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Flame regime estimations of gasoline explosion in a tube

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ABSTRACT

Flame regime of gasoline-air mixture explosion is related to chemical reaction, turbulent flow and heat and mass transfer. Experimental data of gas velocity, pressure and flame temperature of gasoline-air mixture explosion in a tube at the equivalence ratio of 0.72, 1.00 and 1.28 were preliminarily acquired. Then, fluctuating velocities, overpressures, and burned and unburned gas temperatures at early stage (50 ms), intermediate stage (150 ms) and last stage (250 ms) in three explosions were determined through the analysis of the experimental data. Finally, the Damköhler number and Reynolds number of the early, intermediate and late stage were calculated respectively, and the flame regimes for each stage were estimated through the Damköhler number vs. Reynolds number diagram. Results show that all the flames at early, intermediate and late stage of the three explosions have the same regime of flamelets-in-eddies. The conclusions can provide some useful references for further study of the flame regime and the numerical analysis model selection of gasoline-air mixture explosion.

1. Introduction

Flames of gasoline-air mixture explosion in confined space behave as typical premixed turbulent flames whose regime also depends on chemical reactivity, heat and mass transfer. Generally speaking, different flame combustion regimes lead to different explosion characteristics, such as overpressure, pressure rise rate and flame speed. Turbulence makes the flame front surface wrinkled and twisted (Steinberg and Driscoll, 2009; Steinberg et al., 2009; Zhang et al., 2014a), resulting in influences on heat and mass transfer (Shin and Lieuwen, 2012; Wang et al., 2013; Yi et al., 2012), and on the chemical reaction (Nishimura et al., 2013; M. Zhang et al., 2013, 2014b; Won et al., 2014; Du et al., 2014). Therefore, identifying the flame regime is of great significance to understand and to model the system.

Study on flame combustion regime is the hotspot and difficulty point in combustible gas combustion and explosion field (Bell et al., 2007; Mansour and Chen, 2008; Mukaiyama et al., 2013; Yuen and Gülder, 2013; P. Zhang et al., 2014). Williams (1986) and Abraham et al. (1985) divided turbulent premixed flame into three modes: wrinkled laminar-flame regime, flamelets-in-eddies regime and distributed-reaction regime, according to a criterion composed of kolmogorov microscale l_k, turbulence integral scale l_0 and laminar flame thickness δ_L. In this model, Damköhler number (Da) and Reynolds number (Re_{l_0}) are firstly calculated, and then the regime of the turbulent flame can be determined by a chart of Da vs. Re_{l_0}, as shown in Fig. 1.

In the Fig. 1, region above the thick solid line ($l_k/\delta_L = 1$) represents the regime of wrinkled laminar-flame, which meets Williams-Klimov criterion (Williams, 1986), and region below the thick solid line ($l_0/\delta_L = 1$) represents the regime of distributed-reaction, which meets the Damköhler criterion (Abraham et al., 1985). The region between these two thick solid lines represents flamelets-in-eddies regime. So the flame regime can be judged by Fig. 1 as long as the Da and Re_{l_0} are identified.

Da (Abraham et al., 1985) is a dimensionless parameter defined as,

$$Da = \frac{\tau_{flow}}{\tau_{chem}} = \frac{l_0/v'_{rms}}{\delta_L/S_L} = \left(\frac{l_0}{\delta_L}\right)\left(\frac{S_L}{v'_{rms}}\right) \quad (1)$$

where, τ_{flow} is the flow characteristic time, τ_{chem} is the chemical characteristic time, l_0 is the turbulent integral scale, v'_{rms} is the turbulent fluctuating velocity, δ_L is the laminar flame thickness, S_L is the laminar flame speed. l_0/δ_L represents the flame geometry dimension rate, and v'_{rms}/S_L represents the flame relative turbulence intensity.

The Reynolds number Re_{l_0} is defined as:

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Nomenclature

l_k	kolmogorov microscale, m
l_0	turbulence integral scale, m
δ_L	laminar flame thickness, m
Da	Damköhler number, dimensionless
Re_{l_0}	Reynolds number, dimensionless
τ_{flow}	flow characteristic time, s
τ_{chem}	chemical characteristic time, s
v'_{rms}	gas turbulent fluctuating velocity, m/s
S_L	laminar flame speed, m/s
$S_{L,ref}$	laminar flame speed under the reference state, m/s
ρ	density of the combustion flame, m^3/kg
μ	dynamic viscosity of the combustible gas, kg/m^2 s
∅	equivalence ratio, dimensionless
v(t)	instantaneous gas velocity at a time of *t*, m/s
$\bar{v}$	average gas velocity, m/s
T_u	unburned gas temperature, K
T_b	burned gas temperature, K
P, P_{ref}	pressure (overpressure) and reference pressure, Pa
γ	temperature index, dimensionless
β	pressure index, dimensionless
B_M, B_2, $∅_M$	constants determined by fuel type
α	thermal diffusivity rate, m^2/s

$$Re_{l_0} = \frac{\rho v'_{rms} l_0}{\mu} \quad (2)$$

where, ρ represents the density of the combustion flame, and μ represents the dynamic viscosity of the combustible gas.

It can be seen from the analysis mentioned above that the flame regime of the gasoline-air mixture explosion would be determined as long as v'_{rms}, l_0, δ_L and S_L are obtained. Unfortunately, it is very difficult to obtain these parameters directly in laboratory. However, these parameters can be estimated by the other experimental data, such as the gas average velocity, the temperature of the burned and unburned gas, and the overpressure.

In this paper, experiments of gasoline-air mixture explosion under different equivalence ratios were carried out in a tube and the gas average velocity, temperatures of the burned and unburned gas, overpressure and other parameters were measured. Then, the Damköhler number Da and Reynolds number Re_{l_0} were calculated, and the flame regimes were estimated.

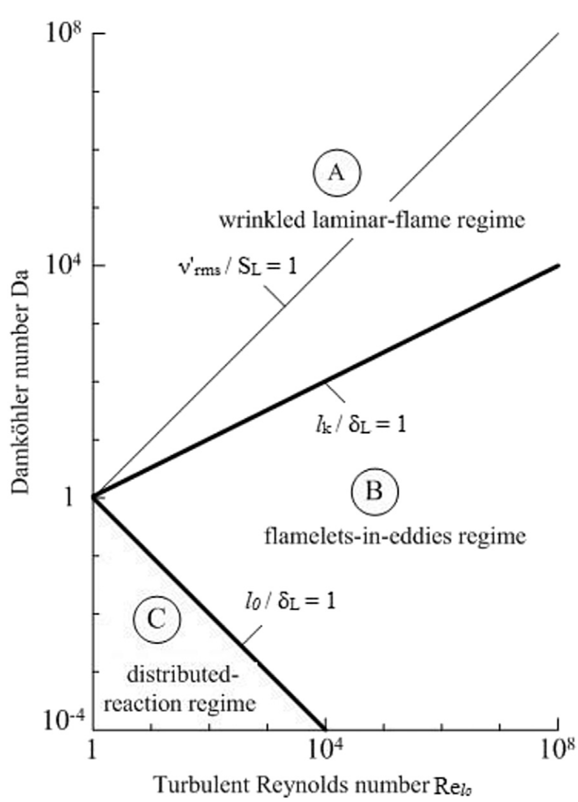

Fig. 1. Regime distribution of the turbulent premixed flame based on values of Da and Re_{l_0} (Williams, 1986).

2. Experimental apparatus and method

The experimental equipment used was mainly composed of a tube (containing a observation section), a vacuum circulating pump, a gasoline evaporation apparatus, a data acquisition system, an ignition system, a high speed camera and a computer, as schematically shown in Fig. 2. The data acquisition system includes a pressure collection system, a concentration and temperature acquisition equipment and a gas velocity acquisition equipment.

The dimension of the tube is 200 × 200 × 6100 mm, and the length of the observation section is 300 mm. The gasoline evaporation apparatus and a vacuum circulating pump were used to form a uniform gasoline-air mixture in the test tunnel. Details of structure and working principle of the gasoline evaporation apparatus can be found in reference P. Zhang et al. (2013) or D. Yang et al. (2013).

The pressure measurement system consisted of a pressure sensor, a data acquisition card and a computer. Overpressure history of the explosion process was recorded by three pressure transducers located along the test tunnel with same interval, and the average values of the three transducers' records were used to represent the explosion in the tube. The concentration measurement system was composed of a GXH-1050 infrared analyser (Junfang physicochemical Science and Technology Institution of Beijing) and a NHA-502 automotive emission analyser (Nanhua instruments Co. Ltd.). Concentration of the gasoline vapour was measured by the GXH-1050 infrared analyser, and other gaseous concentrations were measured by the NHA-502 automotive emission analyser.

Temperatures of the burned and unburned gas were measured by a temperature acquisition device, which mainly consisted of three thermocouples, an acquisition card and a computer. The thermocouples used in the experiments were S-filament thermocouple probe (Beijing East Summit Technology Inc.), which could measure the temperature of the instantaneous gas. The diameter of the filament was 0.0005 inch, and response time was about 5 ms, Sampling frequency was 200 Hz. These three thermocouples were located at 50 cm, 305 cm and 560 cm away from the ignition end of the tube respectively.

It is difficult to directly measure the fluctuating velocity of the turbulence during a gasoline-air mixture explosion. The instantaneous velocity was recorded by a high temperature hot wire anemometer (model: 6162, Kanomax Japan, Inc.), the average gas velocity was calculated through the sum of all instantaneous velocity records dividing the total sampling number, finally, the velocity fluctuation was obtained by subtracting the instantaneous