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Experimental and LES investigation of premixed methane/air flame propagating in a chamber for three obstacle BR configurations

Peng Chen [a, b, *], Yanchao Li [b], Fujun Huang [b], Shilong Guo [b], Xuanya Liu [c]

[a] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing, 100083, China
[b] Faculty of Resources & Safety Engineering, China University of Mining and Technology (Beijing), Beijing, 100083, China
[c] Tianjin Fire Research Institute of MPS, Tianjin, 300381, China

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ABSTRACT

The paper aims at revealing the effect of blockage ratio (BR) on the flame acceleration process and the flame-vortex mechanism in an obstructed chamber based essentially on the experimental and numerical methods. In the experiments, high-speed video photography and pressure transducer are used to study the flame shape changes and pressure dynamics. In the numerical simulations, large eddy simulation (LES) with the flame surface density (FSD) model is applied to investigate the interaction between the moving flame and vortices induced by obstacle. The results demonstrate that the flame propagation process can be divided into four stages, namely spherical flame, finger-shaped flame, jet flame and volute flame for three obstacle BR configurations, and a small recirculation zone is observed above the obstacle only for BR = 0.5. The peak of flame tip speed and pressure growth rate increases with the blockage ratio. The generation and evolution of the vortex behind the obstacle can be attributed to the initial flame acceleration, while the subsequent flame deceleration is due to the flame-vortex interaction. In addition, the transition from a "thin reaction zones" to a "broken reaction zones" is also observed in the simulation.

1. Introduction

The methane/air deflagration accidents occur frequently in coal mines and natural gas pipelines. In these accidents, the premixed flame propagating away from an ignition source often interacts with obstacles along their path. The coupling of the moving flame and the vortex induced by the obstacle will disturb the flame and increase its surface area, in turn, the pressure growth rate (Dorofeev, 2011; Kessler et al., 2010; Sarli et al., 2009a,b). Therefore the profound comprehension of the flame-vortex mechanism is essential for industrial safety.

More recently, laboratory-scale experiments have become the prior method of investigating the flame acceleration in an obstructed chamber. Masri et al. (2000) pointed out that the obstacle with square cross-sections results in the faster flame acceleration than circular and triangular cross-sections, and the flame tip speed increases with increasing blockage ratio. Hall et al. (2009) studied the effects of position and frequency of obstacles on turbulent premixed propagating flames in a vented chamber, and found that the peak overpressure can reach a limit with increasing obstacle number and overpressures will rise when the obstacles are stacked closer. Sarli et al. (2009a,b) captured the vortex structure behind the obstacle using the particle image velocimetry method (PIV), and suggested that the large-scale vortex plays the dominant role in the evolution of the flame shape along the path. Nevertheless, the accurate mechanism that correlates the flame structure, the vortex, speed and resulting overpressure, is not well explored yet only by the experimental method.

Thanks to the growing computational performance and the application of parallel computing, large eddy simulation (LES) has become an approved tool to model the flame propagation process in an obstructed chamber. Compared with the classical Reynolds-averaged Navier–Stokes (RANS) model, LES can offer an improved representation of turbulence, which explicitly resolves the large turbulent structures in a flow field and models the small structures. For applications of LES in the combustion simulation, the choice of the sub-grid scale (SGS) combustion model is still one of the crucial procedures (Sarli et al., 2010; Wen et al., 2012). So far, great efforts

* Corresponding author. State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing, 100083, China.
E-mail address: chenpeng@cumtb.edu.cn (P. Chen).

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have been devoted to the development and validation of SGS combustion model. Johansen and Ciccarelli, 2013 modeled the initial flame acceleration and the effects of unburned gas flow field development on the flame propagation in an obstructed chamber using the dynamic Smagorinsky–Lilly Subgrid model and Boger flame surface density combustion model. Xu et al. (2015) analyzed the flame shape changes and the flow field in a semi-confined chamber with three obstacles mounted inside using a turbulent flame speed closure (TFC) model. Sarli et al. (2010) assessed the capacity of different sub-grid scale combustion model proposed for LES of turbulent premixed combustion, and pointed the power-law flame wrinkling model provides the best quantitative predictions for flame speed and pressure peak without adjusting any constants and parameters.

The present work describes a combined experimental and numerical study of premixed methane/air flame propagating in a chamber at various obstacle BR configurations. The primary of this study is to further reveal the effect of blockage ratio on the flame behavior, and especially explain the formation of the recirculation zone above the obstacle. In addition, the regime of flame-vortex interaction is also explored with the FSD model.

2. Experimental apparatus

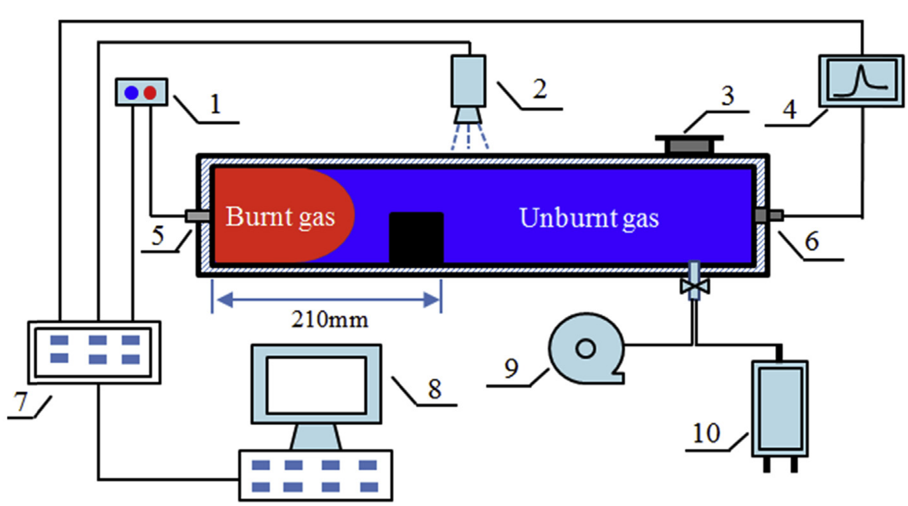
The experimental apparatus is schematically shown in Fig. 1. It consists of a constant volume combustion vessel, a high-speed photography system, a pressure recording system, a gas mixing system, a high-voltage ignition system and a synchronization controller. The combustion vessel has dimensions of 80 mm × 110 mm × 500 mm, and the two lateral panels of the duct are constructed of quartz glass for allowing optical access, while the upper and lower walls are made of stainless steel. A discharge vent is set up close to the right end of duct for safety. The 40 mm thick rectangular obstacle is placed at about 210 mm from the ignition end. The obstacle blockage ratio (BR) is related to the gap between the obstacle, h, and the channel height, H, through the following relationship:

$$BR = 1 - \frac{h}{H}$$

A stoichiometric mixture of methane/air is prepared in the gas mixing device via the method of partial pressures. The mixture used in the experiments is a combination of 99.9999% pure methane and dry air. Before the mixture is fed into the duct through an isolating valve, the combustion vessel is evacuated by a vacuum pump. The combustible mixture is allowed to become quiescent by incorporating a short time delay (approximately 60 s) into the gas filling sequence before ignition. The mixture is ignited by high-energy igniter with energy in the range of 3–20 J and the ignition site is located at the center of the left end wall. The high-speed camera is used to record the changes in the flame shapes and position as a function of time. The speed of the high-speed video camera in the experiment is 960 frame/s. A PCB piezoelectric pressure transducer (model 112A05) is used to record the pressure transient in the duct and the transducer is placed at the center of the right end wall. The pressure data is recorded using HIOKI 8847 dynamic data recorder made in Japan, which provides eight channels, and the highest waveform sampling rate of each channel is 20 MS/s. The spark igniter, data recorder and high-speed video camera are controlled by the synchronization system.

3. Large eddy simulation (LES) and SGS combustion models

The flame propagating in an obstructed chamber usually undergoes transition from a laminar to turbulent regime. The details and validation of the LES model applied here can be described elsewhere (Bi et al., 2012; Xiao et al., 2012). The LES model equations are obtained by filtering three-dimensional instantaneous conservation equations of mass, momentum, energy and chemical species, jointed to the constitutive and state equations. The flame propagation is modeled by a transport equation for the reaction progress variable, c, which is defined as a normalized mass fraction of products such that c = 0 in the fresh mixture and c = 1 in the burnt products:



(1) spark igniter, (2) high-speed video camera, (3) discharge vent, (4) data recorder, (5) ignition electrode, (6) pressure transducer, (7) synchronization controller, (8) computer, (9) vacuum pump, (10) gas mixing device.

Fig. 1. Sketch of experimental apparatus.