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Proceedings of the Combustion Institute 33 (2011) 125–150

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Micro and mesoscale combustion

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Abstract

A review of research and development on micro and mesoscale combustion is presented, with an emphasis on fundamental understandings achieved in the field during the last decade. Due to its small scale nature, increasing effects of flame–wall interaction and molecular diffusion are the characteristic features of micro and mesoscale combustion. After brief review of device developments, overview of fundamentals in micro and mesoscale combustion as well as possible future directions is presented.

Keywords: Microscale combustion; Mesoscale combustion; Microcombustion

1. Introduction

With the recognitions of broad potential applications not only for electrical power but for heat and mechanical power sources, combustion at small scales (micro and mesoscales) is collecting growing attentions these days [1–4]. Possible applications are sensors, actuators, portable electric devices, robots, rovers, unmanned air vehicles, thrusters, industrial heating devices, and furthermore, heat and mechanical backup power sources for air-conditioning equipments in hybrid vehicles and freight transportations as well. Needless to say, the concept is based on the nearly two-order higher energy densities of hydrocarbon fuels than the existing modern batteries.

Along with the demands for further developments of small scale combustion devices, fundamentals on micro and mesoscale combustion also collect increasing interests through the technical challenge to overcome quenching issues due to the large surface-to-volume ratio of small scale devices. Thermal and chemical stability managements are required to establish stable combustion in micro and mesoscale devices. Thermal stability managements by the heat recirculation displayed the several novel phenomena such as flame bifurcation, weak flame, extinction and re-ignition instabilities, spinning flames and pattern formations. From the aspect of flame–wall chemical coupling, new concept catalytic combustion and non-equilibrium effects at wall on combustion are started to be explored. Understanding on oxygen absorption led to extremely low-temperature operation of microscale catalytic combustion. In this paper, recent applications and fundamentals of micro and mesoscale combustion are reviewed and summarized. Future directions and expectations will be also discussed.

2. Scaling for microscale combustion

In small scale combustion systems, surface-to-volume (S/V) ratio is large due to the small characteristic length scale. The large S/V ratio leads to the severer heat-loss effect on small scale

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doi:10.1016/j.proci.2010.09.005

combustion systems. Hence, clear understanding on flame extinction, which is governed by the ratio of heat-loss to the heat generation described in theory of non-adiabatic flames [5,6], is important. Discussion on quenching diameter can be made by assessing the heat loss from a flame with finite diameter. It is essentially equivalent to the discussion based on Peclet number, in which the ratio of quenching diameter to the flame thickness is considered.

Discussion on flame extinction by Peclet number, defined as the ratio of longitudinal to radial heat transfers, is also of use. It can be widely applied to flame extinction by replacing loss mechanisms. Simple comparison between residence and chemical time scales by Damköhler number is also useful for blow-off type extinction.

Reynolds number is generally small due to the small characteristic length scale in small scale system. Therefore, flow condition in microscale system often remains in laminar, while it sometimes reaches to the transition regime in mesoscale system. Since turbulent mixing is least expected, molecular diffusion is primary mechanism for mixing. Thus, molecular diffusion may control overall characteristics or performance of microscale systems with low velocity forced flow or non-premixed flames.

To overcome the effect of large heat loss on small flames, stability management is required. One of the effective stability managements is heat recirculation through channel wall. To understand the characteristics of heat recirculation process, Biot number, which is defined as the product of heat transfer coefficient and characteristic length divided by thermal conductivity of the solid, is of use. It is denoted as thermally thin wall if $B < 0.1$, where the heat resistance in the solid phase is small and surface heat resistance is predominant. For transient process, thermal and mass diffusion characterized by Fourier number, defined by the ratio of the product of thermal or mass diffusivity and characteristics time scale divided by the square of the characteristic length scale, is also important. Accordingly, characteristics of heat recirculation process for a stationary flame in a channel and those for propagating flame are quite different.

Unequal thermal and mass diffusivities often lead to manifestations of the diffusive-thermal instabilities. In microscale combustion with heat generation, heat transfer through wall is combined with gas-phase heat transfer, resulting in modified thermal and mass transfer balance. Thus, effective Lewis number should be estimated for describing the onsets of instabilities based on the diffusive-thermal instability.

If the length scale of the system is extremely small (or it is under the reduced pressure), Knudsen number, defined as the ratio of mean free path to the characteristic length scale, becomes large and the continuum assumption of fluid mechanics is no longer a good approximation. Although current microscale combustion does not often address this issue, some attempts have been made in this direction by paying attention on the concentrations and temperature discontinuities at wall.

In this paper, the term “microscale combustion” is used for combustion which involves characteristic length scales closely related to “quenching distance,” particularly when it plays critical role on the addressed phenomena. Therefore, topics with length scales not only smaller than 1×10^{-3} m physical-scales are dealt in this paper. The term “mesoscale combustion” will also be used for the cases with characteristic length scales obviously larger than 1 mm but remains characteristic features of microscale combustion. It is often used to highlight specific features of microscale combustion using scale-up model approach.

3. Application of microscale combustion

3.1. Microscale combustion for mechanical power

3.1.1. Microscale gas-turbines and internal combustion engines

Based on the high energy density of hydrocarbon liquid fuels, scale-down approach of existing rotating machinery and internal combustion engines for portable power sources have been conducted.

MEMS-based silicon gas-turbine engines were developed at MIT [7–10]. The micro gas-turbine is a 10 mm diameter by 3 mm thick, toward electrical power output up to 20 W at rotor speed of 2.4×10^6 rpm, consuming 7 g/h of H_2 fuel. Hydrogen-fueled micro combustor produced exit gas temperature in excess of 1800 K by a micro combustor having 66 mm^3 chamber [11]. Stable hydrocarbon combustions were also demonstrated by a micro combustor having 195 mm^3 chamber [9] and six-wafer catalytic micro combustor [12].

Tanaka, Esashi and co-workers at Tohoku, collaborating with IHI, demonstrated that the world’s smallest-class gas-turbine which operates Brayton cycle [13]. It has a compressor of 16 mm diameter, a turbine of 17.4 mm diameter, an annular combustor and a dummy electromagnetic generator. The impellers are connected by one piece of Inconel shaft of 8 mm diameter as shown in Fig. 1 right. Brayton cycle was established when pressure at the compressor inlet became negative (minus a few kPa below the atmospheric pressure) at the rotation speed of 360,000 rpm and the combustor temperature of 800–900 °C. Hydrogen was used for the demonstration.