LAMINAR FLAME PROPAGATION OF HYDROGEN-AIR MIXTURES IN TUBES[+]

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Abstract

The laminar flame speed of hydrogen-air mixture as a function of the composition of the unburned gases has been measured during the pre-pressure period, in tubes of diameters (0.038, 0.048, 0.057 & 0.1 m.) using optical technique. A detailed density correction scheme was employed for determination of burning velocities from the measured flame speed.

A mathematical model is employed to calculate the emissivity and temperature of flame, assuming that the dominant emitting specie is water vapour. The maximum values of burning velocity, flame speed, and flame temperature occur in a rich mixture of hydrogen concentration of about (40%) independently of tube diameter. Burning velocities of hydrogen-air mixtures measured at (298^oK) and (100kPa) agree well with the published results.

A correlation equation has been derived from the observed burning velocities covering a hydrogen-concentration range of (10-70 volume %) and a tube diameter range of (0.038 – 0.1 m.), at initial mixture temperature (Tu = 298^oK) and (Po=100 kPa).

المستخلص

تم في هذا البحث قياس سرعة انتشار اللهب الطباقية (Burning Velocity) لخليط الهيدروجين مع الهواء المسبق الخلط باستخدام طريقة الأنبوب والتقنية البصرية ولمدى واسع من النسب المئوية للهيدروجين في الخليط حيث تم قياس الزمن الذي تستغرقه جبهة اللهب لقطع مسافة محددة. وتم قياس درجة حرارة اللهب عن طريق قياس الطاقة المنبعثة من جبهة اللهب وحساب شعاعية اللهب.

تم دراسة تأثير قطر الأنبوب على سرعة انتشار اللهب الطباقية وتمت جميع القياسات خلال فترة ثبوت الضغط (Pre-Pressure Period) وذلك لأستخدام طريقة نسبة الكثافة (Density Ratio Method) في حساب سرعة انتشار اللهب. أقصى قيمة لسرعة انتشار اللهب ،سرعة جبهة اللهب وكذلك درجة حرارة اللهب تحدث عند النسبة الحجمية للهيدروجين (٤٠%) غير معتمدة على قطر الأنبوب.

تم الحصول على نتائج مقاربة للنتائج العملية المنشورة لسرعة انتشار اللهب لخلائط الهيدروجين مع الهواء المقاسة عند درجة حرارة ابتدائية (298^oK) وضغط ابتدائي(١٠٠ kPa) مما يؤكد دقة الطريقة والأجهزة المستخدمة في القياس. كذلك تم اشتقاق معادلة تطبيقية لسرعة انتشار اللهب للنتائج التي تم الحصول عليها. فالمعادلة تأخذ بنظر الاعتبار تأثير النسبة المئوية الحجمية للهيدروجين في الخليط للمدى (١٠ – ٧٠%) وكذلك تأثير قطر الأنبوب للمدى (0.038-0.1m.) على سرعة انتشار اللهب لخليط الهيدروجين– هواء.

Nomenclature

Su	Laminar burning velocity (m/s.).
S_f	Laminar flame speed (m/s.).
T_u	Unburned gas temperature (K).
P_o	Initial pressure (100kPa).
T_b	Burned gas temperature (K).

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ρ_u Unburned gas density (kg/m^3).
ϕ Hydrogen concentration percentage.
N Mole ratio = moles of burned gases per moles of unburned gases in equilibrium.
δ Flame thickness (mm).
I Flame thickness factor.
$\bar{\lambda}$ Mean thermal conductivity of flame region (W/m.K).
Cp Mean specific heat of flame region (J/mol. K).
ε Emissivty o flame.
σ Stefan-Boltzmann constant=5.6697*10^{-8} W/m^2.K^4
d Tube diameter (m).
D Dimensionless tube diameter (d/0.038).
E Emissive power (W).

2- Introduction

The study of combustion of hydrogen-air is interesting, as it may play an important part in future technology. Therefore, detailed knowledge on flames in hydrogen-air mixtures at various compositions is desired and important in designing and estimating the performance of combustion systems where hydrogen is used as a fuel. A program to study the basic combustion phenomena of hydrogen was initiated several years ago. This paper concerns the laminar burning velocity (S_u), which is an important fundamental parameter, it is one of the most essential parameters for analysis and interpretation of the combustion phenomena.

The burning velocity is the velocity, relative to the unburned gas, at which a plane, one-dimensional flame front a long travels the normal to its surface. It depends on the composition of the mixture and its initial temperature and pressure. Correct results can be expected only if no heat is extracted by and through the combustion vessel. Although, the theoretical definition of the burning velocity is simple, the same can not be said of its practical measurements [1].

Andrews et al. [1], have reviewed the various methods of measuring burning velocity. It was concluded that closed vessel explosion techniques give good results. In the present work results are presented for the emissivity, temperature, flame speed and burning velocity of hydrogen-air mixtures derived by tube method. The optical technique has been used in measuring the laminar flame speed (S_f), for a wide range of hydrogen concentration percentages. The effect of tube diameter upon the burning velocity was is discussed.

1- Experimental Apparatus and Procedures

Measurements of flame speed and flame temperature in the pre- pressure period were made using a horizontal copper- tubes having internal diameters of (0.038, 0.048, 0.057 and 0.1 m) and length of (1.92 m). A schematic diagram of the equipment is given in Figure(1) for one tube.

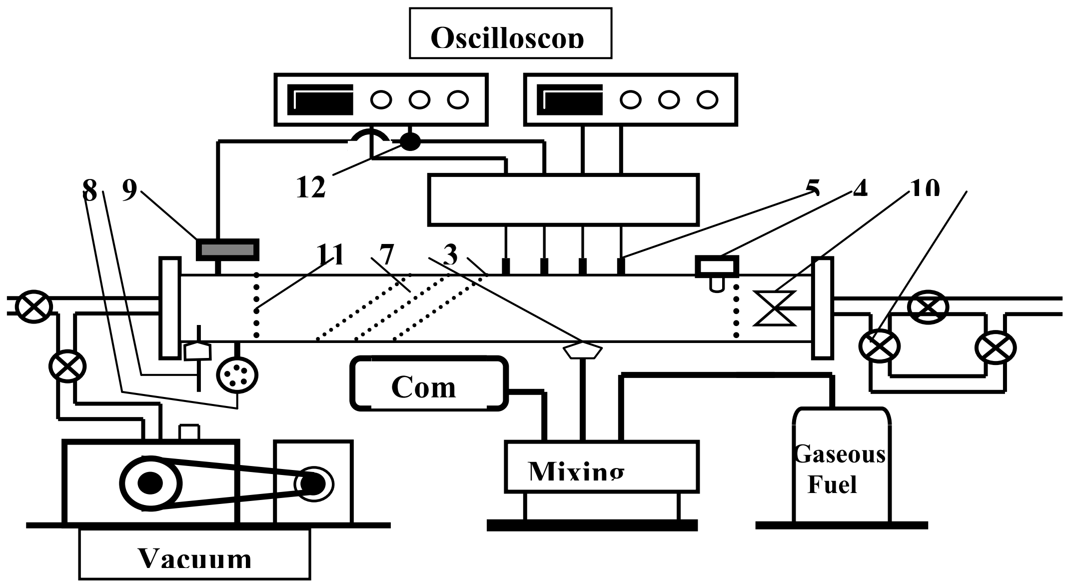
Connection of other parts to the tube is done by welding to achieve closed system for getting a nearly complete vacuum. The system can be used for different types of gaseous and liquid fuels under different conditions.

Mixtures preparing operation plays an important role in a melioration of the combustion phenomenon. This operation is made depending on the partial pressures of the constituents according to Gibbs-Dalton law, in a separate mixing unit, which had previously been evacuated to (0.00l kPa).

The combustion tube is sufficiently purged of any previous mixture, and then refilled with the prepared mixture to atmospheric pressure. The mixture is left for five minutes to become homogeneous, before ignition.

Mixtures are ignited at the open end of the combustion tube by ignition unit (giving ignition energy of about 3 Joule). The occurrence of flame is monitored by a two dual channel digital storage oscilloscope, and by four photodiodes, (0.25 m) apart, upon which is imposed a transient temperature rise, resulting in voltage signals which are detected by the oscilloscopes. So the time of any two successive signals and the value of voltage signal are recorded and used to obtain the flame speed and flame temperature respectively.

The first photodiode is (0.2 m) apart from the spark ignition plug to ensure that measurements occur at fully developed flame front.



No.	Part	No.	Part
1.	Copper tube.	7.	Heating tape.
2.	Drying unit.	8.	Vacuum pressure gauge.
3.	Inlet valve	9.	Thermocouple.

Fig. (1) Schematic diagram of the experimental apparatus

3- Experimental Results and Discussion:

The flame temperature has been obtained using the following equation:

$$Tb = \left(E / \varepsilon.\sigma\right)^{0.25} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots(1)$$

A mathematical model given by [2], is employed to calculate the emissivity of flame (ε), assuming the flame of uniform temperature , composition and the dominant emitting species is water vapour.

Hydrogen flames emit chiefly infrared bands of (H_2O), [3]. So the present results were obtained for emission bands within the infrared. There are four important emission bands for water vapour, the center of the first band has a wave length of (1.38μm), while the other bands have (1.87, 2.7 & 6.3μm). The individual absorption band consists of a large number of absorption lines because in the wave length range considered, the molecules change their vibrational and rotational energy simultaneously. The individual lines actually have a finite thickness and a shape similar to that of a probability curve. So, for water vapour one can carry out spectral calculations using detailed informations about the mean line intensity and mean line width to spacing ratio at each spectral location.

A computer program is made for computing the basic parameters of the emissivity of flame .The flame energy (E) was measured via photodiodes. The magnitude of voltage signal is proportional to the intensity of radiation from flame front, therefore the value of the emissive power (E) is obtained and used in conjunction with the calculated emissivity to obtain the flame temperature from equation (1).

The results are obtained for a wide range of hydrogen concentration percentages at different beam lengths (i.e tube diameters).

Figures (2 and 3) show the flame emissivity and temperature respectively, which have been measured for hydrogen-air mixtures using different tube diameters. The emissivity is affected by temperature in two ways: the molecular- absorption and emission coefficients of the gas increase somewhat, but the number of absorbing gas molecules in a fixed path length at a fixed partial pressure decreases. It can be observed that for a given tube diameter, the emissivity (ε) decreases as the mixture strength goes from the lean limit towards the stoichiometric, and then increases as the rich limit is approached. This behaviour of the emissivity results from the correlation of flame temperature with the mixture strength.

The results indicate a large dependence of (ε) upon the tube diameter (i.e beam-length or path-length). It can be observed that with increasing tube diameter the emissivity increases, as the number of radiating molecules in a given path length at a fixed total pressure of one atmosphere increases.

Figure (4) shows the measured flame speed (S_f) as a function of the hydrogen concentration percentage for the four tubes used in the present work.

Using the density ratio method introduced by [4], the burning velocity (Su) is calculated from the measured flame speed (S_f) assuming ideal gas behavior, by employing the following relation, which is valid at pre-pressure period of combustion.

$$S_u = \frac{T_u}{T_b}.I.N.S_f \qquad \ldots(2)$$

where (I) is the flame thickness factor and (N) is the mole ratio, which is [the ratio of the number of moles of products to that of reactants]. Procedures were suggested for estimation of (I) for constant volume bomb measurements by [4], [5] and [6]. In the present work, the magnitudes in (I) and (N) have been calculated using the analysis of [4]. Figures (5&6) show the variation (N) and (I) with the mixture strength.

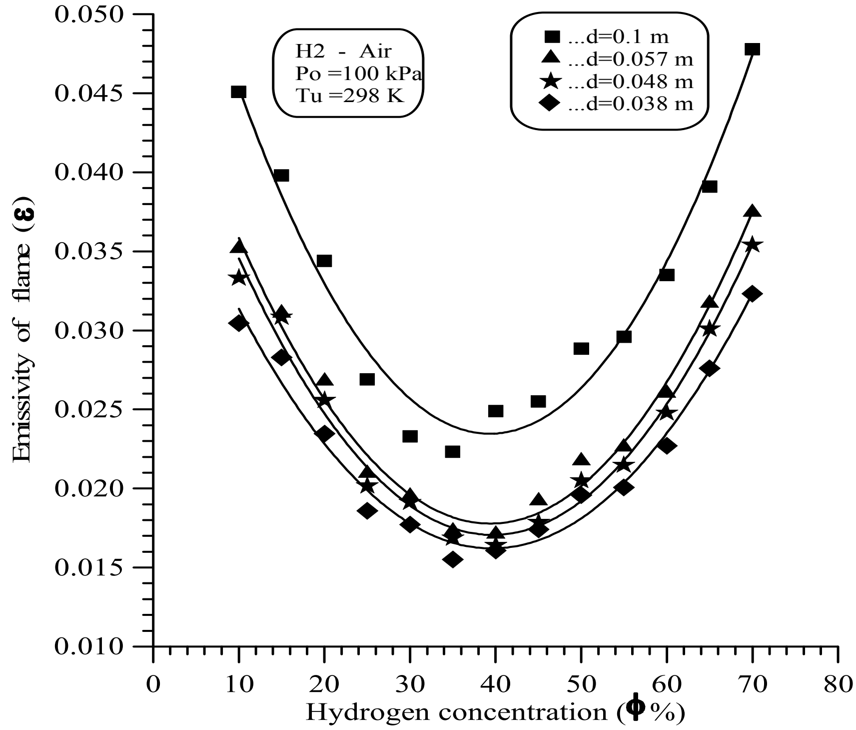


Fig. (2) Emissivity of flame as a function of Hydrogen concentraion for different tube diameters.

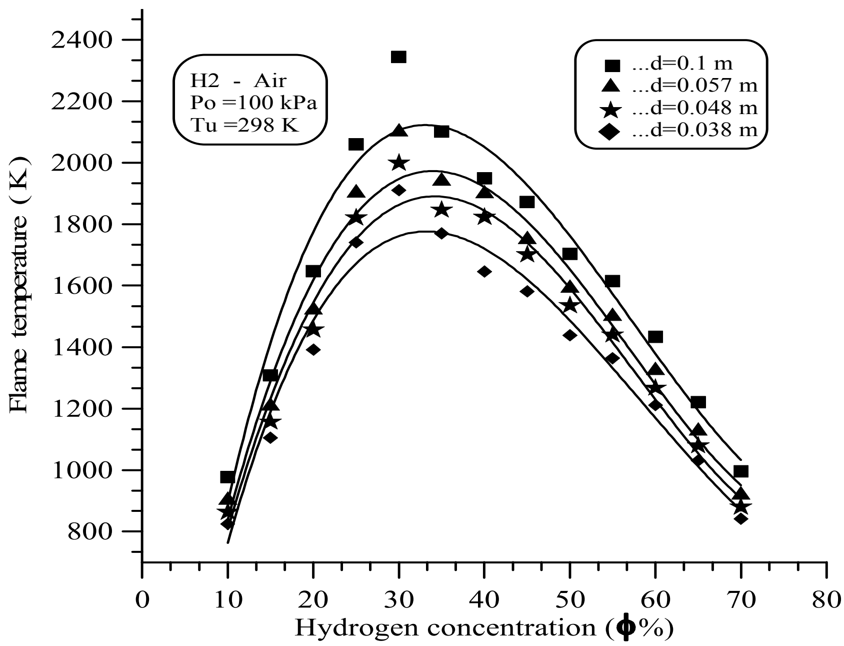


Fig. (3) Flame temperature as a function of Hydrogen concentration for different tube diameters.

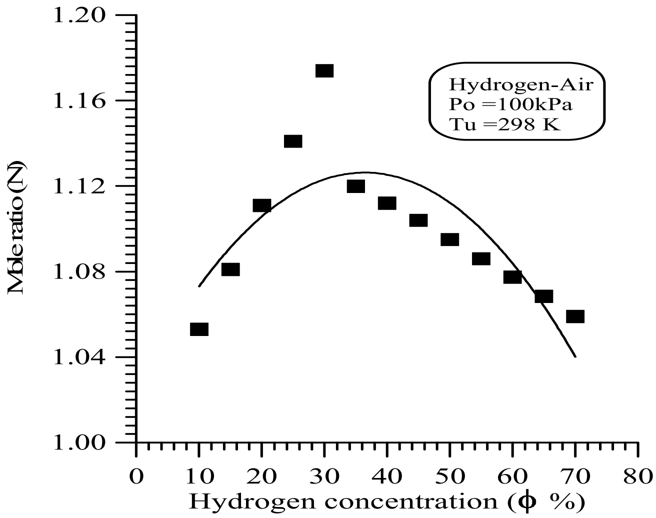


Fig. (5) Variation of mole ratio with Hydrogen concentration percentage.

The flame thickness is calculated according to [7] by using the following equation:

$$\delta = \frac{2\bar{\lambda}}{S_u . C_p . \rho_u} \qquad \text{............(3)}$$

The variation in flame thickness with hydrogen concentration percentage, as obtained in the present work, is shown in Figure. (7), for different tube diameters

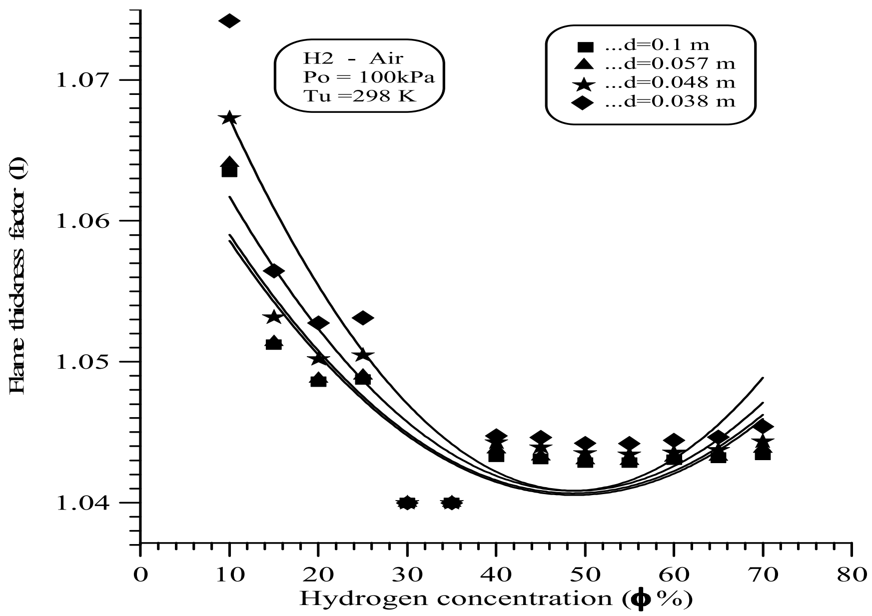


Fig. (6) Flame thickness factor as a function of Hydrogen concentration for different tube diameters.

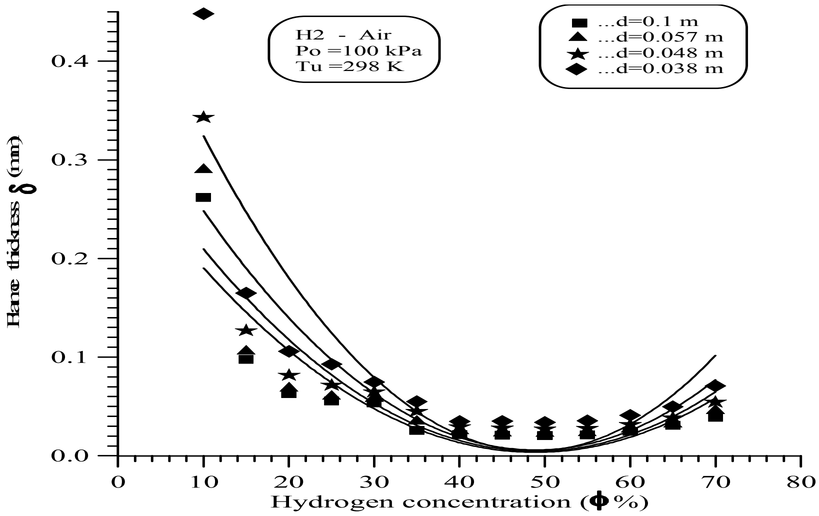


Fig. (7) Flame thickness as a function of Hydrogen concentration for different tube diameters.

This parameter increases rapidly as the flammability limits are approached, and this can account for the attendant greater relative spread of burning velocity. Flame thickness is reduced with increase in tube diameter, and this leads to more accurate numerical values of burning velocity.

3.1- <u>Burning Velocities</u>

The burning velocities of hydrogen-air mixtures were obtained from the measured flame speed and flame temperature by using equation (2). Results were obtained for unburned mixture temperature of 298^{o}K at initial pressure of (100 kPa).

The first set of experiments was conducted using a tube of (0.1 m) diameter.To validate the method and the apparatus used in the present work, the above set of measurements were taken with hydrogen –air mixtures at (298^{o}K) and (100 kPa), to be compared to reported burning velocity data. Measured burning velocity is shown in Figure(8) along with other investigator's data. It can be observed that the agreement is good and this confirms the validity of the method used.

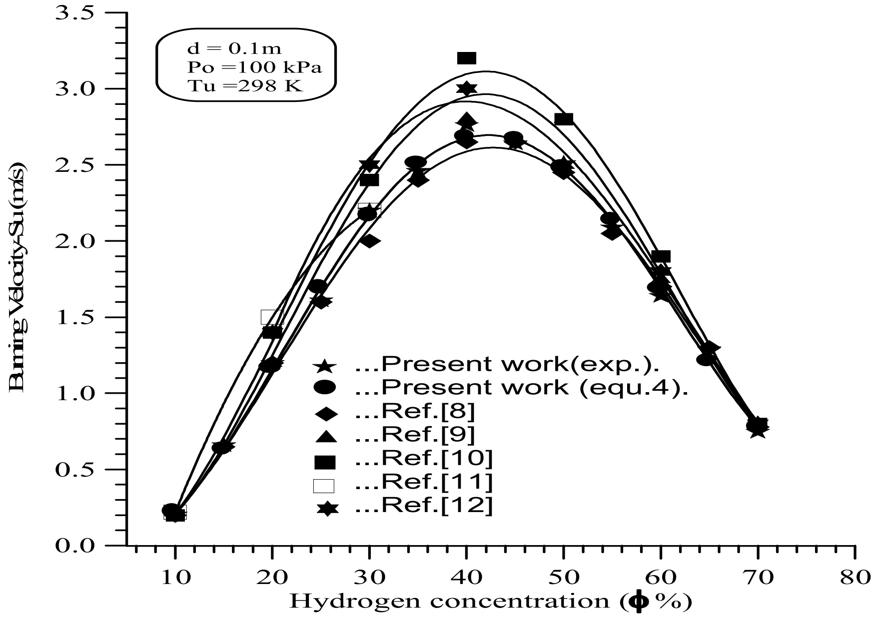


Fig. (8) Comparison of present results with the data of previous investigators for hydrogen-air mixtures.burning velocity as a function of hydrogen concentration .

3.2 The Effect of Tube Diameter on the Burning Velocity

Figure(9) shows the variation in burning velocities with the hydrogen concentration percentage, for different tube-diameters. The data points represent the mean values of more than ten repetitive experiments at each hydrogen-air percentage ratio. The burning velocity becomes maximum at a ratio of about (40%) independently of the tube diameter, and decreases gradually on either side of the maximum. It can be observed that the effect of tube diameter appears clear near the maximum value of burning velocity on either side and this effect decreases as the lean and rich limits of flammability are approached, as the spread of results tends to be nearer. This is mainly due to quenching of flame at tube wall, which brings about the termination of chain branching reaction that affects the flame temperature, [13]. The latter effect seems to be greater on the higher values of burning velocity in comparison to lower values.

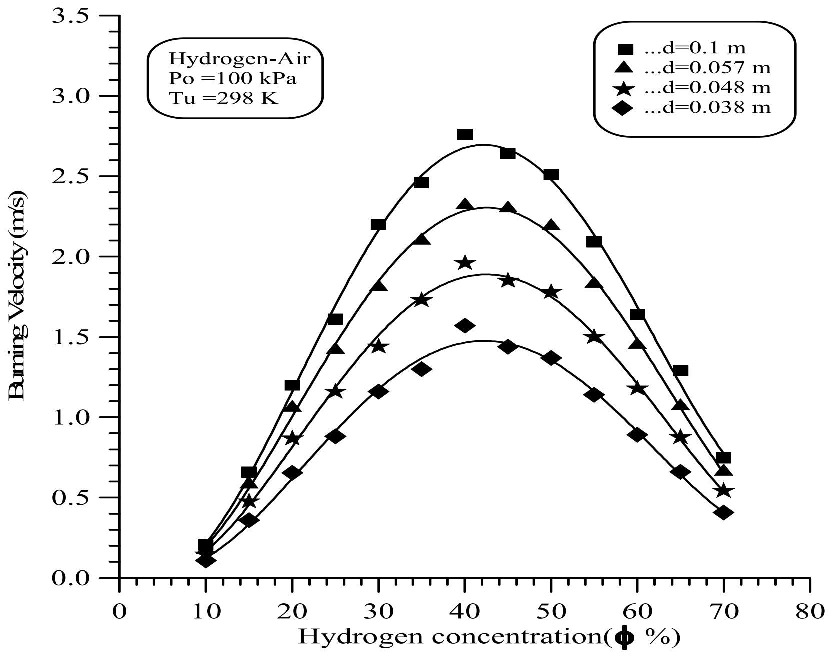


Fig. (9) Burning velocity as a function of Hydrogen concentraion for different tube diameters.

3.3- Tube Diameter Dependence of Burning Velocity

As shown in Figure. (9), the measured burning velocities can be represented as a function of hydrogen concentration percentage and tube diameter by fitted curves. The following empirical expression estimates the burning velocities for the ranges $(10 \leq \phi \leq 70)\%$ and $(0.038 \leq d \leq 0.1\ m)$, at $Tu=298^{o}K$ and pressure of 100 kPa with small deviations.

$$Su(\phi, D) = a + b\phi + c\phi^2 + d\phi^3 + e\phi^4 \qquad \text{.....(4)}$$

where a, b, c, d & e are constants varying with dimensionless tube diameter (D) as follow:

$a = 76.0212 - 72.1953\ D + 19.9248 D^2$

$b = -10.914+6.9122D-2.3284D^2$
$c = 0.229597+0.48311D-0.06001D^2$ (5)
$d =-0.00317-0.0124D+0.0017825D^2$
$e = [2.5322+6.5843D-0.82219D^2]*10^{-5}$

The maximum difference between experimental data and those calculated by using equation (4) is less than ± 5%, as shown in Figure(8) for the tube of diameter (0.1 m).

4- <u>Conclusions</u>

Laminar burning velocities of hydrogen-air mixtures have been determined over a wide range of hydrogen concentration percentages and tube diameters, using advanced optical technique, and employing density ratio method.

The experimental results obtained for hydrogen – air mixtures suggest that the density ratio method and the tube method with the new optical technique, by which the measurements were confined to the pre pressure combustion period, yield reliable burning velocity data.

The following empirical relation represents the mixture strength and tube diameter dependence of burning velocity:

$S_u (\phi, D) = a + b\phi + c\phi^2 + d\phi^3 + e\phi^4$

where:

$a = 76.0212-72.1953 D +19.9248D^2$
$b = -10.914+6.9122D-2.3284D^2$
$c = 0.229597+0.48311D-0.06001D^2$
$d =-0.00317-0.0124D+0.0017825D^2$
$e=[2.5322+6.5843D-0.82219D^2]*10^{-5}$

which can be used with an error of ± 5% for the following conditions ($T_u = 298^oK$), (ϕ = 10– 70)%, (d =0.038– 0.1 m) & P_o = 100 kPa.

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