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Cellular pattern formation in detonation propagation

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Abstract

The relation between the soot track on smoked plate records and the frontal structure of gaseous detonations was experimentally studied to clarify the mechanism of cellular pattern formation by using combination images of high-speed schlieren pictures, self-emission images of the reaction front, and the smoked plate record. Several materials were tested as alternatives to soot particles of smoked foil technique to record detonation structure. The experimental results show that the triple point trajectory coincides with the soot track and that cellular cell-like patterns are obtained for $CaCO_3$ particles, fly ash, heat-sensitive paper, and pressure-sensitive paper. An asymmetrical cellular pattern in the smoked plate record is exhibited in the case of the pressure-sensitive paper, while a symmetrical pattern is observed for the other materials. This asymmetry is successfully explained by the temporal response of the pressure-sensitive paper from evaluation of time integration of pressure, namely impulse to time varying loading. Estimation of wall shear stress and tensile strength of agglomerated particles layer on the basis of an analogy to particle entrainment from fine powder layers shows the critical particle diameter for removal of particles. However, the shear stress is found to be not strong enough for removal of particles located in the triple point trajectory. Finally other additional mechanisms for local detachment of particles are discussed.

Keywords: Detonation; Cellular pattern; Smoke foil record; Particle entrainment; Adhesive force

1. Introduction

In the study of gaseous detonations, the smoked foil technique [1–3] has been widely used to record variations of cellular patterns owing to its simplicity and robustness in visualizing the front structure of gaseous detonations. It is well known that the size of the cellular pattern depends on the mixture type and its initial conditions. Because the cell size can be treated as a characteristic length of the mixture, it has been widely investigated under various experimental conditions. While a smoked foil is a standard and robust experimental tool to record cellular structure, only limited information can be obtained from the smoked foil record. Several explanations for the mechanism of soot track formation have been proposed: (1) micro-vortices generated along a slip line behind the triple shock sweep loose soot particles off the smoked plate [4]; (2) variations in the direction and magnitude of the shear stress generated by a flow in the boundary layer cause

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entrainment and accumulation of the soot particles [5,6]; and (3) isochoric combustion and a spherical propagating blast wave having a circular flame remove the soot particles [7].

With regard to the smoked foil record, Pintgen et al. have reported that the soot track is not consistent with the location of the triple point predicted from OH-LIF measurement [8]. They determined the triple point location as the intersection of the incident shock wave and the Mach stem based on visualization of the reaction front and the calculated induction zone length. The physical mechanism by which the soot track is formed is important for understanding the characteristics of detonations, because it is closely related to the detonation front structure. However, experimental evidence supporting the above explanations is not sufficient. In addition, much fruitful information on the nature of detonation can be expected if other visualization tools for recording the detonation front structure are developed.

In the present work, the relation between the soot track and the detonation front structure has been studied experimentally to clarify the mechanism of the soot track formation. The correspondence of the triple point lying in the detonation front to the soot track has been established using a combination of high-speed schlieren photographs, self-emission images captured using an ICCD camera, and the smoked plate record. As alternatives to soot particles, other materials have been tested to record the detonation front structure. Furthermore, the mechanism of the soot track formation has been discussed based on an analogy to particle entrainment from fine powder layers.

2. Experimental apparatus

The detonation tube used for visualization of the detonation front structure is shown in Fig. 1a. It consists of a stainless steel tube, and it has a length of 2598 mm and a rectangular cross-section of 2 mm × 35 mm except for the pre-detonator. The tube contains a 400-mm-long pre-detonator, 1550-mm-long guide section, 98-mm-long test section, and 550-mm-long damping section for avoiding the effects of wave reflection at the tube end. A pair of quartz windows was fixed to the side walls of the test section for visualization of the detonation front. In the present work, two optical systems were provided. One is a standard schlieren system using a high-speed camera, and the other is an ICCD camera for capturing self-emission images of the reaction front. The ICCD camera was placed at an angle of ~7° to the optical axis of the schlieren system. Deformation of the ICCD image due to the inclination of its optical axis was corrected using graphics software. By coating the inner surface of one observation window with soot, the present optical setup provided for three types of combination images: (1) schlieren + self-emission, (2) schlieren + smoked window record, and (3) self-emission + smoked window record. In the second case, the observation window was partially coated with soot, as shown in Fig. 1b.

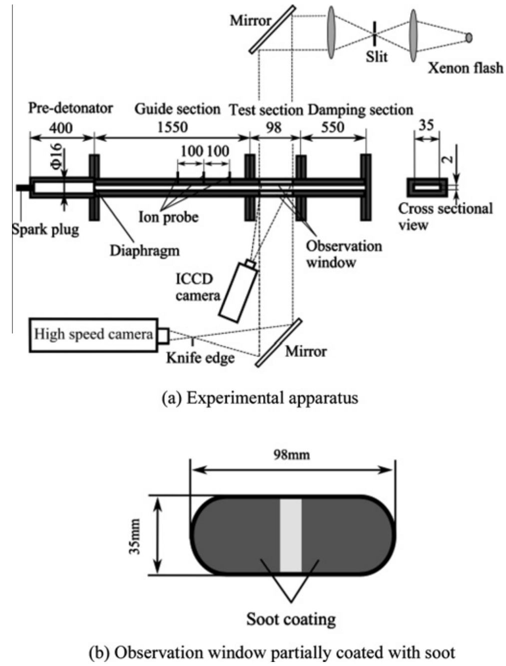

Fig. 1. Schematic of experimental apparatus and optical setup.

A different detonation tube was used for the experiment in which alternative materials were tested for recording the cellular pattern. This tube has a test section inside which a 40-mm-wide and 3-mm-high narrow channel is formed using a pair of 1500-mm-long stainless steel plates. A detailed description of the detonation tube is given in Ref. [9]. The tested materials were $CaCO_3$ particles, Al_2O_3 particles, and fly ash. These were placed directly on one side of the stainless steel plate. In addition, heat-sensitive paper used for thermal facsimiles and pressure-sensitive paper (Fujifilm, "Prescale," LLWPS) were also evaluated as alternative tools for recording the cellular pattern.

In the present work, stoichiometric hydrogen–oxygen mixtures diluted with argon were used as a test gas under an initial pressure p_0 varying from 30 to 42 kPa. The steadiness of the detonation propagating in the guide section was determined from velocity measurements using ion probes mounted at the end of the guide section.