CONSTANT VOLUME COMBUSTION CHARACTERISTICS OF HHO GAS

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Rezumat. Viteza normală de ardere laminară reprezintă o caracteristică importantă a tuturor combustibililor gazoşi. Determinarea ei se poate face prin experimente desfăşurate în celule experimentale închise în care se produc procese de ardere la volum constant. Lucrarea prezintă metodologia şi tehnica utilizată pentru determinarea acestei caracteristici în cazul gazului HHO, aparent un nou amestec hidrogen-oxigen obţinut într-un nou tip de electrolizor.

INTRODUCTION

The laminar burning velocity is one of the most important properties characterizing the combustion of homogeneous fuel-air mixtures. It is a parameter controlling the heat delivery in confined spaces leading to explosions, and is entering several models of turbulent combustion and quenching; it also affects the ignition limits, ignition energy and ignition delay of a fuel-air mixtures. The laminar burning velocity is correspondingly of practical importance for evaluation of explosion hazard in confined spaces or for the design and analysis of internal combustion engines and industrial burners.

The laminar burning velocity has been measured for a variety of fuels, at atmospheric pressure and various temperatures, using tubes and burners, and at elevated pressures and temperatures, using constant volume bombs. These fuels included hydrogen, pure hydrocarbons and mixtures of hydrocarbons with hydrogen, or with chemically inert diluents gases [1] … [16]. For the hydrocarbons-air mixtures with hydrogen addition, it was found that the laminar flame velocity can be linearly correlated with a parameter Yh_2, expressing the relative quantity of hydrogen [13]–[15].

The mixtures of hydrocarbon-air enriched with hydrogen attracted the specialists even in the early 70's as a method to improve the efficiency and emissions of the spark ignition engines. It appeared as a possibility to shift the engine stable operation to leaner fuel-air mixtures, and as a solution to enhance the combustion of some fuels like methane. One of the main limitations in using the hydrogen addition to the main commercial fuels at car engines is its generation and storage on board.

To avoid the storage problems, in the last years, the possibilities to produce hydrogen continuously on board were studied. The hydrogen production by electrolysis of water using the engine output as a source for the energy needed, appeared thus as a technical solution to be explored.

Recently, an apparently new mixture of hydrogen and oxygen called HHO gas has been developed by Hydrogen Technology Applications Inc. of Clearwater, Florida (International patent pending). The new HHO gas is produced with a new type of electrolyzer, which is presented as remarkable by its high efficiency of the gas production. The HHO gas composition would include not only the conventional mixture of hydrogen and oxygen, but also some additional species [17].

The present paper presents experimental measurements of the rate of pressure rise at 2 bar initial pressure and laminar flame velocity evaluation for the HHO gas, in comparison with the similar results obtained with stoichiometric hydrogen-oxygen mixtures. The experiments were conducted in a constant volume bomb and therefore give results which are valid over an elevated range of pressure and temperature.

EXPERIMENTAL APPARATUS AND PROCEDURE

The combustion bomb used in this study was cylindrical, with an internal capacity of 0.146 liters and was designed for pressures up to 150 bar. Optical access to the combustion bomb was provided by two 95 mm diameter and 50 mm thickness quartz windows, mounted at its opposite ends.

Mixtures were ignited using an electrical system provided with, an inductive/capacitive discharge circuit and a spark plug with two electrodes of stainless steel, which extend to the center of the bomb. The electrical discharge parameters were measured with a high voltage probe Tektronix P6015 and a current probe Tektronix P6021.

The combustion bomb was provided with three main instrumentation systems Figure 1.

The dynamic pressure rise inside the bomb was measured with a Kistler 601A piezoelectric transducer, fitted flush to the wall, and a Kistler 5001C charge amplifier. Spherical symmetry and centering of the flame front could be checked by comparing its arrival time at four ionization probes, spaced around the perimeter of the median plane of the bomb. A general survey of the combustion process and a check of the model used for calculating the burning velocity were obtained by the record of the successive positions of the flame front using a Schlieren visualization technique. The system was provided with a high-speed camera CCD model Mega Vision MS70K, capable of taking up to 91250 frames per second, Figure 2.

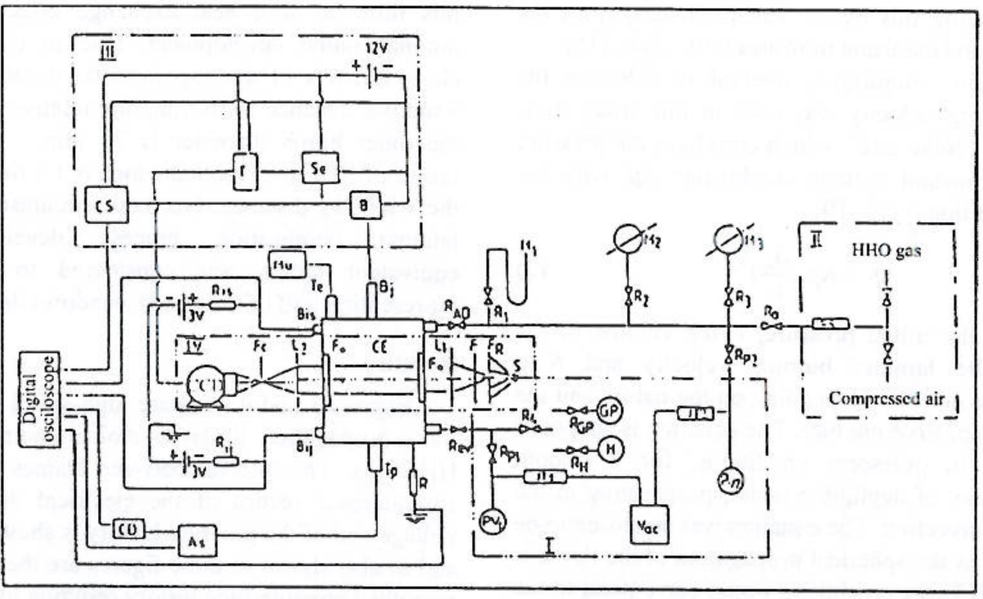

Fig. 1. Scheme of the experimental set-up, with gas handling systems and instrumentation.

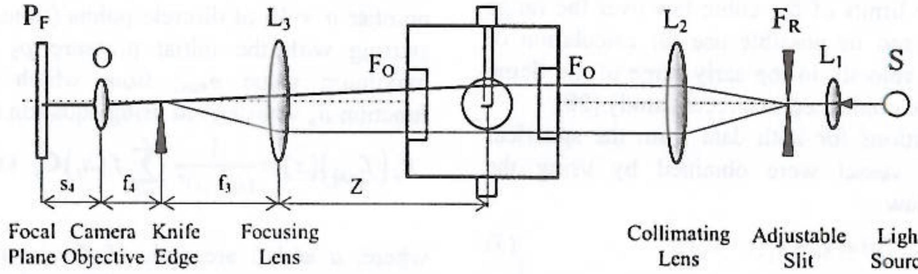

Fig. 2. Scheme of the optical system.

The sensitivity λ of the optical system by applying the equation

$$\lambda = z + (1-M)^{*} f_3/M + s_4/M^2, \qquad (1)$$

where, M is the magnification parameter of the imaging system, $M = f_4/f_3 = 0.054$, was $\lambda = 16833$. The optical records of the flame front positions were synchronized with the pressure and ionization probes signals and stored by a digital oscilloscope Yokogawa DL 9400. All the records were triggered by the voltage signal of the electrical discharge.

Two additional systems were provided for the evacuation of the burned gas from the bomb and its filling with the fresh gas, at the desired composition and pressure (systems I and II shown in Figure 1).

To prepare for a run, the bomb was cleared firstly by the displacement of the burned gas with compressed air. The bomb was then empted with two vacuum pumps (Pv_1 and Pv_2), connected at the two ends of the bomb, until a final pressure of 0.5 mm Hg was reached. The vacuum was checked with a mercury manometer (M1) having two arms of 0.5 m and finally with two Pirani gauges (JT_1, and JT_2) connected to a vacuum-meter (Vac). For a vacuum pressure of 0.5 mm Hg, it was appreciated that the residual burned gas at the beginning of a new run, was less than 1% [15].

The HHO gas was admitted slowly inside the bomb until the pressure of 2 bar was reached, this being the base condition investigated. In the case of hydrogen-oxygen mixture hydrogen was admitted firstly to the bomb until the calculated partial pressure was reached, the manifold was then repumped, and oxygen was than admitted to the final pressure of 2 bar. The measurement of partial pressures and final pressure was made with calibrated Bourdon gauges, with a precision of 0.6% in the domain 0…4 bar. The air used for the displacement of the burned gas was provided by a special compressor, to avoid any traces of oil. The humidity of the gas filling the bomb was avoided by a special filter with silicagel, fixed on the admission line.

After the filling procedure, 3…5 min were allowed the temperature to equilibrate, and the turbulence to dissipate.

ANALYSIS OF DATA

Calculation of the laminar burning velocity from the pressure-time history

The laminar burning velocity can be determined from the measured pressure-time history in the combustion bomb by first solving for the rate of mass fraction burned and then dividing this by the calculated density of the unburned gas and the flame front area [10]...[12], [15].

A different, simplifying method to calculate the laminar burning velocity was used in this study. It is based on the "cubic law", which correlates the pressure rise during constant volume combustion Δp, with the time from ignition t, [18, 19],

$$\Delta p = Kp_0 \frac{S_u^3}{V} t^3 \qquad (2)$$

where, p_0 is the initial pressure, V the volume of the vessel, S_u the laminar burning velocity and K a dimensionless constant depending on the nature and the state of the explosive mixture. The equation is supposed to be valid in quiescent conditions, for a smooth spherical flame, of negligible width, propagating in the absence of convection. The equation was supposed to be valid as long as the spherical propagation of the flame is not disturbed. These conditions would correspond to the early stage of flame propagation, with small changes of pressure. This method was considered appropriate for this comparative study of HHO gas and hydrogen-oxygen stoichiometric mixtures.

The validity limits of the cubic law over the range $p_0 \le p \le 2\ p_0$, and its possible use for calculation of normal burning velocity in the early stage of the flame propagation were confirmed in a recent study [20].

Best correlations for both data from the spherical and cylindrical vessel were obtained by using the modified cubic law

$$\Delta p = k_1 + k_2 (t - k_3)^3 \qquad (3)$$

with the additional parameters k_1 and k_3, representing corrections of imprecision in time and in pressure measurement.

According to equation (1) the significance of the overall constant of the cubic law is

$$k_2 = Kp_0 \frac{S_u^3}{V} \qquad (4)$$

For a spherical vessel and an isothermal compression of the unburned gas, it was found [21]

$$K = \frac{4\pi}{3}\left(\frac{\Delta p_{\max}}{p_0}\right)\left(\frac{p_{\max}}{p_0}\right)^2 \qquad (5)$$

and

$$k_2 = \Delta p_{\max}\left(\frac{p_{\max}}{p_0}\right)^2 \cdot \frac{S_u^3}{R^3} \qquad (6)$$

where, $p_{\max}$ is the maximum pressure reached in the constant volume combustion, in the early stage of combustion investigated, and R – the radius of the vessel.

The equation (6) was used to calculate the laminar burning velocity, for a radius R equivalent to a sphere, comprised inside the cylindrical combustion bomb. It was considered that the laminar combustion process starts with the spark discharge and lasts until the flame front reachs for the first time the bomb walls. During this time no wall heat exchange effect disturbs the laminar flame development. Due to the geometrical characteristics of the experimental bomb – the quartz windows distance is 36 mm, one relative the other, and the inner bomb diameter is 72 mm – an equivalent radius of 32.7 mm resulted which is 1.8 times the half of the windows distance. On these circumstances, for the laminar combustion process development, the equivalent radius was considered to be 18 mm, representing half of the quartz windows distance.

Results

Figures 3 and 4 compare high-speed records of the flame propagation, for H_2-O_2 stoichiometric mixture and HHO gas. The interval between frames is 16.4 μs. A simultaneous record of the electrical discharge high-voltage and of the pressure history is shown in Figures 5 and 6; also shown in these figures are the corresponding smoothed pressure-time history resulting by a mathematical treatment with Bernstein polynomials technique, and the cubic model pressure trace.

The original recorded pressure, represented by number of successive steps values was reduced to a number n = 40 of discrete points (time, pressure value) starting with the initial pressure p_0 up to the first maximum value $p_{\max}$, from which the polynomial function B_n was derived using equation (7),

$$B_n\left(f_{[a,b]}\right)(x) = \frac{1}{(b-a)^n} \cdot \sum_{i=0}^{n} f(a_i)\, C_n^i \cdot (x-a)^i \cdot (b-x)^{n-i} \qquad (7)$$

where, a and b are ends of the interval where the f function is given, a_i intermediary points $a_i = a + i\cdot(b - -a)/n$ on $[a, b]$, $i = 0,\ldots,n$ for which the pressure values are known, $a_0 = a$ şi $a_n = b$.

The edge of the flame appears reasonably well defined on Figures 3 and 4 already starting from the third frames. The flame kernel is centered in the spark plug gap and is spherical. If the time origin is considered coincidental with the increasing part of the electrical discharge high voltage (after it goes down approximately 3.25 kV) one can consider an initial phase of flame kernel development, with an increase in pressure above the initial 2 bar of only 0.25 percent. The first phase corresponds thus to 5 frames for the hydrogen-oxygen mixtures and to 7 frames for HHO gas.

The next distinctive phase on the optical records is represented by a spherical propagation for both gases, until the flame front reaches the closest walls: the frame number 17 for the hydrogen-oxygen gas, and the frame number 19 for the HHO gas. No disturbance due to buoyancy is apparent. It is confirmed that the pressure limit of 4 bar, accepted when calculating the laminar burning velocity is not exceeded when the flame is close to the quartz windows, corresponding frame number 10 for hydrogen-oxygen mixture and 12 for HHO gas with a pressure increase of 17% for H_2-O_2 stoichiometric mixture and 14% for HHO gas. The last 7 frames characterizing the development stage of flame propagation seems to be more similar to a planar flame travel between two opposite plane parallel plates. At the end of this stage the pressure was 4.34 bar for H_2-O_2 mixture and 4.18 bar for HHO gas. Another supplementary 7 frames for hydrogen-oxygen mixture, and 9 frames for HHO gas, the flame propagates along the walls with a corresponding smoothed pressure rise up to 15.6 bar and 15.2 bar correspondingly, until the flame undergoes a transition to detonation. The occurrence of detonation is evidenced by an intense illumination of the bomb and high amplitude oscillations of the pressure.

The set of parameters k_1, k_2 and k_3 in the cubic law (3) calculated for the studied gases are shown in Table 1.

By means of equation (6) laminar burning velocities 11.00 m/s for the hydrogen-oxygen stoichiometric mixture and 10.46 m/s for the HHO gas were obtained.

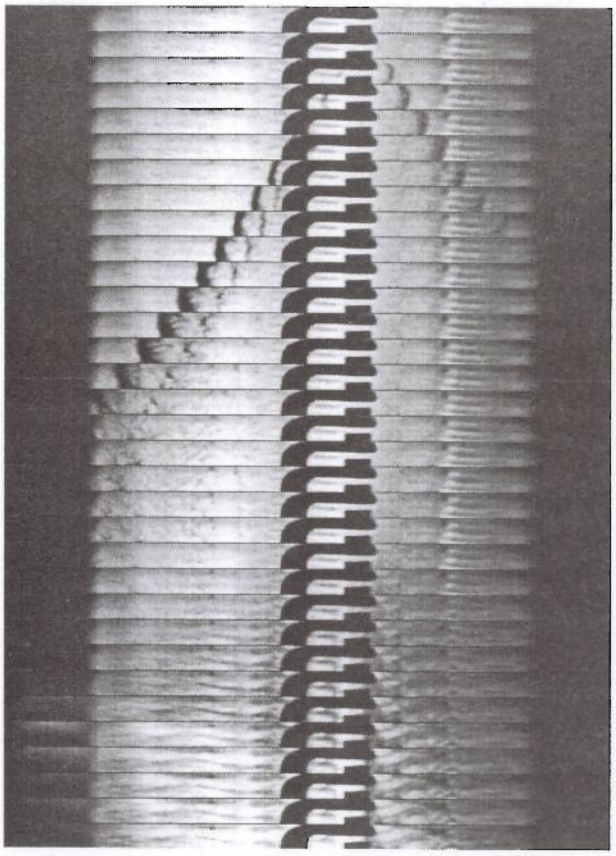

Fig. 3. High-speed motion picture record by Schlieren optical technique of flame propagation in a stoichiometric hydrogen-oxygen mixture. Frames frequency 61000/s, initial pressure 2 bar.

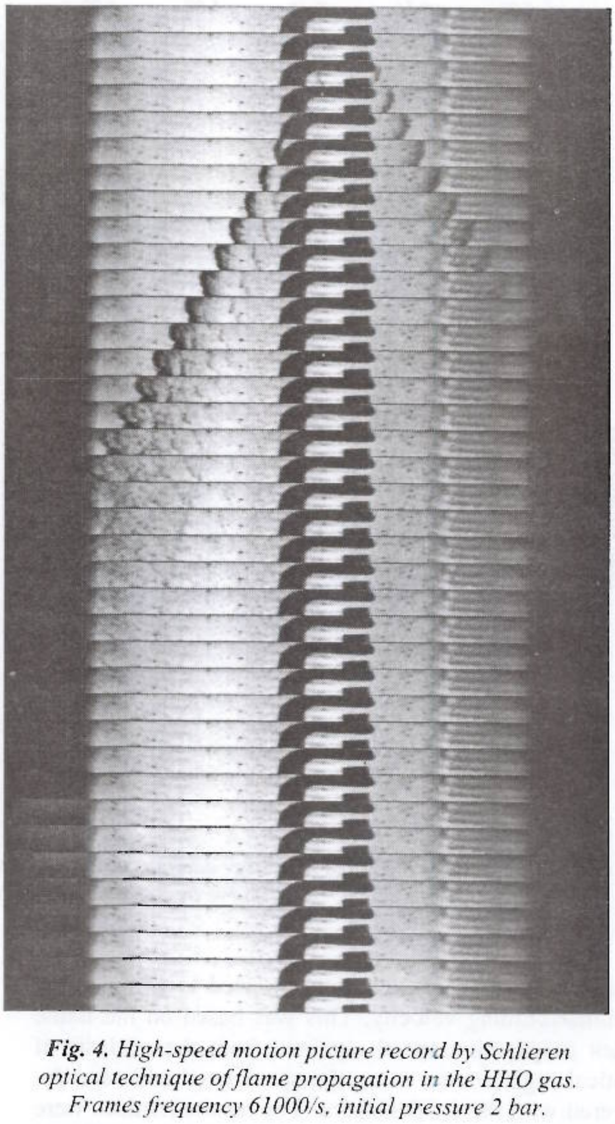

Fig. 4. High-speed motion picture record by Schlieren optical technique of flame propagation in the HHO gas. Frames frequency 61000/s, initial pressure 2 bar.

Table 1. Best fit parameters for Eq. (3), applied to pressure rise during combustion, at the initial pressure p_0 = 2 bar

Gas	k_1 [bar]	$k_2 \times 10^{-4}$[bar·s^{-3}]	$k_3 \times 10^3$ [s]	Correlation coefficient
H_2-O_2, stoich.	2.004	189.01	0.578	0.9994
HHO	2.006	149.92	0.338	0.9993

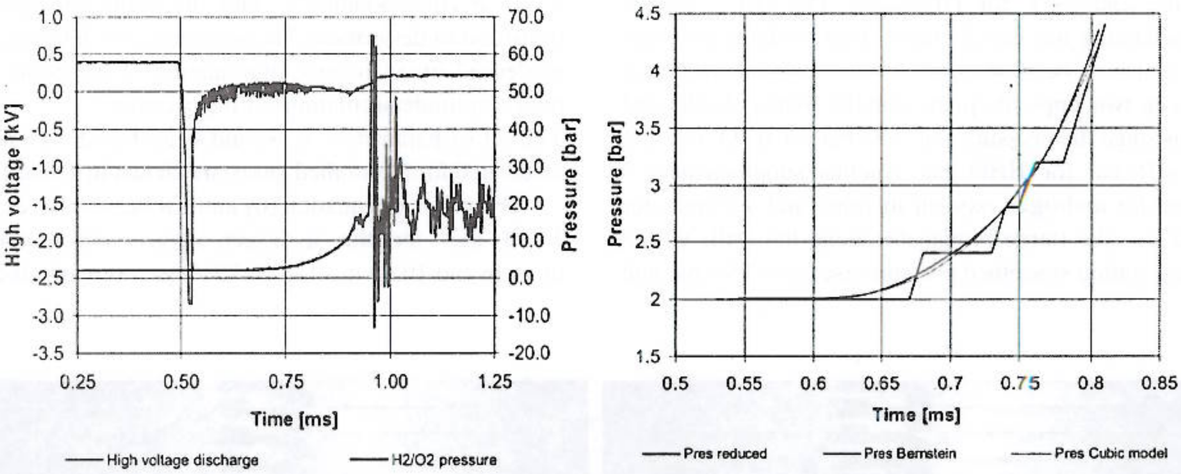

Fig. 5. High voltage electrical discharge and pressure-time histories at hydrogen-oxygen stoichiometric mixture burning (a); original and smoothed pressure curve by Bernstein and cubic model polynomials (b).

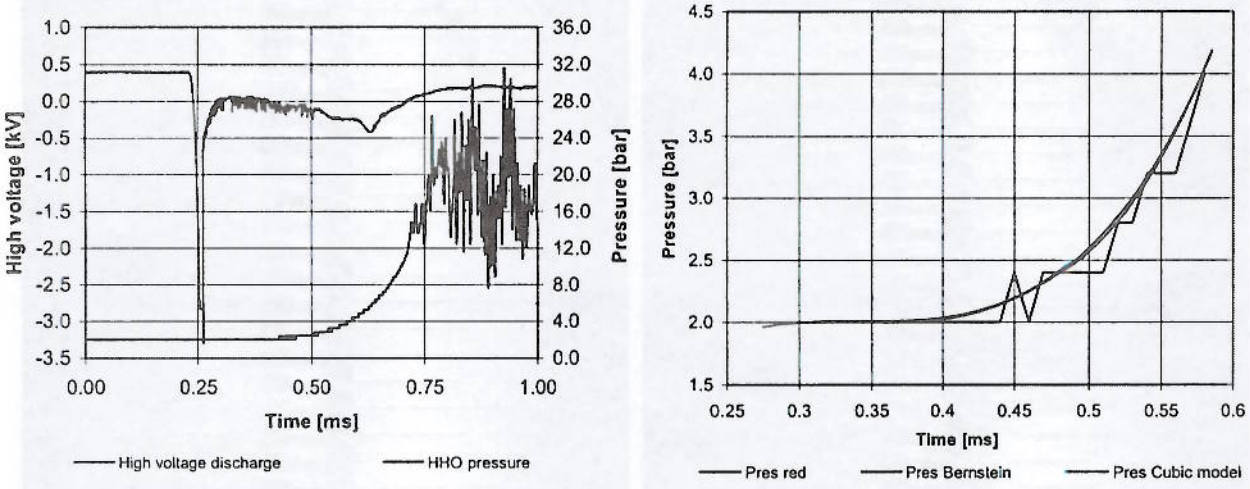

Fig. 6. High voltage electrical discharge and pressure-time histories at HHO gas burning (a); original and smoothed pressure curve by Bernstein and cubic model polynomials (b).

Another method was additionally used to evaluate the laminar burning velocity. This was based on the flame front propagation speed obtained from the analysis of optical registrations using the specialized software delivered with the CCD camera. The resulted values were 111.78 m/s for hydrogen-oxygen stoichiometric mixture and 90.98 m/s for HHO gas. Assuming the same expansion index 8.33 for both gases, as for the stoichiometric H_2-O_2 mixture, the corresponding laminar flame velocities obtained were 13.41 m/s and 10.92 m/s respectively.

CONCLUSION

It can be considered that the combustion characteristics of the two gases are close, with somewhat lower chemical activity of the HHO gas. This is evident by a longer phase of flame kernel formation and development, and by a 5% lower laminar burning velocity. An uncertainty of calculated values should be considered, for the stoichiometric hydrogen-oxygen mixture laminar burning velocity, the comparison with other reported data (i.e. 11.82 m/s [22]) gives a deviation of ± 13.5%.

REFERENCES

[1] Gray, K., Linnett, J., Mellish, C., *Burning velocity determinations. Part 9. Propylene+air and propane+air mixtures*, Trans. of the Faraday Society, 48, 1155–1163, 1952.

[2] Manton, J., von Elbe, G., Lewis, B., *Burning velocity measurements in a spherical vessel with central ignition*, Fourth symp. (international) on combustion, Baltimore, Williams & Wilkins, pg. 358, 1953.

[3] Gibbs, G., Calcote, H., *Effect of molecular structure on burning velocity*, Journal and Engineering Data, 4, 226–237, 1959.

[4] Scholte, T., Vaags, P., *The burning velocity of hydrogen-air mixtures and mixtures of some hydrocarbons with air*, Combustion and Flames, 8, 495–501, 1959.

[5] Rallis, G., Garforth, A., Steinz, J., *Laminar burning velocity of acetylene-air mixtures by the constant volume method: Dependence on mixture composition, pressure and temperature*, Combustion and Flames, 9, 345–356, 1965.

[6] Andrews, G., Bradley, D., *Determination of burning velocities: A critical review*, Combustion and Flames, 18, 133–153, 1972.

[7] Metghalchi, M., Keck, J., *Laminar burning velocity of propane-air mixtures at high temperature and pressure*, Combustion and Flames, 38, 143–154, 1980.

[8] Ryan III, T., W., Lestz, S., S., *The laminar burning velocity of Isooctane, N-heptane, Methanol, Methane and Propane at elevated temperatures and pressures, in the presence of a diluent*, SAE Paper 800103, 1980.

[9] Molkov, V., Nekrasov, V., *Normal burning velocity of acetone-air flames in dependency of pressure and temperature*, Fizika Gorenya i Vzryva, 17, 45–49, 1981.

[10] Metghalchi, M., Keck, J.,C., *Burning velocities of mixtures of air with methanol, isooctane and indolene at high pressure and temperature*, Combustion and Flames, 48, 191–210, 1982.

[11] Milton, B., E., Keck, J., C., *Laminar burning velocities in stoichiometric hydrogen and hydrogen-hydrocarbon gas mixtures*, Combustion and Flames, 58, 19–22, 1984.

[12] Rhodes, D., B., Keck, J., C., *Laminar burning speed measurements of indolene-air diluent mixtures at high pressures and temperatures*, SAE Paper 850047, 1985.

[13] Yu, G., Law, C., K., Wu, C., K., *Laminar flame speeds of hydrocarbon-air mixtures with hydrogen addition*, Combustion and Flames, 63, 339–348, 1986.

[14] Sher, E., Ozdor, N., *Laminar burning velocities of n-Butane/air mixtures enriched with hydrogen*, Combustion and Flames, 89, 214–221, 1992.

[15] Apostolescu, N., Chiriac, R., Miron, D., *Caracteristiques de la combustion laminaire de quelques melanges hydrogene-hydrocarbures gazeux*, Revue ENTROPIE, 182, 13–20, 1994.

[16] Oancea, D., Razus, D., Ionescu, N., I., *Burning velocity determination by spherical bomb technique. II Application to gaseous propylene-air mixtures of various compositions, pressures and temperatures*, Revue Roumaine de chimie, 45, 319–330, 2000.

[17] Santilli, R., M., *A new gaseous and combustible from water*, International Journal of Hydrogen Energy, 31, 1113–1128, 2006.

[18] Maisey, H., *Gaseous and dust explosion venting*, Chemical and Process Engineering, 527–535, 1965.

[19] Zabetakis, M., *Flammability characteristics of combustible gases and vapors*, US Bureau of Mines Bulletin No. 627, 1965.

[20] Razus, D., Oancea, D., Movileanu, C., *Burning velocity evaluation from pressure evaluation during the early stage of closed-vessel explosions*, Journal of Loss Prevention and the Process industries, 19(4), 334–342, 2006.

[21] Nagy, J., Conn, J., Verakis, H., *Explosion development in a spherical vessel*, US Bureau of Mines, Report no. 7279, 1969.

[22] Zitoun, R., Deshaies, B., *Burning Velocities of Rich H_2-O_2 Flames under Cryogenic Conditions*, Combustion and Flame 109, 427–435, 1997.

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Dr. Dorin Stanciu (Catedra de Termotehnică, Facultatea de Inginerie Mecanică, Universitatea POLITEHNICA din București)

Modelare și simulare numerică în dinamica gazelor

Marți 21 februarie 2006 orele 14.00

Ing. Dipl. Raluca Cazanescu (Institutul de Proiectări Construcții Tipizate (IPCT), București)

Studii de caz privind reabilitarea termică a unor clădiri din România

Luni 20 martie 2006 orele 14.00

Prof. Hideo Kawahara (Shipping Technology Department, Oshima National College of Maritime Technology)

Dynamic Vortical Structures in a Two-Dimensional Bluff-Body Slot Burner

(*Continuare în pagina 115*)