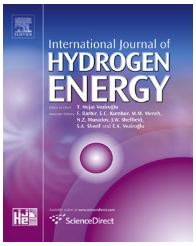
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 11087–11092

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Prediction model for self-similar propagation and blast wave generation of premixed flames

Woo Kyung Kim [a,*], Toshio Mogi [b], Kazunori Kuwana [c], Ritsu Dobashi [d]

[a] Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, UK
[b] Graduate School of Engineering, The University of Tokyo, Japan
[c] Department of Chemistry and Chemical Engineering, Yamagata University, Japan
[d] Department of Chemical System Engineering, The University of Tokyo, Japan

ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form
18 June 2015
Accepted 24 June 2015
Available online 27 July 2015

Keywords:
Flame acceleration
Self-similar propagation
Expanding spherical flame
Blast wave
Explosion

ABSTRACT

This paper presents a simple model to predict the flame speed and the blast pressure during an unconfined gas explosion. The proposed model is a modification to the fractal-based model proposed by Gostintsev et al. In the original model, the flame radius, r, is expressed as a function of time, t, as $r/(\kappa/\varepsilon S_L) = c_g[t/(\kappa/\varepsilon^2 S_L^2)]^\alpha$, where κ is the thermal diffusivity, ε is the volumetric expansion ratio, S_L is the laminar burning velocity, c_g is the model constant, and α is the acceleration exponent. The present model expresses model constant c_g using the properties of gas mixture. In this study, field experiments of gas explosion are conducted for hydrogen/air, methane/air, and propane/air mixtures confined in a 1- or 27-m^3 regular cubic plastic tent. The experimental results demonstrate the nature of self-similarity in the explosions and the experimental acceleration exponent associated with a fractal dimension is evaluated. The model is developed by using the concept of self-similarity and an acoustic theory. The predicted flame speed and the blast pressure are compared with experimental data of larger-scale hydrogen/air, methane/air and propane/air explosions under a wide range of conditions. The model predictions agree reasonably well with the experimental data, validating the proposed model.

Introduction

When a large scale unconfined explosion of a premixed gas occurs, the blast wave is a major hazard in industrial plants as well as other places where large amounts of combustible gases are stored or used. The generation of a blast wave in an unconfined space is strongly affected by the flame acceleration due to obstacles and flame induced instabilities such as the diffusional-thermal, hydrodynamic, and Rayleigh-Taylor instabilities [1]. The effect of flame acceleration due to the diffusional-thermal instability and hydrodynamic instability on the blast wave intensity has been confirmed experimentally [2–4]. The results show that the flame acceleration in the initial stage of propagation is occurred by diffusional-thermal instability and then the acceleration is dominated by hydrodynamic instability as the flame propagates. Understanding the flame accelerative dynamics in an unconfined explosion is therefore crucial for predicting the intensity of a blast wave as confirmed by previous studies [1–4]. This acceleration was

---

[*] *Corresponding author.*
E-mail address: youwoo2@gmail.com (W.K. Kim).

http://dx.doi.org/10.1016/j.ijhydene.2015.06.123

evaluated using a fractal dimension experimentally and numerically [5–11]. Although the values of fractal dimension were suggested by a number of theoretical and experimental studies [5–11], the results are inconclusive to apply to accidental gas explosions. The further studies on the evaluation of the flame acceleration could be merited. Further, in the actual accidental gas explosions, the flame acceleration by obstacles considerably affects the blast wave strength. The effect of obstacles may be more significant than self acceleration of flame.

The flame speed, V_f, in uniform obstacle fields is derived by Dorofeev [12,13] based on geometrical considerations.

$$V_f = a^2 b\varepsilon(\varepsilon - 1)S_L\left(1 + \frac{4}{3}\frac{\varepsilon y}{x}\frac{r^{\beta}}{(\varepsilon x)^{\beta}}\right)\left(\frac{r}{\delta}\right)^{1/3} \tag{1}$$

where a, b, and β are model parameters, r is the flame radius, ε is the volumetric expansion ratio, S_L is the laminar burning velocity, δ is the flame thickness, x is the distance between obstacles, and y is the characteristic size. This equation gives the flame speed (with or without obstacles) proportional to $(r/\delta)^{1/3}$.

On the other hand, the flame acceleration due to flame induced instabilities without obstacle was studied by Gostintsev et al. [7], who suggested based on the results of large-scale experiments that the speed of a hydrodynamically unstable, outwardly propagating spherical flame can be expressed as

$$V_f = c_g\alpha\frac{(\varepsilon S_L)^{2\alpha-1}}{\kappa^{\alpha-1}}t^{\alpha-1} \tag{2}$$

where c_g is the model constant proposed by Gostintsev et al. [7], κ is the thermal diffusivity, and α is the acceleration exponent, whose value is 1.5 according to Ref. [7]. The continuous increase in flame speed is understood as a result of the fractal-like self-similarity of flame. Since the study of Gostintsev et al., various values of the acceleration exponent were proposed by other researchers [7–20], while Bradley again confirmed that flame radius depends upon $t^{1.5}$ [8]. According to Ref. [5], the exponent depends on the intensity of diffusional-thermal instability as well as that of hydrodynamic instability. Because of this complexity, determining its value under various conditions remains a challenge, although many attempts have been made to evaluate the acceleration exponent. The acceleration exponent is important when evaluating the flame acceleration during a gas explosion, because it affects the resultant explosion intensity. As for the value of model constant c_g, Gostintsev et al. [7] proposed $c_g = 2.0 \times 10^{-3}$ for all gases, whereas Refs. [21,22] determined its values under various conditions by fitting experimental data with Eq. (2); it was found that the value depended on gas properties. The values of model constant c_g were between 1.5×10^{-3} and 7.01×10^{-3} [21,22].

A major objective of the present paper is to validate the Gostintsev model, Eq. (2), in evaluating the flame acceleration and the generation of blast wave. In particular, the dependence of the model constant c_g on gas properties is theoretically discussed, and a modified model is developed. Additionally, the field experiments of combustible gas mixtures are conducted to investigate the nature of the self-similarity in large scale expanding spherical flames. The present model is validated by comparing its predictions with the results of field experiments.

Experimental rig

Field experiments of gas explosion are conducted for hydrogen/air, methane/air, and propane/air mixtures confined in a 1- or 27-m^3 regular cubic plastic tent made of a stainless-steel frame and a polyethylene sheet of 0.1 mm thickness. A photograph of the rig is shown in Fig. 1. Ignition is made by an electric spark provided by an igniter (15 kV, 20 mA) at the center of the tent. A combustible gas is mixed with air in the tent and circulated by a circulation pump. The gas concentration is measured by a gas concentration measuring instrument (Riken Keiki Co., FI-21) at the top and the bottom of the tent. The flame front is tracked at 1000, 2000, or 2500 frames per second, depending on the flame speed, using a high speed camera. In the present study, infrared photography in addition to visible photography is recorded. The pressure wave generated by a gas explosion is simultaneously recorded by piezoelectric sensors at several distances (8 m, 20 m, 30 m and 50 m) from the tent. In addition, the internal pressure in the tent was also measured using a pressure transducer. No significant pressure increases are observed during the experiment, confirming that the effect of the tent material is negligible, and the present experiment can simulate an unconfined explosion.

Results and discussion

Acceleration exponent and self-similarity

Fig. 2 plots experimentally measured acceleration exponent as a function of $Pe - Pe_c$, where the Péclet number, Pe, is a

Fig. 1 – A photograph of the experimental rig (27 m^3 cubic plastic tent).