numerical calculation; Microgravity

1. Introduction

Many researchers have investigated flame spread phenomena of a fuel droplet array. These fundamental investigations have led to a better understanding of the flame spread mechanism in

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doi:10.1016/j.proci.2004.08.194

spray combustion. Flame spread in fuel droplets occurs in diesel engines or gas turbine combustors. A better understanding of the flame spread of fuel droplets may improve the performance of practical combustors. From the viewpoint of fundamental combustion science, indeed, the flame spread of fuel droplets is related to appearance process of the group combustion of fuel droplets. In addition to normal gravity experiments, microgravity experiments have been performed for flame spread of a fuel droplet array, since well-defined conditions for experiments are possible without natural convection in microgravity. For example, the flame spread of a fuel droplet array at normal pressure was investigated by Brzustowski et al. [1] and Okajima et al. [2]. Okajima et al. [2] conducted microgravity experiments with *n*-heptane, benzene, and ethanol as fuels, and demonstrated that the flame spread rate decreases monotonically with an increase in droplet interval. They also reported an increase of the flame spread limit at large droplet intervals in microgravity. In addition to these studies in a normal pressure environment, microgravity experiments in a high-pressure environment have also been conducted. Yoshida et al. [3] conducted flame spread experiments in a high-pressure environment up to 0.5 MPa, as well as experiments at normal pressure environment using *n*-heptane, ethanol, and *n*-decane as fuels. They showed that the flame spread rate decreases with an increase in environmental pressures or droplet interval. Also, Kato et al. [4,5] have conducted normal and microgravity experiments at pressure up to 0.7 MPa using *n*-decane and *n*-hexadecane as fuels. They showed that the flame spread rate has a maximum value at a certain droplet interval, and explained that the difference in the trend of flame spread rate with results by Okajima et al. [2] results in the differences in volatility of fuels. Recently, Park et al. [6] and Kobayashi et al. [7] have reported flame spread experiments of an *n*-decane droplet array at pressures up to 5.0 MPa, which is higher than the critical pressure of the fuel. They found a complicated change of the flame spread rate over a wide pressure range. Also, fuel vapor jet behind an unburned droplet was observed during their experiments.

While flame spread of a fuel droplet array has been vigorously investigated experimentally as mentioned above, theoretical or numerical work in the area is limited. Also, there has been little investigation concerning the effects of ambient temperature on flame spread. It is important to understand the effect of ambient temperature on the flame spread of fuel droplets, since spray combustion is often employed, not only at high pressure, but also at high-temperature environments in real combustors. Recently, theoretical considerations on the flame spread process of a fuel droplet array have been conducted by Umemura [8,9]. The considerations are applicable to a wide temperature range up to auto-ignition temperature of fuel droplets. He classified different flame spread modes, and established a flame propagation mode map, which predicts the appearance condition of each mode based on two non-dimensional parameters. One parameter is a non-dimensional droplet interval, S/d_0, where S is the droplet interval and d_0 is the initial droplet diameter. Another parameter is a non-dimensional ambient temperature, RT/L, where R is the universal gas constant, T is the ambient gas temperature, and L is the latent heat of the fuel. Also, the authors of the present study conducted numerical calculation on the flame spread of an *n*-decane droplet array in a high-temperature ($T = 573$ K) environment with S/d_0 up to 8 [10]. The appearance of a different mode with an increase of S/d_0, which was predicted by the mode map, was verified by the calculations.

In the present study, similar numerical calculations at normal temperature ($T = 300$ K) with S/d_0 up to 10 are newly performed, to compare with the theoretical prediction over a wide range of RT/L and S/d_0. These numerical calculations are also compared with the results of microgravity experiments recently conducted by the authors [11,12].

2. Numerical method

The present study employs the same numerical model as in the previous one [10]. Therefore, only an outline of the numerical method is presented here. The analytical domain is an axisymmetric, two-dimensional cylindrical plane, since flame spread phenomena can be considered axisymmetric in a microgravity environment. Figure 1 shows the analytical domain in the numerical calculations. Velocity in the whole domain is zero, as initial condition. Gas flow velocities at outer boundaries are extrapolated from the inner domain in accordance with the constant pressure ($P = 0.1$ MPa) as boundary condition, in subsequent calculations. A droplet at the left edge of an array is ignited by a heat source located near the droplet. When a stable flame spread is achieved, the heat source is removed to suppress

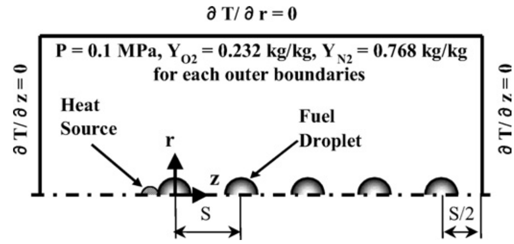

Fig. 1. Analytical domain.