USING EXPANDING SPHERICAL FLAMES METHOD TO MEASURE THE UNSTRETCHED LAMINAR BURNING VELOCITIES OF LPG–AIR MIXTURES

Tran Manh Vu
University of Technology, VNU-HCM
(Manuscript Received on December 01st, 2008, Manuscript Revised April 25th, 2009)

ABSTRACT: *In the present study, a technique making expanding spherical flames in a constant volume combustion bomb is presented for determining burning velocities of unstretched laminar flames, and applied to liquefy petroleum gas (LPG)–air mixtures. The experimental setup consists of a cylindrical combustion chamber coupled to a classical schlieren system. Flame pictures are recorded by a high speed camera. The laminar burning velocities of LPG–air mixtures are measured over a wide range of preheat temperatures, initial pressures and equivalence ratios. The effects of these initial conditions on the laminar burning velocities are also examined in this paper.*
Keywords*: Combustion; expanding spherical flames method; laminar burning velocity; Schlieren system*

1. INTRODUCTION

With increasing concern about the energy shortage and environmental protection, research on improving engine fuel economy and reduction of exhaust emissions has become the major research aspect in the combustion community and engine development. And because of limited crude oil reserves, the development of alternative fuel engines has attracted more and more concern. In recent year, the use of liquefied petroleum gas (LPG) as an alternative fuel has been promoted. There have been many studies about the LPG mixtures used in engines of the two wheels motorcycle and small bus in Vietnam [1,2]. Many researches showed that using LPG–air in engines will reduce the air pollution [3,4]. The laminar burning velocity is a key parameter of both fundamental and practical significant. The accurate determination of laminar burning velocity of combustible mixtures have received particular attention as being: (i) a basic physiochemical property of the premixed combustible gasses, (ii) important in studying flame stabilization, (iii) directly determines the rate of energy released during combustion, (iv) a fundamental parameter that influences the performance and emissions of the combustion process in many combustion devices [5], (v) needed to understand the laminar flamelet concepts [6], (vi) a property that affects the quench layer thickness, ignition delay time and ignition energy of the combustible mixture and (vii) needed to calibrate and validate the chemical reaction mechanisms for combustion simulations of different applications. There are several techniques for measuring the laminar burning velocity of combustible gas, such as flat counterflow flames [7,8], flat adiabatic flames stabilized above a perforated plate burner to achieve nearly stretch-free conditions [9,10], freely (outwardly) propagating spherical flames [11,12], etc. The combustion bomb method introduces the outwardly propagating spherical flame and has been widely used due to its simple flame configuration, well-defined flame stretch rate and well-controlled experimentation [11,13]. Practically, the outwardly propagating flame is more similar to flame propagation in spark-ignited engines [14].

The object of this study is to measure the unstretched laminar burning velocities of LPG–air mixtures using the schlieren photographic method and a high-speed camera in a constant volume bomb (or called freely propagating spherical flames method) at equivalence ratios of 0.7 to 1.4, initial pressures of 50, 100 and 150 kPa, and preheat temperatures between 300 K and 400 K.

2. MEASUREMENT OF LAMINAR BURNING VELOCITY

Laminar burning velocity can be deduced from schlieren photographs as described in [12]. For a spherically expanding flame, the stretched flame velocity, S_n, reflecting the flame propagation speed, is derived from the flame radius versus time data as:

$$S_n = \frac{dr_u}{dt} \qquad (1)$$

where r_u is the radius of the flame in schlieren photographs and t is the time. Therefore, S_n can be directly obtained from the flame photo.

The flame stretch rate, α, proposed by Williams [15] defines flame stretch as the fractional time rate of change of a flame surface element of area A:

$$\alpha = \frac{1}{A}\frac{dA}{dt} \qquad (2)$$

where A is the surface area of flame. For a spherically outwardly expanding flame front, the flame stretch rate can be simplified as:

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{1}{4\pi r_u^2}\frac{8\pi r_u\, dr_u}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \qquad (3)$$

The flame speed can be related to flame stretch rate through the linear relationship given by Bradley et al. [12]:

$$S_l - S_n = L_b\,\alpha \qquad (4)$$

where S_l is the unstretched flame speed, and L_b is the Markstein number (Markstein length) of burned gases. From Eqs. (1) and (3), the stretched flame velocity, S_n, and flame stretch rate, α, can be calculated.

The unstretched flame speed, S_l, can be obtained as the intercept value at $\alpha = 0$, in the plot of S_n against α, and the burned gas Markstein number L_b is the slope of S_n–α curve.

The unstretched laminar burning velocity, u_l, is deduced from S_l using:

$$u_l = S_l \frac{\rho_b}{\rho_u} \qquad (5)$$

where ρ_u is the density of the unburned and ρ_b is that of the burned gas at the adiabatic flame temperature.

Equation (5) is valid only at infinite radii for which the curvature can be neglected. For smaller radii, necessary to determine u_n as a function of α, Eq. 5 is modified to give:

$$u_n = S\left[S_n \frac{\rho_b}{\rho_u}\right] \qquad (6)$$

in which S is a generalized function and it depends upon the flame radius and the density ratio, and accounts for the effect of the flame thickness on the mean density of the burned gases. The expression for S in the present study used the formula given by Bradley et al. [11]:

$$S = 1 + 1.2\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right] - 0.15\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right]^2 \tag{7}$$

where δ_l is laminar flame thickness, given by $\delta_l = \nu/u_l$, in which ν is the kinematic viscosity of the unburned mixture.

Bradley et al. [11] presented a second definition of stretched burning velocity, u_{nr}, which is based on the rate of appearance of burned products. Because of the finite flame thickness, values of the two burning velocities differ. At smaller radii the effect of flame thickness is important, but it is less so at larger radii. As the radius tends to infinity, both u_n and u_{nr} tend towards u_l. In [11], u_n and u_{nr} were shown to be related by:

$$u_{nr} = \frac{\rho_b}{\rho_u - \rho_b}\left(S_n - u_n\right) \tag{8}$$

3. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

3.1. The cylindrical bomb

The present experiment is conducted in a stainless steel, cylindrical constant volume bomb (D = 200 mm, L = 220 mm) equipped with two opposites quartz windows (100 mm diameter, 40 mm thick) at two circular sides to make the inside observable. Two tungsten electrodes (dia. 0.5 mm), located along a diameter of the cylinder, are linked to a high voltage source (about 10 kV). The gap between the electrodes is adjustable and is usually fixed around 1 mm. Ignition is produced at the centre of the cylinder. The combustible mixture is heated by 3 electric heaters to obtain the desired preheat temperature. An absolute-pressure transducer, model Kistler 6061B, with a charge amplifier Kistler 5011, are used to monitor the pressure change in the cylindrical bomb with the pressure histories recorded by a digital oscilloscope, as shown in Fig. 1.

3.2. Mixture preparing and measurement technique

The detailed contents of LPG used in this study are listed in Table 1.

Firstly, a vacuum pump is used to extract air inside the bomb to a certain pressure P_v below the atmospheric pressure. After that, the reactant mixture of LPG and air is prepared by adding gases at appropriate partial pressures to reach the desired initial pressure P_u.

$$\Delta P = P_u - P_v = X_1 \times \left(P_u - P_v\right) + X_2 \times \left(P_u - P_v\right) \tag{9}$$

where ΔP is the amount of mixture pressure needed for adding gases into the chamber, X_1 is mole fraction of LPG and X_2 is mole fraction of air in the mixture ($X_1 + X_2 = 1$).

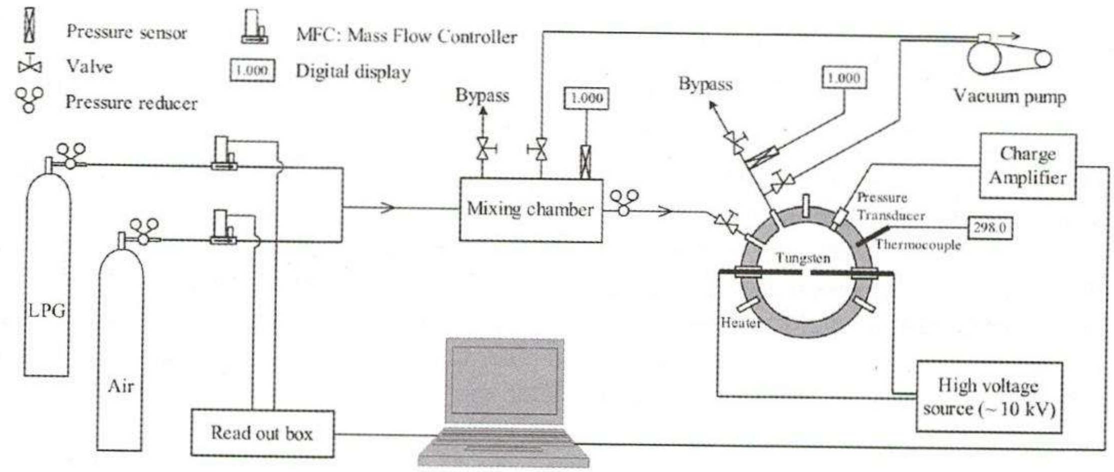


Fig 1. Schematic of the flow system.

Table 1. Contents of LPG components

Component	n-C_4H_{10}	C_3H_8	i-C_4H_{10}	C_4H_8	C_5H_{10}	C_3H_6	C_2H_6
Volume fraction (%)	42.52	27.61	25.76	1.70	1.44	0.94	0.03

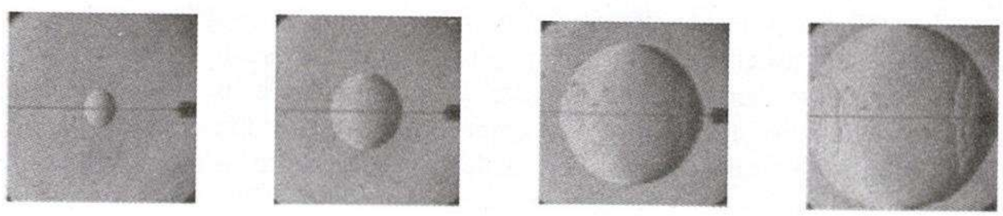


Fig 2. Schlieren images of the flame evolution in the cylindrical bomb.

The reactant mixture is allowed to stand 15 minutes in order to let the mixture quiescent. When ready preparing, the combustible mixture is spark-ignited at the centre of the chamber using minimum spark ignition energies to control ignition disturbances. The flame propagates spherically, as shown in Fig. 2. The flame propagation sequence is imaged with schlieren photography and recorded using high-speed digital motion camera (Phantom v7.2). Present measurements are limited to flames having diameters larger than 12 mm to avoid ignition disturbances and smaller than 50 mm to limit pressure increases during the measuring period to values less than 0.7% of the initial pressure. After combustion is completed, the chamber is vented to the laboratory exhaust system and then purged with dry air to remove condensed water vapor prior to refilling for the next test.

The characteristics of the ignition can influence the measured value of burning velocity. As we know, the role of an ignition is to initialize a flame, which can overcome the tendency for the flame to quench because of the high stretch rate during the early stage of flame propagation. The ignition energy, above the minimum ignition energy, can lead to very apparent flame propagation, due to the expansion of the spark plasma and the conductive energy transfer from it. Ignition energies were adjusted by trial so that they were close to the minimum ignition energy in order to minimize effects of initial flame acceleration due to excessive ignition energies. The chosen ignition energy in this paper is 45mJ.

4. RESULTS AND DISCUSSIONS

4.1. Stretched flame velocity

In order to characterize the flame propagation regarding the stretch that is applied to it, one can plot the evolution of the stretched flame velocity in function of the flame radius, as shown in Fig. 3. It is obvious that the stretched flame velocity gives a decrease at the initial stage, and then increases gradually with the radius. The flame radii are analyzed only beyond 6 mm at which ignition effects could be discounted.

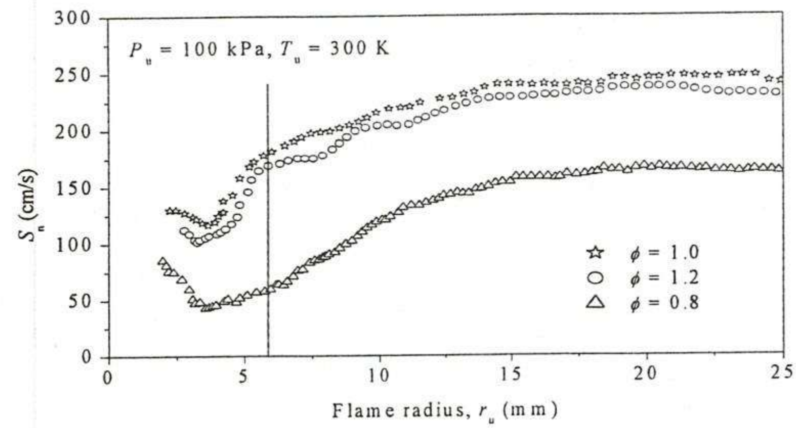
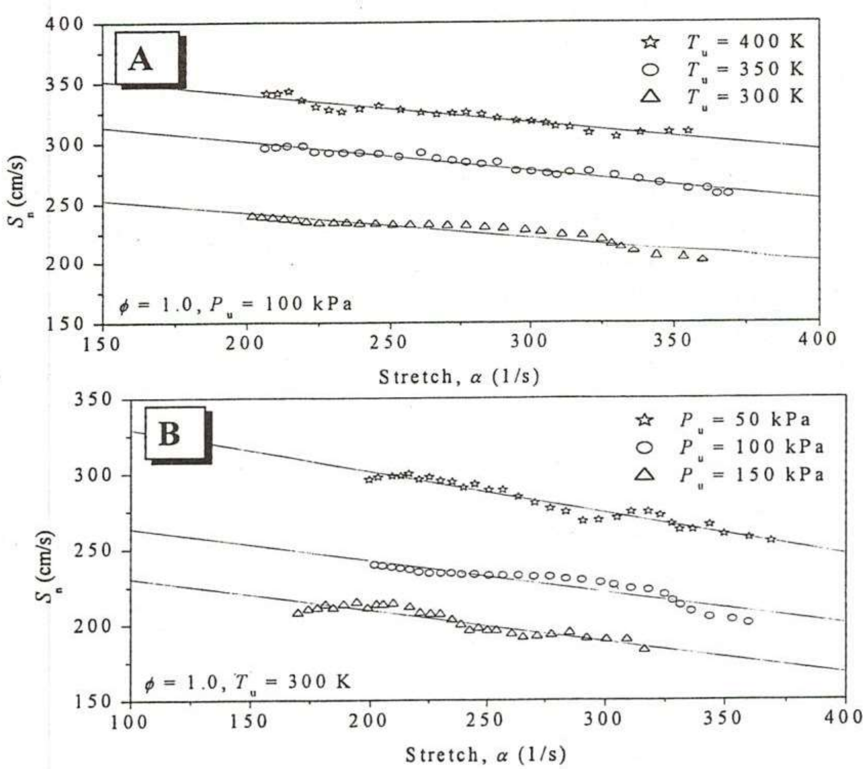


Fig 3. Variations of stretched flame velocity, S_n with flame radius, r_u, and equivalence ratio, ϕ, for LPG–air mixtures at 100 kPa and 300 K.



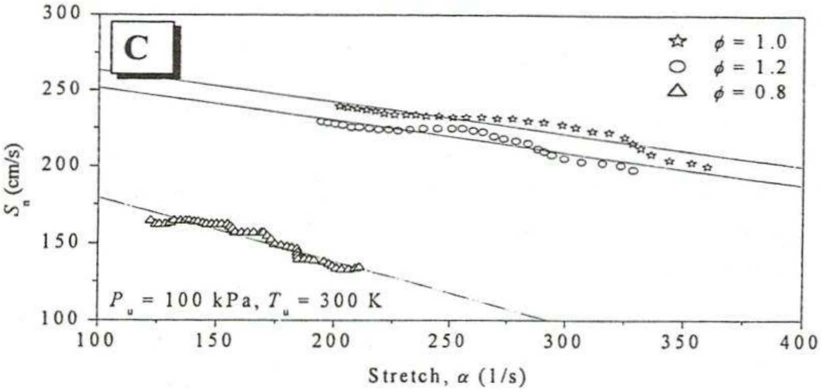


Fig 4. Variations of stretched flame velocity, S_n with flame stretch, α, and A: preheat temperatures, B: initial pressures, C: equivalence ratios, ϕ, for LPG–air mixtures. The unstretched laminar burning velocities are obtained by a zero stretch extrapolation (intersections of lines with y-axis).

Fig. 4 gives the stretched flame velocities, S_n, versus the flame stretch rates, α, at different preheat temperatures, initial pressures, and equivalence ratios. Removing the parts influenced by ignition energy, a linear correlation between the stretched flame speed and the flame stretch rate is found. As mentioned above, the unstretched flame speed, S_l, is obtained by extrapolating the line to $\alpha = 0$, while the gradient of the S_n–α curve gives the value of the Markstein number.

Shown in Fig. 5 are the variations of u_n and u_{nr}, obtained using Eqs. (6) and (8), with stretch for different preheat temperatures, initial pressures, and equivalence ratios, respectively. The difference between u_n and u_{nr} can be clearly seen. The rate of mixture entrainment, u_n, usually increases with stretch rate increases, except the case of $\phi = 0.8$. In contrast, the mass burning velocity u_{nr}, which is the burning velocity related to the production of burned gas, is always reduced by stretch. The processes of mixture entrainment and burned gas production occur in different parts of the flame; u_n is defined at the front of the flame and u_{nr} at the back. The difference between u_n and u_{nr} expresses the influence of flame thickness. The value of $(u_n - u_{nr})$ is largest at small radii (large stretch) where the flame thickness is of a similar order to the flame radius. In practical, the curves of u_n and u_{nr}; against the total stretch rate are extrapolated to zero stretch rate, they give almost the same value of u_l. This provides an alternative way to determine the unstretched laminar burning velocity in contrast with that of using Eq. (5).

4.2. Unstretched laminar burning velocity

Fig. 6 shows the experimental unstretched laminar burning velocities for LPG–air mixtures at 100 kPa and 300 K, over a range of equivalence ratios. As shown in this figure, LPG–air almost shows similar unstretched laminar burning velocities with n-butane–air [16], and the present results fall between those of propane–air [17] and iso-butane–air mixtures [16]. The maximum unstretched laminar burning velocity of LPG–air mixture at 100 kPa and 300 K is about 41.8 cm/s at $\phi = 1.1$.

And shown in Fig. 7 are measured laminar burning velocities versus equivalence ratios for LPG–air mixtures with the preheat temperature of 300 K, at 50, 100 and 150 kPa. It shows that the unstretched laminar burning velocities decrease with the increase of initial pressure.

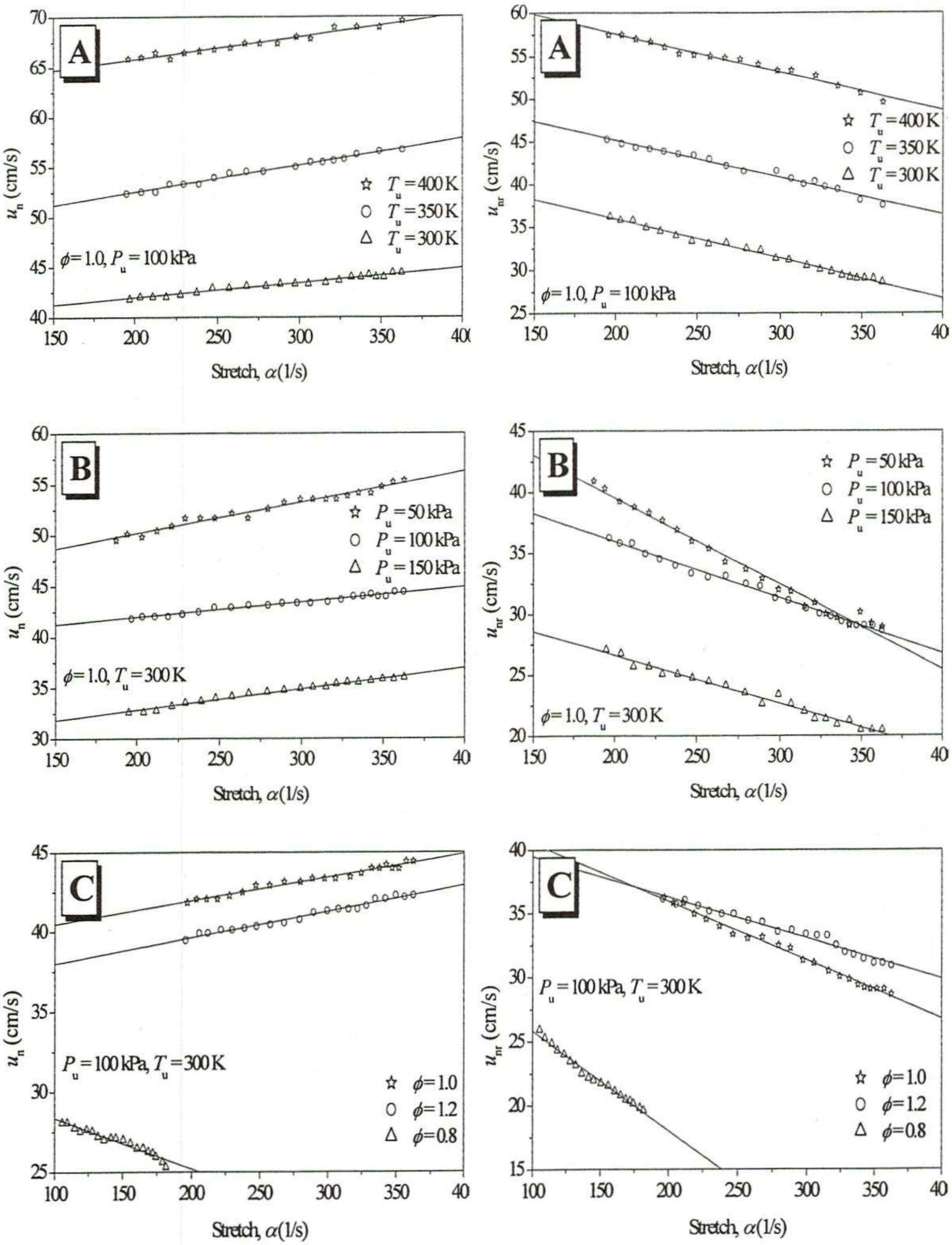


Fig 5. Variations of u_n and u_{nr} with flame stretch, α, and A: preheat temperatures, B: initial pressures, C: equivalence ratios, ϕ, for LPG–air mixtures.

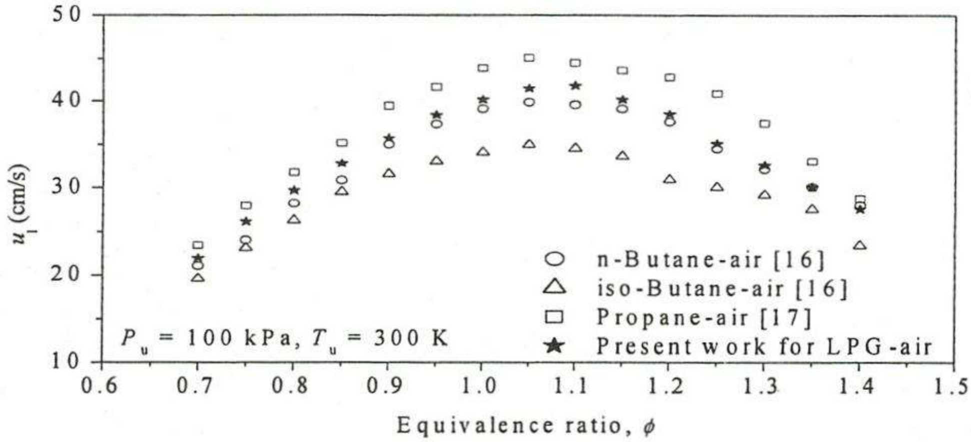


Fig 6. Experimental unstretched laminar burning velocities as a function of equivalence ratio, ϕ, for LPG–air mixtures at 100 kPa and 300 K, where the results of butane and propane are plotted as well.

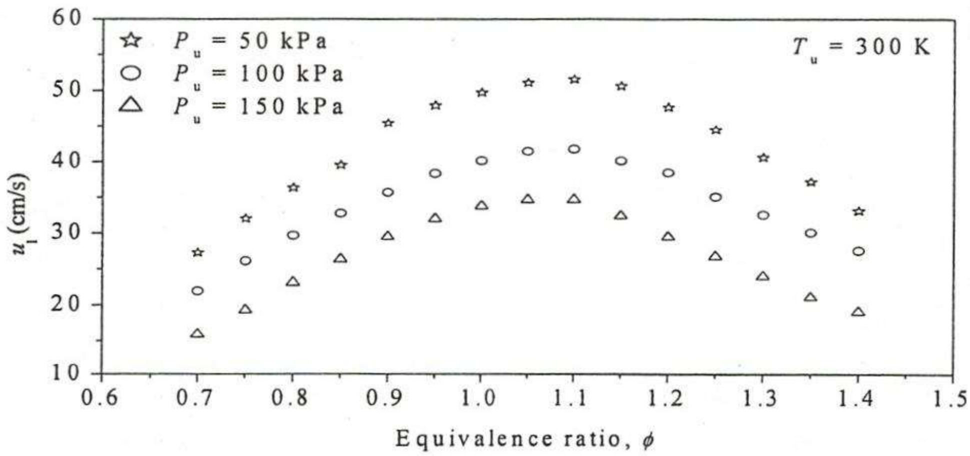


Fig 7. Experimental unstretched laminar burning velocities as a function of equivalence ratio, ϕ, for LPG–air mixtures at different initial pressure.

5. CONCLUSIONS

In this paper, the unstretched laminar burning velocities of LPG–air mixtures were measured over a wide range of preheat temperatures, initial pressures and equivalence ratios, using expanding spherical flames method. The maximum unstretched laminar burning velocity of LPG–air mixture at 100 kPa and 300 K is about 41.8 cm/s at ϕ = 1.1. The speeds of expanding spherical flames were shown to increase with increasing flame radius. Measured unstretched laminar burning velocities increase with decreasing initial pressure and increasing preheat temperature. Because a flame has a finite thickness, two different stretched burning velocities have been recognized, one based on the disappearance of the unburned mixture, and another based on the appearance of the burned products. The different values for a given flame stretch were also shown in this study.

SỬ DỤNG PHƯƠNG PHÁP ĐO SỰ DI CHUYỂN CỦA MÀNG LỬA HÌNH CẦU ĐỂ XÁC ĐỊNH VẬN TỐC CHÁY CHẢY TẦNG KHÔNG CO GIÃN CỦA HỖN HỢP LPG–KHÔNG KHÍ

Trần Mạnh Vũ
Trường Đại học Bách Khoa, ĐHQG-HCM

TÓM TẮT: *Bài báo giới thiệu một phương pháp đo sự di chuyển của màng lửa hình cầu trong buồng cháy đẳng tích để xác định vận tốc cháy chảy tầng không co giãn của hỗn hợp khí dầu mỏ hóa lỏng (LPG)–không khí. Bộ thí nghiệm bao gồm một buồng cháy hình trụ tròn có gắn kính trong suốt ở hai đầu để có thể quan sát được sự hình thành và di chuyển của màng lửa bên trong. Sự di chuyển của màng lửa theo thời gian được ghi lại bằng máy quay phim cao tốc. Vận tốc cháy chảy tầng của hỗn hợp LPG–không khí được đo ở nhiều điều kiện nhiệt độ và áp suất khác nhau, với nhiều độ đậm đặc khác nhau để nghiên cứu sự ảnh hưởng của những điều kiện ban đầu này đến vận tốc cháy chảy tầng của hỗn hợp.*

REFERENCES

[1]. Bui Van Ga, T*he two wheels motorcycle running on Liquefied Petroleum Gas (LPG): a solution for urban air pollution in Vietnam,* 6th ASEAN Science Technology Week, 221, Brunei, 17–19 September (2001).

[2]. Bui Van Ga, Tran Van Nam, Ho Tan Quyen, Tran Dien, *Design the small bus run with Liquidized Petrol Gases (LPG) on vehicle Daihatsu Hijet Jumbo 1.6*, International Conference on Automotive Technology, ICAT'02, Paper 034, Hanoi, 24–28 October (2002).

[3]. Bui Van Ga, Tran Van Nam, *Combustion of LPG–Air lean mixture: a solution for pollution reduction of motorcycles in Vietnam*, The 6th General Seminar of the Core University Program "Environmental Science and Technology for sustainability of Asia", 361–367, Kumamoto, Japan, 2–4 October (2006).

[4]. Ning Z., Chan T.L., *On-road remote sensing of liquefied petroleum gas (LPG) vehicle emissions measurement and emission factors estimation*, Atmospheric Environment 41, 9099–9110 (2007).

[5]. Bayraktar H., Durgun O., I*nvestigating the effects of LPG on spark ignition engine combustion and performance,* Energy Conversion and Management 46, 2317–2333 (2005).

[6]. Lipatinkov A.N., Chomiak J., *Turbulent flame speed and thickness: phenomenology, evaluation and application in multi-dimensional simulations,* Progress in Energy and Combustion Science 28, 1–74 (2002).

[7]. Egolfopoulos F.N., Zhu D.L., Law C.K., *Experimental and numerical determination of laminar flame speeds: mixtures of C_2–Hydrocarbons with oxygen and nitrogen*, Proceedings of the Combustion Institute 23, 471–478 (1990).

[8]. Vagelopoulos C.M., Egolfopoulos F.N., Law C.K., F*urther considerations on the determination of laminar flame speeds with the counterflow twin flame technique*, Proceedings of the Combustion Institute 25, 1341–1347 (1994).

[9]. Bosschaart K.J., De Goey L.P.H., D*etailed analysis of the heat flux method for measuring burning velocities,* Combustion and Flame 132, 170–180 (2003).

[10]. Coppens F.H.V., De Ruyck J., Konnov A.A., *The effects of composition on burning velocity and nitric oxide formation in laminar premixed flames of* $CH_4 + H_2 + O_2 + N_2$, Combustion and Flame 149, 409–417 (2007).

[11]. Bradley D., Gaskell P.H., and Gu X.J., *Burning velocities, Markstein lengths, and flame quenching for spherical methane–air flames: a computational study, Combustion and Flame 104, 176–198 (1996).*

[12]. Bradley D., Hicks R.A., Lawes M., Sheppard C.G.W., and Woolley R., *The measurement of laminar burning velocities and Markstein numbers for Iso-octane–Air and Iso-octane–n-Heptane–Air mixtures at elevated temperatures and pressures in an explosion bomb,* Combustion and Flame 115, 126–144 (1998).

[13]. Sun C.J., Sung C.J., He L., Law C.K., *Dynamics of weakly stretched flames: quantitative description and extraction of global flame parameters*, Combustion and Flame 118, 108–128 (1999).

[14]. Law C.K., Jomaas G., Bechtold J.K., *Cellular instabilities of expanding hydrogen/propane spherical flames at elevated pressures: theory and experiment.* Proceedings of the Combustion Institute 30, 159–167 (2005).

[15]. Williams F.A., *Combustion Theory*, 2nd edition, Benjamin, (1985).

[16]. Davis S.G., Law C.K., *Determination of and Fuel Structure Effects on Laminar Flame Speeds of* C_1 *to* C_8 *Hydrocarbons*, Combustion Science and Technology 140, 427–449 (1998).

[17]. Law C.K., *Reduced kinetic mechanisms for applications in combustion systems*, Springer, pp. 15–26, (1992).