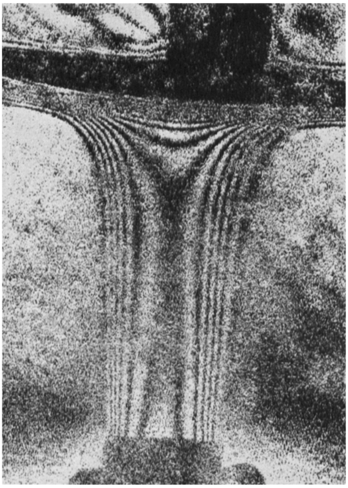

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Fig. 1b.

The Laminar Flame Speed of Methane-Oxygen Mixtures and Some Remarks on Flame Pressure

The laminar burning velocity S_L of methane-oxygen mixtures at normal pressure and temperature (760 Torr, 20°C) has been the subject of several papers [1-6]. The data for stoichiometric mixtures are in the range 3.2-6.2 m/sec, and since flame stability correlations use functional relations of S_L^2, there is a real need for reliable data. The purpose of this letter is to check the published data and to supply new experimental material.

The flow rates of O_2 and CH_4 (technical grade, i.e., > 99.5% and > 99% respectively) were measured with calibrated flowmeters, and the flows were mixed and smoothed in a suitable arrangement. Measurements were carried out with nozzle burners of 1.52 and 2.44 mm diameter, with contours as described by Lindow [7]. The pressure drop observed with unignited mixtures shows the formation of a boundary layer which is similar to that found for larger nozzles with the particle track technique [7].

Ordinary flame photographs yield the linear part of the cone edge and the corresponding angle. Information is available [7, 8] about the real free-stream velocity u_F just before the flame front and the volumetric mean velocity u_M of nozzle flow, neglecting streamline deflection from the original direction at the nozzle mouth. This deflection has to occur, and is pronounced for the case $u_F < u_M$. Recalculating and correlating the data we get a more general relationship, appropriate for rough estimations of the velocity difference between the isothermal core velocity u_{iso}—formerly used for flame velocity calculations—and u_F (see Fig. 1). Because of the very similar nozzle

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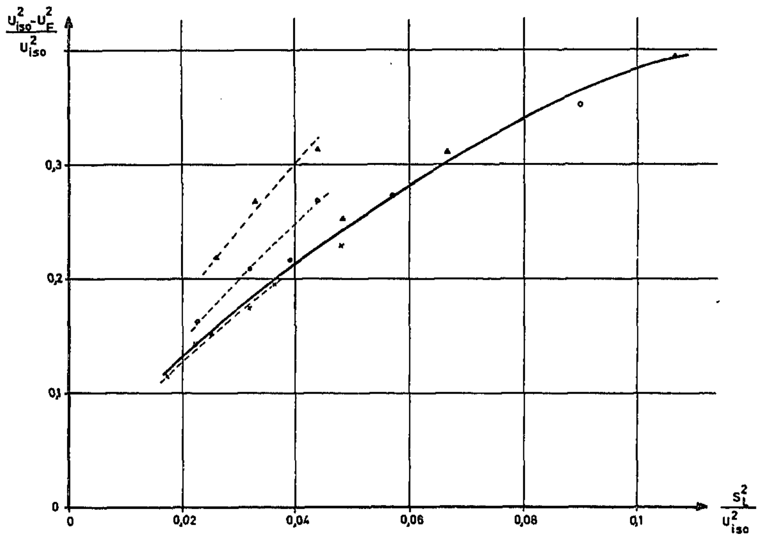

Fig. 1. Correlation between defect of impact pressures and flame back pressure: the symbols (∇, o, x) belong to different, but constant, S_L; ——— : Lindow [7]; - - - - - : Edmondson, Heap [8].

contours the boundary layer formation [7] could be calculated for the data [8].

The particular coordinates are chosen because the defect of impact pressures is related to the flame pressure characterized by S_L^2.

The values u_F, necessary for the calculation of S_L, and S_L itself, are determined with the same iteration process using the full line curve in Fig. 1 (first estimate e.g., $u_{F_o} = u_{iso}$).

This was done, because the data obtained for a given mixture composition at different flow rates and values of S_L yield a curve in Fig. 1 quite similar to that using previous data [7]. Its vertical position is very sensitive to the value used for S_L, so it is reasonable to use the previous data [7] as a standard.

The laminar flame velocities were obtained with an error of ±5% and these are plotted against the equivalence ratio ϕ in Fig. 2.

Flame velocities using the 1.52 mm nozzle were up to 10% higher than for the other nozzle with the larger differences for the richer mixtures. The values using the 2.44 mm nozzle were considered to be closest to the plane laminar flame velocity, because there was less curvature effect on the flame velocity with this burner.

In general, the stability of flames on nozzles is poor for lean mixtures and this is responsible for the lack of data in this region; the "better" the nozzle the worse is the stability. We tried to get some information with a bunsen burner, but the scatter of data is comparatively high. Thus this part of the curve in Fig. 2 is drawn as a broken line. Curves 1 and 6 were obtained using a pressure bomb, a method which is somewhat problematic in interpretation, since there are questions about the flow behavior of the unburned part of mixture. Besides this, the results do not agree with

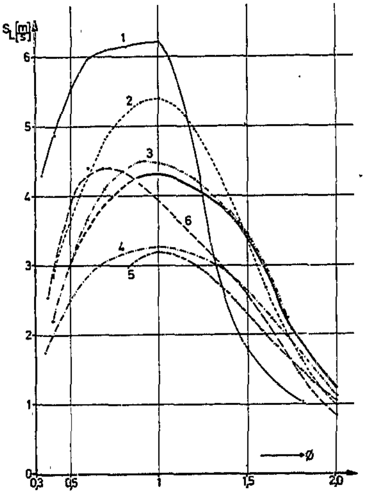

Fig. 2. Laminar burning velocity of CH_4/O_2 mixtures 760 Torr, 20°C; ϕ = equivalence ratio:

Reference		*Method*	*Gas*
———————	1	const. pressure bomb	
– – – – – –	2	unknown	O_2 with 3–4% N_2
–··–··–	3	nozzle, direct photogr., flame surface	
–·–·–·–	4	pipe, direct photogr., flame surface	O_2 with 1.5% N_2
–~–~–	5	unknown	
– – – –	6	const. pressure bomb	93% CH_4, rest C_2H_6, C_3H_8, N_2, O_2
——— – –		this work: nozzle, direct photogr., cone angle, free-stream velocity u_F; see Fig. 1.	

each other with respect to their absolute values and to the slopes for fuel rich mixtures. Curves 2 and 5 refer to publications in which the methods of measurement are not reported, so that a critical comparison cannot be made. The values from curve 4 are too small because direct photography overestimates the area of the flame surface. This phenomenon is particularly marked when a burner of very small diameter is used; the effect is well illustrated by the work of von Elbe and Mentser [11], who measured burning velocities of acetylene-oxygen mixtures which were far too low; see Bartholomé [12].

We conclude that our data correspond best with those of Singer and Heimel [3], who also worked with a nozzle burner but used the flame surface for determination of the flame velocity.

The work of Bollinger et al. [9] suggests that laminar burning velocities cannot be obtained with any degree of accuracy by means of pressure measurements unless these are taken directly before and behind the flame front (see also Ref. 10). For fast, high temperature flames, which are small in order to achieve laminar flow conditions, this is nearly impossible.

We wanted to study some effects which we believe have been usually undervalued, and therefore determined the static pressure difference between the nozzle mouth and the environment for the cases with and without flame. By compensation of the isothermal pressure difference with an appropriate bypass system, the capacity pressure gauge allowed measurements of such pressure differences—"flame pressures"—with an accuracy of ±10%, good enough for our purpose.

There are three main regions through which the gas must pass between the nozzle orifice and the nearly vertical exhaust stream (Fig. 3). In the first region a small pressure rise occurs, caused by an expansion of the streamlines and measured indirectly. This was even found directly [7] but was considered to be an error of the measurement.

After the first region, the short distance through the flame s_F to $s_{F'}$ follows (in a first approach this thickness was taken as 10. a/S_L, with the thermal diffusivity a taken at 20°C) where the pressure decreases by $\Delta p_R < \Delta p_t$, the theoretical flame pressure for an infinitely thin flame. With respect to the following section $s_{F'} - s_E$ a variation of Δp_R along the cone flank was not considered—though this exists because of the decreasing radius of curvature and because of wall and tip anomalies. Δp_R in this sense is an integral mean value over the cone surface, about 0.9 Δp_t for our nozzles. Contrary to air-flames, buoyancy forces can be neglected within $s_{F'} - s_E$ because of the high Froude-numbers. Velocity gradients–equivalent to friction forces–will still exist within a certain wedge of the control space, but the main part of radial momentum can only be diminished by use of a suitable pressure field. This was done–as an approach–for the whole space with variable heights $s_E - s_{0'}$, variable functions $\alpha(x)$ of angle of exhaust streamlines and some density ratios ρ_0/ρ_F. Computations of $(p_E - p_{SF'})/\Delta p_t$ yield remarkably constant values of about 45%. Hereafter height and angle of streamlines were chosen so as to be consistent with mean values of R_E (Fig. 3) found by axial momentum balance, photographed colored flames, and temperature measurements made outside the flame. A typical result is shown in Fig. 4. Agreement between computed and measured "flame pressures" is not satisfying, but is sufficiently good to demonstrate the necessity of pressure increase within the first part of the exhaust and the impossibility of getting accurate flame velocity data by the method of flame pressure.

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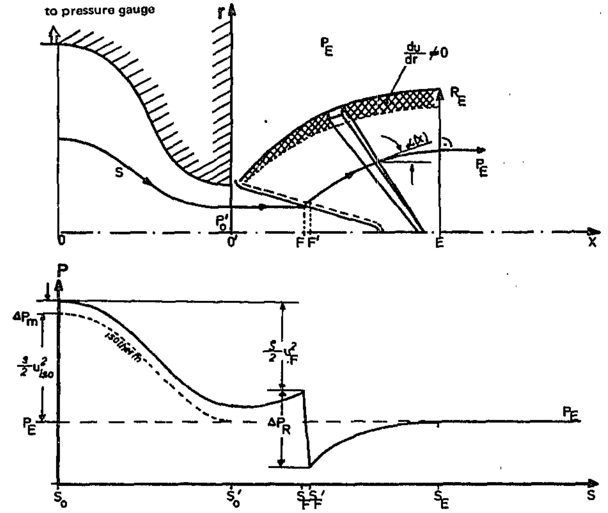

Fig. 3. Path of gas along coordinates s through the nozzle (0–0'), the flame cone (0'–F'), and the control space for momentum balance (F'–E); pressure course below.

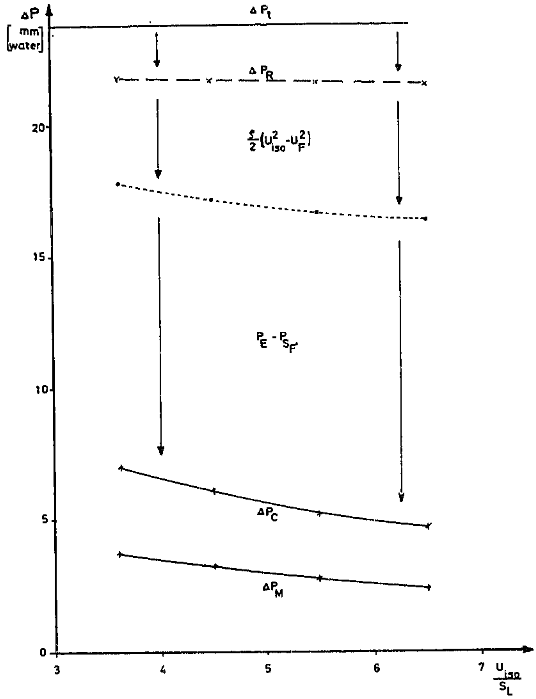

Fig. 4. Pressure relations as function of isothermal cone velocity; CH_4/O_2 at $\phi = 1$; Δp_c computed, Δp_M measured "flame pressures."

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